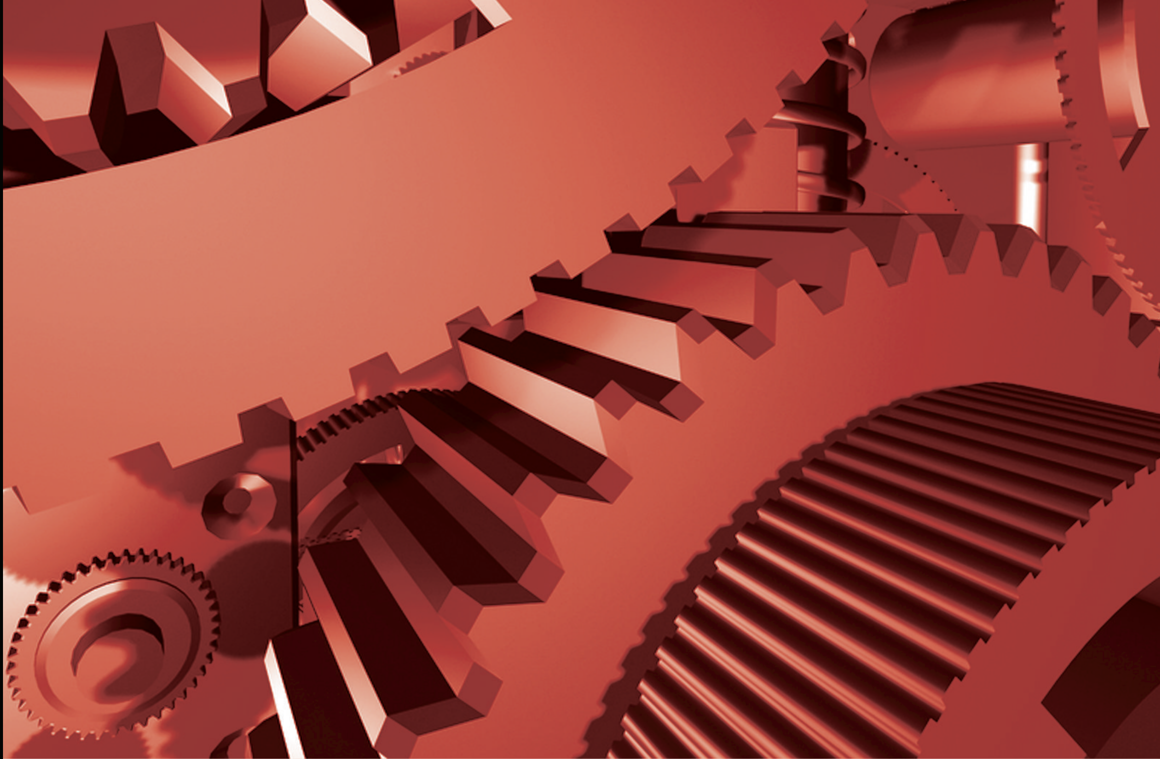

INTEGRATED RELIABILITY

Condition Monitoring and Maintenance of Equipment

JOHN OSARENREN

CRC Press
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Contents

Preface xvii
Acknowledgments xix
Introduction xxi
Summary of Chapters xxv

1. Overview for Condition Monitoring and Maintenance of Equipment in the Industries of the Future 1
1.1 Increasing the Existing Maintenance and Operations of Industrial Equipment Productivity in Plants 1
1.2 Analysis of Maintenance and Operations of Industrial Equipment Productivity in Plants 2
1.2.1 Failure Patterns 3
1.2.2 Causes of Failures 4
1.2.3 Threads between Common Failures 5
1.2.4 Identification and How to Combat the Common Failures of Industrial Equipment in the Industries of the Future 7
1.3 Condition Monitoring and Maintenance of Industrial Equipment in the Industries of the Future 9
1.4 Existing Maintenance Strategies of Industrial Equipment in the Industries of the Future 13
1.4.1 Breakdown or Run-to-Failure Maintenance 14
1.4.2 Preventive or Time-Based Maintenance 14
1.4.3 Predictive or Condition-Based Maintenance 14
1.4.4 Proactive or Prevention Maintenance 15
1.5 Limitations of Existing Condition Monitoring and Maintenance Strategies of Industrial Equipment in the Industries of the Future 16
1.6 Maximum Achievable Reliability Condition and Maintenance Requirements for Part–Process–Equipment System with the TI Technique 18
1.7 Equipment Reliability Degradation and Failure Variation Control with the TI Technique 24
1.8 Equipment Reliability Growth and Optimum Condition Variation Control with the TI Technique 25
1.9 Conclusions 27
References 30

2. Integrated Reliability of Material–Part–Equipment System Life Cycle with the Technological Inheritance Technique 31
2.1 Introduction to Integrated Reliability Condition Monitoring and Maintenance Process of Material–Part–Equipment System Life Cycle 31
2.2 Measuring the Impact of Equipment IRCMM on a Business 35
2.3 Equipment–Part Life Cycle and Phase-Out Conditions 37
2.4 Equipment Failures and Part Replacement System 44
2.5 Measuring the System Reliability Degradation and Rate of Failures with the TI Technique 45
2.6 Concepts and Feasibility of Part Material: Manufacturing Method of Part–Equipment System Reliability Condition Control with the TI Coefficient 46
2.6.1 Corrosion Resistance 47
2.6.2 Wear Resistance 48
2.6.3 High-Temperature Materials 49
2.7 Hard Alloy–Coated Part Surface Quality and Process Performance Variations with the TI Model 50
2.8 Material, Part, and Process Selection for Wear-, Corrosion-, and Temperature-Resistant Applications in the Industries of the Future 52
2.8.1 Material Selection Process 53
2.8.2 Manufacturing Process Selection for Producing Parts with Hard Alloy Surfaces 54
2.8.3 Selection of Equipment Part with Hard Alloy–Coated Surfaces and Reliability CM and Maintenance Data Collection Program 55
2.9 Measurement Points 56
2.9.1 Measurement of Strength and Stress Parameters 56
2.9.2 Measurement of Quality and Failure Parameters during the Manufacturing Processes 57
2.10 Optimum Selection of Parts, Manufacturing Processes, and Industrial Equipment System for Maximum Achievable Reliability with the TI Technique 58
2.11 IRCMM of Material and Manufacturing Processes and Equipment with the TI Technique 59
2.12 Developing Quality, Reliability Growth, Degradation Chain, and Maintenance Cost Program with TI Coefficients 60
2.13 Conclusion 62
References 64

3. Reliability Growth and Degradation of System Condition Monitoring with the Technological Inheritance Technique 65
3.1 Reliability Definitions 65
3.2 Integrated Reliability Theory for Manufacturing Process, Part, and Equipment System CM with the TI Technique............ 66
3.3 Component and System Reliability Growth and Degradation Assessment with the TI Technique 69
3.3.1 Probability of Failure Events with Given Degradation Measures 70
3.3.2 Probability of a Failure Event Considering the Random Component Failure Conditions 72
3.3.3 Dynamics of the System and Component Degradation Process 73
3.4 Maximum Achievable Reliability Requirements of Hard Alloy–Coated Part in the Manufacturing Process and Equipment for Wear- and Other Competing Failure-Resistance Applications 75
3.5 Integrated Reliability CM of the Manufacturing Process and Equipment System 76
3.5.1 Accelerated Reliability Growth, Degradation, and Failure Testing Device with TI Coefficients 78
3.5.2 Quality–Reliability Parameter Selection and Design of Equipment Part and Environmental Conditions 80
3.5.3 Manufacturing Process, Part, and Equipment Reliability CM and Maintenance with TI Model–Based Analysis............ 81
3.5.3.1 Tolerance Factor 81
3.5.3.2 Manufacturing Process Analysis 82
3.5.3.3 Integrated Reliability Testing with TI Model–Based Analysis 82
3.6 IRCMM of Manufacturing Processes and Equipment Mechanism with the TI Model 83
3.7 Quantitative and Qualitative Assessments of Integrated Reliability Coefficient Test 84
3.8 IRCMM with TI Coefficient Assessment for Manufacturing Processes and Industrial Equipment 87
3.9 Reliability Condition Growth Prediction Using Multivariate Quality with the Multivariate Regression Model 88
3.9.1 Reliability Condition Degradation Monitoring of Manufacturing Processes, Parts, and Industrial Equipment with TI Assessment 89
3.9.2 Meeting System Reliability Goal and Requirement with the TI Technique 91

3.10 Setting Integrated Reliability Requirements with Multivariate Regression and TI Models 92
3.10.1 Reliability Requirements 92
3.10.2 Reliability Growth and Degradation Function with the TI Model 93
3.10.3 Cost Function for Manufacturing Processes, Parts, and Equipment with the TI Model 95
3.11 Optimization of Reliability CM and the Maintenance of Processes, Parts, and Equipment with the TI Technique 97
3.12 Developing Reliability Growth and Degradation Improvement Tests for Optimum Component Conditions and the Failures of Equipment with the TI Technique 99
3.12.1 Procedure for Reliability Growth and Degradation Improvement with the TI Model 101
3.12.2 Benefits 101
3.12.3 Capabilities 102
3.13 Conclusions 102
References 104

4. Role of Technological Inheritance Technique for Condition Monitoring and Maintenance of Industrial Equipment 107
4.1 Integrated Reliability Condition Monitoring and Maintenance Assessment with the Technological Inheritance Technique 107
4.2 IRCMM Route with the Mathematical TI Model 110
4.2.1 Technological Chain for IRCMM of Parts, Manufacturing Processes, and Industrial Equipment with the TI Model 111
4.2.2 Analysis of the TI Model for IRCMM of Equipment Using the Regression Equation 113
4.3 Determination of Component Quality and Failure Mode Condition Characteristics with the TI Model 118
4.4 Multiple Mathematical Modeling for IRCMM of Parts, Manufacturing Processes, and Industrial Equipment with the TI Technique 123
4.5 Determination of Component Reliability Degradation and Maintenance with the TI Model 124
4.6 Determination of Component Reliability Growth and Maintenance with the TI Technique 126
4.7 Benefits of the Role of the TI Technique in IRCMM of Manufacturing Processes, Parts, and Industrial Equipment 127
4.8 Conclusion 129
References 131

5. Maximum Achievable Reliability Design for Critical Parts of Equipment with Technological Inheritance Model 133
5.1 Robust Design of Hard Alloy–Coated Part Surface for Wear-, Corrosion-, and Temperature-Resistant Applications 133
5.2 Design of Experiments for Maximum Achievable Lifetime Reliability of Hard Alloy–Coated Critical Part Surface Conditions 134
5.3 Planning the Design of Experiment for Maximum Achievable Quality–Reliability Chain of Critical Parts, Manufacturing Processes, and Industrial Equipment with the Multivariate Regression Model 135
5.4 Statistical Experimental Planning of a Multifactorial Design for Optimum Quality and Reliability of Parts, Processes, and Equipment Conditions 137
5.5 Experimental Plan of the Second-Order Design for Optimum Reliability of Part, Process, and Equipment Conditions 141
5.6 Rotatable Experimental Plan Design for Optimum Reliability of Part, Process, and Equipment Conditions 143
5.7 Multivariate Regression Models for Hard Alloy Workpiece Surface Quality Condition for Wear and Other Competing Failure Resistance Applications by Rotary Cutting with Plasma Flame 144
5.8 Multivariate Regression Models of a Hard Alloy–Coated Part Surface Condition for Wear and Other Competing Failure Resistance Application 147
5.9 Multivariate Regression Model Analysis of a Hard Alloy–Coated Part Surface Condition for Wear and Other Competing Failure Resistance Application 148
5.10 Determination of the Optimum Rotary Cutting with Plasma Flame Machining and Workpiece Surface Quality Conditions for Reliability Requirements 150
5.11 Reliability Requirements and Measurement Characteristics for Integrated Reliability Monitoring and Maintenance of Parts and Equipment with a TI Model–Based Program 154
5.11.1 Reliability Requirements 154
5.11.2 Component and System Reliability Condition Degradation and Failures with the TI Model–Based Design 156
5.12 Reliability Testing and Measurement of Reliability Growth and Degradation of Part, Process and Equipment System with a TI Model–Based Program 163
5.13 Component and Process Performance Condition Profile with the TI Model–Based Design 167
5.13.1 Machining Process Performance Factors 167
5.13.2 Component Surface Quality Factors 167

5.14 IRCMM Mechanisms with TI Coefficients for Wear and Other Competing Failure Resistance Applications 169
5.15 Design Procedures for Integrated Reliability Monitoring and Maintenance of Machine Parts, Manufacturing Processes, and Industrial Equipment with the TI Model–Based Technique 170
5.16 Conclusions 172
References 174

6. Selection of Coating Materials, Parts, and Equipment System with the Technological Inheritance Technique 175
6.1 Characteristics of Industries of the Future 175
6.2 Existing Materials Models and Databases 176
6.2.1 Digital Product and Process Modeling That Impacts Crosscutting Programs 177
6.2.2 Material Reducibility and Affordability 177
6.2.3 Variation and Quality Control with the TI Model 179
6.2.4 Advanced Maintenance Technologies for Component Reliability and Process Performance of the IOFs 179
6.3 Selection of Nickel-Based Alloys for Corrosion-Resistant Applications 180
6.4 Selection of Self-Fluxing Alloy Powders for Wear and Temperature Resistance Applications 181
6.5 Optimum Selection of Materials for Failure-Resistant Coatings with Multivariate Regression and a TI Model–Based Program 183
6.5.1 Mean Time to Failure 186
6.5.2 Mean Time for Corrective Maintenance 187
6.5.3 Maintenance/Repair Cost 187
6.5.4 Failure Rate 187
6.6 Optimum Component/System Reliability Selection 188
6.6.1 Independent Variables 188
6.6.2 Dependent Variables 188
6.6.3 Multiple Quality Parameters of Parts A, B, C (y_i) 189
6.6.4 Conditions of Industrial Processes and Equipment (x_i) 189
6.6.5 Coating Materials for Wear, Corrosion, and High-Temperature Resistance 189
6.6.6 Coating Deposition Techniques 190
6.7 Reliability Testing for Optimum Condition and Failures of Coating Materials with Multivariate Regression and TI Model–Based Design 190
6.8 Conclusions 192
References 195

7. Reliability Growth Condition of Coating Material and Deposition Process with a Technological Inheritance Model–Based Program 197
7.1 Existing Selection of Part Surface Coating Material and Deposition Process for Wear and Other Competing Failure Resistance Applications 197
7.2 Coating Deposition Techniques and Processes for Wear, Corrosion, and Temperature Failure Resistance Applications 199
7.2.1 Thermal Spraying Techniques and Processes 200
7.2.2 Thermal Spraying: High-Velocity Oxyfuel, Arc, and Flame Processes 202
7.2.3 Plasma Spraying 203
7.2.4 Flame Spraying 203
7.2.4.1 Failure Resistant Applications 204
7.2.4.2 Coating Quality 204
7.3 Mechanical Properties 205
7.4 Industrial Experience of Thermal Spraying Processes for Failure Resistance Applications 206
7.5 Recommendations and Its Future 207
7.6 Reliability Test for Growth of Hard Alloy–Coated Materials and Workpiece Surface Optimum Conditions with a TI Model–Based Program 208
7.6.1 Analysis 209
7.7 IRCMM of Hard Coating Materials and Coated Workpiece Part Surface with a TI Model–Based Program 213
7.8 Conclusions 215
References 216

8. Reliability Growth Condition of Machining and Grinding Processes of Hard-Coated Workpiece Surface 219
8.1 Machining Hard Alloy Material and Hard Alloy–Coated Workpiece Surface for Wear and Other Competing Failure Resistance Applications 219
8.1.1 Machining of Nickel-Based Hard Alloy–Coated Part Surface 220
8.1.2 Practical Guide for Machining Hard Alloy Coating Materials 220
8.1.3 Tool Materials for Machining Hard Alloy Materials 221
8.2 Self-Propelled Rotary Tooling 222
8.3 Selecting Surface Finish Processes for Hard Alloy–Coated Workpiece Surface with the Multivariate Regression Model 224

8.4 Multivariate Regression Model for Hard Alloy Workpiece Surface ... 226
8.4.1 Reliability Growth for Hard Alloy–Coated Workpiece Surface Finish with the TI Model ... 227
8.4.2 Optimum Reliability with the TI Model ... 228
8.4.3 Determination of the Optimum Rotary Cutting with Plasma Flame and Workpiece Surface Quality Conditions ... 231
8.5 Surface Finishing with Grinding Hard-Coated Machine Part Surfaces ... 238
8.5.1 Surface Finishing Method of Grinding Hard Alloy Coating Materials ... 238
8.5.2 Endurance Limit ... 239
8.5.3 Disadvantages of Finishing Hard Alloy Materials with Grinding ... 240
8.5.4 Neural Network Modeling with the TI Technique ... 241
8.5.5 Advantages of Rotary Cutting with Plasma Spray for Machining Hard Coatings and the TI Model ... 242
8.6 Benefits of Machining Hard-Coated Precision Machine Part Surfaces with Rotary Cutting Plasma Spray and the TI Model ... 243
8.7 Critical Features Produced by the Surface Finish of Nickel-Based Hard Alloy–Coated Part Surface ... 245
8.8 Integrated Reliability Testing for Reliability, Optimum Growth, Degradation, and Failure of Hard-Coated Machine Part Surface during Machining and Grinding Processes with the TI Model ... 248
8.9 Integrated Reliability Monitoring and Maintenance of Processes, Parts, and Equipment with a TI Model–Based Program ... 249
8.10 Conclusions ... 251
References ... 253

9. Reliability Growth, Degradation, and Fatigue Failure of Nickel-Based Hard Alloy–Coated Part Surface ... 255
9.1 Failure Analysis of Mechanical Components ... 255
9.2 Definitions of Failure Characteristics ... 257
9.3 Types and Categories of Failures ... 258
9.4 Physics of Fatigue ... 259
9.5 Characteristics of Fatigue Failures ... 261
9.6 High-Cycle Fatigue ... 262
9.7 Probabilistic Nature of Fatigue ... 262
9.8 Low-Cycle Fatigue ... 263
9.9 Fatigue and Fracture Mechanics ... 263

9.10 Factors That Affect Fatigue Life and Its Resistance to Failure 264
9.10.1 Tensile and Compressive Mean Stress.... 266
9.10.2 Surface Treatments 267
9.10.3 Sequence Effects.... 267
9.10.4 Manufacturing Methods.... 267
9.10.5 TI.... 268
9.11 Parameters of Component and Process Condition for Fatigue Reliability Analysis.... 268
9.11.1 Geometry 269
9.11.2 Loading 270
9.11.3 Material 270
9.11.4 TI.... 270
9.12 Fatigue Prediction and Lifetime of Component Analysis 271
9.12.1 Stress Concentration.... 272
9.12.2 Stress Measurement.... 273
9.12.3 Load Spectrum 273
9.12.4 Stress Life–Based Damage, Reliability Growth, and Degradation Estimation 273
9.12.4.1 Material *S–N* Curve 273
9.13 Reliability Fatigue Analysis with Modular and Virtual Instruments Using the TI Technique 274
9.14 Fatigue Results.... 275
9.15 Moving from the Physical to Virtual Assessments of Materials, Parts, and Equipment with the TI Technique 276
9.16 Criteria for Virtual Assessment of Fatigue Reliability with the TI Technique 277
9.16.1 Criteria of Customer's Requirements and Demands.... 277
9.16.2 Criteria of Durability or Reliability.... 278
9.17 Design for Maximum Achievable Fatigue Reliability with the TI Technique 279
9.18 Fatigue Reliability Test, Measurement, and Virtual Assessment of Manufacturing Processes and Equipment with a TI Model–Based Program.... 280
9.19 Conclusions.... 285
References 287

10. Reliability Degradation, Wear, and Competing Failure Modes of Nickel-Based Hard Alloy–Coated Part Mating Surface 289
10.1 Resistance to Wear and Competing Failure Modes of Equipment 289
10.2 Types of Competing Failure Modes with Wear for Industrial Equipment and Their Preventive Techniques.... 290
10.3 Wear Factors and Mechanisms of Equipment.... 292

10.4 Wear Reliability Degradation and Failure Concept with TI Coefficients 293
10.4.1 Effects and Control of Wear with TI Coefficients 293
10.4.2 Wear Failure Analysis of a Tribosystem with TI Coefficients 296
10.5 Maximizing the Wear Resistance and Reliability and Minimizing the Failures of Parts in Equipment with the TI Model 298
10.5.1 Mating Part Surfaces and Wear Condition Monitoring and Maintenance Technology with the TI Model 299
10.5.2 Component and Process Reliability Condition Monitoring and Maintenance of a Tribosystem with the TI Model 300
10.6 Wear and Wear Resistance Coefficient Testing with TI Coefficients 301
10.6.1 Component and Process Conditions of Industrial Equipment with a TI Model–Based Program 301
10.6.2 Wear and Competing Failure Test Analysis with the TI Model 307
10.7 Integrated Reliability Curve Analysis for Wear Resistance Degradation and Competing Failures of Equipment with the TI Model 310
10.8 Conclusions 314
References 316

11. Integration of Reliability, Condition Monitoring, and Maintenance of Industrial Equipment 317
11.1 Existing Preventive and Predictive Maintenance Program of Equipment 317
11.1.1 Reliability Condition Monitoring and Maintenance Tasking 317
11.1.2 Getting Started on the Preventive Maintenance Improvement Process 318
11.1.3 Guidelines for Improving a Preventive and Predictive Maintenance Program 319
11.2 Improving the Existing Preventive and Predictive Maintenance of Parts, Processes, and Equipment with an IRCMM Program 323
11.3 New Concept of Preventive and Predictive Maintenance Program with a TI Model–Based Program 324
11.4 Integrated Reliability Monitoring and Maintenance Characteristics with a TI Model–Based Program 325
11.4.1 Function-Based Maintenance Approach 326
11.4.1.1 Scheduled Restoration and Scheduled Discard Tasks 329

11.4.2 Component-Based Maintenance Approach 330
11.5 Integrating Component and Process Function Condition–Based Maintenance with the TI Model 331
11.6 Integrating Reliability CM of Parts, Manufacturing Processes, and Equipment with a TI Model–Based Program 336
11.7 Integrated Reliability Monitoring and Maintenance Curve with the TI Model 337
11.8 Developing Cost-Effective IRCMM Programs for Manufacturing Processes, Parts, and Industrial Equipment with the TI Model 340
11.9 Benefits of Integrating Reliability, CM, and Maintenance of Manufacturing Processes and Industrial Equipment with the TI Model 341
11.10 Conclusions 343
References 344

12. Integrated Reliability of Equipment with a Technological Inheritance Model–Based Simulation Technique 345
12.1 Computer Simulation with the Technological Inheritance Model for Integrated Reliability Monitoring and Maintenance of Manufacturing Processes and Industrial Equipment System 345
12.2 Developing an Intelligent Multivariate Sensor for Measuring and Monitoring Tool Wear, Workpiece Quality, and Machining Process Performance 346
12.2.1 Machining Process CM System of a Hard Alloy–Coated Workpiece Surface with a TI Model–Based Simulation 350
12.2.2 Object-Oriented Simulation Model in an Automatic Control Software Development Framework with the TI Technique 358
12.3 TI Model–Based Simulation Program for IRCMM of Parts and Equipment in the Industries of the Future 363
12.3.1 Software Process Control Limits 363
12.3.2 Software Process Anomalies 363
12.3.3 Software Sensibility 364
12.3.3.1 Software Process and Component Control Limits 364
12.3.3.2 Process Anomalies 365
12.3.3.3 Software Sensibility 365
12.4 TI Model–Based Software Program 367
12.5 Determination of the Control Limits and Threshold Points with the TI Technique for IRCMM of Parts, Processes, and Equipment 368

12.6 IRCMM of Manufacturing Processes and Equipment Distribution Curve with the TI Model 371
12.7 Algorithm for IRCMM of Machine Part, Manufacturing Process, and Equipment System with a TI Model–Based Simulation Program 372
12.8 Conclusions 375
References 376

13. Integrated Reliability with a Technological Inheritance Model–Based Program in the Industries of the Future 379
13.1 Role of Technological Inheritance–Model Based Programs for Integrated Reliability Condition Monitoring and Maintenance of Manufacturing Processes and Equipment 379
13.2 IRCMM Technology of Critical Parts, Processes, and Rotating Equipment 380
13.3 Instrumentation of IRCMM Technology with a TI Model–Based Program 382
13.3.1 IRCMM Tools with a TI Model–Based Program 384
13.3.2 Development of Instruments and Data Acquisition and Analysis and Presentation of Software for IRCMM Technology 386
13.4 Integration of Acquisition, Analysis, and Presentation of Data with a TI Model–Based Software Program 389
13.5 IRCMM Tools with TI Coefficient Variation Control Limits 391
13.6 Integrated Reliability Condition Monitoring Tools and Features of Parts, Processes, and Industrial Equipment with a TI Model–Based Program 394
13.7 Component and Process TICSs 395
13.8 TI Coefficient Transfer Function for Communication Networks and Signal Processing 396
13.9 Cost-Effective Integrated Reliability Condition Degradation Monitor for the Detection of Distributed Defects and Failures in Parts and Industrial Equipment with a TI Network System 399
13.10 Real-Time Component and Process Data Acquisition and Automation with a TI Model–Based Software Program 401
13.11 IRCMM of Hard Alloy Critical Part Surfaces with a TI Model–Based Program in the Industries of the Future 402
13.11.1 Power Plant Monitoring 402
13.11.2 Oil Refinery 403
13.11.3 Rolling Mill 404
13.11.4 Other Applications 404
13.12 Conclusions 405

14. Integrated Reliability with a Technological Inheritance Model–Based Network Program in the Industries of the Future 407
14.1 Integrated Reliability Condition Monitoring and Maintenance Strategies 407
14.2 Working Conditions of the IRCMMS with the TI Coefficients ... 411
14.2.1 Component and Process Condition Variations 411
14.2.2 Applicable Monitoring and Maintenance Tasks 412
14.3 Application of the IRCMMS with a TI Model–Based Software Program 413
14.4 Online Monitoring and Maintenance with a TI Model–Based Program 415
14.5 Integrating Critical Component Reliability with a Process Control System Using the TI Model–Based Program 418
14.6 IRCMM Curves for Manufacturing Processes, Assembly Process, and Industrial Equipment 420
14.7 IRCMM for a Typical Turbine with the TI Model–Based Program 424
14.8 Conclusions 426

15. Integrated Reliability Management with a Technological Inheritance Model–Based Program in the Industries of the Future ... 429
15.1 Effective Reliability Condition Monitoring and Maintenance Management with a Technological Inheritance Model–Based Program 429
15.2 IRMMM for Manufacturing Processes and Industrial Equipment Systems 431
15.3 IRMMM Tasks with a TI Software Program for Manufacturing Processes, Parts, Industrial Equipment, and Sensor System 434
15.4 IRCMM Technology of Manufacturing Processes, Parts, and Industrial Equipment with a TI Device Manager Software 441
15.5 Functions of a Device Manager 442
15.6 Efficient Hardware System for the Management of Integrated Reliability Monitoring and Maintenance Technology 445
15.6.1 Efficient Device Management Software for IRCMM Technology 449
15.7 Management of IRCMM Technology with a TI Model–Based Program 452
15.8 Benefits of IRCMM Management Systems with a TI Software Program in the Industries of the Future 456
15.9 Conclusions 459

Preface

This book contains 15 chapters and highlights the solutions to common failures and reliability problems of equipment in the industries of the future (IOF) through an integrated reliability condition monitoring and maintenance (IRCMM) with a technological inheritance (TI) model–based program. This program relates all the operating conditions of a critical machine and equipment part or a group of generic parts throughout its life cycle, starting from design through to actual service application. A mathematical relationship of desired operating processes and workpiece conditions is developed as a multivariate regression model that relates with its machine/equipment part failure mechanism. A design of experiment has been used to assess rotary cutting and turning with plasma flame conditions of a hard alloy–coated workpiece surface for wear and other competing failure resistance applications and to develop a multivariate regression model. The multivariate regression model has been used to predict the optimum quality data of a shaft in a bearing–shaft assembly in rotating equipment, while the optimum data are used as the initial characteristic inputs for determining parts and equipment life and reliability with the help of the TI model. The TI coefficients are used to transfer and control component and part quality from the initial (optimum metallurgical condition, optimum hard alloy coating deposition condition, and optimum new machine/equipment condition with an optimum part surface finish condition) to final operation (functional failure condition). The IRCMM with a TI model–based program is used to select desired components; predict maximum achievable reliability of components and systems and the time and conditions of part failures; detect failures; determine reliability degradations, and potential and functional failures; and calculate life cycle, warranty, and maintenance costs. Each chapter describes how the set objectives of the book are implemented accordingly, which results in the following:

- A solid comprehensive and analytical overview of operations and maintenance that offers a viable and cost-effective platform for an IRCMM program of manufacturing processes and equipment in the IOFs
- Improvement of the material–part–equipment system life cycle, reliability conditions, and manufacturing process productivity for wear, corrosion, and temperature resistance applications
- Maximizing the component and system reliability growth of parts and equipment and minimizing reliability degradation at minimum

life cycle and maintenance costs within the framework of a condition-based maintenance

- The role of the TI technique for IRCMM of industrial processes and plant equipment
- Developing a robust design for IRCMM of industrial processes and equipment with the TI technique
- Selection of coating materials, parts, and equipment system with IRCMM with the TI technique
- Maximizing the reliability growth condition of coating material and deposition process with a TI model–based program
- Maximizing the reliability growth condition of machining and grinding processes of a hard-coated workpiece surface with a TI model–based program
- Minimizing the reliability degradation and fatigue failure of a nickel-based hard alloy–coated part surface with a TI model–based program
- Analyzing the reliability degradation, wear, and other competing failure modes of a nickel-based hard alloy–coated part mating surface with a TI model–based program
- Integrating reliability, CM, and maintenance of parts, manufacturing processes, and industrial equipment with a TI model–based program
- Developing integrated reliability condition and maintenance technology for manufacturing processes, parts, and industrial equipment with the TI model–based simulation technique in the IOFs
- Introduction of a cost-effective integrated reliability monitor and maintenance strategy with a TI model–based software program
- Management of IRCMM of manufacturing processes, parts, and industrial equipment in the IOFs

Based on these outstanding results, this book introduces a cost-effective integrated reliability growth monitor, integrated reliability degradation monitor, TI coefficient sensors, and a maintenance tool that supplies real-time information for predicting and preventing potential failures of manufacturing processes and equipment from the seat of an asset manager, a maintenance user, and an operator. This book can be used by maintenance, operations, and production engineers; researchers; industrialists; and students to plan, analyze, monitor, select, predict, measure, test, and design maintenance models.

The book has been written for easy understanding both in text and illustrations so that readers can benefit fully and be able to transform data into useful information toward a sustainable development in reliability CM and maintenance organizations.

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Introduction

The industrial benchmark of component quality, process performance, and system reliability standards coupled with worldwide competition has put today's industrial plants, parts, and equipment under intense financial pressure, while operations and maintenance budgets are usually among the first to be cut. This type of trend presently shows no sign of changing, which means that plants, processes, parts, and equipment must therefore increase the productivity of their existing manufacturing, maintenance, and operations teams while continuing to look for ways to reduce life cycle, monitoring and maintenance costs, waste, energy, and the common failures from the IOFs.

Fortunately, there are still opportunities for reliability improvement in almost every operation from design through manufacturing to service application. Industry benchmarks can help estimate the potential in plants, manufacturing processes, and equipment, but it is still necessary to keep the plant and equipment running smoothly and safely, with the goal of using a maintenance budget, personnel, and tools more efficiently, and thus spend less, maintain, and also improve plant, process, and equipment reliability. Greater productivity, reliability, and economic benefits are possible when operators have the tools and information to continuously optimize quality, reliability, and other economic factors for the loops they control and to reduce monitoring and maintenance costs of parts and equipment. Many of the factors that affect plant, process, and equipment economics change frequently from raw material costs to market demand for process, part quality, and reliability outputs. In an ideal world, operators would constantly adjust energy and feedstock sources, product mix, equipment used, and other variables to optimize the economic performance of the plant. In the real world, however, operators seldom get any real-time feedback on the economic, quality, and reliability effects of their actions. They could be unaware that they are losing a lot of money by running the plant, equipment, and machines at suboptimal operating conditions. Even if they have the information, they may not have the tools needed to evaluate complex interactions between design, manufacturing, and equipment condition variables and to determine the best operating points or optimum operating conditions before it changes again toward failures and catastrophic damages.

Predictive maintenance, failure situation prevention, economic optimization, and similar cost-effective strategies offer clear productivity and cost benefits. But predicting potential failures, random failures, and functional failures as well as the effect of changing conditions requires a constant flow of real-time information, not just about the process, but also about the different components and parts of equipment that make it work.

This is actually something traditional automation architectures cannot easily provide. Industrial plants, processes, and equipment are therefore being hampered by the existing automation architecture that cannot supply the real-time data needed to predict failures and prevent potential failures in the maintenance of manufacturing processes, parts, and equipment.

The industries that practice predictive maintenance rely on the vibration monitoring approach, which of course presently provides best results that are expensive to achieve and can only point to failures and defects of the system, but cannot locate the area or detect the cause of the failure. This approach can be replaced with a cost effective condition-based approach that enhances the quality and reliability of components/systems.

Knowing the quality, reliability, and failure conditions of equipment and detecting the locations of failures, the nature and cause of equipment failure go beyond the functions of traditional reliability-centered maintenance, especially when they have to do with the reliability of parts and components of equipment throughout their entire life cycle. This is the question that drives the author to provide a sustainable solution with IRCMM of manufacturing processes, parts, and equipment with a TI model–based program.

The process of identifying or determining, analyzing, and addressing the causes of failure should begin early, before we have anything to test, continue during developmental and operational testing, and continue into actual use, hence the need for a TI model–based program. The TI model–based program that includes design of experiments, parameter design, and statistical design characteristics, such as component stress–strength interference, is a modern progressive automation architecture that provides constant flow of real-time information throughout design, manufacturing, and operations.

The TI technique is the transference of the properties or qualities of a component from the initial design through manufacturing processes to the final stage in the equipment process. It has been used in this book to develop a multivariate regression model and to select a power model that relates all similar components, parts, equipment, and parameters of a particular system together under a single platform. It has also been used to design sensors that measure reliability growth and degradation and monitors that keep track of potential, random, and functional failures, while the designed diagnostics help detect and determine the root cause of failures and control their variations from operation to operation at any point in time to suit a desired manufacturing function and service application and also to optimize process and system conditions.

This technique has been very useful in the optimization of rotary machining and turning with plasma flame on a hard-coated surface that provided benchmark reliability requirements, accelerated testing measures, and real-time reliability integration results of a workpiece, rotary tool bits, and machine tool conditions with the main control system that leads to maximum benefits in the IOFs. The TI model has helped maximize system reliability and minimize failures at minimum maintenance cost and also integrate reliability, CM, and maintenance under a single platform with an automated control system.

The integration of automated process control systems and component reliability monitoring systems was done with the help of the TI model in this book. The TI model is used to transfer the optimum quality and reliability characteristics of a critical part from the initial to the final stage of a reliability CM and maintenance process. The model is also used to correlate the optimum preceding operation and the next proceeding operation with the quality conditions of a critical part in a CM and maintenance route technology. The aim of this book is therefore to optimize the machining process condition of a hard alloy–coated cylindrical critical part surface and transfer the optimum component quality conditions from an initial operation to the final operation for wear and other competing failure resistance applications with the IRCMM program, which is achievable with the implementation of the objectives of this book.

The IRCMM of manufacturing processes, parts, and equipment with a TI model–based program has provided long-lasting solutions to the challenges facing vibration monitoring techniques and other modern condition-based maintenance and monitoring systems.

Summary of Chapters

Chapter 1: Overview for Condition Monitoring and Maintenance of Equipment in the Industries of the Future

Industry sustainability, global competition, and the need to maximize equipment reliability require the integration of reliability CM and maintenance precision practices with a cost-effective assessment technique. It is essential for the IOFs, which account for more than 80% of the energy consumed and more than 90% of manufacturing wastes that are also capital intensive, face global competition, are cyclical, produce commodity products, and have mature markets. The need to identify the common failures of parts and equipment such as wear, corrosion, and high temperature is quite desirable and reliable. The reliability of parts and components in most industries cannot be readily and timely assessed by operators, thereby lacking the knowledge of the impacts that they have on the overall effectiveness of equipment, and as such, potential failures and defects are left undetected until they become functional failures that cause catastrophic damages. Equipment part defect and failure issues are indeed largely the result of manufacturing process–induced anomalies, which need to be combated with the help of integrated reliability protection, reliability CM of potential failures, and maintenance prediction operations together for added value to the individual protection and prediction systems that have become islands of information in the different IOFs.

Existing manufacturing processes for producing a hard alloy–coated workpiece surface do not offer clear productivity and cost benefits; also, the traditional maintenance and operation automation architecture cannot easily provide the required constant flow of real-time reliability information for parts and components that make it work. Although industrial experience has proved that a faster time to market can provide competitive advantages and economic benefits to most part and equipment manufacturers, such drive should not be allowed to negatively impact component quality, reliability of industrial equipment and architecture, and their maintenance strategies. The process control system of the traditional automation architectures cannot show much more than the process variables and any associated trends or alarms, thereby providing no way to monitor part and equipment failures and as such offering no way to detect the early-warning signals of potential failures that eventually lead to wear, corrosion, and high temperature during manufacturing processes and component conditions.

In this modern stage of scientific and technological development, the demand for wear, corrosion, high temperature, strength, reliability, and other characteristics of hard alloy coating materials is fast increasing in such a manner that the traditional machine tool-bit material can no longer deliver high machining productivity, which eventually ends up in suboptimal surface quality/reliability of parts and equipment. Traditional methods of increasing tool life for machining a hard alloy–coated part surface are not reliable and cost-effective, and there is therefore a need to work out a cutting and machining method that is based on new principles of interaction between tool bits and workpiece on a lathe machine tool. The use of standard automation tools, optimum selected hard alloy coating materials, and process condition can help speed up part development time with fast cutting and machining methods, reduce errors and defects, and increase service life and profit margins while ensuring high quality and reliability designs at minimum life cycle and maintenance costs. The author introduces a modern cutting and machining method that will be implemented in this book for accelerated lifetime reliability testing, machining cutting, and turning of hard-coated workpiece surfaces to provide maximum part quality, equipment lifetime reliability, and tool life cycle and maintenance costs, providing optimum baseline/standard, global benchmark, and requirements. The optimization of these new progressive testing, cutting, and machining method conditions would provide the optimum quality–reliability–performance/life baseline and requirement data for operating manufacturing processes, parts, and equipment and monitoring and maintenance systems.

The analysis of the existing reliability CM and maintenance of manufacturing processes, parts, and equipment system revealed that most failures were not age related, where the equipment failed because of length of use, which meant that time-based preventative maintenance is pointless in most cases, but requires reliability condition–based maintenance throughout a critical part life cycle for higher reliability, life, and effectiveness of equipment. A critical equipment part that is properly manufactured with optimum process conditions for wear, corrosion, temperature, and other failure resistance applications and installed into equipment without any errors will operate at the highest level of reliability and performance, which ideally is at its design requirement, but as the life performance progresses, degradation and failure are bound to occur, which require reliability CM and precision maintenance strategy to combat the degradation in order to sustain the desired high-level reliability/performance with minimum maintenance cost. Existing vibration CM of equipment and analysis is presently the most effective way to evaluate component and system reliability for achieving the best precision maintenance practices, extend equipment longevity and reliability, and avoid unplanned shutdowns. But the existing vibration technique is expensive and cannot be used to detect early potential failures and cannot be used to select cost-effective components (materials, manufacturing processes, and equipment and conditions) to suit desired requirements.

Integrating component reliability with process performance condition control for greater benefits is possible with the technological inheritance (TI) technique, which is used to control and measure the varying process performance and component quality conditions. The TI technique can be applied to all desired critical components of manufacturing processes, materials, parts, equipment, and maintenance strategies, including energy impacts, vibration, measurement points, and part construction to determine the maximum reliability, performance, and life at minimum maintenance cost. The TI technique is a new and advanced integrating reliability growth and degradation assessment technique that allows the simulation of different operating conditions in the algorithm to be tested over a wide range of conditions safely and on demand in the laboratory and can also easily repeat the test to compare and fine-tune codes without leaving the laboratory, which is a highly essential step toward a sustainable development in reliability CM and maintenance of industrial equipment. A TI simulation program can be used to measure and test component reliability growth for maximum reliability of parts and equipment assessments and also reliability degradation that leads to failure of industrial equipment at minimum life cycle cost. The TI software program is used for cost-effective reliability testing, design, maintenance, and management in the IOFs. The application of a TI software program as a model and hardware in loop-based network systems can be used to debug, test the code, evaluate control, monitor the condition, and provide optimum condition requirements for cost-effective maintenance and management of industrial equipment in the desired IOF.

Chapter 2: Integrated Reliability of Material–Part–Equipment System Life Cycle with the Technological Inheritance Technique

The integrated reliability condition monitoring and maintenance (IRCMM) process focuses on continuous improvement throughout the life cycle of industrial equipment for wear and other competing failure resistance applications. The goal of continuous improvement requires CM of lifetime reliability growth/degradation, quality, and cost of parts and materials throughout the life cycle to attain maximum achievable reliability of industrial equipment with minimum operating, maintenance, and life cycle costs. The IRCMM process comprises manufacturing processes and an equipment system that consists of parts and components that make it work toward achieving optimum lifetime reliability in aggressive media of wear, corrosion, and high temperature failure modes.

A hard alloy–coated shaft surface of a bearing–shaft assembly in a system can provide maximum achievable surface quality and reliability for industrial equipment. Selected self-fluxing powder coatings based on nickel are recommended as hard alloy materials for hardening and reconditioning surfaces of rapid wearable shafts working in aggressive media, wear, and high-temperature conditions. The wear resistance requirements of this type of hard coating in frictional contact with steel (friction of boundary lubrication) is four to nine times higher than the wear resistance of steel in steel–steel pairs and steel–iron pairs under specific loads of 1.5×10^6 to 10×10^6 Pa and sliding velocities of 8–54 m/min; within this range, the amount of wear of steels working in pairs with hard coatings is reduced by a factor of 1.5–2.5 times. The friction coefficient in pairs of hard coating–steel with initial roughness number Ra = 0.16–0.3 μm is 1.8–2.2 times lower than in pairs of steel–steel, but with constant surface roughness, the amount of wear is 2–10 times reduced.

The optimization of hard alloy quality–reliability–performance–life chain structure forms the basis for understanding the best manufacturing, monitoring, maintenance, and operations for improving shaft and equipment reliability as well as the life cycle cost of the improvement. The measurement of integrated reliability monitoring and maintenance impact of manufacturing and equipment on a business further reveals a different definition from the traditional definition of reliability toward reliability improvement. An assembly of parts can never be more reliable than its least reliable part or process in a quality–reliability–performance–life chain structure. The least reliable manufacturing process, which is the machining of a hard alloy–coated shaft surface, requires a new progressive method for maximum achievable quality and reliability. The new progressive machining process condition is optimized with the design of experiment to develop a multivariate quality regression model. The optimized machining process condition and the shaft hard alloy–coated surface quality parameters are used for integrated reliability monitoring and maintenance of manufacturing process and equipment with TI coefficients.

TI coefficients are used to determine the optimum reliability of equipment part design, the quality of manufacture, the precision of its assembly/installation, and the purchasing and storage quality control, along with the standard of monitoring/maintenance and workmanship care. Component reliability growth, degradation, and its optimum threshold data can be measured with the TI coefficient, which is deduced with a multivariate quality regression model. Equipment reliability degradation, mean time to failure, and its failure threshold data can be measured with the TI coefficient, which is deduced with the help of the TI model. Component multivariate quality–reliability growth–degradation modeling can be used to select optimum parameters, part conditions, and costs and monitor the strengths and failures of materials and component. Equipment quality–reliability degradation with the TI model is used to detect failed parts and to monitor the stress, defects, reliability degradation, and failures from *rough operation* induced by poor operating practices and bring likely implications on production to the attention of operation and plant managers. The IRCMM process outcome with the desired target is possible with the integrated reliability coefficient that is used to plot quality/reliability–performance/life curves that help us understand the extent of the risk placed on components, parts, and equipment by human activities in the different IOFs.

Chapter 3: Reliability Growth and Degradation of System Condition Monitoring with the Technological Inheritance Technique

This chapter highlights the essence of combining two different definitions of reliability to formulate and achieve the objectives of IRCMM of processes, parts, and industrial equipment toward a positive impact on people, business, and system/component reliability improvement. The two different reliability definitions are applied under a single TI model–based platform. Integrated reliability is defined as the ability of a component/system to perform a required function under stated conditions and to determine and evaluate the maximum achievable process performance and component quality condition of a system, within a specific period of time and operating condition with minimum life cycle costs. The TI technique integrates the definitions that are used to optimize IRCMM of parts, manufacturing processes, and equipment, which will help increase the lifetime and failures of parts/equipment in aggressive applications of different IOFs. This solid theory of reliability and engineering technique applied in this chapter provides the foundation for developing reliability requirements of materials, manufacturing processes, parts, and industrial equipment through a cost-effective integrated reliability monitoring and maintenance program with the TI technique that performs appropriate reliability analyses, tests, and tasks to ensure that wear, corrosion, and high temperature resistance parts can meet their desired goals.

The goal of this work is to attain the maximum achievable reliability of hard alloy–coated part surface designed to resist wear and other competing failure modes operating in aggressive applications and sustain optimum quality part condition from initial to final equipment reliability for a specific desired lifetime at minimum life cycle costs. The maximum achievable reliability requirements of a hard alloy–coated part in equipment at minimum costs in aggressive applications are possible with an IRCMM with a

TI model–based program that helps extend the part life to maximum and time to failure and cost-effectively perform maintenance tasks. IRCMM with a TI model–based program helps detect and fix potential/functional failures (defects, degradations, premature failures, errors, infant mortality failures, random failures, etc.) early from the design of wear and other competing failure resistance parts through manufacturing processes to its final service operations in operating rotating equipment for aggressive media of the IOF.

A multivariate surface quality regression model is developed to predict the optimum part quality and process performance conditions as well as wear, corrosion, and high temperature failure modes during the machining of a hard-coated mating part surface. The application of this regression model creates the foundation for relating and integrating all the operations involved in the system together under one platform, where the optimum finished quality condition of part data are used as initial reliability data and start-up conditions of an equipment or machine. TI as a degradation assessment model is used to control the optimum data variations for a lifetime reliability and the condition threshold data of parts and equipment for its failures and determine the operating performance control limits and also transfer data from operation to operation or from point to point within an operation. The TI model can also be used to design a TI coefficient sensor and integrated reliability monitor, to test for optimum selection of maintenance strategies, and to detect system/component potential and functional failures.

The TI coefficient sensor is used to measure reliability growth that selects the optimum conditions of parts, processes, and equipment and measure reliability degradation for detecting the failure conditions of parts and equipment, while the integrated reliability monitor is used to monitor and fix potential/functional failures. The application of TI coefficient sensors (TICSs) and integrated reliability monitors under a single IRCMM program will help improve reliability, CM, and maintenance and provide the necessary tools to operators and maintenance personnel for maximum achievable reliability at minimum life cycle and maintenance costs.

Chapter 4: Role of Technological Inheritance Technique for Condition Monitoring and Maintenance of Industrial Equipment

Researchers have shown that many of the quality parameters of parts and equipment are formed not only during the finishing operations of a manufacturing process but also during its initial operations toward maximum achievable component and system reliability, which can be assessed with the TI technique. The TI technique is used to determine the properties of a component that make it unique within its class to achieve maximum part reliability and process performance from initial to final operation in a technological–manufacturing system of the IOFs. In any manufacturing, monitoring, and maintenance process, there is a high frequency of negative inheritance from the initial qualities of a workpiece operation (errors in shapes, surface roughness, surface stress, etc.), and it is also possible to inherit positive qualities (surface hardness, strength, etc.), which are transferred to the final manufacturing operation and in turn sustained over a long time during equipment or service operations.

The optimum selection of part, manufacturing process, and equipment condition parameters with the TI technique can definitely help maximize component/system reliability, process performance, and service lifetime and minimize failure and maintenance costs. The technique is followed up in such a way that the desired quality of parts that positively influences its service life, system/component reliability, and process performance is kept during the period of development so that the negative defect and failure traits are eliminated early in the initial operations as well as throughout the service operations. A multivariate quality regression model of a hard alloy–coated part surface provides the initial optimum component quality data for the TI model to develop an IRCMM program for manufacturing processes and industrial equipment as well as for its real-time testing and control of component/system reliability during operations. The technological chain series of an integrated reliability monitoring and maintenance program consists of a series of manufacturing processes and service equipment operations that can produce the desired part surface quality/reliability and process performance condition parameters. The chain condition is optimized during the manufacturing surface finish process, and the optimized condition is transferred to the next proceeding equipment operation where the optimum service lifetime and reliability of components are sustained for an optimized IRCMM period of time by a cost-effective maintenance strategy with the help of the TI technique.

A multivariate quality regression model provides the foundation for an integrated reliability monitoring and maintenance program for critical rotating equipment as well as for the optimization process and the use of the initial optimum data for implementing the TI model for real-time operations and assessments. The model is used to select and integrate the most appropriate hard alloy–coated mating part surface quality parameters and process performance factors during the design stage and select optimum materials, manufacturing processes, parts, equipment, and instruments throughout the different stages of operations. It is also used to test the degradation rate of the quality of parts and the process performance degradation rate as well as the failures of parts, equipment, and instruments in a technological system. The results of the test are used to determine the reliability of parts, equipment, and instruments, their remaining lifetime, and the process performance; detect failures; identify the failed parts and the failure modes; and plan and schedule predictive maintenance.

In an IRCMM program, the component/system quality and reliability degradation rate and the performance change rate do correspond with a particular desired period, and this can be assessed, measured, and calibrated with the help of the TICS and monitored with an integrated reliability monitor. The initial hard-coated part surface quality and reliability growth/degradation rate, which is directly related to the rate of change of process performance parameters, are incorporated into process conditions to serve as the input data during service operations with the help of the TI model. The TICS and integrated reliability monitor are used to assess, control, and evaluate component/system reliability degradation with an initiation time and failure growth time toward maximum achievable lifetime reliability and minimum maintenance cost. The knowledge of the roles of the TI technique has helped obtain full benefits of IRCMM of manufacturing processes, parts, and industrial equipment.

Chapter 5: Maximum Achievable Reliability Design for Critical Parts of Equipment with the Technological Inheritance Model

A robust reliability component is one that works as required regardless of variations in the manufacturing process, mating hard-coated part, or equipment system resulting from deterioration, defects, and failures during operations, within a specific period of time. Since the relationship of the hard alloy–coated part, process, and equipment models for wear resistance applications is unknown, it is necessary to use design of experiments to develop a multivariate regression model to achieve optimum quality values toward a more robust design.

A multivariate regression model for materials and hard-coated parts is developed in this chapter to predict the multiple component quality and process performance condition parameters for wear and other failure resistance applications.

These multiple component quality and process performance condition parameters are optimized with the application of the TI model to provide the best wear-resistant mating part surface, as well as for the best reliability requirements for components, processes, and equipment of the manufacturing, monitoring, and maintenance systems. Design of experiments with the TI model is used to desensitize a component's reliability and process performance characteristic variation in critical hard alloy–coated mating part, process, and equipment system design parameters.

The TI model has been applied in this chapter to select, integrate, test, and validate the reliability design of an experiment for maximum achievable reliability of hard alloy–coated mating parts, processes, and industrial equipment. IRCMM with the TI model program is used for optimum selection, test for the failures of hard alloy–coated critical parts, hard alloy materials, manufacturing processes, industrial equipment, and reliability instrument systems and to monitor reliability growth/degradation in the IOFs. Integrated reliability testing is used for optimum selection and detecting failures of machine tools, equipment, machine parts, materials, processes, instruments, and maintenance strategies during real-time operations. Integrated reliability testing with the TI model of real-time operating manufacturing processes, parts, and equipment system enhances automation and results in cost-effective software and network programs.

The design of TICS for measuring reliability growth and degradation as well as integrated reliability monitor and maintenance tools with TI model–based technique is essential for data acquisition. The acquired reliability data are used to develop the IRCMM curve for materials, parts, and processes. The IRCMM curves are used for optimum selection, monitoring of potential/functional failures, and maintenance of failed parts, processes, and equipment and to develop a maintenance decision-making diagram. The design procedures for an integrated reliability monitoring and maintenance program of parts, processes, and industrial equipment with the TI model–based technique have been outlined in this chapter.

Chapter 6: Selection of Coating Materials, Parts, and Equipment System with the Technological Inheritance Technique

Environmental regulations and performance requirements of materials, parts, processes, and equipment have become stringent, while industries and companies are now looking for better hard alloy high-temperature materials and near-net-shape processing technologies at a reduced cost of raw materials, parts, processes, equipment, manufacturing, and maintenance operations. Most existing tools, materials, and process models are inadequate for predicting and validating the desired material properties and performance requirements as well as detecting failures throughout the stages of manufacturing, monitoring, and maintenance operations.

Industrial experiences have proved that the casting of titanium-based parts and other hard alloy–coated part surfaces requires labor-intensive repetitive monitoring of material properties and component performance in production processes and service operations, which add to the cost of attaining maximum achievable quality, reliability, and performance. Maximum achievable reliability, performance, and durability of a component/system are presently difficult to design, since they involve a lot of variables like wear, manufacturing processes, assembly, hard alloy coating material nonhomogeneity, and residual stresses that analytical durability analysis cannot adequately consider using existing methodology, tools, and models. The design of a multivariate regression model is needed to determine the maximum achievable component/system quality and reliability requirements for wear coating materials and other failure resistance applications. This chapter has outlined the common industrial problems of plant, parts, and equipment such as wear, corrosion, and high temperature failure modes as well as materials modeling and database development for the IOFs.

It has been ascertained from industrial experiences that the hardening of machine part surfaces with selected specialized hard alloy coating materials for wear, corrosion, and high temperature resistance applications has helped to enhance component quality and reliability, but requires a desired process, component, and service condition requirements. Researchers have ascertained that the service condition of a hard alloy coating material provides the following characteristics: the wear resistance of hard alloy coating in frictional contact with steel (friction of boundary lubrication) is four to nine times higher than the wear resistance of steel in steel–steel pairs and steel–iron pairs under specific loads of 1.5×10^6 to 10×10^6 Pa and sliding velocities of up to 8–54 m/min; within this range, the amount of wear of steels working in pairs with hard coatings is reduced by 1.5–2.5 times, while the friction coefficient in pairs of hard coating–steel with initial roughness number Ra = 0.16–0.3 μm is 1.8–2.2 times, which is lower than in pairs of steel–steel, but with a more efficient finished surface roughness, the amount of wear will be reduced 2–10 times.

The optimum selection and design of cost-effective hard alloy coating materials, deposition processes, hard-coated parts, and maintenance strategies are possible with the help of a multivariate regression model, which is also used to predict optimum component quality and process performance conditions. These conditions are selected or designed as the baseline requirements for all components and processes of a system as well as input data for the TI model. The introduction and application of the TI model and multivariate regression model has now made it possible to provide real-time measurements of component properties like hardness, residual stress, and dimensional accuracy like surface roughness, surface wavelength, and component growth/degradations, which has helped better understand the relationship between the quality of materials, processes, parts, and equipment during manufacturing, maintenance, and service operations toward maximum achievable quality, reliability, and performance.

The application of the TI model and multivariate model for component/system assessment within manufacturing processes and monitoring and maintenance operations enables the TICS and integrated reliability monitor to be designed and components/systems to be operated cost-effectively and maintained with a precise strategy in order to meet their desired durability, reliability, and performance at reduced costs of raw materials, parts, and equipment. With TICSs and integrated reliability monitors, it is possible to select the optimum conditions for materials; predict the maximum and minimum resistance to wear, corrosion, temperature, and fatigue, and time to failure; and detect the root causes of failures, reliability, and other performance characteristics.

The TI model is used to integrate different component failure modes with a single metric and also uses TI coefficients to determine failure resistance conditions or the reliability of components/systems and integrate reliability, CM, and maintenance operations of processes, parts, and equipment. The service and maintenance operations in many industries are still reactive due to problems arising from incomplete understanding of the day-to-day behavior of materials, parts, processes, and equipment as well as the lack of methods for determining the factors involved in product and machine breakdown, but an IRCMM program with the TI model provides the development of smart, reconfigurable CM and maintenance tools to reduce production time and dimensional variations caused by process performance degradations.

An IRCMM program with the TI program provides a TICS and tool that select the optimum requirements for material and deposition process conditions as well as modeling and database development in the IOFs.

The integrated reliability of machine parts and equipment with optimum reliabilities of hard alloy–coated materials and deposition processes would also require suitable surface finishing methods to achieve maximum wear, corrosion, and high temperature resistance characteristics that meet desired applications of the IOFs.

Chapter 7: Reliability Growth Condition of Coating Material and Deposition Process with a Technological Inheritance Model–Based Program

Researchers have ascertained that self-fluxing powders based on nickel are hard alloy coating materials having a wide application for hardening and reconditioning surfaces of rapidly wearable parts working in aggressive media of wear, corrosion, and high temperature conditions. These coatings have complex structures, consisting of minutely dispersed superhard phases of carbides, borides, and carboborides with microhardness up to 40×10^3 MPa, uniformly distributed in hard metallic matrix–based solid solutions and complex nickel-based eutectic. The service load condition and environment requirements of these hard alloy coatings range with a specific pressure of 1.5×10^6 to 7.0×10^6 Pa and a sliding velocity of up to 8 m/s and are recommended and selected for applications with friction part pairs (e.g., shaft–bearing assembly) in water, NaOH, and CH_3COOH of 10%–50% concentration. The wear resistance of this type of hard alloy coating in frictional contact with steel (friction of boundary lubrication) is 4–9 times higher than the wear resistance of steel in steel–steel pairs and steel–iron pairs under specific loads of 1.5×10^6 Pa and sliding velocities of 8–54 m/min, and the amount of wear of steel working in pairs with hard alloy coatings within the recommended given load range and environment requirements is reduced by a factor of 1.5–2.5 times, while the friction coefficient in pairs of hard alloy coatings in steel with initial surface roughness Ra = 0.16–0.30 μm is 1.8–2.2 times lower than in pairs of steel–steel, but with constant surface roughness, the amount of wear is reduced 2–10 times, hence the need to optimize process and part surface conditions with the TI technique for maximum lifetime reliability of components and systems.

The material design for maximum achievable reliability for a hard alloy–coated part surface considers not only the specific part surface roughness but also other surface quality parameters like hardness and stress as well as the specific coating deposition process conditions and other manufacturing processes like machining and grinding for a more robust design that suits the desired service and environmental conditions. A multivariate regression model for nickel-based hard alloy–coated cylindrical part surfaces has been developed with a machining manufacturing process for predicting and selecting optimum component quality parameters, process performance factors, reliability condition requirements, and failure characteristics of components/systems. Integrating environmental and hard alloy–coated part surface quality conditions with process performance conditions under a single platform for determining the optimum reliability requirements of coating materials, coated parts, and processes as well as the control of reliability growth and degradation/failure is possible with the application of the TI model. An integrated reliability mechanism is therefore developed with the application of a multivariate regression model and TI to analyze, monitor, and determine the desired reliability growth, optimum reliability, reliability degradation, and wear with other competing failure modes of friction part surfaces and systems and sustain the optimum values for a specific lifetime.

Integrated reliability monitors and TICSs have been developed for real-time reliability growth/degradation and failure data acquisition, analysis, control, and presentation. An IRCMM program is used as a decision-making guide, used to test component and process reliability growth/degradation, and used to detect failures and select a suitable cost-effective maintenance strategy for manufacturing processes and equipment in the different IOFs.

Chapter 8: Reliability Growth Condition of Machining and Grinding Processes of Hard-Coated Workpiece Surface

Machining of hard alloy–coated parts for wear, corrosion, and high temperature resistance applications generates high temperatures at the cutting edge that impair the quality and reliability of various cutting tool materials. Commercially available cutting tool materials are currently being applied at moderate speed conditions when machining hard alloy coatings, hence with lower machining productivity. Self-propelled rotary tooling (SPRT) can significantly improve tool life when the cutting tool is set at the optimum inclination angle, while much higher cutting speeds and feed rates are achieved when machining hard alloy coating parts with SPRT, relative to conventional cutting tools, without pronounced adverse effects on tool life and machining performance, quality, and reliability due to the lower cutting temperature generated. Although prolonged machining by SPRT tends to lower the surface roughness value, thus improving surface finish, it cannot meet the desired dimensional specifications of critical hard alloy–coated machine parts in equipment operating in aggressive wear applications of the IOFs.

This chapter introduces a new cost-effective machining process known as rotary cutting with plasma flame (RCPF) for an optimum surface finish that meets the desired dimensional specifications of critical hard alloy–coated machine parts in equipment operating in aggressive wear applications of the IOFs. In SPRT, the cutting speed (V) is the most influential factor on the surface quality parameter (i.e., surface roughness [Ra]) toward dimensional specification focus, but in RCPF, electrical current (I) is the most influential factor on the multivariate surface quality parameters (e.g., surface roughness [Ra], hardness [HRC], stress compression intensity factor [ε], wavelength [λ], and kinematic coefficient [K]), which of course are the focus of material performance and reliability specifications, and may not require any grinding process.

The traditionally expensive grinding method is generally used to finish a hard alloy coating part surface to produce a fine surface finish, with very fine tolerances, but provides a lesser reliability due to its induced tensile stress than the same surface quality of a hard alloy–coated part machined by RCPF. The advantages of the new and advanced machining method make it possible to optimize manufacturing process conditions, friction part surface conditions, and monitoring and maintenance conditions as well as the determination of maximum achievable reliability of parts and equipment in the IOFs. The optimized data provide optimum component/system reliability, lifetime, performance, monitoring, and maintenance requirements with standard set targets for integrated reliability monitoring and maintenance of manufacturing processes, parts, and industrial equipment.

A multivariate regression model for multiple quality parameters of parts with the process conditions of RCPF has ascertained that RCPF for a single run provides the following quality parameters: profile wavelength, $\lambda = 0.66\ldots1.0$ mm; surface roughness, Ra = 1.8…4.1 μm; hardness, 60…63HRC; surface layer compression intensity factor, $\varepsilon = 1.8\%–4.1\%$; and kinematic precision coefficient, $K = 0.520–0.660$. Compared to this, a prolonged process run will achieve 10 times better quality and reliability growth conditions of hard alloy–coated part surfaces.

It is also ascertained that the conditions of the machining process (the RCPF for machining hard coatings) are significant in the following decreasing order of influence—I, S, V, L, t—for the influence of the quality condition of hard alloy–coated part surface, which is quite different from the traditional method of machining.

The TI technique helps transfer the optimum values from the finish operation of the manufacturing processes to the initial operation of industrial equipment, where the optimum reliability value is sustained for a maximum specific period of its lifetime by a cost-effective precision maintenance strategy with the help of the same technique at minimum life cycle cost. A software program for data acquisition, analysis, and presentation of a manufacturing and industrial equipment system is developed for automotive implementation of IRCMM tasks. The program together with the TI model can also be used to design measuring instruments, diagnostics, prognostics, monitors, data acquisition devices, and other reliability tools. The automation of IRCMM of manufacturing processes and industrial equipment is possible with TI model–based simulation techniques.

An IRCMM program is used as a decision-making guide, reliability growth/degradation test, and for the selection of a cost-effective precision maintenance strategy.

Chapter 9: Reliability Growth, Degradation, and Fatigue Failure of Nickel-Based Hard Alloy–Coated Part Surface

The different performance/reliability target requirements in design, manufacturing, and service operations of a component/system can be seen by how the durability and reliability process is determined within the different IOFs and how it is used to increase component/system performance/reliability from design through manufacturing processes and service operations. The design of a part and its durability depends on the component base, user base, manufacturing base, and value base, and all these require different levels of durability, as in the case of fatigue with different lives of a component.

The existing three basic methodologies used to determine the life of components can help predict lifetimes but cannot improve reliability life.

An integrated reliability method that can predict life and improve reliability has been introduced in this book through the use of component stress/quality–reliability conditions against process cycles/performance–life conditions. The stress against the cycles to failure curves is usually derived from tests on samples of materials for life prediction and design assurance but does not determine life improvement, design optimization, or component/system reliability; hence, the author has decided to apply the TI technique that is based on system/component reliability and design optimization. The maximum predicted life of a component and system by fatigue analysis without the TI technique does not guarantee maximum component/system reliability, simply because of the fact that some of the factors and characteristics of reliability have not been considered by designers and manufacturers. The TI model that considers all the necessary factors and characteristics of component/system reliability and also guarantees maximum achievable reliability of part, process, and equipment with maximum achievable part condition resistance to fatigue failures has been adopted by the author.

Fatigue reliability degradation analysis with the TI model can therefore be used to fully assess the conditions of components/systems during design and manufacturing processes and service operations. It also provides for optimum life prediction, minimum acceptable reliability, potential and functional failures, and optimum useful service life of components. The results of can be used to set up maintenance control limits, predict failure modes, detect root cause of failures, and determine maintenance requirements as well as life improvement and design optimization. Fatigue reliability degradation analysis with the TI model is cost-effective, since it can determine maximum fatigue resistance coefficient and minimum probability of component failure at minimum cost as opposed to fatigue analysis.

An IRCMM program will therefore provide a measuring device for fatigue resistance coefficients and its quality degradations and select an optimum maintenance strategy for industrial equipment. The program determines the maintenance costs and component/equipment reliability through a virtual means of assessment as well as for optimum selection of components and maintenance strategies. The change from physical to virtual assessment of reliability growth/degradation with the help of the TI model enables components, systems, and equipment to be designed to suit quality–reliability and performance–life criteria with full consideration of design, manufacturing processes, material nonhomogeneity, and residual stresses. The program applies a nondestructive testing method that provides an accurate prediction of fatigue reliability, time to failure, fatigue reliability growth and degradation of components/equipment, and monitoring and maintenance costs in the appropriate IOFs.

Chapter 10: Reliability Degradation, Wear, and Competing Failure Modes of Nickel-Based Hard Alloy–Coated Part Mating Surface

The relationship between wear and the multiple variable factors that characterize the type and properties of component materials, surface conditions, process conditions, friction, lubrication, and others can now be determined with a multivariate regression model developed in this chapter. The multivariate regression model has helped determine the reliability, performance, and lifetime requirements for hard alloy coating materials, hard alloy–coated part mating cylindrical surfaces, and the service conditions of desired equipment and helped optimize and predict component/system reliability. The optimized component/system quality–reliability condition can be incorporated and integrated into process performance conditions with the help of the TI model for the automation and implementation of IRCMM under a single platform. Wear of parts and equipment can be estimated by the total time, service condition of components/parts, and cost of restoring the performance (the length of service life), as well as by the probability of sustaining the original condition parameters of the equipment within the prescribed desired control limits during the specified service period.

The service life of most machines, mechanisms, and equipment is determined by the wear resistance of the hard-coated mating part surfaces. Wear resistance is the property of a material that resists the degradations or changes in the dimensions of machine parts in a particular friction condition. An increase in the wear resistance or the quality factor of a kinematic mating hard alloy–coated part surface—which can be used to determine the reliability coefficients of component/system, mechanisms, and equipment—increases the durability coefficient of such part surfaces.

The reliability coefficient of kinematic mating hard alloy–coated part surfaces is a function of all the failure resistances or the quality parameters of a particular hard alloy–coated cylindrical part surface, which can be used to fully assess component and system conditions, instead of the wear-resistant coefficient. The quality factor, which is the function of all the quality parameters of a particular mating hard alloy–coated part surface, can be used to assess component/system conditions. The surface quality parameters of the mating hard alloy–coated part are converted to equate the values of the TI coefficient for quality control, which in turn is used to determine the quality factor, reliability coefficient, and failure resistance coefficient. The reliability and service life of equipment can also be determined by the wear rates of mating parts or by the reliability degradation rates of parts, which can now be expressed in terms of power condition functions.

Integrated reliability coefficient is the integral function of mating parts' quality conditions, process condition, and power condition, whose coefficient depends on the material, geometric factors, process conditions, and surface treatment. Integrated reliability analysis can be performed by constructing the specific curves from quality–reliability and performance–life data and using a practical understanding of wear and other competing failure mode characteristics, symptoms, and warning signs to get an idea about the underlying failure condition for a tribosystem.

The author is focused on the development of automated methods of wear and other competing failure resistance analyses that use data acquisition devices to measure reliability growth and degradation as well as standardized rules for constructing curve diagrams to describe component and equipment reliability. Before attempting to design an experiment for maximum wear resistance coefficient, we must ensure that we have properly analyzed and understood the need to integrate reliability and CM with tribological systems, which is done with the TI model. An integrated reliability test, together with the TI model, will be used to assess and evaluate the component/equipment with wear and other competing failure resistance conditions. A robust design with an integrated reliability nondestructive testing technique that provides accurate prediction of reliability growth/degradation and wear resistance and other failure modes of components/equipment has been developed in this book.

Chapter 11: Integration of Reliability, Condition Monitoring, and Maintenance of Industrial Equipment

Most organizations in the maintenance and reliability field have very weak preventive and predictive maintenance programs that contain ambiguous and needless tasks at unnecessary frequencies, because of the lack of a cost-effective monitoring and maintenance program for the maximum returns of net asset and reliability of equipment in plants. At the same time, in most plants, there are several sources of information that lead to problems like equipment delay information, maintenance work orders, quality data, and failure reports in terms of mean time between failure statistics, preventive and predictive maintenance strategies of industrial equipment.

IRCMM with a TI model–based program is used to select maintenance strategies, monitoring tools, and real-time data acquisition devices, which provide accurate information to operators and maintenance personnel. This new cost-effective program, together with the TI model, provides a single metric for the assessment of parts, processes, and industrial equipment from concept and design through installation and operations of equipment. The program is used to set up the desired control and reliability CM limits and to develop cost-effective preventive and predictive maintenance strategies for maximum achievable reliability at minimum life cycle and monitoring/maintenance costs.

The TI technique is used to integrate reliability, CM, and maintenance of parts, processes, and equipment and to further enlarge and maximize the maintenance task interval from the initial component condition to its final failure state condition at minimum monitoring and maintenance costs. This integration with a single TI coefficient helps meet desired standards and baseline requirements of design, development, and maintenance and optimize system performance.

The optimized reliability growth and degradation data are used to set up maximum reliability threshold points for the selection of maintenance strategies, parts, processes, equipment, and tools and to set up minimum reliability threshold points that determine the incipient failure state of parts and equipment. The TI model is used to determine the component quality condition factor of the different failure modes that occur in particular components and the component reliability growth and degradation, which is used to plot the integrated reliability monitoring and maintenance distribution curves/mechanisms and to assess parts, manufacturing processes, and industrial equipment. This offers the benefits of optimum selection, accurate detection of failures, and cost-effective integrated reliability test programs.

An integrated reliability test program with the TI model–based simulation technique provides the data to plot reliability curves/mechanisms during manufacturing processes and equipment operations and to test for optimum reliability and failures of industrial equipment. The role of integrating reliability, CM, and maintenance with the TI model on IRCMM therefore helps maximize the control and monitoring limits of industrial equipment conditions; set up maximum and minimum threshold points; and test design, developments, monitoring, maintenance, and management of parts, processes, and equipment in the different IOFs.

Chapter 12: Integrated Reliability of Equipment with the Technological Inheritance Model–Based Simulation Technique

The TI model–based simulation technique is the application of a mathematical model that provides the necessary information about reliability CM and maintenance at a specific instance and over time. Quantifying the reliability and performance of manufacturing processes and equipment system for the various values of its input parameters is done with the quantified measurements of TI coefficients, which is very useful in monitoring the lifetime and failure characteristics as well as in maintenance and management decision process. The simulation model is able to evenly produce numbers that follow a given theoretical mathematical model or empirical reliability distribution.

A mathematical model with TI coefficients is used to represent multiple quality parameters of a critical part surface (surface roughness, hardness, wavelength, stress concentration factor, and precision coefficient) for an IRCMM of a particular group of hard-coated critical machine parts (e.g., bearings and shafts) and critical equipment (e.g., pumps, generators, and machine tools) that is applied to simulate real-time operating conditions of parts, manufacturing processes, and equipment.

The IRCMM automation of an industrial plant with the application of the TI model–based simulation technique is considered as a synergic blend of man, machine, and methods in working activities whose execution leads to the manufacturing of desired part surface quality condition outputs, starting with set optimum quality inputs of a particular critical part surface and equipment condition data, monitoring/maintenance conditions, set points, and threshold values. The development of an object-oriented simulation model in an automatic control framework is possible with the help of the TI technique. The multivariate statistical process with TI coefficients helps model the relationship between multiple quality condition parameters of an initial optimum operation and the final operation of a monitoring and maintenance system.

The optimum conditions scaled between zero minimum level and one maximum level for IRCMM of manufacturing processes, parts, and equipment are determined with the TI model–based simulation technique. The reliability growth and degradation coefficients are used to plot the integrated reliability distribution curve for the determination of component reliability, process performance, and health data as well as the monitoring levels (0, +1), the optimum operating condition levels of parts/equipment, and the baseline requirements for a monitoring/maintenance design system. The manufacturing process, part, and industrial equipment reliability condition monitoring and maintenance requirements as well as the reference set points and observations are always clearly displayed in an integrated reliability monitor, while the data collected from the reliability curve are used to determine the process variations, potential/functional failures, errors, reliability growth/degradations, and the required suitable maintenance actions. A cost-effective IRCMM function derived from the integrated reliability curve can be programmed through an algorithm based on a TI software program.

Chapter 13: Integrated Reliability with a Technological Inheritance Model–Based Program in the Industries of the Future

The role of IRCMM with a TI software program offers a cost-effective engineering solution in today's plant, process, part, and equipment system reliability monitoring that includes protection monitoring, prediction monitoring, performance monitoring, reliability growth/degradation monitoring, and online monitoring. Online monitoring enables smart field devices like TICSs to be integrated in the digital plant architecture in order to provide users around the plant and across the enterprise with the information needed to make decisions.

Integrating industrial equipment protection monitoring into process control allows for automated plant shutdown when required while carrying out component reliability degradation monitoring and maintenance during start-up and real-time working conditions.

Prediction, prevention, reliability growth/degradation monitoring, and performance monitoring with real-time operating data are full protection for the baseline requirements of manufacturing processes, parts, and industrial equipment.

Maintenance personnel benefits from predictive, preventive, and reliability performance capabilities are maximized with the help of the TI model, which allows component/system reliability and health feedback to process automation for operators to know the effects their actions have on the reliability and heath of equipment in the IOFs. The integrated reliability monitor delivers field-based intelligence, while TICSs are used to measure part, process, and equipment reliability growth and degradation parameters. Protection monitoring is controlled along with the process so that a plant shutdown is safe and equipment failure impact is minimal with an integrated equipment protection and process control system, where the process control condition is determined with the TI coefficient, while the condition variation is measured with TICSs.

IRCMM tools with a TI software program are a cost-effective online/offline predictive and proactive engineering solution to the common problems in the different IOFs. The use of predictive and proactive tools with a TI software program can more effectively identify wear, corrosion, temperature, and fatigue failure modes much earlier than traditional predictive/proactive programs as the power of the tools are multiplied when they are used together or as a network system.

Software solution process input data that make data available for analysis and presentation are designed in this chapter with the help of a TI software program for an IRCMM structure of manufacturing processes, parts, and industrial equipment. The optimum selection and design of the hardware structure network system are carried out with the help of a TI software program. Integrated reliability monitors and cost-effective precision maintenance tools are used to monitor reliability growth/degradation and to detect distributed defects and failures in critical parts and equipment and fix the failures with the help of a TI network program.

Chapter 14: Integrated Reliability with a Technological Inheritance Model–Based Network Program in the Industries of the Future

The ability of manufacturing processes, parts, and industrial equipment to adjust its own functionality according to its reliability, health, and lifetime status is an integral part of a self-maintenance paradigm, which requires both process functional intelligence and component reliability intelligence that can be determined with the help of a TI software program. IRCMM technology together with the process loop network system provides optimum reliability, health, lifetime, and automatic cost-effective precision maintenance.

This technology requires the following components:

- TICSs
- Integrated reliability growth and degradation monitors
- Failure mode detectors
- Integrated reliability growth and degradation testing devices
- Integrated reliability diagnostic and prognostic transmitters
- Maintenance strategy, component, and system selectors
- Monitoring and maintenance cost calculators
- Maintenance managers
- Decision-making guide
- Computers and other necessary equipment

The main advantages of IRCMM technology over the existing vibration technology are its integration capability of reliability, CM, and maintenance and its cost-effective protection, prediction, and detection features as well as the optimum selection and testing devices it offers with a TI model–based program. IRCMM with the help of a TI software program is used to monitor the reliability growth and degradation of components/systems from the initial to final operation of design, manufacturing processes, parts, and industrial equipment. The program can be used for optimum component/system selection and design of integrated reliability monitoring and maintenance tools in the network system for manufacturing processes, parts, and industrial equipment.

An integrated reliability monitor is hybrid hardware that performs multiple functions on a single platform for reliability growth/degradation monitoring while an integrated reliability transmitter is hybrid hardware that performs multiple functions on a single platform for a cost-effective proactive maintenance. The online monitoring and maintenance function of IRCMM with the help of a TI software program now makes it possible to continuously obtain information about component/system reliability, lifetime, and the health of a whole range of gas or steam turbines, generators, compressors, fans, motors, pumps, and other critical equipment.

Integrated reliability condition and maintenance with the help of a TI software program is used to construct integrated reliability–performance distribution curves/mechanisms of manufacturing processes, parts, and equipment system for the selection of maintenance tasks and strategies as well as for reliability CM and maintenance analysis. The program is a complete solution strategy for protecting critical industrial equipment that covers three real-world scenarios, which are based on multiple reliability monitoring and maintenance functions.

Integrated reliability condition and maintenance with the help of a TI software program offers multiple benefits that determine the desired level of monitoring and maintenance that is required to keep the system at the needed level of capacity, effectiveness, and reliability at minimum life cycle costs in the IOFs.

Chapter 15: Integrated Reliability Management with a Technological Inheritance Model–Based Program in the Industries of the Future

IRCMM management examines the role of a TI network program in minimizing the risk of safety, component/system failures, and loss of profitability as well as in dealing with risk reduction tools that best fit maintenance requirements, overall equipment effectiveness, and maintenance strategies. The optimum selection of tools, processes, parts, equipment, and maintenance strategies is done with the help of a TI software program. The IRCMM tasks have been selected based on the level of reliability, CM, and maintenance of parts, processes, and equipment with the use of reliability distribution curves that apply the TI model.

IRCMM management with a TI software program focuses on the improvement of all the phases of predictive and proactive maintenance processes during design, manufacturing processes, and equipment operations. The program is used to develop a device manager whose job is to monitor the instrumentation, keep all configurations and calibrations current, and maintain the database of processes, parts, and industrial equipment through the checks and balances of TICSs. The device manager is also used for continuous monitoring of the failures, reliability growth/degradations, and status of critical control points identified as essential to the safety, protection, lifetime, and selection of optimum conditions of parts/equipment.

The device manager performs the following primary functions for manufacturing processes, parts, and equipment:

- Configuration management
- Calibration management
- Diagnostics and prognostic management
- Reliability growth and degradation management
- Documentation management
- Optimum component and system selection management
- Monitoring and maintenance management
- Root cause of failure and equipment reliability evaluation management
- Other forms of management

Research has shown that half of equipment failures that cause downtime typically involve mechanical critical equipment such as pumps, motors, compressors, and turbines, and therefore, the application of IRCMM with a TI model–based program will maximize productivity and reliability while keeping the equipment in continuous service, using an integrated reliability network to optimize reliability, lifetime, and overall effectiveness of manufacturing processes, parts, and industrial equipment. A TI software program applies online monitoring information with integrated reliability monitors, diagnostic/prognostic transmitters, and precision maintenance strategies with a cost-effective device manager that shows which manufacturing process, part, or equipment needs service soon and which does not. Integrated reliability growth and degradation monitors are used to show the changes between the optimum and minimum component/system reliability condition data over time and can be used to calculate the financial impact of these changes so as to weigh the cost of suboptimal reliability condition against the cost of shutting down for maintenance.

Device management improvement is possible by integrating new advances in online optimum IRCMM systems and flexible communication technologies with a TI model–based software program. TICSs mounted to the part–equipment system provide raw signals to the processing unit of parts, instruments, valves, and equipment, while the unit analyzes the signals using integrated reliability monitors and reliability diagnostic transmitters, which then supply diagnostic data to determine the root cause and severity of abnormal situations. Integrated reliability monitoring and maintenance with a TI software program provides benefits to equipment and operators as well as to the staff that maintain the equipment so that they are immediately alerted to problems such as fatigue, stress, wear, cracks, vibrations, corrosion, cavitation, and high temperature.

A TI software program is applied to integrated reliability monitoring and maintenance management in order to optimize reliability, lifetime, and life cycle costs of parts, processes, equipment, instruments, and maintenance strategies toward minimizing the maintenance cost, operation cost, and monitoring technology cost as well as the total ownership cost of processes, parts, and industrial equipment. The existing reliability monitoring and maintenance management route is optimized and compared with the new IRCMM management route technology using a TI software program for optimum selection of components/systems in the different IOFs. This book offers an IRCMM management route with a TI software program as the best program, since it integrates reliability with CM and maintenance data acquisition, analysis, and presentation into a single unit for maximum benefits at minimum cost toward a sustainable development and management in the IOFs.

1

Overview for Condition Monitoring and Maintenance of Equipment in the Industries of the Future

1.1 Increasing the Existing Maintenance and Operations of Industrial Equipment Productivity in Plants

Industry sustainability, global competition, and the need to maximize equipment and lifetime reliability require the integration of reliability condition monitoring (CM) and maintenance precision practices. This practice will allow fewer personnel to work fewer hours viably as well as to operate and maintain more equipment at minimum cost while also offering higher efficiency, higher availability, higher quality, and higher profits with capital equipment. The above type of practice will increase the productivity of existing maintenance and operation teams to maximize the reliability of equipment while continuing to look for ways to minimize life cycle cost. Fortunately, there are still opportunities for improvement in almost every operation, starting from design through production to facilitate operations with a cost-effective assessment technique. Industry benchmarks with an assessment technique can help you estimate the potential in your own plant and facility. When it comes to maintenance, operation, and reliability, the use of benchmark or key performance indicator (KPI) should not be a *program of the month* but rather a technique for responsible industrial equipment, process, and part improvement designed to achieve sustained levels of world-class performance [1]. An analysis to examine an organization and its equipment then addresses the basics of work order planning and scheduling and moves on through the total organization focusing on improvement efforts and the maximization of plant equipment reliability. The two fundamental components for the maximization of plant and facility equipment reliability are based on the people and plant equipment.

If proper input data of failure-resistant measures are provided to the production process, it means all properly designed parts and will produce at optimum levels of performance. With skilled and knowledgeable people working together effectively and focused on equipment improvement, it will lead to maximum achievable reliability. To achieve maximum reliability with maximum level of success, the following five key elements must be core to any improvement program:

1. Improving overall equipment and part effectiveness, quality, and reliability
2. Improving process performance with maintenance efficiency and effectiveness
3. Training for all employees involved
4. Involving operators in the daily maintenance and upkeep of the equipment
5. Early equipment management and maintenance prevention design

When these five key elements are the focus of improvement, company's experience increasingly better equipment availability, rates of performance, rates of product quality and reliability. They also benefit from improved safety and environmental performance and timely product deliveries to their customers. In advanced companies, what makes these five elements so powerful is that everyone in the plant is focusing on a specific KPI—overall equipment effectiveness (OEE)—which in turn improves overall process effectiveness. When all benchmarking and KPI improvements are focused on improving OEE, the measurable improvement will be seen in [1]

- Equipment and part quality/reliability
- Production throughput and process performance
- Controlled expenses and maintenance costs

In this book, we shall deal with the essentials of system/component reliability monitoring and precision maintenance strategies from design through development of parts to its service operations.

On this note, it is quite necessary to analyze the existing maintenance and operations of industrial equipment productivity in plants, such that the results can be used to develop the integrated reliability condition monitoring and maintenance (IRCMM) program.

1.2 Analysis of Maintenance and Operations of Industrial Equipment Productivity in Plants

Almost every maintenance organization sets some sort of failure elimination goal. The problem is that this goal is often set without fully understanding what a failure is. In some organizations, equipment is not considered failed unless it is totally inoperative. In others, equipment is considered failed if there is some partial loss of function such as reduced production rate or off-quality production outside their normal targets. Arguments are constantly erupting over whether or not a failure actually occurred. Eliminating failures requires a slightly different outlook on what constitutes a failure.

Let us begin by taking a look at the definition generated by Nowlan and Heap in their seminal work on reliability-centered maintenance [2].

> …Without a precise definition of what condition represents a failure, there is no way to assess its consequences or to define the physical evidence for which to inspect. The term failure must in fact, be giving a far more explicit definition that "an inability to function" in order to clarify the basis of Reliability-Centered Maintenance.
> …A failure is an unsatisfactory condition. In other words, a failure is an identifiable deviation from the original condition which is unsatisfactory to a particular user.

They further define two types of failures:

> …A functional failure is the inability of an item (or the equipment containing it) to meet a specified performance standard and is usually identified by an operator.
> …A potential failure is an identifiable physical condition which indicates a functional failure is imminent and is usually identified by a Maintenance Technician using predictive using or quantitative preventive maintenance.

Predictive or condition-based maintenance is based on the concept that there is sufficient time between when the potential failure is detected and the functional failure for the organization to react and prevent functional failure. This interval is known as the p–f interval.

This definition means that it is up to the individual organization to decide what constitutes an unacceptable condition. This decision significantly impacts whether or not an organization will actually be able to establish failure patterns and eliminate all functional failures except for those they have decide to accept by making a run-to-failure or no scheduled maintenance decision.

1.2.1 Failure Patterns

Age and reliability studies conducted on aircraft components over a period of years revealed the six basic age–reliability relationships shown in Figure 1.1. The vertical axis of these curves represents the conditional probability of failure, and the horizontal axis represents time in service after installation or overhaul.

What is particularly striking about these curves is the very low percentage of items that displays a distinct wear-out region, the large number of items that displays a random failure region, and the extremely high percentage of items that displays an infant failure region. Only patterns A and B that

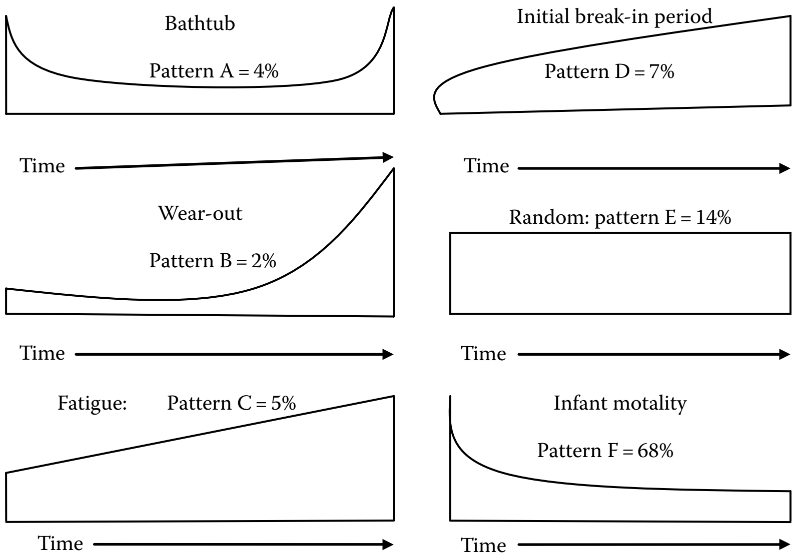

FIGURE 1.1
Aircraft component failure patterns (Nowlan and Heap, John Moubray). (From Smith, R., Failure reporting, analysis, corrective action system made simple, SMRP, Newsletter, 2010.)

represent only 6% of the items studied displays the wear-out region denoted by a rapidly increasing conditional probability of failure at the right-hand end of the curve. Ninety-five percent of the items studied had at least some region of random failures denoted by a flat region in the curve. Pattern C was the only curve that did not have some region of random failure. This means that 95% of the equipment in the study may benefit from some form of CM and that only 6% may benefit from time-based replacement or overhaul.

It is important to recognize the significance of pattern F, or infant mortality; 68% of the items studied had a high conditional probability of failure immediately after installation and commissioning. The majority of item failures were being induced by activities directly related to time-based replacements and overhauls. The overall maintenance strategy present at the time was extremely faulty and was not achieving the desired goals of restoring, protecting, and preserving the function of the equipment in the safest, most economical manner. At this point, it is highly essential to look at the maintenance activities and operations that impact reliability and cause failures.

1.2.2 Causes of Failures

All equipment failures are governed by the simple laws of physics present in everyday life. Friction, erosion, corrosion, stress, and impact are the physical basis for most failures. It is the interaction of humans with the equipment that determines whether these causes occur normally or abnormally.

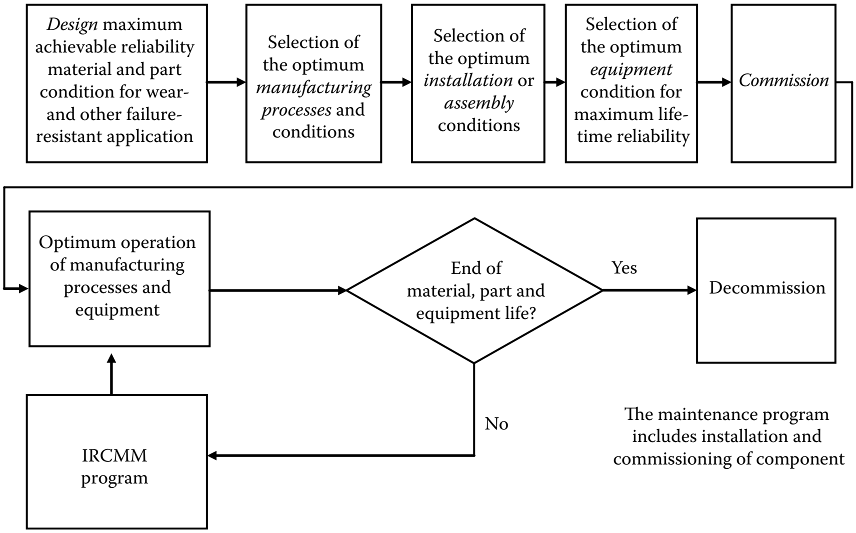

FIGURE 1.2
Manufacturing processes and equipment component life cycle for maximum achievable reliability.

As we can see in Figure 1.2, human interaction with the equipment occurs at every phase or operation of an item's life. Substandard performance and errors at any phase will result in decreased reliability, resulting in lower profits, more environmental incidents, and more safety incidents. In general, PM activities are designed to either prevent the physical sources of failure from occurring or remove the item before degradation caused by those very small percentages of equipment that will benefit from time-based replacement or overhaul. A preventive replacement/overhaul (PM) strategy is dependent on knowing which equipment has the wear-out pattern and what the best time is to perform the PM.

A failure elimination strategy is driven by finding those actions that create random failures, infant failure, and early wear-out failure and eliminating them. The failure reporting, analysis, and corrective action system (FRACAS) is designed to help the organization detect common failure modes, determine the causes of the failure modes, and eliminate them. Table 1.1 [2] shows that stopping at the physical root of a failure will probably not eliminate future failures of the same type. The root cause analysis (RCA) absolutely has to address the human side of the failure equation.

1.2.3 Threads between Common Failures

The common failures that stem from design, manufacturing, and maintenance errors would have to be eliminated before they have the chance of being passed on to installation and equipment operation levels by the

TABLE 1.1
Sources of Failures

Source	Failure Characteristics
Design errors	Early wear-out
	High frequency of random failures
Manufacturing process errors	Infant failures
Installation process errors	Infant failures
Commissioning process errors	Infant failures
Operating equipment process errors	Infant failures
	Early wear-out
	High frequency of random failures
Maintenance process errors	Infant failures
	Early wear-out

TABLE 1.2
Basic Failure Types (Reliability Center)

Failure Type	Characteristics
Crisis and functional	Deviation from normal is sudden and severe.
	Usually demands immediate attention.
	Will bring to it whatever resources.
	It needs to correct itself.
Chronic and potential	Deviation from normal is not severe.
	Deviation is often viewed as a normal part of operations.
	Occurs routinely.
	Sneaks under the radar.

Source: Smith, R., Failure reporting, analysis, corrective action system made simple, SMRP, Newsletter, 2010.

different organizations. Actually, the failures we see in an organization are either crisis failure or chronic failures. Table 1.2 [2] shows the characteristics of the two types. The primary thing to remember is that solving chronic failures actually changes the system's overall output. The goal with FRACAS is to be able to recognize the chronic failures, determine and eliminate the cause, and spread that solution across the organization either nationally or internationally.

In most instances, crisis failures will be analyzed and the root cause will be eliminated. With a good FRACAS, we will be able to see the commonality of failure modes that create chronic failures. We will be able to use the data to determine which of the failure patterns the failure modes fit and take appropriate action to eliminate them. The beauty of a well-defined corporate-level FRACAS is that failures in every facility can be tracked and failure modes that are common across the entire corporation can be tracked and addressed. That translate into substantial reduction in overall cost. You may find in a certain region, that a brand of pump that suffers early seal failure in facilities are experiencing fewer failures with different failure patterns for the same failure mode. In any case, the failure patterns will be easier to determine because the significant failure modes have been recorded and analyzed using the proper tools. The reason for the different failure patterns from the same common failure mode is also the same reason for the different quality conditions from the same common quality and performance parameters. The reason is based on the root measures of quality/performance or failure resistance parameters that can be controlled from the initial to final operation of a particular component and system of a plant and industry. An effective control of these common quality parameters from the initial to final operation will help to eliminate chronic and crisis failures or the potential and functional failures as well as the common failure modes as they occur on a particular component or system. The common caused failures by equipment at component level or system environment conditions have impact on the failure and degradation rates that should be taken into account while considering the process performance and component quality parameters. Several environment conditions such as temperature change, humidity, vibration, or shock voltage fluctuation that prevailed in many applications can cause simultaneous failure of some or all units of the system. The operating conditions of the components may also degrade due to fatigue, wear, corrosion and temperature, aging, etc., so the failures of units are also influenced by their lifetime. The necessary degradations can be determined by integrating time-based and state-dependent failure rate of units that practically and exclusively occur in many electrical/mechanical types of equipment. For more stringent reliability requirements, the influence of different operating conditions such as supply voltage, temperature frequency, and logic level along with time-varying failure rates should be integrated in the equation when predicting process performance and component quality as well as reliability. It is therefore necessary to identify the common failure modes of equipment in different industries so that they can be fed into design, development, monitoring, and maintenance operation models for standard reliability requirements and prediction of process performance and component quality data.

1.2.4 Identification and How to Combat the Common Failures of Industrial Equipment in the Industries of the Future

The characteristics of industries are documented in detail in the technology road maps [3]. Only a sample of the most important material needs of the industries, especially the needs that are common to the IOFs, is included in this book. Table 1.3 summarizes important material needs of the industry of the future (IOF), shows the relative importance of each crosscutting problem to individual industries, and lists one or two of the majority problems each industry faces. The importance of each industry's crosscutting materials

TABLE 1.3

Status of the Industry of the Future Technology Road Maps

Industry Sector	Road Maps	Date Released
Agriculture	The Technology Roadmap for Plant/Crop-Based Renewable Resources 2020: Research Priorities Fulfilling a Vision to Enhance US Economic Security through Renewable Plant/Crop-Based Resource Use	February 1999
Aluminum	Aluminum Industry Technology Roadmap	May 1997
	Inert Anode Roadmap: A Framework for Technology Development	May 1998
	Aluminum Industry Roadmap for the Automotive Market: Enabling Technologies and Challenges for Body Structures and Closures	May 1999
	Technology Roadmap for Bauxite Residue Treatment and Utilization	February 2000
Chemicals	Catalysis Technology Roadmap	June 1997
	Technology Roadmap for Computational Fluid Dynamics	October 1997
	Vision 2020 Separations Roadmap	November 1998
	Technology Roadmap for Materials of Construction and Maintenance in the Chemical Process Industries	December 1998
	Technology Roadmap for Computational Chemistry (draft)	September 1999
Forest products	Agenda 2020: The Path Forward—An Implementation Plan	1999
Glass	Glass Technology Roadmap Workshop	September 1997
Metal casting	Metal casting Industry Technology Roadmap	January 1998
Mining	Mining Industry Roadmap for Crosscutting Technologies	1999
Petroleum refining	None	
Steel	Steel Industry Technology Roadmap	1997, revised February, 1998
Forging	Forging Industry Technology Roadmap	November 1997
Heat treating	Report of the Heat Treating Technology Roadmap Workshop	April 1997

problem is based on the prevalence of the problem and how well it is being addressed. The Oak Ridge National Laboratory (ORNL) has performed an independent analysis of the material needs of the IOFs based on the road maps, and the results of their analysis were presented to the committee and included in the committee's deliberations. Three things in Table 1.3 stand out immediately. First, many of the industries have some similar, if not identical, needs; thus, selecting truly crosscutting research and development (R&D) should not be difficult. Second, many of the important material needs are in areas that are considered uninteresting, unexciting, or not on the cutting edge of technology. This fact must be considered as Office of Information Technology (OIT) project managers establish the scope and extent of R&D programs. Third, a few areas of materials research are extremely important to *all* of the industries. Progress and improvements in these areas would, therefore, have the biggest impact on energy savings and waste reduction. These areas are corrosion, wear, high-temperature materials, and materials modeling database development, where wear, corrosion, and high temperature have been identified as the common functional failure modes of industrial equipment. There is also the need to identify the potential failures during manufacturing and service in this book. Therefore, it is necessary to carry out interdisciplinary R&D in manufacturing and service CM for specific industries, so as to provide long-lasting solutions to potential failure (e.g., machining and grinding defects) during manufacturing operations and in the early stage of service (e.g., wear, corrosion, and temperature) of equipment in different industries. This long-lasting solution to both potential and functional failures of equipment is possible by carrying out performance CM that provides cost-effective precision maintenance. At this juncture, we shall look at CM of equipment.

1.3 Condition Monitoring and Maintenance of Industrial Equipment in the Industries of the Future

Starting anew, a machine part that is properly built and installed into equipment without any errors will operate at a particular level or service requirements of performance, quality, and reliability, which ideally are its design requirements. As its operating life progresses, degradation occurs. At this point, it should not be assumed that degradation is normal and nothing can be done about it, which is definitely not the case. The acceptance of equipment failure as normal is incorrect. Regardless of the reasons for degradation, the item can no longer meet its original service requirements and its level of component and process performance falls. By detecting the loss in condition of the change in the component and process performance level, you have a means to forecast a coming failure. Figure 1.3 [4] represents a *typical* degradation process experienced by equipment. In a period of normal operation, which is under optimum component and process conditions, the different parts a system works smoothly until there is an external force that acts on the system causes it to change or act otherwise, thereby affecting its performance. This change gradually, or rapidly in some cases, worsens to the point that the equipment cannot reliably and safely deliver its duty. If it continues in operation, any of the parts will fail or reach a functional failure condition and the equipment will stop working.

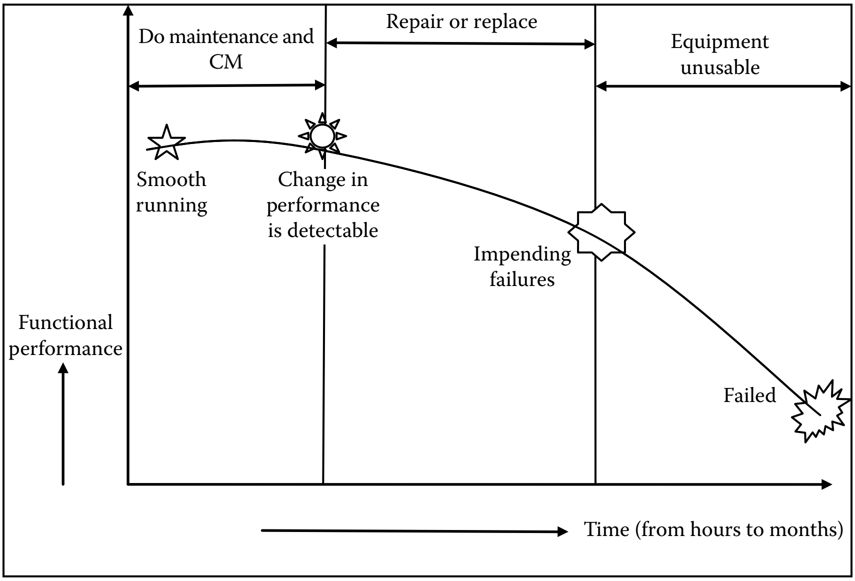

FIGURE 1.3
Manufacturing and equipment condition degradation process.

There are many ways to identify a change in equipment condition. Some commonly used ones are changes in vibration, changes in power usage, changes in operating performance, changes in temperatures, changes in noise levels, changes in chemical composition, increase in debris content, and changes in the volume of material. The most important issue is to spot the telltale signs of failure early or determine a potential failure level/point so that you have time to plan and prepare an organized and least-cost correction. Once the equipment is broken, you will have to spend whatever time, money, and resources it takes to get back in operation fast. This explains why the leading companies have created a *CM technician* position in their organization, and like the oiler and greaser long used to lubricate equipment and stop bearing failures, they get the *CM man* out among the equipment looking for potential failure signs. Such a person will save you a great deal of lost production and frustration. It is not necessary to spend vast amounts of money on oil analysis programs, thermographic cameras, state-of-the-art vibration analysis equipment, ultrasonic listening devices, and the like. It is wise to use such technologies selectively when accuracy of results is critical. But you can do a great deal of CM of mechanical equipment accurately enough yourself with a laser gun to tell temperature, an automotive stethoscope to hear noise, low-cost bearing vibration detector to note change in bearing vibration, laboratory filter paper to separate debris in oil, and a magnifying glass and magnet to check the debris content, plus your own five senses.

When you need expert help for more accurate results, or a measured opinion on the implications to continued operation, or the equipment is particularly critical to your business and you do not have the necessary expertise and skills in-house, subcontract those specialties in at the time.

With around 80% of equipment failures being totally unpredictable based on the equipment's age, you must have a maintenance strategy to deal with them. The around 20% time-based repetitive failures are addressed by doing preventative maintenance and planned replacement maintenance. But non-time-related failures cannot be addressed by renewal-based maintenance strategies; they require different solutions. If you apply renewal-based maintenance strategies to non-time-related failures, you will waste about 80% of your money, time, and effort! With time-random failures, the simplest (but not the only) management strategy to use is to inspect your equipment and look for evidence of degraded conditions. You can use a continuous means of monitoring condition by trending equipment's performance graphically (e.g., power use vs. throughput). Or you can introduce periodic inspections; you must set the time periods at a frequency that will let you spot the change well before the impending failure. Figure 1.4 shows a frequency inspection period that will detect the degrading performance well before the failure.

But doing condition-based maintenance will only marginally reduce your maintenance costs. The main thing CM does for you is to tell you that

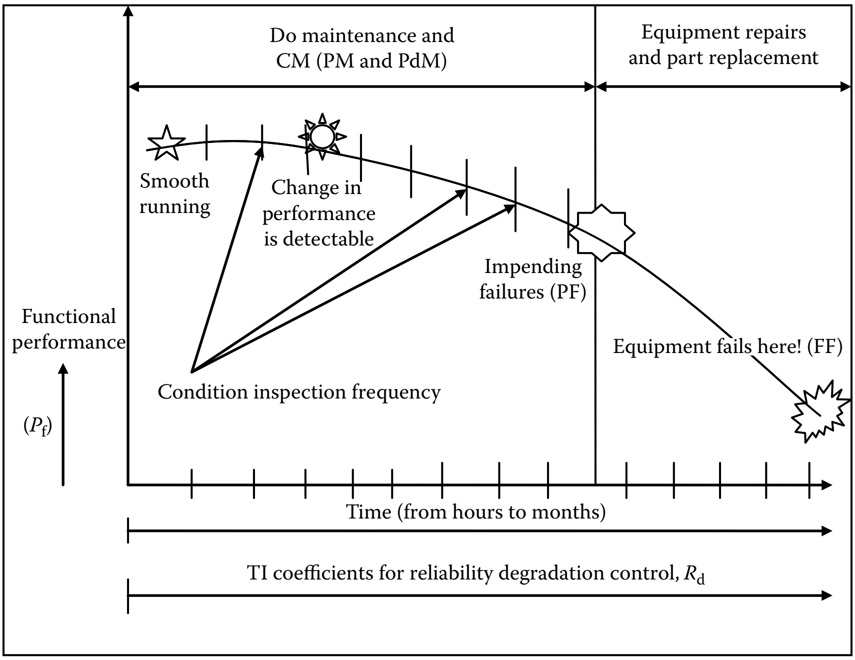

FIGURE 1.4
Setting the condition inspection frequency.

you have a problem in time to deal with it in a low-cost way. It does not stop the problem. If CM is based on condition inspections, the condition periods can be set in such a way that they correspond with the frequency that will let you spot the changes well at any phase of the operation before the impending potential failure. This interval can be done from operation to operation in a manufacturing process and also from point to point or one data event to another in a sequential order. This method helps to identify the defects that lead to failures. This step can therefore be used to remove failure modes as well as to drastically reduce maintenance costs. When you discover the cause of failure through CM and how you can get rid of it, you will then have the assurance that it cannot randomly occur at anytime in the future after it is repaired. Only by removing failure modes will you significantly reduce your future maintenance cost. This book will therefore provide the necessary tools and techniques that will reduce future maintenance cost and improve component and system reliability monitoring as well as predict time to failure and prevent the common failures before they can cause catastrophic damages. The CM and maintenance strategies, like many other processes, may evolve from an ad hoc level up to an optimized level. The monitoring and maintenance strategy maturity does not necessarily indicate the sophistication of the monitoring, maintenance tactics, and technologies that an organization may apply. Some organizations may use various kinds of CM and maintenance tools but seldom measure the performance, quality, and reliability of their processes and associated costs.

On the other hand, some organizations may use various kinds of CM and maintenance system in place but conduct very sophisticated performance and reliability growth/degradation measurements. When the component reliability growth/degradation and process performance growth/degradation are measured and tracked, one will concomitantly realize the need for optimization, which indeed is the transition from a maintenance department to a maintenance system. In an optimized process, the optimal amount of IRCMM, planned maintenance, and run-to-failure maintenance will be identified taking into account various performance criteria. It would not be a surprise, for instance, if in some cases the best practice would be a 100% run-to-failure policy without any need for CM and planned maintenance [5]. In this book, we shall deal with some issues of various performance criteria that would be taken into consideration when developing an integrated reliability condition monitoring and maintenance strategy (IRCMMS). The impact of this strategy should be predictable and measureable and, indeed somewhere around the component reliability and process performance, dependability on the operating unit. Among the most sensible measures of performance is the component reliability growth and degradation or throughput of the unit. The reliability and performance growth/degradation analysis must consider the random, premature, and wear-out nature of failures. This is only possible with the IRCMM program with the technological inheritance (TI) technique.

At this juncture, it is necessary to note that this program applies the TI technique that can relate reliability with time, operating/maintenance cost, quality condition of critical equipment parts, and equipment effectiveness in the IOFs. The technique will be used to maintain critical machine parts and equipment throughout their life cycle. This type of technique should be able to transfer the quality parameters of machine part from an initial stage of operation to the final stage in a particular manufacturing—assembly line. The limitations and challenges of the existing maintenance strategies of industrial equipment in the IOFs can be curbed with this new technique—known as TI that is able to transfer positive quality characteristics (quality–reliability growth) until it reaches a maximum achievable quality–reliability. It can also be applied to eliminate the negative quality characteristics (potential failures, component defects, and functional failures) as well as predict the time and condition of failures of parts and equipment in the IOFs. TI is the transfer of quality characteristics of an object from an initial operation to the final operation of a particular technological process. The TI technique can be used to design maximum achievable reliability into machine parts and equipment as well as design optimum conditions of manufacturing processes and equipment. It can be used to select optimum conditions of machine parts, processes, equipment, and maintenance strategies as well as to integrate, detect failures, and develop cost-effective CM and maintenance program of industrial equipment in the IOFs. The new cost-effective IRCMM with the TI technique would offer more economic and technical benefits when compared with the existing CM and maintenance strategies of industrial equipment in the IOFs.

1.4 Existing Maintenance Strategies of Industrial Equipment in the Industries of the Future

The existing maintenance operations and strategies fall into the following different categories:

- Breakdown of run-to-failure maintenance
- Preventive or time-based maintenance
- Predictive or condition-based maintenance
- Proactive or prevention maintenance

1.4.1 Breakdown or Run-to-Failure Maintenance

The basic philosophy of this maintenance strategy is to allow industrial equipment to run to failure and only repair or replace damaged equipment when obvious problems occur. Studies have shown that the costs to operate in this fashion are about $18 per horsepower (0.746 kW) per year [6]. The advantage of this approach is that it works well if equipment shutdowns do not affect production and if labor and material costs do not matter.

The disadvantages are that the maintenance department perpetually operates in unplanned/crisis management maintenance activities with unexpected production interruptions and the plant must have a high inventory of spare parts to react quickly. Without a doubt, it is the most inefficient way to maintain a facility. Futile attempts are made to reduce costs by purchasing *cheap* parts and hiring *cheap*, labor further aggravating the problem. Frequently, the personnel are overworked and understaffed arriving at work each day to be confronted with a long list of unfinished work and a half dozen new *emergency* jobs that occurred while they were at home in the evening.

1.4.2 Preventive or Time-Based Maintenance

This philosophy consists of scheduling maintenance activities at predetermined time intervals where you replace damaged equipment before obvious problems occur. Done correctly, studies have shown that the costs to operate in this fashion are about $13 per horsepower (0.746 kW) per year. The advantage of this approach is that it works well for equipment that does not run continuously and the personnel have enough knowledge, skill, and time to perform the preventive maintenance (PM) work. The disadvantages are that the scheduled maintenance may be done too early or too late. It is quite possible that reduced production could occur due to potentially unnecessary maintenance. In many witnessed perfectly good machines disassembled, good parts were removed and discarded, and the new parts improperly installed. For some, squirting grease into bearings every month is their idea of a PM program.

1.4.3 Predictive or Condition-Based Maintenance

This philosophy consists of scheduling maintenance activities only if and when mechanical or operational conditions warrant by periodically monitoring the machinery for excessive vibration, temperature, and lubrication degradation or observing any other unhealthy trends that occur over time. When the condition gets to a predetermined unacceptable level, the equipment is shut down to repair or replace damaged components in the equipment to prevent a more costly failure from occurring. Done correctly, studies have shown that the costs to operate in this fashion are about $9 per horsepower

(0.746 kW) per year. The advantages of this approach are that it works very well if personnel have enough knowledge, skill, and time to perform the predictive maintenance (PdM) work. The repairs to equipment can be scheduled in an orderly fashion, and it allows you some lead time to purchase materials for the necessary repairs reducing the need for a high parts inventory. Since maintenance work is only performed when it is needed, there is a likely increase in the production capacity.

The disadvantages are that maintenance work may actually increase if the personnel improperly assess the level of degradation in the equipment. To observe the unhealthy trends in vibration, temperature, or lubrication, this approach requires the facility to procure equipment to monitor these parameters and provide training to in-house personnel. The alternative is to outsource this work to a knowledgeable contractor to perform predictive/condition-based duties. If an organization had been running in the breakdown/run-to-failure mode and/or the PM style, the production and maintenance management must conform to this new philosophy, which can be problematic if the maintenance department is not allowed to purchase the necessary equipment, provide adequate training to the people to learn the new techniques, are not giving the time to collect the data, or are not permitted to shut down the machinery when problems are identified.

1.4.4 Proactive or Prevention Maintenance

This philosophy utilizes all of the PdM/PM techniques discussed earlier in accordance with root cause failure analysis to not only detect and pinpoint the precise problems that occur but also insure that advanced installation and repair techniques are performed including potential equipment redesign or modification to avoid or eliminate problems from occurring. Done correctly, studies have shown that the costs to operate in this fashion are about $6 per horsepower (0.746 kW) per year [2]. The advantages of this approach is that it works extremely well if personnel have enough knowledge, skill, and time to perform all of the required activities. As in the predictive-based program, repairs to equipment can be scheduled in an orderly fashion but then additional efforts are made to provide improvements to reduce or eliminate potential problems from repetitively occurring. Again, repairs to equipment can be scheduled in an orderly fashion and it allows lead time to purchase materials for the necessary repairs reducing the need for high parts inventory. Since maintenance work is only performed when it is needed, and extra efforts are put forth to thoroughly investigate the cause of the failure and then determine ways to improve the reliability of the machinery, there can be a substantial increase in production capacity.

The disadvantages are that this requires extremely knowledgeable employees in preventive, predictive, and prevention/proactive maintenance practices or a knowledgeable contractor who works closely with the maintenance personnel in the root cause failure analysis phase and then assist in the repairs or design modifications. This requires procurement of equipment and properly training personnel to perform these duties. If an organization had been running in the breakdown/run-to-failure mode and/or the PM style, the production and maintenance management must conform to this new philosophy, which again can be problematic if the maintenance department is not allowed to purchase the necessary equipment and tools, provide adequate training to the people to learn the new techniques, are not given the time to collect the data, are not permitted to shut down the machinery when problems are identified, are not given the time and resources to conduct the failure analysis, and then do not modify the component or procedure to increase the reliability. There is therefore the need to cost-effectively select a suitable maintenance condition and strategy with the help of an IRCMM program of equipment in the IOFs, thereby providing a long-lasting solution to the limitations of existing CM and maintenance strategies.

1.5 Limitations of Existing Condition Monitoring and Maintenance Strategies of Industrial Equipment in the Industries of the Future

Existing predictive maintenance, proactive maintenance, abnormal situation prevention, economic optimization, and similar strategies offer clear productivity and cost benefits. But it is necessary also to know that traditional maintenance automation architecture cannot easily provide the required constant flow of real-time information, for processes and myriad pieces of equipment, machine parts, maintenance strategies, and other technologies that make it work. The existing control system cannot show much more than the process variable and any associated trends or alarms. Existing vibration CM of equipment and analysis is presently the most effective way to evaluate component and system reliability for achieving the best precision maintenance practices, extend equipment longevity and reliability, and avoid unplanned shutdowns. This existing vibration technique is too expensive and cannot be used to monitor equipment reliability and detect early potential failures as well as cannot be used to select cost-effective components (materials, manufacturing process, and equipment) and conditions to suit the desired requirements. It can only be used to point the failure, but cannot be used to detect the location or type of failure.

Unless an experienced operator notices that something does not look right, the potential failures could grow until it causes a process upset or equipment failure. If these potential failures are not detected before assembly of parts, there is the possibility of passing some potential failures into the next operations and systems. Of course, there is a known fact that 40% of failures during service operations are induced by manufacturing processes. These are problems and limitations that require a long-lasting solution for sustainable development in design, manufacturing, and maintenance.

What is actually needed is to provide long-lasting solutions to the earlier limitations of manufacturing processes and equipment by detecting or predicting such potential failures before they increase operational and maintenance costs through reliability CM and providing the reliability growth and degradation tools to leverage that information so that operators and maintenance personnel can be more with the resources available or with even less and also monitor reliability growth and degradation throughout the life cycle of a critical part from design through manufacturing and service operations. In a nutshell, the key challenges facing modern reliability CM and maintenance managers and its solutions can be summarized as follows:

- Optimum selection of suitable parameters, processes, and practices of CM and maintenance strategies that meet the desired wear, corrosion, and temperature application requirements of the different IOFs
- Identification of potential wear and other competing failures and elimination during manufacturing processes and early equipment operations; detection and prediction of functional failures at minimum maintenance cost
- Integration of CM and maintenance with engineering support and cooperation of all the people and departments of design, manufacturing, and operations involved
- Development and application of the most cost-effective tools to leverage desired information so as to do more with available resources that can fulfill the expectations and requirements of the owners of critical equipment, the users of the assets, and the society as a whole
- Application of TI models and software program for real-time manufacturing and equipment reliability information and practices throughout a critical part life cycle for wear, corrosion, and high-temperature application as well as the maintenance and management of industrial equipment

At this juncture, it is worth mentioning that the TI technique can be used to measure real-time quality growth that leads to maximum achievable quality and quality degradation that leads to failures with time, lifetime, mean time to failure, mean time between failures (MTBF), risk of occurring failure and maintenance cost. This technique will therefore help to provide the common metrics for determining quality, life, health, maintenance cost, performance, and effectiveness of equipment at a minimum life cycle cost. This technique will also offer a long-lasting solution to the challenges CM and maintenance managers face, providing positive solutions to the common problems and failure modes of the IOFs by integrating CM and maintenance. Integrating CM and maintenance will lead to maximum achievable quality and maximum achievable reliability within a specific period of time. Maximum achievable reliability can therefore be designed into products for specific time and application with the help of the TI technique.

1.6 Maximum Achievable Reliability Condition and Maintenance Requirements for Part–Process–Equipment System with the TI Technique

For any system, one of the first tasks of reliability engineering is to adequately specify the reliability and maintenance requirements derived from the overall availability needs. Setting only availability targets is not appropriate. Reliability requirements address the system itself, including test and assessments and associated tasks and documentation. Reliability requirements are included in the appropriate system or subsystem requirements specification, test plans, and contract statements. Provision of quantitative minimum targets (e.g., MTBF/failure rate) is not sufficient. Reliability requirements should drive a (system or part) design to incorporate features that prevent failures from occurring or limit consequences of failure. To derive these requirements in an effective manner, a system engineering–based risk assessment and mitigation logic should be used. The requirements may be part of the output from functional or other failure analysis. The maintainability requirements address the costs of repairs as well as repair time. Testability requirements provide the link between reliability and maintenance and should address the detection ability of failure modes (on a particular system level), the isolation levels, and the creation of diagnostics (procedures). Reliability engineers should also address requirements for various reliability tasks and documentation during system development, test, production, and operation. The TI technique is used to maximize the quality of the part–process–equipment system and minimize the system failures at a minimum life cycle cost as well as integrate reliability, CM, and maintenance.

The IRCMM of parts, processes, and equipment involves data collection, analysis, presentation, and controlling the reliability growth, degradation, and maintenance cost of critical components with a single metric under a single platform. The single metric is used to determine the system and component reliability characteristics of parts, processes, and equipment. This new technique is also used to integrate the design, manufacturing processes, and industrial equipment operations as well as reliability, monitoring, and maintenance strategies together with a single metric under one platform. This involves maintenance implementations from start to finish, which is from design through manufacturing, installation and on to equipment operation. With this technique, it is possible to design the maximum achievable reliability into parts, processes, and equipment as well as sustain an optimum reliability condition for a desired lifetime at minimum maintenance costs. The optimum value of an inherent reliability that a given piece of part, process, and equipment can achieve is largely determined by design and manufacturing along with the quality of components, assembly, installation, etc. Although the operational reliability, which is the actual level that a given piece of equipment can achieve, is always less than the inherent, this can be enhanced with the use of appropriate manufacturing processes, assembly, and installation, as well as operating with optimum manufacturing, assembly/installation, and equipment conditions with suitable maintenance practices. Both the inherent and the operational reliability must be carefully considered in order to achieve optimum reliability of parts and equipment. Realistic functional requirements of parts, processes, and equipment need to be identified. Reliability specifications of both components and the overall system need to be developed to meet that functionality. Reliability specifications need to be stated and appropriate testing done, while the installation specifications need to be indentified and followed from start to finish. The computerized maintenance management of component and system reliability, monitoring, and maintenance data acquisition can be determined with the help of the new approach known as the TI technique.

The TI technique is the transfer of the quality and reliability characteristics of components from the initial stage of production to its final stage including design through installation and the operation of parts, processes, and equipment. Integrated reliability monitoring and maintenance with the TI technique is therefore a preventive, predictive, and proactive strategy, which is both time and condition based as shown in Figure 1.5. This technique can be used to select suitable monitoring and maintenance strategies from the existing technologies in Figure 1.6. Based on the success of the existing online monitoring and maintenance system as well as the limitations of vibration monitoring and maintenance of processes and equipment, it would therefore be necessary to apply IRCMM with the TI technique for a long-lasting solution to the current gaps, vibration monitoring limitations, and issues of industrial future trends in order to provide maximum service life for industrial equipment at minimum cost, energy, and wastes. The TI technique will be used to transfer the quality and reliability characteristics of components from the initial to the final stage of production and operation processes. It can therefore be used to eradicate negative traits, defects, and failures while maximizing the positive quality and reliability characteristics of parts, processes, and equipment.

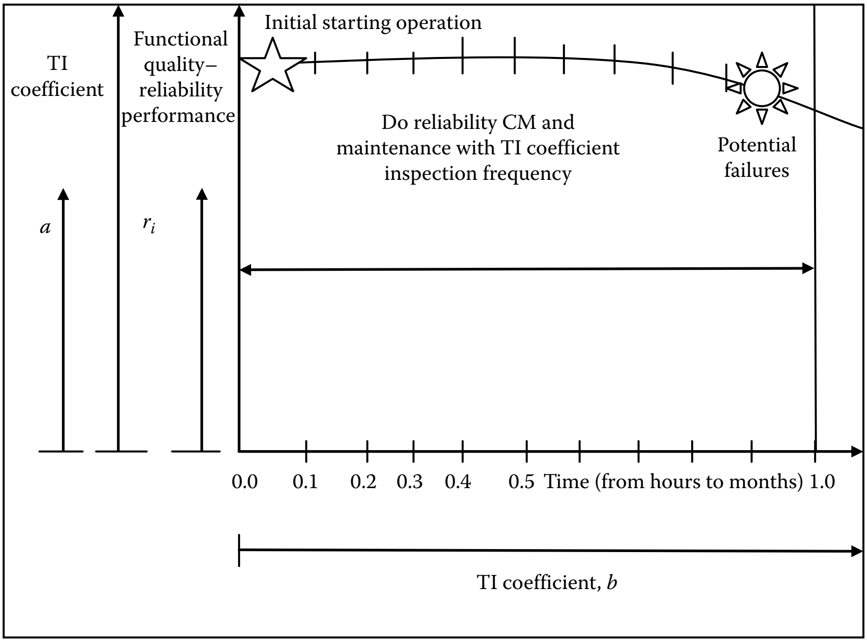

FIGURE 1.5
Reliability condition monitoring and maintenance with TI coefficient inspection frequency.

The technique will be used to correlate the reliability growth and degradation of parts, processes, and equipment as well as control their variations from one point, level, and condition to the other and from time to time. The goal of this new IRCMM system is to integrate reliability, CM, and maintenance for maximum achievable reliability of a material, part, process, and equipment as well as to select the best components and detect, diagnose, and predict faults, defects, and failures before they cause catastrophic damages with the right information and the right personnel in order to get more out of design, manufacturing, operation, and maintenance systems without unexpected emergencies and downtime at minimum costs. This will help to determine the optimum operational limits of the material system for safety, lifetime, and reliability as well as establish the degree of mechanical, physical, and chemical compatibility the material, part, monitoring, and maintenance strategies must have with the system reliability improvement and optimization as shown in Figure 1.7. It will also help to select the most sustainable reliability characteristics from the existing optimum maintenance models, detect faults and failures at all stages of an industrial process, and predict maximum quality and reliability data for design, manufacturing, and service operations at optimum cost and energy consumption. Since the need to work on a corporate standardization of integration and its process works from the initial to the final stage

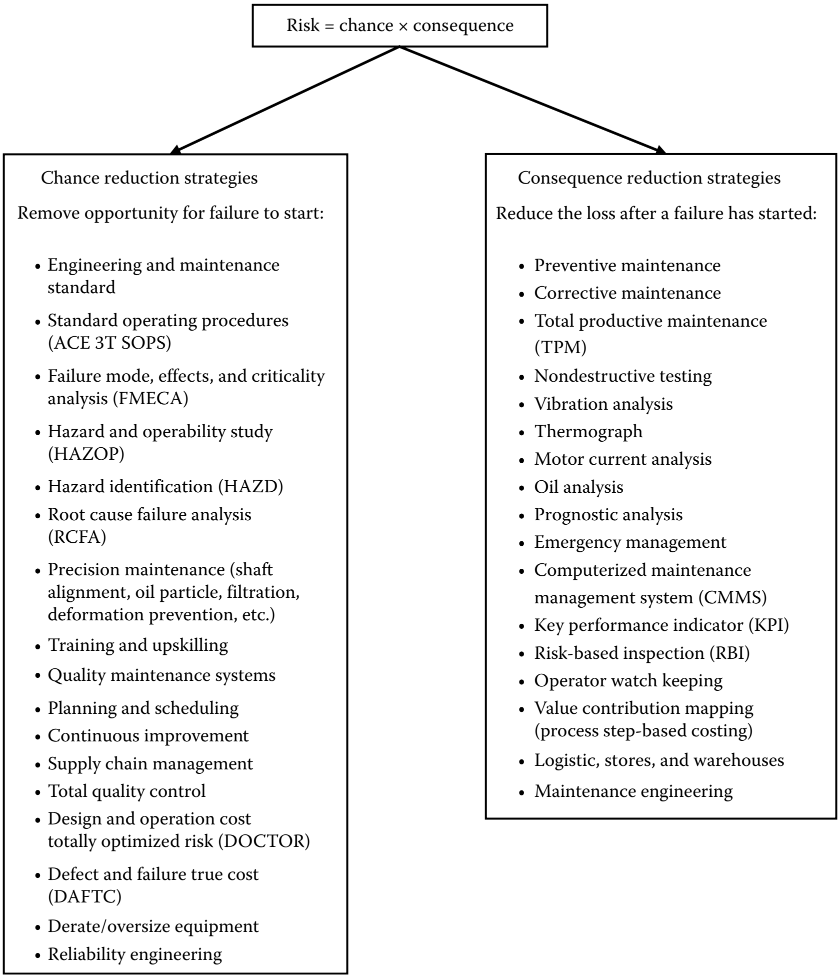

FIGURE 1.6
Various risk management methods. (From Smith, R., Failure reporting, analysis, corrective action system made simple, SMRP, Newsletter, 2010.)

of manufacturing processes and service operations is eminent, the integration of automated process control systems and industrial equipment monitoring systems with the help of the TI technique must be centered on the correlation of material conditions, process conditions, and multiple quality–reliability characteristics of the parts of industrial equipment. This technique will help eliminate the limitations of the direct measurement of quality and reliability parameters, which of course will provide a new direction and solution to the challenges modern monitoring and maintenance of industrial processes and equipment face. It will therefore help extend the life and reliability as well as reduce the chance of failure at

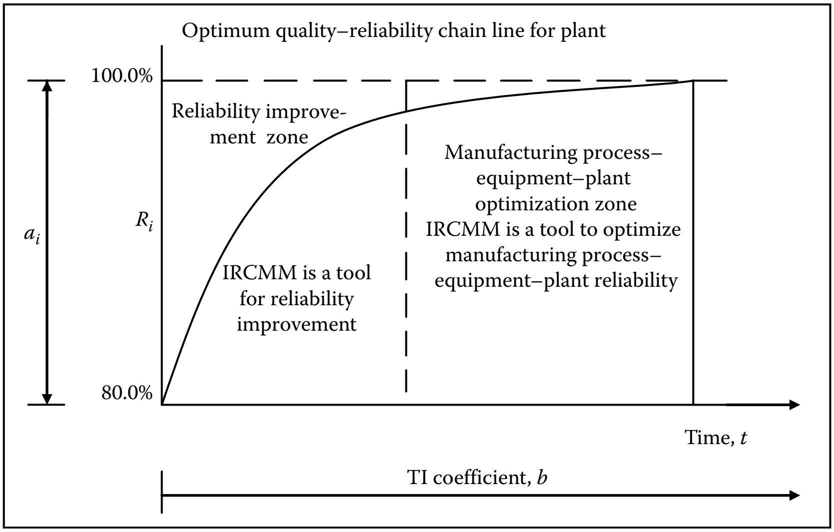

FIGURE 1.7
IRCMM with TI technique.

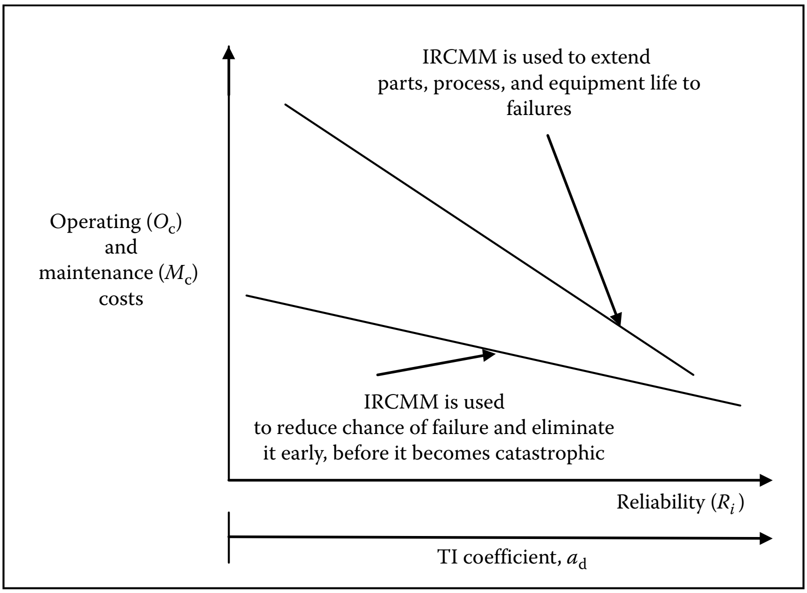

FIGURE 1.8
IRCMM with TI coefficient.

minimum maintenance costs, as demonstrated in Figure 1.8. The TI coefficients then become the component and system conditions' control parameters and requirements, which make all criteria accessible via one system. With this technique, unnecessary work is eliminated based on actual condition rather than just recommend time intervals and standard baseline requirements, which can be used for optimum selections and comparisons as seen in Figures 1.9 and 1.10. By establishing ranges and limits for operational parameters, processes, and practices, current and forecast mechanical, physical, and chemical component conditions can be determined proactively with the different operations. This of course allows for maintenance to be done when necessary and to be carried out proactively. Real-time effectiveness factor, quality factor, and integrated reliability and maintenance cost data of process, parts, and equipment can be now be considered during the annual planning cycle, as well as for real-time integrated reliability monitoring and maintenance decision flow with the TI technique. Through persistent use of the IRCMM program, it will be possible to acquire equipment part quality factor, reliability growth and degradation coefficients, mean time to failure, and maintenance of life cycle costs with the help of the TI technique, which can also be used to select, control, integrate, and optimize as well as achieve start-up precision. This will definitely help build knowledge and improve workmanship standards that bestow plant and equipment in excellent conditions. It will also deliver

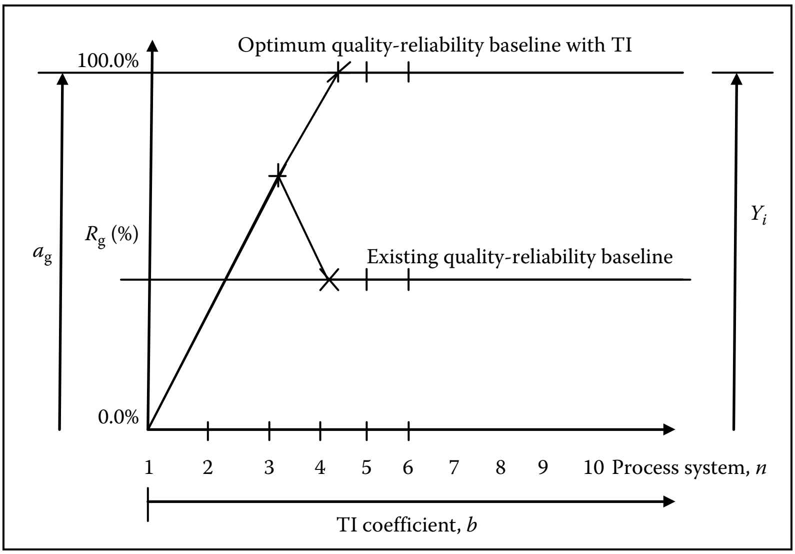

FIGURE 1.9
System quality–reliability baseline requirements with TI technique.

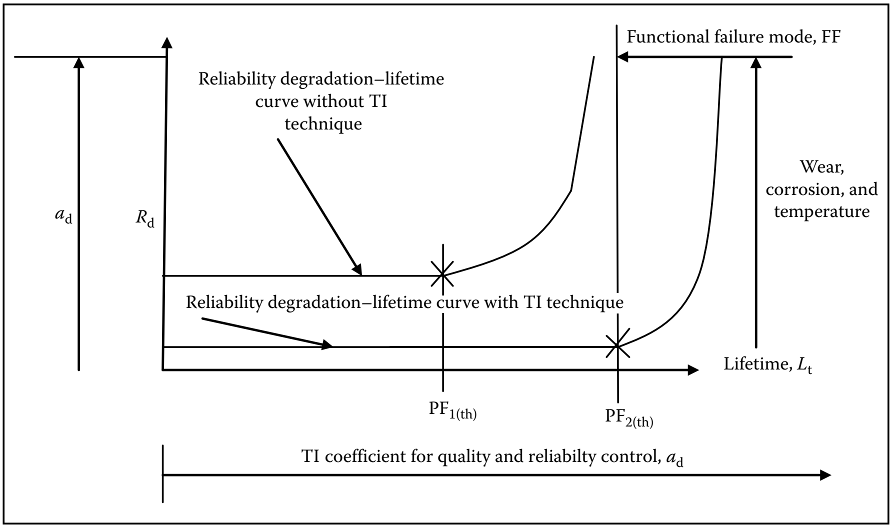

FIGURE 1.10
System reliability–failure baseline requirements of processes, parts and equipment with TI technique.

low operating risk to parts and a maximum chance of a highly reliable and long trouble-free equipment lifetime at minimum life cycle costs.

1.7 Equipment Reliability Degradation and Failure Variation Control with the TI Technique

Figure 1.6 identifies many strategies available to control the risk placed on equipment parts. Those from the left-hand column reduce the chance of failure. Those on the right only reduce the cost of failure, but the chance remains unchanged. Notice in Figure 1.6 that CM, as it is usually done, does not reduce the chance of failure. It only spots impending failure and lets you turn the repair work into a planned maintenance work instead of a breakdown job. Since the failure has already been initiated, and if it is not addressed on time, the equipment will surely break down. Proactive maintenance and PdM are used to address the failure that has already started. This is where the IRCMM program is applied. The program is used to identify the root cause the potential failure of the interval period between the potential and functional failures. The program is also used to select the appropriate cost-effective maintenance strategy. Figure 1.8 shows the outcome of the IRCMM program with the TI technique as well as the effect of reliability growth and TI coefficients on one's business in using cost-effective CM.

This type of CM improves operating life and reliability, which can yield up to the maximum achievable reliability or the optimum quality–reliability conditions of components. The maximum achievable reliability is used as a baseline requirement point or level for maximum availability, reliability, quality, and life of components and systems (see Figures 1.9 and 1.10). It forms the final condition for the manufacturing process and the initial condition for new equipment. Control limits for reliability CM can also be used as a tool to stop failures with the help of the TI technique. From the initial operation to the final operation, it is a tool to reduce the chance of parts failing and also to select a suitable cost-effective maintenance strategy as shown in Figure 1.8. TI technique is used to transfer some positive quality parameters and stop the transfer of impending failures from one operation to the other towards achieving optimum quality–reliability condition of components and systems.

1.8 Equipment Reliability Growth and Optimum Condition Variation Control with the TI Technique

When the TI technique is used to gather information on the chance of failure, it becomes a tool to optimize equipment and part reliability. This is when the reliability growth leads to the maximum achievable reliability or optimum reliability of a component, while reliability degradation leads to functional failure at minimum maintenance cost. With it you confirm that reliability growth and degradation variations have been controlled to the precision outcomes you want for parts manufacturing operations, assembly, installation, lubrication, and workmanship. You use it to prove the starting quality–reliability of a part from the initial manufacturing operation to the final operation and the starting machine/equipment condition. You do the quality–reliability testing with the TI technique as part of the maintenance work. If the TI coefficient or quality factor levels are too low after assembly or any operation, you can identify the cause and rectify it before moving on to the next operation in the manufacturing process and before letting the equipment go into service. Test for electrical connections (hot spots) with a thermograph camera before handing the equipment back for operation, take an oil sample when the equipment is running at operating temperature, and get the start-up wear particle count. In this way, IRCMM with the TI model–based program is used to prove that the equipment has been set up with the best chance of achieving high reliability. It is also the evidence you need to prove to people that risk is truly minimized. As a direct consequence, you will get lower operating/maintenance costs and gain equipment availability and reliability. By applying the model-based program, you will be able to optimize the reliability at minimum maintenance cost, thereby reducing the chance of equipment failure from undetected defects. By guaranteeing high reliability from start to finish, your failure avoidance will deliver drastically lower operating and maintenance costs. This effect on operating and maintenance costs and reliability growth and degradation, with the help of IRCMM with the TI model–based program, serves as an optimizing and information tool. This program will also help minimize the limitations of existing vibration monitoring for industrial processes and equipment, providing a new direction for long-lasting solutions to the challenges modern condition-based monitoring and maintenance systems face. The aim of this book is to optimize the surface finish machining condition of a hard alloy–coated cylindrical part and transfer its optimum quality parameters from an initial service operation to its final operation for maximum achievable reliability of equipment with minimum maintenance costs. This aim can be achieved with the following objectives:

1. To provide a solid comprehensive and analytical overview of operations and maintenance that offers a viable and cost-effective platform for the IRCMM program of manufacturing processes, parts, and equipment in the IOFs
2. To improve the material–part–equipment system quality–reliability condition and the manufacturing process performance for corrosion-, wear-, and temperature-resistant applications
3. To maximize component and system reliability growth of parts and equipment and minimize reliability degradation at minimum life cycle costs within the framework for reliability, CM, and maintenance
4. To highlight the role of the TI technique for IRCMM of industrial processes, parts, and plant equipment
5. To develop a robust design for IRCMM of industrial processes and equipment with the TI technique
6. To understand fatigue analysis within condition-based monitoring of equipment parts and the measurement of reliability degradation and defects on the structural integrity of a critical part in dry running and submerged applications
7. To understand wear with other competing analysis within condition-based maintenance monitoring of equipment parts and the measurement of reliability degradations and defects on critical mating parts in dry running and submerged application
8. To design integrated reliability monitoring and maintenance of manufacturing processes, parts, and industrial equipment with the design of the experiment and the TI model

9. To carry out the reliability monitoring and maintenance of hard coating part surfaces and process conditions during manufacturing processes and equipment operation with the design of the experiment and the TI model
10. To integrate reliability, maintenance, and CM of industrial equipment under a single platform
11. To develop an integrated reliability maintenance monitoring technology for production processes, parts, and industrial equipment with TI model–based simulation technique in the IOFs
12. To develop an integrated reliability monitoring and maintenance strategy for manufacturing processes and industrial equipment with a TI model–based software in the IOFs
13. To introduce a cost-effective integrated reliability monitor and maintenance strategy with a TI model–based software program
14. To manage integrated reliability monitoring and maintenance of manufacturing processes, parts, and industrial equipment in the IOFs

1.9 Conclusions

1. The IOFs that account for more than 80% of the energy consumed and more than 90% of manufacturing wastes are also capital intensive, face global competition, and are cyclical, subject to producing quality part surfaces for failure-resistant equipment, and having mature markets in the world economy.
2. The reliability of parts and equipment cannot be readily and timely assessed by operators, thereby lacking knowledge of the impacts that they have on the overall effectiveness of equipment, and as such, potential failures and defects are left undetected early until they become functional failures that can cause catastrophic damages.
3. Equipment part defect and failure issues are largely the results of manufacturing process–induced anomalies, which need to be combated by integrated reliability protection, reliability CM of potential failures, and maintenance prediction operations for added value to the individual protection and prediction systems that were once islands of information in the different IOFs.
4. Existing manufacturing processes for producing hard alloy–coated workpiece surface do offer clear productivity and cost benefits, but the traditional monitoring, maintenance, and operation

automation architecture cannot easily provide the required constant flow of real-time reliability information for parts and components that make it work.

5. Industrial experience has proved that a faster time to market can provide competitive advantages and economic benefits to most part and equipment manufacturers, but such drive should not be allowed to negatively impact component quality and reliability of industrial equipment as well as their maintenance strategies.
6. The traditional automation architectures cannot show you much more than the process variables and any associated trends or alarms, thereby providing no way to monitor part and equipment failures and as such offering no way to detect the early warning signals of potential failures during manufacturing and equipment operations, which hinder system reliability, wear-, corrosion-, and temperature-resistant applications.
7. In this modern stage of scientific and technological development, the demand for wear, corrosion, high temperature, strength, reliability, and other characteristics of hard alloy coating materials is fast increasing in such a manner that the traditional machine tool-bit material can no longer deliver high machining productivity, which eventually ends up in suboptimal surface quality of parts and equipment performance.
8. The traditional methods of increasing tool life for machining hard alloy–coated part surface are not reliable and cost-effective, and as such, there is therefore a need to work out a cutting and machining method that is based on new principles of interaction between tool bits and workpiece on a lathe machine tool.
9. The use of standard automation tools and optimum selected hard alloy coating materials and process conditions can help speed up part development time with fast cutting and machining method to reduce errors and defects as well as increase service life and profit margins while ensuring high-quality, reliability designs at minimum life cycle and maintenance costs.
10. The author introduces a modern cutting and machining method that will be implemented in this book for testing, cutting, and turning hard alloy–coated workpiece surfaces for maximum part quality and equipment reliability at a minimum tool life cycle and maintenance costs.
11. The optimization of the new progressive testing, cutting, and machining method conditions would provide the optimum database for quality, reliability, and failures as well as for the operating manufacturing processes and equipment reliability, CM, and maintenance requirements.

12. The analysis of the existing reliability, CM, and maintenance of manufacturing and equipment system revealed that most failures were not age-related, where the equipment failed because of length of use, which meant that time-based preventative maintenance was pointless in most cases but requires condition-based monitoring and maintenance throughout a critical part life cycle for higher reliability, life, and effectiveness of equipment.
13. A critical equipment part that is properly manufactured with optimum process conditions for a wear-resistant application and installed into equipment without any errors will operate at a particularly high level of reliability and performance, which ideally is at its design requirement, but as the life performance progresses, degradation and failure are bound to occur, which require reliability CM and precision maintenance strategy to combat the degradation in order to sustain the desired high-level reliability at a minimum maintenance cost.
14. Existing vibration CM of equipment and analysis is presently the most effective way to evaluate component and system reliability to achieve the best precision maintenance practices, extend equipment longevity and reliability, and avoid unplanned shutdowns.
15. The existing vibration CM technique is expensive and cannot be used to detect early potential failures as well as cannot be used to select cost-effective components like materials, manufacturing processes and equipment, and their conditions that suit desired requirements.
16. Integrating component reliability condition with process performance condition control system for greater benefits is now possible through the use of CM and maintenance with the TI technique, which is used to control and measure the varying process performance and component quality conditions.
17. The TI technique can be applied to all desired critical components of manufacturing processes, materials, parts, equipment, and maintenance strategies, including energy impacts, vibration, measurement points, and part's construction to determine the maximum component reliability, process performance, and life at minimum maintenance cost.
18. The TI technique is a new and advanced model-based integrating program that allows the simulation of different operating conditions with the algorithm that can be tested over a wide range of conditions safely and on demand in the laboratory and also can easily repeat the test to compare and fine-time codes without leaving the laboratory, which is highly essential toward a sustainable development in reliability, CM, and maintenance of industrial equipment.

19. A TI model–based simulation program can be used to measure and test component reliability growth for maximum reliability of parts and equipment assessments and also reliability degradation that leads to failure of industrial equipment at a minimum life cycle cost.
20. A TI model–based software program is used for cost-effective reliability testing, design, maintenance, and management in the IOF.
21. The application of a TI model–based software program and hardware in the loop can be used to debug, test the code, evaluate control and CM, and provide optimum condition requirements for a cost-effective reliability, CM, and maintenance of industrial equipment.

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2

Integrated Reliability of Material–Part–Equipment System Life Cycle with the Technological Inheritance Technique

2.1 Introduction to Integrated Reliability Condition Monitoring and Maintenance Process of Material–Part–Equipment System Life Cycle

Integrated reliability condition monitoring and maintenance (IRCMM) focuses on continuous improvement throughout the life cycle of the material–part–equipment system. The knowledge of the equipment life cycle is important because it provides a basis for understanding how and where reliability engineers enter into the process of designing, manufacturing, maintaining, and operating the part–equipment system. The life cycle of the part and equipment system consists of seven phases:

1. Concept and feasibility phase
2. Design phase
3. Part manufacturing phase
4. Part surface finish phase
5. Installation and assembly phase
6. Equipment and part operation phase
7. Phase-out and part wear-out phase

These phases provide the framework for tracking and monitoring reliability improvement throughout the equipment life cycle phase and guidance on when and where to apply resources. Life cycle cost concepts are introduced to help understand the impact on expenditures and cost of ownership when reliability is initiated at different phases of the life cycle. The integrated reliability monitoring and maintenance process provides a means for systematically improving reliability throughout the equipment life cycle. It is an iterative process of setting goals, evaluating, comparing, and improving systems that consists of five basic steps:

1. Establishing maximum achievable reliability as the goal and maximum wear-resistant design requirements for materials and surface finished equipment parts
2. Application of the technological inheritance (TI) technique for achieving maximum reliability of components and systems
3. Evaluation of material, surface finish, and equipment reliability with the TI technique
4. Comparing the results of evaluation to the goals and requirements as well as making decisions for the step in the technological system for reliability CM and maintenance of components and systems
5. Identification of common failures in the IOFs and root causes of failures and eliminating the failures during manufacturing and equipment operations using the IRCMM program

The process then returns to step 2 and repeats steps 2 through 5 until the goals and requirements are met. The role of management in implementing the integrated reliability monitoring and maintenance program will be discussed in the last chapter. Management has responsibilities in establishing and implementing the process. These responsibilities include establishing the right environment and choosing individuals to supervise the effort. The activities and tools used in applying the integrated reliability monitoring and maintenance process are discussed in more detail in the later chapters. There is an effective and systematic way to include reliability in material, surface finish, and part design. This is done with the help of the TI technique that is used to implement the required task from the initial operation to the final operation following the shortest cost-effective monitoring and maintenance route in the structure of a technological chain.

The technological chain structure of manufacturing a hard alloy–coated part for wear- and other competing failure-resistant applications is shown in Figure 2.1. This figure highlights the workpiece multivariate surface quality parameters and the condition factors of the manufacturing processes. The failure events of this monitoring and maintenance chain are identified as the low productivity and reliability of a hard alloy–coated surface machining process, infant mortality failure, random failure, and wear-out failures of an operating machine/equipment. It is almost practically impossible to machine hard alloy–coated surfaces with traditional tool bits, which eventually does not meet the maximum reliability requirements but ends with low productivity and low reliability as seen in Figure 2.2. The machining process of a hard alloy–coated workpiece surface for wear- and other competing failure-resistant applications with multivariate quality surface parameters is expressed in Figure 2.3.

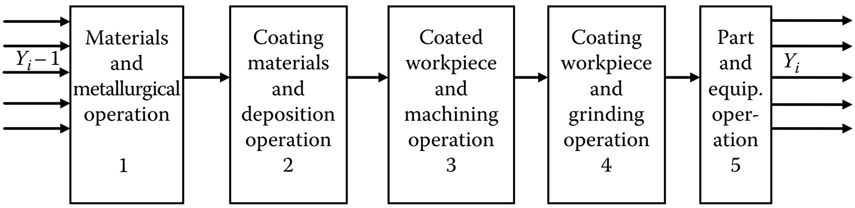

FIGURE 2.1
The technological chain structure for producing hard alloy–coated part for wear- and other competing failure-resistant application with part surface quality parameters.

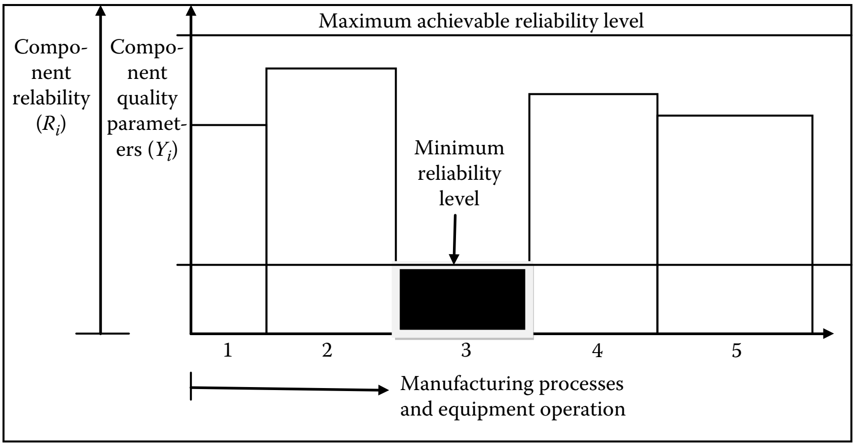

FIGURE 2.2
The component quality–reliability chain of a hard alloy–coated part for wear- and other competing failure-resistant application with manufacturing process and equipment system.

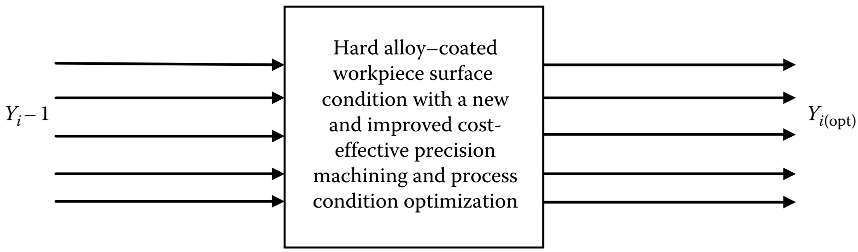

FIGURE 2.3
The new machining process of a hard alloy–coated part surface for wear- and other competing failure-resistant application with multiple quality surface parameters.

From Figure 2.3, Y_1 is the hard alloy–coated part surface quality parameters:

where Y_1 is the surface hardness of the part
Y_2 is the surface stress concentration factor of the part
Y_3 is the surface wavelength of the part
Y_4 is the surface roughness of the part
Y_5 are other parameters (wear, corrosion, fatigue, temperature, etc.)

while X_{3i} is the machining process performance conditions

The existing material, part, and process models for predicting material, part, and process quality parameters (Y_i) and conditions (X_i) are not adequate and sometimes not even available. But if all the necessary parameters and factors are not considered during design, and if all the requirements are set according to material, part, and process system performance as well as operating conditions, it leads to suboptimal outcomes and requirements. For a higher level of machining a hard alloy workpiece surface, a new and improved progressive machining process is needed. This book provides a new cost-effective machining method for maximum achievable reliability. A hard alloy coating material and coated part surface multivariate quality regression model is developed and optimized to set up optimum baseline requirements for components and systems of wear- and other failure-resistant applications. The new machining process of a hard alloy–coated part surface for wear- and other competing failure-resistant applications with multiple quality surface parameters is shown in Figure 2.3. The multiple component operating quality condition can be integrated to form a single-compound quality factor (Q_f) for material and part as a function of the quality parameters (Y_i), while the process operating performance condition factor (P_f) is a function of the performance characteristics (X_i). The integration is possible with the TI technique. When the component and system conditions (Y_{iopt} and X_{iopt}) are optimized, the component and system reliability conditions are also optimized (R_{iopt}), which implies that under this optimum condition, $Y_{iopt} = Q_{f(iopt)} = R_{(iopt)}$. The same rule applies to $X_{iopt} = P_{f(iopt)} = E_{iopt}$, where Q_f is the hard alloy–coated part surface quality factor, which is a function of the TI coefficients for component quality parameters, and P_f is the process performance factor ($P_{f(iopt)}$) or ($E_{(iopt)}$), which is the optimum effectiveness of the machine/equipment. These optimum conditions are very important for the selection, critical indexing, and comparison of desired materials, parts, and process, as we will see later in this book with the help of the TI model. The technological chain structure for making integrated reliability improvements throughout an equipment coated part surface life cycle is developed with the help of the TI technique.

The integrated reliability improvement process provides a means for making advancements when it is applied to equipment early in the design stage, through manufacturing and service operations, thereby making improvements to existing equipment. This improvement is made possible with the application of the TI technique that can be used to select optimum conditions of components and systems, detect potential failures, and eliminate the failures before it can cause catastrophic damages. The technique is also used to test the optimum reliability conditions, reliability degradation, and failure rates of materials, parts, processes, and equipment throughout the life cycle of an equipment part. The knowledge of an existing critical equipment coated part surface life cycle with the application of the TI technique is important because it provides the following:

- The IRCMM process for manufacturing wear- and other competing failure-resistant part surface
- A basis for understanding the best monitoring and maintenance practices for improving part and equipment reliability as well as the cost of the improvement
- Reliability CM and maintenance data for feedback and forward information toward optimization
- A measure on the impact of parts and equipment reliability on a business

The life cycle costs of the coated part provide a perspective on the impact of initiating the reliability improvement process early in the equipment life cycle. A thorough knowledge of life cycle costs and life cycle operation relationships with coated part quality helps to achieve better equipment at lower total costs, which helps to improve equipment reliability and business profitability.

2.2 Measuring the Impact of Equipment IRCMM on a Business

The standard definition of reliability does not say much about the effects of equipment failure on business and people. You know when you have unreliable plant, part, and equipment due to the fact that people are angry because it fails so often. In companies with equipment reliability problems people are busy repairing failures over and over again. This practice never ends, and you go home each day knowing there will be more trouble the next day. At the same time, you also know that when you have reliable equipment because it performs as it is intended without failures, the business likely makes good profits with low operating costs controlled to a narrow, known range. Under such a condition, you will have enough time to do your work well. A place with reliable equipment is a happy and safe place.

Measuring equipment integrated reliability monitoring and maintenance is important if you want to improve and cost it. Reliability is measured traditionally as the average time between failures, known as mean time between failures (MTBF), but the drawback with only measuring time is that there is no indication of the value of that level of reliability. If you do not know what reliability is worth, you may spend lots of money on small improvements that have little impact on reliability, or worst still, not spending enough money on business indicator. Reliability must also be measured by the money made or lost for business. A measure of improving reliability needs to show improving profitability and quality. At this point, a measure of improving reliability in terms of time, money, and quality needs to show improving profitability. For companies that measure production and quality by weight, a standard profitability indicator that reflects reliability is expressed as follows:

Unit cost of production ($/T) = Operating costs in the period ($)/total saleable throughput (tonnage or kW), where 1T = 3.861 kW [1]

Figure 2.4 shows what these measures indicate.

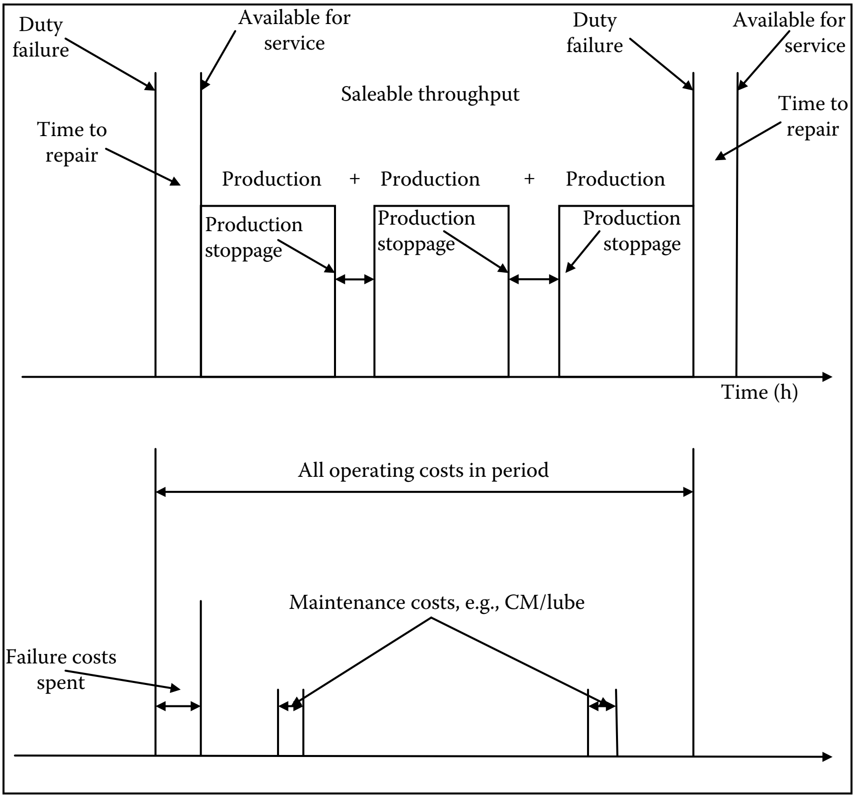

FIGURE 2.4
Reliability ought to measure time and operating cost. (From Mike, S., Condition based maintenance strategy for equipment failure prevention, lifetime-reliability.com, 2014.)

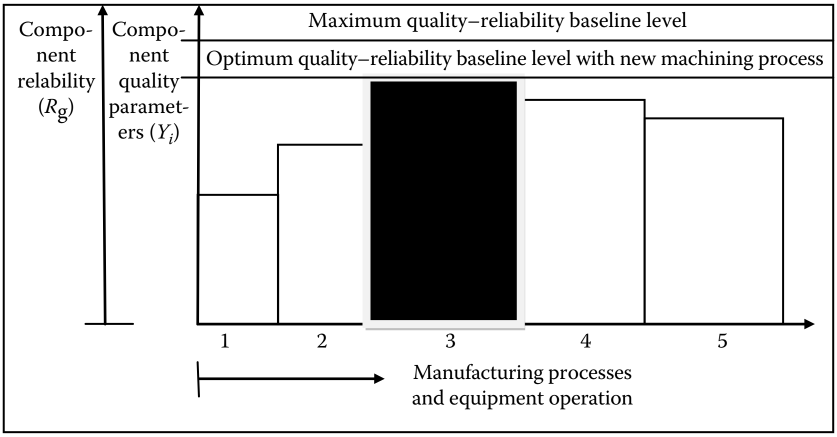

FIGURE 2.5
Improving quality–reliability growth of a hard alloy–coated part work-piece surface with a cost-effective precision machining process.

It is best to know the costs spent on an item of equipment, exactly what they were spent on, and what they were spent to do. If you do not have good records of equipment problems, with their associated costs and changed conditions over the equipment life, it will probably be difficult to identify suitable actions and prepare justifications to fix them. To get the detail needed to fully analyze the cause of your reliability problems, it requires continuous life cycle tracking and monitoring of the lifetime, quality/failure, and cost of your equipment down to the individual critical part with hard alloy–coated surface that used a cost-effective precision machining process as shown in Figure 2.5. The reliability degradation and failures of critical steel shaft–bearing surfaces is seen to have the highest level among other working parts of a machine/equipment when evaluated with the help of the TI technique as shown in Figures 2.6 and 2.7. The TI coefficient for quality–reliability condition is optimized at the surface of a critical part coated with hard alloy materials, which reduces component degradation and failure rate to a minimum and maintains the optimum conditions for a specific lifetime at minimum operating/maintenance cost as seen in Figures 2.8 and 2.9.

2.3 Equipment–Part Life Cycle and Phase-Out Conditions

The equipment–part life cycle begins when the idea for the equipment–part is conceived and optimized and ends when the equipment/part is no longer useful. The life cycle consists of a phase that describes the state of design,

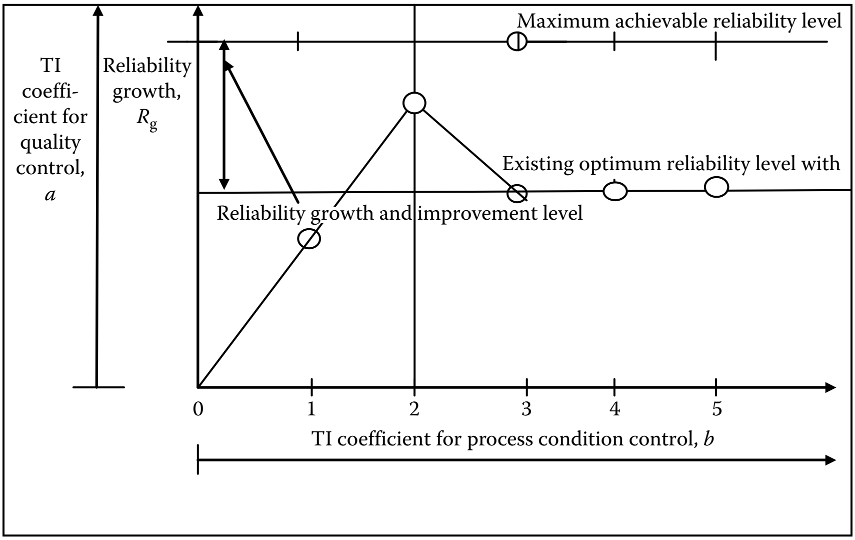

FIGURE 2.6
The reliability growth of a hard alloy–coated part work-piece surface and the manufacturing processes with TI coefficients.

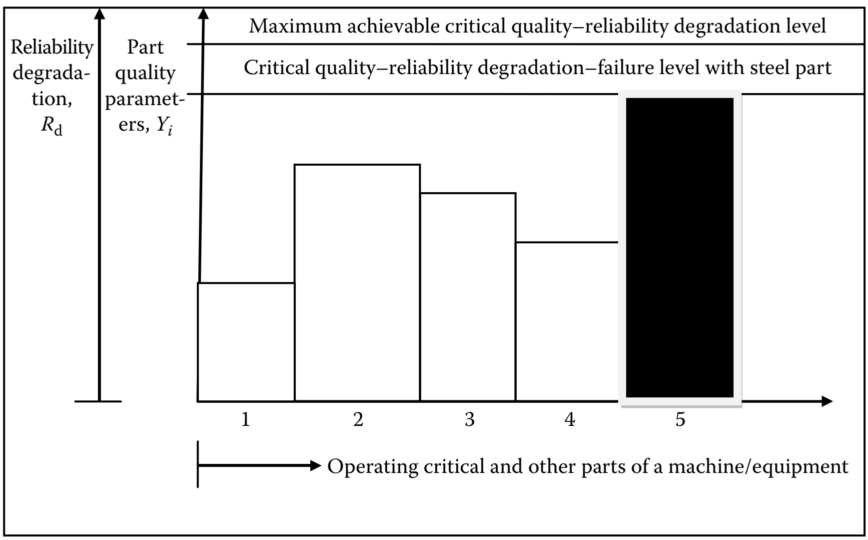

FIGURE 2.7
Reliability degradation and failures of a critical steel shaft–bearing surfaces and other working parts of a machine/equipment.

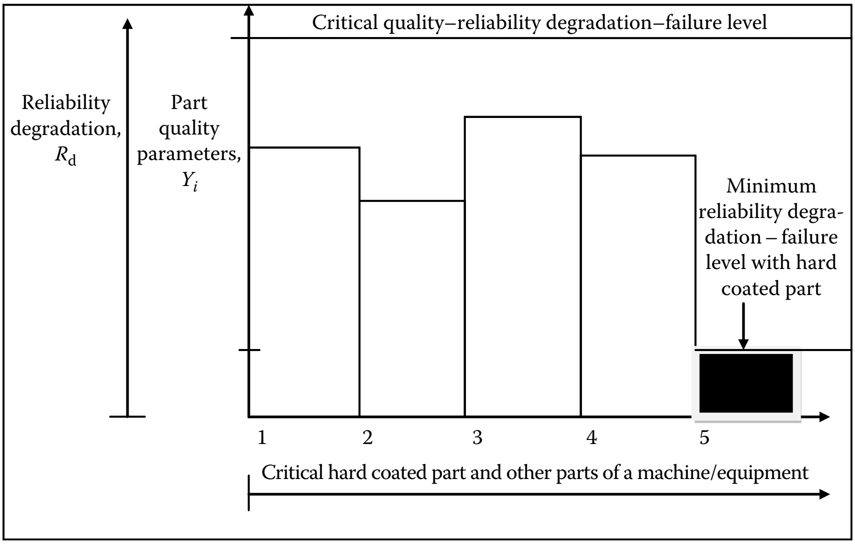

FIGURE 2.8
Reliability degradation and failure-resistant surface of a critical hard-coated part and other working parts of a machine/equipment.

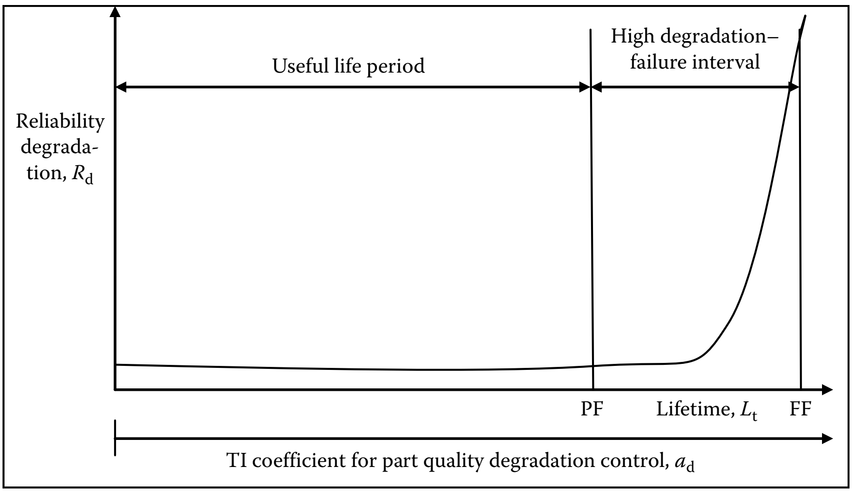

FIGURE 2.9
Reliability degradation and failures of a critical hard alloy–coated part surface and other working parts of a machine/equipment with TI technique.

process of development, and production or operation of equipment/part. A working knowledge of these phases enables proper planning and execution of the activities and functions necessary for designing, manufacturing, and operating reliable equipment/part in a cost-effective manner. The reliability condition measurement in each of the six cycle phases in terms of quality, time, and money will enhance the profitability of the business through the knowledge of design, development, and service conditions of part/equipment in the industries of the future (IOFs). At this point, it will be necessary to discuss about the quality, time to failure, and operating and maintenance cost of your equipment part and component, which is the secret to successful equipment reliability. Integrated reliability therefore deals with the measurements of time to failure, maintenance cost, and the quality of components, which can be determined with the TI technique. Since equipment is made of parts and components combined in assemblies that work together to allow it to operate, each part and component can be assessed with mechanical, chemical, and other properties for any particular application. Figure 2.10 shows how we combine parts to form a shaft–bearing assembly. It shows a bearing in an electric motor housing carrying a shaft, a typical situation in many industrial machines. There are 14 parts in the assembly. The 14th item is the lubricant. When you look closely at how the assembly is built, you find that it is configured such that parts work with others in a sequence. Figure 2.11 identifies a portion of the sequence of parts that allow the shaft to turn in the bearing.

All industrial equipment is built as a series arrangement of parts and components working together to perform the required duty. Once you have a series arrangement of working parts, the series reliability depends on each one working properly. A simple example shows you what happens. Figure 2.12 is the same as Figure 2.11, except with a failed part. Without correct lubrication, the series connection can be lost and the assembly cannot survive in service. If this assembly were in a piece of equipment, the equipment fails. A sequence arrangement of parts only requires one item in the series to fail and the whole assembly fails. When the assembly fails, the equipment stops. The intended messages in Figures 2.11 and 2.12 are that the reliability of a piece of equipment is totally dependent on the reliability of its individual parts. If one fails, the machine fails. If one part is in a bad condition, the entire equipment is at an ever-increasing risk of breakdown. We can calculate the reliability of a series system mathematically. In Figure 2.13, each part has its own reliability, "R". This same rule applies to manufacturing processes that produce a hard alloy–coated workpiece surface. The component reliability and process performance depend on a set of component properties or quality parameters (Y_i) and process properties or performance parameters (X_i). The relationship between the part quality condition and the reliability condition is directly dependent on the optimum part finish condition, where $Y_{i\text{opt}} = Q_{\text{fopt}} = R_{\text{opt}}$. Also the optimum process/equipment performance condition can be expressed as $X_{i\text{opt}} = P_{\text{fopt}} = R_{\text{opt}}$, which is used to calculate the

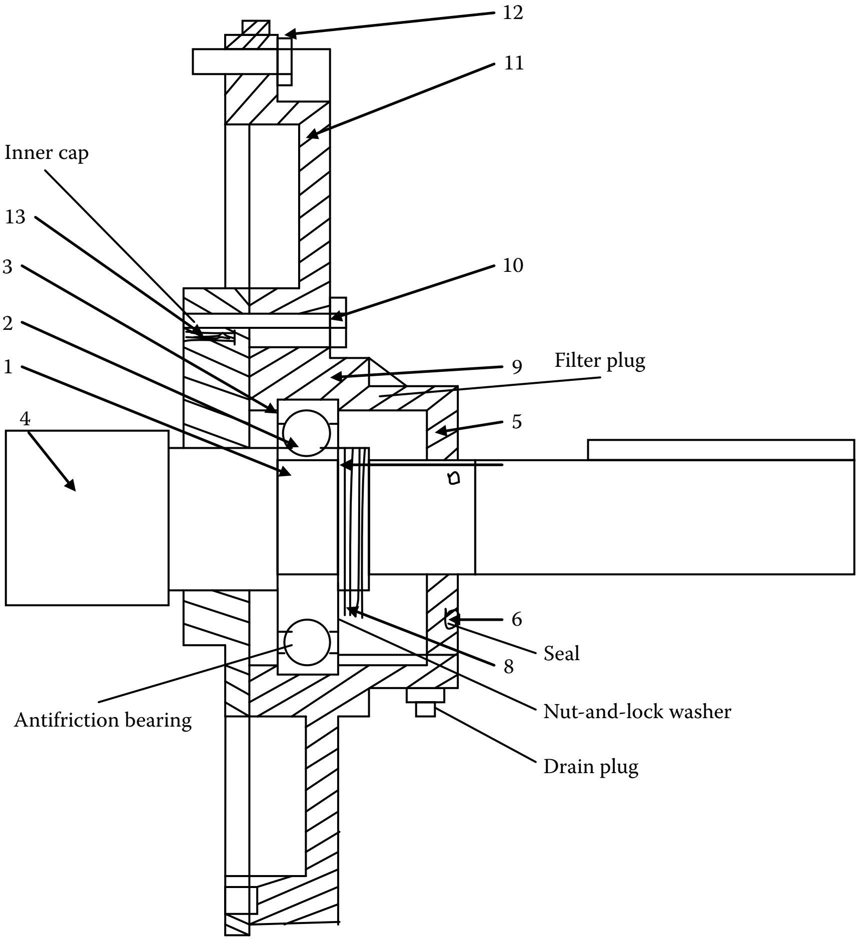

FIGURE 2.10
A typical shaft–bearing housing of a machine/equipment. (From Mike, S., Condition based maintenance strategy for equipment failure prevention, lifetime-reliability.com, 2014.)

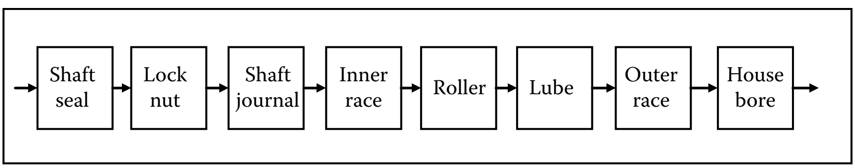

FIGURE 2.11
The series arrangements of parts that allow the shaft to turn in bearing housing. (From Mike, S., Condition based maintenance strategy for equipment failure prevention, lifetime-reliability.com, 2014.)

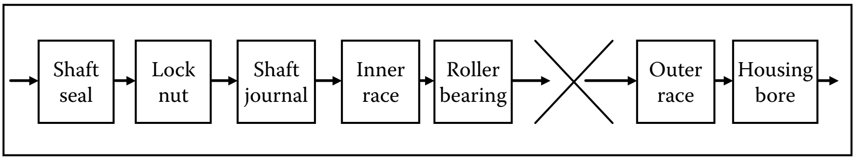

FIGURE 2.12
The reliability of a series arrangement depending on the reliability of its components. (From Mike, S., Condition based maintenance strategy for equipment failure prevention, lifetime-reliability.com, 2014.)

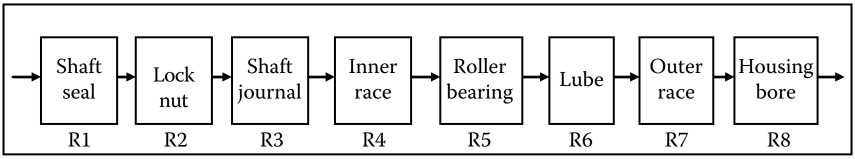

FIGURE 2.13
Every part in a machine has its own reliability. (From Mike, S., Condition based maintenance strategy for equipment failure prevention, lifetime-reliability.com, 2014.)

component reliability of items in a series/system. System reliability is the multiplication of the reliabilities of the individual items in the series/system. Therefore, system reliability (R_{sys}) is expressed as follows:

$$R_{sys} = R_1 * R_2 * R_3 * \cdots * R_n \tag{2.1}$$

At this point, it is worthy to note that an assembly of parts can never be more reliable than its least reliable part/component in an equipment/process (e.g., worn out part of a shaft) or in a manufacturing process (e.g., machining operation of hard alloy–coated part surface, which is the least reliable component in the system). You can never improve an equipment item's reliability more than its least reliable part or component of the system. Understanding this reliability principle is important for everything you do in the field of maintenance and reliability improvement. If you want to improve your equipment reliability and machines, you first must ensure that each of their parts, processes, and parameters is evenly and highly reliable, hence the need to determine the quality–reliability requirements by optimizing the critical hard alloy–coated part surface quality parameters and process/equipment conditions for wear- and other failure-resistant applications (see Figures 2.14 and 2.15). The optimized conditions can be sustained for a period of time. Under this period of time, it is necessary to operate and maintain the parts and equipment and processes with suitable practices and strategies. The TI coefficient is used to select suitable practices/strategies from the initial optimum condition to a critical degradation threshold point, where potential failure starts till it gets to a functional failure point over time. The functional

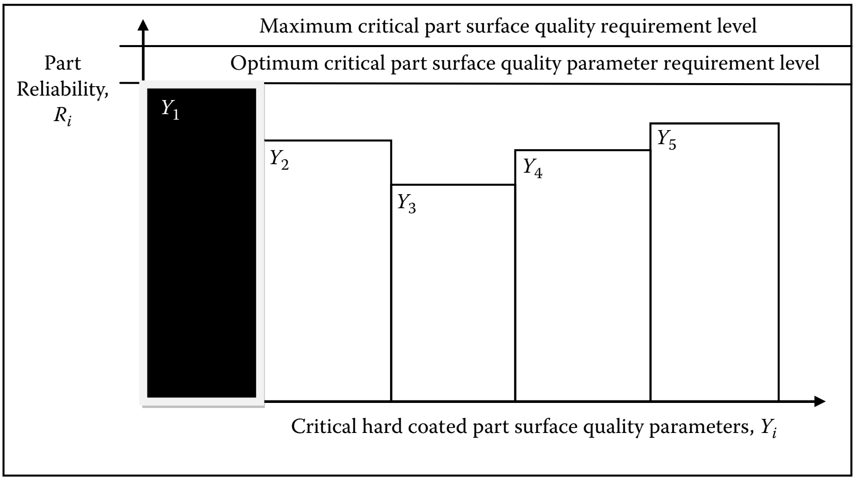

FIGURE 2.14
The quality–reliability requirements of the optimized critical hard alloy–coated part surface quality parameters for wear- and other failure-resistant applications.

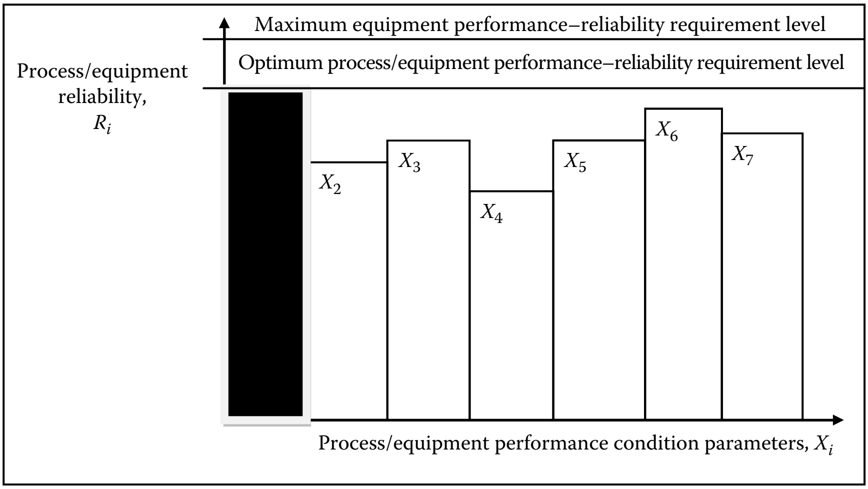

FIGURE 2.15
The performance–reliability requirements of an optimized process/equipment condition parameters for wear- and other failure-resistant applications.

failures like wear, corrosion, fatigue, and temperature as well as their individual and integrated reliability requirements can be assessed with TI coefficients. TI coefficients can be used to determine and evaluate materials, parts, processes, and equipment as well as to detect equipment failures during operations and also select a suitable maintenance strategy for maximum reliability at minimum operating/maintenance costs (Figure 2.16).

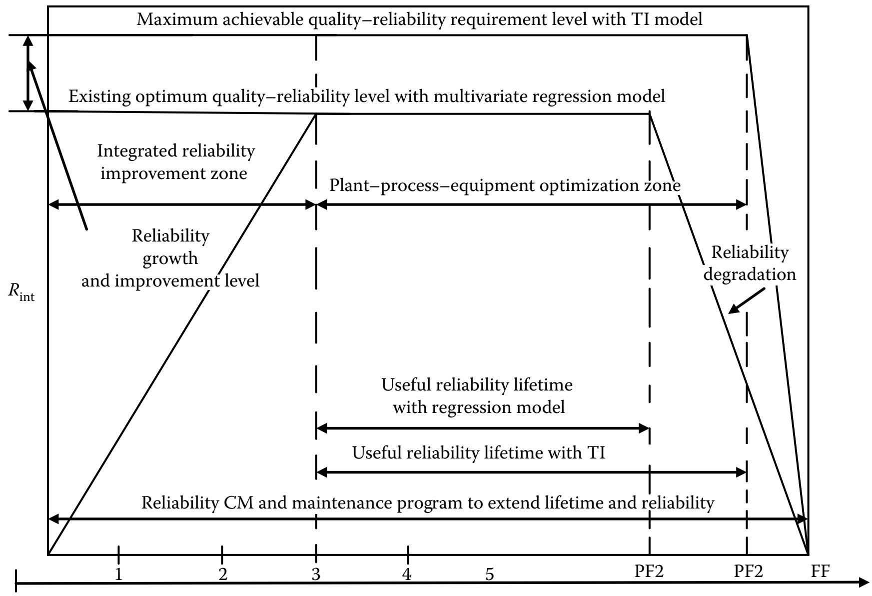

FIGURE 2.16
Integrated reliability of a critical hard alloy–coated part surface and mating parts of a manufacturing process and equipment with TI technique.

2.4 Equipment Failures and Part Replacement System

When we do preventive maintenance or breakdown maintenance, replace parts and/or lubricant in a machine and then put the equipment back into service. The new parts start their life, while the parts not replaced continue theirs. There is also the very possibility that parts that were minimally stressed before the invasive maintenance become stressed due to poor maintenance or negative inheritance and even that some of the new parts installed are stressed during assembly. Now within the machine, there are old parts still in good health, parts that have accumulated stress and approaching end of life, distressed parts ready to fail from accumulated overloads, and new parts starting into service with their inherent design limitations. What then is the reliability of the whole machine?

We know that equipment reliability depends on individual part reliability. The distressed part has a very poor reliability (likely to fail soon), while the new parts should have much higher reliability (likely to fail sometime in the future). Overall, the equipment is not more reliable than the most distressed part. What then can you do now to improve the reliability of the distressed parts? You can stop the equipment and replace that with a new one. The operation group would be very unhappy to learn that the equipment again needs to stop. Also, you must know which parts are in distressed; else you may replace the wrong ones and the equipment will still fail soon. There is another thing you can do to reduce the chance of overstressing the part. If the chance of excess stress is substantially reduced, the distressed part has a greater prospect of lasting longer. Lowering the stress on machine parts greatly improves the odds for higher equipment reliability. This can be as simple as improved housekeeping, such as keeping breathers clear of dust to prevent lubricant contamination and cleaning rubbish/rags and dust/dirt buildup off electric motors, bearing housings, and gearboxes to improve heat loss. You can also use reliability CM to monitor the stress, defects, reliability degradation, and failures from *rough operation* induced by poor operating practices and bring the likely implications on production to the attention of operation and plant managers, or with the use of the TI model and some monitoring and maintenance tools, it is quite possible to assess and eliminate the potential failures of parts, equipment, and plants. The latter is the essence of this book. We shall therefore apply the IRCMM program to monitor the stress, defects, and failures of materials and assess manufacturing methods and equipment part system conditions by measuring the system reliability degradation conditions and the rate of failures with the TI technique.

2.5 Measuring the System Reliability Degradation and Rate of Failures with the TI Technique

Parts working together form a series system called machines and all the parts and component reliability give the total reliability of the system/equipment. When any working part fails, the machine fails because the reliability of the system has degraded to the point of failure. All the failed parts are identified and the component reliability degradation and system reliability degradation threshold points, which represent the potential failure (PF), can be measured with TI coefficients. Once any of the critical part reaches the failure points, the machine/equipment fails. This can occur as infant mortality, random, and wear-out failure, since it has been designed into the component or system. These failures can be potentially captured and measured with TI coefficient sensors that measure the reliability degradation of a component/system. The measurement of a potential failure (PF) represents the sum of all the functional failures (FF) including infant mortality, random, and wear-out failures. The reliability degradation data are used to plot the reliability degradation and failure rate curve for a machine from the rate of its parts' degradation. Figure 2.13 shows the reliability of a typical machine/equipment with three working parts. An example could be bearing seal and shaft in a bearing housing of a centrifugal pump or an electric motor. The *integrated reliability degradation curve* of a machine/equipment consists of individual *green*, *blue*, and *red* parts. Such curves represent numbers of parts expected to fail in a period from particular circumstances. The *blue* part has wear-out characteristics and is replaced on breakdown. The *red* part has an infant mortality characteristic. Sometimes it fails early; other times it is later. The *green* part is characterized by a life of random failures that can happen at any time. When a part fails, it reaches the degradation threshold points; the machine/equipment also fails.

The curve reflects the whole machine's rate of failure, which is the sum of its parts' failure rates. The more often they fail, the higher the machine's failure rate. When parts do not fail, the rate fails. The machine's failure rate curve is called integrated reliability degradation rate of occurrence of failure (IRDROF). The IRDROF is representative of the reliability of the machine design, the quality of manufacture, the precision of its installation, its production abuse, and the purchasing and storage quality control, along with the standard of maintenance and workmanship care.

The integrated reliability rate of failure (IRROF) curve for a machine reflects what happens to its parts, moving up and down as materials, load, and geometry of a part fail. When we take the parts' failure history of many identical machines, we get the mean or steady average that represents the IRROF curve as shown in Figure 2.16. The curve provides the reasons why equipment and machines fail during their lives. First, parts fail and then machines and equipment will then stop. The solution to equipment reliability is therefore to improve parts' life cycle reliability (material and load and geometry life cycle reliability). The limiting maximum achievable reliability of parts is set by their design through the optimization of part material—manufacturing method equipment system condition. This book will highlight the optimization of a machining process condition for hard-coated workpiece with the help of a design of experiment and a multivariate quality regression model. The optimum surface quality values of the coated part and the machining process conditions can be used as the initial data in a TI model for system reliability condition control.

2.6 Concepts and Feasibility of Part Material: Manufacturing Method of Part–Equipment System Reliability Condition Control with the TI Coefficient

Before the optimization of the system condition, it will be necessary to find the failure events where the failure rate is highest in the system. In our case, machining a hard-coated surface part with a traditional tool-bit material provides low productivity and performance. It is therefore necessary to increase the quality and performance with a new progressive machining method in order to increase system reliability. Apart from the machining process, it is also necessary to increase the material hardness to a desired level for wear-resistant applications. The base hardness of the base material is low, while the hardness of the surface coated material can be used to suit desired wear-, corrosion-, and temperature-resistant applications. The higher the hardness, the higher the wear resistance and the lifetime reliability, and the manufacturing processes for achieving the desired specifications of a finished part must be well selected.

The new machining process method for hard-coated surface can be used to analyze the reliability growth and degradation as well as failure of a critical part or group of parts of a system with TI coefficients. The need for the design of a new machining process, component, and system may be based on existing one that can no longer perform its intended function or on customer requirements for which the necessary component or system does not exist. During this phase, marketing and sales personnel, customer service representatives, design and reliability engineers, and manufacturing engineers work together with the customers. The initial material selection for coating shaft surface–bearing assembly in different industries is based on the documents from the technology road maps [2] containing a sample of the most important material needs of the IOFs, while the final selection is determined with TI coefficients for wear- and other competing failure-resistant applications. Wear, corrosion, and high temperature have been identified as the common material failure modes for shaft or coated shaft in different industries. The initial analysis of the common material failures of a critical part like a shaft can be discussed as follows.

2.6.1 Corrosion Resistance

Corrosion and oxidation are ubiquitous problems in industry, and there are no perfect solutions for corrosion resistance applications. Through research, they can be mitigated, however, by the development of materials, coatings, and procedures that can withstand specific process conditions. The chemical process industry has long had serious corrosion problems that affect efficiency of production (necessary downtime, achievable process rates), product purity (contamination), energy usage, and maintenance costs. The following excerpt from the chemical industry road map will give the reader an idea of the serious needs of this industry. Materials are needed to withstand high temperatures (1000°F–3000°F) while retaining superior properties of strength, ductility, and corrosion and wear resistance. One of the greatest causes of equipment failure in the chemical process industry is damage due to corrosion and high temperatures. Material with enhanced resistance to organic acid environments could improve plant operations and maintenance requirements. Improved materials for chlorine-based processes are another high opportunity area. Equipment that is more resistant to chlorine and other halogens would reduce the cost of many of the current corrosion problems encountered in dealing with these materials. Refractory coatings for high-temperature furnaces are critical opportunity areas where new materials could have a significant impact on energy and maintenance costs. The development of high-temperature nonstick surfaces could potentially improve maintenance of the chemical process equipment. Most available nonstick coatings degrade or become volatile at high temperatures, limiting their usefulness in high-temperature conditions. The glass industry also has serious corrosion problems. In fact, molten glass has been referred to as a universal solvent. Note that materials that can function effectively in very aggressive environments are mentioned in several different connotations. The lack of cost-effective materials that perform adequately in glass furnace environments is another key barrier. In particular, there is a strong need for better refractory materials that can withstand very high temperatures, erosion, and corrosion, but not adversely affect the quality of the product. Another material-related impediment is the performance limits of materials that contact the glass and are exposed to harsh operating environments. Advancement in these areas has been partly limited by a lack of good data on material properties. Ceramics, composites, and ceramic coatings are obvious materials for high-temperature applications, but the environmental degradation of these materials is a serious problem. Oxide ceramics are clearly preferable for use in oxidizing conditions but often do not have the necessary mechanical or temperature capability (within the cost restraints of the industry). Silicon carbide and silicon nitride have the high-temperature capability, and silicon carbide is particularly resistant to wear. However, both monolithic and composite materials oxide and corrode in severe conditions found in many industrial processes. Many different coatings are used to mitigate corrosion and oxidation problems, but they only delay the inevitable. No universal coating has been developed. The oxidation of coatings is mentioned as a problem in five of the eleven IOF road maps. Clearly, a fruitful area of research and development (R&D) would be the design, production, and characterization of more effective coatings for failure-resistant applications.

2.6.2 Wear Resistance

The wear of materials has caused very serious problems in many industries. Equipment that comes in contact with even mildly abrasive substances is subject to wear and requires repair, or even replacement. In the forestry industry, dirt and sand on incoming logs causes wear on the equipment. In agriculture, equipment that bites into the earth is subject to serious wear problems; the same is true for equipment used in the mining industry. In most severe conditions, tools with diamond inserts or composite (e.g., tungsten carbide/cobalt) inserts are used to maximize lifetime. In surface mining, as in other industries, wear is a complex problem. Abrasion is the principal problem in the mining industry, but impact, erosion, galling, scuffing, fretting, and rolling contact are problems as well. The forging industry would benefit greatly from new materials for dies and die making. The highest priority research for die making and materials is the development of a multiattribute, heterogeneous die that eliminates the need for lubricants. This would be an engineered die that would have different material characteristics in various parts of the die to match the specific performance requirements of that area. This would provide greater wear resistance in areas that have a lot of material movement across them and would minimize friction and lubrication needs. Another research approach to extend die life is to develop coating and cladding of the die material.

2.6.3 High-Temperature Materials

Because the rates and efficiencies of many processes increase with high temperature, there is always a demand for materials that can operate at higher temperatures. However, the cost of metallic materials increases as the operating temperature increases because the alloying elements necessary to increase temperature limits are themselves expensive. Gas turbines operate at the highest temperatures for metallic materials. Several technologies will have to be developed for low-emission, cost-competitive, small gas turbine power systems for the distributed generation of electricity. The firing temperature will have to be increased substantially without exceeding the low life cycle cost required by end users. Material developments will include thermal barrier coatings, advanced sealing techniques, and high-thrust-bearing ceramic matrix composite combustor liners, ceramic turbine vanes, and other stationary components. Although the scale-up of single-crystal alloys has been accomplished, they cannot be produced at an acceptable cost for stationary turbines. In addition, users will require durable, long life barrier coatings for oxidation resistance. An Office of Industrial Technology (OIT) program has developed one successful new material from an intermetallic compound, Ni_3Al. Research on Ni_3Al was begun at Oak Ridge National Laboratory (ORNL) in 1981 and continues even today. A number of other laboratories and universities have also been working with the ORNL team. As this example shows, industries that request the development of new high-temperature materials must be aware of the long timeline for development. Between 1981 and 1996, ORNL spent about $27 million on this program. Trials of Ni_3Al began in 1993, and Bethlehem Steel Corporation is now using the material in steel mill rolls and has placed a large order with Sandusky International for more. Other applications are now being evaluated, but the Bethlehem Steel order is the first substantial recognition of the usefulness of Ni_3Al-based alloys.

The cost for the steel mill rolls is now 50% of the cost in 1993. Because no failures have been experienced so far, lifetimes have not been determined. The heat treatment industry could also benefit from higher-temperature operations. This industry requires improved heating-source materials, alternatives to radiant tube heating for more uniform temperatures, improved furnace-fan materials with increased creep strength, and advanced insulation materials to improve furnace efficiency, cost, and performance. The road map for the heat-treating industry identifies a need for a number of new materials that could operate in higher processing temperatures and the development of compositions optimized for specific heat treatments. General Motors has been evaluating heat treatment (carburization) fixtures made from the alloys developed at ORNL. Although Ni_3Al-based alloys have been shown to be much more resistant to carburization than the usual steels used in this application, as of 1996, no large orders had been placed because no component failures had been experienced so failure mechanisms were not known. Users have been reluctant to proceed until an economic incentive for their use has been demonstrated.

Therefore, interdisciplinary R&D, with customization for specific industries, plant, equipment, and parts system, will be necessary to provide long-lasting common solutions or maximum achievable reliability of components and systems through optimum materials, manufacturing method, and equipment selection programs to solve the common failure modes of the system in different IOFs. In practice, industrial equipment failures are typically more frequent than expected for their design limits. This higher rate can be caused through wrong installation, bad operating or housekeeping practice, bad supply chain and stores management, or less than ideal maintenance. Fortunately, the induced failure rate of machines is highly malleable depending on your choice of applied maintenance policies, operating policies, purchasing and store practices, installation accuracy, and the assembly precision of the machines' parts. The rate of occurrence of failure can be minimized by carrying out CM and maintenance from the initial to the final operation of particular parts' life cycle (i.e., from design through manufacturing processes to equipment/machine operation). The application of a technique that controls the quality of the parts' workpiece, the manufacturing process, and equipment conditions is highly needed to achieve maximum reliability and minimum failures. The technique will help to remove excessive stress and other competing failures as well as stop machine equipment failures and maximize the quality–reliability characteristics of the system.

2.7 Hard Alloy–Coated Part Surface Quality and Process Performance Variations with the TI Model

Hard alloy–coated parts in series with other group of parts in a system of an equipment work together to form a system. When any working part fails, the machine fails. You can draw the machine/equipment reliability degradation rate to failure curve for a machine from the rate of its parts' failure. We can greatly reduce the risk of failure through our choice of actions and our degree of diligence in doing them. Using a good policy, process, and technique without also controlling the quality of the execution does not guarantee improved reliability. Doing the actions diligently intend to aim at the acceptable range of values, but lack of precision and poor control over quality lead to excessive variability in parameter values. Generally, they get it right, but not always. Quite often they end up with the parameter values either too high or too low. If the target value for the quality parameters is too high, there can be bad outcomes. An optimum wear-resistant and strength outcome values with desired target is achievable with the TI technique, which is used to plot machine/equipment integrated reliability degradation rate to failure curves that help us to understand the extent of risk placed on our parts by our activities and events. If we know the outcome or requirements of the part surface quality parameters (like hardness, surface stress, surface roughness, and surface wavelength of a workpiece/machine part), we will want to ensure we do those occurrences that lead to good lifetime reliability and prevent those that cause our parts to degrade fast or fail and increase chance of failure. To reduce the chance of equipment failure, you need to prevent the situation where its parts are overstressed or experience fatigue or suffer contamination, corrosion, and high-temperature events. In this book, we shall focus on increasing the hardness of the shaft surface with hard alloy coating materials for maximum achievable wear-resistant requirements in aggressive areas of different IOFs. Machining a hard-coated shaft surface with a traditional cutting tool bit will definitely offer low productivity and sometimes practically impossible. Therefore, it is necessary to select suitable machining methods or design a new progressive method for maximum achievable quality or optimum reliability determination. At this juncture, it is expedient to create the situation where controls are applied intentionally to reduce the range of quality and reliability parameter outcomes to those that are beneficial. The TI model will be used to select the material, method, and equipment, and the control reliability model will be used to select the material, method, and equipment as well as control reliability growth toward optimum values and degradation toward failure values. Such controls give more accuracy and precision to achieving the parameter's outcome. The parameter data are used to draw the desired machine/equipment reliability degradation rate to failure curve:

1. Determine machine/equipment reliability degradation rate to fatigue, wear, corrosion and high-temperature failure curves.
2. Select optimum materials, methods, parts, equipment, CM, and maintenance strategies for fatigue-, wear-, corrosion-, and high-temperature-resistant applications.
3. Develop a reliability growth and maintenance cost program using the multivariate regression model.

4. Develop a reliability degradation and failure program using the TI model.
5. Develop an IRCMM program of manufacturing processes, parts, and equipment using the multivariate regression model and TI model.

2.8 Material, Part, and Process Selection for Wear-, Corrosion-, and Temperature-Resistant Applications in the Industries of the Future

The selection of materials and methods for wear-, corrosion-, and temperature-resistant applications is an important part of technological advancement and manufacturing activities. However, material selection has since been viewed as a random process. Methods and approaches to solving material problems have now been developed using the TI technique that may help clarify needs and reduce the degree to which material selection must be considered. Material application, performance, and manufacturability are all key parts in the selection for wear-, corrosion-, and temperature-resistant applications, but the general methods are also extensible to other areas of material selections. There is great deal of interest in replacing hard metallurgical coatings with materials and systems that are more environmentally benign and are capable of providing equal or better performance than those materials they replace. Material replacement efforts have traditionally relied on the quick approach where a material is simply substituted for another. This particular approach rarely ensures success. Numerous factors must be taken into account when choosing a replacement for a hard coating. These factors include the temperature, workforce pressure, chemical environment, material compatibility, elastic constants, and cost. If more environmentally benign materials were easily substituted for traditional hard materials, then they would have been long ago. Since there is no direct substitution, it is therefore necessary to tailor the replacement materials to the specific application. The main tasks in material selections for wear-, corrosion-, and temperature-resistant applications are to first specify the performance needs and then the financial needs. The order of these activities is important because, while a lower cost component part may be preferred, less expensive part performance must be suited to the task. It is very difficult to specify a part mainly on cost without knowing the performance design limits. The information base and deposition technique developed for one class or materials can typically be extended to other materials in the same class. The general surface selection methodology for one class of materials may be extended to other unrelated classes. A wear material may be used to reduce dimensional changes due to unwanted material removal, reduce frictional losses, tailor the physical performance of a component, and provide a physically stable working surface.

Wear can be divided into several categories such as adhesive and abrasive wear that take place during sliding contact.

Surface fatigue, deformation wear, impact or loading rate phenomenon and corrosive wear can happen during surface sliding contacts.

Corrosive wear is caused by the interaction of the wear surface with the local environment.

These wear mechanisms may act singly or in combination with one another to alter a surface.

The proper selection of material for a wear application will strongly depend on both the type of wear to be countered and the wear environment. The wear environment can be dry, wet, warm, cold, and so on. Wear phenomenon is a factor in applications where it might not be readily apparent. Optical windows that are exposed to the neutral elements have a need for wear protection, where dust, sand, and ice can impact and roughen soft optical surfaces. Fan and propeller blades in water can experience wear by cavitation erosion and bug and dust impact erosion in air.

2.8.1 Material Selection Process

The classic method of selecting wear, corrosion, and temperature material is to utilize what has always been used in the past for a particular application. The reason for this approach is because it works. For example, steel ball bearings are relatively inexpensive and are superb at what they do if they are not pushed beyond their performance limits. A good reason would be needed to replace steel ball bearings in an application for an alternative material or a different type of bearing. Changes in performance needs such as increased rotational speeds, a need for mass or volume reduction, altered mechanical shock environment, or increased reliability could lead to a demand for alternative materials. Each wear application needs to be approached as a unique situation if a "best result" is to be achieved. It is therefore necessary to use the following guidelines for rapid selection and insertion of an optimal wear system into operational use:

1. Specify the maximum operational limits of the wear, corrosion, and temperature material system for safety and lifetime application. Properties that make some wear films excellent for one particular application may be completely unsuitable for other uses.
2. Specify the normal operational parameters and acceptable performance criteria of the wear material system. Performance criteria would include the number of cycles of use and the physical and chemical exposure environment before, during, and after use. This step provides for the selection of a broad range of materials

and technologies that could fit the needs of the application. No preemptive elimination of technology should be attempted at this stage. Some of the materials and technologies may later be found to be mutually exclusive or inappropriate for use at a later point. Preemptive preselection at this point may eliminate POOR candidates but also serve to too narrowly focus the material search too early in the process. Early candidate elimination is attractive, but it can eliminate an entire class of potential solution, but perhaps not the best solution. The more care that is taken during this crucial step will enable the actual material selection phase to be much smoother in terms in performance, availability, and price.

3. Establish the degree of mechanical, physical (thermal expansion, dielectric constant, etc.), and chemical compatibility the wear material must have with the system. The real process of wear material selection begins once the preceding steps have been taken.
4. Material availability and cost are closely related factors usually taken into account at the same time. The cost of a particular wear material is almost exclusively controlled by its availability. Availability is directly controlled by prevalence of use (numerous examples exist of high-priced finished parts made from more common materials than their lower-cost cousins) with the attendant savings resulting from high-volume manufacturing. The availability of raw materials and ability to work, shape, and form those materials can also influence material cost. Cubic boron nitride is an extremely hard wear material not found in nature and is produced mainly as a bulk power in a high-pressure growth apparatus in limited batches. The powder is then used as a loose abrasive or it can be reworked into a solid piece of tooling. For all practical purpose, cubic nitride is unavailable as a directly applied coating. The need to process the material after its synthesis, physical properties, and manufacturing processes at minimum cost of tooling to provide maximum achievable reliability is possible with the integrated reliability monitoring and maintenance program. At this point, we shall now look at how manufacturing process are selected for producing parts with hard alloy surfaces.

2.8.2 Manufacturing Process Selection for Producing Parts with Hard Alloy Surfaces

Process selection is a second-tier consideration in most instances of wear, corrosion, and temperature material selection. The physical properties of wear coatings may vary depending on the deposition method and technique. The standard cost savings from continuous and semicontinuous manufacturing methods such as extrusion and rolling versus stamping and milling operations also apply for wear materials. The method of manufacturing becomes very important when directed or textural property characteristics of material need to be considered. Many of the physical, optical, chemical, and electrical properties of wear, corrosion, and temperature films will be controlled or modified by their degree of deviation from perfection imparted during manufacture. This is a common consideration in the areas of composite manufacture. The component materials of a composite structure are only slightly more important than the manner in which they are arranged in space of their component parts as influenced by their method of manufacture. The physical properties of parts for wear-, corrosion-, and temperature-resistant applications can be modified and controlled by altering the conditions of the manufacturing processes through the integrated reliability monitoring and maintenance program.

2.8.3 Selection of Equipment Part with Hard Alloy–Coated Surfaces and Reliability CM and Maintenance Data Collection Program

This book will provide the basis for suitable selection of manufacturing processes, equipment, and machine parts for condition data collection program. Creating an equipment and part list is a logical process that will provide a smooth flow for data collection. Selection of the eligible equipment and part will determine the size of the database. The measurement points for each equipment and part will define the locations at which data will be collected. Measurement parameters will characterize how the data will be collected and trended. In order to generate the list of equipment, process, and part system to be included in a monitoring and maintenance program, there would be an immediate decision to include everything in the plant. Indiscriminately including all equipment, processes, and parts in the plant could result in unnecessary data collection. Certain machines may not require data collection if they are only operated infrequently such as stepper motors or standby equipment. The components and systems should be selected and monitored using specially developed testing programs. Any equipment, process, and part, which are operating continuously, should be a candidate for the list. The equipment, process, and part list, which will most likely begin on paper, should include the equipment name, horsepower, bearing type(s), plant location, and operating speed. Optionally, other items may be added to this list, such as bearing operating temperatures, fluid flow rate, and pressures. If available, the maintenance and economic history of equipment should be gathered. After this information has been assembled, the list can be subdivided into three categories. These categories are critical, essential, and general purpose. Critical equipment should be candidates for permanent instrumentation due to their production impact should they fail. Economic factors, such as replacement cost or maintenance expenses, should be considered to justify permanent instrumentation. This equipment should always be monitored. Essential equipment usually provides major support for the production process and may be partially spared. These components and system should be monitored, but due to their support functions, they may be candidates for permanent instrumentation. General-purpose equipment will include all other machines in the plant. This category will most likely be a much larger list than the other categories and include all other machines in the plant and quite possibly consume the bulk of the maintenance budget. Each category of the system list can be further subdivided into equipment that operates nominally and those that are troublesome. The troublesome equipment should be an immediate candidate for the final list. They are good candidates to *cut your teeth* on since the probability of improvements in operation is quite high once corrective action is taken that is based upon collected data. General-purpose components that are not troublesome and essential components, along with the unmonitored critical components, can be listed for routine monitoring on a monthly cycle. When the troublesome components are operating normally, they can be monitored on a monthly cycle. After the final list has been generated, the next step will be to decide the measurement points for each component.

2.9 Measurement Points

Measurement points are the actual locations at where data are to be collected. The manufacturing processes for the production of a critical machine part and equipment with bearings, shafts, and other parts are included in the list of points. Generally, each part is developed to resist failures (the common problems of industrial equipment, e.g., wear, corrosion, and temperature). Due to equipment construction and operating conditions, the data not need be collected at each part. The data collector operator should not be overlooked, since the operator is working with the equipment. An operator will observe certain situations, which will not be identified by measurement. They are usually entered annually during the data collection process. Finally, now that various manufacturing processes, equipment, parts, and the measurement points are defined as the bit of information needed, this will now be the basis on how the equipment, manufacturing processes, and parts will be analyzed. This involves defining the measurement parameters (e.g., reliability growth and degradation, mean time to failure, operating/maintenance costs) for each measurement point.

2.9.1 Measurement of Strength and Stress Parameters

At each measurement point, all types of data within the control limit must be collected. Reliability growth/degradation data may be collected from the deviation from an optimum initial quality condition point to a final quality condition point. Component and system construction with operating conditions will dictate which type of quality–reliability parameters to include.

Data collection of the reliability CM and maintenance program is implemented on equipment, manufacturing processes, bearings, shafts, and other parts. These parts will generate specific frequencies related to the equipment, part and process conditions. These data collectors offer a measurement of quality, reliability growth, and degradation parameters, which can provide early detection of part defects and failures. Process variables, such as temperatures, pressure, or flow rate, and part variables, such as surface roughness, surface hardness, surface stress, and surface wavelength, may be added to the measurement parameters list where provisions have been made that allow the data to be input automatically by the data collector. In addition to machine part surface condition, proper measurement parameter selection will provide information about the balance state, alignment condition, and general condition of the processes, parts, and equipment. The measurement of machine part surface multiple quality parameters can be integrated into process condition variables, including misalignment, and imbalance data would be input automatically by the data collectors. The measurement data can be used for the following: (1) determination of optimum quality and reliability values for maintenance, manufacturing, and operation requirements; (2) as a criticality index for classification and criteria requirements; (3) selection of critical equipment, process, and part baseline conditions; and (4) prediction of time and condition of failures, detection of potential failures, control and monitoring of reliability growth and degradations, managing resources of plants, and setting up control limits for integrated reliability monitoring and maintenance of manufacturing processes and equipment.

2.9.2 Measurement of Quality and Failure Parameters during the Manufacturing Processes

The following manufacturing processes may be considered to meet the desired reliability requirements as well as the maximum achievable reliability of products with optimum process conditions:

- Metallurgical process
- Coating deposition process
- Machining process
- Grinding process
- Assembly process

A multivariate regression model is used to determine the optimum quality values of a hard alloy–coated part surface as well as the process performance values and predict the time and conditions of failure.

The TI model can be used for optimum selection of processes, integration of the manufacturing processes and maintenance system, prediction of the time and condition of failures, prediction and proactive maintenance and determination of the maintenance costs, and provision of other economic benefits.

The application of these two models will help develop and select a cost-effective IRCMM program for wear- and other failure-resistant applications, through the measurement of component/system reliability growth, degradation, and failures.

2.10 Optimum Selection of Parts, Manufacturing Processes, and Industrial Equipment System for Maximum Achievable Reliability with the TI Technique

The integrated reliability monitoring and maintenance program together with the TI technique will offer maximum achievable reliability with minimum failure rates and maintenance costs. This type of monitoring allows maintenance to be scheduled or actions taken to avoid the consequences of failure, before the failure occurs. It also offers the opportunity to monitor and control reliability growth that leads to maximum achievable reliability. With an IRCMM program that starts from an optimum reliability reference of part surface quality parameter value and process conditions, baseline requirements are used to identify impending potential failures, defects, and damages as well as optimum reliability and maintenance cost.

The right characteristics of machine parts, material, and processing choices make a big difference to manufacturers of industrial equipment products such as tools, pumps, motors, valves, and actuators. Such products contain many components and a wide variety of materials—metals, plastics, ceramics, carbon, and composites. The engineering properties of these materials (hardness, stress, pores, strength, etc.) determine product performance and reliability. But organizations also need to consider cost and environmental impact. Designers must not only meet functional and potential requirements; they must also take into account the practicalities of procurement, the supply of quality–reliability data flow, and global manufacturing processes while satisfying regulations and quality standards. For maximum achievable quality–reliability chain, there is the need to increase hardness to a maximum value and reduce stress to a minimum value. In order to attain maximum achievable hardness cost-effectively, you will need to coat the surface of the workpiece with cost-effective alloy materials. Machining hard alloy coatings can be sometimes impracticable, thereby reducing reliability instead of increasing it, which in turn negatively affects the next grinding operation. It is necessary to select or design a cost-effective turning method to increase reliability in order to meet the desired requirements. Also there is a need to find and develop a cost-effective technique for machining hard alloy–coated workpiece surface that meets desired requirements and maximum achievable reliability. In achieving these multiple quality–reliability chain, objectives require the right information on materials, their properties, and their processing practices. It also requires practical tools and integration technique to manage, access, and apply the information in design, manufacturing processes, maintenance, and operations.

In a manufacturing enterprise, you typically use hundreds of different materials, parts, processes, and equipment supporting hundreds of different applications. Your organization is probably split across different businesses or sites. Regulation and global manufacturing pose further challenges. The integrated reliability monitoring and maintenance program can help you consolidate and control all relevant materials, parts, processes, equipment data, and information and use them to make better, more consistent material decisions enterprise-wide. Results are lower costs, reduced risk, and fewer manufacturing and maintenance problems. To succeed, manufacturing enterprises need to do much more than simply deliver products that excel at their required function. They must meet wider product design objectives that allow them to address strategic drivers such as cost, environment legislation, and global manufacturing process/equipment system and quality–reliability chain. Material, load, and geometry choices are central to these objectives. Sustainable success requires strategies that ensure these decisions are optimized not just for individual designers but also across the enterprise, which of course can be achieved with the TI technique. This technique combines consideration of the engineering performance of individual equipment with their technological, economic, and environmental properties. Also the technique helps designers and maintenance personnel apply the program easily and consistently. The program can be used to predict, prevent, and detect failures at early stages of manufacturing and service operations with minimum maintenance cost. This program can be used to design optimum reliability into production processes, parts, and industrial equipment as well as select the component/system.

2.11 IRCMM of Material and Manufacturing Processes and Equipment with the TI Technique

The objective of the reliability monitoring and maintenance function is to optimize CM and maintenance cost while maximizing the reliability maintenance task, which is effective when it

- Increases the MTBF or mean to time failures (MTTF)
- Increases the reliability and quality factors
- Increases the maintenance efficiency index (MEI)

- Reduces the consequences of potential (P_f) and functional failures (F_f)
- Reduces the risk of multiple failures (F_m)
- Reduces warranty cost (W_c) and maintenance cost (M_c)

The reliability CM and maintenance program is focused on using real-time data to prioritize and optimize the operating manufacturing process and equipment system conditions.

Such a system will determine the manufacturing process and equipment system reliability and act only when maintenance is actually necessary. Development in recent years has allowed extensive instrumentation of manufacturing processes and equipment with better tools for analyzing condition data, but the maintenance personnel will now be more than ever able to decide what the right time is to perform maintenance on manufacturing processes and equipment. Reliability CM and maintenance together with the TI technique will be applied to design cost-effective instruments, which are less expensive than the ones already installed and can be easily embedded in the equipment or machines with minimum investment. This technique is used to measure data, analyze it, present it, and convert it into actionable knowledge about reliability growth and degradation of manufacturing processes and equipment at minimum maintenance cost.

2.12 Developing Quality, Reliability Growth, Degradation Chain, and Maintenance Cost Program with TI Coefficients

The optimum quality factors, $Q_{f(i\text{opt})}$, of a workpiece for different failure modes must be determined experimentally through a multivariate regression model. The multivariate regression model for the surface finish of a particular workpiece is developed and the surface finish condition is optimized with the help of the TI technique. The optimum values are used to set up the baseline quality–reliability requirements for all the manufacturing processes, assemblies, and equipment operations. The optimum conditions of the workpiece, machine part, and equipment conditions can be maintained to meet the desired lifetime with a suitable cost-effective integrated reliability condition monitoring and maintenance strategy (IRCMMS), which can be developed with the help of the TI model. TI coefficients of the IRCMMS are used to determine the quality factor (Q_f), reliability growth (Ri_g), warranty cost (W_c), reliability degradation (Ri_d), potential failure, (P_F), functional failure (FF), and maintenance cost (M_c). The functional failure of a material, part, and equipment is related to the quality parameters (Y_i) and the process conditions (X_i). For example, the wear-resistant steel of an equipment part is used in areas where there is likely to be a high degree of abrasion or wear of the steel plate. Typical applications are in truck beds, attachments to diggers and earth movers, and processing applications in the mining industry. The key quality for wear-resistant steels is their hardness. The benefit of using abrasion-resistant steel is that the plant, machinery, or construction working life can be extended considerably. This can significantly improve the reliability, durability, and safety of structures and equipment. It also helps in reducing the maintenance costs associated with wear and breakdown of plant. Lower Brinell Hardness (HB) generally provide good cold bending properties and good weldability. Weldability is not generally reduced as the hardness increases. Wear-resistant steels are not appropriate for use at temperatures over 250°C as the heat can cause changes to the material properties. Yields for 400 HB steel, for example, are in the region of 1100 MPa with tensile strengths of about 1250 MPa. There is therefore the need to select hard alloy powder materials for wear-, corrosion-, and high-temperature-resistant purposes to meet the needs of different industries. This involves hardening the working surfaces of equipment parts with hard alloy powder materials through coating techniques. Self-fluxing powders based on nickel are recommended hard alloy materials that have a wide application for hardening and reconditioning surfaces of rapid wearable parts working in aggressive media, wear, and high-temperature conditions. (This hard alloy powder is similar in chemical composition to those of the granulated spheroid zed alloy powders described earlier.) The fluxing powder is slightly different with a lower content of oxygen and other impurities, although classified according to composition. These coatings have complex structures, which consist of minutely dispersed particles to composition. These coatings have complex structures, which consist of minutely dispersed superhard phases of carbides, borides, and carboborides with microhardness up to 40×10^3 MPa, uniformly distributed in a hard metallic matrix based on solid solutions and complex nickel-based eutectic. These hard coatings are chemically resistant to different active media.

On the basis of a research work [3], the material requirements for wear-resistant and its competing corrosion- and high-temperature-resistant purposes have been ascertained to be within the range of specific pressure of 1.5×10^6 to 7×10^6 Pa and sliding velocity up to 8 m/s; it is possible to recommend nickel-based self-fluxing powder materials for friction pairs in water and in solutions of NaOH and CH_3COOH of 10%–50% concentration.

The wear resistance of this type of hard coatings in frictional contact with steel (friction of boundary lubrication) is 4–9 times higher than the wear resistance of steel–steel pairs and steel–iron pairs under specific loads of 1.5×10^6 to 10×10^6 Pa and sliding velocity up to 8–54 m/min; within this range, the amount of wear of steels working in pairs in with hard coatings is reduced by a factor of 1.5–2.5 times. The friction coefficient in pairs of hard coating–steel with initial roughness number R_a = 0.16–0.3 μm is 1.8–22 times lower than in pairs of steel–steel, but with constant surface roughness, the amount of wear is 2–10 times reduced [4]. These hard coatings are highly worn and corrosion resistant, capable of withstanding impact and hard conditions under abrasive wear at temperature up to 600°C.

They are used for reconditioning, hardening, and maintenance of valves, camshafts, blades, fans, rotors, bearings, shafts, and sleeves of hydraulic pumps, motors, generators, compressors, and parts of other rotating equipment. At this juncture, it is worthy to note that the existing selection of materials depends almost solely upon the experience of technicians and material personnel, and accuracy requires an extremely significant amount of information and pure luck, which of course is the primary reason why condition-based programs fail due to suboptimum condition selection. In IRCMM together with the TI program, it is possible to select the optimum conditions of materials, processes, and equipment and predict the maximum and minimum resistance to wear, corrosion, and temperature, time to failure, and reliability growth and degradation coefficient characteristics at minimum life cycle and maintenance costs.

2.13 Conclusion

1. The IRCMM process focuses on continuous improvement throughout the life cycle of critical parts and industrial equipment for wear- and other competing failure-resistant applications.
2. The goal of continuous improvement requires CM of lifetime reliability, quality, and cost of parts and materials throughout the life cycle to attain maximum achievable reliability of industrial equipment with minimum operating, maintenance, and life cycle costs.
3. The manufacturing process and equipment system must consist of parts and component that make it work toward achieving optimum lifetime reliability in aggressive media of wear, corrosion, and high-temperature failure modes.
4. A hard alloy–coated shaft surface of a bearing–shaft assembly in a system can provide maximum achievable surface quality and reliability of industrial equipment.
5. Self-fluxing powders based on nickel are recommended as hard alloy materials for hardening and reconditioning surfaces of rapid wearable shafts working in aggressive media wear and high-temperature conditions.
6. The wear resistance requirements of this type of hard coatings in frictional contact with steel (friction of boundary lubrication) is 4–9 times higher than the wear resistance of steel in steel–steel pairs and

steel–iron pairs under specific loads of 1.5×10^6 to 10×10^6 Pa and sliding velocities of 8–54 m/min; within this range, the amount of wear of steels working in parts with hard coatings is reduced by a factor of 1.5–2.5 times; the friction coefficient in pairs of hard coating–steel with initial roughness R_a = 0.16–0.3 μm is 1.8–2.2 times lower than in pairs of steel–steel, but with constant surface roughness, the amount of wear is 2–10 times reduced.

7. The reliability of bearing–shaft assembly in pumps, motors, generators, compressors, turbines, and other rotating equipment in different IOFs can be greatly improved with shaft hardening while applying reliability CM and maintenance strategies.
8. The technological chain structure for the production shaft surface with hard alloy coating, machining of the coated part surface, and grinding toward wear- and other competing failure-resistant applications is cost-effective when the TI technique is applied.
9. The technological chain structure together with the TI technique forms the basis for understanding and measurement of the best and worst manufacturing, CM, maintenance, and equipment operations for improving shaft and equipment reliability as well as the life cycle cost of the improvement.
10. The measurement of IRCMM impacts of equipment on a business reveals a different definition from the traditional definition of reliability.
11. An assembly of parts or processes can never be more reliable than its least reliable parts or process in a technological chain structure.
12. The least reliable manufacturing process in the technological chain is the machining process of hard alloy–coated shaft surface, and it therefore requires a new progressive method for maximum achievable quality and reliability.
13. The new progressive machining process condition is optimized with design of experiment to develop a multivariate quality regression model.
14. The optimized machining process condition and the shaft hard alloy–coated surface quality parameters are used for IRCMM of equipment with TI coefficients.
15. TI coefficients are used to determine the reliability of machine design, the quality of manufacture, the precision of its installation, its production abuse, and the purchasing and storage quality control, along with the standard of maintenance and workmanship care.
16. Component reliability growth and its optimum threshold data should be measured with TI coefficients, which are deduced with a multivariate quality regression model.

17. Component reliability growth utilizing the multivariate quality model is used to select optimum parameters, part conditions, and costs as well as to monitor the strength of materials and maintenance strategies.
18. Equipment reliability degradation, mean time to failure, and its failure threshold data can be measured with the TI coefficient, which is deduced with the help of the TI model.
19. Equipment reliability degradation utilizing the TI model is used to detect failed parts and to monitor the stress, defects, reliability degradation, and failures from *rough operation* induced by poor operating practices and bring the likely implications on production to the attention of operation and plant managers.
20. The IRCMM process outcomes with desired target are possible with an integrated reliability coefficient that is used to plot reliability curves that help us understand the extent of the risk placed on components and equipment by human activities in different IOFs.

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3

Reliability Growth and Degradation of System Condition Monitoring with the Technological Inheritance Technique

3.1 Reliability Definitions

Reliability may be defined in several ways:

- The idea that something is fit for purpose with respect to time
- The capacity of a device or system to perform as designed
- The resistance to failure of a product or system
- The ability of a product or system to perform a required function under stated conditions for a specified period of time
- The probability that a functional unit will perform its function for a specified interval under stated conditions

Reliability engineers rely on the probability theory and reliability theory based on reliability definition and techniques. Many engineering techniques are used to explain reliability engineering, such as reliability prediction, Weibull analysis, thermal management, reliability testing, accelerated life testing, and the technological inheritance (TI) technique. Due to the large number of reliability techniques, their expense, and the varying degrees of reliability required for different situations, this book will therefore develop an integrated reliability program to specify the reliability tasks that will perform condition monitoring (CM) and maintenance of manufacturing processes, parts, and equipment system under a single platform with the help of the TI technique. The function of this reliability engineering technique is to develop the reliability requirements for manufacturing processes, parts, and equipment system under a single platform with the help of the TI technique, establish an adequate integrated reliability condition monitoring and maintenance (IRCMM) program, and perform appropriate analyses and tasks to ensure that component and system do meet its requirements at minimum life cycle cost.

3.2 Integrated Reliability Theory for Manufacturing Process, Part, and Equipment System CM with the TI Technique

Integrated reliability theory is the foundation of reliability engineering with the help of the TI technique. For engineering purposes, reliability is defined as the probability that a device will perform its intended function during a specified period of time under stated conditions.

Mathematically, this may be expressed as

$$R(t) = \int_{t_i}^{t_{\max}} fx \, dx \tag{3.1}$$

where

fx is the failure probability density function

t is the length of the period (which is assumed to start from time zero), but in relation to reliability CM and maintenance with the TI technique

Y_i is the resistance to failure probability density function

In this case, the resistance to failure function is expressed through the component quality factor Q_f.

Therefore, the mathematical expression of reliability will be given as

$$R(t) = R(a) = \int_{a_i}^{a_{\max}} Y_i \, da = \int_{a_i}^{a_{\max}} Q_f \, da \tag{3.2}$$

where

Y_i is the hard-coated part surface quality parameter, which is a function of X_i, ($Y_i = f(X_i)$)

X_i is the process performance parameter, when $R(t)$ is expressed in terms of TI coefficient for process conditions (X_i) as $R(t) = R(b)$, where $R(b)$ is process reliability

Q_f is the quality factor of a part or component condition, which is the function of a TI coefficient of hard-coated part surface quality parameters ay_i and process performance parameters bx_i

Reliability engineering applied to CM and maintenance with the TI technique is concerned with four key descriptive elements:

- First, reliability is a probability. This means that there is always some chance for failure. Reliability engineering is concerned with meeting the specific probability of success, at a specified statistical confidence level, where the maximum TI coefficient levels is 1.0 and the minimum TI level is 0.0

- Second, reliability is predicted on the *intended function*. Generally, this is taken to mean operation without failure. However, even if no individual part of the system fails, but the system as a whole does not do what was intended, then it is still charged against the system reliability. In the case of integrated reliability, the manufacturing and equipment system requirements specification is the criterion against which reliability is measured with TI coefficients.
- Third, reliability applies to a specified period of time. In reality, this means that the manufacturing process, part, and equipment system has a specified chance that it will operate without failure before a specified period of time. Integrated reliability engineering must therefore ensure that components, parts, and materials function during the specified time. Units other than time, like resistance to failure or the quality of parts and materials used, can be expressed in terms of the component quality factor that can also be used to measure and evaluate reliability. A piece of mechanical equipment may have a reliability rating value in terms of cycles of use, component quality growth, and component quality degradation during use.
- Fourth, reliability is restricted to operation under stated conditions (manufacturing and equipment conditions.) This constraint is necessary because it is impossible to design a system for unlimited conditions, but with the TI technique, multiple operations, processes, practices, and parameters can be integrated under a single platform or program. The operating component quality factor growth ($Q_{f(g)}$) and degradation ($Q_{f(d)}$) conditions during use in a particular environment can be addressed during design, testing, and CM and maintenance of manufacturing process–part–equipment system. The reliability coefficient R_k can be expressed in terms of $Q_{f(g)}$ and $Q_{f(d)}$ as follows:

$$R_{k(g)} = \int_{t_{min}}^{t_{max}} Q_{f(g)}\, dt \tag{3.3}$$

$$R_{k(g)} \underset{a_{min}}{\overset{a_{max}}{\equiv}} Q_{f(g)}\, da \tag{3.4}$$

where

$R_{k(g)}$ is the reliability growth coefficient of components
$Q_{f(g)}$ is the quality factor growth of components

$$R_{k(d)} = \int_{t_{min}}^{t_{max}} Q_{f(d)}\, dt \tag{3.5}$$

$$R_{k(d)} = \int_{a_{min}}^{a_{max}} Q_{f(d)}\, da \tag{3.6}$$

where

$R_{k(d)}$ is the reliability degradation coefficient of components

$Q_{f(d)}$ is the quality factor degradation of components

The system reliability growth coefficient $R_{ikg(sys)}$ can be expressed as

$$R_{ikg(sys)} = R_{k1(g)} \cdot R_{k2(g)} \cdots R_{kn(g)} \tag{3.7}$$

$$R_{ikd(sys)} = R_{k1(d)} \cdot R_{k2(d)} \cdots R_{kn(d)} \tag{3.8}$$

where

$R_{ikd(sys)}$ is the system reliability degradation coefficient of the different components of the system (process, parts, and equipment)

i = 1, 2, …, n, where n is the number of components

The system reliability degradation coefficient $R_{ikd(sys)}$ can be expressed as

$$R_{ikd(sys)} = R_{k1(d)} \cdot R_{k2(d)} \cdots R_{kn(d)} \tag{3.9}$$

where

$R_{ikd(sys)}$ is the system reliability degradation coefficient of the different components of the systems (process, parts, and equipment)

i = 1, 2, …, n, where n is the number of components

Component and system reliability degradation modeling is an effective reliability analysis tool with failures caused by degradation. If the mechanism of the degradation is known, a mechanism-based model should be used. If the physics of degradation are not clear, a model that provides the best statistical fit to the data can be used. This type of model is referred to as a statistical-based model.

Since there are two types of degradation failures, which are soft failures and hard failures, the desired degradation failure for a hard-coated part has to be defined.

Soft failure is a gradual loss of performance. The failure would be defined at a specified level of degradation—$R_{d(d)}$—which is the reliability degradation threshold or the reliability of a component potential failure, $R(pf)$ (e.g., 65% of the initial failure output or potential failure [PF]). Hard failure is defined as the event when the product stops working due to degradation, which is expressed as the reliability degradation of the functional failure state, $R_{d(FF)}$. In our case, we shall focus on the modeling of soft failures, through a multivariate quality regression model for hard alloy–coated part surface. The regression model will be used to determine the maximum and minimum reliability growth and degradation requirements of hard alloy–coated part surface.

3.3 Component and System Reliability Growth and Degradation Assessment with the TI Technique

During the early stages of developing a hard alloy–coated part surface and prototyping the manufacturing and equipment systems, reliability often does not meet customer requirements. A formal test procedure is needed to aim at discovering and fixing the causes of unreliability, through reliability improvement test from design through development to service operation. This test focuses on system design, system assembly, and component selection weaknesses that cause failures. A typical reliability improvement test procedure would be to run a prototype system, as the customer might for a period of several weeks, while a team of engineers and technicians (design, quality, reliability, manufacturing, etc.) analyze every failure that occurs. This team comes up with the root cause for failures and develops design and/or assembly improvements to hopefully eliminate or reduce the future occurrence of that type of failure. As the testing continues, the improvements the team comes up with are incorporated into the prototype, so it is expected that reliability will improve during the course of the test.

While only one model is applicable when a repairable system has no improvement or degradation trends, there are infinitely many models that could be used to describe a system with a decreasing repair rate (reliability growth models). Fortunately, one or two relatively simple models have been very successful in a wide range of industrial applications, which are the power model and exponential model. Two models that have previously been described will be used in this book. The regression and power models will be used to assess the reliability condition of equipment. The regression model is used to determine the optimum values of the quality conditions of components and the process performance conditions and provide the initial data for the power model to assess the reliability degradation and failures of processes, parts, and equipment. The combination of these two models provides a different approach for modeling the rate of occurrence of failure incidences for a repairable system. Time is measured by the system power-on hours from initial turn-on at time zero to the end of system life.

Failures occur as a given system ages and the system is repaired to a state that may be the same as new, or better, or worse. The frequency of repairs or failure rates may be increasing, decreasing, or staying at a roughly constant rate. This can be demonstrated through the procedures that monitor the numbers of failures (N) that occurs in a system within a specific time (t) under given conditions. Let $N(t)$ be a counting function that keeps track of the cumulative number of failures of a given system from time zero to time t. $N(t)$ is a step function that jumps up one every time a failure occurs and stays at the new level until the next failure.

Every system, component, and parameter will have its own observed $N(t)$ function over time. If we observed the $N(t)$ curves for a large number of similar systems and *averaged* these curves, we would have an estimate of $M(t)$—the expected number (average number) of cumulative failures by time t for these systems. The derivative of $M(t)$, denoted $m(t)$, is defined to be the repair rate or the rate of occurrence of failures at time t or integrated reliability degradation failure rate (IRDFR).

A flexible model (which has been very successful in many applications) for the expected number of failures in the first t hours, $M(t)$, is given by the polynomial [1].

$$M(i) = at^b; \text{ for } a, b > 0 \tag{3.10}$$

The time to the first failure (PF) for a power law process has a distribution with the component quality condition a_i, which is a function of the part surface quality (Y_i), and the process performance condition b_i, which is a function of the operating conditions (X_i).

3.3.1 Probability of Failure Events with Given Degradation Measures

The advances in materials science, manufacturing processes, and quality–reliability engineering have led to few or no hard failures at normal conditions or even at accelerated conditions; hence, it is difficult to obtain the accurate reliability estimation based on life data. Reliability prediction based on degradation modeling can be an efficient and alternative method to estimate reliability for some highly reliable parts or systems. As the component quality, Y_i, and process performance, X_i, parameters gradually degrade to a critical potential threshold level, which therefore defines systems and components as degradation (soft) failure. Many components and critical parts like shaft–bearing assembly or mechanical systems exhibit this type of failure mode. Performance degradation measurements contain credible, accurate, and useful information about component and system reliability. However, most of the previous research has been focusing on reliability prediction based on a single degradation measure or component failure mechanism level. In practice, some mechanical systems like manufacturing processes for producing wear-resistant parts may consist of multiple components, and critical parts like shafts may have multiple degradation measures, so it is necessary to simultaneously consider multiple degradation measures. There is a need for developing a multivariate regression model and a TI model involving multiple growth and degradation measures in this book. For component quality prediction, a multivariate regression model is developed, while for system reliability prediction, a multivariate degradation model is used. The role of the TI technique is to integrate multiple component quality parameters (Y_i) and process performance parameters (X_i) and integrate the optimum component parameters ($Y_{i\text{opt}}$) into process conditions under a single platform with a single metric, known as TI coefficients, *a* or *b*. Assume that the TI coefficient *b* contains *m* degradation measures (b_1, b_2, b_3, …, b_m). The standard definition of a degradation failure event would therefore be $U_{i-1}^{m}\left\{b_i > d_i\right\}$, where d_i is the critical level for the *i*th degradation measure. One implication of this definition is that given the degradation levels in *b*, we know exactly whether a failure occurs or not. It is a black-and-white definition without reference to how likely a failure will happen given the degradation levels. In the following equation, we use a logistic function to define the probability of a failure event given the values for the degradation measures *b* [7]:

$$\Pr\left\{failure\ \ (x)\right\} = \frac{e\beta^{1x}}{1+\beta^{1x}} = \exp\left(\sum_{i-1}^{m}\beta_i x_i\right) / 1 + \exp\left(\sum_{i-1}^{m}\beta_i x_i\right) \qquad (3.11)$$

The reason to choose a logistic function in Equation 3.11 is its standard statistical technique to predict the distribution of a binary variable given process condition predictors in *x* for wear- and other failure-resistant applications. For a given wear failure degradation level, such as the wear size on a shaft, the certainty of a catastrophic failure such as the breakdown of the equipment is better calculated by a probabilistic measure between 0 and 1. This probability measure is not only related to the level of the wear size, but it is a function of the environmental stress and the TI coefficients (*a* or *b*) as well. The larger the stress (e.g., the load the shaft is supporting), the more likely a hard failure will occur. Integrating the component quality condition (1) into the process performance condition (2), you will be able to identify the potential failures (*PF*) and fix them before it causes catastrophic damages. In the simple data with mating hard alloy part surface pairs of the observed degradation measures and the response value of whether a hard failure (*FF*) occurs, we can estimate the coefficients β in Equation 3.11. With the TI model, parameter *a* can be integrated with *b* and the component quality and process performance degradations can be measured to assess the wear and other competing failure conditions of parts and equipment, using the TI model, which is expressed as

$$Y_i = aY_{i-1(\text{opt})}^{\;b} \tag{3.12}$$

3.3.2 Probability of a Failure Event Considering the Random Component Failure Conditions

The TI model is defined as the probabilistic measure to indicate the likelihood of a failure given the degradation levels X with degradation measures in b and a. This technique gives a generic description of this measure by considering the stochastic nature of the part surface stresses, surface roughness, surface wavelength, and other failure events applied to the system. This description is also related to the usual definition of a failure event using criterion whether the degradation level exceeds the critical value d or degradation failure threshold point, measured as a_{th} and b_{th}. Figure 3.1 illustrates the component degradation process and random stress with failure event that affect the likelihood of the occurrence of a failure.

Both process degradation levels and component random stress with other failure events affect how a system is successfully running. The stress and

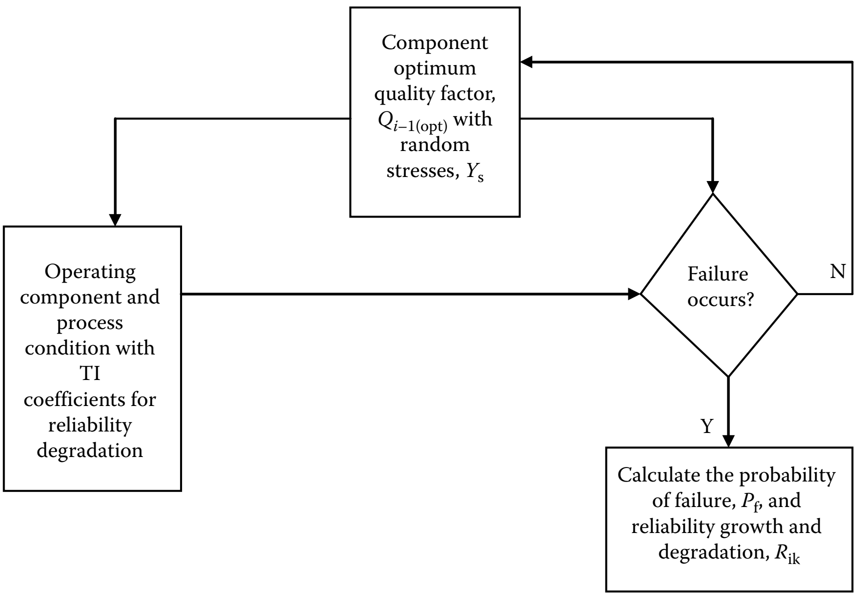

FIGURE 3.1
Reliability growth and degradation in operating process conditions with random stress and the likelihood of occurrence of a failure using TI coefficients.

failure event levels, at the same time, will also affect how the degradation process evolves. Using the a_i vectors to denote the random stress variables, we can define a failure event in the following way:

$$\{\text{Failure}\} = \{f(b, a) > 0 \tag{3.13}$$

One example of $f(b, a)$ using the definition of critical levels d is as follows:

$$f(b, a) = \text{Max}_{i-1}^{m}\{b_i - d_i, a_{\text{th}}\} \tag{3.14}$$

With the TI model, Max_{i-1}^{m} is replaced with the initial optimum component surface quality, $Y_{i-1(\text{opt})}$:

$$f(b, a) = Y_{i-1(\text{opt})}\{b_i - d_i, a_{\text{th}}\} \tag{3.15}$$

Equation 3.15 implies that if the function $f(b, a) > 0$, there exists a degradation variable r for which $b_r > d_r$, a_{th}, which implies the occurrence of the failure. The critical level d_i in Equation 3.15 is a decreasing function of the stress with other failure event levels a_i, indicating that the higher the stress with other failure event levels, the lower the r threshold so that the degradation process is more likely to cause the failure. Using the degradation failure definition in Equation 3.12, we can calculate the probability of a failure event given the degradation levels in b as a_{d}, which is the TI for surface quality degradation:

$$\Pr\{\text{Failure } (b)\} = \int_{a} Ia_{\text{d}} Y_{i-1(\text{opt})^b} \tag{3.16}$$

where

Ia_{d} is an indicator function

$Y_{i-1(\text{opt})}$ is the system/part failure probability density distribution (pdf) with the component/part stress and other failure variables

3.3.3 Dynamics of the System and Component Degradation Process

We use a TI model to describe the degradation dynamics. The system indicates that the degradation rate does not only depend on the current degradation levels from the process conditions (b_i), but it also has to do with the component stress and other failure event levels from part surface quality conditions (a_i); for example, consider the wear size in a shaft; the current size of the wear determines how fast a wear grows over the next period; It is why a wear grows very slowly in the initial stage, while it grows much faster when it is visible to the eyes. On the other hand, the growth rate also depends on various stresses and other failure event levels such as how much load the shaft supports and how cold is the temperature. The TI model is also used to describe the dynamics of the degradation process:

$$\frac{db}{dt} = K(b, a) \tag{3.17}$$

where $K(b, a)$ can be a nonlinear function. But this book considers the linear version of Equation 3.17, which is expressed as

$$\frac{db}{dt} = F_b + G_a \tag{3.18}$$

where F and G are two matrixes, and the random component stress with other failure variables a is normally distributed with mean μ_a and variance $\sum a$, and with the TI technique, we can further deduce that stress variables are uncorrelated between any two different time points, that is, $\text{cov}(a_i, a_j) = 0$ for $i \neq j$; therefore, $a - \mu_a$ is a multivariate white noise. We further deduce that the degradation process starts with the initial state b_0. At this point, where it starts, the part quality conditions are at the optimum level ($Y_{i-1\text{opt}}$), where the degradation value for $b_0 = 0$ and the reliability coefficient value $R_k = 1.0$. It progressively degrades uniformly for a period of useful time until it gets to failure threshold points, of degradation failure, a_{th} and b_{th}, after which it rapidly enters into a failure state (*FF*). At this juncture, it is also important to note that there is a correlation between the initial operation/event and the subsequent event/operation. Apart from the correlation between operations, there is also a correlation relationship within any operation. This relationship is expressed in a TI model, $Y_i = aY_{i-1}{}^b$, where Y_i is the final surface quality or degradation parameter, Y_{i-1} is the initial surface quality or degradation parameter, while a is the TI coefficient for transferring quality or degradation parameters from point to point and from operation to operation, and b is the TI coefficient for controlling process performance or degradation parameters within an operation. TI coefficients can be used to select and determine suitable component multiple quality growth ($Y_{i(g)}$) or degradation condition parameters ($Y_{i(d)}$), expressed as the quality factor ($Q_{f(g)}/Q_{f(d)}$), and process multiple performance condition factors (P_f), expressed as the process performance factors, ($P_{f(g)}/P_{f(d)}$). The overall system reliability (R_{ksys}) of component and process conditions is a function of Q_f and P_f, which is given as

$$R_{ki(sys)} = f(Q_f, P_f) \tag{3.19}$$

With Equation 3.19, reliability growth and degradation as well as life cycle and maintenance costs can be deduced for component and system reliability assessment with the help of the TI technique. The system reliability coefficient can be expressed in terms of the component quality factor ($Q_{f(opt.)}$) and process performance factor ($P_{f(opt.)}$) at a ratio that is equal to 1.0 at an optimum condition. This implies that the component quality factor can be converted to the process performance factor and vice versa:

$$R_{ki(sys)} = Q_{f(opt.)} : P_{f(opt.)} = 1.0 : 1.0 \tag{3.20}$$

Maximum achievable reliability requirements can therefore be set mathematically with the help of a multivariate regression model and can be controlled with the TI model for different failure-resistant applications.

3.4 Maximum Achievable Reliability Requirements of Hard Alloy–Coated Part in the Manufacturing Process and Equipment for Wear- and Other Competing Failure-Resistance Applications

Component and part reliability requirements can be specified using multiple performance parameters and criteria such as quality factor, time, and maintenance cost with the help of the TI technique. Although the most common existing reliability parameter is the mean time between failures (MTBF), which is only associated with degradation growth stage and can also be specified as the failure rate or the number of failures during a given period, but these parameters are very useful for systems that are operating on a regular basis, such as most vehicles, machinery, and electronic equipment. At this point, it should be noted that reliability increases as MTBF increases. The MTBF is usually specified in hours but can be used as the probability of mission success. Since this parameter is not enough for assessing manufacturing processes and equipment operating conditions, then component quality factor, process performance factor, and maintenance cost can therefore be used to determine reliability. For example, reliability of a scheduled aircraft can be specified as a dimensionless probability or percentage. In so-called zero-defect experiments, only limited information about the failure distribution is acquired. Here the stress, stress time, or sample size is so low that not a single failure occurs. With the TI technique, both the upper and lower limits and the initiation and growth degradation parameters can be determined from the initial to final life cycle operations. This looks good for the customer if there are no failures. In a study of a more intrinsic failure distribution, which is often a material property, higher stresses are necessary to get failure in a reasonable period of time. Several degrees of stress have to be applied to determine an acceleration model. The empirical failure distribution is often parameterized with a Weibull or a power model. It is generally done to model the early failure rate that has an exponential distribution. This less complex type of model has only one parameter—the constant failure rate. Due to the fact that reliability is a probability, even highly reliable systems have some chance of failure. However, existing methods of testing reliability requirements are problematic for several reasons. A single test is insufficient to generate enough statistical data. Multiple tests or long-duration tests are usually very expensive. Some tests are simply impractical. Reliability engineering with the TI technique is used to design a realistic and affordable test program that provides enough evidence with multiple parameters that meet system requirements under a single platform. Statistical confidence levels are used to address some of these concerns with the help of the TI model. This model is used to select the best combination of parameters and tests. A system reliability model testing that can perform at various levels, such as component, subsystem, and system, as well as such that can address many factors during testing, such as extreme temperature and humidity, shock, vibration, surface quality, and heat parameters, is highly essential for different industries. Reliability models with TI coefficients, R_{ki} for components and $R_{\text{ki(sys)}}$ for systems, can now be applied for an effective test strategy at all levels of design, development, and operations so that all parts are exercised in relevant environments. This integrated reliability testing strategy for design, operations, and maintenance of components in different environment conditions is developed with the help of a TI model, which combines quality–reliability chain conditions for components, establishment of an adequate component reliability, process performance of appropriate analyses and tasks to ensure that the component/system meets it requirements toward a sustainable development in the monitoring and maintenance organizations across the different industries of the future. This is possible with integrated reliability CM of manufacturing and equipment system using the TI technique.

3.5 Integrated Reliability CM of the Manufacturing Process and Equipment System

Integrated reliability CM is the process of determining the component quality and process performance condition of machinery while in operation. This is the process of systematic data collection and evaluation for identifying the changes in performance or quality condition of a system, or its components, such that remedial action may be planned in a cost-effective manner to maintain reliability.

While the basic definition of CM may have general application across many industries based on the objectives for condition-based maintenance (CBM), it may vary greatly through the following ways:

- CM uses selected measurements to detect changes in operating conditions. Many failure modes have measurable responses and develop over periods of time. These are the ideal applications for CBM. Sampling may be continuous (e.g., turbomachinery) or periodic (e.g., monthly survey on conveyor drive).
- CM gives early warning of potential failure. If the measured parameters are well chosen and properly measured and analyzed, there will be valuable information gained for maintenance planning purposes. It is essential that what defines *normal* is understood and documented so that the severity of variations can be measured.
- CM gives information about the nature of the failure. From this, a prognosis should be determined. The rate of sampling and access to maintenance history on the machine may have an influence on the quality of the final decisions made.
- CM allows management of failure to full life potential. Identification of a failure mode does not necessarily mean that an immediate maintenance action is needed. Just when maintenance action must be taken is the toughest part of managing a CBM program! Your reputation may depend on it! The best course is to involve as many informed people in the decision-making process.
- CM evaluates corrective action. Immediately after a machine has been repaired, it should be subject to CM testing. This will potentially identify assembly or installation faults that may lead to early failure (infant mortality) or affirm the quality of improvement achieved through the application of improved work practices or maintenance standards. The most commonly used techniques of CM are as follows:
  - Vibration measurement and analysis
  - Oil condition and wear debris analysis
  - Thermography
  - Non destructive test (NDT), especially thickness testing
  - Performance trending, for example, flow rate measurement

The data gathered from operating condition inspections and performance monitoring trends will increasingly appear alongside process plant performance, and component quality data can be used to assign maintenance priorities and maximize plant uptime and equipment reliability with TI techniques. Maximum equipment reliability is possible when a part surface finish quality condition is determined with a component multivariate quality regression model by a progressive machining process.

3.5.1 Accelerated Reliability Growth, Degradation, and Failure Testing Device with TI Coefficients

The methodology of a multivariate quality regression model from a progressive machining process of a hard alloy–coated critical part surface is applied to a TI degradation model data in order to analyze an accelerated quality–reliability testing and simulation chain. The purpose of this simulation is to study the effect of component condition with random stress on an electric motor shaft–bearing housing assembly and to predict their reliability under operating conditions of critical components in equipment.

The reliability of a typical electric motor shaft–bearing housing assembly is strongly dependent on the degradation model of the system process performance condition characteristics such as current versus power and temperature. The influence of physical degradation on the degradation rate of the electric motor shaft–bearing housing assembly characteristics is affected by the shaft–bearing characteristics themselves. The correlation between reliability and degradation modes is so common; this book provides a multivariate TI model that correlates the probability of failure or reliability and degradation modes. Electric motor shaft–bearing housing assembly degradation modes with the TI model can be used to evaluate rapid degradation through an integrated component condition with operating process condition. Higher current density, voltage, or temperature or rapid power reduction is due to rapid component degradation conditions, which can be measured with the help of TI coefficients. When the process performance reaches a specified rapid degradation level (degradation failure or potential failure), it is defined by a multivariate regression model, which is used to determine the critical maximum and minimum quality–reliability values, where the critical minimum quality value represents the condition of degradation failure threshold point. A monitoring device can be used to track down this degradation failure threshold point throughout the development and service from the initial to final process operations.

An automatic accelerated degradation test can be carried out and the data recorded to determine the failure times and conditions and to control the applied factors. An automatic accelerated degradation test device is designed as shown in Figures 3.2 and 3.3 [7].

Figure 3.3 is a circuit diagram for testing an electric motor shaft–bearing housing assembly, which consists of the power supply, adjustable resistor, and environmental stress conditions. The adjustable resistor is connected

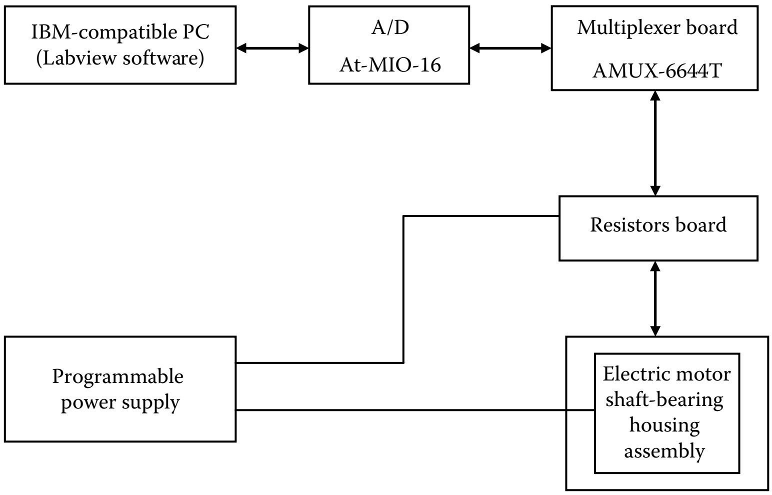

FIGURE 3.2
The layout of an automatic accelerated reliability growth and degradation test device.

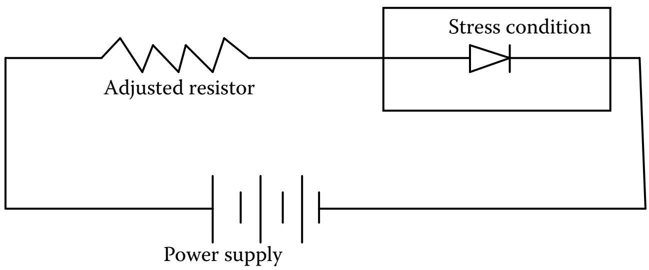

FIGURE 3.3
The circuit diagram for reliability growth and degradation testing in machine tools and rotating equipment.

to the electric motor shaft–bearing housing assembly. The voltage of the resistor is monitored in order to determine the current of the electric motor shaft–bearing housing assembly. It should be pointed out that it is assumed that the resistance of the adjustable resistor does not change with time. The component degradation of a shaft in the electric motor or rotating equipment is determined by a TI coefficient or measured by a sensor at room temperature every 50 h. With the TI model, the component degradation measure estimation at specific time *t*, component condition, and failures can be recorded. The data can be used to calculate the failure probability and reliability.

3.5.2 Quality–Reliability Parameter Selection and Design of Equipment Part and Environmental Conditions

For any system and component, there will be a range of environmental conditions that it will have to withstand during the part–equipment system life in service. The main environmental factors that can affect component and system reliability are

- Temperature
- Vibration
- Shock
- Humidity
- Dirt and other contamination
- People
- Electrical and electronic equipment that is further subjected to voltage transients, including static discharge
- Electromagnetic effects: Certain other environmental stresses can affect reliability in certain cases. Examples of these are
- Radiation
- Lubricant condition
- Attitude or vacuum
- Pollution
- Salt spray

For each environment, the whole range of part and process parameters must be considered, as well as the rate of change when appropriate. For example, the rate of change of temperature is often more critical to reliability than its maximum or minimum operating temperature, since cycle temperature change can initiate fatigue damage. Environmental stresses do not operate in isolation and the combined effect can often be more damaging than a single condition. For example, temperature cycling combined with vibration can lead to factor crack propagation in many stress components. People are a special category of the environment, from the perspective of the product. People, whether users, maintainers, or handlers, can generate many of the stresses listed earlier and can affect reliability in other ways often difficult to foresee.

People drop and bump products, they pack them incorrectly, they operate control in the wrong sequences, they forget to fasten panels, and they do not always maintain equipment properly. The designer must be aware of all these and the product must be designed and tested to ensure that it is as robust as practicable against these conditions of treatment.

For a design to be reliable in the range of environments, it is likely to have to withstand or resist failures during its expected service life, and it is essential that the design team takes into account all the stresses and combinations of stresses that might be applied. The designers must be aware of the stress application range, ideally written into the product specification. In order to ensure that all stresses and stress combination have been properly considered, a formal stress analysis should be performed. The review should be performed by a team, including the designers, and by specialists who can advise on aspects such as environmental resistance of components and systems that are greatly influenced by the quality of components, effectiveness of the processes, operating conditions, monitoring of the operating conditions, and a suitable maintenance strategy. A cost-effective integrated reliability testing program with the TI model that considers the different multiple manufacturing, part, and equipment factors is therefore highly essential and needful. It therefore means that environmental, manufacturing process, part, and equipment condition parameters need to be taken into consideration for maximum achievable reliability design with the help of the TI technique.

3.5.3 Manufacturing Process, Part, and Equipment Reliability CM and Maintenance with TI Model–Based Analysis

Manufacturing process and equipment conditions are always subject to variability. The designers must pay attention to tolerance, manufacturing process, and degradation test methods. This requires that the design team is thoroughly familiar with the manufacturing processes and their likely workpiece variations with the different operations and that production engineers should work closely with the designers. The variation of environmental conditions and manufacturing process variability inevitably combine to affect reliability. The hard alloy–coated part designs therefore must take into account the following.

3.5.3.1 Tolerance Factor

Tolerance technique is a statistical method for optimizing the tolerances of parts that must fit together or operate together when the hard alloy–coated part surface quality parameters value or specification is to be met as cost-effectively as possible. Tolerance can also be useful in optimizing yield from component, for example, of bearing–shaft assemblies. A simple example of tolerance analysis is the case where a shaft must fit into a hole, both having variation about the normal diameters. Traditional *worst-case* tolerance would specify that the higher limit on the shaft diameter was lower than the lower limit of the hole diameter, so all shafts would fit all holes. However, if the dimensions were distributed normally, most combinations would not have a close fit. Statistical tolerance enables us to calculate the probability of a shaft not fitting a hole. It shows that a slightly larger proportion of combination will not fit statistical tolerance but that the average clearance will be much less. In practice, other factors will have to be taken into account, such as *surface roughness* and the statistical process control methods used in production. In many cases, the part values and tolerances are set by the manufacturer. Therefore, the circuit designer cannot apply the statistical tolerance technique to the same level of refinement for most component combinations. In such applications, it is necessary to assess what the critical parameter combinations are from the tolerance and parameter variation point of view and to apply statistical tolerance and parameter variation control with the TI model for maximum performance. Where multiple tolerance possibilities exist, the statistical integrated reliability testing with the TI model can be extended to cover these. Such a model can be used to optimize such designs, by showing what the most significant sources of variation are and enabling these to be controlled at their optimum values.

3.5.3.2 Manufacturing Process Analysis

The manufacturing processes involved in the production of a critical hard alloy–coated part for wear and other competing failure modes (like shaft) are as follows:

- Metallurgical
- Coating deposition
- Machining
- Grinding

The TI model can be used to analyze the reliability conditions of the processes and the workpiece from the initial operation to the final operation. Using the reliability CM and maintenance curve, it is possible to detect any defect or failure, such that it can be corrected first before proceeding to next operation till you are able to attain the maximum achievable reliability.

3.5.3.3 Integrated Reliability Testing with TI Model–Based Analysis

This technique can be applied since it combines manufacturing process, tolerance, equipment, and environmental characteristics together, and it is capable of carrying out unit, multiple, and system testing in terms of component and system reliability (R_i), integration testing in terms of combining reliability growth (R_g) and reliability degradation (R_d), and system testing in terms combining the different component reliabilities (R_{sys}). The TI technique combines elements of control theory and statistical design to optimize hard alloy–coated part designs in relation to their ability to be *robust* to variations in the environment, production, and service operation. The coated part can be considered with the output value (specification) affected by control inputs; by external factors such as environmental changes, handling, and operation; and by internal factors such as production-induced variations such as component, process, and material variations as well as service conditions. Our challenge is to design the hard alloy–coated part so that its quality output values, within the specification limits, are maintained despite the expected range of variation of all the internal variations that can affect it. This challenge is tackled by integrating the coated part surface condition and the process conditions with the TI model.

3.6 IRCMM of Manufacturing Processes and Equipment Mechanism with the TI Model

The reliability of components is governed by various mechanisms by which they may fail. These mechanisms are dependent on the design, processes, and operational environment of devices. In order to reduce the incidence of failure, it is necessary to determine and study the modes of failure and resistance to failure mechanism and feed the information back to design and production for the required corrective action. In addition to the feedback, it is important that information be supplied to the user concerning the overall reliability of the devices under normal operating conditions. It is, however, often necessary to represent such conditions by some other more convenient reliability test conditions (e.g., thermal stress), and it is consequently essential that these tests be related to operating conditions in a known manner. These latter tests are the accelerated life tests carried out to evaluate manufacturing and equipment reliability by statistical analysis of the results. The correlation between such tests and operating conditions may be determined by workpiece resistance to failure and the wear-out mechanism for the devices, where the activation energies for these mechanisms are obtained from a series of step stress and overstress tests as well as reliability growth and degradation tests. It is necessary that the physics of failure mechanisms and their levels of activity be considered together during real-time operations. It is common practice to employ screening procedures such as microscopic examination and *burn-in* programs to enable immediate rejection of defective components or to accelerate gross failure potential in a short time. With TI technique and the procedure for testing the component and the system reliability evaluation, assessment, and cost-effectiveness are inevitable and can now be fully considered with the following workpiece surface failure resistance parameters:

- Workpiece surface hardness
- Workpiece surface stress
- Workpiece surface roughness
- Workpiece surface wavelength
- Others

3.7 Quantitative and Qualitative Assessments of Integrated Reliability Coefficient Test

An integrated reliability coefficient test applies two different kinds of assessment: one approach is characterized as a relative comparison of system complexity between generic systems and the second approach is a calculation model where the components' lifetime, quality level, and maintenance system are included (this is more of a design tool that can be used in the assessment and development of a particular system). The integrated reliability assessment takes into account each component and its different criticality to the system function, the effects of possible growth and degradation with time, and the quality control of components. All components with the same estimated lifetime, which is considered to be equality critical to the system function, shows that a component either works or does not work. With a maintenance system, it is assumed to bring in both approaches that incorporate all storage units and components directly related to bearing loop: sensors, controllers, pumps, heat exchangers, etc.

The estimate of reliability according to the first approach is based on a generic list of main components used in the generic systems. All components are treated on a general level, that is, a pump is simply a pump with a certain lifetime, no matter whether it is part of a Swedish or a Dutch system. An average lifetime of each component is assumed based on literature studies and contacts with different experts.

From a component lifetime, yearly component reliability is calculated according to

Failure probability per year = 1/lifetime (years)

Reliability per year = 1 − failure probability per year

The system yearly reliability is calculated by simply multiplying the reliabilities of the system's individual components. The figure called characteristic reliability factor expresses a mean value of the reliability of the system per year, and it is meant to be used as a base of comparison between the analyzed system designs. This characteristic reliability factor can be determined with the help of the TI coefficient that expresses the mean value of component and process condition parameters in a technological system. It can therefore be used to determine the maximal and optimal baselines for designs, optimal selections and comparisons of critical components or systems, conversation table of standard formulations, and design of diagnostic and prognostic devices (Table 3.1).

The maximum achievable reliability of each component can be obtained when all the factors like wear resistance, corrosion resistance, and fatigue

TABLE 3.1

Failure Requirement Characteristics and Assessments for Manufacturing Processes, Parts, and Equipment

Failure Requirement Characteristics	Possible Features and Values
Type and mode of failure	Total number of failure per unit time, $N_f = 0.0/\text{year}$
Wear failure	
Fatigue failure	
Corrosion failure	Critical potential number of failure, $PF_c = 1.0$ time/year
Temperature failure	
Scope of failure	Localized to a critical part surface quality factor, $Q_f = 0.0–0.2$
On part surface, Y_i	
• Roughness	
• Hardness	
• Wavelength	Localized to process functional performance factor, $P_f = 0.0–0.2$
• Stress	
• Kinematic coefficient	
On process condition, X_i	
State when failure occurs	Normal, $FF = 10\%R_{ki}$
Critical potential failure, PF_c	
Functional failure, FF	Degradation mode
	$PF_c = 65\%R_{ki}$
Response types	Notify selected users and other systems
	Switch to degradation mode
	Shutdown-affected capabilities
	Totally
Response measurements	Maximum Reliability growth coefficient Threshold point, $R_{kig(thmax)}$
	Minimum Reliability degradation coefficient Threshold Point, $R_{kid(thmin)}$
	Maintenance cost (M_c)
	Warranty cost (W_c)

resistance of reliability are designed into the product with the use of TI coefficients. These coefficients provide common component characteristics like component materials, geometry, and load for all the different failure modes as well as common parameters like surface roughness, surface hardness, surface stress, and surface wavelength for the different component characteristics. The failure mode with the highest TI coefficient provides the baseline for optimal reliability design. This is possible by optimizing each process condition of the production system as well as optimizing the surface quality condition parameters of a critical generic component (e.g., bearings, rotating shafts, and other critical parts of industrial equipment). The TI technique provides a single metric that integrates the different factors of the different systems from initial to final operations of a technological process.

This technique is used to determine the criticality index of all the components of the system. The system/component reliability is optimized to determine the reliability CM requirements for the IRCMM program.

The program will apply diagnostic and prognostic techniques with the TI model to obtain statistical failure estimates. It will be used to measure and quantify the following:

- Criticality index of components/systems
- Component/process condition variations
- Transfer functions and ratios
- Factorial levels

The program can also be used to analyze the failure resistance parameters and their effects on lifetime, reliability, and performance of industrial equipment. There are many examples of failure due to a lack of knowledge about the requirements that those installations and operations have to meet in a long-term perspective. Fortunately, those bad examples have become much less common, but it is essential that new designers, manufacturers, and maintenance personnel are aware of them in order to avoid the pitfalls in future installations and operations. Long-lasting high performance requires durable components that are achieved through the use of high-quality materials appropriately chosen for a particular application.

In the case of shaft–bearing housing in rotating equipment, for example, there are some special aspects to be aware of related to high temperature due to friction. The shaft–bearing set itself is of course the component exposed to the highest stress, but the more conventional components should also be considered. As the stress on these mating parts sometimes gets much higher than on the corresponding components in rotating equipment, there is greater need to check their durability. In qualification tests, a shaft–bearing assembly has to pass in order to fulfill these requirements that are designed in such a way that within a reasonable period of time, the tests are able identify the most serious and the most frequent failures that may occur during the lifetime of the bearing. Thus, a number of tests are performed—high-temperature resistance, wear resistance, and corrosion resistance and mechanical load tests. For example, as the requirements on bearing tests are a compromise between test costs and quality assurance level, combined to give a better assessment of overall equipment reliability can be determined through the use of resistance to failure factor. The combination of two or more of the previously mentioned resistances to failure parameters under a single metric is possible with the application of the TI coefficient for reliability control. With this coefficient, component reliability (R_i) can be determined in terms of component and process conditions, which can be expressed in terms of component quality or resistance to failure parameters (Y_i) and process condition parameters (X_i). Yi is the different quality condition parameters of a component, which can be represented by a single metric, known as TI coefficient a, while X_i is the different performance parameters of a process, represented by the TI coefficient b. These coefficients can be used to determine integrated reliability (R_{in}), which combines the reliability of components and process conditions together. It helps to determine the growth and degradation of the quality factor of components (Q_{fi}) as well as the growth and degradation of process performance factor, (P_{fi}). The knowledge of integrated reliability (R_{in}) in terms of Q_{fi} and P_{fi} will help to determine the reliability growth ($R_{\text{k(g)}}$) and reliability degradation ($R_{\text{k(d)}}$) of components and systems. This will definitely help determine component reliability requirements, predict maximum achievable reliability requirements, detect failures and transfer these properties from one operation or point to the other, and use the data to plan, analyze, assess, and maintain components and systems with the help of the TI model.

3.8 IRCMM with TI Coefficient Assessment for Manufacturing Processes and Industrial Equipment

The component quality parameter with the TI model of machine parts, processes, and equipment is expressed as [2]

$$Y_i = aY_{i-1}{}^b \tag{3.21}$$

where

Y_i is the final quality output parameter of an operating component condition

Y_{i-1} is the optimum initial input quality parameter of an operating component condition *a* is the TI coefficient of an operating component quality condition variation control within the limits of minimum and maximum achievable reliability requirements

b is the TI coefficient of an operating process/equipment condition variation control within a stated optimum process/equipment operating performance

The minimum and maximum achievable component condition parameters and requirements for any specific application can be determined experimentally as well as during real-time operations with the TI technique. The TI models of these component conditions can be obtained with component quality conditions (e.g., surface roughness, surface hardness, surface wavelength, stress concentration factor). The mathematical model can be used to assess and evaluate fatigue, wear, and integrated reliability of components. The model can be used to construct the trends and patterns of each quality parameter as well as the combined multiple parameters under a single metric known as the quality factor (Q_f), which provides an accurate method for a cost-effective integrated reliability monitoring and maintenance of manufacturing processes, parts, and industrial equipment. With the knowledge of the maximum achievable reliability and the minimum acceptable reliability, baseline requirements for design, manufacturing, and maintenance can be set. The reliability growth from minimum to the baseline requirement and the reliability degradation from the baseline reliability minimum can also be determined with TI coefficients.

3.9 Reliability Condition Growth Prediction Using Multivariate Quality with the Multivariate Regression Model

In practice, a system may consist of multiple components (e.g., metallurgical, coating deposition, machining, grinding, assembly, and equipment event data, which can be expressed as process conditions [X_i]), or a component may have multiple degradation measures like the different part surface quality parameters (Y_i) for wear, corrosion, and temperature failure modes, so it is necessary to simultaneously consider multiple degradation measures. In this book, we shall first explore the correlation between the component quality growth and manufacturing processes with the multivariate regression model. We shall use the experimental function to define these relationships, predict multiple quality parameters, and assess the optimum component quality parameter (Y_{opt}), minimum acceptable quality parameter (Y_{min}), and minimum life cycle cost ($L_{cc(min)}$). We use these optimum measures as initial inputs for the TI model to determine the probability of failures and reliability of components and systems. We use the TI model to describe the evolution of the degradation process by incorporating both the component degradation dynamics and random stress effects. Finally, the degradation dynamics, which is capable of transferring quality characteristics and eliminate faults and failures, is used to predict the reliability function.

3.9.1 Reliability Condition Degradation Monitoring of Manufacturing Processes, Parts, and Industrial Equipment with TI Assessment

The reliability degradation data evaluation of a component or system can include a number of different reliability analyses. Depending on the phase of the component life cycle, an integrated reliability analysis can be performed, and it is also possible to anticipate the reliability effects of design changes and corrections. The different reliability analyses are all related and can be examined from different perspectives in order to determine possible problems and assist in analyzing corrections and improvements.

The goal is always to identify the potential reliability problems as early as possible in the component life cycle. While it may never be too late to improve the reliability of a component, changes to a design are orders of magnitude less expensive in the early part of a design phase rather than once the component is manufactured or in service. With the use of integrated reliability monitoring and maintenance program with the help of a TI model, it is possible to monitor all the parts of design, development, and equipment operations by evaluating their reliability growth and degradation. Reliability is a broad term that focuses on the ability of a component to perform its intended function. Mathematically speaking, assuming that an item is performing its intended function at time zero, reliability can be defined as the probability that an item will continue to perform its intended function without failure for a specified period of time under stated conditions. Since reliability plays an integration role in design, manufacturing, and service operations of a component, it therefore means that, reliability growth and degradation be used to integrate all the component/system conditions during design, manufacturing processes, and service operations. It can also be used to integrate the different testing and evaluation analysis under a single platform. These are carried out with the help of the TI technique, since it can be used to determine the maximum and minimum achievable reliability of component/system as well as the reliability growth and degradation at minimum cost.

Once the reliability growth and degradation values for the components have been quantified, an analysis can be performed in order to determine if that system's reliability goal will be met. In this book, we shall consider an example of a system with three components connecting reliability monitoring and maintenance cost in series:

- Component (A) for a given time or with a specific condition is R_w(%)—the reliability of a wear resistance component.
- Component (B) for a given time or with a specific condition is R_c(%)—the reliability of the corrosion-resistant component.
- Component (C) for a given time or with a specific condition is R_{ht}(%)—the reliability of a high-temperature-resistant component. A set of reliability goals of R_{gs} = 90%, for example, is required for this system. In this case, components A, B, and C could be seals, bearings, and shafts of any rotating equipment.

If the reliability of the system is, for example, of R_{gh} = 50.4%; obviously, this is far short of the system's required reliability performance. It is apparent that the reliability of the system's constituent components will need to be increased and upgraded in order for the system to meet its goal. The overall system reliability goal will not be met by improving the reliability of just one component (parameter, process, and part). The next logical step would be to try to increase the reliability of two components. The question now becomes which two? One might also suggest increasing the reliability of all three components. A basis for making such decisions needs to be found in order to avoid the *trial and error* aspect of altering the system's components randomly in an attempt to achieve the system reliability goal. There are cases, however, where increasing the reliability of one component results in achieving the system reliability goal. Consider, for example, a system with three components connected reliability-wise in parallel, where the reliabilities for each component for a given time are R_w = 60%, R_c = 70%, and R_{ht} = 80%. A reliability goal, R_{gs} = 99%, is required for this system. The initial system reliability is

$$R_{sys} = 1 - (1 - 0.6)\,(1 - 0.7)\,(1 - 0.8) = 0.976$$

The above system reliability is inadequate to meet the goal in terms of time. Once again, we can try to meet the system reliability goal by raising the reliability of just one of the three components in the system. With the application of the TI technique, the system reliability, $R_{ki(sys.)}$ goal can be met by optimizing the component quality condition parameters (Y_{iopt}) and process performance conditions (X_{iopt}). Maximum achievable reliability can therefore be built into critical components (shaft, bearing, etc.) for multiple failure mode applications at minimum cost.

3.9.2 Meeting System Reliability Goal and Requirement with the TI Technique

In order to improve component A, B, or C to reach the desired reliability goal, the reliability engineer is faced with another dilemma: which of the component's reliability should be improved? This presents a new aspect to the problem of allocating the reliability of the system. Since we know that the system reliability goal can be achieved with at least one critical unit, the question becomes one of how to do this most efficiently and cost effectively. We will need more information to make an informed decision as to how to go about improving the system's reliability. How much does each component need to be improved for the system to meet its goal? How feasible is it to improve the reliability of each component rather than radically improving only one? In order to answer these questions, we must introduce another variable, *cost*, into the problem. Cost does not necessarily have to be in terms of money. It could be described in terms of nonmonetary resources, such as time and coefficients. By associating cost values to the reliability of the system's part, one can find an optimum design that will provide the required reliability at a minimum cost. This problem can be solved with the help of the TI technique, since it can be used to determine and evaluate the costs of a component part/system at any stage of design, manufacturing processes, and service operations.

For the purpose of reliability optimization, we also need to define a limiting maximum achievable reliability that a component will approach, but not reach. The costs near the maximum achievable reliability are very high, and the actual value for the maximum reliability is usually dictated by technological or financial constraints. In deciding on a value to use for the maximum achievable reliability, the current state of the art of the component in question and other similar factors will have to be considered. In the end, a realistic estimation based on engineering judgment and experience will be necessary to assign a value to this input. Note that the time associated with this maximum achievable reliability is the same as that of the overall system reliability goal. Almost any component can achieve a very high reliability value, provided the mission time is short enough. For the purposes of optimization, the reliability values of the components are associated with the time for which the system reliability goal is specified. For example, if the problem is to achieve a system goal of 90% reliability at 1000 hr, the maximum achievable reliability values entered for the individual components would be the maximum reliability that each component could attain for a mission of 1000 hr.

As the component reliability, coefficient, R_{ki} approaches the maximum reliability coefficient, $R_{ki(max.)} = 1.0$, the cost function approaches infinity. The maximum achievable reliability acts as a scale parameter for the cost function. By decreasing $R_{ki(max.)}$, the cost function is compressed between

$R_{ki(min.)} = 0.0$ and $R_{ki(max.)} = 1.0$. The optimum values $R_{ki(opt.)}$ and $C_{i(opt.)}$ can be obtained with the help of the TI technique, which can extend component/system reliability from 90% to 95% and more.

3.10 Setting Integrated Reliability Requirements with Multivariate Regression and TI Models

The method of implementing the reliability optimization through a multivariate quality regression model for a hard alloy–coated part is used to arrive at initial optimum surface quality specifications for a set of components, operations of manufacturing processes, and parts in a bearing–shaft assembly. In this chapter, we assumed a current reliability for the components. One has to choose an arbitrary (lower) initial reliability for each component while allowing the algorithm to *travel up* to the target, and since researchers have ascertained that machining hard-coated part provides low productivity and reliability with traditional tool bits. When doing this, it is important to keep in mind the fact that both distances from the target (the distance from the initial arbitrary value and the target value) for each component is also a significant contributor to the final results. If one wishes to arrive at the results using only the cost functions, then it may be advantageous to set equal initial or final reliabilities for all components and systems (e.g., for all the manufacturing processes for producing a desired part surface finish). With the use of the TI coefficient, it is possible to determine the initial and final reliabilities and to integrate cost and reliability functions under a single platform or program. The initial optimum part surface quality data from the multivariate regression model are fed into the TI model to achieve maximum reliability with minimum maintenance costs. These data are used to set reliability requirements for part, process, equipment, monitoring, and maintenance operations.

3.10.1 Reliability Requirements

A reliability requirement is a dependability requirement that specifies a required amount of reliability, which is a quality factor ($Q_f = 1.0$ or $P_f = 1.0$) that is defined as follows.

Reliability derived through the quality or performance factor is the degree to which something operates without failure under given conditions during a given time period.

The objectives of the reliability requirement are to

- Ensure that something will function properly for long periods without failure
- Thereby minimize any unintentional disruptions in operation

At this point, it is worth knowing that the existing reliability requirements are typically specified in terms of the following measurements:

- The MTBF (e.g., shall be at least 1 month)
- The maximum acceptable probability of the failure during a given time period (e.g., shall not exceed 0.001% per year)
- The maximum permitted number of failures per unit time (N_{fmax}.) (e.g., the component shall not fail more than an average of 3 times/year)

The scope of reliability requirement can be

- A business enterprise
- An application
- A component

The reliability requirements can be identified and specified in terms of quality or process performance factor with the help of multivariate regression and TI models.

3.10.2 Reliability Growth and Degradation Function with the TI Model

The purpose of reliability growth testing is to find out the optimum quality–reliability condition of components and systems, while reliability degradation testing is to find the failure degradation threshold point and the functional failure. This is possible with the use of the TI technique. The reliability testing device contains measuring sensors for measuring the growth in the quality–reliability of a part from the initial quality data and also the growth in the performance of the manufacturing process. An initial optimum quality data of a particular critical part surface condition or the optimum performance data of a progressive manufacturing process (e.g., a machine process of a hard alloy–coated part) is acquired and stored in a database device for later use. The optimum quality and performance conditions of a hard alloy–coated part surface by a progressive and productive manufacturing process are attained with the help of a multivariate regression model. The optimum results of this model are used to calculate reliability growth, degradation, and failure data. When the reliability growth does not get to optimal level, the degradation rate is measured for upgrade and necessary corrections before you can proceed to the next operation in the technological system. The TI model is used for the full analysis and evaluations of component and system reliability. These data can be used to construct the integrated reliability monitoring and maintenance curve. Potential and functional failures can happen at any phase of the technological chain, but with integrated reliability monitoring and maintenance with a TI model–based program, it is possible to meet customer's reliability requirements of components and systems at minimum maintenance costs. The reliability growth and degradation data are measured with TI coefficient sensors (TICSs). It is worth mentioning at this point that the optimum quality data of the hard alloy–coated part are used as the initial data input in the TI model for the determination of reliability degradation and failure characteristics. Industrial equipment with critical hard alloy–coated part surface (e.g., shafts) can be evaluated and assessed with the TI model and TICS for quality–reliability degradation and failure control, monitoring, and testing.

The purpose of reliability degradation testing is to discover potential problems throughout manufacturing and service equipment from the initial stage and, ultimately, provide confidence that the system meets its reliability requirements. Reliability degradation testing may be performed at several levels. Manufacturing processes and equipment systems can be tested at component, circuit board, unit, assembly, subsystem, and system levels. The test level nomenclature varies among applications. For example, performing environmental and developmental stress test at lower levels, such as part surfaces with hard alloy coatings or small assemblies, captures and identifies problems during real-time operations before they cause functional failures at higher levels. Reliability testing can be done during each level of integration from the initial operation through full-up system testing to final operation, developmental testing, and operational testing thereby reducing program risk. System reliability is calculated at each test level to determine degradation with the help of the TI model. Reliability degradation coefficients and failure data monitoring, reporting, analysis, and maintenance activities are often employed to improve reliability as testing progresses. The drawbacks to an extensive testing are time and expense; hence, a TI model–based reliability testing program under a single platform helps reduce time and cost to a minimum. It is therefore feasible to test all component and system requirements under the same platform. Some systems are prohibitively extensive to test, some failure modes may take years to observe, some complex interactions result in a huge number of possible test cases, and some tests require the use of limited test ranges or other resources. In such cases, a combination of different approaches to testing is used; in our case, accelerated life testing, design of experiments, and simulations will be applied in the program. The key aspect of reliability testing in our program is defining *potential failure*, such as in the machining of hard alloy–coated part surface, and functional failure, such as wear out in equipment. Test plans and procedures can be developed for each reliability test to meet the desired reliability requirements, and results can be documented in official reports of integrated reliability monitoring and maintenance software program. In the case of integrated reliability monitoring and maintenance with the help of a TI model–based software program, mathematical experimental plans for the reliability growth and degradation tests of hard-coated part surface conditions, manufacturing process condition parameters, and equipment performance factors shall be carried out, to determine component and system reliability, mean time to failures, number of failures, lifetime, process performance, and life cycle and maintenance cost characteristics with the TI model, which would be used to evaluate the following:

1. Component/system optimum reliability for selection, warranty, business, and customer's profitability
2. Component/system reliability degradation rates and failures for monitoring and maintenance practices
3. Component/system reliability integration for upgrade and development
4. Component/system integrated reliability testing and measurements
5. Component/system integrated reliability design, sensors, monitors, and instruments
6. Component/system integrated reliability monitoring and maintenance program
7. Component/system optimum lifetime
8. Component/system health
9. Component/system optimum performance
10. Component/system life cycle and maintenance costs

3.10.3 Cost Function for Manufacturing Processes, Parts, and Equipment with the TI Model

There is always a cost associated with changing the design due to change of manufacturing process, use of higher-quality materials, retooling costs, monitoring and maintenance costs, etc. The cost as a function of the reliability for each of the manufacturing process and equipment operations must be quantified before attempting to improve the reliability. Otherwise, the design changes may result in a system that is needlessly expensive or overdesigned. Developing the *cost of reliability* relationship will give the engineer an understanding of which components to improve and how to best concentrate the effort and allocate resources in doing so. The first step will be to obtain a relationship between the cost of improvement, monitoring, maintenance, and reliability. The preferred approach would be to formulate the cost function from actual cost data. This can be done with the TI technique. If an IRCMM program is in place, the costs associated with each stage of improvement and maintenance can also be quantified. Defining the different costs associated with different components is also useful in formulating a model of component cost as a function of reliability. However, there are many cases where no such information is available, but with the TI model, it is quite possible to integrate a cost function into reliability.

For this reason, a general TI model of the cost versus the component reliability will be developed for performing reliability optimization in this book. With the TI model, one needs to quantify a cost function for each component, C_i, in terms of the reliability coefficient:

$$C_i = a_{\mathrm{i(d)}} \cdot (R_{\mathrm{ki}}) \text{ (2.2)}$$

where

R_{ki} is the current reliability coefficient of each component, which should be maximum TI coefficient for quality degradation, "$a_{\mathrm{i(d)}}$" control

This function should

- Look at the current reliability of the component, recurrent
- Look at the maximum and minimum possible reliability of the component

Allow for different levels of difficulty (or cost) in increasing the reliability of each component. It can take into account the following:

- Design issues
- Supplier issues
- State of technology
- Integration issues
- Automation issues
- Time to market issues
- Maintenance issues
- Monitoring issues

Thus, for the cost function to comply with these needs, the following conditions should be adhered to:

- The function should be constrained by the minimum and maximum reliabilities of each component (i.e., reliability must be less than one and greater than the current reliability of the component or at least greater than zero).

The function should not be necessarily linear but rather quantify the fact that it is incrementally harder to improve reliability. The function should be asymptotic to the maximum achievable reliability.

Once the cost functions for the individual components have been determined, it becomes necessary to develop an expression for the overall system cost:

$$C_{\mathrm{i}}(\mathrm{sys}) = C_1\left(R_1\right) + C_2\left(R_{\mathrm{k}2}\right) + \cdots + C_n\left(R_{\mathrm{k}n}\right), \quad \mathrm{i} = 1, 2, \ldots, n \tag{3.22}$$

In other words, the cost of the system is simply the sum of the costs of its components. This is regardless of the form of the individual component cost functions. They can be of the general behavior model in BlockSim or they can be user-defined. Once the overall cost function for the system has been defined, the problem becomes one of minimizing the cost function while remaining within the constraint defined by the target system reliability and the reliability ranges for the components. The latter constraints in this case are defined by the minimum and maximum reliability values for the individual components with the help of the TI model.

3.11 Optimization of Reliability CM and the Maintenance of Processes, Parts, and Equipment with the TI Technique

Optimization of component/system reliability represents a significant opportunity for industries to save energy; improve process, part, and equipment reliability as well as their health; keep abreast of changing environmental and safety regulations; and increase plant productivity. Case studies have shown that better component and system design application of mechanical seals, bearings, shafts, and part system supports can save a substantial amount of energy. This same attention to the selection of part upgrade and maintenance technology as well as operation of the entire system can improve plant safety and environmental compliance, improve equipment reliability, and reduce overall maintenance costs. A software tool to assist in the calculation of comparative life cycle and maintenance costs for managers when selecting and buying seals, bearings, couplings, shafts, and others for use in their rotating equipment is highly essential. Companies these days are expected to improve their financial performance while dealing with stringent environmental regulations; increased optimum process, component conditions, and safety requirements; and increased cost of raw materials and energy, among other things. In turn, attention is being given to the need to reduce costs and optimize reliability CM of manufacturing, parts, and equipment in the short term. A strong emphasis on short-term cost reduction, however, can encourage some buyers to focus primarily on *initial cost* when evaluating investments and operating decisions, possibly ignoring collateral effects that can have a significant impact on operating costs throughout the life of their equipment. Buyers, who take a longer-term, more holistic approach, look beyond the initial cost to identify these collateral effects, estimate their financial implications, and consider the total life cycle of the investment and operating decisions they make.

When it comes to seals, bearings, couplings, shafts, and its support systems used on rotating equipment, maintenance and reliability engineers always had an intuitive understanding of the life cycle cost trade-offs between the *lowest initial cost* and *best available technology*. They understand that dilutive fluids injected into process stream through seal and bearing support systems can create a large energy burden downstream, where these same fluids must be removed to restore process integrity. They also know that when equipment suffers repetitive failures, the consequences on maintenance expenditures and resources, equipment downtime, safety, and environmental compliance can significantly exceed the initial cost of even the most sophisticated part systems.

Faced with pressure from plant management and purchasing to reduce maintenance expenditures, many of these engineers have tried to present life cycle cost arguments for buying the best available technology and optimizing the long-term costs for their facilities. This has been difficult without an agreed-upon industry approach for the analysis of life cycle cost for mechanical seals, bearings, and other part support systems—even though there is a broad consensus that life cycle cost can and should be an effective management tool in any cost reduction effort. The optimization method together with the TI technique is a very powerful tool for allocating reliability. However, if actual cost information is available, then one can use the cost data instead of using the default function. Additionally, one can also view the feasibility in the default function as a measure of the difficulty in assuming that they also follow the same cost function with the corresponding feasibility values. If fault tolerance is a viable option, a reliability cost function for adding parallel units can be developed as demonstrated previously. Another method for developing a reliability cost function would be to obtain different samples of components from different suppliers and testing the samples to determine the reliability of each sample type. From these data, a curve would be fitted through standard regression techniques and an equation defining cost as a function of reliability could be developed. If reliability growth and degradation models have been successfully implemented, the development, life cycle cost, and maintenance cost over the respective time stages can be applied to the growth and degradation models as well as the integrated reliability CM models, resulting in equations that describe reliability and cost relationships. For a CM model, the life cycle and maintenance costs over the respective development time stages can result in equations that describe reliability and cost relationships. This equation can be entered into BlockSim as a user-defined cost function with the help of the TI technique. The maximum, minimum, and optimum reliability of components/systems can be determined from the integrated reliability CM model of an operating component and system (R_{ki}), which is a product of the TI coefficient (a_i) and the optimum reliability of the previous process ($R_{\text{ki}} - 1$).

The maximum achievable reliability $R_{\text{kimax}} = a_{\text{imax}}$, while the minimum reliability $R_{\text{kmin}} = a_{\text{imin}}$, and the optimum reliability $R_{\text{kiopt}} = a_{\text{iopt}}$, when operating at optimum conditions of processes and equipment.

The optimum allocation scheme for a particular system is

$$R_{\text{kisys(opt)}} = R_{\text{k1opt}} * R_{\text{k2opt}} * R_{\text{k3opt}} \cdots R_{\text{k}n-\text{1opt}} * \ R_{\text{k}n\text{opt}}$$
$$= a_{\text{1opt}} * a_{\text{2opt}} * a_{\text{3opt}} \cdots a_{n\tilde{\text{n}}\text{1opt}} * a_{n\text{opt}} \quad (3.23)$$

The total allocation cost is

$$C_{\text{isys}} = C_1 * (R_{\text{k1}}) + C_2 * (R_{\text{k2}}) + C_3 * (R_{\text{k3}}) + \cdots + C_{n-1} * (R_{\text{k}n-1}) + C_n * (R_{\text{k}n})$$
$$= C_1 * (a_1) + C_2 * (a_2) + C_3 * (a_3) + \cdots + C_{n-1} * (a_{n-1}) + C_n * (a_n) \quad (3.24)$$

3.12 Developing Reliability Growth and Degradation Improvement Tests for Optimum Component Conditions and the Failures of Equipment with the TI Technique

Reliability growth, degradation, and failure test are possible with the help of multivariate regression and TI models. TICSs for reliability degradation controls are used to measure and assess parts, processes, and equipment through an IRCMM program.

The program can be used to evaluate and assess the rotors, stators, rotor starter air gap, and cracks of the bearings, shafts, and other critical parts of the mechanical conditions of equipment. The technique is used to determine reliability degradation, degradation rates, defects, and failures and to carry out service life tests and the monitoring of process and equipment conditions. Since in many cases, one-time test can only be used to determine if problems are present, more often, monitoring is required to determine severity and changes in conditions of processes, parts, and equipment.

Process condition parameters like current and voltage data are acquired directly from the motor control center while the equipment is in operation. Also it is possible to collect the number of cycles and the revolutions of shafts as well as shaft and process performance degradations while the equipment is in operation. The collected data are then used to determine phase imbalance, motor load, power factor, power harmonics, and the impact of the driven equipment on the motor and to determine the speed, stress, and reliability growth and degradation coefficients of components. Rotor bar and stator eccentricity (air-gap) characteristics are assessed. In addition, degraded bearings and shafts can also be observed or assessed with the TI technique. This technique is particularly useful in accessing mechanical conditions when it is not possible or convenient to make vibration measurements. It is essential to note at this point that the technique provides a more cost-effective CM and maintenance of processes, parts, and equipment than the vibration technique. With the TI technique, the motor baseline signature is known, and the information of a predictive/preventive maintenance engineer is also known and available for *how long is needed to replace or repair a motor?* and *the component and system conditions of failures*. Actually, rarely can a one-time test provide these data. However, integrated reliability degradation monitoring will give this input by providing an indication or rotor degradation appears, it will be clear from one test how rapidly the rotor circuit is degrading. Testing over several weeks or months will confirm if the rotor is stable and not changing. The number over starts and stops that a motor experiences is very important with regard to rotor change. A motor with a high on-off duty cycle is much more likely to show rapidly increasing rotor degradation than a motor that runs constantly. Process, part, and equipment conditions are factored into the trending data to provide a much clearer indication of their health and reliability in the system.

In trending and monitoring the driven load and equipment, it is the driven load that is more important to the predictive/preventive maintenance professional than is the motor. In any case, the TI technique is used to differentiate and integrate the motor, load, material, geometry, and friction characteristics. Reliability degradation testing and trending with TI procedures (Figure 3.4) are useful for reliability designs, manufacturing, monitoring, and maintenance of processes, parts, and equipment because it helps determine the maximum achievable output, which can be used to obtain the customer's maximum required or desired service life with

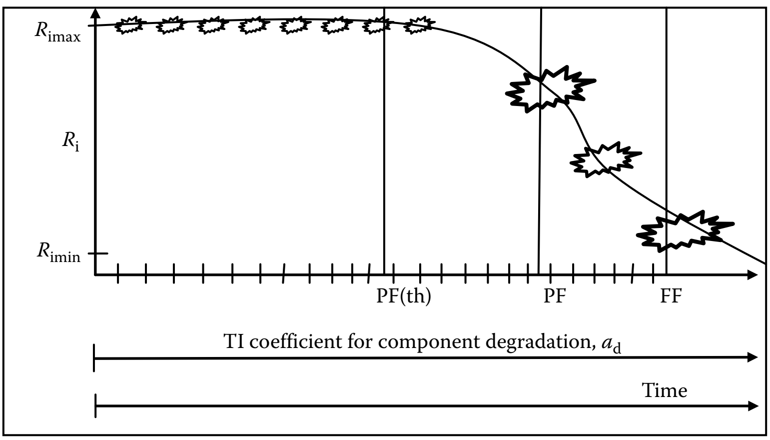

FIGURE 3.4
Reliability growths, degradations, and failure estimation with TI coefficients.

minimum life cycle and maintenance costs. An integrated reliability CM program is therefore useful for both reliability growth and degradation assessments, since it measures the quality growth or quality degradation with the TICS, and data are used to calculate component/system reliability, failure rates, mean time to failures, potential and functional failures, as well as life cycle and maintenance costs.

3.12.1 Procedure for Reliability Growth and Degradation Improvement with the TI Model

The design of integrated reliability coefficient testing program with the TI technique is used to establish the following:

- Reliability growth and optimum component/system reliability analysis during manufacturing and equipment system operations
- A cost-effective reliability degradation, degradation rates, and failure analysis during manufacturing and equipment system operations
- Cost-effective reliability degradation, degradation rates, and wears with other failure mode analysis during manufacturing and equipment system operations
- A component and system IRCMM program
- Preventive, predictive, and proactive maintenance program
- Integration of reliability, CM, and maintenance program
- Automation with TI model–based software and tool programs
- Computerized management of integrated reliability monitoring and maintenance of part, process, and equipment system

3.12.2 Benefits

1. The integrated reliability testing program with the TI model–based software ensures that components and systems meet maximum achievable reliability, service lifetime, and safety objectives throughout the design, manufacturing, and service operation.
2. It is used to design I/O instruments that help measure reliability growth/degradation and time to failures and develop reliability curves/trends and mechanisms during design, manufacturing, and service operation with the TI model.
3. The program is used to estimate component and system warranty cost as well as the life cycle and maintenance costs.
4. It is used to automate and integrate reliability, CM, and maintenance of industrial equipment based on the TI model and hardware in a loop.

5. It is used to test for optimum component and system reliability and for failures prior to making changes, at any stage of design, manufacturing, and service operations.
6. It is used to determine the maximum achievable resistance to failure modes of components and systems at minimum cost as well for integrated reliability monitoring and maintenance of parts, processes, and equipment with the TI technique.

3.12.3 Capabilities

1. Integrated reliability monitoring and maintenance analysis with the TI technique
2. Optimum achievable reliability estimate with component quality and reliability predictor
3. Reliability optimization and cost-benefit analysis with manufacturing process condition selector
4. TICSs
5. Reliability and failure problem identification with process and component failure detectors
6. Fatigue, wear, and other competing failure mode diagnostics
7. Integrated reliability monitor
8. Life cycle and warranty cost analysis with TI BlockSim
9. Reliability goal and requirement setting and optimal allocations for design maintenance map
10. Resistance to failure modes or integrated reliability monitoring and maintenance curves/mechanisms

3.13 Conclusions

1. This book applies the combination of two different definitions of reliability to formulate and achieve the objectives of IRCMM of processes, parts, and industrial equipment toward a positive impact on people, business, and system/component reliability improvement.
2. The two different reliability definitions applied under a single TI model–based platform are the resistance to failure or quality condition of a component and system and the ability of a component to perform a required function under stated conditions for a specified period of time.

3. Reliability, which is defined as the resistance to failure of a component, can be used to determine the maximum achievable resistance to wear failure and other competing failure modes that meet a desired process performance, component quality, and environmental requirements within a specified period of time.
4. Integrated reliability is therefore defined as the ability of a component/system to perform a required function under stated conditions and to determine and evaluate the maximum achievable process performance and component quality condition of a system, within a specified period of time, and operating condition with minimum life cycle costs.
5. The TI technique integrates the definitions used to optimize the IRCMM of parts, manufacturing processes, and equipment, which will help to increase the lifetime and minimize the failures of parts and equipment in aggressive applications of different industries of the future.
6. The solid theory of reliability, engineering, and TI technique applied in this book provides the foundation for developing reliability requirements of materials, manufacturing processes, parts, and industrial equipment through a cost-effective IRCMM with TI model–based program that performs appropriate reliability analyses, tests, and tasks to ensure that wear-, corrosion-, and high-temperature-resistant parts can meet their desired goals.
7. The goal of this work is to attain the maximum achievable reliability of hard alloy–coated critical part surface designed to resist wear and other competing failure modes operating in aggressive applications and sustain optimum quality part condition from initial to final equipment reliability for a specified desired lifetime at minimum life cycle and maintenance costs.
8. The maximum achievable reliability requirements of hard alloy–coated critical part in equipment at minimum costs in aggressive application are possible with an IRCMM with a TI model–based program that helps to extend the part life to maximum and time to failure and perform monitoring and maintenance tasks cost-effectively.
9. IRCMM with a TI model–based program helps to detect and fix potential/functional failures (defects, degradations, premature failures, errors, infant mortality failures, random failures, etc.) early from the design of wear- and other competing failure-resistant parts through manufacturing processes to its final service operations in operating equipment for aggressive media of the industries of the future.

10. The multivariate surface quality regression model predicts optimum part quality and process performance conditions as well as wear, corrosion, and high-temperature failure modes during the machining of hard-coated part surface.
11. The application of multivariate hard-coated critical part surface quality regression model creates the foundation for relating and integrating all the operations involved in the system together under one platform, where the optimum finished quality condition of part data are used as initial reliability data and start-up conditions for equipment or machines.
12. The TI model is used to control the optimum data variations for the lifetime reliability condition threshold data of parts and equipment for its failures and determine the operating performance control limits and also transfer data from operation to operation or from point to point within an operation.
13. The TI model can also be used to design a TICS and integrated reliability monitor and can be used to test for optimum selection of maintenance strategies and for detecting system/component potential and functional failures.
14. A TICS can be used to measure reliability growth to select optimum conditions for parts, processes, equipment, and maintenance strategies and measure reliability degradation for detecting the failure conditions of parts and equipment, while integrated reliability monitor is used to monitor and fix potential/functional failures.
15. The application of TICSs and integrated reliability monitor under a single IRCMM program will help to improve reliability, CM, and maintenance and provide the necessary tools to operators and maintenance personnel for maximum achievable reliability at minimum life cycle and maintenance costs.

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4

Role of Technological Inheritance Technique for Condition Monitoring and Maintenance of Industrial Equipment

4.1 Integrated Reliability Condition Monitoring and Maintenance Assessment with the Technological Inheritance Technique

It is indeed quite interesting to note that it is just of recent that manufacturers resolved an aspect of quality control concerning the outcome of a manufactured machine part that is mainly dependent not only on the manufacturing surface finish but also on the manufacturing process conditions and their methods. Researchers have shown that many of the surface quality parameters of machine parts are focused not only on the surface finish operations of a manufacturing process but also on the initial and final operations for sustainable system reliability. The surface quality parameters of a part that are formed early in the process need to be sustained and transferred to the final surface finish and equipment operation, while the developing quality parameters are being transferred from one process to another in such a way that the undesired negative traits are eliminated while the positive characteristics are sustained to achieve maximum reliability. The transference and sustenance of the positive qualities of a component and the elimination of the defects are possible with the technological inheritance (TI) technique.

TI is therefore defined as a technique that transfers component condition parameters (e.g., qualities, defects, degradations, and failure characteristics of an object) from its initial manufacturing operation to the final operation in a technological process, which in turn influences the service operation (industrial equipment or machines) and the lifetime of components/systems. Inheritance is the process by which one object can acquire the properties of another object. This is important because it supports the concept of hierarchical classification. If you think about it, most knowledge is made manageable by hierarchical (i.e., top-down) classifications. Without the use of hierarchies, each object would have to explicitly define all of the characteristics. Using the TI technique, an object need only define those properties that make it unique within its class (e.g., the machine part reliability, quality, defect, and failure mode). It can inherit its general attributes from its parent part and base material. Thus, it is the inheritance mechanism (e.g., reliability inheritance mechanism or distribution) that makes it possible for one object to be a specific instance of a more general case and structure.

A typical example is highlighted from a research work [1] to describe the inheritance mechanism and conditions of an alloy-steel-coated machine part surface. Four groups of the same coated sample were used. The surface finish of these samples after heat treatment produced the following different surface quality condition results:

Group 1 with rough machining: Surface roughness number, R_z = 80 μm

Group 2 with rough machining: Surface roughness number, R_z = 20 μm

Groups 3 and 4 with grinding: Surface roughness number, R_z = 0.32 μm

After undergoing the earlier operations, all the samples went through the same conditions of hardening, with hardness = 61.5–62 HRC, where HRC is Rockwell C Hardness.

The hardened surface samples were finished by grinding that provided the surface roughness number, R_a = 0.16 μm.

A friction test was carried out on the entire specimen with disks of hardness = 63–64 HRC to determine their wear-resistant conditions and coefficients.

The experiment ascertained that most of the specimens were worn out with some cracks and defects in group 1.

In group 2, the quantity of specimen that had cracks and defects was less than that of group 1, while group 4 had no cracks and defects at all.

It is quite interesting to note that with the same surface roughness number of specimens, the physical and service conditions of machine parts were different in quality, which can be explained with the following findings:

- The area with macrosurface roughness of the rough machined part that was finished by grinding experienced a cross-sectional heat up, which eventually led to changes in the structural layer of the machine part. At the lower part of the rough surface, the amount of heat was observed to be lesser than that of the upper part and subsequently the structural layer of the machine part. The upper surface area and the lower part of the rough surface kept alternating when cutting through the cross section of the workpiece. Under this condition, the surface layer of the workpiece became irregular. This of course meant that the structure developed some internal tresses, which led to the formation of crevices, defects, and cracks that eventually caused wear.
- The more the size of surface microroughness, the more the structure of the surface layer became irregular, and also the more the nonuniformity of the surface finish by grinding, and thus more the probability of having micro crevices, defects, and cracks in the parts.

The previous illustration is an example of an indirect inheritance, which is the transfer of the negative surface quality (e.g., large size in surface roughness) from one operation to the other as the transfer of negative qualities of the workpiece sublayer (nonuniform structure), which eventually affects the component/system reliability. There can also be a direct inheritance, when it is a combined operational transfer of the same characteristic trait of quality. An example of such is the geometrical copying of initial errors, defects, and failures that emanate from the shape of the workpiece. If, for example, in an initial manufacturing process (e.g., coating deposition process), the workpiece is oval shape, it means that in the final operation (e.g., grinding), the workpiece would retain the oval traits, even if it is in a lesser degree, which in turn affects the reliability of the system.

In any technological process (e.g., reliability monitoring and maintenance), there is usually more frequent occurrence of the negative inheritance from the initial component/system qualities or the root cause of failure (e.g., errors in shapes, surface roughness, surface wavelength, surface stress). However, it is also possible to inherit positive qualities, which seek to be retained till the finished product in the final process. For example, if after the heat treatment of a workpiece, it produced a very high hardness with a uniform microstructure in the surface layer, it would be necessary to retain and carry forward this sort of quality to the finished product by the final operation, which eventually helps to achieve maximum reliability. With this concept, it will be necessary to select suitable manufacturing processes or design a machining method with heat treatment of hard alloy–coated surface for maximum quality–reliability, since there is no existing suitable productive machining method of a hard alloy–coated workpiece, which is a critical failure event in the reliability monitoring and maintenance process.

At this juncture, it is therefore necessary to select a suitable machining method and the optimum component conditions of a reliability monitoring and maintenance process with the TI technique. The full consideration of both positive and negative inheritance is quite essential for optimum selections toward a robust design of reliability monitoring and maintenance program as well as for reliability assessment of parts, processes, and equipment. The prolonged combination of the different operations in a technological process of a reliability monitoring and maintenance route for wear-resistant applications with the help of the TI technique defines the qualities of a workpiece or part. Some of the qualities can be kept along and sustained to the final operation, while some would be eliminated quite early in the technological process or route. This sequential tendency and ability in the improvement of component quality or reliability depends on many factors. These factors first and foremost depend on the nature of components, methods, and conditions of manufacturing processes and maintenance of machine parts. The technological chain involved in manufacturing processes and maintenance of machine parts acts like a *barrier* [1,2]. In this respect, some of the qualities of a workpiece cannot overcome the barrier and as such would not influence the surface finish operations and the qualities of the workpiece in their final operations. Some of the factors of such *barrier* may allow some qualities to pass through the process but, in some cases, may lose its initial power, which in turn influences the final quality in a very little way. The most significant existing *barrier* is that of heat treatment operations and operations that are associated with plastic deformations.

TI can be followed up in such a way that the desired qualities of parts that can positively influence its service life and reliability are kept during the period of the manufacturing processes so that the negative quality traits are eliminated within the initial operations. In connection with this, therefore, the new methods for calculating and analyzing the interactive operating system; the physical and mechanical properties of a workpiece; the specifications, clearances, and allowances of parts; the selection of maintenance and monitoring techniques; and machining and finishing conditions must take into consideration the action of TI, which aims at maximizing the quality of machine parts, processes, and equipment as well as minimizing its defects, failures, and maintenance cost. One of the most cost-effective methods that provide solution to this problem is the multivariate statistical process control with the TI technique. The determination of optimum technological route and system conditions utilizing the TI technique would help to select optimum materials, deposition techniques, and machining process, part, and service conditions and predict time of failures and reliability coefficients of machine parts, processes, and equipment. The TI model is used in this book to design the experiments for maximum achievable reliability of components and systems and to design measuring instruments of TI coefficients, quality coefficients, and random number determination. It is also used to develop reliability test device/software, reliability monitoring network programs, and design integrated reliability monitors, prognostics, diagnostics, and other tools for integrated reliability monitoring and maintenance of industrial equipment.

4.2 IRCMM Route with the Mathematical TI Model

A mathematical model is a mathematical representation of an object and, in this case, is a function that describes the physical, mechanical, and chemical properties of a hard alloy–coated part and the manufacturing processes for producing hard alloy–coated part and equipment in an integrated reliability condition monitoring and maintenance (IRCMM) route for

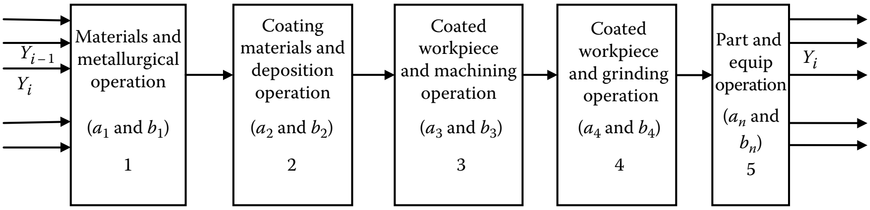

FIGURE 4.1
A typical IRCMM chain for wear- and other competing failure-resistant application with the TI model.

industrial equipment. The series of the operations involved in an IRCMM route of a manufacturing process and equipment that would produce the desired mechanism condition parameters (quality, performance, reliability, and others) is called technological chain [2]. A typical IRCMM chain is shown in Figure 4.1.

4.2.1 Technological Chain for IRCMM of Parts, Manufacturing Processes, and Industrial Equipment with the TI Model

Figure 4.1 shows the technological chain of *n* operations for the IRCMM of critical rotating equipment. The different operations are illustrated as follows:

Operation 1 is the optimum metallurgical material condition of critical parts for equipment with the help of IRCMM.

Operation 2 is the optimum coated material deposition condition of critical parts for equipment with the help of IRCMM.

Operation 3 is the optimum machining condition of the critical parts for equipment with the help of IRCMM.

Operation 4 is the optimum surface finish condition using the grinding method of the critical parts for equipment with the help of IRCMM.

Operation 5 is the optimum surface condition with assembly or installation process with the help of IRCMM.

Operation 6 is the optimum performance condition of the equipment with the help of IRCMM.

Operation 7 is the optimum initial event condition with the help of IRCMM.

Operation 8 is the optimum steady operating event condition with the help of IRCMM.

Operation 9 is the degradation and potential failure condition with the help of IRCMM.

Operation 10 is the functional failure condition with the help of IRCMM.

The following are the critical machine parts or components:

- Rotary shafts
- Bearings
- Bushes
- Sleeves
- Others
- (*k* is the number of critical parts)

The following are the common failures modes:

- Wear
- Corrosion
- High-temperature impact
- Fatigue

The following are industrial equipment:

- Generators
- Pumps
- Compressors
- Motors
- Others

The selected coating material for an experiment is NiCrBSi, while the base material is steel.

A multivariate regression model for quality parameters of a coated surface machine part (Y_i) will be used to determine process and equipment condition characteristics (reliability [R_i], lifetime [L_t], health [H_i], failure modes [F_i]) with the help of the TI model with the following quality parameters, (Y_i):

- Surface roughness (Y_1)
- Hardness (Y_2)
- Stress concentration factor (Y_3)
- Surface wavelength (Y_4)
- Relative speed of kinematic coefficient (Y_5)

TI model (Y_i)

- TI model: $Y_i = aY_{i-1}{}^b$, for part quality

The mathematical model of the initial, Y_{i-1}, and the final, Y_i, part surface quality parameter with TI is given as $Y_i = a \cdot Y_{i-1}^{b}$ [2], where a is the TI coefficient for transferring and monitoring condition parameters (quality, reliability, and health of parts) and b is the TI coefficient for transferring and monitoring the conditions of the processes and equipment conditions. The TI structure of a critical machine part, production process, and equipment is shown in Figure 4.1.

4.2.2 Analysis of the TI Model for IRCMM of Equipment Using the Regression Equation

Figure 4.1 illustrates the technological chain of n operations for the IRCMM of a critical mating part in rotating equipment. The desired characteristics of a hard alloy–coated part surface can be incorporated into an operating process or equipment, which is represented as Y_{i-1}, the initial data of operating process conditions—X_i. The relationship for any operating technological chain is therefore expressed as $Y_{i-1} = X_i$. This is to say that the quality characteristics of the part obtained during the preceding operation are the initial performance characteristics of the operating process. When the quality condition of a part is optimized during a surface finish process and is transferred to the next operation (e.g., equipment, installation/assembly operation), it helps to maximize the service life and reliability of components. That means the maximum part surface quality during the initial service operation is also the maximum reliability of a component without failure. This is possible and can be analyzed with the help of the TI model.

The following is the analysis of the role of the TI technique on the precision characteristics of a technological process, which also applies to the multiple quality parameters of a part surface (e.g., surface roughness, hardness, stress concentration factor, surface wavelength, microstructure, and all other properties, which fall under the quantitative evaluation of component reliabilities).

The analysis of a technological chain is used to assess the relationship between the initial and final errors (potential failure or degradation failures) and qualities of parts, from the different operations of the whole technological system, the degree of influence by each operation on the precision or quality parameters of a finished product, and the optimum requirement of precision and quality parameters on the intermediary operations, and to concretize the structure of the whole system and predict the desired precision, reliability, quality, performance, and other condition parameters when there are changes in any of the operation. The analysis of a technological chain is done throughout all the manufacturing operations, starting with the first initial operation. Typical experimental data of a model were obtained by measuring the samples in 3–4 batches of the rotary shafts before and after any operation as done in book [2]. With this, it is necessary to juxtapose the result in order to make sure that the measurements for all the parts are done under the same conditions. The requirement for the volume of samples and data precision of the measurement is discussed in [2]. The correlation–regression analysis is more effective for multiple operations. That is why the analysis of the experimental data starts with the verification of the observations. When the result of the verification is positive, there would therefore be the need to establish and carry out an initial verification for the character relationship $Y = f(X)$ of an empirical regression function (Figure 4.2). Each point of the correlation field satisfies the individual rotary shaft in each batch that is represented by the coordinates X_i and Y_i, which equal the precision parameters of these parts before and after a particular operation. In order to obtain the coordinate points 1, 2, 3 of the empirical regression line, the whole range of change, X or Y, is divided into 3 … 5 zones and each zone of X^1 and Y^1 is determined to be the coordinates of the said points.

If the empirical regression line is a straight line, it follows that the data of the pair correlation coefficients should be calculated. If the pair coefficient r_{xy} is positively verified, it would be therefore necessary to calculate the equation coefficients:

$$Y = a + bX^1 \tag{4.1}$$

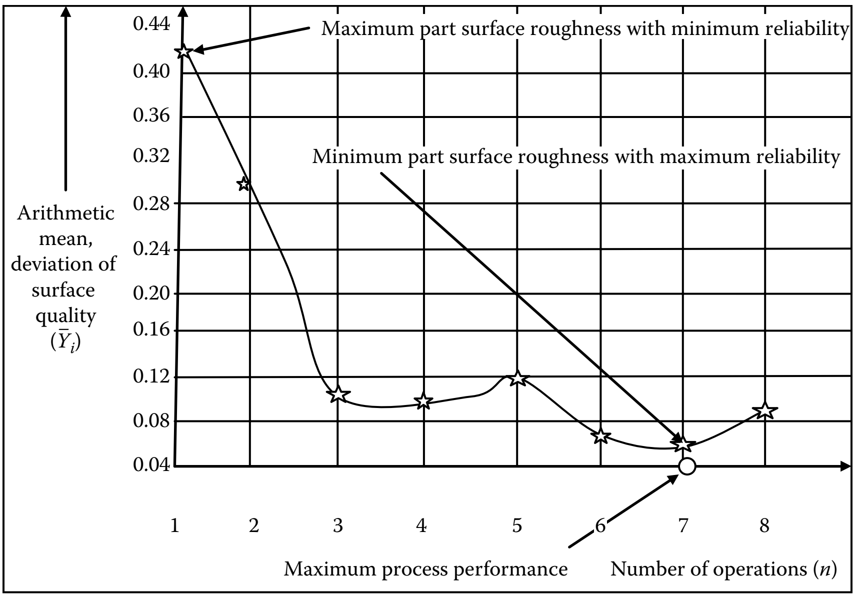

FIGURE 4.2
The arithmetic mean characteristics for the maintenance of piston ring surface quality conditions with manufacturing processes.

where bX^1 is the inheritance error, which is part of the process error from the initial operation (or the workpiece surface error) that is being transferred into the finished part surface, by the process operation, and a is the process error of any particular operation, which depends on the conditions of any particular operating process, which does not depend on the initial error.

The methods of calculating the equation coefficients of Equation 4.1 and their verification as well as the determination of the validation of the regression equation are all shown in books [1,2]. If the pair coefficients r_{xy} have been verified, it means that the empirical correlation ratio (ηe) can be calculated and then validated. If the value of ηe is insignificant, it means that between X and Y, no mutual relationships exist and such an operation is therefore a *barrier* on the system route for precision or the quality parameters under study.

In the case where the value of ηe is significant, there is therefore the need to choose the curve that best describes the study function, $Y = f(X)$. For the chosen curve relationship, it follows that the theoretical correlation ratio (ηt) should be calculated and substituted for ηe. If the difference between their values is insignificant, it means that the chosen curve has adequately described the study process and part. The calculation and verification methods for validation are shown in these works [1]. The final conclusion about the application of any of the regression equation for describing the study process can only be done after its validation with the help of Fisher's criteria.

Researches have shown that the process of multioperational changes for the quality control of a machine part is, in many cases, of linear characteristic functions [1]. The regression analysis can therefore form the basis of a technological chain for IRCMM of rotating equipment in this book and will be looked at from the viewpoint of the linear characteristic relationship, $Y = f(X)$, as in Equation 4.1. Analyzing the inheritance error bX^1, it is possible to ascertain some important remarks in any functional technological process [2]. If $b = 0$, the initial error is fully corrected, while the precision characteristics of the proceeding operation is determined only by the process error a of the operating process. When $b = 1$, the initial error can never be corrected. More than that, there is an added processing error by the operating process, due to the fact that the precision value or quality characteristic is lower than that of the preceding operation.

When $0 < b < 1$, the initial error is partly corrected. The lesser the value of b, the lesser the inheritance error, bX^1, and the more the corrective action of the operating process. Under this condition, the process error a must be such that it satisfies the condition of $a < (1 - b)X^1$, where X^1 is the arithmetic mean value of the initial error. In this case, the precision of the method or the quality characteristics of the processing operation will be higher than that of the preceding (initial) operation. If $b > 1$, the error is transferred with force (inheritance error is more than the initial error). Such a situation is possible, for example, when thermal treatment is carried out (e.g., accelerated life test of materials). In the case of $b < 0$, it satisfies a superficial correction of the errors from the preceding operation. In practice, the probability of such a case is very low. Coefficient b in Equation 4.1 is known as the transfer coefficient, while the value is the correction coefficient (e.g., integrated reliability condition maintenance). The process error of an operating process for a particular condition in a functional technological process remains relatively constant, and subsequently, it can be transferred into systematic errors (integrated reliability condition monitoring [CM]).

In order to increase the precision of methods or the quality characteristics, it is necessary to tend toward the reduction of a with the help of a corrective level of proper settings of the process. In this case, error a is a defect of the technological process, and to reduce it, the operations would need to be developed. This can be done with the TI coefficient for component quality control (1) and also for process performance control (2). Further development is done when component quality conditions can be incorporated or integrated into process conditions, which of course is possible with the TI model, $Y_i = a \cdot Y_{i-1}{}^b$ [2].

The characteristic function of Equation 4.1 simulates the TI role of developing process and component errors/failures from an operating process condition in relationship with the preceding operation. That is the reason why the TI model for any operating process is justified, since it is capable of keeping the conditions from carrying out a particular operating process (irrespective of the selection of the process performance conditions [X_i] by a precision method that has been obtained from the preceding operation). Such is never said about the coefficient of accuracy, $\varepsilon = \bar{X}/\bar{Y}$, the value that does not remain constant for any particular proceeding operation but depends on the selection of the initial values of the process error. When there is a linear correlation between the initial and final errors, the dispersion of the final method that caused the error is [2]

$$S_y^2 = b^2 S_x^2 + S_{yx}^2 \tag{4.2}$$

where

S_y^2, S_x^2 are the dispersion of the final and initial errors, respectively
S_{yx}^2 is the dispersion of the method error on a particular operating process

The first part of Equation 4.2 is S_y^2, which is transferred from the preceding operation. Let $A = S_{yx}^2 / S_y^2$, which characterizes S_y^2 that arises from a particular operating process, while $B = b^2 S_x^2 / S_y^2$, that which is transferred from the preceding operation. Substitute the expressions into Equation 4.2 the values of coefficient $b = r_{xy} \cdot S_y / S_x$ and multiply it with a converter to obtain [2]

$$S_{yx}^2 = S_y^2 \left(1 - r_{xy}^2\right) \tag{4.3}$$

Equation 4.2 serves mainly for the determination of a combined tolerance on the precision parameters of parts, worked upon in the preceding operations, when the tolerance of the same parts' parameter or condition is being worked upon by a particular operating process. If the dispersion of the method that causes the error satisfies the law of normal distribution [2], it satisfies the precision coefficient $K_t = (i)/\delta$ [2], where K_t is the precision coefficient, (i) is the parameter control limit field, and δ is the parameter control tolerance [2]:

$$\omega_x = 2lS_x = \delta_x, \quad \omega_y = 2lS_y = \delta_y \tag{4.4}$$

Substitute the values of S_x and S_y obtained from Equation 4.4 in Equation 4.2 and multiply it with a converter to obtain [2]

$$\delta_x = \sqrt{\delta y^2 - 4l^2 S^2 yx / b} \tag{4.5}$$

where l is a coefficient that is chosen from [2], which depends on the volume of the specimens or the number of operations in the technological chain. If the results of the technological chain consist of n operations, which are obtained by n models with initial and final errors, the mean value of the component quality $(\overline{Y_n})$ for the nth operation can be determined by the following formula [2]:

$$\overline{y_n} = \left[\prod_{i=1}^{n} b_i\right]\overline{x_1} + \left[\prod_{i=2}^{n} b_i\right]a_1 + \left[\prod_{i=3}^{n} b_i\right]a_2 + \cdots + a_n, \tag{4.6}$$

where $\overline{x_1}$ is the arithmetic mean of the initial process error on the first operation. The arithmetic mean data of the component and process errors are assessed and evaluated with the help of the TI coefficient for process performance control b and the TI coefficient for component quality control a. The optimum component quality condition, $Y_{i-1(\text{opt})}$, obtained by a multivariate regression model serves as input data during service operations. Regression analysis therefore provides the foundation for IRCMM of critical rotating equipment with the TI model. After obtaining the optimum component quality and process performance condition data, they are used as input data for implementing the TI model, which is capable of assessing direct, indirect, and combined inheritance errors [2]:

$$Y_i = a \cdot Y_{i-1}^{\ b} \tag{4.7}$$

In the case of wear resistance and other competing failure-resistant applications, a part surface multivariate regression model is developed to determine the optimum critical part surface quality parameters (Y_i), and this is fed into the TI model of Equation 4.7 to determine component and process errors and failures during operations. The TI model plays the following major roles:

- Integrating component quality (Y_i) into the operating process performance (X_i) as the optimum initial data, with the capacity to determine the quality, performance, and reliability control limits and precisions.
- Monitoring of component quality and process performance growth and degradation as well as controlling their limits and setting optimum threshold points for quality, failure, and costs.
- Proactive and predictive maintenance through the reduction of component and process stresses throughout the life cycle by using CM with TI coefficients to monitor the stress from rough operation induced by poor operating practices and bringing the likely implications on manufacturing processes to the attention of operations and plant managers.
- Improvement of system reliability by ensuring that each component and part is highly reliable, since an assembly of parts or component can never be more reliable than its least reliable part or component.
- System and component reliability test is done throughout the life cycle to meet set requirements.
- Measurement of reliability growth, degradation, and failure rates of components, parts, and equipment.
- Stoppage of the risk of excessive stress, high reliability degradation and equipment failures.
- Determination of life cycle and maintenance costs of components and systems.
- Component quality and process performance control through direct, indirect, and combined inheritance.

4.3 Determination of Component Quality and Failure Mode Condition Characteristics with the TI Model

An existing typical analysis of a technological chain for monitoring and maintaining a particular critical machine part comprising of *n* operations between its initial and final quality, failure modes, and process condition characteristics would be highlighted in this section. The existing initial and final characteristics of a critical machine part are highlighted as shown in Figure 4.1. With the help of this figure, the trend of characteristics can be analyzed in all the processes for the manufacturing, monitoring, and maintaining routes. With the application of the TI technique, it will be possible to select the most appropriate parameters, processes, parts, equipment, and instruments throughout the different stages of production and maintenance. The TI model can be used to analyze, assess, and evaluate maximum and minimum achievable quality, reliability, and performance of parts, processes, equipment, instruments, and the technological system as shown in Figure 4.4.

The existing analysis of a technological chain for a particular critical piston ring comprising of n operations or data events within an operation (d) between its initial and final quality, failure modes, and process conditions is highlighted with the following problems and solutions:

Problem 4.1 [2]. There is the need to fix a tolerance (δx) on a defected workpiece of a piston ring, if the tolerance on the workpiece from the finished piston ring is known, δy = 50 mkm. Given the measurements for 100 piston rings before and after processing, the following relationship between the initial and final failure mode was established:

$$\bar{y} = 0.21\bar{x} + 25; \quad S_y = 7 \text{ mkm}; \quad r_{xy} = 0.454$$

Using Equation 4.3, the dispersion of method errors can be determined:

$$S_{yx}^2 = 7^2(1 - 0.454^2) = 38.9 \text{ mkm}^2$$

From the book [2], n = 100, l = 3.6; the tolerance on the workpiece is determined as follows:

$$\delta x = \sqrt{50^2 - 4 \times 3.6^2 \times 38.9 / 0.21} = 104 \text{ mkm}$$

If in the results of analyzing the technological chain comprising of n operations, n equations between initial and final failure modes are obtained, the arithmetic mean values of Y_n for nth operations are determined.

Problem 4.2 [2]. The technological process for producing a piston ring and the control of the piston ring defects. The technological chain consists of seven operations. The results of the experiment are shown in Table 4.1. The characteristics of the workpiece defect are as follows:

$$\overline{x_3} = 0.28 \text{ mm}, \quad S_3 = 0.122 \text{ mm}$$

The graph of the changes in arithmetic mean values is shown in Figure 4.2, while the graph of the changes in the geometric mean deviation of piston ring defect along the route of a technological process (zero on the Z-axis satisfies the characteristics of a ring workpiece) is shown in Figure 4.3.

TABLE 4.1

Existing Typical Analysis of the Performance CM and Maintenance Process Operations with the Surface Quality Characteristics of a Piston Ring

Operations	Equations	r_{xy}	S_y	$\overline{Y}$
Operation 1	$\overline{Y_{x1}} = 0.615\overline{X_1} + 0.037$	0.874	0.106	0.209
Operation 2	$\overline{Y_{x2}} = 0.38\overline{X_2} + 0.024$	0.608	0.048	0.105
Operation 3	$\overline{Y_{x3}} = 0.45\overline{X_3} + 0.044$	0.674	0.53	0.091
Operation 4	$\overline{Y_{x4}} = 0.82\overline{X_4} + 0.014$	0.869	0.047	0.089
Operation 5	$\overline{Y_{x5}} = 0.365\overline{X_5} + 0.043$	0.684	0.043	0.075
Operation 6	$\overline{Y_{x6}} = 0.280\overline{X_6} + 0.054$	0.584	0.038	0.075
Operation 7	$\overline{Y_{x7}} = 0.525\overline{X_7} + 0.042$	0.554	0.036	0.081

Source: Kane, M.M., *Fundamentals of Scientific Researches in Manufacturing Industries*, Minsk, Belarus, 1987, 232p.

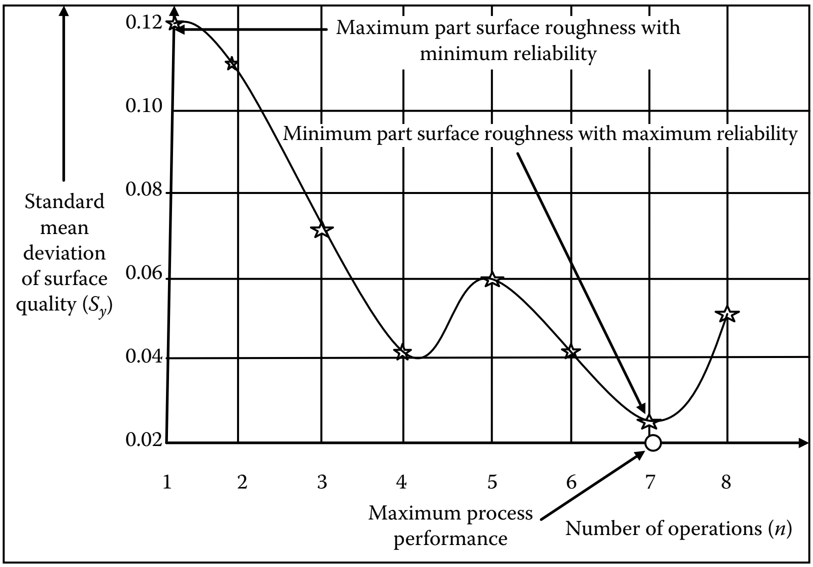

FIGURE 4.3
The standard mean characteristics for the maintenance of piston ring surface quality conditions with manufacturing processes.

The analysis of the data in Table 4.1 and the graphs shown in Figures 4.2 and 4.3 provide the following conclusions:

1. Piston ring warping developed from a foundry operation is observed to be reducing along the route of a technological process. The insignificant increase in warping on the seventh operation is explained

by the reduction of the piston ring rigidity as a result of the sharpening of the torsion bar groove. An increase in the characteristics of a scattered warping in the third operation is explained by the vibration and heat fields that led to the occurrence of the residual stresses in the workpiece.

2. In each operation of the technological chain, the warping of the piston ring is reduced due to the improvement in their geometric forms, but at the same time it also increases because of the residual stress. The free member in the regression equation is used to determine the increase in warping.
3. The grinding operation provides a significant corrective capability. But in connection with this particular operation, there was a remarkable method error ($a = 0.044$ mm) that occurred, although the general reduction of warping after this particular operation is insignificant.

As a result of this analysis, it is therefore necessary to recommend that higher attention should be given to the grinding (finishing) operation. This analysis helps explain the reasons for the occurrence of the inherent failures in equipment and the need to find the means of reducing these potential failures. The TI model is therefore applied to solve these problems and provide long-lasting solutions for a sustainable development in reliability, CM, and maintenance. It is also used to select the most appropriate parameters and determine the most cost-effective processes and equipment for the attainment of most achievable quality, reliability, and performance of a component or system. The technological model is used to determine part degradation and failures since it is the relationship of initial and final operations.

The relationship between workpiece degradation and the finished piston ring characteristics that correspond with Equation 4.8 is expressed as

$$
\begin{aligned}
Y_7 = {} & (0.615 \times 0.387 \times 0.45 \times 0.82 \times 0.365 \times 0.28 \times 0.525) Z_3 \\
& + (0.387 \times 0.45 \times 0.82 \times 0.365 \times 0.28 \times 0.526) 0.037 \\
& + (0.45 \times 0.82 \times 0.365 \times 0.525) 0.024 + (0.82 \times 0.365 \times 28 \times 0.525) 0.44 \\
& + (0.365 \times 0.28 \times 0.525) 0.014 + (0.365 \times 0.28 \times 0.525) 0.014 + (0.28 \times 0.525) 0.043 \\
& + 0.525 \times 0.054 + 0.042 + = 0.0047 Z_3 + 0.08
\end{aligned}
\tag{4.8}
$$

Analyzing the obtained equation, it is possible to make the conclusion that the study of technological chain for the monitoring and maintenance of parts, processes, and equipment exhibit a huge corrective, predictive, and proactive capability. The failures on the finished piston rings therefore arise mainly from the process errors of each operation in the technological chain (cooperative inheritance). It also possesses an improvement capacity (direct inheritance) and failure condition detection (indirect inheritance).

Since the challenge of technologists is to establish the reasons of these problems and failures and find the means of reducing the problems and failures before they can cause catastrophic damages.

Applying Equation 4.8, it is possible to determine the optimum number of passes n in a particular operation to obtain definite precision, quality, reliability, and performance characteristics on the finished parts or components [2]. In connection with these passes for the same conditions, coefficients b and a in the regression equation remain constants for different passes.

In this case, Equation 4.8 will be $Y_n = b_n Z_1 + b_n{-}1a + b_n{-}2a + \cdots + a$.

After a series of passes,

$$n = \frac{1g(Y_n - a) - 1g[Z_1 - a/(1-b)]}{1gb} \tag{4.9}$$

From Formula (4.7), it follows that in a particular operation, the workpiece error is corrected in one or many passes only in the conditions

$$Z_1 - Y_n > ab/(1-b) \tag{4.10}$$

Therefore, a particular condition parameter is used for the integrated reliability maintenance monitoring analysis of components and systems.

Problem 4.3 [2]. A batch of shafts was processed on a machine tool. The precision after processing was $Y = 0.05$ mm. The mean error of the blank is $Z = 0.25$ mm. The previous researches established that the initial and final errors for carrying out each pass are related with the equation $Y_z = 0.6Z + 0.02$. It is therefore necessary to determine the number of passes for obtaining the specified precision method.

Checking the condition with Equation 14.8, $0.25 - 0.05 > 0.2 \times 0.6/(1 - 0.6)$. That is, $0.2 > 0.03$.

To determine the number of passes, "n", where, n is expressed as: $n = \{1g(0.05 - 0.02) - 1g[0.25 - 0.02/(1 - 0.6)]/1g \times 6 =$ Regression equation (4.8) is obtained from the different researches of one and the same operation, usually differentiate it from each other. The significance verification of this discrepancy is carried out by the method described in the works of [2].

When designing a multiple parameter method for a machine part, process, and equipment, it can be seen as a structural system with its main cell being called operation. The common structure of the technological process is represented as complex multiple systems that start with different characteristics of machine part condition parameters (Y_{10}, Y_{20}, …, Y_{m0}) and subsequently end with a set of the same parameters in a final operation (Y_{1p}, Y_{2p}, …, Y_{mp}).

These changes are determined by the action of a set of technological factors (t_{11}, t_{21}, …, t_{n1}) for each operation (L_i) in the technological process (e.g., manufacturing process, part, and equipment operations) where m is the number of the component quality parameters, p is the number of operations in the technological process, and n is the number of technological process factors.

For the description of the relationship between quality parameters of a component within its neighboring operations, it would be necessary to use different kinds of functions like polynomial, degree of an equation, and parabola.

The parameters of this relationship can be expressed through technological process factors, which act on the different operations, and also with the help of different types of equations.

A set of relationship between the final and initial component condition parameters with the help of TI coefficients and process factors on all stages of operations forms the multiple mathematical model of a technological process. This is used to design the TI models for integrated reliability maintenance monitoring of machine parts, production processes, and equipment. These multivariate mathematical models are used to assess the TI mechanism of a critical part, production process, and equipment and compare it with the existing ones.

4.4 Multiple Mathematical Modeling for IRCMM of Parts, Manufacturing Processes, and Industrial Equipment with the TI Technique

The general multiple mathematical model for any component part condition parameters (e.g., reliability, durability, resistance to failures) can be expressed as [2]

$$\begin{gathered}\left\{Y_{1p}=a_1(t_{11},t_{12},\ldots,t_{1n},t_{21},t_{22},\ldots,t_{2n},\ldots,t_{l1},t_{l2},\ldots,t_{ln},\ldots,t_{p1},t_{p2},\ldots,t_{pn},Y_{10});\right\}\\ \left\{Y_{2p}=a_2(t_{11},t_{12},\ldots,t_{1n},t_{21},t_{22},\ldots,t_{2n},\ldots,t_{l1},t_{l2},\ldots,t_{ln},\ldots,t_{p1},t_{p2},\ldots,t_{pn},Y_{20});\right\}\\ \left\{Y_{mp}=a_m(t_{11},t_{12},\ldots,t_{1n},t_{21},t_{22},\ldots,t_{2n},\ldots,t_{l1},t_{l2},\ldots,t_{ln},\ldots,t_{p1},t_{p2},\ldots,t_{pn},Y_{m0})\right\}\end{gathered} \tag{4.11}$$

When a set of technological factors (t_{11}, t_{21}, …, t_{n1}) for each operation (L_i) in the production and service processes is optimized, each operation will function at the same level. If the level is scaled between the maximum value "+1" and the minimum value "0".

When the system operates at optimum level, the previous model can be expressed as

$$Y_{mi} = a_{im} \cdot Y_{mi-1} \tag{4.12}$$

where

Y_{mi} is the final component condition parameters in an operating system/process

Y_{mi-1} is the initial component condition parameters from the previous system/process

a_{im} is the TI coefficient for component condition control

This simplified model can be used to define the roles of the TI technique in an integrated reliability maintenance monitoring of components and equipment.

4.5 Determination of Component Reliability Degradation and Maintenance with the TI Model

In real time, component condition degradation is essentially an integrated fraction of reliability or the power running though the system whose coefficient depends on material geometric and load factors such as stress concentration and surface treatment—represented as component condition parameters (Y_i) and service condition parameters (X_i). These multiple parameters can be integrated with a single metric known as TI coefficients, used to control, monitor, and maintain defects/failures caused by degradation. The TI coefficients are therefore used to determine and predict system/equipment reliability degradation and power degradation, detect defects/failures, and select the materials, tools, and conditions of operations. Consider an example of system/equipment operations with M possible failure modes (e.g., wear, corrosion, temperature). This implies that $M = f(m_1, m_2, m_3)$, and for each failure mode (m_i), it will be presumed that there is a corresponding surface degradation value, $Y_i(m)$, that captures the reliability degradation of that operation from minimum to maximum reliability in a particular failure mode (F_w) caused by wear (m_1), corrosion (F_c), and high temperature (F_t). In the case of wear backlash, m could represent the operation of a motor, generator, pump, compressor, and other rotating equipment over a certain function, and $Y_i(F_w)$ would then be the amount of wear according to Equation 4.1 for that function. It is assumed that the future failure modes, F_t, at time t, are selected randomly and independently from the fixed probability distribution $Y_i(F_t)$. Thus, a posteriori usage history of the platform can be written as $\{F_t\}$ $Nt = 0$. Further, it is assumed that there is a linear damage accrual rule, so that the total degradation, $Y(\mathrm{N})$, after N usage intervals is

$$Y(\mathrm{N}) = \sum_{t=1}^{N} Y(F_i) \tag{4.13}$$

Given the failure threshold point, $Y_{i\mathrm{thresh}}$, for a given surface quality of a critical part, the failure time or degradation time, is defined as the $\mathrm{N_f}$ or $\mathrm{d_t}$ as the point at which $Y(\mathrm{N})$ $Y_{i\mathrm{thresh}}$. When making a prediction, it will not be difficult to predict the future usage history of the platform, which can be written as $\{F_t\}$ $Nt = 0$. Further, it is assumed that there is a linear damage accrual rule, so that the total degradation, $Y(\mathrm{N})$, after N usage interval is expressed as:

$$Y(\mathrm{N}) = R_{\mathrm{ki}} = \int_{i}^{N} (Y_i F_{\mathrm{t}})dt \tag{4.14}$$

Given the failure threshold, $Y_{i\mathrm{thresh}}$, for a given component. The failure time is defined as the $\mathrm{N_f}$ or $\mathrm{d_t}$ as the point at which $Y(\mathrm{N})$ $Y_{i\mathrm{thresh}}$. When making a prediction, it will not be difficult to predict the future usage failure modes of the platform because of the help of TI coefficients used to determine the values of surface quality degradation threshold point, ($\mathrm{Y_{dthresh}}$), and component reliability, (R_{ki}). This leads to the certainty of future degradation and the times of its occurrences, which we account for using probability and reliability theories. In terms of component quality parameters (Y_i), with TI coefficient, "a_{id}" component reliability coefficient, R_{ki} is expressed as:

$$R_{\mathrm{ki}} = \int_{ta_{\min}}^{ta_{\max}} (a_i F) da_{\mathrm{it}} \tag{4.15}$$

Equation 4.15 can be expressed in terms of the component surface quality degradation factor, (Q_{id}) as:

$$R_{\mathrm{ki}} = \int_{t\min}^{t\max} (Q_{\mathrm{id}})dt \tag{4.16}$$

Finally, if we are interested in a specific statistics (e.g., 98% confidence time at minimum computational cost), the TI technique can be applied to any n or t for optimum computational life cycle cost that takes into consideration the manufacturing process conditions and the reliability growth coefficient, (R_{kg}) reliability degradation coefficient, (R_{kd}) and integrated reliability (R_{in}) of components.

4.6 Determination of Component Reliability Growth and Maintenance with the TI Technique

During manufacturing processes, the reliability of a component part continues to increase from the initial to the final operation with the finishing processes. When finishing parts with hardened surfaces, productivity becomes low, and finding the right method to produce the desired maximum achievable reliability of components for certain applications is difficult. Traditionally, the use of suboptimum finishing conditions and manufacturing processes becomes the only option, which of course could induce early failure during service. With the help of the TI model, component condition growth can be monitored and measured so that early problems and potential failures can be detected and eliminated in order to achieve the maximum reliability growth coefficient in terms of time:

$$R_{kg(t)} = \int_{t\min}^{t\max} (Q_g)dt \tag{4.17}$$

Reliability degradation coefficient in terms of time, $R_{kd(t)}$ is expressed as

$$R_{kd(t)} = \int_{t\min}^{t\max} (Q_d)dt \tag{4.18}$$

During manufacturing processes, real-time data of TI coefficients "a_i" and "b_i" can be measured and collected by a data acquisition device or a TI coefficient sensor (TICS), which is used to determine the component quality factor, reliability growth coefficient, (R_{kg}) reliability degradation coefficient, (R_{kd}) and integrated reliability, (R_{in}) of components in terms time and TI coefficients. Integrated reliability monitoring and maintenance of manufacturing processes, parts, and equipment with the TI model can lead to maximum achievable reliability and minimum acceptable failure and minimum life cycle costs as shown in Figure 4.4.

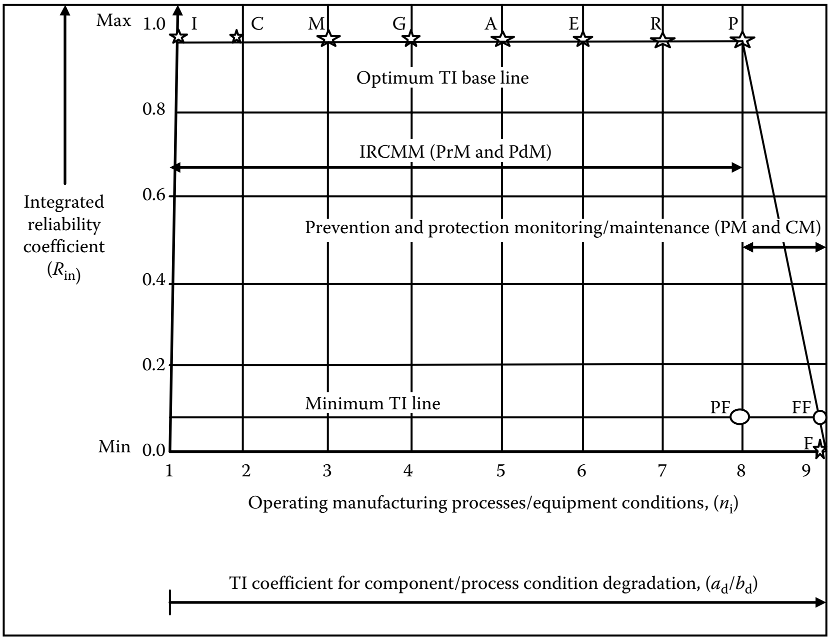

FIGURE 4.4
IRCMM of manufacturing processes and equipment with TI model–based program.

4.7 Benefits of the Role of the TI Technique in IRCMM of Manufacturing Processes, Parts, and Industrial Equipment

1. Thermal treatment of hard coating materials during manufacturing operation can be used to carry out accelerated life test for wear- and other competing failure-resistant applications with the TI technique.
2. The TI technique can be used to monitor the quality and failures of hard alloy–coated materials, maintain and control the variations, and model the multiple surface quality conditions of a critical hard alloy–coated part.
3. Model the multiple surface quality conditions of a critical hard alloy–coated part with optimum machining process conditions for wear- and other competing failure-resistant applications in order to determine maximum achievable reliability of components and systems and predict the type, time, rate, and condition of failures.

4. An achievable optimum multiple quality condition of a critical hard alloy–coated part can serve as the baseline reliability requirements for the design of a group of identical parts and materials of the same generic component, manufacturing process, and equipment with the help of the TI technique.
5. The TI technique determines the optimum process performance condition of the surface finish for producing hard alloy–coated part for wear- and other competing failure-resistant applications to serve as the baseline requirements for all the preceding manufacturing processes as well as the proceeding operations of monitoring and maintenance of equipment.
6. The component multiple quality and process condition parameters can be determined with a multivariate regression model that is used to predict the quality factor of the component, the effectiveness factor of the process, the performance index of the system, the reliability of components/systems, and the reliability growth, while the TI model uses the results of the regression model as the initial data to determine degradations and the time, type, and conditions of failures of parts, processes, and equipment.
7. The TI model is used to integrate the multiple hard alloy–coated part surface quality parameters, multiple failure modes, multiple manufacturing processes, and multiple service condition parameters and integrate reliability, monitoring, and maintenance.
8. The TI technique offers the possibility of monitoring friction degradation failure and preventing it and eliminating the failure mode as well as predicting the time of failure and detecting the cause of both potential and functional failures.
9. The optimization of component quality and process performance with the TI model can be used for optimum selection of part, process, equipment, monitoring, and maintenance strategies before purchase at minimum costs.
10. Integrating reliability, CM, and maintenance under a single program as well as integrating the different parameters with a single TI coefficient helps automate and enhance the robust design of the IRCMM program.
11. Design of reliability coefficient measuring instruments, data acquisition device, monitors, diagnostics, and prognostic tools with the TI model will help to provide standard cost-effective tools and software for the IRCMM program.
12. The TI model is useful in designing software programs for suitable selection, measurement, monitoring, maintenance, testing, analysis, and management.

13. Design of a cost-effective management program for integrated reliability monitoring and maintenance of parts, manufacturing processes, and industrial equipment with the TI model will lead to a sustainable development in the industries of the future.

4.8 Conclusion

1. Researchers have shown that many of the quality parameters of parts and equipment are formed not only during the final surface finish operations of a manufacturing process but also during its initial operations toward maximum achievable component and system reliability, which can be assessed with the TI technique.
2. The TI technique is used to determine the properties of a component condition (e.g., hard alloy–coated part surface quality, process performance, defects, failures) that make it unique within its class to achieve maximum part reliability and process performance from initial to final operation in a technological manufacturing system.
3. In any manufacturing, monitoring, and maintenance process, there is usually more frequent occurrence of the negative inheritance from the initial qualities of a workpiece operation (e.g., errors in shapes, surface roughness, surface stress, etc.), and it is also possible to inherit positive qualities (e.g., surface hardness, strength), which is transferred to the final manufacturing operation and in turn sustained over a long time during equipment or service operations.
4. The optimum selection of part, manufacturing process, and equipment condition parameters with the TI technique can definitely help maximize component/system reliability, process performance, and service lifetime and help minimize the failures and maintenance costs.
5. The TI technique is followed up in such a way that the desired quality of parts that positively influences its service life, system/component reliability, and process performance is kept during the period of development, so that the negative defect and failure traits are eliminated early in the initial operations as well as throughout the service operations.
6. A multivariate quality regression model of hard alloy–coated part surface provides the initial optimum component quality data for the TI model to develop the IRCMM program for manufacturing processes and industrial equipment as well as for its real-time testing and control of component/system reliability during operations.

7. The technological chain series of an IRCMM program consists of a series of manufacturing processes and service equipment operations that can produce the desired part surface quality/reliability and process performance condition parameters.
8. The technological chain condition is optimized during the manufacturing surface finish process, and the optimized condition is transferred to the next equipment operation, where the optimum service lifetime and reliability of components are sustained for an optimized IRCMM period of time by a cost-effective maintenance strategy with the help of the TI technique.
9. A multivariate quality regression model provides the foundation for integrated reliability monitoring and maintenance program for critical rotating equipment as well as for the optimization process and the use of the initial optimum data for implementing the TI model for real-time operation and assessments.
10. The application of the TI model helps select the most appropriate required hard alloy–coated mating part surface quality parameters and process performance factors during the design stages and select optimum materials, manufacturing processes, parts, equipment, and instruments throughout the different stages of operations.
11. The TI model is used to integrate the multiple quality parameters, processes, and practices with a single metric under one platform toward maximum achievable quality, reliability, and lifetime of parts, processes, equipment, and instruments of a technological system.
12. The TI model is used to test the degradation rate of the quality of parts and the process performance degradation rate as well as the failures of parts, equipment, and instruments in a technological system.
13. The results of the test are used to determine the reliability of parts, equipment, and instruments, their remaining lifetime, and the process performance, detect failures, identify the failed parts and the failure modes, and plan and schedule maintenance works.
14. The multivariate quality regression model of a hard-coated part is used to predict the optimum quality parameters and the conditions for wear, predict the failure modes of a hard-coated part and other failure-resistant applications, and select the desired parameters, parts, processes, and practices.
15. The results are used to develop wear-, corrosion-, and temperature-failure-resistant mechanisms and also integrated reliability mechanisms.

16. The component/system quality degradation rate and the performance change rate correspond with the monitoring period, which can be assessed and calibrated with the help of the TI coefficients and measured by TICSs and monitored with an integrated reliability monitor.
17. The hard-coated quality and reliability growth/degradation rate, which is directly proportional to the rate of change of process performance parameters, can be incorporated into process conditions to serve as the input data during service operations with the help of the TI model.
18. The TICS and integrated reliability monitor are used to assess, control, and evaluate component/system reliability degradation with an initiation time and failure growth time toward maximum achievable lifetime reliability and maintenance cost that meets the desired component/system reliability requirements.
19. The knowledge of the roles of the TI technique has helped to obtain full benefits of IRCMM of manufacturing processes, parts, and industrial equipment.

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5

Maximum Achievable Reliability Design for Critical Parts of Equipment with Technological Inheritance Model

5.1 Robust Design of Hard Alloy–Coated Part Surface for Wear-, Corrosion-, and Temperature-Resistant Applications

A robust hard-coated part surface is one that works as intended with full consideration of variation in the part's manufacturing process, variation resulting from deterioration, and variation during real-time operations. The robust design of a hard alloy–coated part surface for maximum reliability is achievable through understanding which part and process design parameters are critical to the achievement of a performance characteristic and what the optimum values are to achieve the maximum reliability and quality characteristics that minimize failures and life cycle costs. When the operation of the part quality parameters and process performance condition characteristics can be mathematically related to part and process design parameters, the optimum part surface quality and the process performance parameters can then be determined with a regression model and a technological inheritance (TI) model. Since the hard alloy–coated materials, coated part, and process performance relationships are unknown, there is therefore the need for the design of experiments, which will help to develop a multivariate regression model that can aid in determining the part optimum quality and process performance conditions, which of course can be used to determine the optimum reliability and wear resistance coefficients of hard alloy–coated critical part surfaces, machine tools, and industrial equipment, thereby developing a more robust design.

5.2 Design of Experiments for Maximum Achievable Lifetime Reliability of Hard Alloy–Coated Critical Part Surface Conditions

Design of experiments is based on the objective of desensitizing the hard alloy–coated part quality surface, reliability characteristic, and process performance conditions to variations in critical cylindrical part surface and process design parameters. Genichi Taguchi developed the concept of *loss to society*. In this concept, variability in critical design parameters will increase the loss to society, which is an expanded view of the traditional, internally oriented cost of quality. This is a quadratic relationship of increasing costs (loss to society) as these critical design parameter values vary from the desired mean value of the parameter. To consider quality and reliability implications during design, the design process can be segmented into three stages. The first stage, system design, establishes the functionality of the product, the physical product envelope, and general specifications. The second stage, parameter design, establishes specific values for design parameters related to physical and functional specifications. It is during these first two stages that the designer has the greatest opportunity to reduce product costs through effective functional design and parameter specification. The third stage, tolerance design, establishes the acceptable tolerances around each parameter or target. The third stage typically will add costs to the product through efforts to ensure compliance with the tolerances associated with product parameters.

Since an organization cannot cost-effectively inspect quality into the product, it must focus on minimizing variability in the part through part and equipment design. The part needs to be designed so that they are robust—their reliability is insensitive to this naturally occurring, difficult to control variation. Design of experiment techniques provide an approach to efficiently design industrial experiments, which will improve the understanding of the relationship between part and equipment condition parameters. This efficient design of experiments is based on a fractional factorial experiment, which allows an experiment to be conducted with only a fraction of all the possible experimental combinations of parameter values. Orthogonal arrays are used to aid in the design of an experiment. The orthogonal array will specify the test cases to conduct the experiment.

The approach to designing and conducting an experiment for determining the effect of part, process, and equipment system reliability parameters on the different operations from the initial stage to the final stage of a maintenance route is represented later in the text. The experimental results can be summarized into a metric called the integrated reliability signal that jointly considers how effectively the mean value (signal) of the reliability and quality parameters has been achieved and the amount of variability (reliability growth, degradation, defects, and failures) that has been experienced. As a result, a designer can identify the parameters that will have the greatest effect on the achievement of a component and system maximum reliability characteristic. The design parameters are identified in an inner array or design factor matrix, which specifies the factor level, or design parameter test cases. The experimental setup allows the identification of the design parameter values or factor levels that will produce the best performing, most reliable, or most satisfactory component over the expected range of factors. With the resulting understanding from the experiments and subsequent analysis, the designer can identify parameter values that maximize achievement of component and system reliabilities and minimize the effect of failures, defects, and errors thereby achieving a more robust design; identify parameters that have no significant effect on reliability (in these cases, tolerances can be relaxed and cost reduced); and identify parameter values, which reduce cost without affecting reliability or variation. These steps take initial effort but can reduce cost and improve the reliability of the manufacturing processes and industrial equipment. Design of experiment techniques offer a framework for developing a more rigorous understanding of the relationship of process and equipment reliabilities from the initial to the final operation in a technological maintenance route, thereby leading to improved design decisions. This model-based design presents a comprehensive approach to experimental design, analysis, process, and design decision-making through a mathematical planning technique and modeling.

5.3 Planning the Design of Experiment for Maximum Achievable Quality–Reliability Chain of Critical Parts, Manufacturing Processes, and Industrial Equipment with the Multivariate Regression Model

The objective of this design is to achieve a maximum level of hard alloy–coated part surface reliability and quality that is compatible with the manufacturing, operation, and maintenance of requirements. It has to be demonstrated that the availability of the safety systems assembled in equipment and installed in the plant meets the required reliability and availability. Using the integrated reliability condition and maintenance curve program, we can translate these graphic and experimental results to reliability and availability requirements at the subsystem and system levels.

The next step is the identification of the desired failure modes (wear, corrosion, and high-temperature impact, fatigue, and others) that will prevent us from achieving the target availability and the maximum achievable reliability of components. After the identification of the desired failure modes, we can evaluate the most cost-effective and progressive way to resolve the problems through the design of hard coating materials and coated part multivariate regression model and the application of the TI model. We have to execute the selected tasks at the correct frequencies and integrate a number of these tasks together; the work is on the same manufacturing processes and the same industrial equipment, using the same trade skills at the same frequency, which is known as the assembly of maintenance task routine. These routines will integrate all time-based tasks, condition-based monitoring and maintenance, as well as failure finding and reliability tasks together under a single platform with the TI technique.

When we execute integrated reliability condition monitoring and maintenance (IRCMM) tasks, we will be able to detect potential and functional failures. We can carry out failure finding tasks and identify whether items subject to hidden failures are in a working state. If they are in a failed state, we have to carry out breakdown maintenance work to restore it to a working condition. Lastly, we will allow certain items of equipment to run to failure, and some others will fail in service as a result of poor operation or maintenance, which will also require breakdown maintenance. We have to make a provision for such corrective and breakdown work in our plan. Various tools

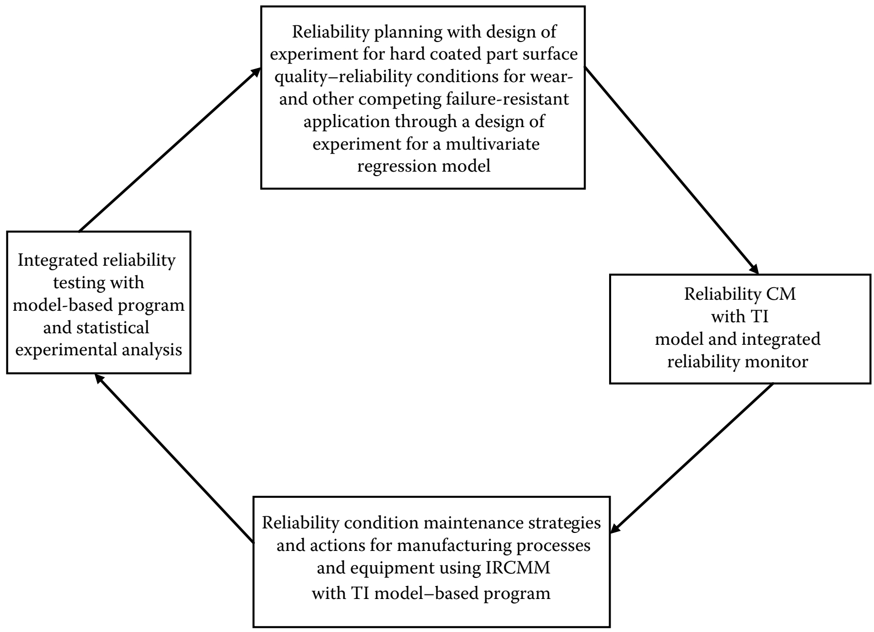

FIGURE 5.1
The IRCMM cycle of hard alloy critical part in manufacturing processes and equipment with the TI model–based program.

are available to assist us in planning this work, but the author has chosen to apply the TI technique to plan, design, monitor, maintain, and manage IRCMM of equipment. Planning the design of experiment for the IRCMM cycle of manufacturing processes and equipment encompasses all the tasks that require a continuous proactive work done from design through manufacturing processes in a production line of critical parts to its corresponding service operations, as can be seen in Figure 5.1.

5.4 Statistical Experimental Planning of a Multifactorial Design for Optimum Quality and Reliability of Parts, Processes, and Equipment Conditions

The mathematical models presented in this book for maximum achievable reliability of part, process, and equipment system can be designed through a multifactorial experimental plan. This plan helps reduce the time of the experiment.

In order to reduce the time and increase the efficiency of the experiment, there is the need to set up the interval of factors for the process conditions before carrying out the experiments. First and foremost, it is necessary to define the limits in the changes of independent factors, which highlight the physical nature of the experiment and the equipment used (e.g., temperature at melting points, plasticity of metal limits, angular velocity limits, machine tool feeds).

After that, it would be necessary to define how to change the factor level inside the experimental fields. There are two main criteria for choosing the points that describe the test conditions of an experiment:

1. A relative precision data of the different sections in an experimental field
2. The characteristic features of an experimental function

In many cases, the data do not always have the same precision in different sections in an experimental field. It can be expected, for example, that for a lot of mechanical systems, the tests carried out when the power is low or when the pressure is small would provide the least precision. Therefore, if the error analysis shows on any section of the experimental field, there would be a need for more test points. It must be noted that firm rules should not be established on such that shows how many additional points. Calculation, therefore, should be done where such doubtful data exist. If the precision in measurements is the same for all the factors, it means the distance between the points on the experimental curve is constant in the whole length of the curve.

A preknowledge of the characteristics of the function $Y_i = f(X_i)$ is essential, where Y_i is the surface quality parameter of a critical part and X_i is the operating condition of a process or an equipment. This can be obtained through a linear function with the help of a different algebraic formation, which allows the choice of the desired interval between points to be made, not just to obtain a symmetric convenient curve but such that it can provide for all the sections and curves with the same precision of experimental data.

The design of a mathematical model for component and system condition parameters will adopt the linear function $Y_i = f(X_i)$ to describe the process. The disadvantages of a mathematical model derived with the help of regression analysis are the correlation relationship coefficients, the difficulty in validation of the errors in calculating the optimization parameters, and the interpretation of the physical nature of the regression equation. Regression analysis on the whole is effective and suitable, since it allows for the substitution of all the information concerning the process to be in a compact form. The disadvantages of the classic regression analysis in many ways can be eliminated with the help of a statistical plan of an experiment. On the basis of a statistical experimental plan, the use of an orderly plan of distributing and placing the test points in the environment of the factors and its transfer into new system coordinates are necessary.

In a linear problem (linear regression analysis), it is possible to consider k-factors—X_1, X_2, …, X_k—in a k-form environment (and it is also still needed to add a fictitious variable for the validation of a free member in the regression equation), which can be expressed as

$$\eta = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_k x_k \tag{5.1}$$

The problem of obtaining the validation of b_i regression coefficients $\beta_i(b_i \rightarrow \beta_i)$ can be solved using the traditional (one factorial plan) method, by varying each factorial level. The method sets the level of each factor, one after the other. When the factor is done on two levels (+1 and −1), the test is repeated nth times, dispersion validation of the regression coefficient,

$$\sigma^2\{b_i\} = \frac{\sigma^2\{(y_i - y_0)/2\}}{n} = \frac{\sigma^2\{y\}}{2n} \tag{5.2}$$

where $b_i = (y_i - y_0)/2(b_i = t_{g\alpha})$ as shown in Figure 5.2. This value does not depend on the common number of factors under consideration as much as each of them is under separate study. The values of b_i define the result of the two mean measurements, which are being given by the value of the dispersion of regression coefficient.

The aim of the experimental plan is to find the model of a process in the form of a polymer for the first or second order known as the plan of the first or second order.

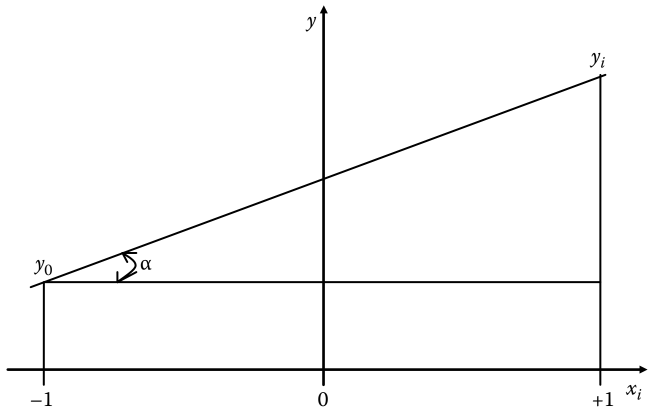

FIGURE 5.2
The determination of the regression coefficient with two points.

The first stage of the experimental plan is to choose the conditions. On the basis of the condition, you need to know the experimental field: the main factor level, the interval, and the precision of the fixed factors. When the choice of the experimental field is done, it is necessary to consider the principal limits of factor levels with its physical nature, technical–economical indexes, equipment, instruments, and useful information concerning the process. The main factor level (zero point) consists of a central field for the change of that particular factor. If the aim of the experiment is to optimize some parameters, the zero point would need to be spread in such a way that it comes close to the position that provides the optimum parameter. In this case, within the zero point factor level, the proceeding tests will produce the best value for the optimization parameter. If the aim of the experiment is to design models of a particular process, it means behind the zero point, it would adopt the mean or middle of the interval change of that factor. On the choice of interval variations for factor levels, you can set up limits *upper* and *lower*. Interval variation cannot be less than the error of the one carrying out the experiment, fixing the factor level of the upper and lower levels. On the other side, interval cannot include such factor level, where the upper and lower levels show behind the field of definition. If the interval is not more than 10% of the field of definition, it is assumed narrow; not more than 30%, medium; and the rest of the cases, wide. When solving the problem of optimization, the first series of test stretches to choose such field changes in the factor level, as if it is possible to have the fastest movement to optimum. In the problems of interpolation, the interval variation of the factor level contains all the experimental fields. The factor level as a rule is chosen symmetrically to the zero point, which is known as the lower or upper level. In this case, interval variation is the distance on the coordinate axis between the main, upper, and lower factor levels. For the expression of the condition of experiment and the processing of experimental data, the scale on the axis is chosen in such a way that the upper level agrees with the constant field of definition, so that it can always be possible to move into new system coordinates. Z_i and Z_{2j} are in alignment with the lower and upper limits in terms of the level changes in the *j*-factor and *y*-parameter of optimization.

In the case of a 2-factor problem, the field factorial environment is in the form of a rectangle (Figure 5.3) with coordinates $1(Z_{21};\ Z_{12})$, $2(Z_{11};\ Z_{12})$, $3(Z_{21};\ Z_{22})$, $4(Z_{11};\ Z_{22})$.

Z_{0j} and the coordinates of any point, Z_{ij}, represent the coordinates of the central field. Substitute the factor level of Equation 5.1 into the coded form, where j_j is the interval variation level of the *j*-factor. Substitute it in Equation 5.1.

Instead of Z_{ij} coordinate input points 1…4, you can then obtain them in a new system of unitless coordinates with the origin in the center of the experimental field (Figure 5.4):

$$x_{ij} = \frac{z_{ij} - z_{0j}}{j_j} = \frac{z_{ij} - \dfrac{z_{1j} + z_{2j}}{2}}{\dfrac{z_{1j} - z_{2j}}{2}} = \frac{2z_{ij} - z_{1j} - z_{2j}}{z_{1j} - z_{2j}} \tag{5.3}$$

The precision of the fixed factor level defines their stability in the tests, and the precision of the instrument is high when the measurement is

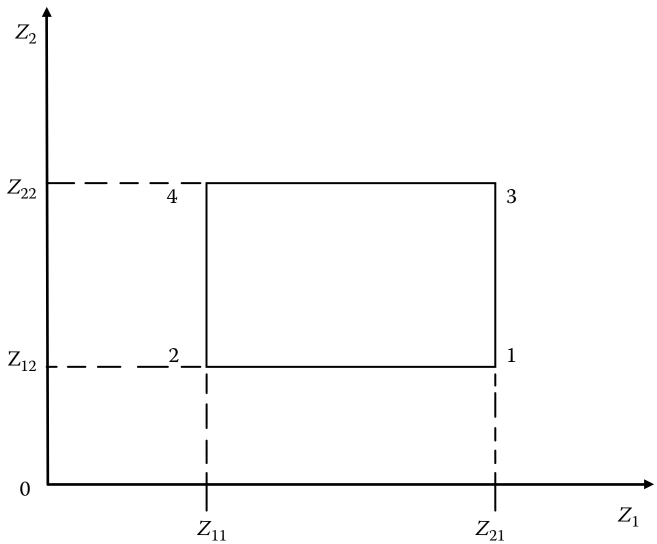

FIGURE 5.3
The arrangement of factorial experiment in a natural system of coordinates.

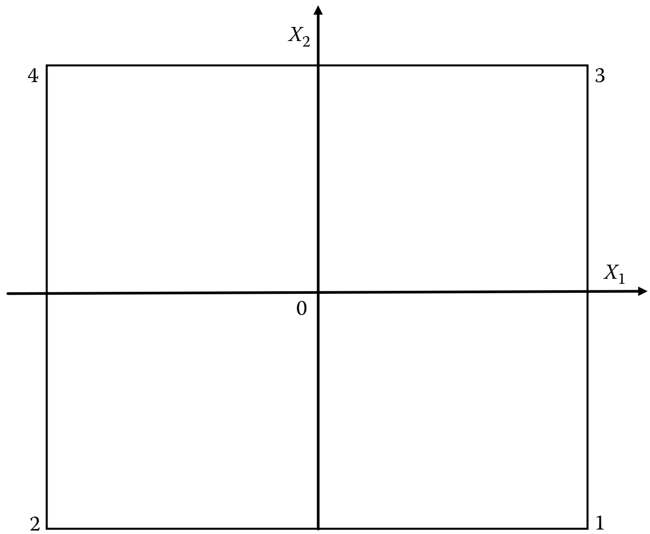

FIGURE 5.4
The arrangement of factorial experiment in a coded system of coordinates.

carried out with an error that is not more than 1%; medium, not more than 5%, and low, not more than 10% [2].

5.5 Experimental Plan of the Second-Order Design for Optimum Reliability of Part, Process, and Equipment Conditions

An experimental plan that contains all possible combination of all the factors on a definite number of levels that equal the same number is known as the full factorial plan. If the number of factor is known, it is possible at once to find the number of test necessary for realizing all possible combinations of the factor levels:

$$N = P^k \tag{5.4}$$

where
P is the number of factor levels
k is the number of factors

If the number of the levels of each factor equals two, it means it is a full factorial plan of the experimental form 2^k.

In the case of 2 factors, all possible combinations of their levels can be found easily. As the number of factor increases, the necessity of knowing some ways of constructing matrices arises.

The properties for constructing the matrices of the plan 2^k are as follows:

1. $\sum_{i=1}^{N} X_{ij} = 0$

where X_{ij} is the level of the *j*-factor for *i*-tests, *N* is the number of tests, and $j = 0,1, \ldots, k$.

2. $\sum_{i=1}^{N} X_{2ij} = N$

3. $\sum_{i=1}^{N} X_{ui} X_{ji} = 0; \quad u \neq j; u, j = 0, 1, \ldots, k$

If with the help of the full factorial experimental plan, it is not possible to design an adequate mathematical model of the process in the form of the first order, then it would be necessary to find the multiple factorial form of the second order. With this aim, it is necessary to use the compositional plan:

$$N = 2^k + 2k + 1$$

where

k is the number of factors

2^k is the number of tests for a full factorial plan

$2k$ is the number of star points in the factorial environment, which has the coordinates (±α; 0; 0; …, 0); (0; ± α; …, 0); …, (0; 0; …, ± α); α-star distance

The tests in the central plan, that is, the point of the factorial environment with the coordinates (0; 0; …, 0)

The values of the star distance α depends on the number of factors:

K	2	3	4	5
α	1.0	1.215	1.414	1.547

The regression equation using the compositional experimental plan can be expressed as

$$Y = b_0^* + b_1X_1 + b_2X_2 + \cdots + b_kX_k + b_{12}X_1X_2 + \cdots + b_{(k-1)k}X_{k-1}X_k + b_{11}X^* + \cdots + b_{kk}X_k^*, \tag{5.5 }$$

where $X_{ji}^{*} = X_{ji}^{2} - 1/N\sum_{j-1}^{N} X_{2ji}$.

In the regression equation of the usual form is expressed as:

$$Y = b_0 + b_1X_1 + b_2X_2 + \cdots + b_kX_k + b_{12}X_1X_2 + \cdots + b_{(k-1)k}X_{k-1} \\ X_k + b_{11}X_1^2 + b_{22}X_2^2 + \cdots + b_{kk}X_k^2 \tag{5.6}$$

$$b_0 = b_0^{*} - \frac{b_{11}}{N}\sum_{j-1}^{N} X_{ji}^2 - \cdots - \frac{b_{kk}}{N}\sum_{j-1}^{N} X_{jk}^2$$

The regression coefficient of the orthogonal-mode plan is marked with different errors for the attainment of the optimization parameter and also has a different dispersion, which of course changes from one point to the other. Due to the disadvantages of this plan, it is necessary to use the rotatable plan [1,2].

5.6 Rotatable Experimental Plan Design for Optimum Reliability of Part, Process, and Equipment Conditions

The rotatable experimental plan provides a higher precision in its mathematical expression for describing the process than the orthogonal-mode plan. This is due to the increase in the number of tests of the central plan with the base of the star distance α. The main property of the rotatable plan is the independent dispersion of y-values from the rotation of coordinates for the plan. With this, the dispersion is the same on equal distance from the central plan. A suitable mathematical experimental plan is selected to suit the design of any particular mathematical model for optimizing the condition parameters of a part with a hard alloy–coated surface (Table 5.1).

A suitable plan will be selected for mathematical multiple regression models for materials, coating deposition, machining, and grinding of hard alloy–coated surface part. The models are used to predict and optimize the in-process surface quality parameters with manufacturing processes. The results of the optimization of the machining process are used to set up the control limits and the threshold points for accurate IRCMM of industrial processes and equipment.

TABLE 5.1

Matrix of a Typical Mathematical Experimental Plan for a Part Surface Quality Condition with Manufacturing Processes

No. of Tests	X_0	X_1	X_2	…	X_k	Y_1	Y_2	…	Y_m
1.	+	+	+	…	+	Y_{11}	Y_{21}	…	Y_{m1}
2.	+	−	+	…	−	Y_{12}	Y_{22}	…	Y_{m2}
3.	+	+	−	…	−	Y_{13}	Y_{23}	…	Y_{m3}
4.	+	−	−	…	+	Y_{14}	Y_{24}	…	Y_{m4}
5.	+	+	+	…	+	Y_{15}	Y_{25}	…	Y_{m5}
6.	+	−	+	…	−	Y_{16}	Y_{26}	…	Y_{m6}
7.	+	+	−	…	−	Y_{17}	Y_{27}	…	Y_{m7}
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
n	+	−	−	…	+	Y_{1n}	Y_{2n}	…	Y_{mn}

5.7 Multivariate Regression Models for Hard Alloy Workpiece Surface Quality Condition for Wear and Other Competing Failure Resistance Applications by Rotary Cutting with Plasma Flame

A multivariate linear regression analysis is not widely used in practice. Instead, most researchers use multiple linear regression procedures, one dependent variable at a time. However, simulation studies suggest that this practice is ill advised. If the primary goal of a study is prediction accuracy like the case study of this book, the use of a multivariate linear regression analysis is recommended. Multivariate procedures take into account the correlations among the dependent variables ignored by a univariate analysis. This is also the case for multivariate procedures used to select the best subset of variables when building multivariate models.

Multivariate linear regression procedures are used in practice to explain the variation in a vector of dependent (criterion) variables by employing a set of independent (predictor) variables using observational (nonexperimental) data. In these settings, the goal of the researcher is usually to select a subset or all of the predictors that account for the variation in the dependent variables. The theory associated with the discipline is usually used to define the initial set of predictor variables. In such studies, the goal is to discover the relationship between the dependent variables and the *best* subset of predictor variables. Multivariate linear regression procedures are also used with experimental data. In these situations, the regression coefficient is employed to evaluate the marginal or partial effect of a predictor on the dependent variable given the other predictor variables in the model. In both of these situations, one is usually concerned with estimation of the model parameters, model specifications, and variable selection, or in general mode calibration and sample model fit.

In this book, predictor variables are selected to maximize the surface quality parameters and measure and monitor the conditions of the part as well as the optimum set points and the control limits of rotating and stationary equipment. To achieve this, a mathematical model of a hard-coated rotary shaft is designed for optimum surface quality and efficient monitoring characterization. In order to obtain the mathematical model, a new modern progressive method of machining and finishing hard-coated rotary shaft known as rotary cutting with plasma spray has been adopted, while a central composite uniform plan design of the second order was applied [3,4].

The parameters of the optimization process for optimum quality and efficient monitoring of rotating equipment are as follows:

Y_1 – K—kinematic coefficient of a rotary tool bit: $K = V_R/V$

V_R—the speed for the distance traveled by the tool's cutting edge

V—cutting speed

Y_2 – λ—profile wavelength of the machined surface, mm

Y_3 – R_a—surface roughness number, μm

Y_4 – (Hardness Rockwell C)—hardness of the machined surface, kg/mm²

Y_5 – ε—surface stress concentration factor after machining, %

The independent variable factors are as follows:

X_1 – I—plasma-arc current, A

X_2 – L—the distance between the plasmatron and rotary tool bit, mm

X_3 – S—feed rate of the rotary tool bits, mm/rev

X_4 – V—cutting speed, m/s

X_5 – t—cutting depth, mm

The constant factors are as follows:

Material of the tool bits—cemented carbide WC6

Diameter of the tool bits (round edge) D = 46 mm

Tool bit angle of cut $\gamma = 17°$, $\alpha = 12°$

Tool bit angle of setting $\phi = 22°$, $\beta = 24°$

In these experiments, we used plasmatron *PBP-402* with a 3 mm diameter nozzle opening, which is perpendicular to the work surface with a distance of 12 mm from it. The flow rate of plasma formation of gas–air is Q = 35…40 L/min.

Hard coatings from powdered materials (*PG-CP4*) with hardness of 60…62 HRC are used as the specimen. The diameter of the sample rotary shaft d = 85 mm. Experiments were carried out on a lathe machine, *IK61*. Machining was carried out by a second reverse single-turned scheme as seen in Figures 5.5 and 5.6.

The rotary tool bit is set in a way that allows the heating spot to be closed when cutting from the side of the machined surface (Table 5.1).

The results of the tests, from the matrices of the central composite rotatable design of the second order, were carried out with the aid of a computer. The regression coefficients were verified by the use of *Student's criterion* and the validation of the regression equations by Fisher's criterion. It was found out that not all the coefficients were significant with 95% coefficient confidence and also ascertained that all models were validated with 5% level of significance.

The following expressions are the mathematical models that determine the characteristic relationship of the kinematic coefficient, profile wavelength, surface roughness of a machined surface, surface hardness, and surface compression intensity of hard-coated rotary shaft from the different factors of the process in rotary cutting with plasma flame.

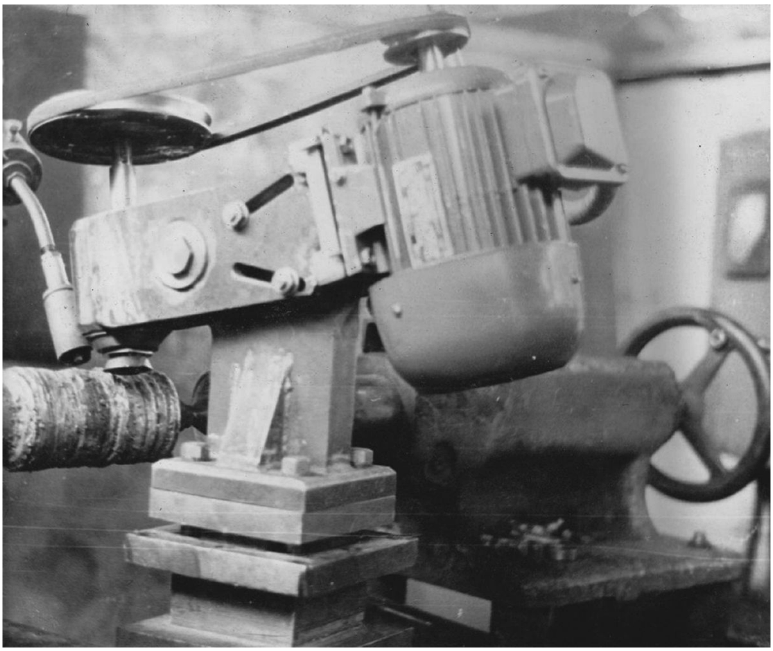

FIGURE 5.5
Rotary cutting with plasma spray set up.

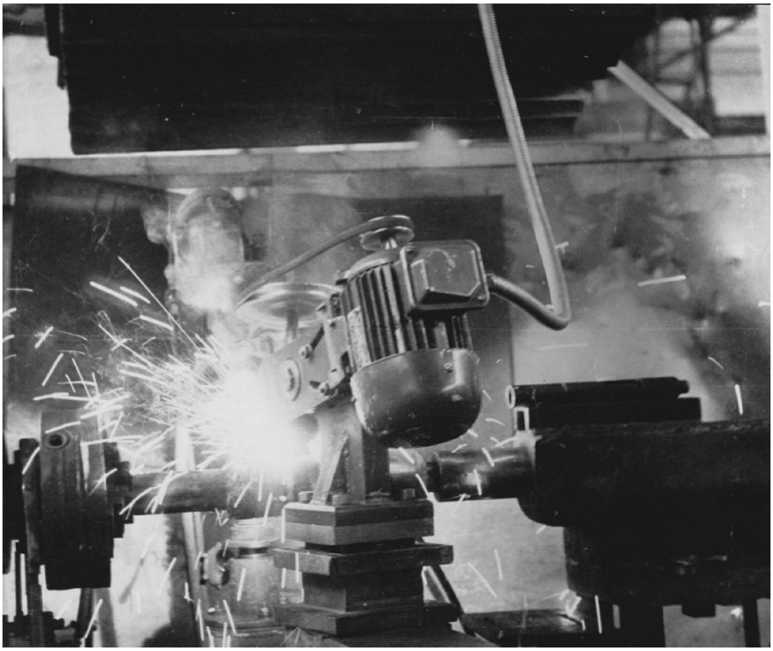

FIGURE 5.6
Rotary cutting with plasma spray and turning of workpiece.

5.8 Multivariate Regression Models of a Hard Alloy–Coated Part Surface Condition for Wear and Other Competing Failure Resistance Application

$$\begin{aligned} Y_1 = {} & 5.25 + 2.26X_1 - 1.79X_2 + 1.07X_3 - 1.28X_4 - 1.08X_5 - 0.23X_1X_2 + 0.82X_1X_3 \\ & - 3.07X_1X_4 - 1.38X_1X_5 + 0.29X_2X_3 - 0.56X_2X_4 + 0.25X_2X_5 + 0.26X_3X_4 \\ & + 1.31X_3X_5 + 0.28X_4X_5 + 0.94X_1^2 + 0.99X_2^2 - 0.36X_3^2 + 0.99X_4^2 - 0.15X_5^2 \end{aligned} \tag{5.5}$$

$$\begin{aligned} Y_2 = {} & 61.34 - 1.52X_1 - 0.35X_2 + 1.06X_3 + 0.73X_4 + 0.23X_5 + 0.22X_1X_2 \\ & + 0.22X_1X_3 + +0.72X_1X_4 + 0.47X_1X_5 - 0.53X_2X_3 + 0.22X_2X_4 + 0.47X_2X_5 \\ & + 0.97X_3X_5 - 0.77X_1^2 - -0.52X_2^2 - 1.67X_3^2 - 1.14X_4^2 - 0.64X_5^2 \end{aligned} \tag{5.6}$$

$$Y_3 = 2.91 - 0.72X_1 - 0.24X_2 + 0.68X_3 + 0.79X_4 - 0.07X_5 - 0.27X_1X_2 + 0.28X_1X_4 + 1.27X_1X_5 - 0.02X_2X_3 - 0.34X_2X_4 - 0.25X_2X_5 - 0.30X_3X_4 + 0.21X_3X_5 + 0.30X_4X_5 - 1.11X_1^2 + 0.08X_2^2 + 0.09X_3^2 - 0.55X_4^2 - 0.34X_5^2 \quad (5.7)$$

$$Y_4 = 0.71 + 0.04X_1 - 0.15X_2 - 0.07X_3 + 0.004X_4 - 0.033X_5 + 0.089X_1X_2 + 0.032X_1X_3 - 0.032X_1X_4 - 0.024X_1X_5 + 0.111X_2X_3 - 0.108X_2X_4 - 0.023X_2X_5 - 0.131X_3X_4 + +0.059X_3X_5 - 0.057X_4X_5 + 0.068X_1^2 + 0.127X_2^2 + 0.051X_3^2 + 0.103X_4^2 + 0.043X_5^2 \quad (5.8)$$

$$Y_5 = 0.6598 - 0.0186X_1 + 0.01096X_2 + 0.0254X_3 - 0.0191X_4 + 0.00396X_5 - - 0.0021X_1X_2 + 0.00056X_1X_3 + 0.0068X_1X_4 - 0.0073X_1X_5 - 0.0026X_2X_3 + 0.0042X_2X_4 + 0.0136X_2X_5 + 0.0263X_3X_4 - 0.0051X_3X_5 + 0.0069X_4X_5 - 0.0103X_1^2 - -0.0096X_2^2 - 0.0236X_3^2 - 0.0235X_4^2 - 0.0261X_5^2 \quad (5.9)$$

5.9 Multivariate Regression Model Analysis of a Hard Alloy–Coated Part Surface Condition for Wear and Other Competing Failure Resistance Application

The determination of the influence of the different factors of rotary cutting with plasma flame on K, λ, R_a, HRC, and ε and also optimization of the cutting conditions of the process are carried out by mathematical models (5.5) through (5.9) using the methods worked out by the theory of experimental design. In this case, both significant and the nonsignificant coefficients were used, considering the fact that the latter ascertains the said values of the previous functions.

The graphical representation of these mathematical models for the different multiple quality parameters is shown in the research work of [2], while a single cross-sectional curve function of Y_1, Y_2, Y_3, Y_4, Y_5 is seen in Figure 5.7. This single curve is used to monitor the quality and performance of industrial processes as well as the health of equipment. It is also used to select

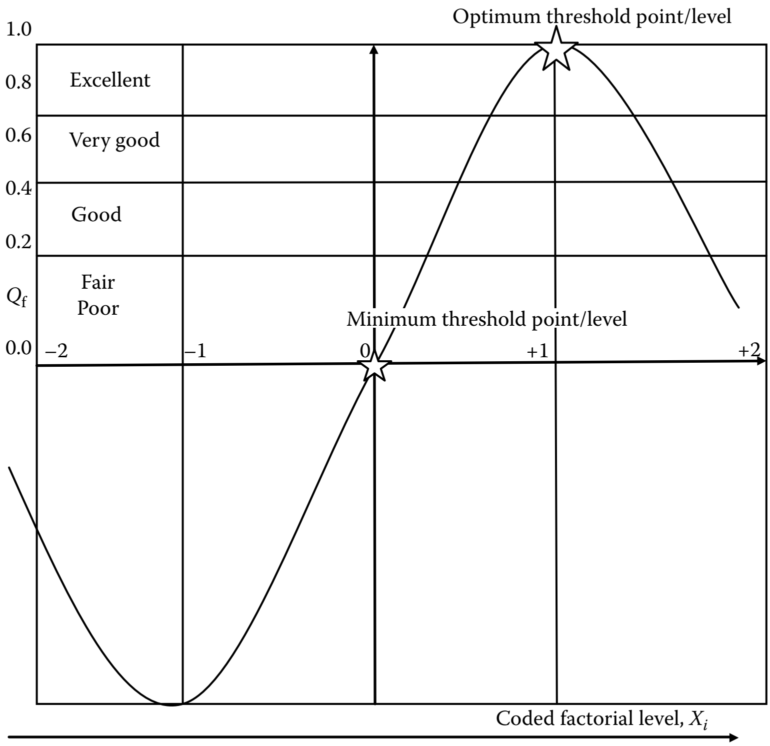

FIGURE 5.7
Determining the optimum workpiece quality factor and process coded factorial level conditions for component and system reliability requirements.

optimum values of materials, parts, processes, equipment, instruments, and manufacturing and maintenance routes. The single curve can easily be analyzed graphically and numerically to achieve the desired purpose.

For reliability maintenance purposes, with the multivariate mathematical model, a regression equation was set up to contain two variables as the testing independent factor and determinant dependent variable. In this case, the rest factors remain at zero level for that particular matrix.

The relationships obtained from the graphical representations are limited by the conditions of extrapolation from –2 to +2. Analysis obtained from the multiple regression models and the graphical relationships has helped to determine the degree of influence of the factors on the optimization parameters. From the data analysis in Table 5.5, it is seen that the quality parameters are differently influenced by the rotary cutting with plasma flame factors. With all the experimental factors, the most influential on the surface quality factor is in their decreasing order of significance: current of the plasma arc, feed rate, cutting speed, distance between tool bit and plasmatron, and depth of cut (*I*, *S*, *V*, *L*, *t*).

With this analysis, it is clear that the order of influence is quite different from the traditional trend, which of course has a remarkable impact on machine ability and reliability engineering.

5.10 Determination of the Optimum Rotary Cutting with Plasma Flame Machining and Workpiece Surface Quality Conditions for Reliability Requirements

The determination of optimum rotary cutting condition with plasma flame for machining hard alloy–coated part surface has been used to solve the problem of optimization for multiple parameters. In this case, exhaustive methods of selecting different variants were adopted [2] and were used to solve complex problems by finding their extreme conditions using mathematical models for multiple parameters of optimization. In these experiments, the use of data from existing mathematical models in different variants was adopted. The initial data for finding the optimum variant are shown in Table 5.2. From the results of the calculations, the data of the sixth variant were selected to be the optimum. The verifications were carried out by using complex index of the optimization parameters in rotary cutting with plasma flame for the machining of hard coatings. Such index was adopted as a general function of *desire* by Harrington [5]. Desire is understood as the desiring level of optimum parameters.

A special *scale of desire* is worked out. The value of d changes from 0 to 1. The value $d = 1$ corresponds to the maximum possible level of optimum parameter.

The function of desire is expressed by the following equation:

$$d = e^{-ea}$$

where

e is the natural logarithm; $e = 2.718$

a is the nondimensional value of the optimum parameter

For the use of the functions and *scale of desire* values of optimum parameters, Y_i is first of all changed to a nondimensional value a that corresponds to the desire.

A general function desire is formed as a geometrical mean desire of the separate optimum parameters and is determined by the following expression:

$$d = \sqrt[n]{d_1 d_2 \ldots d_n}$$

The complex index of optimum parameter of rotary cutting with plasma flame for machining hard coatings is maximal in the sixth variant. Subsequently, conditions of rotary cutting with plasma flame of the sixth variant can be accepted as optimum. The optimum process conditions for wear-, corrosion-, and high-temperature-resistant purposes can be determined and applied for an integrated reliability monitoring and maintenance of industrial processes, parts, and equipment.

TABLE 5.2

Initial Data for Plotting the Graphs for Optimum Workpiece Surface Quality and Rotary Cutting with Plasma Flame Performance Conditions

Workpiece Surface Quality Parameters (Y_i)	Rotary Cutting with Plasma Flame Factors (X_i)	Rotary Cutting with Plasma Flame Factor Level (−2)	Rotary Cutting with Plasma Flame Factor Level (−1)	Rotary Cutting with Plasma Flame Factor Level (0)	Rotary Cutting with Plasma Flame Factor Level (+1)	Rotary Cutting with Plasma Flame Factor Level (+2)
Workpiece surface roughness, R_a, μm (Y_1)	X_1	4.49	3.93	5.25	8.45	13.53
	X_2	12.79	8.03	5.25	4.45	5.63
	X_3	1.67	3.82	5.25	5.96	5.95
	X_4	11.77	7.52	5.25	4.96	6.65
	X_5	6.81	6.18	5.25	4.02	2.49
Workpiece surface hardness, HRC, kg/mm^2 (Y_2)	X_1	61.30	62.09	61.34	59.05	55.22
	X_2	59.96	61.17	61.34	60.47	58.56
	X_3	52.66	59.76	61.34	60.76	56.90
	X_4	55.32	59.47	61.34	60.93	58.24
	X_5	58.32	60.47	61.34	60.93	59.24
Workpiece surface stress concentration factor, % (Y_3)	X_1	−2.81	2.52	2.91	1.08	−2.97
	X_2	3.71	3.23	2.91	2.75	2.75
	X_3	1.91	2.32	2.91	3.68	4.63
	X_4	−0.87	1.57	2.91	3.15	2.29
	X_5	1.61	2.64	2.91	2.55	1.41
Workpiece surface wavelength, λ, mm (Y_4)	X_1	0.902	0.738	0.71	0.818	1.062
	X_2	1.518	0.987	0.71	0.687	0.918
	X_3	1.054	0.831	0.71	0.691	0.774
	X_4	0.908	0.809	0.71	0.808	1.133
	X_5	0.948	0.786	0.71	0.720	0.816
Kinematic coefficient of rotary tool bit, K (Y_5)	X_1	0.6558	0.6681	0.6598	0.6309	0.5814
	X_2	0.5995	0.6392	0.6598	0.6618	0.6433
	X_3	0.5146	0.6108	0.6598	0.6616	0.6162
	X_4	0.6041	0.6554	0.6598	0.6172	0.5467
	X_5	0.5475	0.6297	0.6598	0.6377	0.5633

The results of the mathematical relationship between the kinematic coefficients of rotary tool bits, profile wavelength, surface roughness, and hardness of the surface layer, the surface stress concentration factor, and the rotary cutting with plasma flame factors that allow the determination of machining conditions of hard coatings provide the best quality characteristics of the coated surface layer. It is ascertained that rotary cutting with plasma flame provides the quality parameters of the profile wavelength, λ = 0.66…1.0 mm; surface roughness, R_a = 1.8…4.1μm; hardness, HRC = 60…63; surface stress concentration factor, ε = 1.8%–4.1%; and kinematic precision coefficient, K = 0.520–0.660. It is also ascertained that the factors of the machining process—rotary cutting with plasma flame—for hard coatings provide a decreasing order of significance arranged as follows: *I*, *S*, *V*, *L*, and *t*.

A single optimum model curve for hard-coated surface quality factor (Q_i) with rotary cutting with plasma flame condition factor level is plotted graphically with the data of the most optimum variant of factor levels (Figure 5.7 and Table 5.2). The optimum variant of the workpiece surface quality conditions can be determined from the plotted single graph (Figure 5.7), as well as with the use of the designed multivariate quality regression models (Equations 5.5 through 5.9). With the help of this single curve graph, it is now possible to move easily from modular to virtual measurements. Instead of using so many sensors of surface quality parameters (Y_i), a single multivariate TI coefficient sensor (TICS) for reliability degradation control can now be used. Also, the reliability degradation and failure signals can now be captured in real time with a data acquisition device. An accelerated reliability growth, degradation, and failure test is possible during manufacturing processes and equipment with the TI model. The optimum workpiece surface quality and cutting with plasma flame condition factors in this book are used as an accelerated reliability growth, degradation, and failure test to determine component quality and process performance condition control limits as well as the reliability requirements of components and systems with the help of the TI model. The TI coefficient *a* is used to control the component quality conditions, while coefficient *b* is used to control the process performance conditions. The part surface quality factor, (Q_f) is function of the different multiple surface quality (Y_i) can be determined with the TI coefficient *a*. The process performance condition (performance factor [P_f]) is function of the different multiple process condition (X_i) can also be determined with the TI coefficient *b*. The optimum results are used to set quality, failure, and cost threshold points for IRCMM of industrial processes, parts, and equipment. The data for plotting the graphs for determining the optimum workpiece surface quality conditions are shown in Tables 5.2 and 5.3.

TABLE 5.3

Optimum Workpiece Surface Quality and Rotary Cutting with Plasma Flame Performance Conditions

Workpiece Surface Quality Parameters (Y_{iopt})	Rotary Cutting with Plasma Flame Factors (X_{iopt})	Rotary Cutting with Plasma Flame Factor Level (0)	Rotary Cutting with Plasma Flame Factor Level (+1)	Workpiece Surface Quality Parameters and Values or Cost-Effective Threshold Point (Y_{ic})	Workpiece Surface Quality Parameters and Values or Acceptable Failure Threshold Point (Y_{if})
Workpiece surface roughness, R_a, μm (Y_{1opt})	X_{1opt}	5.25	8.45	1.8	4.1
	X_{2opt}	5.25	4.45		
	X_{3opt}	5.25	5.96		
	X_{4opt}	5.25	4.96		
	X_{5opt}	5.25	4.02		
Workpiece surface hardness, HRC, kg/mm² (Y_{2opt})	X_{1opt}	61.34	59.05	63.0	60.0
	X_{2opt}	61.34	60.47		
	X_{3opt}	61.34	60.76		
	X_{4opt}	61.34	60.93		
	X_{5opt}	61.34	60.93		
Workpiece surface stress concentration factor, % (Y_{3opt})	X_{1opt}	2.91	1.08	1.8	4.6
	X_{2opt}	2.91	2.75		
	X_{3opt}	2.91	3.68		
	X_{4opt}	2.91	3.15		
	X_{5opt}	2.91	2.55		
Workpiece surface wavelength, λ, mm (Y_{4opt})	X_{1opt}	0.71	0.818	0.66	1.00
	X_{2opt}	0.71	0.687		
	X_{3opt}	0.71	0.691		
	X_{4opt}	0.71	0.808		
	X_{5opt}	0.71	0.720		
Kinematic coefficient of rotary tool bit, K (Y_{5opt})	X_{1opt}	0.6598	0.6309	0.66	0.52
	X_{2opt}	0.6598	0.6618		
	X_{3opt}	0.6598	0.6616		
	X_{4opt}	0.6598	0.6172		
	X_{5opt}	0.6598	0.6377		

5.11 Reliability Requirements and Measurement Characteristics for Integrated Reliability Monitoring and Maintenance of Parts and Equipment with a TI Model–Based Program

5.11.1 Reliability Requirements

- Requirement input by designer
- System reliability = 95%
- Required maximum material/part reliability = 95%
- Required minimum material/part reliability = 65%
- Required maximum part surface hardness = 63 HRC
- Required minimum part surface hardness = 60 HRC
- Required minimum part surface stress concentration factor = 1.8%
- Required maximum part surface stress concentration factor = 4.6%
- Required maximum part surface roughness = 4.1 μm
- Required minimum part surface roughness = 1.8 μm
- Required maximum part surface wavelength = 1.0 mm
- Required minimum part surface wavelength = 0.66 mm
- Required maximum part surface kinematic coefficient = 0.660
- Required minimum part surface kinematic coefficient = 0.520
- Required maximum ;process operating current = 80 A
- Required minimum process operating current = 20 A
- Required confidence level = 95%
- Required time = 100%

Required input from users

- Test time = 100
- Failure = 0
- Optimum TI coefficient for part surface quality condition control in an operating process (e.g., equipment and machine tool), $a_i = 1.0$
- TI coefficient of part condition for potential failure modes, $a_i(F_p)$
    - a_{1V}—vibration = 0.55
    - a_{2S}—stress = 0.60
    - a_{3W}—wear = 0.65

- a_{4C}—corrosion = 0.50
- a_{5T}—high temperature = 0.55
- a_{6F}—fatigue = 0.45
- Others = 0.35

- TI coefficient of part condition for functional failure modes, $a_i(F_f)$
  - a_{1V}—vibration = 0.20
  - a_{2S}—stress = 0.20
  - a_{3W}—wear = 0.20
  - a_{4C}—corrosion = 0.20
  - a_{5T}—high temperature = 0.20
  - a_{6F}—fatigue = 0.20
  - Others = 0.20

Output data

- Reliability of components from the final manufacturing process operation (R_{pi}) and equipment operation (R_{ei}) = 0.95
- Reliability growth rate (R_g, %) = 100
- Reliability degradation rate (R_d, %) = 20
- Quality factor of components (Q_f) = 1.0
- Process performance factor (P_f) = 1.0
- Maintenance cost (M_c) = 0.1

Signal and waveform generation

- Digital signals
- Analog signals

Simulation

- Simulation interface
- Mathematical models
- Mechanism curves
- Metrics

Areas of application

- Integrated reliability monitoring and maintenance of manufacturing processes, parts, and equipment for the industries of the future

- Integrated reliability design of processes, parts, materials, instruments, and equipment
- Integrated reliability testing of manufacturing processes, parts, and equipment for the industries of the future
- Optimum reliability selection of manufacturing processes, parts, materials, instruments, maintenance strategies, and equipment for the industries of the future

5.11.2 Component and System Reliability Condition Degradation and Failures with the TI Model–Based Design

The component quality and process performance degradation coefficients can be measured with TICSs (a_i/b_i). The products of the different quality parameters make up the desired conditions of a component (Q_f), while that of the performance parameters make up the desired conditions of a process (P_f). The most influential component and process parameter on lifetime reliability (e.g., surface roughness, current, speed) can be used individually to assess and evaluate the conditions of the component, process, and system. The TI coefficient of each of these critical parameters (Y_i and X_i) and their products (e.g., Q_f and P_f) can also be used to assess and evaluate component and system conditions. It therefore means that the relationship between them can be expressed as $a_{\text{ra(opt)}} = Q_{\text{f(opt)}}$, $b_{i\text{(opt)}} = P_{\text{f(opt)}}$, $b_{\text{v(opt)}} = P_{\text{f(opt)}}$, which can be used to assess the conditions of component (R_c) and system reliability (R_{sys}). The component quality factor (Q_f) is a product function of all the different TI coefficients of the different quality parameters (a_{Yi}):

$$Q_f = a_{1Y1} \cdot a_{2Y2} \cdots a_{nYn} \tag{5.7}$$

The process performance factor (P_f) can be determined by the product of all the different TI coefficients of the different process condition parameters (X_i):

$$P_f = b_{1X1} \cdot b_{2X2} \cdots b_{nXn} \tag{5.8}$$

The component performance factor (P_f) can be used to assess the quality factor of the components (Q_f), which is expressed as

$$\text{P}_{\text{f(opt.)}} : \text{Q}_{\text{f(opt.)}} = 1.0 : 1.0 \tag{5.9}$$

Therefore, the reliability coefficient $R_{\text{k}i}$ is expressed as

$$R_{ki} = \int_{t_{min}}^{t_{max}} P_f \, dt \tag{5.10}$$

It can also be expressed as

$$R_{ki} = \int_{t_{min}}^{t_{max}} Q_f \, dt \tag{5.11}$$

where

R_{ki} is the component/process reliability
t_{max} is the maximum operating time
t_{min} is the initial operating time
P_f is the performance factor
Q_f is the component quality factor

At this point, when the component, process, and equipment are operating at optimum condition, where the TI coefficient for process performance control $b = 1.0$, it means the TI model, $Y_i = aY_{i-1}{}^b$, will therefore become linear and expressed as

$$Y_i = aY_{i-1(opt)} \tag{5.12}$$

This formula can therefore be used to solve the problem of component and system wear-resistant condition degradation and monitoring of parts, processes, and equipment. With the optimum hard alloy–coated part quality surface condition with quality parameters measured with the different traditional instruments of different units as seen in Table 5.3 for wear-resistant and CM applications, the TICS for measuring a_i is used to determine the component quality factor, Q_f, which ranges between 0.0 and 1.0. $Q_{f(opt)} = 1.0$ is the optimum quality factor, and $Q_{f(min)} = 0.0$ is the minimum quality factor. When the component or system starts to degrade from optimum condition to minimum as seen in Table 5.4, a typical degradation curve of $Y_i/Q_f/R_k$ versus a_d can be plotted as shown in Figure 5.8. With Table 5.4, the data derived from component and system quality CM with the TI model–based design can be used to set the maximum threshold point for quality, cost-effectiveness, and productivity through Y_{imax}, Q_{fmax}, and R_{kmax}, which implies that the ratio of $Y_{imax} : Q_{fmax} : R_{kmax} = 1.0$. The minimum threshold point that determines the failures of components is set at $Y_{imin} : Q_{fmin} : R_{kmin} = 0.0$. The TICS is used to measure the component/system condition changes from maximum to minimum. When the failure occurs at random,

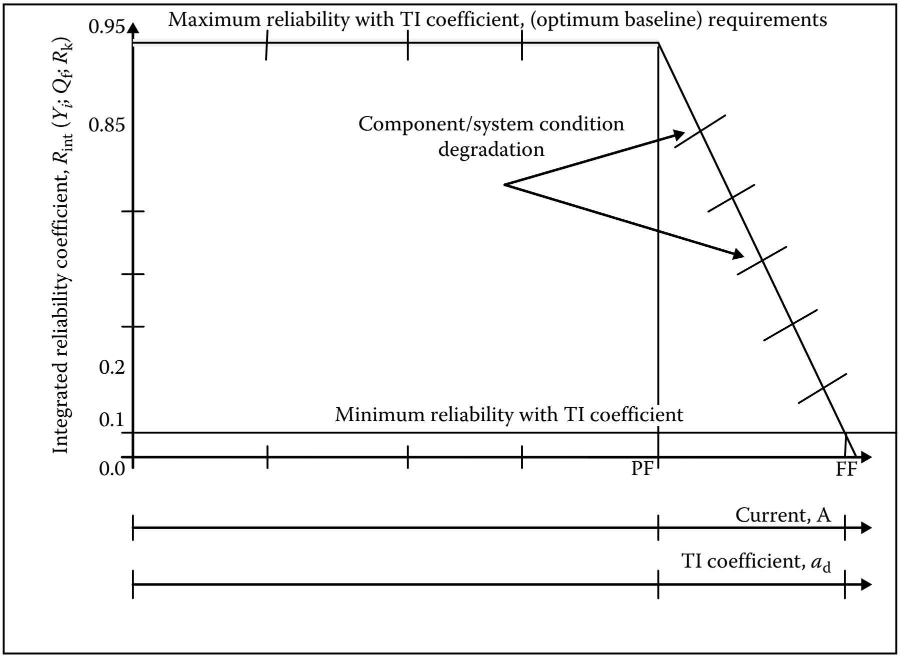

FIGURE 5.8
Integrated reliability curves of manufacturing processes and equipment conditions with the TI coefficient.

it will be necessary to monitor the part, process, and equipment from the initial to final operation with the help of the TI model. But when the failure occurs systematical or serially, the monitoring interval is set in such a way that it can capture all the failures that occur with the help of the TI model. The TI coefficient is used to integrate the different failure modes (wear coefficient [k_w], corrosion coefficient [k_c], fatigue coefficient [f_k], etc.) and calculate system reliability. It is also used to select the most influential and cost-effective component or system in terms of quality, reliability, and maintenance cost requirements. With the help of a convertible quality–reliability–maintenance cost chain requirement table, it is possible to find the requirements of the component and system for desired applications. Once the desired component and system requirement is known, the actual real-time quality, reliability, and maintenance cost can be calculated or measured with TICSs. Before using these types of sensors, we shall, first and foremost, deduce and assess the component and system with the following equations in an IRCMM program.

The first important equation to consider in this program is the designed multivariate quality part surface regression model, which is used as the initial data, $Y_{i-1(opt)}$, for evaluating the TI model:

TABLE 5.4

Component and System Quality Condition Monitoring with TI Model–Based Design

Test No.	Quality/Performance Degradation Coefficients with Inheritance Coefficients with Sensor (a_i/b_i)	Optimum Initial Part/ Equipment Quality Conditions for Wear-Resistant Applications (Y_{i-1})opt.	Final Part/ Equipment Condition Degradation (Y_{di}/Q_f)
1.	1.00	0.90	$Y_{d1}/(Q_{f1} = 0.900)$
2. Opt. selection	**0.95**	**0.90**	$\mathbf{Y_{d2}/(Q_{f2} = 0.855)}$
threshold	0.90	0.90	$Y_{d3}/(Q_{f3} = 0.810)$
3.	0.85	0.90	$Y_{d4}/(Q_{f4} = 0.765)$
4.	0.80	0.90	$Y_{d5}/(Q_{f5} = 0.720)$
5.	0.75	0.90	$Y_{d6}/(Q_{f6} = 0.675)$
6.	0.70	0.90	$Y_{d7}/(Q_{f7} = 0.630)$
7.	0.65	0.90	$Y_{d8}/(Q_{f8} = 0.585)$
8.	0.60	0.90	$Y_{d9}/(Q_{f9} = 0.540)$
9.	0.55	0.90	$Y_{d10}/(Q_{f10} = 0.495)$
10.	0.50	0.90	$Y_{d11}/(Q_{f11} = 0.450)$
11.	0.45	0.90	$Y_{d12}/(Q_{f12} = 0.405)$
12.	0.40	0.90	$Y_{d13}/(Q_{f13} = 0.360)$
13.	0.35	0.90	$Y_{d14}/(Q_{f14} = 0.315)$
14.	0.30	0.90	$Y_{d15}/(Q_{f15} = 0.270)$
15.	0.25	0.90	$Y_{d16}/(Q_{f16} = 0.225)$
16. Min. failure	**0.20**	**0.90**	$\mathbf{Y_{d17}/(Q_{f17} = 0.180)}$
threshold	0.15	0.90	$Y_{d18}/(Q_{f18} = 0.135)$
17.	0.10	0.90	$Y_{d19}/(Q_{f19} = 0.009)$

$$Y_i = a_i Y_{i-1(\text{opt})}^{\ bi} \tag{5.13}$$

where
- a_i is the TI coefficient for quality–reliability control
- b_i is the TI coefficient for process condition control
- $Y_{i-1(\text{opt})}$ is the initial quality of a mating part in an equipment
- Y_i is the final quality of the mating part, which can also serve as the baseline requirements for other parts that make the system work

When $b_i = 0$, $Y_i = a_i$

$$Y_{i(\text{opt})} = a_{i(\text{opt})} = Q_{\text{f(opt)}} = R_{\text{k(opt)}} \tag{5.14}$$

This expression in (6.2) is used to validate quality and selection requirements of materials and parts:

$$Y_{i(\min)} = a_{i(\min)} = Q_{\text{f(min)}} = R_{\text{k(min)}} \tag{5.15}$$

When $b_i = 1$,

$$X_{i(\text{opt})} = b_{i(\text{opt})} = P_{\text{k}i\text{opt}} = R_{\text{k(opt)}} \tag{5.16}$$

$$X_{i(\min)} = b_{i(\min)} = P_{\text{k}(\min)} = R_{\text{k}(\min)} \tag{5.17}$$

Between the interval of $Y_{\min}$ and $Y_{\max}$, the quality and reliability of a part/equipment and, between $X_{\min}$ and $X_{\max}$, the performance and reliability also continue to grow positively toward a maximum achievable value. This is known as reliability growth (R_g), performance growth (P_g), and quality growth (Q_g). Also the reverse interval of $Y_{\max}$ to $Y_{\min}$ and $X_{\max}$ to $X_{\min}$, the quality and reliability of part/equipment and process performance, respectively, continues to degrade negatively toward a minimum acceptable value. This degradation is known as reliability degradation (R_d), performance degradation (P_d), and quality degradation (Q_d). The interval between the minimum acceptable growth/degradation and maximum achievable growth/degradation is regarded as the baseline trend/curve of growth, optimum, and degradation. Any deviation from the baseline or curve is a result of a fault, defect, and aging that can develop into failures. The baseline and curve trend can be plotted for the reliability, quality, and failure resistance of materials and parts against the operating conditions of manufacturing processes and equipment as well as the production time and life cycle/maintenance costs. Any deviation and behavior of materials and process conditions can be observed from the normal curve (integrated reliability mechanism), and this can be used for monitoring and maintenance at any time or any point throughout manufacturing processes and equipment operations. With this trend of reliability growth, reliability degradation, potential failure, functional failure, time to failure, defects, failure rates, maintenance costs, and other maintenance characteristics can be determined.

The second equation to be considered is the mean time to failure (MTTF):

$$\text{MTTF} = \frac{\sum \{\text{period between detection and failure}\}}{n_\text{f}} \tag{5.18}$$

where

the period is the total sum of the time between detection and failure of all failures

n_f is the number of failures

With the TI model for quality degradation, $Q_\text{d} = a^*Q_{\text{opt}}$, or $Y_\text{d} = a^*Y_{i-1(\text{opt})}$, for part conditions, but for process conditions, $b_{\text{opt}} = X_{i\text{opt}}$. At this level, the manufacturing process is running with optimum conditions as a baseline, and any deviation from this optimum baseline is a degradation, fault, and defect, which may eventually lead to failure. The time of degradation, fault, defect, and failure can also be determined with the TI coefficient a_i.

Therefore with respect to time,

$$\text{MTTF} = \frac{\sum \{T_f - T_d\}}{n_f} \tag{5.19}$$

where
T_f is the time of failure
T_d is the time the failure was detected

In terms of the TI coefficient, MTTF can be expressed as $a_f : a_d = T_f : T_d$:

$$\text{MTTF} = \frac{\sum \{a_f - a_d\}}{n_f} \tag{5.20}$$

The third equation is the mean time for corrective maintenance:

$$M_{CM} = \frac{\sum \{\text{time for repair / maintenance}\}}{n_f} \tag{5.21}$$

where
time for repair is the total sum of the time spent for repairing the faults/defects in equation 5.21
n_f is the number of corrective maintenance tasks

The fourth equation is the maintenance/repair cost:

$$M_c = \frac{\sum \{\text{cost for repair / maintenance}\}}{n_f} \tag{5.22}$$

With the TI model,

$$M_c = a^* M_{c(N)} \tag{5.23}$$

where
M_c is the repair/maintenance cost
$M_{c(N)}$ is the cost of a new part

The fifth equation is the failure rate:

$$\lambda = \frac{1}{\text{MTTF}} \tag{5.24}$$

With the TI model, reliability degradation ($R_{k(d)}$) is expressed as

$$R_{k(d)} = \int_{Td}^{Tf} Q_{(opt)} d_T \tag{5.25}$$

Reliability growth

$$R_{k(g)} = \int_{Td}^{Tf} P_{k(opt)} d_T \tag{5.26}$$

The sixth equation is the system reliability:

$$R_{sys} = R_{k1} \cdot R_{k2} \cdots R_{kn} \tag{5.27}$$

Component reliability growth

$$R_{kg} = \int_{t_i}^{t_{max}} P_f \, dt \tag{5.28}$$

where
- P_f is the process performance, which can be determined during manufacturing operations by measuring the TI coefficients with the TICSs for process performance controls
- t_i is the different operating times

Once the reliability growth gets to the set optimum threshold point, cost-effective components, parts, and equipment are selected and used, while the data are used for maintenance, planning, and organization.
Component reliability degradation

$$R_{kd} = \int_{t_i}^{t_{max}} Q_{fd} \, dt \tag{5.29}$$

where Q_{fd} is the component quality degradation, which can be determined during equipment service operations by measuring the TI coefficients with TICSs for quality–reliability controls. As the component continues to operate with time, the degradation grows into a failure state, where the possible failure modes that can occur on the same component at the same period of time are wear, corrosion, temperature, vibration, and fatigue. These failures and their defects can be determined and measured with TICSs. These sensors can also be used to generate reliability degradation and failure signals, which can be captured with a data acquisition device in the IRCMM program.

It is also worthy to know that the existing motion and power transducers or sensors (accelerometers, proximity sensors, encoders, and others) can be used to generate the vibration and other failure signals from manufacturing process and equipment operating conditions to determine the incremental reliability performance growth and degradations. The results can be compared with the results acquired by TICSs, which has the advantage of measuring the component and process conditions as well as the different parameters of the component and system. IRCMM of parts, processes, and equipment with TI model–based design is cost effective for the determination of reliability growth and degradation as well as their rates and maintenance costs.

5.12 Reliability Testing and Measurement of Reliability Growth and Degradation of Part, Process and Equipment System with a TI Model–Based Program

Users generally start their work by acquiring wear, corrosion, and high-temperature data into a reliability CM and maintenance program, because their tasks typically require interaction with physical processes. In order to extract valuable information from that data, make decisions on the process, and obtain results, the data need to be manipulated and analyzed. Unfortunately, combining analysis with data acquisition and data presentation is not always a straightforward process. Existing application software packages typically address one component of the application but seldom address all aspects and needs to get to a complete solution. This book is written to address the component–quality–maintenance cost chain requirements from a start-to-finish, fully integrated solution so that customers can seamlessly integrate all phases of their application in a single environment. The single environment may include a data acquisition unit, convertible quality–reliability–maintenance cost chain requirement table unit, monitoring–maintenance unit, measurement–testing–inspection unit, and management unit. The technology and tool that combine the functions of data acquisition, monitoring, maintenance, and inspections can be designed by applying the TI model. While there are many tools that independently address each of the requirements, this book combines all of them with the power of graphical programming and data acquisition hardware, using the power of a personal computer (PC) with the help of a TI model–based design. The IRCMM program of parts and equipment can be tested for reliability growth, optimum, degradation, and failures with the TICS that provides quality–reliability performance characteristics as shown in Tables 5.5 and 5.6.

TABLE 5.5

Integrated Reliability Testing with the TI Model–Based Program

S. No.	Integrated Reliability Monitoring and Maintenance Modes	Material, Part, Process, and Equipment Conditions	TI and Integrated Reliability Curve Trend	Material, Part, Process and Equipment Test and Validation	Benefits, Viability, and Remarks
1.	Optimum reliability mode	$a_{iopt} = 1.0$ $b_{iopt} = 1.0$ $a_i = a_{th(max)}$ $b_i = b_{th(max)}$	Optimum TI, baseline, and requirement trend	System is stable and reliable with a true-positive inheritance status.	Cost-effective proactive monitoring and maintenance strategies. Critical component selections. Low maintenance costs. Acceptance of parts, processes, equipment, and maintenance strategies
2.	Reliability growth mode	$a_{th(min)} < a_i < 1$	Positive TI line	System reliability growth with true-positive status and unreliable with false-positive status.	Predictive and preventive maintenance. Preventive Maintenance (PM) optimization and Condition Based Maintenance (CBM) practices
3.	Reliability degradation mode	$1 < a_i < a_{th(min)}$	Negative TI line	System reliability degradation with false-positive status.	Predictive maintenance and system condition assessment
4.	Failure mode	$a_i = a_{th(min)}$	Minimum TI line. $R_i = 0$ $Q_i = 0$	System failure state with false-negative status.	Shutdown/upgrade and corrective maintenance. Root cause analysis, maintenance effectiveness review
5. Reliability cost	$M_c = a_i{*}N_c$				

TABLE 5.6

Manufacturing Process and Equipment Conditions of Hard Alloy–Coated Surface Quality–Reliability Conditions with the TI Model

S. No.	Manufacturing and Service Process Conditions (X_i, n)	Manufacturing Process and Service Performance Condition Requirements (X_{min}, X_{max})	Manufacturing Process and Service Performance Factor Requirements (P_{min}, P_{max})	TI Coefficient for Manufacturing and Service Performance Control, b	Hard Alloy Coating Materials or Coated Part Surface Quality Requirements (Y_{min}, Y_{max})	Hard Alloy–Coated Material or Part Surface Quality Factor Requirements (Q_{min}, Q_{max})	TI Coefficient for Hard Coating Materials and Coated Part Surface Quality Control, a
1.	Metallurgical operating conditions of hard alloy coating materials (X_i)	Optimum current, I_{opt} = 80 A; minimum current, I_{min} = 20 A	Optimum performance factor, P_{fopt} = 1.0; minimum performance factor, P_{fmin} = 0.0	Optimum TI coefficient, b_{opt} = 1.0; minimum TI coefficient, b_{min} = 0.0	Optimum hardness, HRC = 63.0; minimum hardness, HRC = 60.0; maximum stress concentration factor = 1.8%; minimum stress concentration factor = 4.6%	Optimum quality factor, Q_{opt} = 1.0; minimum quality factor, Q_{min} = 0.0	Optimum TI coefficient, a_{opt} = 1.0; minimum TI coefficient, a_{min} = 0.0
2.	Hard alloy coating deposition operating condition	Optimum current, I_{opt} = 80 A; minimum current, I_{min} = 20 A	Optimum performance factor, P_{fopt} = 1.0; minimum performance factor, P_{fmin} = 0.0	Optimum TI coefficient, b_{opt} = 1.0; minimum TI coefficient, b_{min} = 0.0	Hardness, HRC = 60.0–63.0; stress concentration factor = 1.8%–4.6%	Optimum quality factor, Q_{opt} = 1.0; minimum quality factor, Q_{min} = 0.0	Optimum TI coefficient, a_{opt} = 1.0; minimum TI coefficient, a_{min} = 0.0
3.	Machining operating condition for hard alloy coatings	Optimum current, I_{opt} = 80 A; minimum current, I_{min} = 20 A	Optimum performance factor, P_{fopt} = 1.0; minimum performance factor, P_{fmin} = 0.0	Optimum TI coefficient, b_{opt} = 1.0; minimum TI coefficient, b_{min} = 0.0	Hardness, HRC = 60.0–63.0; stress concentration factor = 1.8%–4.6%	Optimum quality factor, Q_{opt} = 1.0; minimum quality factor, Q_{min} = 0.0	Optimum TI coefficient, a_{opt} = 1.0; minimum TI coefficient, a_{min} = 0.0

(*Continued*)

TABLE 5.6 (*CONTINUED*)

Manufacturing Process and Equipment Conditions of Hard Alloy–Coated Surface Quality–Reliability Conditions with the TI Model

S. No.	Manufacturing and Service Process Conditions (X_i, n)	Manufacturing Process and Service Performance Condition Requirements (X_{min}, X_{max})	Manufacturing Process and Service Performance Factor Requirements (P_{min}, P_{max})	TI Coefficient for Manufacturing and Service Performance Control, b	Hard Alloy Coating Materials or Coated Part Surface Quality Requirements (Y_{min}, Y_{max})	Hard Alloy–Coated Material or Part Surface Quality Factor Requirements (Q_{min}, Q_{max})	TI Coefficient for Hard Coating Materials and Coated Part Surface Quality Control, a
4.	Grinding operating condition of hard alloy coating surfaces	Optimum performance factor, P_{fopt} = 1.0; minimum performance factor, Pf_{min} = 0.0	Optimum current factor, I_{opt} = 1.0; minimum current factor, I_{min} = 0.0	Optimum TI coefficient, b_{opt} = 1.0; minimum TI coefficient, b_{min} = 0.0	Hardness, HRC = 60.0–63.0; stress concentration factor = 1.8%–4.6%	Optimum quality factor, Q_{opt} = 1.0; minimum quality factor, Q_{min} = 0.0	Optimum TI coefficient, a_{opt} = 1.0; minimum TI coefficient, a_{min} = 0.0
5.	Assembly or installation operating condition	Optimum performance factor, P_{fopt} = 1.0; minimum performance factor, P_{fmin} = 0.0	Optimum current factor, I_{opt} = 1.0; minimum current factor, I_{min} = 0.0	Optimum TI coefficient, b_{opt} = 1.0; minimum TI coefficient, b_{min} = 0.0	Hardness, HRC = 60.0–63.0; stress concentration factor = 1.8%–4.6%	Optimum quality factor, Q_{opt} = 1.0; minimum quality factor, Q_{min} = 0.0	Optimum TI coefficient, a_{opt} = 1.0; minimum TI coefficient, a_{min} = 0.0
6.	Equipment or service operating condition	Optimum performance factor, P_{fopt} = 1.0; minimum performance factor, P_{fmin} = 0.0	Optimum current factor, I_{opt} = 1.0; minimum current factor, I_{min} = 0.0	Optimum TI coefficient, b_{opt} = 1.0; minimum TI coefficient, b_{min} = 0.0	Hardness, HRC = 60.0–63.0; stress concentration factor = 1.8%–4.6%	Optimum quality factor, Q_{opt} = 1.0; minimum quality factor, Q_{min} = 0.0	Optimum TI coefficient, a_{opt} = 1.0; minimum TI coefficient, a_{min} = 0.0

5.13 Component and Process Performance Condition Profile with the TI Model–Based Design

5.13.1 Machining Process Performance Factors

- X_1 – I—plasma-arc current, A
- X_2 – L—the distance between the plasmatron and rotary tool bit, mm
- X_3 – S—feed rate of the rotary tool bits, mm/rev
- X_4 – V—cutting speed, m/s
- X_5 – t—cutting depth, mm

The most influential machining process condition factor on wear resistance is plasma-arc current, I (A), with the optimum condition of I = 20–80 A, providing the best hard alloy–coated part quality surface and wear resistance conditions. The process operating current therefore becomes a baseline requirement for other process condition factors. The maximum current and minimum current can be converted to the TI coefficient b, expressed as $I_{max} = 80\text{ A} = b_{max} = 1.0$:

$I_{min} = 20\text{ A} = b_{min} = 0.0$

The TICS for process condition control, b, is used to measure the performances of all the manufacturing processes and equipment operations from the initial to final operations for wear- and other competing failure-resistant applications. The machining process serves as the baseline requirement for all other processes of the same system with the same technological production chain line. The TI coefficient b ranges from 0.0 to 1.0.

5.13.2 Component Surface Quality Factors

- Surface hardness, Y_1, HRC
- Surface roughness, Y_2 (R_a, μm)
- Surface wavelength, Y_3 (λ, mm)
- Surface stress, Y_4 (ε, %)
- Kinematic coefficient (k)

The most influential part quality condition factor on wear resistance is surface hardness with the optimum condition of HRC = 60–63, providing the best hard alloy–coated part quality surface and wear resistance conditions. The part surface hardness therefore becomes a baseline requirement for other components (materials, parts, lubricating oil, etc.). Based on some critical area of applications, a single-parameter requirement like the surface roughness or

TABLE 5.7

Component and Process Quality–Reliability Chain Condition Profile with TI Coefficients

TI Coefficients, *a* and *b*	Process Performance and Component Classifications	Component Reliability Requirements	Process Reliability Requirements	Instruments and Measurement with TICSs a_d and b_g	Applications and Industries
0.8–1.0	Critical process, part, and equipment; highest operating time; failure-free	R_{imax} = MTTF(max) = 80%–100%; $R_{kd(max)}$ = 0.8–1.0; HRC(max) = 63.0; ε = 1.8%; R_a = 1.8 μm; λ = 0.66; K = 1.0 mm; K_w = 0.0; K_f = 0.0; K_c = 0.0; K_T = 0.0; M_c = 0.01–0.1(Nc - New Part/Equipment cost)	R_{imax} = 80%–100%; $R_{kg(max)}$ = 0.8–1.0; I = 80 A; S = 0.195 mm/rev.; V = 1.8 m/s;	Highest reliability growth coefficient, R_{kg}, and lowest reliability degradation, R_{kd}	Optimum process and component selection; proactive condition and maintenance strategy; agriculture
0.4–0.8	Complimentary process, part, and equipment; average operating time; average potential and functional failures	R_{imax} = MTTF(max) = 40%–80%; $R_{kg(max)}$ = 0.4–0.8; HRC(max) = 63.0; ε = 1.8%; λ = 0.66; K = 1.00 mm	R_{imax} = 80%–100%; $R_{kg(max)}$ = 0.8–1.0; I = 80 A; S = 0.195 mm/rev.; V = 1.8 m/s	Average reliability growth coefficients, $R_{kg(ave)}$ and $R_{kd(ave)}$	Suboptimum process and component selection; predictive condition and maintenance strategy
0.0–0.4	Noncritical process, part, and equipment; lowest operating time; frequent functional failures	R_{imax} = MTTF(max) = 0.0%–40%; $R_{kg(max)}$ = 0.0–0.4; HRC(max) = 63.0; ε = 1.8%; R_a = 1.8–4.1 μm	R_{imax} = 80%–100%; $R_{kg(max)}$ = 0.8–1.0; I = 80 A; S = 0.195 mm/rev.; V = 1.8 m/s	Low reliability growth coefficient, R_{kg}, and highest reliability coefficient, R_{kd}	No process and component selection; preventive or corrective condition and maintenance strategy

surface hardness is not enough. A multiple surface parameter in the form of a quality factor, Q_f, which includes surface stress and surface wavelength, is necessary, since this is possible with the use of the TI coefficient to serve as component and system quality–reliability requirements.

The process performance profile is scaled and graded to suit TI, *b*, as shown in Table 5.7.

5.14 IRCMM Mechanisms with TI Coefficients for Wear and Other Competing Failure Resistance Applications

The system reliability of hard-coated mating part surface of different manufacturing processes and equipment of the technological chain can be assessed and evaluated for wear resistance and other competing failure-resistant applications:

$$R_{P(sys)} = Rk_M \times Rk_D \times Rk_M \times Rk_G \times Rk_A \times Rk_E \tag{5.16}$$

Also, system reliability in terms of the parts and components for wear resistance and other competing failure-resistant applications can be used:

$$R_{pi(sys)} = R_{p1} \cdot R_{p2} \cdot R_{p3} \cdots R_{pn} \tag{5.17},$$

where *n* is the number of parts that make the system work in manufacturing processes and equipment. The hard alloy–coated part reliability coefficient is calculated as follows:

$$R_{pi} = \int_{t_{min}}^{t_{max}} Q_p \, dt \tag{5.18}$$

The hard alloy–coated component reliability coefficient is calculated as follows:

$$R_{ci} = \int_{t_{min}}^{t_{max}} Q_c \, dt \tag{5.19}$$

$R_{piopt} = Q_{iopt} = Y_i = 1.0$—optimum component and part operating conditions, which represent the optimum reliability conditions of parts and components. This implies that with the TI model, a single part, process, and parameter can be used to assess and evaluate the component and system, instead of calculating for all the different parts and components that make up the system. The optimum selection of a critical part, process, parameter, and practice as well as integrated reliability with the TI model is all that is needed to solve the problem of calculating for the reliabilities of all the different parts, processes, practices, and parameters. In the same way, $R_{pimin} = Q_{imin} = Y_{imin} = 0.0$—minimum component and part operating conditions, which represent the failure mode conditions (wear, corrosion, fatigue, high-temperature impacts, etc.) of components and systems. This also implies that with the TI model, a single failure mode can be used to assess and evaluate the component and system, instead of calculating for all the different failure modes that can occur in a component or system at the same period of time. Integrated reliability with the TI model is capable of combining reliability growth, degradation, and failure to assess a component and system.

Integrated reliability mechanisms of hard alloy coating materials and part surfaces for wear- and other competing failure-resistant applications can be plotted for the assessment and evaluation of integrated reliability monitoring and maintenance of manufacturing processes and equipment with the TI model.

5.15 Design Procedures for Integrated Reliability Monitoring and Maintenance of Machine Parts, Manufacturing Processes, and Industrial Equipment with the TI Model–Based Technique

1. Determine the design of experiment for maximum achievable component reliability (R_{imax}), surface quality factor (Q_{imax}), and failure resistance coefficient (F_{Rimax}) of a particular hard alloy–coated cylindrical critical part in a machine tool and rotating equipment.
2. Design the mathematical regression models of a hard alloy–coated surface quality parameters (Y_i) with the different manufacturing processes and then determine the optimum, maximum, and minimum quality parameters (Y_{iopt}, Y_{imax}, Y_{imin}) and optimum, maximum, and minimum machine tool and equipment process conditions (X_{iopt}, X_{imax}, X_{imin}).
3. Determine the TI coefficient for quality control *a* and the TI coefficient for process control *b* during the operating machine tool process and equipment applying the TI model and the scale model of the operating functions.

4. Calculate the quality factor $Q_{i\max}$, which is the product of all the TI coefficients for surface quality parameters (aY_i) of the different failure modes.
5. Determine the optimum, maximum, and minimum failure resistance coefficient ($F_{\mathrm{R}i\mathrm{opt}}$, $F_{\mathrm{R}i\min}$, $F_{\mathrm{R}i\max}$), reliability coefficient ($R_{i\mathrm{opt}}$, $R_{i\min}$, $R_{i\max}$), and quality factor ($Q_{i\mathrm{opt}}$, $Q_{i\min}$, $Q_{i\max}$) in terms of TI coefficients a and b.
6. Determine the reliability coefficient (R_i), failure resistance coefficient ($F_{\mathrm{R}i}$), and quality factor (Q_{iy}) of parts with TI coefficients.
7. Determine the reliability coefficient, failure resistance coefficient, and the growth, degradation, defects, and failures of hard alloy–coated part surface as well as the machine tool and equipment condition variations (lifetime, power, efficiency, and others) with scaled control limits.
8. Determine the heath and identify the defects of hard alloy–coated machine part surface, machine tool, and equipment with TI models for health and the following surface quality parameter (Y_i):
    a. Machine part surface roughness (Y_1)
    b. Machine part surface hardness (Y_2)
    c. Machine part surface wavelength (Y_3)
    d. Machine part surface stress concentration factor (Y_4)
    e. Machine part dynamic coefficient (Y_5)
9. Optimum reliability selections of parameters, parts, processes, and equipment with TI coefficients for the following components/system:
    a. Machine tool and equipment parts (bearings, shafts, couplings, gears, seals, etc.)
    b. Materials of parts and for coating surfaces.
    c. Equipment (rotating, stationary, etc.)
    d. Production processes (metallurgical, coating deposition, machining, grinding, etc.).
    e. Optimum operating component/system and process conditions.
10. Reliability testing is done for optimum selections, design, and determining failures of existing machine tools, equipment, machine parts, materials, processes, industrial equipment, instruments, and maintenance strategies.
11. Reliability design of new machine tools, equipment, machine parts, materials, processes, industrial equipment, instruments, and maintenance strategies is carried out where there are no existing ones.
12. Reliability maintenance and monitoring of machine tools, equipment, machine parts, materials, and industrial equipment is cost-effective and possible with the TI model.

13. Optimize hard alloy–coated machine part surface and finishing process condition parameters with TI models.
14. The optimized data are used to set up optimum baselines and requirements for wear- and competing failure-resistant critical machine parts and equipment and set up control limits for condition monitoring and maintenance of industrial equipment.
15. The optimized data are also used to design an IRCMM program as well as integrated reliability test program.
16. The integrated reliability monitoring and maintenance program compares the existing maintenance programs and the new proactive, preventive, and predictive maintenance programs, which are used for optimum selections and testing for failures of the part–material–process–equipment–instrument system as well as for cost-effective integrated reliability monitoring and maintenance strategies with the TI model–based technique in the industries of the future.
17. The application of the TI model–based technique for integrated reliability monitoring and maintenance programs for developing reliable products, software packages, hardware monitors, and sensor measuring instruments, cost-effective selection of components, and reliability testing as well as integrated reliability monitoring and maintenance strategies of machine parts, manufacturing processes, and industrial equipment.

5.16 Conclusions

1. A reliability robust critical part that works according to requirements regardless of variation in manufacturing process, mating hard-coated part surface, and equipment system resulting from deterioration, defects, and failures during operations within a specific period of time has been designed in this book.
2. When the relationship of the hard alloy–coated part, process, and equipment models for wear-resistant applications are unknown, the design of experiments can help develop multivariate regression models for determining the optimum quality values, thereby creating a more robust design.
3. Component wear resistance cannot always be associated with any one property and generally does not directly increase with hardness; however, if other factors are relatively constant, hardness values provide an approximate guide to relative wear behavior among different metal to metal sliding and abrasive applications.

4. A multivariate regression model for materials and hard-coated parts can now be used to predict the multiple component quality and process performance condition parameters for wear- and other failure-resistant applications.
5. The multiple component quality and process performance condition parameters are optimized with the application of the TI model to provide the best wear-resistant mating part surface as well as for the best reliability requirements for components, processes, and equipment of the manufacturing, monitoring, and maintenance system.
6. Design of experiments with the TI model is used to desensitize a component's reliability and process performance characteristic variation in critical hard alloy–coated mating part, process, and equipment system design parameters.
7. The TI model has been applied in this book to validate the reliability design of experiment for maximum achievable reliability of hard alloy–coated mating part, process, and industrial equipment.
8. IRCMM with the TI model program is used for optimum selection, testing for failures of the hard alloy–coated critical part–hard alloy material–manufacturing process–industrial equipment–reliability instrument system, and monitoring of its reliability growth/degradation during operations in the industries of the future.
9. Integrated reliability testing is used for optimum selections and detecting failures of machine tools, equipment, machine parts, materials, processes, instruments, and maintenance strategies during real-time operations.
10. Integrated reliability testing with the TI model of real-time operating manufacturing process, part, and equipment system enhances automation, cost-effective software, and network programs.
11. The design of TICSs for measuring reliability growth and degradation as well as integrated reliability monitor and maintenance tools with the TI model–based program is cost effective.
12. The acquired reliability data are used to develop the IRCMM curve for materials, parts, and processes.
13. The IRCMM curves are used for optimum selection, monitoring of potential/functional failures, and maintenance of failed parts, processes, and equipment and to develop a maintenance decision-making diagram.
14. The design procedures for an integrated reliability monitoring and maintenance of parts, processes and industrial equipment with the TI model–based program have been outlined in this chapter.

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6

Selection of Coating Materials, Parts, and Equipment System with the Technological Inheritance Technique

6.1 Characteristics of Industries of the Future

The characteristics of the industries of the future (IOFs) are documented in detail in the technology road maps. The selection of the most important materials for wear- and other competing failure-resistant needs of industries will be dealt with in this chapter. The already developed multivariate regression model will be used to show the relative importance of each cross-cutting solution to the problems of individual industries. The multivariate regression model is used to predict the optimum quality–reliability characteristics of components and processes in areas that have the biggest impact on energy savings and waste reduction. Areas such as corrosion, wear, and high-temperature materials, hard alloy materials, and modeling/database development are emphasized in this book. The data of this regression model are used as the initial data for the implementation of technological inheritance (TI) models as well as desired baseline requirements for suitable selections and the design of a quality–reliability selection decision diagram as shown in Figure 6.1, which is used to select, test, analyze, monitor, and maintain systems of wear-, corrosion-, and high-temperature-resistant applications at minimum cost with TI models. Finally, this book also reveals the integrated reliability condition monitoring and maintenance (IRCMM) mechanism of hard alloy–coated materials or part surfaces with the help of TI models.

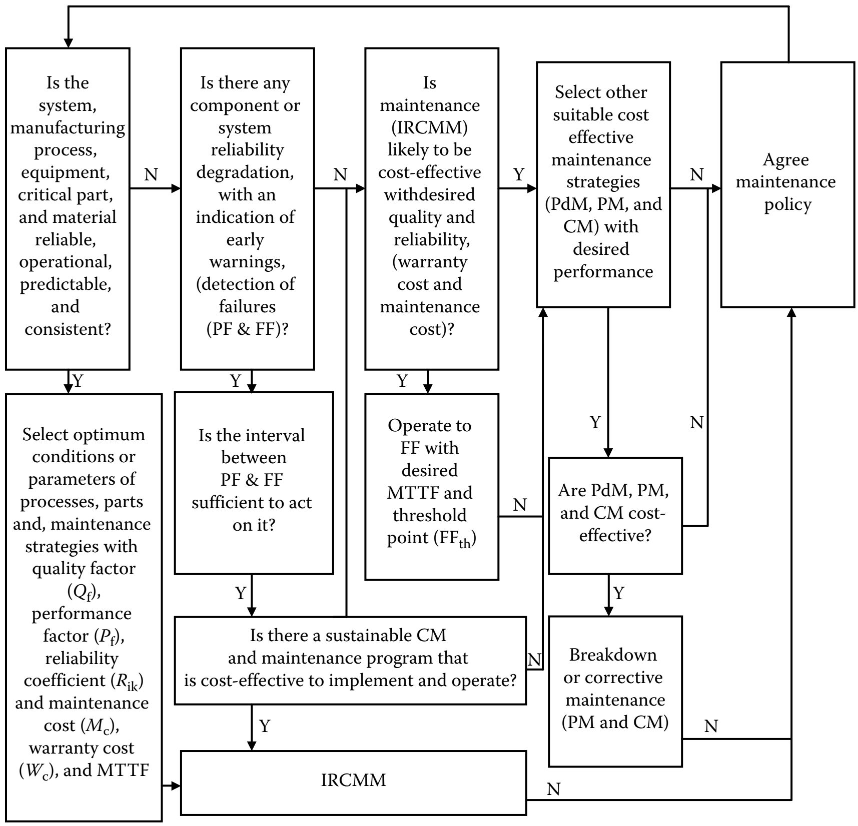

FIGURE 6.1
IRCMM decision diagram with TI model.

6.2 Existing Materials Models and Databases

All of the IOFs have noted the lack of materials modeling capability. In the metal casting industry road map, for example, two outstanding problems related to material properties are cited: (1) a lack of fundamental knowledge of material properties as a function of chemistry and casting route and (2) a lack of operating data for the simulation and modeling of these properties [1–9]. The combined use of models and sensors is an effective approach for controlling processes, preventing failures, lowering costs, and increasing energy efficiency. Materials modeling, linked to materials databases, is important for designing and developing materials. Rapid increases in computing power have made possible materials modeling and the design of materials from first principles. Materials modeling for the design and performance of existing materials under operating conditions requires a database. Even the best materials models will not function properly if the necessary databases are not available. Therefore, the development of materials models must be accomplished in coordination with the development of databases, which could be extremely expensive. Although the need for materials databases is widely recognized, the resources for generating and funding these databases have not been forthcoming. Databases and models are used by designers, producers, and users of materials and are clearly outside the scope of any individual agency. Therefore, interdisciplinary R&D, with customization for specific industries, is now possible with a single TI coefficient under a particular program.

6.2.1 Digital Product and Process Modeling That Impacts Crosscutting Programs

A number of common issues and emerging technologies will impact crosscutting materials programs. These issues include digital product and process modeling capabilities, materials producibility and affordability, variation and quality control, pollution prevention technologies, and advanced maintenance technologies. As competitive pressures force shorter product development and realization cycles, every decision in product and process synthesis requires high-fidelity modeling and simulation to validate physics- or behavior-based design attributes. The effective use of modeling tools for dynamics, thermal, mechanics, material, and behavioral systems is the prerequisite of tomorrow's digital manufacturing. These models and the knowledge base must be shared in a networked and collaborative environment. The most recent workstations are capable of solving intensive engineering problems within hours, sometimes even minutes. For example, with ProCast finite element modeling and simulation tools, engineers can visualize possible cracks in casting parts caused by thermal variations in the manufacturing process. The manufacturer can then use a simulation model–based program with TI coefficients to assist suppliers, manufacturers, and maintenance personnel in altering designs and development processes to deliver near-zero-defect part surfaces that minimize rework, defects, and failures.

6.2.2 Material Reducibility and Affordability

Affordable fabrication of materials is a challenging goal of all manufacturing sectors, especially the aerospace industry. As environmental regulations and performance requirements become more stringent, companies are looking for better superalloy high-temperature materials and near-net-shape processing technologies to reduce the costs of raw materials and manufacturing operations.

Currently, most research tools and process models in the research community are inadequate for predicting and validating material properties in manufacturing processes. For example, the casting of titanium-based aerospace parts requires labor-intensive, repetitive monitoring of material properties in the production process to ensure quality and reliability. Research works on measuring residual stress or stress concentration factor in materials in the production lines would help the industry. The research should expand the focus of monitoring beyond dimensional accuracy toward material performance to provide a better understanding of the quality of processes, machines, and parts. This research that could eventually lead to interdisciplinary research on integrated materials, manufacturing, physics, and computation, which would advance the fundamental understanding of manufacturing science and would benefit all industries, is now possible with the application of TI models. The use of a TI coefficient sensor (TICS), which is model based, helps to measure the stress concentration factor, hardness, and other vital quality parameters for component and process performance with real-time data during operations and in the production lines as well.

The relationship between material hardness, wear resistance, and other mechanical properties is correlated with operating processes, as shown in Figure 6.2. This correlation, which has been developed by a multivariate regression model, can be extrapolated to include other materials, manufacturing processes, parts, and equipment that are not tested with a TI model.

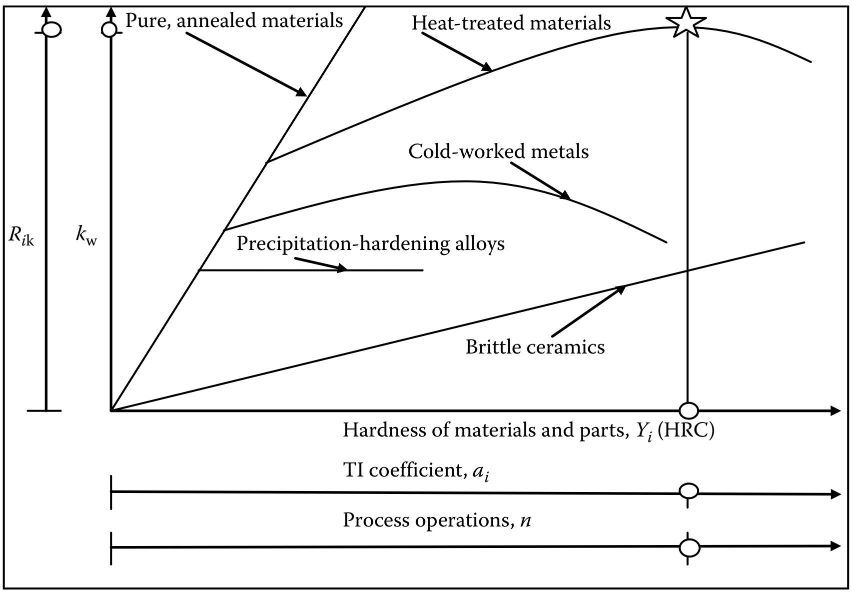

FIGURE 6.2
The relationship of hardness to wear resistance and other mechanical properties with TI model.

6.2.3 Variation and Quality Control with the TI Model

Smart production systems could monitor process variations and lead to higher-quality, less expensive operations. Research could focus on the development of adaptable, reliable, intelligent process-control software that includes real-time, onboard models of machine, process, material, and environment. The objective of guaranteeing process and product quality globally through an integrated engineering regulating point system can now be carried out with TI models. TICSs are used to measure and control product and process variations in the maintenance of IOFs that need reconfigurable, reusable, self-learning, and knowledge-transferable systems that can be added to monitors and process-control systems as advanced monitoring and maintenance strategies.

6.2.4 Advanced Maintenance Technologies for Component Reliability and Process Performance of the IOFs

Service and maintenance are important in maintaining product and process quality and customer satisfaction. The recent rush to embrace computer-integrated technologies in manufacturing industries has increased the use of relatively unknown and untested technologies. The difficulty in identifying the causes of system failures that use these technologies has been attributed to several factors, including system complexity, uncertainties, and lack of troubleshooting tools. Currently, service and maintenance in many manufacturing industries are still reactive. The problem arises from an incomplete understanding of the day-by-day behavior of manufacturing machines and equipment. As discussed in this book, TICSs are developed to measure the performance degradation of components and machines. TI models and the designed multivariate models can now be used for model validation and as tools to predict what would happen when process parameters take on specified values. This book focuses on determining the factors involved in component and machine breakdown and on developing smart, reconfigurable monitoring tools to reduce or eliminate production downtime and reduce dimensional variations caused by process degradation. Achieving these objectives will require intelligent reasoning agents in process controllers to provide proactive maintenance capabilities, such as measurements of component and process performance degradation, fault recovery, self-maintenance, and remote diagnostics. Manufacturing and process industries can now develop or select proactive maintenance strategies to guarantee the quality of process performance and ultimately minimize system breakdowns. This book will help provide solutions to these needs through optimization of the qualities and performances of materials, processes, and parts with the help of the TI technique for optimum IRCMM of processes and equipment. The existing selected materials in the technology road maps for wear-, corrosion-, and high-temperature-resistant purposes are presently hard alloy materials that are difficult to machine, which in turn brings down the quality and performance characteristics of processes and equipment. There is therefore the need to adopt an IRCMM strategy with a model-based program for optimum selection of materials, processes, tools, instruments, parts, maintenance routes, and other reliability maintenance components, which is a standardized technique toward providing a long-lasting solution to the common problems of IOFs.

6.3 Selection of Nickel-Based Alloys for Corrosion-Resistant Applications

The term nickel-based alloys is used for those alloys wherein, with very few exceptions, nickel is the principal element. These nickel alloys are used where corrosion resistance is of greatest importance and metal is exposed to cyclical heating conditions and electrolytic attack. Most commercially available nickel-based hard-facing alloys can be divided into three groups: boride-containing alloys, carbide containing alloys, and Laves phase–containing alloys.

The largest number of nickel alloys is those containing boron. These alloys were first commercially produced as sprayed and fused powders. Currently, most manufacturers such as other hard-facing products market them as well. This group of alloys is primarily composed of Ni–Cr–B–Si–C, the boron content typically ranging from 1.5% to 3.5% depending on the chromium content, which varies from 0% to 15%. High-chromium-containing alloys generally contain a large amount of boron, which forms very hard chromium borides with a hardness of 1800 kg/mm^2 [11,12].

An alternative suitable material for agricultural purposes is the powder material of nickel-based alloy from the Castolin Company in Switzerland [12].

The chemical composition of this type of alloy material is used to coat thickness up to 2 mm, while the grinding process usually finishes it. The alloy is commonly used for hardening and reconditioning tools, crank pins, eccentrics, ratchets and pawl gear, transporting chains, mixers, pushers and various supports, fan blades, scrappers, mixer blades, and cutting auger conveyors [14–19].

PM-12 NiWC-02 is a composite powder material consisting of a mechanical mixture of spheroid zed powder GP-10Ni-01 of the system Ni–Cr–B–Si–C–Fe and very small particles of tungsten carbide WC (35%). It is deposited on mild and stainless steel and iron. Its coating hardness is HRC 57–64 with aeration up to 700°C. Its coating thickness is usually up to 2 mm while finishing is by grinding. An IRCMM decision diagram is used as a guide to test, analyze, and select the optimum conditions of materials and predict the maximum and minimum resistance to corrosion, time to failure, and other reliability characteristics. The component quality factor, process performance factor, and operating power of the process are compared and analyzed with the help of TI coefficients. The selection threshold point is set to determine the time and conditions of desired selections. The set selection threshold points for optimum component and process condition with TI coefficients are expressed as follows:

$$Y_{i(\text{opt})} : Q_{\text{f(opt)}} : a_{i(\text{opt})} : R_{\text{k(opt)}} = 1.0 \tag{6.1}$$

$$X_{i(\text{opt})} : P_{\text{f(opt)}} : b_{i(\text{opt})} : R_{\text{k(opt)}} = 1.0 \tag{6.2}$$

$$Y_{i\text{opt(stress)}} : a_{i(\text{opt})} : R_{\text{k(opt)}} = 1.0 \tag{6.3}$$

$$Q_{\text{f(opt)}} : R_{\text{k(opt)}} = 1.0 \tag{6.4}$$

$$X_{i\text{opt(current)}} : b_{i(\text{opt})} : R_{\text{k(opt)}} = 1.0 \tag{6.5}$$

$$P_{\text{f(opt)}} : R_{\text{k(opt)}} = 1.0 \tag{6.6}$$

For corrosion-resistant applications, $Y_{(\text{stress})}$ is the surface stress concentration factor parameter, known to be most influential for fatigue reliability since it can be calculated with the designed multivariate regression model. TICSs are used to measure a_i and b_i and also to determine the component and system reliability coefficients, component quality factor, and process performance factor. The quality and performance factors combine parameters together to form a single compound factor that can be measured by a single sensor. When the desired set selection threshold condition is satisfactory, selection is made to suit the operating power, the load, and the performance characteristics of a compound or system.

6.4 Selection of Self-Fluxing Alloy Powders for Wear and Temperature Resistance Applications

Self-fluxing powders based on nickel are hard alloy materials having a wide application for hardening and reconditioning surfaces of rapid wearable parts working in aggressive media and wear conditions. The fluxing powder is slightly different with a lower oxygen content and other impurities, although classified according to composition. These coatings have complex structures, which consist of minutely dispersed superhard phases of carbides, borides, and carboborides with microhardness up to 40×10^3 MPa, uniformly distributed in a hard metallic matrix based on solid solutions and complex nickel-based eutectic. These hard coatings are chemically resistant to different active media.

On the basis of research work [10], it has been ascertained that within the range of specific pressure 1.5×10^6 to 7×10^6 Pa and sliding velocity up to 8 m/s, it is possible to recommend nickel-based self-fluxing powder materials for friction pairs in water and in solutions of NaOH and CH_3COOH of 10%–50% concentration.

The wear resistance of this type of hard coatings in frictional contact with steel (friction of boundary lubrication) is 4–9 times higher than the wear resistance of steel in steel–steel and steel–iron pairs under specific loads of 1.5×10^6 to 10×10^6 Pa and sliding velocities of 8–54 m/min; within this range, the amount of wear of steels working in pairs with hard coatings is reduced by a factor of 1.5–2.5 times. The friction coefficient in pairs of hard coating steel with initial roughness number $R_a = 0.16$–0.3 μm is 1.8–2.2 times lower than in pairs of steel–steel, but with constant surface roughness, the amount of wear is 2–10 times reduced [13]. These hard coatings are highly worn and corrosion resistant, capable of withstanding impact and hard conditions under abrasive wear at temperatures up to 600°C.

They are used for reconditioning, hardening, and maintenance of valves, camshafts, blades, fans, rotors, bearings, shafts, and sleeves of hydraulic pumps, motors, generators, compressors, and parts of other industrial equipment. At this juncture, it is worthy to note that the existing selection of materials for a particular load is almost solely relying upon the experience of technicians and material personnel, and accuracy requires an extremely significant amount of information and pure luck, which of course are the primary reasons why condition-based programs fail. The use of models to verify and validate these research data before selection and recommendation for any particular application is beneficial and cost-effective. IRCMM with a multivariate regression and TI model–based program is used to select the optimum material–part–process–practice system and monitor system reliability growth, degradation, and failures with minimum maintenance costs. The selection decision mode of the program is based on the condition of expressions 6.1 and 6.2.

For wear-resistant applications, $Y_{(\mathrm{HRC})}$ is the surface hardness parameter, known to be most influential for wear reliability since it can be calculated with the designed multivariate regression model. With the TI model, a combination of other surface quality (Y_i) and process performance parameters (X_i) can be used in the form of quality factor (Q_f) and performance factor (P_f) for the following selections:

$$Y_{i\mathrm{opt(HRC)}} : a_{i\mathrm{(opt)}} : R_{\mathrm{k(opt)}} = 1.0 \tag{6.7}$$

$$Q_{\mathrm{f(opt)}} : R_{\mathrm{k(opt)}} = 1.0 \tag{6.8}$$

$$X_{i\text{opt(current)}} : b_{i\text{(opt)}} : R_{\text{k(opt)}} = 1.0 \tag{6.9}$$

$$P_{\text{f(opt)}} : R_{\text{k(opt)}} = 1.0 \tag{6.10}$$

For high-temperature-resistant application, $Y_{(\text{T})}$ is the surface temperature parameter, which is unknown since it cannot be calculated with the designed multivariate regression model; we will therefore use the combination of the surface quality (Y_i) and process performance parameters (X_i), which is in the form of quality factor (Q_f) and performance factor (P_f), for the following selections:

$$Y_{i\text{opt(T)}} : a_{i\text{(opt)}} : R_{\text{k(opt)}} = 1.0 \tag{6.11}$$

$$Q_{\text{f(opt)}} : R_{\text{k(opt)}} = 1.0 \tag{6.12}$$

$$X_{i\text{opt(current)}} : b_{i\text{(opt)}} : R_{\text{k(opt)}} = 1.0 \tag{6.13}$$

$$P_{\text{f(opt)}} : R_{\text{k(opt)}} = 1.0 \tag{6.14}$$

6.5 Optimum Selection of Materials for Failure-Resistant Coatings with Multivariate Regression and a TI Model–Based Program

The same group of machine parts with the same service lifetime characteristics and having passed through the same manufacturing processes and assembly for the same service application but with different reliabilities at the initial stages of the same equipment type and operation does not reflect world standard requirements and should not be encouraged to continue. The existing groups of equipment part surface with hard alloy materials developed with the same manufacturing processes do provide the same quality requirements for wear-resistant applications but often start up with different reliabilities in the same equipment. The reason is often due to induced manufacturing failures and installation problems. Since there are many variants of material that are used to harden part surfaces and also coat the surfaces of equipment parts for wear-, corrosion-, and high-temperature-resistant purposes, there is therefore the need to select the optimum variant component for maximum achievable reliability of industrial equipment at minimum cost. The TI model, which is used to maximize the reliability of parts at minimum cost, is applied in this book to select the optimum materials, processes, parts, equipment, instruments, and other devices as well as their operational conditions. The optimum selection of the quality parameters and the conditions of processes and equipment of an initial operation provide the initial data requirements to set up optimum control and threshold levels of the proceeding operations and predict component and process reliability variations (reliability growth, reliability degradation, potential failure, functional failures, maintenance costs, etc.) in manufacturing processes and equipment operations.

For the scope of this book, the reliability optimum baseline of 95% is set for critical part surface condition for wear-, corrosion-, and high-temperature-resistant purposes. In cases where the critical equipment is known, the critical parts are also known, while the reliability baseline requirements are set by the manufacturers. Inherent reliability is always greater than operational reliability, since installation reliability is usually less, but because the measurement is unknown to the operator, he or she continues to operate blindly. This of course is not cost-effective and productive and definitely does not lead to continued reliability improvement. Hence, the need for a cost-effective reliability CM and maintenance program with the TI model can improve the reliability of parts and equipment, by selecting optimum component and process conditions as well as detecting potential problems early enough, thereby taking prompt preventive, predictive, and proactive maintenance actions before it enters into a failed state or before catastrophic damage is done. Reliability CM and maintenance at all stages of design, production, and operation requires a combination of models for materials, parts, processes, and equipment. The models will help determine the reliability requirements and parameters of the system and also control the variations of the parameters at all stages of the monitoring and maintenance route from design through manufacturing processes to service equipment operation. The information from an IRCMM program is used to determine reliability growth and degradation, monitor failures, and select the optimum material, part, process, and equipment conditions. With a multivariate regression model for the determination of reliability requirements and TI model for quality–reliability variation controls with adequate tools, it is possible to select the optimum conditions of materials and coating deposition processes and predict the maximum conditions of materials and deposition processes, time to failure, conditions of failures, and other reliability characteristics. There is therefore the need to design a coating material and deposition process model for wear and other failure mode applications and apply IRCMM with a multivariate and TI model–based program to verify and validate the selected researched data.

The TI model for optimum selection of materials is expressed as $Y_i = a_i Y_{i-1(\text{opt})}^{b_i}$ [20]. The model is used to determine the maximum achievable reliability, quality, and time to failure, condition of failures, and maintenance costs of materials and parts and has been used to develop an IRCMM program. It consists of TICSs for component/process reliability degradation controls. The sensor can be used to measure the reliability growth and the optimum threshold values for selecting the most cost-effective coating materials, its coating deposition process, and maintenance strategy. The sensor can also be used to measure reliability degradation and failures and determine the maintenance costs. The developed multivariate quality regression and TI models are used to verify and validate the following results:

The multivariate quality part surface regression model is used as the initial data, $Y_{i-1(\text{opt})}$, for evaluating the TI model:

$$Y_i = a_i Y_{i-1(\text{opt})}{}^{bi} \tag{6.15}$$

where
- a_i is the TI coefficient for quality–reliability control
- b_i is the TI coefficient for process condition control
- $Y_{i-1(\text{opt})}$ is the initial quality of a mating part in an equipment
- Y_i is the final quality of the mating part, which can also serve as the baseline requirements for other parts that make the system work
- When $b_i = 0$, $Y_i = a_i$

The condition of failure threshold points of a component and process can be expressed as

$$Y_{\text{d(max)}} : a_{\text{d(max)}} : Q_{\text{fd(max)}} : R_{\text{kd(max)}} = 1.0 \tag{6.16}$$

$$X_{\text{d(max)}} : b_{\text{d(max)}} : P_{\text{fd(max)}} : R_{\text{kd(max)}} = 1.0 \tag{6.17}$$

$$Y_{\text{dmax(stress)}} : a_{\text{d(max)}} : R_{\text{kd(max)}} = 1.0 \tag{6.18}$$

$$Y_{\text{dmax(HRC)}} : a_{\text{d(max)}} : R_{\text{kd(max)}} = 1.0 \tag{6.19}$$

$$Y_{\text{dmax(T)}} : a_{\text{d(max)}} : R_{\text{kd(max)}} = 1.0 \tag{6.20}$$

$$Q_{\text{fd(max)}} : R_{\text{kd(max)}} = 1.0 \tag{6.21}$$

$$X_{\text{dmax(current)}} : b_{\text{d(max)}} : R_{\text{k(max)}} = 1.0 \tag{6.22}$$

$$P_{\text{fd(max)}} : R_{\text{kd(max)}} = 1.0 \tag{6.23}$$

Between the interval of $Y_{\min}$ and $Y_{\max}$, the quality and reliability of a part/equipment and, between $X_{\min}$ and $X_{\max}$, the performance and reliability also continue to grow positively towards a maximum achievable value, which is known as the reliability growth (R_g), performance growth (P_{fg}), and quality growth (Q_{fg}). Also, the reverse interval of $Y_{\max}$ to $Y_{\min}$ and $X_{\max}$ to $X_{\min}$, the quality and reliability of part/equipment and process performance, respectively, continues to degrade negatively toward a minimum acceptable value. This degradation is known as reliability degradation coefficient, (R_{kd}), performance factor degradation, (P_{fd}), and quality factor degradation, (Q_{fd}). The interval between the minimum acceptable growth/degradation and maximum achievable growth/degradation is regarded as the baseline trend/curve of growth and optimal degradation. Any deviation from the baseline or curve is a result of a fault, defect, and age that can develop into failures. The baseline and curve trend can be plotted for reliability, quality, and failure resistance of materials and parts against the operating conditions of manufacturing processes and equipment as well as the production time and life cycle/maintenance costs. Any deviation and behavior of materials and process conditions can be observed from the normal curve (integrated reliability mechanism), and this can be used for monitoring and maintenance at any time or any point throughout manufacturing processes and equipment operations. With this trend of reliability growth, reliability degradation, potential failure, functional failure, and time to failure, defects, failure rates, maintenance costs, and other maintenance characteristics can be determined.

6.5.1 Mean Time to Failure

The mean time to failure (MTTF) is calculated as follows:

$$\text{MTTF} = \frac{\sum \{\text{period between detection and failure}\}}{n_\text{f}} \tag{6.24}$$

where
the period is the total sum of the time between detection and failure of all failures
n_f is the number of failures

With the TI model for quality degradation, $Q_\text{d} = a^*Q_\text{opt}$, or $Y_\text{d} = a^*Y_{i-1(\text{opt})}$, for part's conditions, but for process conditions, $b_\text{opt} = X_{i\text{opt}}$. At this level, the manufacturing process is running with optimum conditions as a baseline and any deviation from this optimum baseline is a degradation, fault, and defect, which may eventually lead to failure. The time of degradation, fault, defect, and failure can also be determined with the TI coefficient a_i.

Therefore, with respect to time,

$$\text{MTTF} = \frac{\sum \{T_\text{f} - T_\text{d}\}}{n_\text{f}} \tag{6.25}$$

where
T_f is the time of failure
T_d is the time the failure was detected

In terms of the TI coefficient, MTTF can be expressed as $a_f : a_d = T_f$ and T_d can be expressed as

$$\text{MTTF} = \frac{\sum \{a_f - a_d\}}{n_f} \tag{6.26}$$

6.5.2 Mean Time for Corrective Maintenance

The mean time for corrective maintenance is calculated as follows:

$$M_{CM} = \frac{\sum \{\text{time for repair/maintenance}\}}{n_f} \tag{6.27}$$

where
time for repair is the total sum of the time spent for repairing the faults/defects in Equation 6.27
n_f is the number of corrective maintenance tasks

6.5.3 Maintenance/Repair Cost

The maintenance/repair cost is calculated as follows:

$$M_c = \frac{\sum \{\text{cost for repair/maintenance}\}}{n_f} \tag{6.28}$$

With the TI model,

$$M_c = a^* M_{c(N)} \tag{6.29}$$

where
M_c is the repair/maintenance cost
$M_{c(N)}$ is the cost of a new part

6.5.4 Failure Rate

The failure rate is calculated as follows:

$$\lambda = \frac{1}{\text{MTTF}} \tag{6.30}$$

With the TI model, $R_{k(d)}$—reliability degradation—is expressed as

$$R_{k(d)} = \int_{Td}^{Tf} Q_{(opt)} d_T \tag{6.31}$$

For reliability growth,

$$R_{k(g)} = \int_{Td}^{Tf} P_{k(opt)} d_T \tag{6.32}$$

6.6 Optimum Component/System Reliability Selection

Optimum selection conditions for input requirements of a mathematical model design for maximum achievable reliability and its corresponding service time of a particular critical parts and equipment is possible with TI coefficients. The following variables: sections 6.61–6.67 can be used to determine integrated reliability data as seen later.

6.6.1 Independent Variables

The following are the independent variables used to determine integrated reliability data:

- a_i—the TI coefficient for the control of reliability for the quality parameters of parts A, B, C and the industrial processes and equipment system
- Y_i—integrated reliability of part's and system's multiple parameters
- b_i—TI coefficient for the control of the operating conditions of processes and equipment reliability

6.6.2 Dependent Variables

The following are the dependent variables used to determine integrated reliability data:

- Y_i − 1opt—the optimum inherited reliability of parts from the preceding to the operating process or equipment
- X_i—the reliability of operating processes and equipment

- Optimum $a = Y_{i-1\text{opt}}$(dimensionless)
  - Y_i—the reliability of parts A, B, C
    - Part A—wear resistance
    - Part B—corrosion resistance
    - Part C—high-temperature resistance

6.6.3 Multiple Quality Parameters of Parts A, B, C (y_i)

- y_1—surface hardness
- y_2—surface roughness
- y_3—surface wavelength
- y_4—stress concentration factor
- y_5—precision coefficient
- y_n—others

6.6.4 Conditions of Industrial Processes and Equipment (x_i)

- Production processes
- Metallurgical
- Coating deposition
- Machining
- Grinding
- Industrial equipment
- Generator
- Motor
- Compressor
- Turbine
- Pump
- Machine parts
- Rotary shafts
- Bearings
- Others

6.6.5 Coating Materials for Wear, Corrosion, and High-Temperature Resistance

- Metcoloy 10
- Nickel-based alloys
- Ferromagnetic metals

6.6.6 Coating Deposition Techniques

- Plasma spraying
- Arc spraying
- Flame spraying
- Electromagnetic coating

6.7 Reliability Testing for Optimum Condition and Failures of Coating Materials with Multivariate Regression and TI Model–Based Design

An integrated reliability monitoring and maintenance software program with a combined model-based design is used to test, analyze, evaluate, and select the optimum variant of the coating materials and production processes. Quality, reliability, and maintenance cost data are measured with TICSs or with reliability data acquisition device applying multivariate regression and TI models. The reliability growth of the materials and hard-coated machine part is measured during metallurgical and coating deposition process operations with the use of TICSs. The reliability growth data can also be assessed and predicted with the multivariate regression model. The optimum part condition parameters for any particular failure mode (e.g., wear, corrosion, temperature, fatigue) are determined experimentally to set the quality–reliability–maintenance cost requirements together with the TI coefficient conversion table. The optimum coating material; part and process condition parameters for wear, corrosion, and high-temperature resistance; and the reliabilities of the coating material, parts, and its deposition technique can be determined cost-effectively with the help of an integrated reliability computer network program. The data collected can be used for integrated reliability monitoring and maintenance of materials and parts during manufacturing processes as shown in Figure 6.3.

Manufacturing process types:

1. Metallurgical process
2. Coating deposition process
3. Machining process

Where there is no suitable existing coating material that matches with the base material and deposition technique or due to suboptimum conditions, new component condition parameters for the desired materials, parts, and processes should be designed with the help of the TI

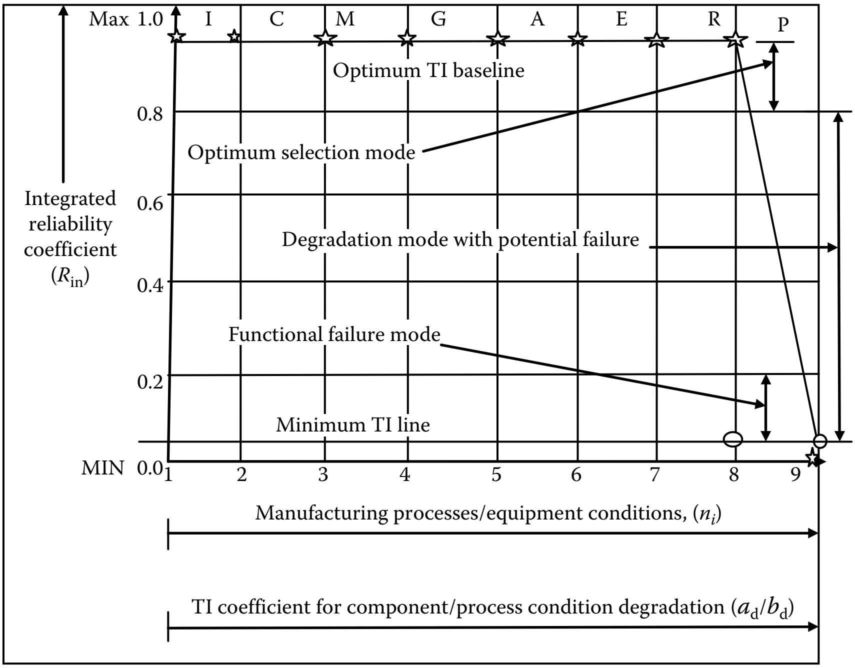

FIGURE 6.3
IRCMM curve with optimum, degradation, and failure conditions of manufacturing processes and systems.

model. In the case where any of the existing coating material and coating deposition techniques are used without the TI technique, possible measurement errors and suboptimum selections are bound or may occur within the process, which could definitely cause damages, false probabilities, and negative inheritance consequences in the subsequent production and service operations. When this potential false reliability is detected early enough within the process with the use of an integrated reliability maintenance-monitoring software program, the reliabilities of materials, parts, and processes are improved.

The designs of the models for materials and parts (Y_i) as well as software defined measurement and instrumentation programs for optimum selections of materials and coating deposition processes as well as for reliability testing and IRCMM analysis with the help of TI coefficients. The TI coefficient *a* is used to measure component and material reliability growth as well as their optimum reliabilities with the TICS. The TI coefficient *b* is used to measure process performance loss and its optimum performance with multivariable performance sensor. An IRCMM software program may include the features of TICSs for measuring component reliability and process performance factors, TI coefficient conversion reliability requirement table, data acquisition device to acquire data, integrated reliability monitors, and integrated reliability test device to analyze, diagnose, transfer, and present data for a cost-effective IRCMM of materials and metallurgical and coating deposition processes.

An IRCMM curve is designed to highlight the relationship between component materials/process quality, reliability and maintenance characteristics and TI coefficients *a* and *b* is shown in Figure 6.3. These curves can be used for optimum selection, cost-effective maintenance, and determination of maintenance cost as well as for cost-effective management.

With the integrated reliability mechanism, it is possible to carry out proactive maintenance from the initial stage to the final stage in material and deposition processes. The graph highlights the fact that as the hardness of the material increases, the wear resistance of the component also increases. It is also true from the graph that the optimum operating deposition process conditions offers a higher value in hardness than the optimum metallurgical process condition for wear-resistant applications. The workpiece's hard alloy surface condition will be subject to machining and grinding to suit the desired component and system reliability requirements for a particular application. This is now possible with IRCMM together with a TI model–based program through reliability growth and degradation assessment of hard alloy–coated material, metallurgical, coating deposition, machining, grinding, and equipment operations.

6.8 Conclusions

1. This work has ascertained that environmental regulations and performance requirements of materials, parts, processes, and equipment have become stringent, while industries and companies are now looking for better superalloy high-temperature materials and near-net-shape processing technologies at reduced cost of raw materials, parts, processes, equipment, manufacturing, and maintenance operations.
2. Most existing tools, materials, and process models are inadequate for predicting and validating the desired material properties and performance requirements in the manufacturing processes as well as detecting failures throughout the stages of manufacturing and service operations.
3. Industrial experiences have proved that the casting of titanium-based parts and other hard alloy–coated part surfaces requires labor-intensive repetitive monitoring of material properties and component performance in the production processes and service

operations, which adds the cost of attaining maximum achievable quality, reliability, and performance.

4. Maximum achievable reliability, performance, and durability of component/system are presently difficult to design, since there are still so many variables like wear, manufacturing processes, assembly, hard alloy–coated material nonhomogeneity, and residual stresses that analytical durability analysis cannot adequately consider with the existing methodology, tools, and models.
5. There is therefore the need to design a multivariate regression model that can determine the maximum achievable quality and reliability requirements for coating materials for wear- and other failure-resistant applications.
6. This book has outlined the common industrial problems as wear, corrosion, and high-temperature failure modes as well as materials modeling/database development for the IOF industries.
7. It has been ascertained from industrial experiences that the hardening of machine part surfaces with selected specialized hard alloy–coated materials for wear-, corrosion-, and high-temperature-resistant applications has helped to enhance system reliability, but requires a desired process, component, and service condition requirements.
8. Researchers have ascertained a typical hard alloy–coated material service condition to be comprising of the following characteristics: The wear resistance of hard alloy coating in frictional contact with steel (friction of boundary lubrication) is 4–9 times higher than the wear resistance of steel in steel–steel and steel–iron pairs under specific loads of 1.5×10^6 to 10×10^6 Pa and sliding velocities of up to 8–54 m/min; within this range, the amount of wear of steels working in pairs with hard coatings is reduced by 1.5–2.5 times, while the friction coefficient in pairs of hard coating steel with initial roughness number R_a = 0.16–0.3 μm is 1.8–2.2 times lower than in pairs of steel–steel, but with a more efficient finished surface roughness, the amount of wear will be 2–10 times reduced with the help of a TI model–based program.
9. The optimum selection and design of cost-effective hard alloy–coated materials, deposition processes, hard-coated parts, monitoring, and maintenance strategies are possible with the help of a multivariate regression model, which is also used to predict optimum component quality and process performance conditions.
10. The optimum component quality and process performance conditions are selected or designed as the baseline requirements for all components and processes of a system as well as input data for the TI model.

11. The introduction and application of the TI model and multivariate regression model has now made it possible to provide real-time measurements of component properties like hardness and residual stress and dimensional accuracy like surface roughness, surface wavelength, and component growth/degradations, which have helped to enhance a better understanding and relationship of the quality of materials, processes, parts, and equipment during manufacturing, maintenance, and service operations towards maximum achievable quality, reliability, and performance.
12. The application of the TI model and multivariate model for component/system assessment within manufacturing processes and monitoring and maintenance operations enables the TICS and integrated reliability monitor to be designed and components/systems to be operated cost-effectively and maintained with precision maintenance strategy in order to meet their desired durability, reliability, and performance at reduced costs of raw materials, parts, and equipment.
13. With TICSs and integrated reliability monitor, it is possible to select the optimum conditions of materials; predict the maximum and minimum resistance to wear, corrosion, temperature, fatigue, and time to failure; and detect the root causes of failures, reliability, and other performance characteristics.
14. The TI model is used to integrate different component failure modes within a single metric and also uses TI coefficients to determine the failure-resistant conditions or the reliability of components/systems as well as integrate reliability, CM, and maintenance operations of processes, parts, and equipment.
15. The service and maintenance operations in many industries are still reactive due to problems arising from the incomplete understanding of the day-to-day behavior of materials, parts, processes, and equipment as well as the lack of methods for determining the factors involved in parts and equipment breakdown, but the IRCMM program together with the TI model provides the development of smart, reconfigurable condition monitoring and maintenance tools to reduce the production time and reduce dimensional variations caused by process performance degradations.
16. The IRCMM program together with the TI model provides a model and sensor that select the optimum requirements for material and deposition process modeling/database development in the IOFs.
17. The overall reliability of parts and equipment with optimum reliabilities of hard alloy–coated materials and deposition processes would also require suitable surface finishing methods to achieve maximum wear-, corrosion-, and high-temperature-resistant characteristics that meet the desired applications of the IOFs.

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7

Reliability Growth Condition of Coating Material and Deposition Process with a Technological Inheritance Model–Based Program

7.1 Existing Selection of Part Surface Coating Material and Deposition Process for Wear and Other Competing Failure Resistance Applications

The selection of a proper coating material for maintenance is the most important step in carrying out such task successfully as seen in the previous chapter. Each coating material has different characteristics, such as strength, shrinkages, and hardness, so there is a material for almost every purpose, which can be predicted with our developed multivariate quality regression model.

When a metallic wire is sprayed, it forms an alloy different from the original one, which therefore means that when choosing a coating material it is necessary to always consider the properties of coating materials for deposition and not just the properties of the original metallic wire. As a result of *spraying*, all sprayed metals are porous and brittle as compared with the wire from which it was sprayed. When metal is sprayed, it tends to shrink slightly and hence set up internal stresses. The real strength of any sprayed coating is the difference between its original inherent strength and these internal stresses. Since the stresses are produced by shrinkage, those metals, which shrink least, will have the least internal stresses. Sprayed metals, which have high tensile strengths and low shrinkage factors, will obviously give the strongest coatings, which are least likely to crack or lift. These points are very important and they explain why wire for spraying should be chosen on the basis of the properties of metallic materials and not on the basis of imitation and consideration of the parent materials.

In general, the maintenance welder will be required to use absolute specifications, in which case the filler metal and welding procedures are spelled out for him or her, where he or she must make a choice [1–6].

In the absence of a specification, if the welder can identify the parent material, he may match the filler material to the parent material as closely as possible. If he cannot identify the material, other than that it is a higher nickel alloy, for example. The best practice is to stay with the higher nickel content and choose the other alloying elements according to his knowledge of what those elements might contribute to the weld deposit under weldment's in service environment.

When depositing comparatively thin coatings on known parent materials, any metal can be sprayed successfully since the metal is chosen with respect to its hardness and wear resistance characteristics or machinability or its corrosion resistance properties. This type of coating is usually carried out on the majority of parts for thin coatings up to 1.5 mm (0.06″).

Surface roughening is generally necessary for coatings over 1.5 mm (0.06″) thickness wherever there is an edge, such as a key way. In this case, high shrinkage metals, such as Sprasteel 10 or Metcoloy 1, should be used. They are also used for coatings over 3 mm (0.03″) thickness wherever there are no edges (such as continuous coatings on cylindrical surfaces, where the conditions of service are extremely severe, where there is danger of layer separation in the coating, or where the coatings are heavy and high shrinkage metals so that danger of cracking exists) [2].

Metcoloy 2 and Sprasteel 10 have the highest properties. Sprasteel 10 should be used for heavy coatings and where the coatings could be machined on a lathe since it can easily be machined by the use of hard alloy tool bits with emulsion lubrication. It hardens during machining and aging, thereby providing high wear resistance properties for machinable steels.

In cases where coating metals are chosen for wear resistance and hardness, steels are machinable on lathes, and where grinding equipment is available, it is recommended to use Metcoloy 2 for heavy coatings with the highest shrinkage.

In cases where service conditions demand maximum hardness and wear resistance, it will be necessary to consider hard alloys like Metcoloy 2, Sprasteel 80, nickel-based alloys, and self-fluxing alloys (16C, Metco 19E).

To finish, Metcoloy 2, which is a stainless steel with a high composition of chromium possessing high corrosion and wear resistance qualities, is the best of all the steels for treating machine parts. It is recommended for cases that demand hard coatings, where corrosion resistance is not essential. This material has a high tensile strength and high shrinkage properties and in practice does not undergo lifting or galling when deposited on shafts. It is not recommended in those cases where high corrosion resistance is a requirement. It can be machined on a lathe with hard alloy tool bits, even at low cutting speed. The best results are obtained by grinding.

Examples of applications include shaft fittings, incorrect machine parts, plain surfaces of all kinds, cylinder sleeves, pistons, valve rods, pump plungers, ring seals, sleeve cover, valve lids, hydraulic press plungers, bearings of crankshafts, and shaft–bearing assemblies.

In order to maximize the output of machinery, it is necessary to make wide use of parts with hardened surfaces, increase the quality of restoration and repair of machine parts, and improve the methods of hardening and reconditioning. Deposition of wear-resistant coatings is a present-day trend in the improvement of the quality, reliability, and service life of machines. The selected hard coating materials in the previous chapter with considerable thickness partially differ in chemical composition and can be classified with respect to the techniques and processes of coating deposition. This type of classification further helps in selecting suitable materials that meet desired reliability requirements and service applications.

7.2 Coating Deposition Techniques and Processes for Wear, Corrosion, and Temperature Failure Resistance Applications

The various techniques of coating deposition are described in [7,8] and may be presented in the following classification:

1. Diffusion deposition of coatings
2. Welding
3. Spraying
4. Fusion
5. Gaseous or vapor–gaseous phase deposition
6. Deposition from solutions
7. Cladding
8. Immersion
9. Surface sintering
10. Electrochemical deposition
11. Combined methods

Hardening and reconditioning of parts with the aid of coatings of considerable thickness are successfully achieved by methods 2, 3, 4, 7, 8, 9, and 11, among which spraying without fusion and with subsequent fusion, fusion welding, and combined methods have found wide application due to their adaptability to manufacture and high efficiency.

At the same time, it should be noted that a production procedure of coating deposition is closely related to the chemical composition of a deposited material. In accordance with this, the materials are subdivided into the following groups:

1. Granulated powders (GPs) used for powder fusion welding.
2. Granulated and high-alloy powder mixtures used for thermal spray with subsequent fusion.
3. GPs and composite thermo-reactive powders used for gas-powder spray without subsequent fusion. In addition, the choice of a production procedure depends on the state of the delivered material. Thus, powder materials produced with granulometric composition can only be used for fusion welding or for spraying, while fusion of the deposited coatings or loose powders is recommended to be done with the aid of a high-frequency current flame torch, a laser beam, and other heat sources [2,7]. In addition to powders, materials intended for the hardening and reconditioning of machine parts are manufactured as powder wires, welding wires, fusion-welding wires, electrodes, strips, etc. The most widely used fusion-welding wires in hardening and reconditioning processes are made of steels. In general, the most popular heavy coatings are those based on iron or (self-fluxing) nickel using thermal spraying process.

7.2.1 Thermal Spraying Techniques and Processes

The demands for engineering coatings are becoming more and more stringent. Environmental concerns are also being considered as an integral part of the design process. For future economic competitiveness and a lower environmental impact, we must therefore turn our attention to processes that use the minimum of resources. Thermal spraying is an attractive coating technique as it offers a wide choice of materials and processes that have a reduced impact on the environment when compared to conventional plating processes. Thermal spray coating techniques such as flame spraying, wire arc spraying, and plasma spraying allow many problems of wear, corrosion, and thermal degradation to be resolved by engineering the surface with tailor-made coatings. For example, turbines can be coated by thermal spraying, allowing their use at higher temperatures.

In the thermal spraying process, heated and melted particles are propelled toward a substrate where they are flattened and quenched very rapidly. A thermally sprayed coating consists of layers of splats, which have a lamellar cross section. Typically the cooling rate of each splat is somewhere in the vicinity of one million degrees per second. This rapidly quenched microstructure can have unique characteristics quite unlike those produced by conventional processing techniques, for example, the extension of solid state solubility, refinement of grain size, formation of metastable phases, and a high concentration of point defects.

There are many variations of thermal spraying technology. In flame spraying, the combustion of a fuel gas is used to heat the material. In atmospheric plasma spraying (APS), the material is melted and accelerated in a plasma jet. To avoid oxidation of the feed material, spraying can be carried out in an inert gas atmosphere, at a reduced pressure (known as vacuum plasma spraying [VPS] or low-pressure plasma spraying [LPPS]). In high-velocity oxyfuel (HVOF) spraying, the material is injected into a high-velocity jet generated by burning a fuel mixed with oxygen at high pressure. Compared with traditional surface modification processes, thermal spraying offers greater thickness capability and no part size restrictions, can be performed in situ, and produces minimal noxious waste. High processing temperatures allow deposition of many high melting point materials onto a relatively cold substrate.

Thermally sprayed coatings have, in recent years, gained widespread acceptance for a variety of industrial applications—the global market for thermally sprayed coatings is currently about $1.35 billion. This growth has been primarily technology led, and high-value plasma coatings hold the lion's share of the market. A vast majority of these applications involve wear resistance, although the use of thermally sprayed coatings in combating high-temperature corrosion also continues to receive considerable industrial and academic interest. These sprayed coatings are applied in order to achieve predetermined life periods under severe operating conditions. For example, thermally sprayed coatings have been used extensively to prevent stress corrosion cracking in high-strength low-alloy steels used for liquid petroleum gas tanks. Other surface properties and functions that are thermally sprayed with coatings can provide beneficial compatibility, electrical resistance/conductivity, thermal barriers, and dimensional restoration.

Extensive use of thermal spray technology has been instrumental in Europe attaining worldwide leadership in the paper and textile industry. Pioneering applications of thermally sprayed wear-resistant coatings to blades, rolls, and looms have allowed a significant increase in production rates. The aeronautic and space industries have also benefited considerably—many components in modern aircraft depend on hard, wear-resistant coatings that can withstand temperatures of about 850°C. This type of application represents approximately 40% of the total market.

Surface protection at high temperatures has become one of the most advanced fields of modern engineering. Diverse examples include rocket thrust chamber linings, chemical reaction vessels, combustion vanes and land-based turbines for aircraft, and hot extrusion dies. These coatings usually consist of carefully selected ceramic and metal layers that provide adequate thermal fatigue resistance and corrosion protection. The use of protective coatings for corrosion prevention has grown rapidly during the past decade, and thermal spray coatings represent a significant portion of this growth based on mechanical properties.

7.2.2 Thermal Spraying: High-Velocity Oxyfuel, Arc, and Flame Processes

The fundamental principles of all thermal spraying processes are similar. A powder or wire is fed through a spray pistol, heated until molten or soft, and sprayed at speed onto a substrate to form a coated surface. The density of the coating is dependent on the material, the state of the particle (solid/liquid ratio) on impact, and the particle velocity. The bond between a sprayed coating and the substrate is primarily mechanical (and not metallurgical or fused). Adhesion of the coating to the substrate depends on all of these factors plus the condition of the substrate surface, which must be clean and roughened by grit blasting or machining prior to spraying. Thermal spraying processes have been widely used for many years throughout all the major engineering industry sectors for component protection and reclamation. Recent equipment and process developments have improved the quality and expanded the potential application range for thermally sprayed coatings. Thermal spraying is divided into four main categories:

1. HVOF spraying
2. Plasma spraying
3. Arc spraying
4. Flame spraying

The benefits of thermal spraying are as follows:

- Comprehensive choice of coating materials: metals, alloys, ceramics, cermets, and carbides.
- Thick coatings can be applied at high deposition rates.
- Coatings are mechanically bonded to the substrate—can often spray coat materials that are metallurgically incompatible with the substrate, for example, materials with a higher melting point than the substrate.
- Components can be sprayed with little or no pre– or post–heat treatment, and component distortion is minimal.
- Parts can be rebuilt quickly and at low cost and usually at a fraction of the price of a replacement.
- By using a premium material for the thermal spray coating, coated components can outlive new parts.
- Thermal spray coatings may be applied both manually and automatically.

A comparison of the thermal spraying process and coating characteristics is shown in Table 7.3.

7.2.3 Plasma Spraying

The plasma spraying process uses a dc electric arc to generate a stream of high-temperature ionized plasma gas, which acts as the spraying heat source. The coating material, in powder form, is carried in an inert gas stream into the plasma jet where it is heated and propelled toward the substrate. Because of the high temperature and high thermal energy of the plasma jet, materials with high melting points can be sprayed. Plasma spraying produces a high-quality coating by a combination of a high-temperature, high-energy heat source, a relatively inert spraying medium, and high particle velocities, typically 200–300 m/s. However, some air becomes entrained in the spray stream and oxidation of the spray material may occur. The surrounding atmosphere also cools and slows the spray stream. VPS or LPPS reduces these problems by spraying in vacuum or a low-pressure, inert gas environment. Plasma spraying is widely applied in the production of high-quality sprayed coatings:

- Spraying of seal ring grooves in the compressor area of aeroengine turbines with tungsten carbide/cobalt to resist fretting wear
- Spraying of zirconia-based thermal barrier coatings (TBCs) onto turbine combustion chambers
- Spraying of wear-resistant alumina and chromium oxide ceramic onto printing rolls for subsequent laser and diamond engraving/etching
- Spraying of molybdenum alloys onto diesel engine piston rings
- Biocompatible hydroxyapatite coatings for prostheses

7.2.4 Flame Spraying

Flame spraying is part of a wider group of coating processes known as thermal spraying. In these processes, a consumable (usually a powder or a wire) is heated and propelled onto a substrate to form a coating. Flame spraying is the oldest of the thermal spraying processes. A wide variety of materials can be deposited as coatings using this process and the vast majority of components are sprayed manually. Flame spraying has distinct advantages, including ease of application and low cost, compared with the other spraying processes. These benefits make it a widely used process. Table 7.1 highlights the typical performance of flame spraying compared with the other thermal spraying processes.

Flame spraying uses the heat from the combustion of a fuel gas (usually acetylene or propane) with oxygen to melt the coating material, which can be fed into the spraying gun as a powder, wire, or rod. The consumable types give rise to the two process variants:

1. Powder flame spraying
2. Wire flame spraying

TABLE 7.1

Comparison of Thermal Spraying Process and Coating Characteristics

Thermal Spraying Processes	Particle Velocity (Ms^{-1})	Adhesion (MPa)	Oxide Content (%)	Porosity (%)	Deposition Rate ($Kghr^{-1}$)	Typical Deposit Thickness (mm)
Flame	40	<8	10–15	10–15	1–10	0.2–1.0
Arc	100	10–30	10–20	5–10	6–60	0.2–10
Plasma	200–300	20–70	1–3	5–10	1–5	0.2–2
HVOF	600–1000	>70	1–2	1–2	1.5	0.2–2

For the powder flame spraying process, the powder is fed directly into the flame by a stream of compressed air or inert gas (argon or nitrogen). Alternatively, in some basic systems, the powder is drawn into the flame using a venturi effect, which is sustained by the fuel gas flow. It is important that the powder is heated sufficiently as it passes through the flame. The carrier gas feeds powder into the center of an annular combustion flame where it is heated. A second outer annular gas nozzle feeds a stream of compressed air around the combustion flame, which accelerates the spray particles toward the substrate and focuses the flame. In the wire flame spraying process, the wire feed rate and flame settings must be balanced to produce continuous melting of the wire to give a fine particulate spray. The annular compressed airflow atomizes and accelerates the particles toward the substrate.

7.2.4.1 Failure Resistant Applications

Flame spraying is widely used where lower coating costs are desired and a lower coating quality can be tolerated. Some typical applications include the following:

- Corrosion protection of structures and components (e.g., bridges, off-shore platforms, blades with aluminum or zinc coatings. Aluminum is more expensive but has resistance to acidic gaseous atmospheres (such as those associated with the products of fossil fuel combustion), as well as neutral solutions, such as salt water. Zinc has resistance to alkaline corrosion. Flame spraying is also used to spray corrosion-resistant thermoplastic polymer coatings.
- Reclamation of worn shafts, particularly of bearing areas with materials such as stainless steel or bronze alloys. The coatings produced are quite porous and lubricants can be absorbed into the coating, enhancing the performance of the bearing.

7.2.4.2 Coating Quality

Two key areas that affect coating quality are surface preparation and spraying parameters. Surface preparation is important for coating adhesion and can affect the corrosion performance of the coating. The main factors are grit blast profile and surface contamination. Spraying parameters are more likely to affect the coating microstructure and will also influence coating performance. Important parameters include gun to substrate orientation and distance, gas flow rates, and powder feed rates. The bond of a thermally sprayed coating is mainly mechanical. However, this does not allow the bond strength to remain independent of the substrate material. There are significant differences between spraying onto carbon steel and stainless steel, for example. This may be due to surface oxide or thermal expansion, and such factors should be considered before applying the coating. All thermal spray coatings contain a degree of internal stress. This stress gets larger as the coating gets thicker. Therefore, there is a limit to how thick a coating can be applied. In some cases, a thinner coating will have higher bond strength.

7.3 Mechanical Properties

The mechanical properties of coatings depend strongly on their microstructure and especially on the porosity and the interlamellar contacts. These depend heavily on the consumables and processing route used. Hardness is one of the key properties of a thermally sprayed coating, as this is often used to give a first approximation of coating wear resistance. Measurements of hardness also allow a quick estimation of coating strength and the quality of spraying, because specific processing defects, such as porosity and unmelted grains, can lower coating hardness.

Carbides and oxides are the hardest thermally sprayed coatings, the most commonly sprayed being WC–Co cermets. Cermets and ceramic coatings are therefore the most suitable for wear applications. The elastic moduli of the A13S sprayed coatings are significantly less than the bulk material. Carbides and oxides typically have a modulus, which is 20%–30% of the bulk value, though this value is heavily dependent on the processing route. Sprayed metal coatings generally have a modulus of about 30% of the bulk value, although this may be comparable with the bulk properties for coatings produced using the LPPS system. The developed multivariate quality regression model can be used to predict the most suitable hardness to the desired service application as well as a technological inheritance (TI) model for its validation and assessment of system reliability growth and degradation. One of the most challenging goals for thermal spray technology is barrier-type coating for corrosion and wear resistance because almost complete removal of through-porosity is required.

Thermally sprayed coatings may not be the answer to every problem involving surface degradation of a component; they are just one weapon in an arsenal. However, the technique does offer a great range of coating operations and provides an appealing opportunity for innovation while putting less pressure on environmental resources as experienced in the different industries of the future.

7.4 Industrial Experience of Thermal Spraying Processes for Failure Resistance Applications

There has been a widespread use of powder materials for maintaining machine parts in different countries over the last decades. Different deposition techniques have been adopted and those mostly used are flame and plasma spraying [2,7,9]. The Metco company has achieved great success in the introduction of flame spraying of wear-resistant coatings.

The technological process of powder deposition consists of preparation of a workpiece surface buildup with sprayed powder and machining of the coating. To achieve a high bonding of the coating with the base, it is necessary to grind to size and machine with corundum crumbs to provide the required surface roughness. After heating the substrate, a thin layer of powder (nickel–aluminum) is deposited. This mixture provides a good bond with the base while the coating layer is deposited on this sublayer. The coating can be of any thickness, although there exists a limit in the size of parts, which can be coated. Grinding and sometimes polishing do the finishing. The specialists of Metco believe that flame spraying is a long-term protective technique for hardening and reconditioning machine parts. This technique for hardening and reconditioning machine parts is able to increase the service life of a part by 2–20 times (depending on the function of the part).

For coating deposition, the company produces the following equipment:

Metco 44: For reconditioning parts having a small amount of wear (after coating, it undergoes machining)

Metco 51: For spraying bronze coatings on bushings and impellers for pumps

Metco 451: For depositing coatings on shaft journals, cylinder sleeves, pump plungers, and other components that demand highly corrosion-resistant coatings

The use of flame spraying of powder materials is widespread in Germany. The technique is used to recondition shaft fits, pins, crank and camshafts, holes on covers and cases, etc. The technological process of flame spraying consists of a workpiece preparation (lathe machining, grinding, or abrasive machining), deposition of coatings (size of grains between 40 and 80 μm), and mechanical machining (turning with high-alloy materials or grinding with corundum or silicon carbide wheels depending on the type of powder). Before depositing the base layer on a workpiece, it is spread with aluminum powder in a nickel sheath. Grinding usually finishes the technique of depositing coatings with laser fusion.

In Bulgaria, flame powder spraying is used to recondition engine valve using WC powder in a nickel matrix. The hardness of the coated layer is 52–62 HRC. The different known hard alloy powder has high wear resistance. The most interesting is the alloy type *Ekefem (nickel-based hard alloy coatings),* patented by the technical institute of the Ministry of Agriculture and food Industry in Bulgaria [9]. It is used to increase the service life of agricultural machine tools. The composition consists of carbide of chromium and boron. The coating is deposited by spraying consumable dissolving electrodes of powder alloys. In Czechoslovakia, flame spraying is used to reclaim plowshares and other agricultural machine digging tools [10]. Plasma deposition of metallic powder with subsequent grinding is being used in Poland for depositing coatings on machine parts like valves, differential gear case, and shaft [10]. This type of technique is also widely used in Czechoslovakia for reconditioning inlet and outlet valves of engine. Plasma spraying in Germany is used for reconditioning fits of connecting rods, shafts, and water pump covers in a specialized repair workshop.

7.5 Recommendations and Its Future

Analysis of literature sources and the experiences of thermal spraying of machineries in the repair industries have enabled us to clarify trends in the usage of powder hard coating materials for the reconditioning of parts by gas flame and plasma spraying. The three methods of flame used for reconditioning and hardening parts are

1. Without fusion
2. With subsequent fusion
3. Direct fusion

Flame spraying without fusion is recommended for reconditioning surface fits of cylinder sleeve, fit portions under plain bearings of certain shafts, agricultural machine tools, etc.

Flame spraying with subsequent fusion is used to recondition inlets and exhaust valve plates.

Welding is also of importance; it is recommended for reconditioning camshafts, face tappets, eccentric cams, agricultural machine tools, etc. This technique is successfully used in different repair workshops of agricultural machinery industries.

Plasma deposition of coatings is used in different branches of manufacturing for increasing the reliability of machines with salvaged parts requiring high wear resistance. The use of this technology on worn surfaces of camshafts helps to increase the service life and reliability of machines.

Inasmuch as it is of considerable importance to use the earlier stated recommended techniques and hard coatings for metal to metal sliding and abrasive applications in machine components, it is not always necessary to use sophisticated materials to combat wear in soil-engaging components. In some instances, carbon steels and cast irons have good wear resistance as recommended in the works [10]. In other cases like abrasive wear by soil, there is little benefit from using expensive hard coatings by spraying. Thus, we must continue to look for progressive cost-effective coating materials and techniques in the future, even as we now have the opportunity to use the multivariate quality regression model to predict and select desired materials and apply the TI model to control and monitor the techniques and processes to meet user's requirements at minimum maintenance costs.

7.6 Reliability Test for Growth of Hard Alloy–Coated Materials and Workpiece Surface Optimum Conditions with a TI Model–Based Program

Integrated reliability monitoring and maintenance with a TI model–based program is used for testing and selecting the optimum variant of the coating material and deposition process as well as for monitoring and maintenance of systems. The program is based on multivariate regression and TI models. With the multivariate regression model, you can plot the critical workpiece surface hardness and surface stress concentration factor versus operating current of the manufacturing processes and equipment as shown in Figures 7.1 and 7.2. The figures will help to predict the best

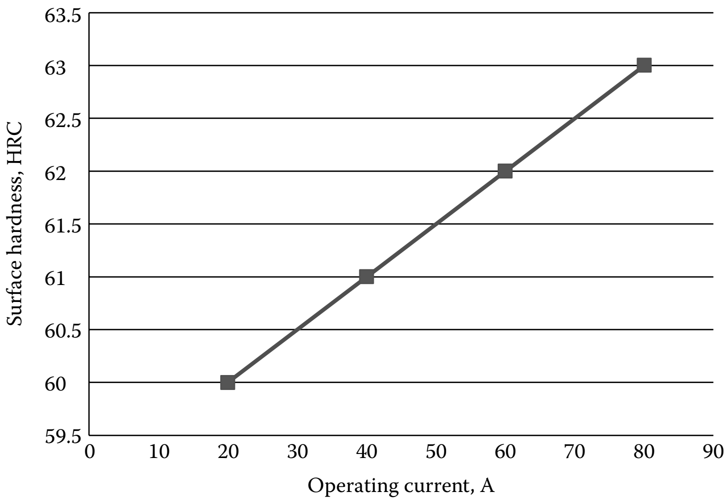

FIGURE 7.1
The influence of operating process current on surface hardness.

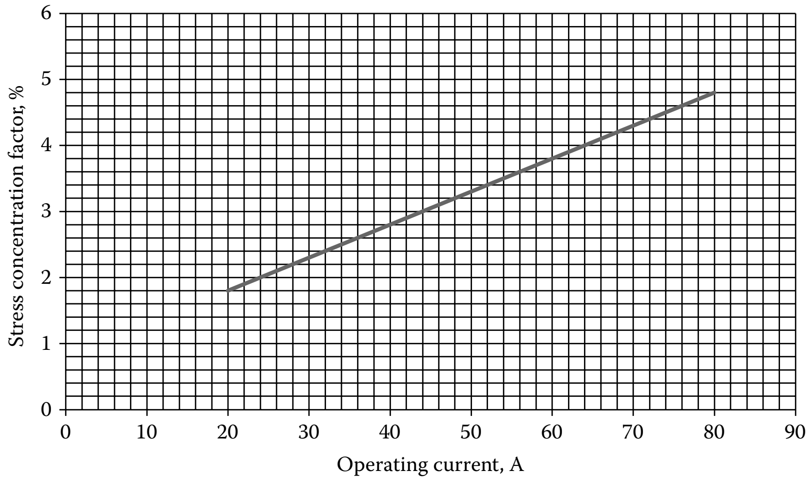

FIGURE 7.2
Hard alloy–coated part surface stress concentration factor load spectrum. *Legend*: 1–2, low stress; 2–3, average low stress; 3–4, average high stress; 5–8, high stress.

surface hardness and stress that meet the required service performance and environmental conditions.

The hard alloy coating material and part multivariate regression model is expressed in terms of hardness as follows:

$$\begin{aligned} Y_4 = {} & 0.71 + 0.04X_1 - 0.15X_2 - 0.07X_3 + 0.004X_4 - 0.033X_5 + 0.089X_1X_2 \\ & +0.032X_1X_3 - 0.032X_1X_4 - 0.024X_1X_5 + 0.111X_2X_3 - 0.108X_2X_4 \\ & -0.023X_2X_5 - 0.131X_3X_4 + 0.059X_3X_5 - 0.057X_4X_5 + 0.068X_1^2 \\ & +0.127X_2^2 + 0.051X_3^2 + 0.103X_4^2 + 0.043X_5^2 \end{aligned} \tag{7.1}$$

where Y_4 is the hard alloy–coated part surface hardness [11] , and the equation 7.1 for surface hardness and operating current, I (A), is given as

$$Y_4 = 0.71 + 0.04X_1 \tag{7.2}$$

The graph is shown in Figure 7.1.

7.6.1 Analysis

As the operating current increases, the hardness of the hard alloy–coated part surface also increases within a specific range of a process control limit, which is between 20 and 80 (A) of the process operating current. With heat-treated materials, it is possible to achieve maximum wear-resistant coated part surface, and applying the TI technique will help to maximize the hardness and minimize the material stress, which is also increasing as shown in Figure 7.2. This in turn also affects the component and system reliability, which implies that as the material and part hardness increases, the reliability increases, and as the stress reduces, the reliability also reduces. The integrated reliability curve or mechanism will help us determine the pattern of growth, rate of growth, optimal condition, degradation, and rate of degradation and failures and detect the times and conditions throughout the life cycle of the materials and parts. The material stress increases as the operating current increases within the operating condition range of the process. The coating material and part model is expressed as

$$\begin{aligned} Y_5 = {} & 0.6598 - 0.0186X_1 + 0.01096X_2 + 0.0254X_3 - 0.0191X_4 + 0.00396X_5 \\ & - 0.0021X_1X_2 + 0.00056X_1X_3 + 0.0068X_1X_4 - 0.0073X_1X_5 - 0.0026X_2X_3 \\ & + 0.0042X_2X_4 + 0.0136X_2X_5 + 0.0263X_3X_4 - 0.0051X_3X_5 + 0.0069X_4X_5 \\ & - 0.0103X_1^2 - 0.0096X_2^2 - 0.0236X_3^2 - 0.0235X_4^2 - 0.0261X_5^2 \end{aligned} \tag{7.3}$$

where Y_5 is the material and hard-coated part surface stress concentration factor, while the relationship between the stress and the operating current is given as

$$Y_5 = 0.6598 - 0.0186X_1 \tag{7.4}$$

The plotted graph is shown in Figure 7.2.

The increasing material stress with the increase in temperature can affect the hardness and reliability of the coated hard surface and therefore needs to be controlled with the help of the TI technique. The TI coefficient can be used to measure the wear-resistant coefficient, which increases as hardness increases. An integrated reliability condition monitoring and maintenance (IRCMM) of the coating materials and the coating deposition process with the TI model can help to maximize surface hardness and minimize the stress.

The wear-resistant coefficient of the hard-coated part surface continues to increase with the increase in the surface hardness of the coated part until it gets to a maximum point where it starts to decrease, as shown in Figure 7.3. With the consideration of material stress and other surface

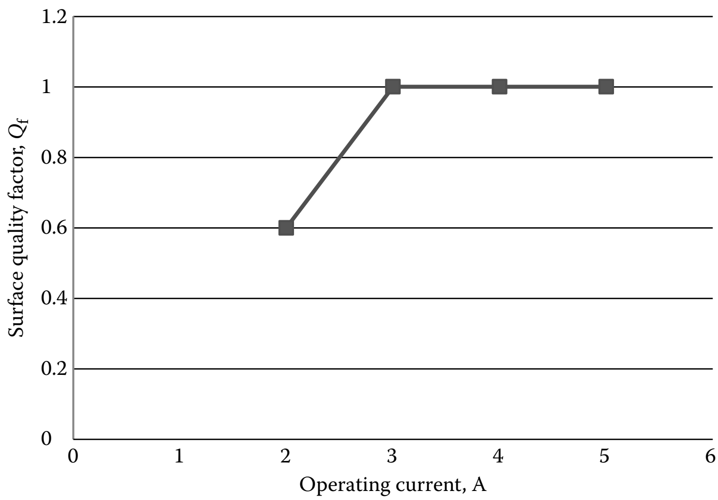

FIGURE 7.3
The influence of operating process current on surface quality factor.

quality characteristics, it has been possible to optimize the hard alloy–coated part and process conditions for maximum achievable reliability, wear, and other competing failure resistance at minimum cost with the application of the TI model. These optimum data can now be used as the baseline reliability, wear resistance, and other failure resistance requirements for hard coating materials, parts, processes, and equipment as shown in Figure 7.4. The optimum surface quality data are fed into the TI model as input date to monitor the system reliability growth, degradation, and failure and maintain it cost-effectively. The TI model will therefore be used to determine wear- and other failure-resistant coefficients as well as the reliability coefficients of hard coatings and hard coating deposition processes. The wear resistance coefficient shows how many times the wear resistance of the given component surface part is higher or lower than the resistance of the base component material that goes to make a new part or component. The same is also used to measure the reliability growth and degradation coefficients of components. The values of these coefficients are established with the help of TI coefficients of coating materials under definite conditions of wear. The determination of wear conditions depends on the different patterns of wear through optimum energy pulse, component wear resistance coefficient (K_w), component condition parameters (Y_i), component reliability growth coefficient (R_{kg}), reliability degradation coefficient (R_{kd}), and system integrated reliability coefficients (R_{int}) with the TI coefficient (a_i). The real-time

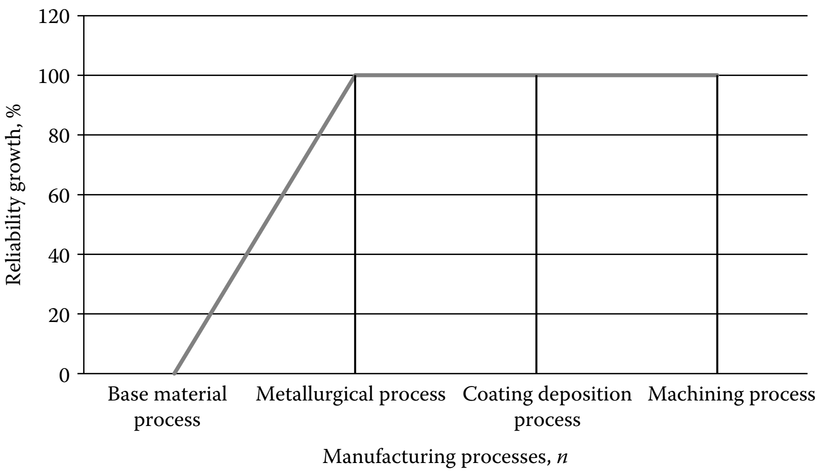

FIGURE 7.4
Reliability growths during manufacturing processes with a cost-effective maintenance strategy.

integrated reliability growth curve of a hard alloy–coated part surface for CM and maintenance is possible with TI model. Real-time data are measured and collected with TI coefficient sensors (TICSs), developed with the help of a TI model–based program. The reliability growth coefficient of the coated materials and hard-coated equipment part is measured during metallurgical and coating deposition process operations. The optimum part condition parameters for any particular failure mode (e.g., wear, corrosion, temperature, fatigue) is determined with the TI model. The optimum coating material, part, and process condition parameters for wear, corrosion, and high-temperature resistance as well as the reliabilities of the coating material, parts, and its deposition technique can be determined cost-effectively, using a new TICS–integrated reliability monitoring computer network system. The data collected can be used for the IRCMM of materials and coating deposition processes (see Figure 7.5).

Technological operating processes for hard alloy coating materials and workpiece surface

1. Metallurgical process
2. Coating deposition process
3. Machining process

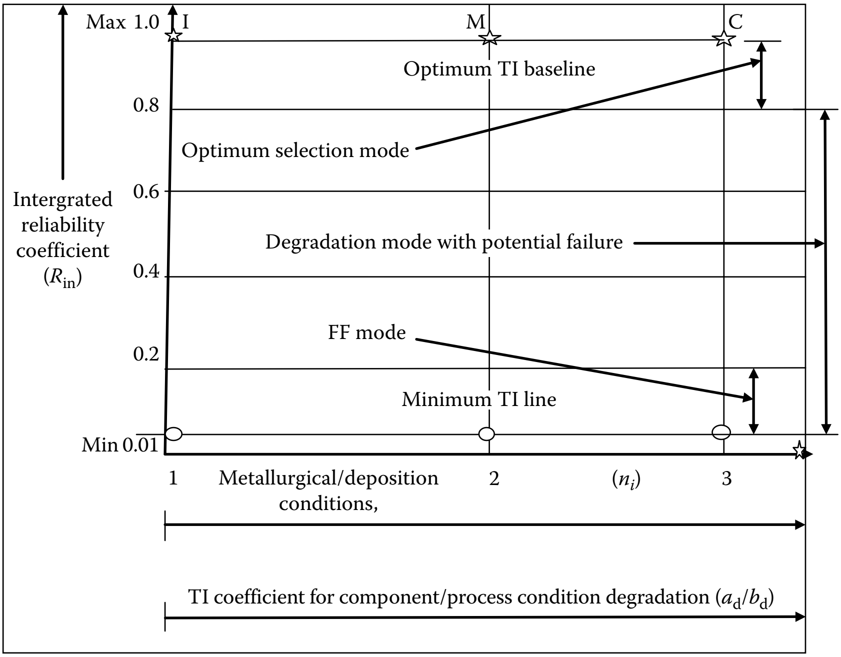

FIGURE 7.5
IRCMM curve of coating materials and coating deposition process with optimum, degradation, and failure conditions.

4. Grinding process
5. Assembly or installation process
6. Equipment process

7.7 IRCMM of Hard Coating Materials and Coated Workpiece Part Surface with a TI Model–Based Program

With the IRCMM decision diagram in the previous chapter, Figure 6.1, and integrated reliability mechanism, Figure 7.5, it is possible to select suitable metallurgical and coating processes that would produce optimum hard coating materials and hard-coated part surface conditions for wear-resistant applications. The TI model is used to test for its optimum reliability coefficient. If it meets its desired optimum reliability coefficient requirements, $R_{\text{Tsys(opt)}} = 1.0$; the processes, materials, part conditions, and maintenance strategy are selected. The expression for the system reliability coefficient for the technological chain of metallurgical and coating deposition processes is given as

$$R_{\text{Tsys}(i)} = R_1 \cdot R_2 = 1.0 \tag{7.5}$$

When the desired reliability coefficient is not met, it means the conditions or one of the conditions is suboptimum and the processes must to tested for failures, degradation, and possible damages.

Where there is no suitable existing coating material that matches with the base material and deposition technique or due to suboptimum conditions, new component condition parameters for the desired materials, parts, and processes are designed with the help of the TI model. In case where any of the existing coating material and coating deposition techniques are used without the TI technique, possible measurement errors and suboptimum selections are bound or may occur within the process, which would definitely cause damages, false probabilities, and negative inheritance consequences in the subsequent production and service operations. When this potential false reliability is detected early enough within the process with the use of an IRCMM software program, the reliabilities of materials, parts, and processes are improved.

The relationship between component materials/process condition parameters and TI coefficients is assessed with the multivariate quality regression model. The hard alloy material and part surface data used to plot reliability and quality parameters with process condition graphs are utilized for optimum selection, cost-effective maintenance, and determination of maintenance cost as well as for cost-effective management.

With the graph, it is possible to carry out proactive maintenance from the initial stage to the final stage in material and deposition processes. The graph highlights the fact that as the hardness of material increases, the wear resistance of the component also increases. It is also true from the graph that the optimum operating deposition process condition offers a higher value in hardness than the optimum metallurgical process condition for wear-resistant applications. The component's hard alloy surface condition will be subject to machining and grinding for the desired specifications for a particular application. The existing technique for selecting machining and grinding processes that suit the hard alloy coating materials and parts is not productive and such requires a more progressive approach for a sustainable development in manufacturing and maintenance industries. IRCMM with TI model–based program can now be used for optimum selection of coating materials, hard alloy–coated workpiece surfaces, machining, grinding processes, and hard alloy–coated part surface condition that meets the reliability requirements of desired equipment.

7.8 Conclusions

1. Researchers have ascertained that self-fluxing powders based on nickel are hard alloy coating materials having a wide application for hardening and reconditioning surfaces of rapid, wearable critical parts working in aggressive media of wear, corrosion, and high-temperature conditions.
2. These coatings have complex structures, consisting of minutely dispersed superhard phases of carbides, borides, and carboborides with microhardness up to 40×10^3 MPa, uniformly distributed in a hard metallic matrix based on solid solutions and complex nickel-based eutectic.
3. These hard alloy coating load and environment requirements range with specific pressure 1.5×10^6 to 7.0×10^6 Pa and sliding velocity up to 8 m/s.
4. These nickel-based hard alloy coatings are recommended for applications with friction part pairs (e.g., shaft–bearing assembly) in water, NaOH, and CH_3COOH of 10%–50% concentration.
5. The wear resistance of this type of hard alloy coatings in friction part surface contacts with steel (friction of boundary lubrication) is 4–9 times higher than the wear resistance of steel in steel–steel pairs and steel–iron pairs under specific loads of 1.5×10^6 Pa and sliding velocities of 8–54 m/min.
6. The amount of wear of steel working in pairs with hard alloy coatings within the given load range and environment requirements is reduced by a factor of 1.5–2.5 times.
7. The friction coefficient in pairs of hard alloy coatings in steel with initial surface roughness R_a = 0.16–0.30 μm is 1.8–2.2 times lower than in steel–steel pairs, but with constant surface roughness, the amount of wear is 2–10 times reduced, hence the need to optimize process and part surface conditions with the TI model–based program for maximum lifetime reliability of components and systems.
8. The nickel-based hard alloy–coated cylindrical part surface (e.g., shaft, bearing) for friction part contact with steel has been designed in this book to withstand wear, corrosion, and high-temperature environments and its stresses during operations for maximum achievable reliability of components and systems.
9. The material design for maximum achievable reliability for hard alloy–coated part surface considers not only the specific part surface roughness but also the other surface quality parameters like hardness and stress as well as the specific coating deposition process conditions

and other manufacturing processes like machining and grinding for a more robust design that suits the desired environmental conditions.

10. A multivariate regression model for nickel-based hard alloy–coated cylindrical part surface has been developed for predicting and selecting optimum component quality parameters, process performance factors, reliability condition requirements, and failure characteristics of components/systems.
11. Integrating environmental and hard alloy–coated part surface quality conditions with process performance conditions under a single platform for determining the optimum reliability requirements of coating materials, coated parts, and processes as well as the control of reliability growth and degradation/failure is possible with the application of the TI model.
12. Integrated reliability mechanism is developed to analyze, monitor, and determine the desired reliability growth, optimum reliability, reliability degradation, and wear with other competing failure modes of friction part surfaces and systems and sustain the optimum values for a specific lifetime with the TI model.
13. Integrated reliability monitors and TICSs have been developed for real-time reliability growth/degradation and failure data acquisition, analysis, control, and presentation.
14. An IRCMM program is used as a decision-making guide, test component and process reliability growth/degradation, detect failures, and select suitable cost-effective maintenance strategy for manufacturing processes and equipment in the different industries of the future.

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8

Reliability Growth Condition of Machining and Grinding Processes of Hard-Coated Workpiece Surface

8.1 Machining Hard Alloy Material and Hard Alloy–Coated Workpiece Surface for Wear and Other Competing Failure Resistance Applications

Machining hard alloy materials and coated workpieces is how easily the material can be cut to the desired shape (surface finish and tolerance) with respect to the tooling and the type of machining processes involved. In the machining operation, tool life, metal removal rate, component forces and power consumption, surface finish generated and surface roughness, hardness, stress of the machined component, and the shape of the chips can all be used to measure the performance and productivity of machining. The machining index can be significantly affected by the properties of the hard alloy coating material, coated workpiece properties and geometry and material of the cutting tool, cutting conditions employed, and other additional factors such as rigidity of the machine tool and cutting environment. Machining productivity and performance can be significantly improved by applying the right combination of cutting tools, cutting conditions, and machine tool that will promote high-speed machining without compromising the surface quality and tolerance of the machined workpiece. This is particularly essential for the economic machining of nickel-based hard alloy coatings on friction pairs in water, NaOH, and CH_3COOH of 10%–50% concentration, whose peculiar characteristics generally impair high machining ability. The driving force for the continual development of many coating materials over the years is the need for harder, stronger, tougher, stiffer, more corrosion-, wear-, and high-temperature-resistant material that can also exhibit high strength to weight ratio, in the case of aeroengine alloy parts, precision parts, and other critical parts in rotating equipment. The use of nickel-based hard alloy–coated parts, precision parts, and critical parts for rotating equipment has increased the demand for materials that have excellent high-temperature, wear-resistant, mechanical, and chemical properties relative to steels and stainless steel alloys originally employed in machine tools and rotating equipment applications.

8.1.1 Machining of Nickel-Based Hard Alloy–Coated Part Surface

The practical guide for the machining of high-temperature alloys for wear, corrosion and high temperature resistant applications [1]. The hardness of many nickel-based hard alloy coatings and other hard coating alloy materials increases significantly upon heat treatment. Formation of the second phase particles makes the alloy both stronger and more abrasive and thus more difficult to machine. Advantage, therefore, lies in machining in the softer state. Typically, the component is machined to near finish dimensions in the solution treated condition, then age hardened, and then finally finish machined to generate the desired surface finish and to eliminate any distortion associated with heat treatment.

8.1.2 Practical Guide for Machining Hard Alloy Coating Materials

1. Machine alloys in the softest state possible.
2. Use a positive rake insert or groove.
3. Use relatively sharp edges.
4. Use strong geometry.
5. Use a rigid setup.
6. Prevent part deflection.
7. Use a high lead angle.
8. When more than one pass is required, vary the depth of cut.

A positive rake cutting edge is recommended for semifinishing and finishing operations whenever possible. Positive rake geometry minimizes work hardening of the machined surface by shearing the chip away from the workpiece in an efficient way in addition to minimizing built up edge. Very light hones or even sharp insert edges are useful in preventing material buildup and improving surface finish during machining. Dull or improperly ground edges increase cutting forces during machining, causing metal buildup, tearing, and deflection of the work material. It is, however, important to note that sharp insert edges are more fragile and susceptible to chipping during machining; thus, honed edges are recommended for most roughing operations where concerns about surface roughness are at a minimum. Sharp edges are then used for finishing operations. Using a large nose radius wherever part geometry does not demand otherwise can reinforce the cutting edge. This has the effect of subjecting more of the tool edge into the cut, decreasing the force at any one point, and preventing localized damage. Machining with a rigid setup prevents vibration and subsequent chatter that deteriorates surface finish and can cause tool fracture. Tighter tolerance can be maintained with rigid setups. Deflection of the work material should be prevented, especially when machining thin-walled components or parts of nickel-based hard alloy coatings. Special precautions like the use of filler metals, special fixture, or backup may be used to prevent movement during machining. Notching, particularly at the depth of cut line, can be minimized by machining with tools with high leading edge angles as more of the cutting edge is engaged in the cut, thus spreading the wear over a larger distance. Applying the ramping or taper turning technique can also eliminate notching during machining. This involves gradual alteration of the depth of cut as the tool traverses along the cutting length, thus spreading the wear along the entire insert edge. This machining technique generally reduces tool wear rate and also prolongs tool life.

8.1.3 Tool Materials for Machining Hard Alloy Materials

Cutting tool materials often encounter extreme thermal and mechanical stresses close to the cutting edge during machining due to the poor machining of hard coating alloys. This usually results to plastic deformation and accelerated tool wear. A major requirement of cutting tool materials used for machining hard-coated alloys is that they must possess adequate hot hardness to withstand elevated temperatures generated at high-speed conditions.

Most cutting tool materials lose their hardness at elevated temperatures resulting in the weakening of the interparticle bond strength and consequent acceleration of tool wear.

The influence of cutting speed on cutting temperature of commercially available cutting tool materials used for machining nickel-based hard alloy coatings is given in Table 8.1 [1].

TABLE 8.1

Influence of Cutting Speed on the Cutting Temperature

Cutting Speed, m/min (m/s)	Voltage, M_v (V)	Temperature, °C (K)
50 (0.8333)	9.0 (0.009)	612 (885.15)
100 (1.6666)	11.9 (0.0119)	763 (1036.15)
150 (2.5000)	13.5 (0.0135)	853 (1126.15)
200 (3.3333)	14.7 (0.0147)	924 (1197.15)
250 (4.1666)	16.1 (0.0161)	1020 (1293.15)
300 (5.0000)	16.6 (0.0166)	1057 (1330.15)
350 (5.8333)	16.8 (0.0168)	1075 (1348.15)
400 (6.6666)	17.6 (0.0176)	1138 (1411.15)
450 (7.5000)	18.4 (0.0184)	1219 (1492.15)
500 (8.3333)	18.3 (0.0183)	1215 (1488.15)

Coated carbide tools, ceramics, cubic boron nitride (CBN)/PCBN (polycrystalline cubic boron nitride) tools, and polycrystalline diamond (PCD) tools are generally used for high-speed machining of aeroengine alloys. Ceramics and CBN/PCBN tools are not usually recommended for machining titanium alloys because of their poor performance due to excessive wear rates as a result of the high reactivity of titanium alloys with ceramics. Efficient and economic machining of nickel-based hard alloy coatings under high-speed conditions requires a good understanding of the cutting tool materials, cutting conditions, processing time, and the functionality of the machined workpiece. Advances in cutting tool materials and machining techniques have resulted to significant increase in metal removal rate when cutting nickel-based hard alloy coatings. These alloys can now be economically machined at higher-speed conditions with recently developed cutting tools and machining techniques. Major improvements in the machining of nickel-based hard alloy coatings have been accomplished with self-propelled rotary tooling (SPRT) but still fall short of the desired optimum reliability requirements of components.

8.2 Self-Propelled Rotary Tooling

Movement of the cutting edge in addition to the main cutting and feed motions is the major difference between rotary cutting and conventional cutting (Figure 8.1). The additional movement of the rotary tool ensures that a portion of the tool cutting edge is involved in machining operation for a

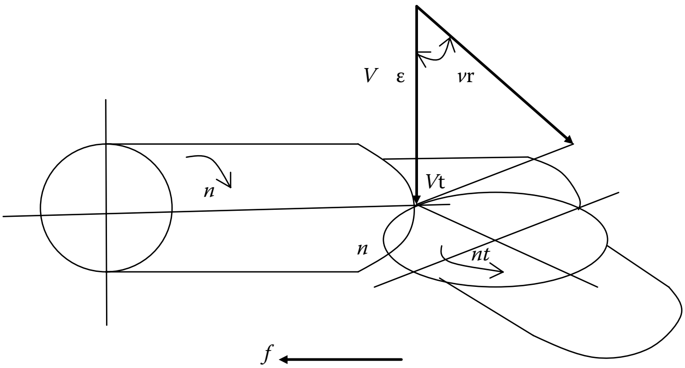

FIGURE 8.1
Self-propelled rotary tooling with hard-coated workpiece surface. (From Shooman, M., *Software Engineering, Design, Reliability, and Management*, McGraw-Hill, New York, 1987; Musa, J., *Software Reliability Engineering, More Reliable Software Faster and Cheaper*, 2nd edn., Author House, Bloomington, IN, 2005; Anderson, D., Wear particle atlas, Report No. NAEC-92-163, Naval Air Engineering Center, Lakehurst, NJ, 1972.)

very brief period, followed by a prolonged rest period that permits the conduction of thermal energy, associated with the cutting process, away from the cutting zone.

Tool rotation is enhanced either by an external driver (in the case of driven rotary tool [DRT]) or by the self-propelled action of cutting forces (for SPRT) exerted on the tool by adjusting its axis at an inclination with respect to the cutting speed. SPRT employs round inserts rotating continuously about its axis as a result of the driving motion impacted by the cutting force, thus minimizing the effect of thermal energy along the entire edge and preventing excessive heating of a particular portion of the insert edge. Table 8.1 highlights the influence of cutting speed on the cutting temperature. The increase of the cutting speed increases the cutting temperature of the hard alloy–coated workpiece surface. The rotary cutting movement helps reduce the temperature and improve the surface quality of the workpiece and the tool bit.

The much reduced tool workpiece contact time in rotary cutting permits conduction of minimum amount of energy into the machined component, consequently minimizing the surface abuse associated with the cutting process. Much higher cutting speeds and feed rates can be achieved when machining aeroengine alloys with SPRT, relative to conventional cutting tools, without pronounced adverse effect on tool life and machining performance due to the lower cutting temperature generated as shown in Figure 8.2.

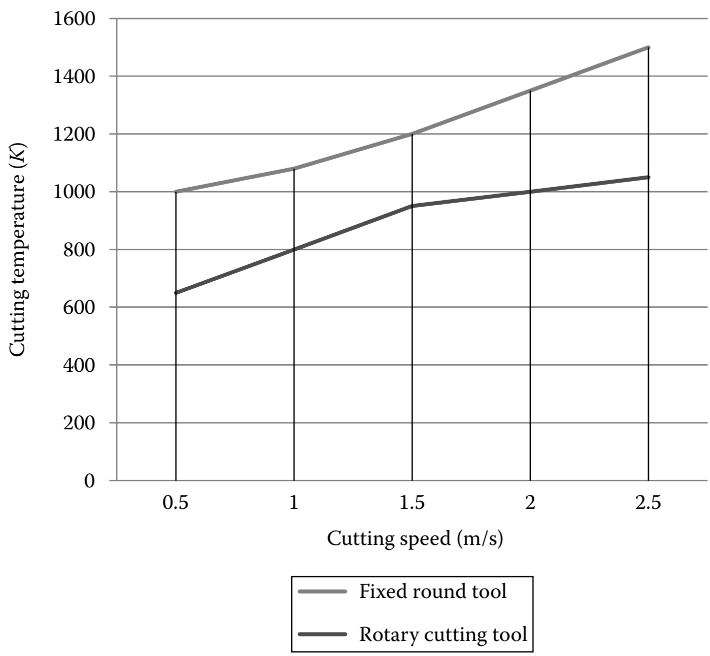

FIGURE 8.2
Cutting temperatures with operating cutting speed of tools.

Prolonged machining tends to lower the surface roughness value, thus improving surface finish. The ideal values (arithmetical mean value) of surface roughness produced under conventional turning can be obtained as $R_a = 0.0321 S_2/r$, where S is the feed rate and r is the nose radius. An increase in the feed rate from 0.25 to 0.4 mm/rev only gave a slight deterioration in the surface finish generated, unlike in conventional turning. This can be attributed to the smearing action between the tool and the workpiece when machining at a higher feed rate. Deterioration in the machined surface occurred when machining with an increased inclination angle from 45° to 60°. Analysis of the machined surfaces shows minimal structural defects on Inconel 718 surfaces produced with the SPRT inserts unlike the pronounced plastic deformation and nucleation observed after machining under conventional turning [1]. The overall surface finish produced with the SPRT can be greatly affected by the stability of the rotary cutting system. A major problem with the rotary cutting technique is maintaining the concentricity or circularity of the cutting edge during machining. This can however be maintained by effective damping of the SPRT system to ensure consistency of the machining performance. Other progressive methods for surface finishing can also be applied. Their performances are discussed later to highlight their differences and benefits in manufacturing and maintenance organizations.

8.3 Selecting Surface Finish Processes for Hard Alloy–Coated Workpiece Surface with the Multivariate Regression Model

Intense international competition has focused the attention of manufacturers on automation as a means to increase productivity and improve quality. To realize full automation in machining, computer numerically controlled (CNC) machine tools are now being used. CNC machine tools require less operator input, provide greater improvements in productivity, and increase the quality of the machined part.

Among several CNC industrial-machining processes, turning is a fundamental machining operation.

For finish hard alloy workpiece turning, tool wear becomes an additional parameter affecting the surface quality of finished parts. Hard turning process can be defined as turning ferrous metal parts that are already hardened into finished components. The greatest advantage of using finish hard turning is the reduced machining time and complexity required to manufacture metal parts and some other benefits are detailed in the literature [5–8]. However, in current hard turning practice, the industry chooses the correct tool geometry less than half of the time, uses proper machining parameters only about half of the time, and uses cutting tools, especially CBN, to their full life capability only one third of the time. These suboptimal practices cause loss of productivity for the manufacturing industry. Improvements to the current process planning for finish hard turning are needed to improve cost effectiveness and productivity of the process.

One of such improvements can be made to finish hard turning by developing predictive models for surface roughness, surface hardness, surface stress, and tool wear when using the appropriate cutting tools like rotary tool with thermal spray.

There are numerous machining factors that affect surface quality in hard turning using such cutting tools, and those effects have now been adequately quantified in this book.

It is recommended for use in a variety of manufacturing industries including the aerospace, manufacturing, automotive, rotating, and stationary machinery sectors where quality is an important factor in the production of bearings, shafts, pins, gears, and others. The quality of the surface plays a very important role in the performance of turning as a good-quality turned surface, which significantly improves fatigue strength, surface hardness, corrosion resistance, and creep life. Surface roughness as one of the main surface quality parameters affects several functional attributes of parts, such as contact causing surface friction, wearing, light reflection, heat transmission, ability of distributing and holding a lubricant, coating, or resisting fatigue failures. Therefore, the desired finish surface is usually specified and the appropriate processes are selected to reach the required quality of components.

Several factors will influence the final surface roughness in a CNC turning operation. The final surface roughness might be considered as the sum of two independent effects: (1) the ideal surface roughness is a result of the geometry of the tool and feed rate and (2) the natural surface roughness is a result of the irregularities in the cutting operation. Factors such as spindle speed, feed rate, and depth of cut that control the cutting operation can be set up in advance. However, factors such as tool geometry, tool wear, chip loads, and chip formations, or the material properties of both tool and workpiece, are uncontrolled. This will definitely affect the surface roughness and other quality parameters like stress, wavelength, and vibration of the machine tool and may cause some defects in the microstructure of both the workpiece and the tool.

One should therefore develop techniques to predict and select the multiple quality parameters of the workpiece before turning in order to evaluate the fitness of machining parameters such as feed rate or spindle speed for keeping desired quality conditions of the workpiece. It is also important that the prediction and selection technique should be accurate, reliable, low cost, and nondestructive. On this note, machining hard alloy workpiece surface turning using rotary tool with thermal spray is applied in this book for multiple surface quality prediction and selection as well as to design a multivariate regression model as given in Chapter 6. The machining process model for hard alloy–coated part surface is expressed in the multivariate surface quality regression model in the following text.

8.4 Multivariate Regression Model for Hard Alloy Workpiece Surface

$$\begin{aligned}Y_1 = {} & 0.6497 - 0.0188X_1 + 0.0108X_2 + 0.02263X_3 - 0.0175X_4 + 0.0043X_5 \\ & -0.0013X_1X_2 + 0.0006X_1X_3 + 0.0080X_1X_4 - 0.0071X_1X_5 - 0.0004X_2X_3 \\ & +0.0038X_2X_4 + 0.0154X_2X_5 + 0.0266X_3X_4 - 0.0038X_3X_5 + 0.0064X_4X_5 \\ & -0.0096X_1^2 - 0.0061X_2^2 - 0.0207X_3^2 - 0.0224X_4^2 - 0.0257X_5^2 \end{aligned} \tag{8.1}$$

$$\begin{aligned}Y_2 = {} & 0.661 + 0.035X_1 - 0.109X_2 - 0.068X_3 + 0.032X_4 - 0.024X_5 + 0.053X_1X_2 \\ & +0.019X_1X_3 - 0.016X_1X_4 - 0.22X_1X_5 + 0.096X_2X_3 - 0.129X_2X_4 - 0.016X_2X_3 \\ & -0.108X_3X_4 + 0.026X_3X_5 - 0.054X_4X_5 + 0.053X_1^2 + 0.197X_2^2 + 0.055X_3^2 \\ & +0.085X_4^2 + 0.048X_5^2 \end{aligned} \tag{8.2}$$

$$\begin{aligned}Y_3 = {} & 4.397 + 2.311X_1 - 1.899X_2 + 1.073X_3 - 1.483X_4 - 1.026X_5 - 0.231X_1X_2 \\ & +0.724X_1X_3 - 3.058X_1X_4 - 1.503X_1X_5 + 0.336X_2X_3 - 0.547X_2X_4 + 0.088X_2X_5 \\ & +0.193X_3X_4 + 1.326X_3X_5 + 0.231X_4X_5 + 1.73X_1{}^2 + 1.331X_2^2 - 0.117X_3^2 \\ & +1.544X_4^2 + 0.167X_5^2 \end{aligned} \tag{8.3}$$

$$\begin{aligned}Y_4 = {} & 62.255 - 1.689X_1 - 0.354X_2 + 0.563X_3 + 1.105X_4 + 0.104X_5 + 0.156X_1X_2 \\ & +0.281X_1X_3 + 0.594X_1X_4 + 0.281X_1X_5 - 0.781X_2X_3 + 0.406X_2X_4 + 0.469X_2X_5 \\ & -0.219X_3X_4 + 0.719X_3X_5 \text{ñ} 0.219X_4X_5 - 0.983X_1^2 - 0.796X_2^2 - 0.671X_3^2 \\ & -1.420X_4^2 - 0.734X_5^2 \end{aligned} \tag{8.4}$$

$$Y_5 = 2.956 - 0.856X_1 - 0.199X_2 + 0.634X_3 + 0.740X_4 - 0.010X_5 - 0.062X_1X_2$$
$$+0.094X_1X_3 - 0.276X_1X_4 + 1.371X_1X_5 - 0.066X_2X_3 - 0.243X_2X_4$$
$$-0.174X_2X_5 - 0.387X_3X_4 + 0.299X_3X_5 + 0.462X_4X_5 - 1.065X_1^2$$
$$+0.009X_2^2 + 0.117X_3^2 - 0.633X_4^2 - 0.424X_5^2 \quad (8.5)$$

The parameters of the machining process condition (X_i) for hard-coated part surface quality (Y_i) are as follows:

Y_1: K—kinematic coefficient of the rotary tool bit, $K = V_R/V$; V_R—the speed for the distance traveled by tool's cutting edge; V—cutting speed
Y_2: λ—profile wavelength of the machined surface, mm
Y_3: R_a—surface roughness number, μm
Y_4: HRC—hardness of the machined, kg/mm^2
Y_5: ε—surface stress concentration factor after machining, %

The independent variable factors are as follows:

X_1: I—plasma arc current, A
X_2: L—the distance between the plasmatron and rotary tool bit, mm
X_3: S—feed rate of the rotary tool bits, mm/rev
X_4: V—cutting speed, m/s
X_5: t—cutting depth, mm

With a given optimum machining process condition (X_i), the optimum hard-coated part surface quality (Y_i) can be predicted using multivariate regression models. The data are used to plot the reliability growth of the surface finish processes for hard alloy–coated workpiece surface.

8.4.1 Reliability Growth for Hard Alloy–Coated Workpiece Surface Finish with the TI Model

Reliability growth analysis for hard alloy workpiece surface finish determines the optimum condition of the workpiece as well as the optimum machining condition. Instead of using reliability growth analysis, most researchers use multiple linear regression procedures, one dependent variable at a time. However, simulation studies of multiple linear regression works suggest that this practice is ill advised. If the primary goal of a study is prediction and lifetime reliability accuracy like the case work of this book, reliability growth analysis through multivariate linear regression and technological inheritance (TI) models is highly recommended. Reliability growth takes into account the correlations among the component dependent quality parameters ignored by univariate analysis. This is also the case for multivariate procedures used to select the best subset of part surface quality and machining process performance variables when building multivariate models.

Reliability growth data are used in practice to explain variation in a vector of dependent (criterion) variables by employing a set of independent (predictor) variables using observational (nonexperimental) data. In these settings, the goal of the researcher is usually to select a subset or all of the predictors that accounts for the variation in the dependent variables. The theory associated with a discipline is usually used to define the initial set of predictor variables. In such studies, the goal is to discover the relationship between the dependent variables and the *best* subset of predictor variables. Multivariate linear regression procedures are also used with experimental data. In these situations, the regression coefficient is employed to evaluate the marginal or partial effect of a predictor on the dependent variable given the other predictor variables in the model. In both situations, one is usually concerned with the estimation of the model parameters, model specifications, and variable selection or, in general, mode calibration and sample model fit.

In this book, predictor variables are selected to maximize the surface quality parameters and measure and monitor the conditions of the part as well as the optimum set points and the control limits of rotating and stationary equipment. To achieve this, a mathematical model of a hard-coated rotary shaft is designed for optimum surface quality and efficient monitoring characterization. In order to obtain the mathematical model, a new modern progressive method of machining and finishing hard-coated rotary shaft known as rotary cutting with plasma spray has been adopted, while a central composite uniform plan design of the second order was applied [12,13].

8.4.2 Optimum Reliability with the TI Model

The determination of the influence in the different factors of rotary cutting with plasma flame (RCPF) on K, λ, R_a, HRC, and ε and also optimization of the cutting conditions of the process are carried out by the mathematical models (Equations 8.1 through 8.5) using the methods worked out by the theory of experimental design. In this case, both significant and nonsignificant coefficients were used, considering the fact that the latter ascertains the said values of the earlier functions.

The graphical representation of these mathematical models for the different multiple quality parameters is shown in a research work [14], while a single cross-section curve function of Y_1, Y_2, Y_3, Y_4, Y_5 is shown in Figures 8.3 through 8.7. This single curve is used to monitor the quality and performance of industrial processes as well as the health of equipment. It is also used to select optimum values of materials, parts, processes, equipment, instruments, and manufacturing and maintenance routes. The single curve can easily be analyzed graphically and numerically to achieve the desired purpose.

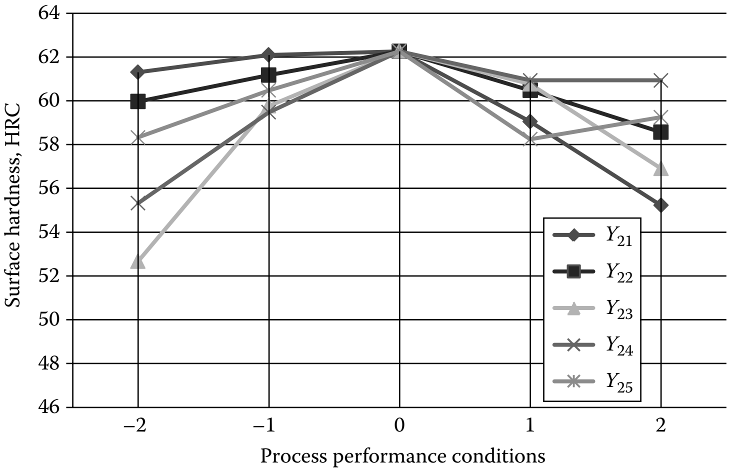

FIGURE 8.3
The influence of process performance conditions on part surface hardness.

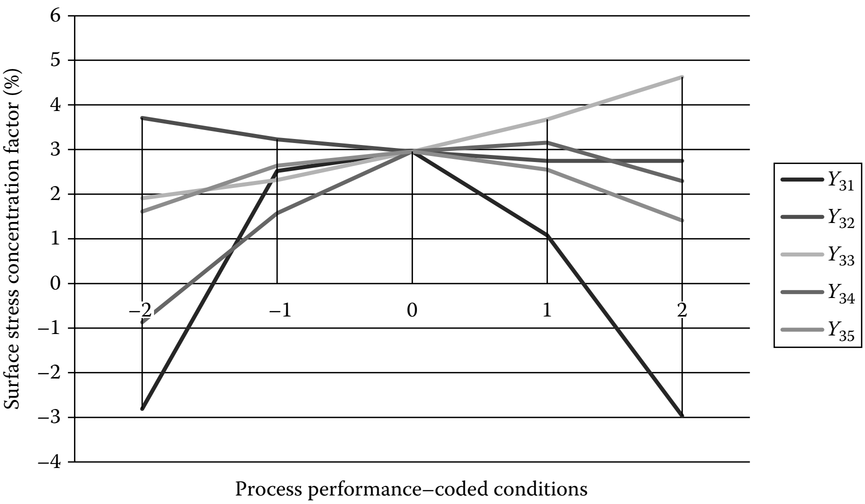

FIGURE 8.4
The influence of process performance conditions on part surface stress concentration factor.

For a reliability maintenance purpose, with the multivariate mathematical model, a regression equation was set up to contain two variables as the testing independent factor and determinant dependent variable. In this case, the rest of the factors remain at zero level for that particular matrix.

The relationships obtained from the graphical representations are limited by the conditions of extrapolation from –2 to +2. Analysis obtained from

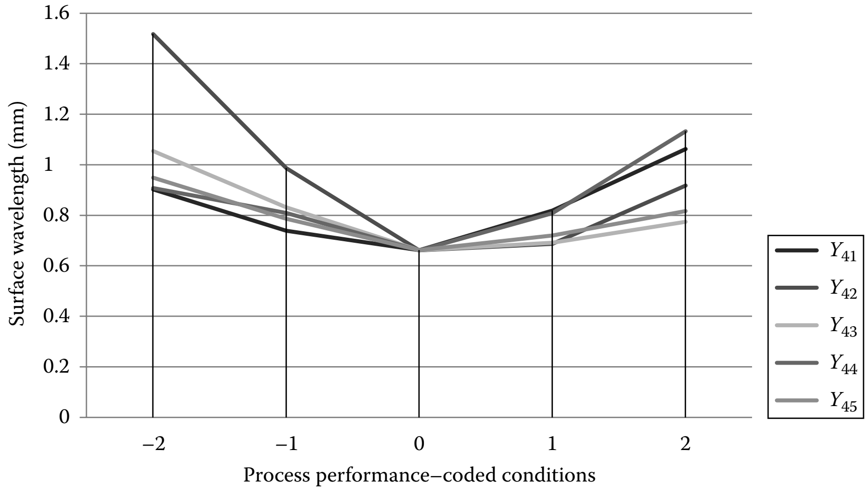

FIGURE 8.5
The influence of process performance conditions on part surface wavelength.

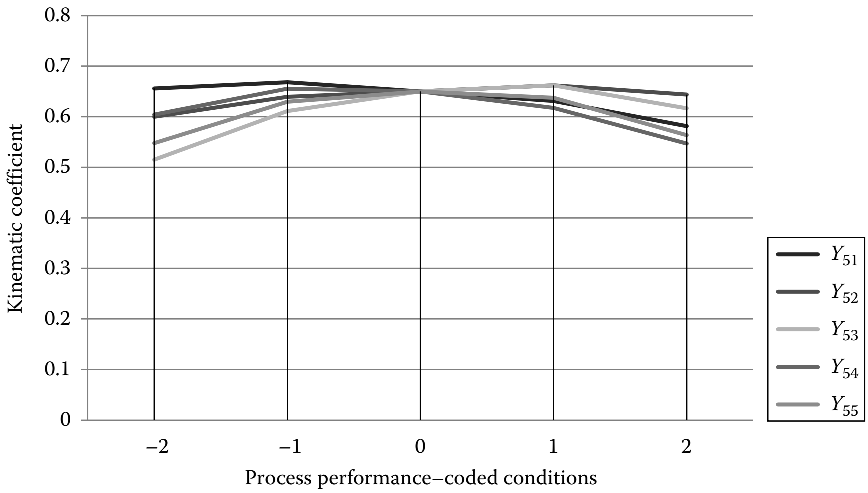

FIGURE 8.6
The influence of process performance conditions on part surface kinematic coefficient.

the multiple regression models and the graphical relationships has helped to determine the degree of influence of the factors on the optimization parameters. From the data analysis in Table 8.2, it is seen that the quality parameters are differently influenced by the RCPF factors.

Of all the experimental factors, the most influential on the surface quality factor is in the order of decrease in their significance—plasma arc current,

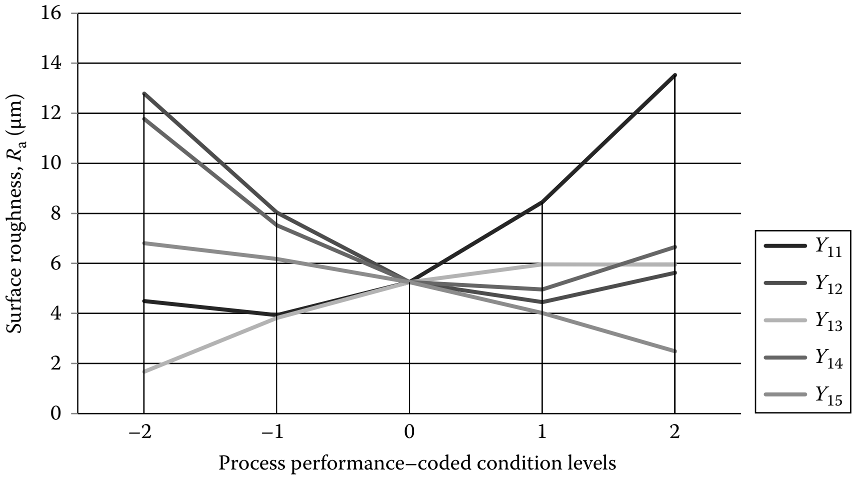

FIGURE 8.7
The influence of process performance conditions on part surface roughness.

TABLE 8.2

Influence of Rotary Cutting with Plasma Machining Factors on the Hard-Coated Workpiece Surface Quality Parameters

		Degree of Influence of Factors on Surface Quality Parameters (%) or Performance				
Factors	**Factor Variables (X_i)**	**Y_1 (*K*)**	**Y_2 (λ)**	**Y_3 (R_a)**	**Y_4 (HRC)**	**Y_5 (ε)**
Plasma arc current	X_1	24.20	13.06	29.66	44.27	35.10
Distance between tool bit and plasmatron	X_2	13.90	40.67	24.37	9.28	8.16
Feed rate	X_3	33.85	25.37	13.77	14.76	25.99
Cutting speed	X_4	22.52	11.94	19.03	28.96	30.34
Depth of cut	X_5	5.53	8.96	13.17	2.73	0.41

feed rate, cutting speed, distance between tool bit and plasmatron, and depth of cut (*I*, *S*, *V*, *L*, *t*)—as obtained from the experiment conducted with the RCPF machine in Figure 8.8.

With this analysis, it is clear that the order of influence is quite different from the traditional trend, which of course has a remarkable impact on machinability and reliability engineering.

8.4.3 Determination of the Optimum Rotary Cutting with Plasma Flame and Workpiece Surface Quality Conditions

The determination of optimum RCPF condition for machining hard coatings can be used to solve the problem of optimization for multiple parameters. In this case, the exhaustive methods of selecting different variants were

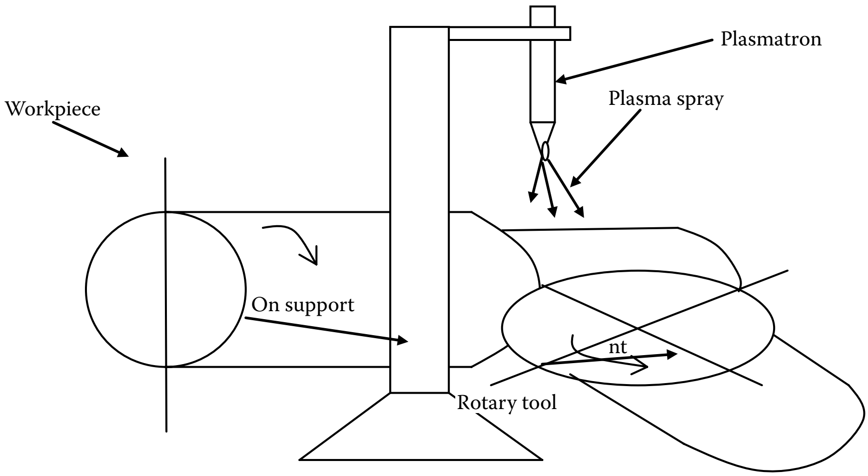

FIGURE 8.8
A rotary cutting with plasma spray machining of hard-coated workpiece surface.

adopted [10,14] and were used to solve complex problems by finding their extreme conditions using the mathematical models for the multiple parameters of optimization. In these experiments, the use of data from the existing mathematical models in the different variants was adopted. The data for finding the optimum variant are shown in Table 8.3.

From the results of the calculations, the data of the sixth variant were selected to be the optimum. The verifications were carried out by using the complex index of the optimization parameters in RCPF for the machining of hard coatings. This index was adopted as a general function of *desire* by Harrington [9]. Desire is understood as this or that desiring level of optimum parameters.

TABLE 8.3
Search for Optimum Variants for Surface Quality and Reliability Requirements

	Code Values for Process Variable Factors (X_i)					Values for Parameter Optimization (Y_i)					
S. No.	X_1	X_2	X_3	X_4	Y_5	Y_1	Y_2	Y_3	Y_4	Y_5	**Desire (d_i)**
1	0	0	0	0	0	0.65	0.66	4.40	62.3	2.96	0.824
2	0	0	0	0	+1	0.628	0.69	3.54	61.6	2.52	0.846
3	0	0	0	+1	0	0.61	0.78	4.47	61.9	3.07	0.793
4	0	0	−1	0	0	0.603	0.78	3.21	61.0	2.44	0.822
5	0	+1	0	0	0	0.654	0.75	3.83	61.1	2.77	0.831
6	−1	0	0	0	0	0.659	0.68	3.26	63.0	2.75	0.899

A special *scale of desire* is worked out. The value of d changes from 0 to 1. The value $d = 1$ corresponds to the maximum possible level of the optimum parameter (Figure 8.11).

The function of desire is expressed by the equation

$$d = e^{-ea}$$

where

e is the natural logarithm; $e = 2.718$

a is nondimensional value of the optimum parameter, which is also termed the TI coefficient for component quality–reliability control [9–11]

For the use of the functions and *scale of desire* values of optimum parameters, Y_i is, first of all, changed to a nondimensional value a that corresponds to the desire.

A general function desire is formed as a geometrical mean desire of the separate optimum parameters and is determined by the expression

$$d = \sqrt[n]{d_1 d_2 \ldots d_n}$$

The complex index of the optimum parameter of RCPF for machining hard coatings is maximal in the sixth variant. Subsequently, conditions of RCPF of the sixth variant can be accepted as optimum. The optimum process conditions for wear-, corrosion-, and high-temperature-resistant purposes can be determined and applied for an integrated reliability monitoring and maintenance of industrial processes, parts, and equipment.

The results of the mathematical relationship between kinematic coefficients of rotary tool bits, profile wavelength, surface roughness and hardness of the surface layer, surface stress concentration factor, and RCPF factors, which allow the determination of machining conditions of hard coatings, provide the best quality characteristics of a coated surface layer. It is ascertained that RCPF provides the quality parameters of the profile wavelength, $\lambda = 0.66\ldots1.0$ mm; $R_a = 1.8\ldots4.1$ μm; hardness = 60…63HRC; surface stress concentration factor, $\varepsilon = 1.8\%-4.1\%$; and kinematic precision coefficient, $K = 0.520-0.660$. It is also ascertained that the factors of the machining process—the RCPF—for machining hard coatings provide the order of decrease in their significance and are arranged as follows: *I*, *S*, *V*, *L*, *t*.

A single optimum model curve for hard-coated surface quality factor (Q_i) with RCPF condition factor level is plotted graphically with the data of the most optimum variant of factor levels shown in Figure 8.9, while the data in Table 8.4 are used to plot the different multiple curves as

TABLE 8.4

Initial Data for Plotting the Graphs for Optimum Workpiece Surface Quality and Rotary Cutting with Plasma Flame Performance Conditions

Workpiece Surface Quality Parameters (Y_i)	Rotary Cutting with Plasma Flame Factors (X_i)	Rotary Cutting with Plasma Flame Factor Level (−2)	Rotary Cutting with Plasma Flame Factor Level (−1)	Rotary Cutting with Plasma Flame Factor Level (0)	Rotary Cutting with Plasma Flame Factor Level (+1)	Rotary Cutting with Plasma Flame Factor Level (+2)
Workpiece surface roughness, R_a, μm (Y_{i1})	X_1	4.49	3.93	4.397	8.45	13.53
	X_2	12.79	8.03	4.397	4.45	5.63
	X_3	1.67	3.82	4.397	5.96	5.95
	X_4	11.77	7.52	4.397	4.96	6.65
	X_5	6.81	6.18	4.397	4.02	2.49
Workpiece surface hardness, HRC, kg/mm² (Y_{i2})	X_1	61.30	62.09	62.255	59.05	55.22
	X_2	59.96	61.17	62.255	60.47	58.56
	X_3	52.66	59.76	62.255	60.76	56.90
	X_4	55.32	59.47	62.255	60.93	58.24
	X_5	58.32	60.47	62.255	60.93	59.24
Workpiece surface stress concentration factor, % (Y_{i3})	X_1	−2.81	2.52	2.956	1.08	−2.97
	X_2	3.71	3.23	2.956	2.75	2.75
	X_3	1.91	2.32	2.956	3.68	4.63
	X_4	−0.87	1.57	2.956	3.15	2.29
	X_5	1.61	2.64	2.956	2.55	1.41
Workpiece surface wavelength, λ, mm (Y_{i4})	X_1	0.902	0.738	0.661	0.818	1.062
	X_2	1.518	0.987	0.661	0.687	0.918
	X_3	1.054	0.831	0.661	0.691	0.774
	X_4	0.908	0.809	0.661	0.808	1.133
	X_5	0.948	0.786	0.661	0.720	0.816
Kinematic coefficient of rotary tool bit, K (Y_{i5})	X_1	0.6558	0.6681	0.6497	0.6309	0.5814
	X_2	0.5995	0.6392	0.6497	0.6618	0.6433
	X_3	0.5146	0.6108	0.6497	0.6616	0.6162
	X_4	0.6041	0.6554	0.6497	0.6172	0.5467
	X_5	0.5475	0.6297	0.6497	0.6377	0.5633

Notes: X_1, plasma arc current; X_2, Distance between tool bit and plasmatron; X_3, feed rate; X_4, cutting speed; X_5, depth of cut.

shown in Figures 8.3 through 8.7. The optimum variant of the workpiece surface quality parameters can be determined from the plotted graph as well as with TI models. From these graphical analysis, the highest influential component quality parameters on wear resistance and reliability are known to be surface hardness and stress concentration factors. The most influential process condition factor is the current. The relationship between the surface quality parameters and the process current is shown in Figures 8.10 through 8.14. The optimum workpiece surface quality

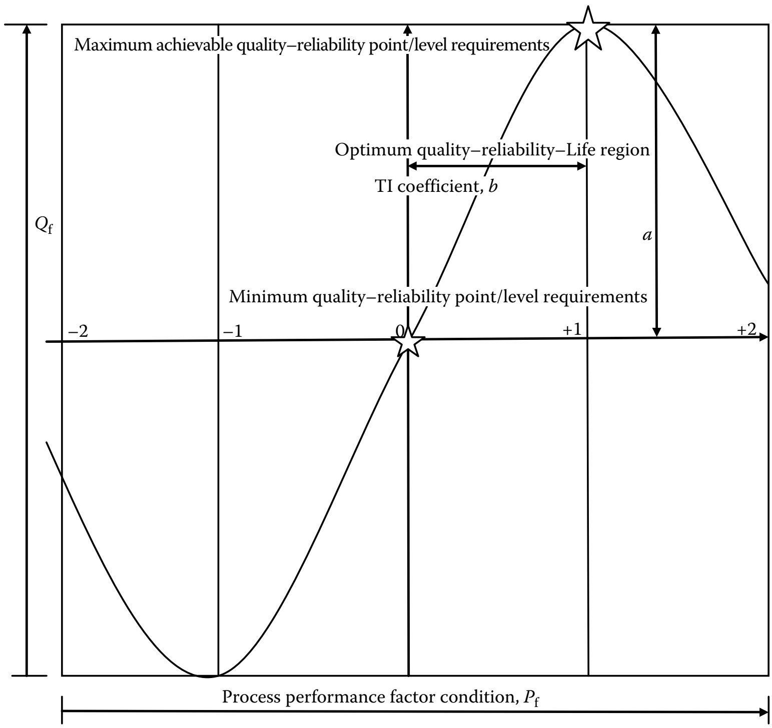

FIGURE 8.9
Determining the optimum workpiece quality factor and process-coded performance factorial level conditions and system reliability requirements.

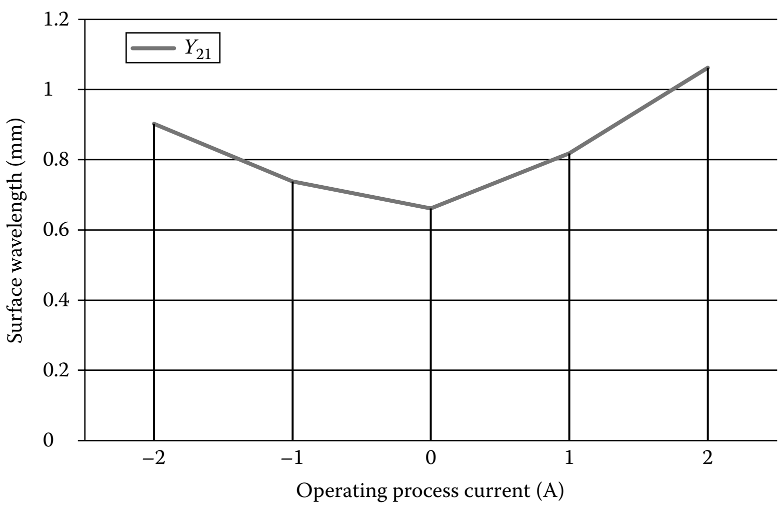

FIGURE 8.10
The influence of operating process current conditions on part surface wavelength.

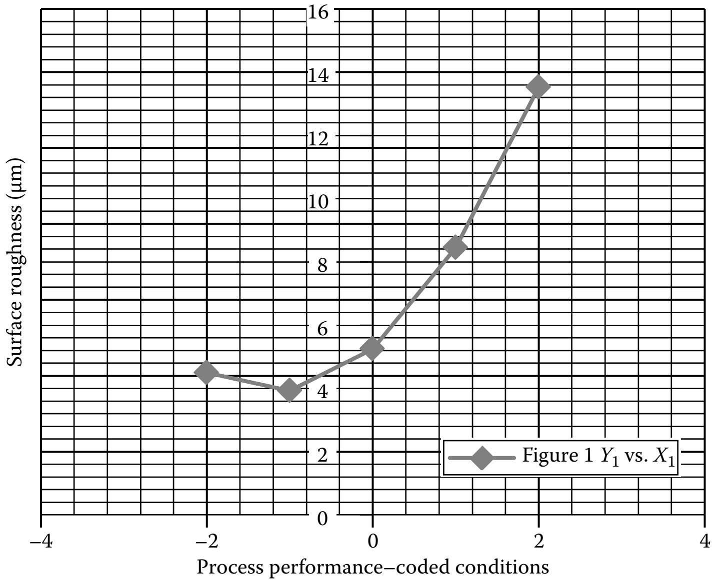

FIGURE 8.11
The influence of the operating process current on coated part surface roughness.

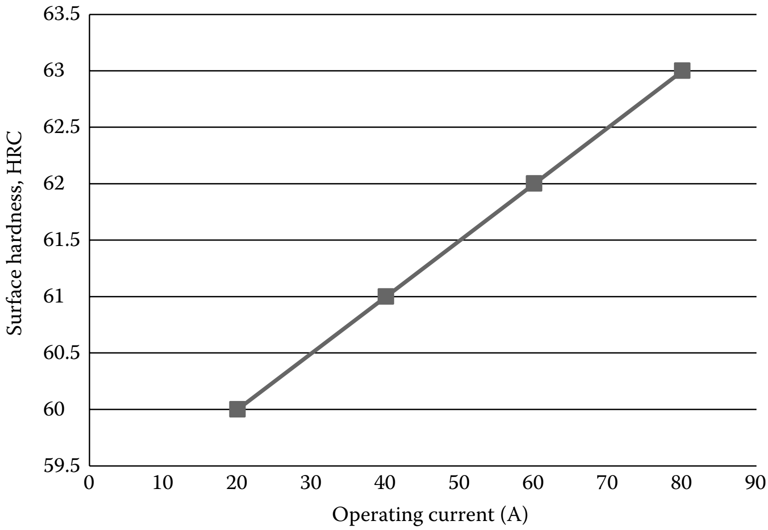

FIGURE 8.12
The influence of operating process current on coated part surface hardness.

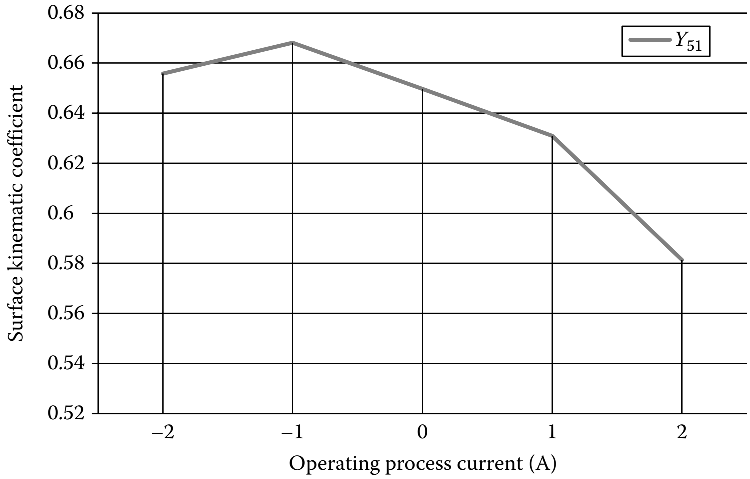

FIGURE 8.13
The influence of operating process current on coated part surface kinematic coefficient.

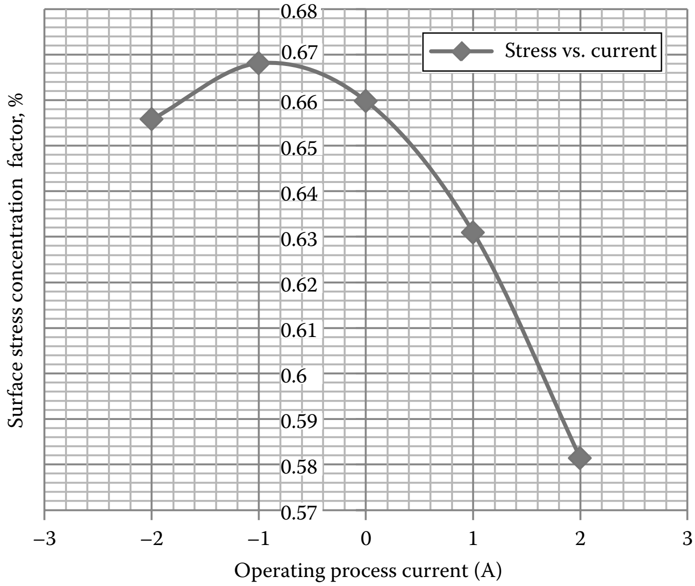

FIGURE 8.14
The influence of operating process current on coated part surface stress concentration factor.

parameters and cutting with plasma flame condition factors are used to determine the control limits and set points for monitoring and maintenance of industrial processes, parts, and equipment.

8.5 Surface Finishing with Grinding Hard-Coated Machine Part Surfaces

Grinding, or abrasive machining, refers to the process for removing material in the form of small chips by the mechanical action of irregularly shaped abrasive grains that are held in place by a bonding material on a moving wheel or abrasive belt. In surface finishing operations (e.g., lapping and honing), these grains are suspended in slurry and then are embedded in a roll-on or reference surface to form the cutting tool. Although the methods of abrasion may vary, grinding and surface finishing processes are used in manufacturing when the accuracy of workpiece dimensions and surface requirements is stringent and the material is too hard for conventional machining. Grinding is also used in cutoff work and cleaning of rough surfaces, and some methods offer high material removal rates suitable for shaping, an area in which milling traditionally has been used. Grinding is applied mainly in metalworking because abrasive grains are harder than any metal and can shape the toughest of alloys. In addition, grinding wheels are available for machining plastics, glass, ceramics, and stone. Conventional precision metal and ceramic components and ultraprecision electronic and optical components are produced using grinding.

8.5.1 Surface Finishing Method of Grinding Hard Alloy Coating Materials

Grinding is the process by which surface material is removed from an object, usually metal, by the abrasive action of a rotating wheel or a moving belt that contains abrasive grains. A grinding wheel can be made by mixing a bonding material, usually clay, with abrasive grains of such substances as silicon carbide or aluminum oxide. The mixture is then shaped into a wheel and hardened. A grindstone is a grinding wheel made by shaping naturally occurring sandstone, which contains abrasive quartz grains. Grinding is used in many manufacturing processes to produce a fine surface finish on an object and to bring the size of an object to within very fine tolerances. A grinding machine has devices that hold an unfinished workpiece and move it past the machine's abrasive wheel or belt, which is driven by a motor. For many products, grinding is only one step in a finishing process that involves additional similar operations such as honing, lapping, polishing, and buffing.

Grinding of hard alloy coated surfaces applied with plasma spray is considered. In order to avoid soiling of grinding wheels and formation of grinding burns on surfaces of W, Ti, and Cr carbide coatings, the use of diamond grinding wheels is recommended when concentrates of carbides is relatively high, and grinding with abrasive wheels at low carbide conc. In all cases, grinding wheels of decreased hardness are recommended. In selecting grinding process conditions of coating, its density and porosity should be used depending on degree of dispersion of initial powders and spraying method. Researchers have noted that grinding and polishing of titanium alloys is 10 times that of grinding stainless steel. Optimum grinding conditions are as follows: belt speed 300–400 m/min (dry) and 450–760 m/min with coolant, Si carbide, or electro-corundum as abrasive. The main features of polishing are large area of contact because of deformation of the polishing tool, continuous application of powder or suspension of abrasive to the polishing tool, and polishing temperature not exceeding 40°C. The surface roughness and residual stress values of the ground superalloys and advanced ceramics were measured using a profilometer and a residual stress analyzer, respectively. The ground surfaces were also assessed using a scanning electron microscope. The effect of undeformed chip thickness on surface topography of the difficult-to-machine materials was also investigated. A higher grinding wheel speed produces a smaller cutting depth and undeformed chip thickness, and thus smaller grinding force, decreased residual surface stress, and better surface finish.

8.5.2 Endurance Limit

Certain materials have a fatigue limit or endurance limit that represents a stress level below which the material does not fail and can be cycled infinitely. If the applied stress level is below the endurance limit of the material, the structure is said to have an infinite life. This is characteristic of steel and titanium in benign environmental conditions.

Many nonferrous metals and alloys, such as aluminum, magnesium, and copper alloys, do not exhibit well-defined endurance limits. These materials instead display a continuously decreasing S–N response. In such cases, fatigue strength for a given number of cycles must be specified. An effective endurance limit for these materials is sometimes defined as the stress that causes failure at 1×10^8 or 5×10^8 loading cycles. The concept of an endurance limit is used in infinite-life or *safe stress* designs. It is due to interstitial elements (such as carbon or nitrogen in iron) that pin dislocations, thus preventing the slip mechanism that leads to the formation of microcracks. Care must be taken when using an endurance limit in design applications because it can disappear due to

- Periodic overloads (unpin dislocations)
- Corrosive environments (due to fatigue corrosion interaction)
- High temperatures (mobilize dislocations)

The endurance limit is not a true property of a material, since other significant influences such as surface finish cannot be entirely eliminated. However, test values obtained from polished specimens provide a baseline to which other factors can be applied. Influences that can affect the endurance limit include

- Surface finish
- Temperature
- Stress concentration
- Notch sensitivity
- Size
- Environment
- Reliability

8.5.3 Disadvantages of Finishing Hard Alloy Materials with Grinding

The following are the disadvantages of finishing hard alloy materials with grinding:

1. Grinding hard alloy material is expensive, which is compared and contrasted in this book, as the cost of grinding Ti is 10 times that of grinding stainless steel.
2. For many products, grinding is only one step in a finishing process that involves additional similar operations such as honing, lapping, polishing, and buffing.
3. Grinding is used in many manufacturing processes to produce a fine surface finish on an object and to bring the size of an object to within very fine tolerances, which is based on dimensional accuracy.
4. Research focused on measuring residual stress in materials in the production lines during the manufacturing process would help the industry to expand the monitoring focus from dimensional accuracy to material performance to provide a better understanding of the quality of processes, equipment, and parts.
5. The endurance limit is not a true property of a material, since other significant influences such as surface finish cannot be entirely eliminated. However, test values obtained from polished specimens provide a baseline to which other factors can be applied.
6. The baseline obtained from polishing may result in mirror-like surface integrity with the desired surface roughness and

dimensional accuracy, but the reliability may still be different with the parts of the same surface roughness.

7. The tensile stress produced by grinding and polishing reduces the quality and reliability of parts, which therefore highlights the need for a rational selection of an optimum finishing method as a baseline and also requiring a change in focus from dimensional accuracy to material, process, and part performances.

8.5.4 Neural Network Modeling with the TI Technique

In the context of workpiece, part and tool CM and maintenance with neural network modeling requires two methods that can be applied, which are either direct or indirect monitoring. Direct methods rely on sensing techniques that measure the wear during a process by using optical, radioactive, and proximity sensors and electrical resistance measurement techniques. However, direct measurement of production line tool wear is not easily achievable because of the complexity of measuring the given signals during the process. With the TI technique, it is possible to measure the TI coefficients for quality growth and degradation data during manufacturing operations. The measurements of these parameters provide data for determining the quality factor, effectiveness factor, performance index, and reliability growth and degradation, including wear, fatigue, and temperature failures of components and systems. Indirect methods measure other factors that are the causes of tool wear such as cutting forces, acoustic emission, temperature, vibration, spindle motor current, cutting conditions, torque, and strain and snapshot images of the cutting tool. The information obtained from these measurements is more than necessary for tool wear measurement; therefore, necessary information should be extracted from them. The information can be used for either modeling the relation between cutting process variables and tool wear and part quality condition variations, or classification of worn or unspent tools as well as worn out parts. Because of their integrating, matching, and approximating capabilities, neural networks with the TI technique are suitable to model material, workpiece, part, and tool wear patterns.

A regression model performs better when test data are generated from experimental design. The multivariate regression models discussed previously with the help of the TI technique have been used to optimize material, workpiece, part, and tool reliability conditions during manufacturing processes. The reliability degradation of a workpiece and tool can now be measured, analyzed, and used to test for failure with the TI technique.

Multivariate regression analysis and neural network with the TI model is applied to finish hard-coated surfaces by rotary turning with thermal spray, which can definitely provide technical and economical advantages over traditional methods.

8.5.5 Advantages of Rotary Cutting with Plasma Spray for Machining Hard Coatings and the TI Model

1. The new machining process of RCPF is presented in this book as an alternative to the existing machining process of hard-coated surfaces by turning for optimum selection of materials, processes, and parts as well as providing requirement baselines for design, manufacturing processes for surface hardening, and monitoring and maintenance of parts, processes, and equipment.
2. In SPRT, the tool cutting speed (V) is the most influential factor on the quality condition parameters of parts like surface roughness (R_a), but in RCPF, electrical current (I) is the most influential factor on the condition parameters of the parts and equipment like lifetime reliability and provides the best values for the surface quality condition parameters like roughness (R_a), hardness (HRC), stress compression intensity factor (ε), wavelength (λ), and kinematic coefficient (K).
3. The machining conditions of RCPF differently influence the quality and lifetime reliability parameters of hard alloy–coated parts, while the most influential factors on the surface quality of parts act in the following decreasing significance order—plasma arc current, feed rate, cutting speed, distance between the tool bit and plasmatron, and depth of cut (I, S, V, L, t)—a trend that is completely different from existing traditional methods.
4. The determination of optimum RCPF conditions for machining hard alloy coatings is used to solve the optimization problem for multiple condition parameters of parts.
5. The optimum hard-coated part surface quality, performance, and health parameters as well as the conditions are determined and controlled by coefficients, which provide a single graphical curve that describes the process.
6. The determination of the optimum quality parameters of part surface hardness, surface roughness, stress concentration factor, surface wavelength, precision coefficient, and microstructure can be achieved with the application of TI coefficients.
7. The machining process of RCPF on hard alloy coatings provides the optimum characteristic that can be used as requirement baselines for design, manufacturing, monitoring, and maintenance purposes.
8. The optimum coefficient data are used to plan, design experiments, monitor, and test the quality, performance, and health of parts as well as the process conditions for the maintenance of industrial processes and equipment with the TI technique.

9. The optimum coefficient data are used to set up the monitoring limit levels of maximum and minimum values, while the control and monitoring values can also be measured in percentages.
10. The TI coefficients can be used to determine the maximum and minimum monitoring parameters as well as the changes from minimum to optimum (reliability, life, and performance growth) and from optimum to minimum (reliability, life, and performance degradations).
11. The design of the optimal multiple surface quality parameters with the TI technique of materials and parts for wear-, corrosion-, and temperature-resistant purposes as well as for the maintenance of processes and equipment.
12. The result of optimizing the conditions of rotary cutting with plasma spray for machining hard coating surfaces has opened up a huge outstanding benefit in design, manufacturing, monitoring, maintenance, and reliability engineering toward a sustainable development in the industries of the future.
13. This book provides the real-time data for predicting machine part and tool surface condition variations in finish hard rotary turning with thermal spray, using both regression analysis and neural network with TI models in design, manufacturing, monitoring, and maintenance organizations toward a sustainable integration.

8.6 Benefits of Machining Hard-Coated Precision Machine Part Surfaces with Rotary Cutting Plasma Spray and the TI Model

1. The result of optimizing the conditions of rotary cutting with plasma spray for machining hard coating surfaces has opened up a huge outstanding benefit in manufacturing and reliability engineering toward a sustainable development in the industries of the future.
2. The results provide the maximum and minimum achievable quality, life, and reliability data of coated machine parts that are used as a more improved baseline and requirements for design, maintenance, and testing applications.
3. Multiple model parameters are integrated by a single graph function, trend, and mechanism to describe the behavior of hard-coated machine part during operation.

4. The technique provides the best quality, reliability, and life data for industrial equipment used in dry and submerged applications that require quality/level, growth, and degradation measurements to be automated.
5. There is a huge possible automation advantage benefit, which is due to the fact that the data can be acquired continuously rather than just the discrete point in time of the maximum and minimum values of the optimization parameters, which of course is further enhanced with the TI technique.
6. The application of the TI technique offers the benefit of level/condition changes of the hard-coated machine part surface based on the new known optimum quality, life, and reliability parameters of parts, processes, and equipment in service.
7. Integrated reliability sensors can be used to measure, calculate, and convert the volume/level/coefficients of irregular geometry/materials with the TI technique, without deriving the equation of dynamic system conditions, which of course is not necessary and users do not have to do the calculation.
8. Users would have the benefits of simply entering the known optimal parameters, the maximum scale corresponding to 100% output, and the sensors can apply standard algorithm for those parameters adjusting the output based on the level/condition coefficients.
9. This technique provides careful evaluation of levels and continuous measurement principles of the process, machine parts, and equipment as well as the trend of mechanism and long-term operating costs of the instrumentation.
10. The designed sensor can be used to measure the maximum and minimum levels of model parameters and also measure the changes/variations within the level intervals as well as the rate of change of these parameters.
11. The results can be used to design data acquisition hardware for signal conversions and acquisitions.
12. The results are used to optimize the processes and integrate the manufacturing and maintenance objectives of minimizing cost and productivity losses by minimizing the wasted cost of further processing, or use of a defective part while maximizing productivity, performance, and reliability.
13. The data collected from this optimization process with the TI technique can be used to predict the reliability coefficient, the time of failure, and the resistance to failure data and detect the cause of failure and also set the control limits for design and testing applications.

8.7 Critical Features Produced by the Surface Finish of Nickel-Based Hard Alloy–Coated Part Surface

The sequence of process steps for machining hard alloy–coated part mating surfaces and the critical features on the surfaces are subject to leaving any of a substantial variety of potential surface defects on the finished coated part. Engine blocks, cylinder heads, bearings, shafts, and other precision parts and downstream assemblies may

- Be produced with defects caused by the specific coating material removal actions of the various equipment and their tools
- Transfer defects to the hard-coated part surface from previous processes that were originally internal defects from a suboptimal casting procedure or raw material composition deficiency
- Cause defects to the hard-coated part surface during operation, fixing, clamping, and other handling steps or equipment misadjustments as well as failures.
- Contaminate particles directly induced and not reliably removed in spite of nominal cleaning and drying operations
- Have parts left off of, misapplied, misconnected, or left unattached on engine, transmission, or overall power train assemblies

The categories of surface dimensional defects that can, and often do, exist at the end of a machine part machining line and prior to part assembly include

- Surface porosity
- Burrs
- Scratches
- Gouges
- Residual metal clips
- Residual nonmetallic *dirt* particles from transport or other handling components
- Absence of a specified feature
- An incompletely located individual feature (relative to some specified datum)
- Offset (incorrect location) of an entire set of specified features
- Incorrect machining of a specific individual feature
- Incorrect machining of all of the features that employ a given specific tool

- Excessive surface waviness indicative of a broken or overworked CNC tool
- Incorrect assembly of components due to interchanging of parts
- Incorrect assembly due to mislocation or misorientation of components

The root cause of defects is highly variable and specific to each machine part line's equipment complement and process settings. Very significantly, the root cause of any particular defect type will determine whether it is

- A random event that is not more likely to occur on a part just because it happened on the immediately previous produced part
- An event that will recur almost after it first occurs
- A condition that reflects a slower change in a process that is drifting out of control until it starts to produce defects with increasing frequency

The probability or likely root causes and physical nature of any defect(s) of concern will determine the appropriate strategy to be followed to reduce their occurrence to the minimum possible frequency. That strategy may call for infrequent or frequent or 100% inspection of parts for defects. It may also call for examination of the entire surface of a finished machine part or assembly. Alternatively, it may only require examination of certain features or areas of a part. If manufacturing objective includes minimizing the costs and productivity losses from production of scrap, the logical remedy is to occur. If the objective is also to minimize the wasted cost of further processing or use of a defective part having random defects, then 100% inspection for those random defects must be considered. Twentieth-century attempts to detect defects in precision machined surfaces have resulted to methods ranging from manual visual inspection to basic mechanical and optimal gauging techniques. The limitations and failures of those methods have been recognized for many years. Specifically, they are often

- Too slow to detect repetitive defects before numerous further unacceptable parts are produced
- Too incomplete and inaccurate to detect an adequate percentage of defects that occur
- Too primitive in their discrimination ability to sort out one defect type from another so that proper remedial action could be taken
- Unable to discriminate certain surface phenomena that are not defects at all, from those that are defects, therefore producing excessive false detections

- In the case of human visual inspection, unreliable in detecting actual infrequent defects due to the well-known human factors of boredom, distraction, and fatigue

Fortunately in the current era, high-definition, high-speed, 3D holographic and multistereo vision automation finally enables reliable defect detection and defect type discrimination to be automatically performed on precision machine parts and assemblies and other types of manufacturing at whatever inspection rate is required. Accurate automated defect detection requires the employment and integration of all the following key technological ingredients:

- Parts or assembly illumination that enhances and distinguishes the fundamental characteristics that highlight or clarify the differences between different types of defects as well as the differences between defects and nondefect surface phenomena (such as a mere 2D blemish or spot). Sensing devices and configurations that can exploit the observable images created by the illumination of the parts/assemblies and capture 3D information with sufficient spatial and spectral resolution. The configuration of quality and reliability algorithm components that incorporate enough knowledge sensitivity and generalization ability to robustly produce correct defect and failure detection decisions. These decisions must be produced across the wide range of different failure and quality instances that occur. While exhibiting that capability, this algorithm suite must be executable at speeds required by the manufacturing operating environment.
- An application definition and development environment and technique that enables the total vision solution illumination, sensors, and algorithms can be implemented and integrated for a new application and enhanced as new information is obtained, within a minimal amount of elapsed time and skilled manpower.
- Integrated reliability maintenance and monitoring program with the TI technique is applied to tackle this challenge toward a sustainable development in manufacturing and maintenance operations.
- The application of the TI technique is used to optimize the production line of hard-coated machine part surfaces, which forms the design baselines and test requirements of maintenance industries for measuring and detecting defects in surfaces of both small and large machine parts, as well as monitoring the reliability of processes, parts, and equipment in real-time operations and also selecting the optimum maintenance strategies to correct degradations, cracks, and failures.

8.8 Integrated Reliability Testing for Reliability, Optimum Growth, Degradation, and Failure of Hard-Coated Machine Part Surface during Machining and Grinding Processes with the TI Model

The multivariate quality regression model is used to determine and predict the optimum quality–reliability conditions of components and processes at minimum costs. The optimum data are used to implement the TI model to determine reliability degradation and failures of parts at minimum cost. A TI coefficient sensor (TICS) is developed to measure reliability growth and degradation as well as for data acquisition and software programs. The sensors are designed to measure optimum reliability, reliability growth, and reliability degradation and failures, test for optimum reliability and failures and select the optimum machining and grinding process conditions for hard alloy–coated part surfaces and are used to evaluate part surface degradation and test component and system failures. The optimum selection of part surface quality parameters and the conditions of machining and finishing processes provides the initial data requirements for the evaluation of components and system reliability. The optimum component and system reliability baseline is set for wear-, corrosion-, and high-temperature-resistant purposes. The optimum component and system reliability baseline is possible with the help of the TI model, which is usually higher than the existing reliability baseline for critical equipment, parts, and surface finish processes. The model makes the inherent reliability induced during manufacturing, which is always usually greater than the operational reliability the same. The installation reliability, which is usually less can also be made equal to the inherent reliability with the application of TI model. Now that the reliability can be determined and evaluated during real-time operations, the operator will now be able to operate with the knowledge and understanding of what is happening in the components and systems. With the help of model-based reliability tests, tools, and software programs together with the TI technique, the operator can now measure, monitor, analyze, and maintain materials, parts, processes, and equipment. With this program, it is therefore possible to detect potential problems early enough and thereby take prompt preventive maintenance action before it enters a failed state or before catastrophic damage is done. It is also possible to select the maximum achievable conditions of materials, parts, processes, and equipment that would help prolong the health and life of components and systems. An integrated reliability monitoring and maintenance program with the TI model can now be used throughout all the stages of design, manufacturing processes, and equipment. The program will also help determine the component and system reliabilities at all stages from design through manufacturing to service operation. The reliability information derived from this network program can be used for testing, selection, design, monitoring, and maintenance of materials, parts, processes, and equipment.

The mathematical model of the different critical parts and systems would be used to develop software programs and design tools needed to measure, test, analyze, and select the most cost-effective variant from the existing manufacturing and grinding processes, parts, equipment, and instruments and monitor the health, reliability performance, and degradation with the help of the TI coefficients.

8.9 Integrated Reliability Monitoring and Maintenance of Processes, Parts, and Equipment with a TI Model–Based Program

The use of a integrated reliability monitor (IRM) to determine reliability optimum, reliability growth, reliability degradation, and failures of components and systems, while TICS is used to measure the TI coefficients for integrated reliability controls, integrated reliability selector (IRS) is for selecting the best parameters, parts, and processes, failure prediction and design of software programs for optimum reliability selection, testing, monitoring and maintenance will help to eradicate and minimize the potential failures arising from poor selections, tensile stresses, dimensional inaccuracies and other causes of process variations before they can cause damages. The integrated reliability monitoring and maintenance program is comprised of all the different functions stated earlier to provide monitoring and maintenance actions to operators and users. The design of models for maximum achievable reliability growth, reliability degradation, and failure coefficients as well as software-defined measurement and instrumentation programs for optimum selection of machining and finishing processes, reliability testing for failures, and integrated reliability monitoring and maintenance is now possible with the help of TI coefficients. The TI coefficient a is used to determine component reliability growth and degradation, and TI coefficient b is used to determine time to failure, process condition factors, and effectiveness factor characteristics as well as the optimum integrated reliability. TICSs can be used to measure the TI coefficients a and b of components and systems. TI coefficient b is used to determine the process effectiveness factor and its optimum performance with TICS for process condition control. The TI model and software program

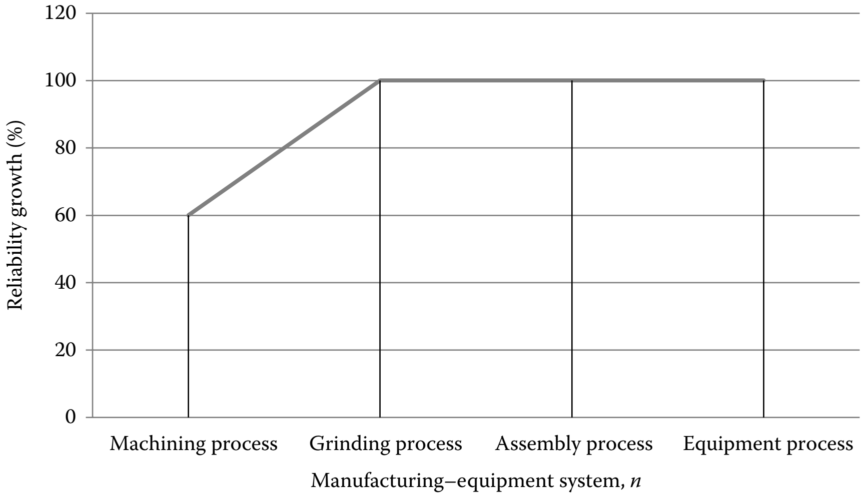

FIGURE 8.15
Reliability growths from machining to equipment system operations.

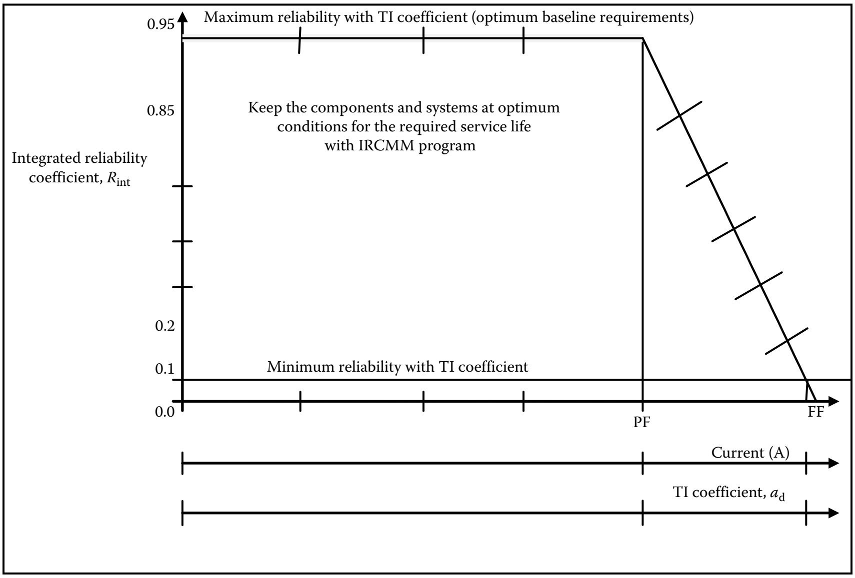

FIGURE 8.16
Integrated reliability curves of manufacturing processes and equipment with IRCMM program.

with the help of TICSs can be used to acquire reliability data, while IRMs are used to analyze, diagnose, transfer, and present data for a cost-effective integrated reliability condition monitoring and maintenance (IRCMM) of a workpiece, coating deposition, machining, and surface finish processes, as shown in Figures 8.15 and 8.16.

The TI model and software program can be used to design a cost-effective integrated reliability monitoring and maintenance program of processes, parts, and equipment and can be used to detect and diagnose failures early enough in the manufacturing processes or in the service operations before they can cause catastrophic damages.

8.10 Conclusions

1. Machining of hard alloy–coated machine parts for wear-, corrosion-, and high-temperature-resistant conditions generates high temperatures at the cutting edge that impair the quality and reliability of various cutting tool materials.
2. Commercially available cutting tool materials are currently being applied at moderate speed conditions when machining hard alloy coatings, hence lower machining productivity.
3. SPRT can significantly improve tool life when the cutting tool is set at the optimum inclination angle.
4. Much higher cutting speeds and feed rates are achieved when machining hard alloy coating part with SPRT, relative to conventional cutting tools, without pronounced adverse effect on tool life and machining performance, quality, and reliability due to the lower cutting temperature generated.
5. Prolonged machining by SPRT tends to lower the surface roughness value, thus improving surface finish, but cannot meet the desired dimensional specifications of critical hard alloy–coated machine parts in rotating equipment operating in wear and aggressive applications of the industries of the future.
6. This book introduces a new cost-effective machining process known as RCPF for optimum surface finish that meets the desired dimensional specifications of critical hard alloy–coated machine parts in rotating equipment operating in wear and aggressive applications of the industries of the future.
7. In SPRT, the cutting speed (V) is the most influential factor on the surface quality parameter (like surface roughness [R_a]) toward dimensional specification focus, but in RCPF, electrical current (I) is

the most influential factor on multivariate surface quality parameters (like surface roughness [R_a], hardness [HRC], stress compression intensity factor [ε], wavelength [λ], kinematic coefficient [K]), which of course are material performance and reliability specification focus.

8. The traditionally expensive grinding method is generally used to finish hard alloy coating part surface to produce fine surface finish, with very fine tolerances, but provides a lesser reliability due to its induced tensile stress than the same surface quality of hard alloy–coated part machined by RCPF.
9. The advantages of the new and advanced machining method make it possible to optimize the manufacturing process conditions, friction part surface conditions, and monitoring and maintenance conditions as well as the determination of maximum achievable reliability of parts and equipment in the industries of the future.
10. The optimized data provide optimum component/system reliability, lifetime, performance, monitoring, and maintenance requirements with standard-set targets for integrated reliability monitoring and maintenance of manufacturing processes, parts, and industrial equipment.
11. The use of common multiple parameters for quality, lifetime, and reliability parameters of hard alloy–coated machine parts with RCPF has been made possible experimentally, with experimental plans for the machining process.
12. A multivariate regression model for the multiple quality parameters of a part with the process conditions of RCPF has ascertained that RCPF for a single run provides the quality parameters of profile wavelength, $\lambda = 0.66....1.0$ mm; $R_a = 1.8....4.1$ μm; hardness = 60…63HRC; surface layer compression intensity factor, $\varepsilon = 1.8\%–4.1\%$; and kinematic precision coefficient, $K = 0.520–0.660$, while a prolonged process run will achieve ten times better quality and reliability growth condition of hard alloy–coated part surface.
13. It is also ascertained that the conditions of the machining process—the RCPF—for machining hard coatings are in the order of decrease in their significance (I, S, V, L, t) for the influence of the quality condition of a hard alloy–coated part surface, which is quite different from the traditional method of machining.
14. The TI technique helps transfer the optimum values from the finish operation of the manufacturing processes to the initial operation of industrial equipment, where the optimum reliability value is sustained for a maximum specific period of its lifetime by a cost-effective precision maintenance strategy with the help of the same technique at minimum life cycle cost.

15. The TI technique is used to plot integrated reliability curve using multiple part surface condition parameters represented by a single metric known as the TI coefficient as well as integrate the optimum component quality condition into the process performance condition and detect failure.
16. The multiple component parameters of the part surface and process performance conditions can be monitored in terms of reliability growth/degradation and at the same time with the single metric, providing adequate and relevant real-time information about the reliability performance, quality, and lifetime of the operating system.
17. The single integrated reliability curve and trend is used to determine reliability, life, and performance as well as their control limits, set threshold points, and the program of IRCMM of manufacturing processes and industrial equipment with the TI coefficients.
18. The single trend is also used to construct an integrated reliability monitoring and maintenance mechanism for fatigue, wear, corrosion, and temperature resistance purposes with the application of the TI model.
19. A software program for data acquisition, analysis, and presentation of a manufacturing and industrial equipment system is developed for automotive implementation of IRCMM tasks.
20. The program together with the TI model can also be used to design measuring instruments, diagnostics, prognostics, monitors, data acquisition devices, and other reliability tools.
21. The automation of IRCMM of manufacturing processes and industrial equipment is possible with the TI model–based simulation technique.
22. An IRCMM program is used as a decision-making guide and reliability growth/degradation test and for the selection of a cost-effective precision maintenance strategy.

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9

Reliability Growth, Degradation, and Fatigue Failure of Nickel-Based Hard Alloy–Coated Part Surface

9.1 Failure Analysis of Mechanical Components

Many examples of failure analysis are commonplace; whether it is a minor maintenance failure or a major failure of natural disasters, one can always learn from the analysis. Some components, for example, brake shoes, belts, and chains, slowly fail from wear for several years. Other parts such as bolts, shafts, and machine frames should never fail. Understanding how the parts fail shows what has to be done to prevent a recurrence. Every failure leaves clues as to why it happened. In more than 90% of industrial cases, a trained person can use the basic techniques of failure analysis to diagnose the mechanical causes behind a failure, without having to enlist outside sources and expensive analytical tools like an electron microscope. Then knowing how a failure happened, the investigation can pursue the human roots of why it happened. There are times, however, when 90% accuracy is not good enough. When personal injury or a large loss is possible, a professional should guide the analysis.

Combining effective failure analysis with a good predictive maintenance program usually results in huge benefits. Depending on the type of facility, it can not only reduce maintenance costs by 20%–30% but also increase production by similar values. However, it does require a cultural change. An effective root cause failure analysis (RCFA) program will substantially reduce this problem. To interpret a failure accurately, the analyst has to gather all pertinent facts and then decide what caused them. To be consistent, the analyst should develop and follow a logical path that ensures a critical feature will not be overlooked. The following steps should be taken:

1. Decide what to do. Is detailed an analysis necessary? Before starting, try to decide how important the analysis is. If the failure is relatively insignificant, in cost and in convenience, it deserves a cursory analysis; the more detailed steps can be ignored. But this strategy increases the chance of error. Some failures may require a 20 min analysis with an 8% probability of being correct, but critical failures require true RCFA, in which no questions are left unanswered. RCFA may require hundreds of man-hours, but it guarantees an accurate answer.
2. Find out what happened. The most important step in solving a plant failure is to seek answers soon after it happened and talk to the people involved. Ask for their opinions because they know the everyday occurrences at their worksite and their machinery better than anyone. Ask questions and try to get first person comments. Do not leave until you have a good understanding of what exactly happened and the sequence of events leading up to it.
3. Make a preliminary investigation. At the site, examine the broken parts, looking for clues. Do not clean them yet because cleaning could wash away vital information. Document the conditions accurately and take photographs from a variety of angles of both the failed parts and the surroundings.
4. Gather background data. What are the original design and the correct operating conditions? While still at the site, determine the operating conditions: time, temperatures, amperage, voltage, load, humidity, pressure, lubricants, materials, operating procedures, shifts, corrosives, vibrations, etc. Compare the difference between actual operating conditions and design conditions. Look at everything that could have an effect on machine operation.
5. Determine what failed. After you leave the site and the immediate crush of the failure, look at the initial evidence and decide what failed first—the primary failures—and what secondary failures resulted from it. Sometimes, decisions are very difficult because of the size of analysis that is necessary. Find out what changed. Compare current operating conditions with those in the past. Has surrounding equipment been altered or revised?
6. Examine and analyze the primary failure. Clean the component and look at it under low-power magnification, 5×–50×. What does the failure face look like? From the failure face, determine the forces that were acting on the part. Were conditions consistent with the design? With actual operation? Are there other cracks or suspicious signs in the area of the failure? Important surfaces should be plotted in a graph and preserved for reference.

7. Characterize the failed piece and the support material. Perform hardness test, dye penetrations, and ultrasonic examination, lubricant analysis, alloy analysis, etc. Examine the failed part and the components around it to understand what they are. Check to see if the results agree with design conditions.
8. Conduct detailed chemical and metallurgical analyses. Sophisticated and metallurgical techniques may reveal clues to material weaknesses for minute qualities of chemical that may cause unusual fractures.
9. Determine the failure type and forces that cause it. Review all the steps listed. Leaving any questions unasked or unanswered reduces the accuracy of the analysis.
10. Determine the root causes. Always ask, why did the failure happen in the first place? This question usually leads to human factors and management systems. Typical root causes like "The shaft failed because of an engineering errors" or "The valve failed because we did not do PM" or "The shaft failed because it was not aligned properly" expose areas where huge advances can be realized. However, these problems have to be dealt with differently. Different analysts use different techniques, but the most practical way for plant people is to properly define failures and categorize them.

9.2 Definitions of Failure Characteristics

- Failure—when a person or component no longer performs as intended.
- Primary failure—the components that failed first and then caused other secondary failures. Primary failures can usually be detected and monitored before they fail catastrophically. For example, a failure bearing may be the monitorable item that will, if neglected, eventually result in secondary failure, the destruction of a gearbox.
- Failure investigation—an analysis of why something happened that does not delve as deeply into causes as RCFA. As a result, the probability of an inaccurate diagnosis increases.
- Fracture face—the exposed surface where the failure actually progressed across the piece. RCFA is done to find out why a failure occurred. It typically reaches into the human and management systems that allowed the failure to happen.

- Stress concentration—physical features that cause the apparent local stress in a part to be greater than the average across the piece. They can result from changes in shapes, from defect, and from changes in metallurgy, and they can increase the local stress tenfold.

9.3 Types and Categories of Failures

Different analysts use different techniques, but the most practical way for plant people to categorize failures is by overload, fatigue, corrosion-influenced fatigue, corrosion, and wear:

- Overload—applying a single load causes the part to deform or fracture as the load is applied.
- Fatigue—fluctuating loads over a relatively long time cause this type of failure and usually leave clues.
- Corrosion—influenced fatigue: The failure is the result of the electrical or biological action of the corrosion, causing a loss of material.
- Wear—a variety of mechanisms result in loss of material by mechanical removal.

At this point, it is important to note that overload failures happen immediately as the load is applied and therefore require a firsthand investigation of the forms. The two common forms of overload failures are usually ductile and brittle, which of course have different appearances.

The most important point to understand when doing failure analysis on a fractured part is that the crack always grows perpendicular to the plane of maximum stress. However, both the nature of the material and the type of failure affect the appearance of the failure face. Ductile materials frequently allow a great deal of deformation, but with brittle materials, there is essentially no deformation. Brittle fracture pieces frequently look as if they could be glued back together. Industrial experience has ascertained that fatigue is the primary failure mode for more than 90% of mechanical failures. Actually, fatigue failures are caused by repeated stress cycles, that is, by fluctuating stress. Four points are important to understanding fatigue:

- Without stress fluctuations, fatigue cannot happen.
- Fatigue happens at stress levels well below the tensile strength of the material.
- Where corrosion is present, the fatigue strength of metals continuously decreases.
- The crack takes measurable time to progress across the fracture face.

TABLE 9.1

Fatigue Strength of Materials

Fatigue Strength	AISI 1020	AISI 4140
Tensile strength, PSI (MPa)	60,000 (0.4136)	150,000 (1.0342)
Yield strength, PSI (MPa)	42,000 (0.2895)	120,000 (0.8274)
Fatigue strength (clean and dry), PSI (MPa)	30,000 (0.2068)	80,000 (0.5516)
Fatigue strength, mild corrosive, 106 cycles, PSI (MPa)	12,000 (0.0827)	20,000 (0.1379)
Fatigue strength, mild corrosive, 109 cycles, PSI (MPa)	7,000 (0.0483)	7,000 (0.0483)

Source: Neville, S., Failure analysis of mechanical components, Maintenance World, 2004.

Interpretation of the failure face can disclose and analyze the forces that caused the crack, the amount of time elapsed from initiation to final failure, the relative size and type of the load, and the severity of the stress concentrations. CM of the condition parameters like fatigue strength of the material (Table 9.1), hardness, stress, microstructure, and other properties from initiation to final failure can also be used to find the root cause of failure. We shall first and foremost at this point look at the physics of fatigue failure mode for better understanding.

9.4 Physics of Fatigue

Fatigue is defined as "failure under a repeated or otherwise varying load, which never reaches a level sufficient to cause failure in a single application." Fatigue cracks always develop as a result of cyclic plastic deformation in a localized area. This plastic deformation often arises, not due to theoretical stresses in a perfect part, but rather due to the presence of a small crack or preexisting defect or notch on the surface of a component. August Wohler was one of the first engineers to study the fatigue phenomenon as it related to railway axles. He realized that knowledge of cyclic loading conditions was crucial and so he measured them on actual vehicles and subsequently constructed a test rig that subjected two axles to the measured loads simultaneously. This test procedure later became known as the rotating bending test. He varied the maximum load and found that as it decreased, the life increased until finally a lower limit load was reached at which point no further failures were observed. It took about 30 years for other workers to present his tabular results in the form of the now familiar stress life (Figure 9.1). A stage I crack undergoing alternating stress leads to persistent slip bands forming along the planes of maximum shear. These bands slip back and forth, much like a deck of cards, and give rise to surface extrusions and intrusions. The surface intrusions form an *embryonic* crack (Figure 9.2) [2].

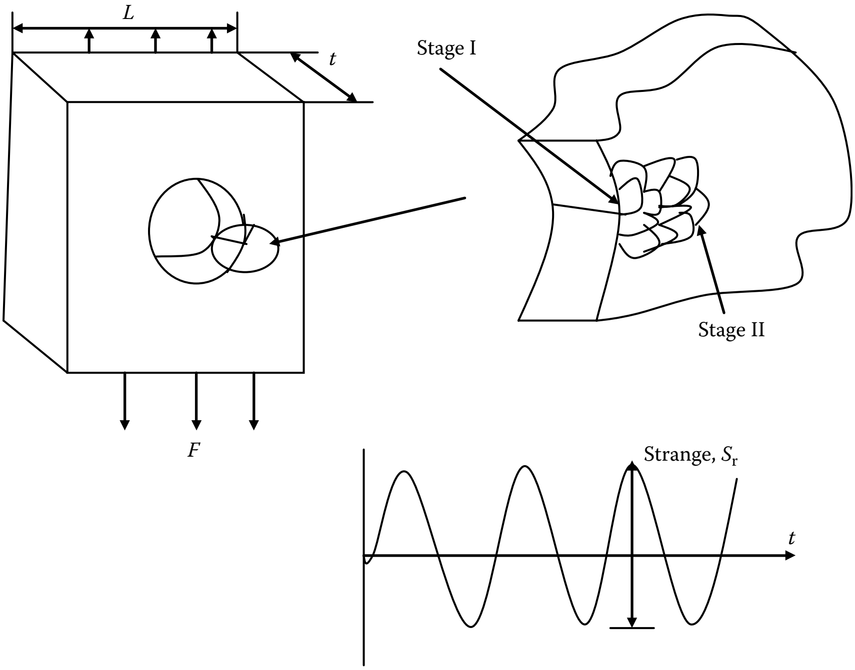


FIGURE 9.1
Illustration of stage I and stage II, stress—life, reliability degradation, and crack growth.

The stage I crack propagates in this mode until it encounters a grain boundary, at which point it briefly stops until sufficient energy has been applied to the adjacent grain and the process continues. After traversing two or three grain boundaries, the direction of crack propagation now changes into a stage II mode. In this stage, the physical nature of the crack growth changes. The crack itself now forms a macroscopic obstruction to the flow of tress that gives rise to a high plastic stress concentration at the crack tip. It should be noted that not all stage I cracks evolve to stage II. A stage II crack grows by a ratcheting mechanism. As the tensile stress increases, the crack tip opens giving rise to local plastic shear deformation. As the tensile stress now decreases, the crack tip closes and the permanent plastic deformation gives rise to a distinctive sawtooth profile known as striation. On completion of the cycle, the microcrack has advanced a small distance and has formed an additional striation. The extent of crack growth is proportional to the range of elastic–plastic crack tip strain applied. Many repetitions of these cycles will result in fatigue failure and the distinctive *beach marks* on the fracture surface. This understanding of the stage II crack growth ratcheting mechanism forms the basis of the linear elastic fracture mechanics' crack propagation fatigue methodology.

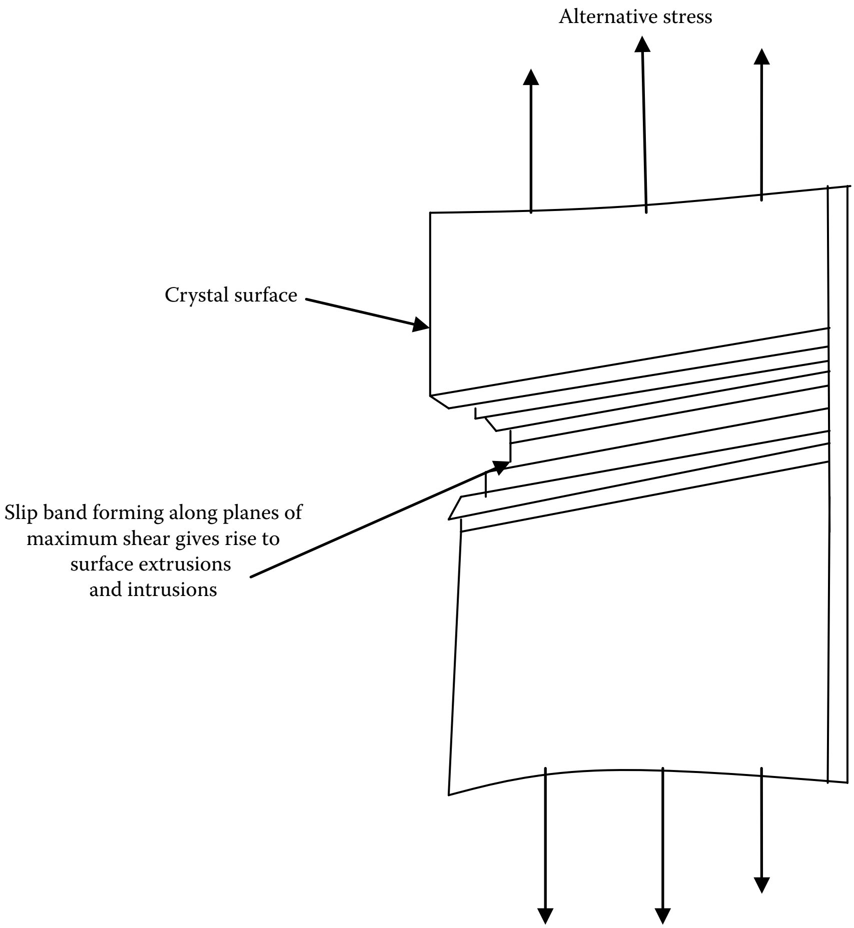


FIGURE 9.2
Illustrations of persistent slip bands.

9.5 Characteristics of Fatigue Failures

The following characteristics are common to fatigue in all materials:

- The process starts with a microscopic crack, called the initiation site, which then widens with each subsequent movement, a phenomenon analyzed in the topic of fracture mechanics.
- Failure is essentially probabilistic. The number of cycles required for failure varies between homogeneous material samples.

- The greater the applied stress, the shorter the life.
- Damage is cumulative. Materials do not recover when rested.
- Fatigue life is influenced by a variety of factors, such as temperature and surface finish, in complicated ways.
- Some materials (e.g., some steel, titanium, and other hard alloys) exhibit an endurance limit or fatigue limit, a limit below which repeated stress does not induce failure, theoretically, for an infinite number of cycles of load. Most other nonferrous metals (e.g., aluminum and copper alloys) exhibit no such limit and even small stresses will eventually cause failure.
- As a means to gauge fatigue characteristics of nonferrous and other alloys that do not exhibit an endurance limit, a fatigue strength is frequently determined, and this is typically the stress level at which a component will survive 10^7 loading cycles.

9.6 High-Cycle Fatigue

Historically, most attention has focused on situations that require more than 10^4 cycles to failure where stress is low and deformation primarily elastic.

In high-cycle fatigue situations, material performance is commonly characterized by an *S–N* curve, also known as a Wöhler curve. This is a graph of the magnitude of a cyclical stress (*S*) against the cycles to failure (*N*). *S–N* curves are derived from tests on samples of the material to be characterized (often called coupons) where a regular sinusoidal stress is applied by a testing machine that also counts the number of cycles to failure. This process is sometimes known as coupon testing. Each coupon test generates a point on the plot, though in some cases there is a runout where the time to failure exceeds that available for the test (see censoring). Analysis of fatigue data requires techniques from statistics, especially survival analysis and linear regression.

9.7 Probabilistic Nature of Fatigue

As coupons sampled from a homogeneous frame will manifest variation in their number of cycles to failure, the *S–N* curve should more properly be an *S–N–P* curve capturing the probability of failure after a given number of cycles of a certain stress. Probability distributions that are common in data analysis and in design against fatigue include the lognormal distribution, extreme value distribution, and Weibull distribution. In practice, a mechanical part is exposed to a complex, often random, sequence of loads, large and small. In order to assess the safe life of such a part, accomplish the following:

1. Reduce the complex loading to a series of simple cyclic loadings using a technique such as rainflow analysis.
2. Create a histogram of cyclic stress from the rainflow analysis.
3. For each stress level, calculate the degree of cumulative damage incurred from the *S*–*N* curve.
4. Combine the individual contributions using an algorithm such as Miner's rule.

Though Miner's rule is a useful approximation in many circumstances, it has two major limitations:

1. It fails to recognize the probabilistic nature of fatigue and there is no simple way to relate life predicted by the rule with the characteristics of a probability distribution.
2. There is sometimes an effect in the order in which the reversals occur. In some circumstances, cycles of high stress followed by low stress cause more damage than would be predicted by the rule.

9.8 Low-Cycle Fatigue

Where the stress is high enough for plastic deformation to occur, the account in terms of stress is less useful and the strain in the material offers a simpler description. Low-cycle fatigue is usually characterized by the Coffin–Manson relation.

9.9 Fatigue and Fracture Mechanics

The account earlier is purely phenomenological and, though it allows life prediction and design assurance, it does not enable life improvement or design optimization. For the latter's purposes, an exposition of the causes and processes of fatigue is necessary. Such an explanation is given by fracture mechanics in four stages:

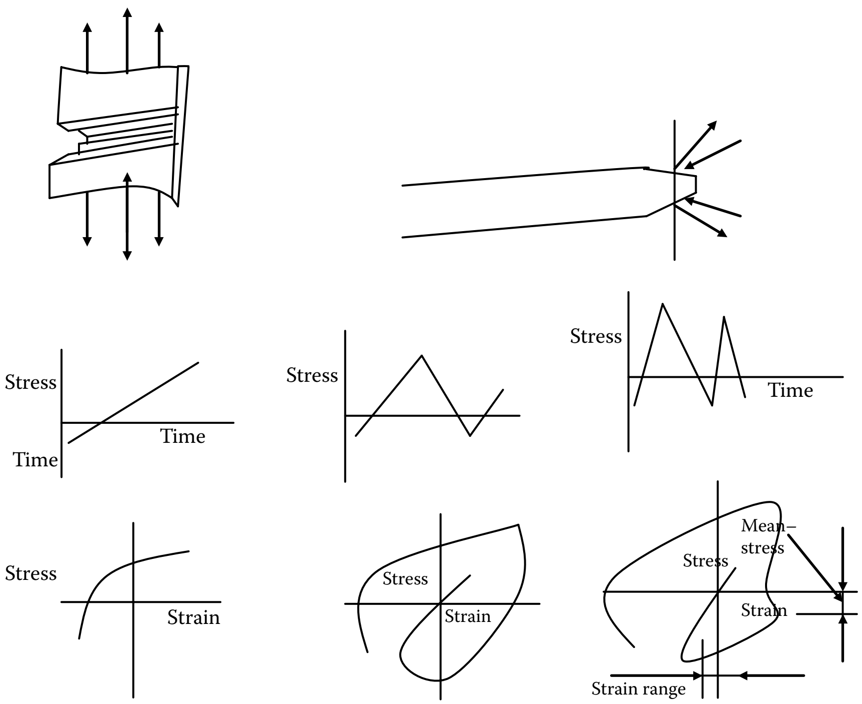
1. Crack nucleation
2. Stage I crack growth
3. Stage II crack growth
4. Ultimate ductile failure

9.10 Factors That Affect Fatigue Life and Its Resistance to Failure

The magnitude of stress including stress concentrations caused by part geometry is an important factor that affects fatigue life. The quality of the surface, surface roughness, scratches, etc., cause stress concentrations or provide crack nucleation sites that can lower fatigue life depending on how the stress is applied. For example, shot peening puts the surface in a state of compressive stress that inhibits surface crack formation thus improving fatigue life. Other surface treatments, such as laser peening, can also introduce surface compressive stress and could increase the fatigue life of the component. This improvement is normally observed only for high-cycle fatigue. Little improvement is obtained in the low-cycle fatigue regime. The most recent development in the field of surface treatments utilizes ultrasonic energy to create residual compressive stresses that surpass those achieved by shot peening, laser peening, and other legacy methods. Ultrasonic impact technology operates within the harmonic frequency range of metals, allowing energy to be delivered deep into the material. Low amplitudes ensure that the metal is not overworked. Surface defect geometry, size, shape and location of surface defects such as scratches, gouges, and dents can have a significant impact on fatigue life. Significantly uneven cooling can lead to a heterogeneous distribution of material properties such as hardness and ductility in the case of alloys and structural composition. Casting defects such as gas porosity and shrinkage voids, for example, can significantly impact fatigue life. In metals where strain rate sensitivity is observed (ferrous metals, copper, titanium, etc.), the strain rate also affects fatigue life in low-cycle fatigue situations. For nonisotropic materials, the direction of the applied stress can affect fatigue life. In case of grain size, for most metals, fine-grained parts exhibit a longer fatigue life than coarse-grained parts. Environmental conditions and exposure time can cause erosion, corrosion, or gas-phase embrittlement, which all affect fatigue life. Arising from the factors that affect fatigue life and its resistance to failure, it is quite obvious that it comprises of the different component, process, and environmental condition parameters. Fatigue reliability is therefore influenced by a number of factors that can actually be summarized as follows:

- Stress or strain range
- Mean stress
- Surface finish and quality
- Surface treatments
- Sequence effects
- Manufacturing methods
- Technological inheritance (TI)
- Stress or strain range

In both stage I and stage II growth, crack development arises through plastic shear strain on a microscopic scale. Consider the plastic shear strain forming



(a) Rise in nominal stress with time

(b) Reduction and rise in nominal stress with time

(c) Total reduction in nominal stress

FIGURE 9.3
Elastic–plastic stress and strain along a stop plane at the root of a crack with integrated reliability condition monitoring and maintenance (IRCMM) strategy.

along the stage I slip planes or at the tip of a stage II crack as a result of the nominal stress time history, shown in Figure 9.1. Figure 9.3a shows the nominal stress rise with time. On a microscopic level, in the presence of a crack or preexisting defect, the stress and strain become plastic and can be plotted in the stress versus strain diagram shown. Figure 9.3b shows what happens when the nominal stress is reduced and then raised by a smaller amount. Again the local stress versus strain can be plotted showing the effect of local yielding. Figure 9.3c shows another reduction in the nominal stress. The stress versus strain plot shows the formation of a hysteresis loop. A loop in the stress versus strain plot indicates the release of strain energy where the total energy released is equal to the area of the loop. This has released a quantity of shear strain energy and this has been expanded in sliding the slip planes or advancing the stage II crack. This illustrates that a *quantum* of shear strain energy is released when the nominal stress is cycled into tension and then back again. Also the larger the stress cycle, the greater the energy released. From the stress life curve shown in Figure 9.1, we see that fatigue life drops exponentially as the stress cycle range increases. This understanding of the elastic–plastic stress and strain behavior at the root of a crack is the basis of the strain life or local strain fatigue methodology.

9.10.1 Tensile and Compressive Mean Stress

A nonzero mean stress influences the rate at which fatigue damage accrues. A tensile stress applied to a stage II crack (Figure 9.4) forces it to open and any stress cycles applied will have a more damaging effect. Conversely, compressive mean stress forces the crack to close, thereby reducing the effectiveness of any applied stress cycle.

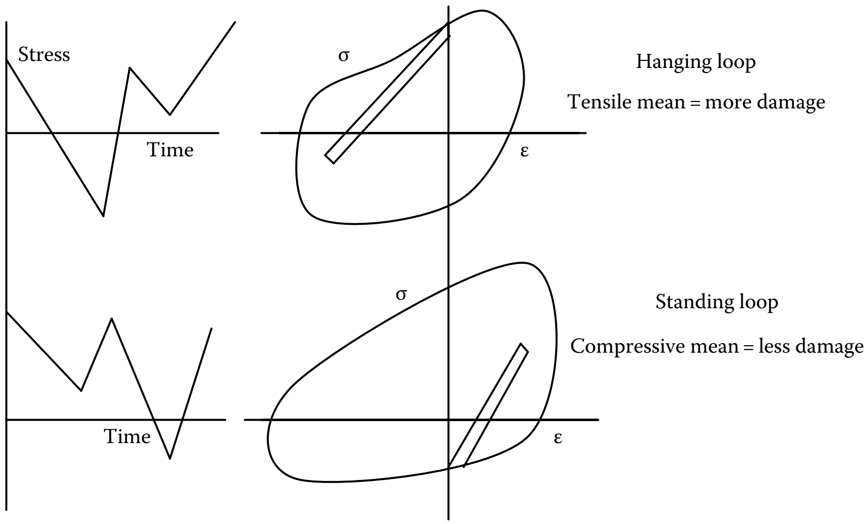


FIGURE 9.4
Illustrations showing the effect of sequence.

9.10.2 Surface Treatments

Surface treatments can be applied to improve the fatigue resistance of a component. These usually work by inducing a residual compressive stress at the surface. Under low-amplitude cycles, the stresses at the surface are significantly lower or even remain compressive. Therefore, the fatigue life is greatly improved. This effect is only true for components subjected to low-amplitude stress cycles. If large-amplitude cycles are applied, then these start to overcome the precompression and the benefit is lost. The effect of surface treatments can be modeled in the same way as surface quality.

9.10.3 Sequence Effects

The sequence in which cycles are ordered can influence the fatigue life. Consider the two time histories shown in Figure 9.4. Both appear to consist of two cycles having the same range and mean stresses. A plot of their elastic–plastic strain response shows that the smaller cycle has a tensile mean in the first example and a compressive mean in the second. Therefore, the first example will create more damage than the second. For most practical analyses, sequence effects are insignificant because the probability of one sequence occurring is equal to that of the other. However, it is worth nothing when planning some simplified and idealized loading sequences.

9.10.4 Manufacturing Methods

This section shows the effect different manufacturing methods can have on the durability process.

A good example of this can be seen when comparing the agricultural and automotive industries. During a consultancy project for an agricultural Original Equipment Manufacturer (OEM), computer-aided engineering (CAE) durability techniques were used in parallel with the OEM using a test durability approach. These were two components being studied: a pivoting rear axle and the chassis frame. The rear axle was a rectangular tube fabricated from a thick plate with pivot attachment and drops for the wheel spindles. For single design iteration, the OEM was able to build a prototype, apply strain gauges, measure data, and analyze these data faster than CAE techniques could be applied. Even with the vehicle frame, a much larger fabricated structure, with a more complicated geometry, the CAE approach was only just as fast as their ability to build and test a new frame. However, the CAE approach did justify itself by identifying a small number of critical locations that were not found from testing. The point of this example is that because these components were relatively simple fabrications, it was possible to follow a test durability strategy quicker than a CAE durability strategy. Within the automotive industry, when dealing with complex stamped and spot welded vehicle body structures, or cast/forged suspension components, it is not possible to make something very quickly and test it. It is the influence of manufacturing methods that goes part of the way to explaining why the automotive industry tends to follow a predominantly CAE durability strategy while the agricultural industry tends to follow a test durability strategy. Within the test durability process, the finishing manufacturing methods have greater influences on the surface layer of components than the initial methods, which in turn influence the service conditions of agricultural machinery. The impact of this influence can be assessed with the TI technique, which would be discussed later in this book.

9.10.5 TI

The TI technique is the transference of the properties of components from the initial to the final stage of a technological system. It helps to liquidate the negative traits of the properties and strengthens the positive properties of the components in order to improve the durability and reliability of industrial equipment. The TI model can therefore be used to establish the relationship between the initial and the final model parameters, which implies that it can be used to optimize the development and service processes of a particular component and system. The optimum condition values of these processes or components are used as performance requirements for design, manufacturing, and service operations and can be used to set the control, monitoring limits, and threshold points for manufacturing and maintenance processes. The maximum and minimum reliability performance of components and systems can therefore be determined with the help of the TI technique, which implies that reliability growth and degradation trend can be established. The reliability trends and changes are used for CM and maintenance of industrial equipment. Further importance and benefits of this technique will be discussed in detail in the latter part of this book.

9.11 Parameters of Component and Process Condition for Fatigue Reliability Analysis

Fatigue reliability and all the factors affecting it are governed by the loading environment to which it is subject, the distribution of stresses and strains arising from that environment, and the response of the material from which it is manufactured. As a result, the major inputs to any resistance to fatigue and degradation analysis are component geometry, service loading, and cyclic material properties. These data are

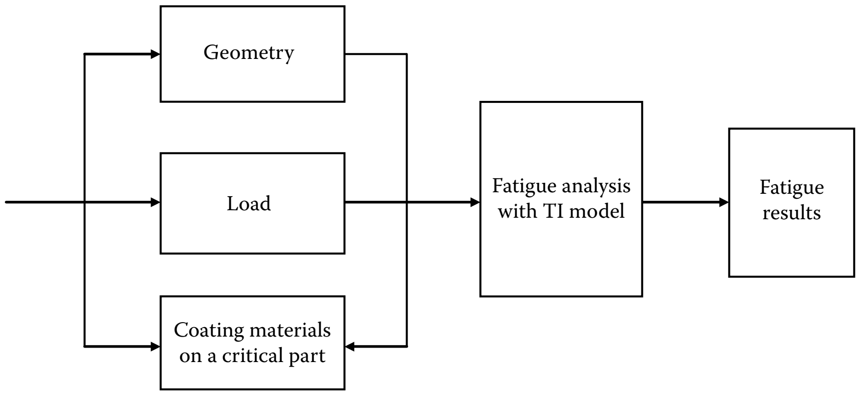


FIGURE 9.5
Component of a fatigue analysis for IRCMM of equipment.

combined in the resistance to fatigue and degradation analysis process to estimate life and reliability as shown in Figure 9.5. Subsequent sections of this book describe each of these inputs in more detail and provide a description of some common resistance to fatigue and degradation analysis methods:

9.11.1 Geometry

In the context of product quality analysis, the term geometry is often used to describe how loads are transformed into stresses and strains at a particular point in a component. The geometry is the function between the externally applied load(s) and the local stress. The effect of geometry may be determined in either one of two ways: firstly, by means of an elastic stress concentration factor, Kt, and secondly, by means of finite element analysis.

Stress concentration factors are used to calculate local stresses and strains at specific locations from their nominal counterparts or from the applied loading. Stress concentration factors for specific geometries are usually obtained from handbooks, experimental stress analysis, or finite element methods. Since the process needs to be repeated for every potential critical location within the component, this approach becomes very cumbersome, particularly in situations where a large number of external loads are applied and multiple critical locations need to be considered. Subsequent sections of this book describe how this is overcome with the use of TI coefficients within a reliability process. TI coefficients are used to determine the reliabilities or resistances to the different failure modes of components as well as the fatigue life at the least possible time and costs.

9.11.2 Loading

Loading information can be obtained using a number of different methods. Local or nominal strains can be measured by means of strain gauges. Nominal loads can be measured through the use of load cells or, more recently, they can be derived externally by multibody dynamic analysis. Since early methodologies relied on measurement from physical components, the application of resistance to fatigue and degradation analysis methods has been confined to the analysis of service failures or, at best, to the latter stages of the design cycle where components and systems first become available. The ability to predict component loads analytically means that physical components are no longer a prerequisite for durability analysis, and so analysis can precede much earlier in the design cycle and throughout manufacturing to the service life with the help of the TI technique. It is important to note that in this context, loading environment is defined as phase-related loading sequences (in terms of time and TI coefficients) that uniquely map the cyclic loads to each external input location on the component.

9.11.3 Material

Another major input to product quality growth and degradation analysis is a definition of how a material behaves under cyclic loading conditions. Cyclic material properties are used to calculate the elastic–plastic stress–strain response and the rate at which fatigue damage accrues due to each fatigue cycle. The material parameters required depend on the analysis methodology being used. Normally, these parameters are measured experimentally and may also be available in various handbooks and other publications. In situations where specific data are not readily available, approximate values may be deduced from static tensile properties such as ultimate tensile strength and ductility. With the help of TI coefficients, resistance to failure or the reliabilities, reliability growth, and degradation can be determined in real time during operations.

9.11.4 TI

Product quality analysis without considering TI would not produce the complete results and accurate assessment of the product. TI is a technique that transfers the properties of components from the initial stage of a technological process to the final stage. It helps to liquidate the negative traits of the properties and strengthens the positive properties of the components in order to improve the durability and reliability of industrial processes and equipment. The importance of this technique will be discussed in detail in the latter part of this book.

9.12 Fatigue Prediction and Lifetime of Component Analysis

Several existing methods for performing fatigue analysis and predicting the lifetime of a material or component include stress life, strain life, crack propagation, and spot weld. The TI method of performing fatigue analysis and predicting the lifetime of materials as well as component stress life, strain life, crack propagation, and fatigue reliability estimation is shown in Figure 9.6.

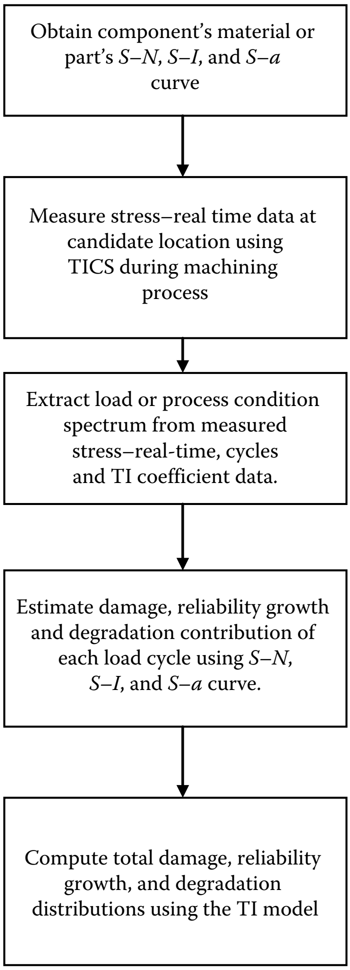


FIGURE 9.6
Stress life–based damage and fatigue reliability estimation process with TI model.

At this point, it is worthy to note the difference between the gross overload that can result in immediate, almost instantaneous catastrophic failures and the fatigue cracks that take time to grow across a part. In a fatigue failure, an incident of a problem can exceed the material fatigue strength and initiates a crack that will not result in a catastrophic failure for millions of cycles. We have observed fatigue failure in 1200 rpm motor shafts that took less than 12 h from installation to final fracture, of about 830,000 cycles. On the other hand, we have also monitored crack growth in slowly rotating process equipment shafts that has taken many months and more than 10,000,000 cycles to fail.

The fatigue zone is typically much smoother than the instantaneous zone, which is usually brittle and crystalline in appearance. Progression marks are indications that the growth rate changed as the crack grew across the shaft and do not appear in many failure faces. There are some complex mechanisms involved in the initiation of a fatigue crack, and once the crack starts, it is almost impossible to stop, because of the stress concentration at the top.

9.12.1 Stress Concentration

Stress concentration is a physical or metallurgical condition that increases the local stress in the part by some factor. A good example is the shaft. We see that the stress in the area of the radius varies depending on the size of the radius. A small radius can increase the stress dramatically. The stress concentration, indicated by the symbol "Kt," can be caused by changes in metallurgy, internal defects, and changes in shape. There are extensive data that indicate that the resultant values depend on both the type of stress, that is, bending and torsion, and the general shapes of the part. Stress concentrations have great effect on crack initiation because of their effect in increasing the local stress. The crack can start solely as the effect of the operating loads or it can be multiplied by the stress concentration factor. The stress concentration requirement of a particular part is developed experimentally or measured directly with the TI coefficient for stress control to provide a long-lasting solution to life fatigue and reliability fatigue. The following figure shows the stress life fatigue analysis process with the TI technique.

Fatigue analysis involves performing experiments to obtain localized loads on a material or part based on the process conditions. Strain gauges and a TI coefficient sensor (TICS) fixed to the component or structure show the load endured during operation by measuring the local stress over time and the TI transfer coefficient.

The load spectrum describes the statistical distribution of the service load experienced during the operating life of a component, represented by a stress range histogram. Load spectra represent the complex load history of a component or structure by a series of cyclic events with simple constant amplitude loads associated with fatigue damage and reliability degradation.

The damage, reliability growth, and degradation contributions can be calculated by comparing the experimental measurements with material fatigue real-time data from manufacturing process condition tests. Fatigue analysis uses material the *S–N* curve or *S–a* curve to describe the fatigue and reliability characteristics of materials, where *S* is the cyclical stress and *N* is the number of cycles to structural failure and *a* is the TI coefficient for quality control.

Using fatigue reliability characteristics, the total damage or reliability growth and degradation of a material or component can be estimated for a particular load history. You can use this to evaluate the lifetime and reliability of a material or component and verify if the design requirements are satisfied.

9.12.2 Stress Measurement

A strain gauge is used to record the stress on a material or component when performing fatigue analysis.

9.12.3 Load Spectrum

There are three methods to compute the load spectrum for a material or component: time domain, frequency domain, and TI coefficient domain, which integrate both the time domain and the frequency domain.

9.12.4 Stress Life–Based Damage, Reliability Growth, and Degradation Estimation

For high-cycle fatigue, you can estimate the damage, reliability growth, and degradation of a material or component based on the nominal stress life method, using stress cycle counting and damage integration with the TI technique. This technique ensures that all stresses in the component are less than the elastic limit at all times and the number of cycles to failure is large and maximized. The stress life–based damage, reliability growth, and degradation estimation with the TI technique involves the following steps.

9.12.4.1 Material S–N *Curve*

An *S–N* curve characterizes the fatigue behavior of materials. It indicates the number of cycles a material can sustain under repeated loading at a given stress level before fatigue occurs. The following figure shows a typical material *S–N* curve.

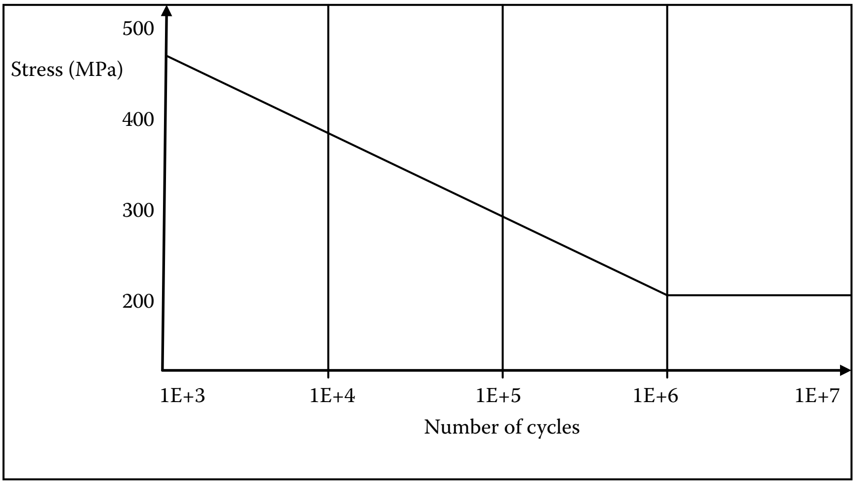


FIGURE 9.7
A typical coating material *S*–*N* curve.

You can produce an *S*–*N* curve by testing specimens under bending loads in the laboratory as well as *S*–*a* curve by testing manufacturing process conditions under real-time operations with the TI technique. You can therefore refine the calculation further with the TI model that considers multiple factors such as loading, material, surface finish, part surface geometry, and *S*–*N* curve reliability under a single platform.

According to the TI model, the resistance to damage is a linear sum of the damage fraction at any stress level in the load spectrum, and the reliability is linear to the reliability growth and degradation as shown in Figure 9.7.

9.13 Reliability Fatigue Analysis with Modular and Virtual Instruments Using the TI Technique

Reliability fatigue analysis with the TI technique can be carried out with a set of modular or virtual instruments, which are used to measure and determine lifetime, reliability growth, and degradation as well as failure, warranty costs, and maintenance costs.

The analysis functions include the following characteristics:

- Maximum and minimum reliability fatigue coefficients
- Maximum reliability fatigue coefficient threshold and warranty costs

- Minimum reliability fatigue coefficient threshold and maintenance costs
- TI cycle counting
- Reliability histogram matrix
- Load spectrum estimation
- *S*–*N* and *S*–*a* curve generation
- Stress life–based damage, reliability growth, and degradation estimation

The result of the previous functions and reliability characteristics is possible through TICSs for component quality and process performance degradation controls. The component quality factor (Q_f) and process performance factor (P_f) data are used to determine reliability growth, degradation, and failures. Apart from the cost-effective use of modular instruments, it also possible to apply virtual instruments consisting of a data acquisition (DAQ) device and reliability growth and degradation software. IRCMM of manufacturing processes and equipment can now be applied successfully and cost-effectively with both modular and virtual instruments.

9.14 Fatigue Results

Fatigue results are usually expressed in terms of the number of cycles, or repeats of a particular loading sequence, required reaching a specific criterion at a location. Sometimes these values are associated with physical quantities such as hours, miles, or fracture of a durability route. Fatigue results can also be determined in terms of fatigue coefficient with the help of the TI coefficient for part surface quality control, a_i. These results are, of course, sensitive to each of the major inputs: loading, geometry, and material. Sensitivity to variation in loading magnitude is particularly acute due to the logarithmic relationship between load and lifetime reliability. A 10% change in load, for example, can alter predicted lifetime reliability by a factor of two. From a designer's point of view, variations in loading conditions are largely the results of variability in customer usage or the operations of manufacturing processes and equipment. To a large extent, this variability is beyond the control of the designer, other than through the provision of adequate safety factors. Material behavior and impact of geometry, on the other hand, can usually be defined more precisely to suit a particular load. The existing fatigue results are usually for life prediction and design assurance, but do not determine life improvement or design optimization.

For design, manufacturing, and service optimization, there is therefore the need to consider the TI technique, which can be used to transfer material, load, and geometry characteristics of components from the initial stage to the final stage of production in the technological process or maintenance route, toward the attainment of maximum quality, reliability, and lifetime. IRCMM with a TI model–based program can therefore be used to optimize and control the quality, fatigue reliability, and lifetime characteristics of materials or components at minimum life cycle costs. This model-based program can also be used for the evaluation and assessment of materials, components, manufacturing processes, and industrial equipment cost-effectively.

9.15 Moving from the Physical to Virtual Assessments of Materials, Parts, and Equipment with the TI Technique

The challenge for durability remains how to accelerate the analysis process. The minimum acceptable analysis period for a *full* analysis is about 12 h, equivalent to running the analysis overnight. Distributed computing together with parallel processing is ideally suited to meet these computational challenges because fatigue life calculations are usually similar at each node or element. Selecting which nodes are to be analyzed more intelligently and optimizing time history reduction methods will go a long way toward meeting the challenge. Adaptive fatigue methods will add intelligence to the fatigue life analysis, taking expert knowledge and implementing it within a software application. The software will choose the most appropriate fatigue method for each location with regard to its service environment that suits reliability requirements and keep a record explaining why choices are made to meet desired requirements. With TI coefficients of the different operations, it is possible to equate fatigue reliability of the process/equipment with inherent reliability (i.e., the manufacturing and equipment system reliability). Part surface quality (Y_i), quality factor (Q_f), and fatigue reliability (R_f) can be related, controlled, and converted with the use of TI coefficients. Under an optimum component and process/equipment condition, the ratio of Y_{iopt}:Q_{fopt}:R_{fopt} = 1.0. The conversion ratio is determined experimentally based on wear- and other failure-resistant applications of parts, which helps change physical quantities to virtual quantities. The change to a virtual development process has been driven by a number of factors, particularly reduced development times, increased model diversity, increased complexity, and the need to optimize performance and cost. This is the reason for introducing the TI technique that can address the actual durability problems encountered during development through manufacturing processes, for example, spot welds, thin sheet seam welds and coatings, as well as finishing hard alloy–coated machine part surfaces. The application of multivariate regression and TI models for material and part assessment within manufacturing processes enables components and systems to be designed to meet their desired durability and reliability criteria. However, there are many variables that analytical durability analysis cannot adequately consider, such as wear, corrosion, temperature, manufacturing processes, assembly, material nonhomogeneity, and residual stresses; with the existing methodology, they can now be analyzed and assessed with the help of a TI model–based program. This model-based program can be used to design the critical part surface condition with maximum resistance to fatigue failure and integrate all the desired characteristic criteria for virtual development in durability, performance, and reliability assessments.

9.16 Criteria for Virtual Assessment of Fatigue Reliability with the TI Technique

There are many different existing technological methods that can be used to maintain machine parts and equipment of the same defects and failures, but the quality and the cost of maintenance will also be different. That is the reason why there is the need to select the technological methods and design parameters that provide maximum reliability and durability with minimum labor, material input for the maintenance of parts/equipment, and life cycle costs, which makes such a process rational or optimum. When selecting a rational method and design and maintenance parameters, it is necessary to consider the technological, economical, environmental, and of course all the factors involved in the overall system. In the first case, it would be necessary to consider all the processes for maintaining a particular group of part from the viewpoint of the part's acceptability. For example, the stems of valve, pusher, rocker roller of engines, and other smaller parts are quite clear that it is not possible to restore these parts with manual arc welding, automatic welding with layer of flux, and some other methods, but they can be repaired and maintained with the methods of electrolysis, deposition of metal coating with subsequent fusion, and others.

9.16.1 Criteria of Customer's Requirements and Demands

The criterion that determines the acceptance of methods or strategies for the maintenance of concrete parts is known to be technological or criteria of customer's requirements. With the help of this criterion, it is possible to choose all the strategies for maintaining certain parts, manufacturing processes, and equipment, but not possible to say which is best among them. That is why the next step will focus on which one of the chosen methods or processes provides the most reliable parts.

9.16.2 Criteria of Durability or Reliability

The criterion that verifies the method or strategy for maintaining parts is known as the criteria of durability or reliability. It is expressed in the coefficient of durability or reliability coefficient for each strategy of maintaining parts, processes, and equipment in the same technological system. With the help of the durability or reliability criteria, it is possible to determine the desired type of maintenance that provides the best quality, reliability, and life of a part or equipment, but it is not possible to say that such a method is rational or optimum, since the maintenance or life cycle cost is unknown. The final decision therefore for selecting a rational or optimum maintenance strategy lies on the basis of the technical–economical criteria, which combine the durability or reliability of parts and the cost of its maintenance.

The technical–economical criterion is determined by the expression [3].

$$C_r \leq K_{R/D} C_p$$

where

C_r is the maintenance cost of parts
$K_{R/D}$ is the coefficient of durability/reliability
C_p is the cost of a new part

This expression shows that sometimes it is profitable to use a costly method that provides a high durability. For example, the cost of maintaining parts with chromium is more than the cost of a new one, but the reliability of the part is twice more than the new one; that is the reason why maintaining parts with chromium is preferable when the wear is within the limits of 0.2–0.3 mm. When repairing machineries or industrial equipment, the volume of work (more than 70%) of all the works is usually corrective maintenance of parts. The virtual method of measuring the coefficient of durability or reliability coefficient can be carried out with the help of the TI technique. The TI technique can be used to determine the optimum values of the quality, durability, and reliability of materials or components as well as the optimum selection of materials or components and the integration of reliability, durability, and maintenance. Fatigue reliability testing, measurement, and virtual assessment during real-time operations of manufacturing processes and equipment are possible with integrated reliability curve with TI coefficients, as shown Figure 9.8.

The optimum values derived by the TI technique can be used as the baseline for design, development, and maintenance.

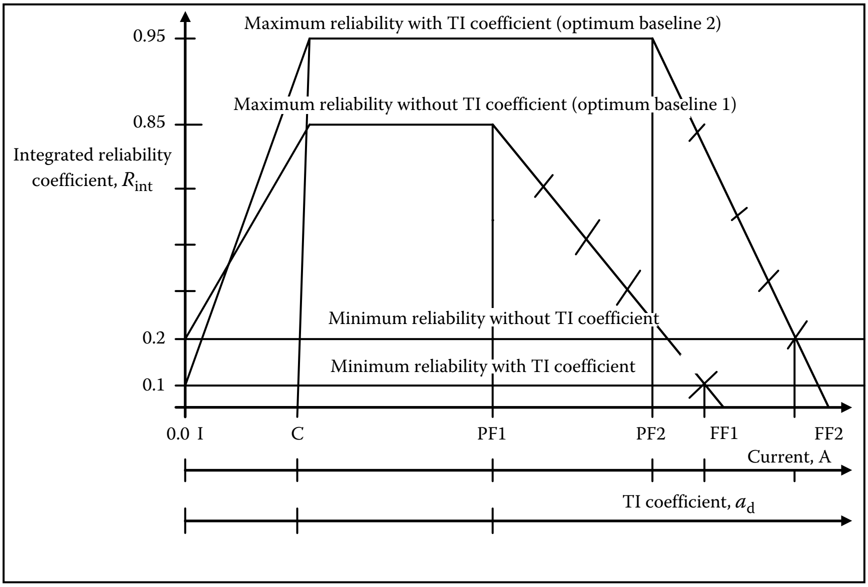


FIGURE 9.8
Integrated reliability curve for fatigue-resistant growth, degradation, and failures of manufacturing processes and equipment with TI coefficients.

9.17 Design for Maximum Achievable Fatigue Reliability with the TI Technique

Structural quality and reliability characteristics will make use of one, more, or the whole functions shown in Figure 9.9. The experimental design for maximum component or material fatigue reliability that offers an optimum model baseline and an efficient fatigue reliability curve or mechanism is done with the help of the TI technique, as shown Figure 9.9.

At this point, it should be known that different industries and organizations do exploit specific subprocesses depending on the component or material quality and reliability requirements. It is usual for laboratory testing to take less time and lesser time during real-time testing to complete than equivalent proving ground tests can achieve through the use of analytical fatigue editing techniques. The design for maximum achievable fatigue reliability with the TI technique offers optimum time and cost with accurate results. Fatigue reliability growth and degradation are determined with the TI coefficient a. The positive inheritance grows from minimum to maximum, while negative inheritance degrades from maximum to minimum. The determination of fatigue reliability growth and

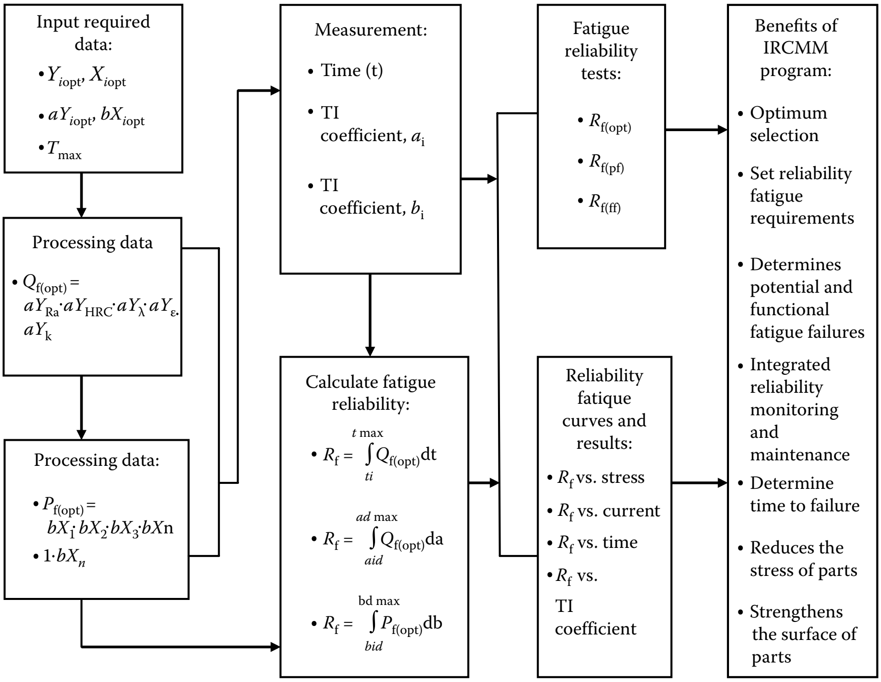


FIGURE 9.9
The structure for reliability degradations and fatigue assessment with TI coefficients.

degradation makes it possible for effective condition monitoring and maintenance of components. It offers great opportunity for optimum selections; detection of defects, errors, and random failures; as well as reliability testing, measurement, and virtual assessments of manufacturing processes and industrial equipment.

9.18 Fatigue Reliability Test, Measurement, and Virtual Assessment of Manufacturing Processes and Equipment with a TI Model–Based Program

TI model–based program for analysis provides the tools needed to acquire data and automate reliability CM and maintenance tasks. Under this single platform, it is possible to control, monitor, and acquire data from plug-in DAQ boards, test instruments, web cameras, and frame grabbers.

Once the data are acquired, you can intuitively explore it and perform live visualization and data analysis. You can then build test systems, verify designs and concepts, and automate repetitive tasks. It is also possible to deploy test applications into other computers.

Within this single environment, you can build flexible test systems, automate testing routines, perform design verification, and analyze and visualize live data as you collect it.

When working with one or more stand-alone instruments such as oscilloscopes, arbitrary waveform generators, and signal analyzers, you use an instrument control toolbox to control the instruments and acquire data from them. You can quickly establish communication with instruments via industry-standard communication protocols and instrument drivers from many manufacturers.

When working with plug-in DAQ boards, you use a DAQ toolbox to connect to devices from measurement computing and digital input and output capabilities with the help of a TI model–based program to control motors and sensors and collect and analyze live data from them.

A DAQ toolbox provides TI blocks for acquiring live or measured data directly into your models or configuring hardware interfaced to DAQ devices. These blocks enable you to quickly evaluate the response of the TI models and algorithms with real-world data, instead of designing systems against static data sets, such as those saved in files. You can also use these blocks to verify and validate your models against live, measured data as part of the system development process.

A DAQ toolbox provides four TI blocks:

- Analog input (acquire data from analog channels for optimum hard-coated part surface quality parameters, $Y_{i(\mathrm{opt})}$, or the quality factor, $Q_{\mathrm{f(opt)}}$)
- Analog input (acquire data from analog channels for optimum process performance parameters, $X_{i(\mathrm{opt})}$, or the performance factor, $P_{\mathrm{f(opt)}}$)
- Analog input (acquire data from analog channels for TI coefficients for quality and performance controls, $a_{i(\mathrm{opt})}/b_{i(\mathrm{opt})}$)
- Analog output (output data to analog channels of part [Q_{fd}], process [P_{fd}], and reliability [R_{kd}] condition degradation)
- Digital input (acquire the latest set of values from digital lines for Y_i, X_i, Q_{f}, P_{f}, and R_{k})
- Digital output (output data to digital lines for Y_i, Q_{f}, $Q_{i\mathrm{d}}$, P_{f}, P_{fd}, and R_{kd})

The output results let you configure hardware from the TI models, which represent a dynamic machine part system (Figure 9.10), including instructing hardware to send data.

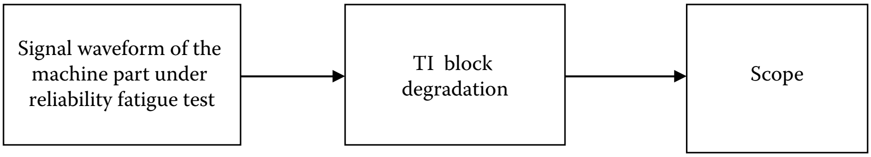


FIGURE 9.10
TI model dynamic machine part system.

The TI block degradation outputs the optimum machine part quality condition input at a current time step of the technological system, using the following equation:

$$R_{id(t)} = \int_{ti}^{t\max.} Q_{f(t)}\, dt \tag{9.1}$$

The equation represents the reliability degradation output of the block, which in this case is the fatigue reliability coefficient ($R_{fd(t)}$), as a function of a machine part or material quality condition (Y_i) or factor (Q_f), and inputs, where Q_f is a vector function of the current simulation time or TI coefficients, a_i and b_i. The material or component condition quality factor, Q_f, is a function of Y_i, which can be expressed as the product of the TI coefficients of the different quality condition parameters, Y_i; the process performance factor (P_f) is a function of X_i. The TI model and block degradation can be used to evaluate and analyze the reliability fatigue of materials and components, as shown in Figure 9.11.

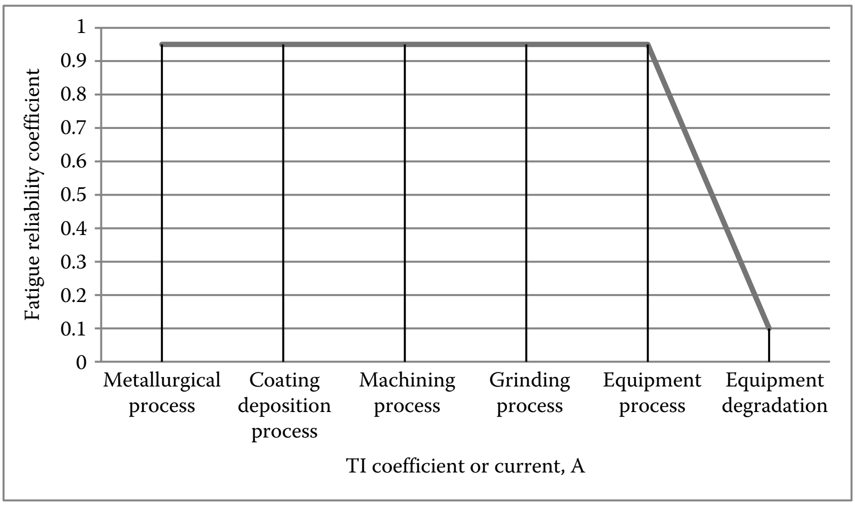


FIGURE 9.11
Optimum fatigue reliability, degradation, and failure during manufacturing processes and equipment operations with TI coefficient.

The program enables you to acquire live data from hardware DAQ and incorporate data directly into TI models. The model enables you to configure parameters including the device type and reliability fatigue coefficient channels and lines. The analog signals also enable you to configure other relevant parameters such as asynchronous and synchronous acquisition, sample rate, block size, and data type.

The test results and analysis from Figure 9.9 can be highlighted with the following points:

1. The fatigue reliability coefficient of components or materials increases as the number of cycles of machine tool shaft rotation increases, until it reaches an optimum level during the operation of the manufacturing processes for the attainment of a desired part surface condition in a specific application.
2. The existing fatigue reliability of components or materials is assessed with a single parametric curve of stress (S) and number of cycles (N), which does not provide for maximum assessment and improvement of materials, parts, processes, and equipment.
3. The application of the TI technique offers the possibilities of using multiple parametric curves for the assessment of materials, parts, manufacturing processes, and equipment.
4. Integrated reliability curve with time, number of cycles, and TI coefficient can be used to determine the maximum achievable reliability, minimum acceptable reliability, maximum achievable lifetime, and reliability growth and degradation of materials, parts, processes, and equipment.
5. The components or material reliability growth and degradation can be measured with TI coefficients during the operations of manufacturing processes.
6. Material or component fatigue reliability growth is directly proportional to the performance growth of manufacturing processes.
7. When the fatigue reliability coefficient decreases within a specific degradation level, the manufacturing process performance also decreases, indicating that there is a manufacturing error, defect, and failure, due to a decrease in any of the process condition parameters.
8. The root cause of materials' or components' fatigue reliability degradation and process performance degradation as well as fatigue failures can be determined with the help of the TI model.
9. The TI model is also used to predict the time, type, and degree of fatigue reliability degradation as well as the optimum fatigue reliability during design and development.

10. TI software programs, DAQ devices, and measuring instruments can be developed to test for optimum fatigue reliability degradations and fatigue failures during manufacturing process operations.
11. The optimum component or material fatigue reliability test with the TI model is expressed with the following conditions: $a_{iopt} = Y_{iopt} = R_{fopt}$ and $X_{iopt} = R_{fopt} = b_{opt}$, where materials, parameters, parts, and processes can be selected with the desired baseline requirements, but when the component or material condition is such that in the reverse condition, it would imply that the process conditions must be subjected to further test and analysis for rejection, upgrade, and maintenance practices.
12. Where the output fatigue reliability signal cannot be measured or tested directly during operation, the input signals of the manufacturing process condition parameters are acquired, analyzed, and tested for fatigue reliability growth, optimum fatigue reliability, fatigue reliability degradation, and fatigue failures.
13. The optimum TI coefficients "a_{opt}" or "b_{opt}" is the same at any point for all the component quality condition parameters (Y_{iopt}), or process conditions parameters (X_{iopt}), involved in the design for maximum achievable fatigue reliability, which can be used as a metric to test, evaluate, and monitor all the component/material quality condition parameters (Y_i) and process condition parameters (X_i).
14. Fatigue reliability curve has ascertained that the traditional manufacturing processes used in producing fatigue-resistant part surface increases its quality and reliability condition from its initial process until a grinding finishing process was used, where an obvious decrease in component or material fatigue reliability condition was observed, irrespective of an increase in the surface roughness quality parameter.
15. The root cause of the manufacturing error, defect, and failure as a result of the decrease in process performance can be determined and corrected during operations with a TI model and software program, thereby avoiding catastrophic damages at the early stages of the service operations.
16. The continuous use of suboptimum component baseline requirements for part design, manufacturing, and maintenance is not cost-effective, but with the application of the TI model, it is possible to achieve optimum baseline requirements.
17. The replacement of the grinding process with a cost-effective finishing process that considers multiple component or material as well as multiple process conditions with the TI technique will help to attain maximum achievable reliability and prevent the transfer of errors and defects from manufacturing processes to an early failed state during its service operation.

18. The use of a multiple parameter curve to assess components or materials with TI has helped to maximize fatigue reliability during the surface finishing process for a desired part surface condition.
19. The optimum fatigue reliability of a component or material is possible with a cost-effective manufacturing process with the application of the TI model that considers multiple parameters and a single integration metric.
20. The TI model can therefore be used to design optimum finishing process conditions with multiple parameters, component condition monitors, and maintenance strategies like preventive, predictive, and proactive maintenance.
21. The fatigue reliability test results with the TI model can be used for planning, management, DAQ, analysis, and presentation.
22. The maximum achievable reliability of a component or material with the TI technique is higher than that of fatigue reliability analysis without the TI technique, since it does not consider multiple quality parameters and multiple process condition parameters with a single integrated metric as well as other desired failure modes like wear, corrosion, and temperature derived from frictional parts.

9.19 Conclusions

1. The effect of the different performance target requirements can be seen by how the durability and reliability process is determined within the different industries of the future and how it is used to increase component/system reliability from design through manufacturing processes and service operations at different levels of reliability requirements.
2. The design of a machine part and its durability depends on the component base, user base, manufacturing base, and value base, and all these require different levels of durability like in the case of fatigue with different lives of the component.
3. The existing basic methodologies used to determine the life of components can help predict lifetimes, but cannot determine reliability life improvements.
4. An integrated reliability method that can predict life and improve reliability of components has been introduced in this book through the use of component stress or quality–reliability conditions against process cycles or performance–life conditions.

5. The stress against the cycles to failure curves are usually derived from tests on samples of materials for life prediction and design assurance, but do not determine life improvement, design optimization, and component/system reliability; hence, the author has decided to apply the TI technique that is based on real-time system/component reliability and design optimization.
6. The maximum predicted lifetime reliability of component and system by fatigue analysis without the TI technique does not guarantee maximum component/system reliability, simply because some of the factors and characteristics of reliability have not been considered by designers and manufacturers.
7. The TI technique that considers all the necessary factors and characteristics of component/system reliability and also guarantees maximum achievable reliability of a part, process, and equipment with maximum achievable part condition resistance to fatigue failures has been adopted by the author.
8. Fatigue reliability degradation analysis with the TI model can therefore be used to fully assess the conditions of components/system during design and manufacturing processes and service operations.
9. Fatigue reliability degradation design optimization with the TI model provides for optimum life prediction, minimum acceptable reliability, potential and functional failures, and optimum useful service life of components.
10. The results of fatigue reliability degradation analysis with the TI model can be used to set up maintenance control limits, predict failure modes, detect root cause of failures, and determine monitoring/maintenance requirements as well as life improvement and design optimization.
11. Fatigue reliability degradation analysis with the TI model is cost-effective, since it can determine maximum fatigue-resistant coefficient and minimum probability of component failure at minimum cost as opposed to fatigue analysis.
12. IRCMM program will therefore provide a measuring device for fatigue resistance coefficients and its quality degradations as well as select optimum maintenance strategy for industrial equipment.
13. IRCMM program determines the maintenance costs and component/equipment reliability through a virtual means of assessment as well as for optimum selection of components and maintenance strategies.
14. The change from physical to virtual assessment of reliability growth/degradation with the help of TI model enables components, systems, and equipment to be designed to suit quality–reliability

and performance–life criteria with full consideration of design, manufacturing processes, material nonhomogeneity, and residual stresses.

15. IRCMM with the TI model–based program applies a nondestructive testing method that provides an accurate prediction of fatigue reliability, time to failure, fatigue reliability growth and degradation of components/equipment, and monitoring and maintenance costs in the appropriate industries of the future.

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10

Reliability Degradation, Wear, and Competing Failure Modes of Nickel-Based Hard Alloy–Coated Part Mating Surface

10.1 Resistance to Wear and Competing Failure Modes of Equipment

Reliability, quality, durability, performance, vibration, noise intensity, lifetime, and other properties of machines, mechanisms, and instruments to a high degree depend on the wear of part surfaces. Wear is the process of destroying or removing materials from the surfaces of hard bodies and (or) the formation of residual deformation during friction that gradually changes the sizes and forms of a body.

It has been ascertained in the industries that 85%–90% of machines are usually out of service due to the wear of components, while only 10%–15% are because of other reasons like damages, which in turn are as a result of changes in the service conditions, caused by the wear of frictional contact surfaces [1].

Wear is the result of degradation (the changes in sizes, forms, masses of components, and others) with a definite unit. Wear resistance is the property of a material that resists the wear (degradation) in a particular friction condition, which is assessed by the value that is inversely the speed or the intensity of degradation. The wear rate is understood as the ratio of degradation to the time taken to cause it ($\gamma = du/dt$), while the wear intensity is the ratio of degradation to the sliding distance, where surface damage has occurred ($I = du/ds$). The value of I is dimensionless if wear and the sliding distance are assessed with the same unit. The challenge facing researchers on friction and wear today is on how to establish a relationship between wear and the multiple variable factors that characterize the type and properties of component materials, surface qualities, process conditions, friction, lubrication, and others. Hence, the need of a cost effective robust multivariate part surface quality regression model that has been designed in Chapter 6 for optimum quality prediction as well as to optimize production technology, the service conditions of components and to predict performance. This chapter and other subsequent chapters of this book will help to throw light and provide long-lasting solutions to the problems facing researchers on friction and wear with other competing failure-resistant applications in the different industries of the future.

10.2 Types of Competing Failure Modes with Wear for Industrial Equipment and Their Preventive Techniques

Apart from fatigue failure, which has been discussed in Chapter 9, there are other types of failure that occur due to frictions of machine parts, which are as follows:

- Wear
- Corrosion
- Electro-erosion
- Deformation
- Loss of elasticity
- Loss of magnetization
- Formation of scales and carbon deposits

Wear is a process of failure and a removal of materials from the surfaces of hard bodies and (or) accumulation of its residual deformation during friction, where there is a gradual change in their sizes and (or) forms of these bodies. The amount of wear is the result of wear that is determined in an established unit. The wear of machinery parts is accompanied with a complex physical–chemical phenomenon that has a lot of influences on its factors. Wear depends on materials, quality of the contacting surfaces, nature and velocity of their mutual movement, nature of contact, loads, type of friction, lubrication, lubricants, and many other factors.

Corrosion is a surface failure of metals in the machine part as a result of oxidation. The process of failure occurs spontaneously with a chemical and electrochemical reaction of metal with the surrounding medium. That is the reason why corrosion failure occurs in working machines and nonworking machines, with a higher degree of corrosion in the latter. Chemical corrosion occurs as a result of the reaction of metal with acid, base, and salt that are always present in the surrounding medium (humidity, carbon dioxide, oxygen, and others). The result is such that it reacts on the surfaces of metals to form a rough brittle layer of ferrous oxide (rust), which greatly reduces the durability of parts. Electrochemical corrosion occurs in the contacting place of two different metals that form electroplating pairs. With the reaction in the place of such contact with salt and acid (electrolyte) solutions, it forms a process of electrolysis, which results in the failures of the more active metal. Corrosion failure occurs in the cabinet and the tail unit of tractors and trucks, surfaces of frames, chases, and other parts. The measures of prevention are by coating of part surfaces with anticorrosion and wear compositions for more valuable and critical parts.

Electro-erosion failure occurs as a result of the reaction of electrical sparks discharged on the surfaces of parts. Such degradation is characterized for the contacts of a magneto interrupter and distributors, electrodes, generator's collectors, and starters. Electro-erosion failure of parts increases when the forces are weakened and when the density of the contacting surface is reduced and also when there is a distortion or incorrect adjustment of the spark intervals between the contacts.

Deformation of parts occurs in the distortion of all the geometrical form of a part, (such as bending, twisting, and warping). Residual deformation takes place under the action of impact or periodic changes in load and temperature. This type of failure happens in tractors and trucks: cam, crank and distributing shafts, frames, front axles of trucks, shafts and axles in transmission, gear fork key, and others. The main reason for the increase in the deformation of parts is the lack of knowledge and incorrect service conditions of machines and inadequate servicing, which leads to overloading of a certain part of the machine as well as the distortion of heat condition.

Loss of elasticity of springs, piston rings, torsion shafts, and other parts as a result of dynamic loads and the action of heat destructs the normal work of a component, which often leads to a full loss of the serviceability of a machine.

Loss of magnetization of a generator armature of an alternating current and the magneto rotor destructs the normal work of these components and the machine as a whole. The reason for the loss of magnetization is because of shaking, impacts, increase in the heat of components, and inadequate servicing.

Formation of scales and carbon deposits of parts worsens the transfer of heat and destructs the heat conditions of the components, which results in the increase of wear and other types of failure in many machine parts. Scale is the deposition of undissolved salt of calcium, magnesium, and other elements inside the part surface of the cooling system in engines. The heat transfer of scale is 50–100 times lower than that of metals. That is the reason why a nonuniform deposition of scales, apart from the worsening of heat transfer, also leads to a nonuniform heat of parts, which results in the formation of warping and cracks of engine blocks and other parts. Carbon deposits are hard and carbon deposits on parts as a result of partial combustion of fuel oil materials or in contact with surfaces of severe heated parts. The formation of scale on the surfaces of a combustion chamber, valve, piston head, and carburetor plugs in engines reduces the power, increases fuel consumption, and often leads to detonation. The formation of scales on the nozzle tips of diesel reduces the quality of spray and causes overheating and weakening of the sprayer needle, which results in the destruction of the normal work of an engine. The deposit of carbon on parts and also the scales reduces the heat transfer of parts, which leads to overheating, warping, formation of cracks, and other defects. In order to reduce the occurrence of malfunctioning, there is the need to remove scales and deposits in order to clean parts before the repairs of machines and also to observe the rules of a technical servicing of machinery and consider all the necessary contributing wear factors.

10.3 Wear Factors and Mechanisms of Equipment

The study and analysis of all the contributing factors are necessary to predict the result of a single wear mechanism, but several sources of deterioration may combine to complicate what might otherwise be a straightforward solution. The chief factors that influence wear are

- Metallurgical variables—hardness, toughness, constitution, and microstructure and chemical composition
- Service variables—contacting materials, pressure, speed, temperature, and surface finish
- Other factors—lubrication and corrosion

Thus, it is impossible to generalize the material's suitability, such as to say a certain composition is the most wear resistant, without considering factors such as service conditions. For example, two materials, one of which is clearly superior to the other for a specific application, may undergo a complete reversal in wear resistance from only slight changes in service conditions. Although strength, hardness, and ductility or toughness is important, wear resistance cannot always be associated with any one property. Wear resistance generally does not increase directly with tensile strength or hardness; however, if other factors are relatively constant, hardness values provide an approximate guide to relative wear behavior among different metals. This is especially true for metal to metal sliding and abrasive applications.

With the multiple component quality and process performance parameters for determining the wear resistance of a specific application, technological inheritance (TI) coefficient is used to estimate and assess the wear resistance and failures of parts and equipment. The TI coefficients can also be used to design a single wear resistance mechanism and wear reliability concept.

10.4 Wear Reliability Degradation and Failure Concept with TI Coefficients

Wear is the process of gradual change and degradation in the dimensions of machine parts during the operation of the machine, which leads to poor quality, performance, and reliability. The rate of wear of individual components in equipment is not uniform but depends on the operating conditions. It also depends on the material of the components, the kind of lubrication, unit pressure, sliding speed, temperature in the joint, and the dust content of the ambient atmosphere.

The three major types of wear are [2]

1. Mechanical wear
2. Molecular wear
3. Corrosive wear

Mechanical wear of mating part surfaces (e.g., bearing and shaft), which is usually not uniform along their lengths. Unequal loads on the surface of the mating parts can cause nonuniform wear that can lead to catastrophic damages of equipment. The effects of wear can be controlled with the help of TI coefficients. Let us look at the effects of wear and how they can be controlled.

10.4.1 Effects and Control of Wear with TI Coefficients

Taking into account that any modern machine is subjected during its service life to operations, repairs, adjustments, and other types of maintenance by which its performance is restored, the machine's wear can be estimated from two different viewpoints [2]:

1. By the total time (and, respectively, cost) spent on restoring the performance (the length of service life)
2. By the probability of retaining the original parameters of the machine within the prescribed limits during the specified service period (the failure-free operation)

The total time criterion may be represented by the coefficient of usage (reliability coefficient [R_k]) R_k is found from the following formula [2]:

$$R_k = \frac{T_o}{T_o + \sum \tau_{oi}} \tag{10.1}$$

where

T_o is the time of operation of the machine during the whole period of service

$\Sigma\tau_{oi}$ is the total machine downtime caused by failures (repair, adjustment, and so on) during the whole period of service

The coefficient of reliability is a dimensionless quantity ($R_k \leq 1$), and the larger its value, the more reliable is the machine.

The downtime due to repair of a given part or joint will be

$$\tau_{oi} = \frac{T_o}{T_i}\tau_i \tag{10.2}$$

where

T_i is the service life of the *i*th part (joint) of the machine

τ_i is the time (or labor) consumption for the repair of the *i*th part (joint), including dismantling, assembly, and adjustment

The ratio T_o/T_i shows how many times during period *T*o the given part was repaired. Then from Equation 10.2, the coefficient of reliability will be

$$R_k = \frac{1}{1 + \sum \frac{\tau_i}{T_i}} \tag{10.3}$$

From Equation 10.3, it follows that the main method for increasing the reliability of a machine is in the reduction of the time spent in repairs and maintenance and the extension of the service life of the component parts. Therefore, in most machines and mechanisms, the service life is determined by the wear of their joints and mating part surfaces.

In the general case, wear rate can be expressed as a power function [3]:

$$\gamma = K_w P_m V_n \tag{10.4}$$

where

P is the pressure

V is the velocity

K_w is the coefficient that characterizes the wear resistance and the running conditions, where $0 < K_w < 1$

The wear rate of mating parts, A_1 and A_2, can be expressed as

$$K_w = \frac{A_1}{A_2} = \frac{Y_{i1}}{Y_{i2}} \tag{10.5}$$

With this concept, the component quality (Q_f), process performance (P_f), and wear conditions ($Y_{HRC(ff)}$) can be related together with the help of TI coefficients. This implies that the ratio $Q_{f(max)} : P_{f(max)} : Y_{HRC(max)} = K_{w(max)} = 1.0$ and $Q_{f(min)} : P_{f(min)} : Y_{HRC(min)} = K_{w(min)} = 0.0$.

Primarily the materials of the sliding pair, geometry of the surfaces in contact, and lubrication effect can be evaluated and assessed by the wear coefficient K_w, which can be determined by the TI coefficient a_i.

The wear rate can therefore be expressed in terms of the TI coefficient as

$$\gamma = a_i P_m V_n \tag{10.6}$$

The wear resistance and failure mechanism of a tribosystem can therefore be determined with the help of the TI model: $Y_i = a_i Y_{i-1}{}^{bi}$. With this model, Y_{i-1} is the initial quality condition, while Y_i is the final quality condition, and a_i is the TI coefficient for quality control, while b_i is the TI coefficient for process condition control. When b is optimal, which means $b = 1.0$, $Y_i = aY_{i-1(opt)}$. In equipment, the initial quality condition of part, $Y_{i-1(opt)}$, is integrated into the operating process condition, like pressure (P), velocity (V), current (I), and others (X_i). Therefore, Equation 10.1 can be written in terms of the TI model as

$$\gamma = a_i Y_{i-1(opt)} \tag{10.7}$$

This equation can be used to construct a wear reliability bathtub curve of a tribosystem versus time with the TI coefficient, as presented in Figure 10.1.

Wear can be divided into three stages:

1. Running in (decreasing failure rate)
2. Stationary wear (low *constant* failure rate)
3. Severe wear (increasing failure rate)

The first stage, running in, is relatively short. This stage can be taken care of with the application of the TI model through an integrated reliability condition monitoring and maintenance (IRCMM) program. The program will help increase the reliability to maximum and also help to extend the useful lifetime of the critical parts of the equipment. The second stage, stationary wear, should occur over a prolonged period of time at a minimal (mild) wear rate. Severe wear results from continuous surface interaction or lubricant degradation. The third stage can and should be prevented by maintenance.

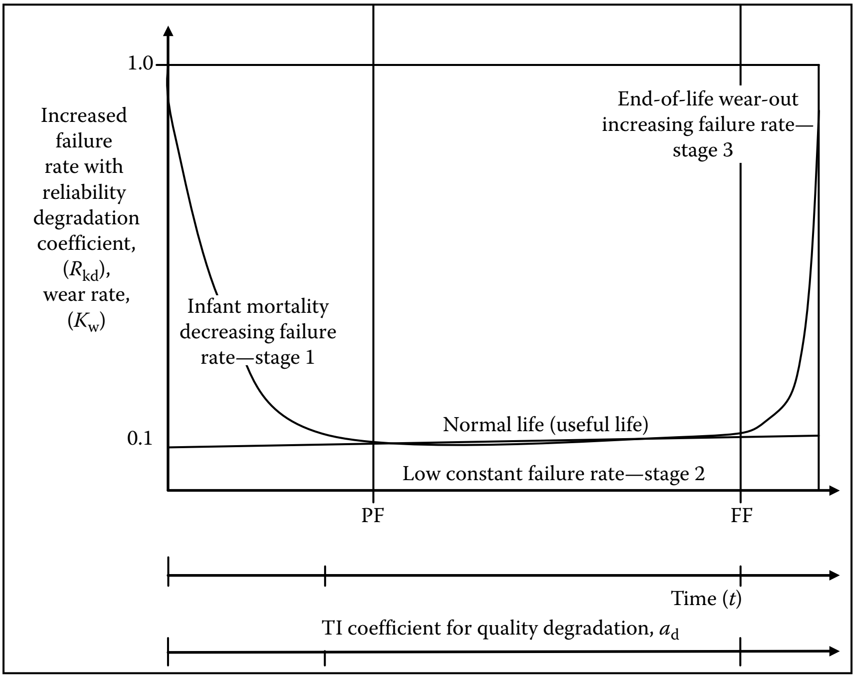

FIGURE 10.1
Reliability bathtub curve with TI coefficient.

The stages of wear combined with a variety of wear modes make wear simulation and prediction difficult. This problem requires a systematic approach. A new IRCMM strategy developed in this book will be used to maximize the reliability of machines and minimize the failures, throughout all the stages of tribosystem. Surface damage features and wear failures are the objects most often examined when considering the wear mode and mechanism of machines. The degradations of component quality (Y_i) and quality factor (Q_f), as well as the degradation of process conditions (X_i) and the process performance (P_f), provide valuable information on the mode and mechanism of wear with the use of the TI model. The model parameters can also give information on the occurrence of severe wear and the necessity of maintenance. This is the reason for wear failure analysis, maintenance, and testing of production processes and industrial equipment since this is condition based.

10.4.2 Wear Failure Analysis of a Tribosystem with TI Coefficients

Wear failure analysis is based on the understanding of its relationship with the quality of parts, process performance conditions, character of surface damage, the state of lubricant, and service conditions of machineries. This relationship can be expressed and assessed with the TI model. The model allows one to obtain qualitative information on the type of surface damage (fatigue, cutting, turning, grinding, etc.), severity of loading, local temperature, and the quality of lubricant. The interpretation of the information is challenging because tribological behavior and the characteristics of wear are not clearly defined and therefore require the use of a model for interpretation of data. The use of the TI model is a valuable source of information about machine durability, reliability degradation and performance degradation, and wear failures.

According to existing commonly accepted concepts, wear patterns can be divided into six main types:

1. Bathtub curve
2. Constant or gradually increasing conditional probability of failure, ending in a wear-out zone
3. High infant mortality, which drops eventually to a constant or very slowly increasing conditional probability of failure
4. Slowly increasing conditional probability of failure, but with no identifiable wear-out zone age
5. Conditional probability of failure, then a rapid increase to a constant level
6. Constant conditional probability of failure at all ages

The analysis can be performed by detecting the specific curves and patterns from wear failure samples and, using a practical understanding of wear characteristics, symptoms and warning signs to form an opinion about the underlying wear condition for the tribosystem. The TI model employs an automated method for reliability, wear resistance, wear failure, and other competing failure analysis. This automated approach in this method uses data acquisition device, calculating and standardized rules for representing, integrating the pattern and curve descriptions as well as choosing an appropriate classification method. This book therefore provides an integrated reliability approach for the common problems (wear, corrosion, and high temperature of machine parts) of the different industries with the help of the TI model. The TI model for reliability, wear resistance, wear, and other competing failure provides the following benefits:

- Material evaluation
- Mating part surface evaluation
- Component quality CM
- Process performance CM

- System reliability CM
- Wear reliability degradation and failure analysis
- Corrosion reliability degradation and failure analysis
- Fatigue reliability degradation and failure analysis
- Temperature reliability degradation and failure analysis
- Integrated reliability growth and degradation analysis
- IRCMM program
- Integrated reliability data acquisition, calculation devices, and data analysis
- Standard integrated reliability rules for representing patterns, curves, and conditions

10.5 Maximizing the Wear Resistance and Reliability and Minimizing the Failures of Parts in Equipment with the TI Model

Increasing the wear resistance of the mating pairs of mechanisms, machines, and equipment can increase the wear coefficient (K_w), as well as the reliability of kinematic pairs. The methods of increasing the wear resistance, reliability, and service life include the following:

- Selection of a robust design for mechanisms, machines, parts, and equipment
- Reduction of the load, forces, and stresses on the friction surfaces of mating parts
- Strengthening and hardening the surfaces of parts with coatings for the maintenance of equipment
- Limitations of wear factors such as speed of wear for each joint and contact
- Wear equalization and integration principles with reliability, condition monitoring, and maintenance
- Automatic compensation of wear and application of the TI model

The earlier measures help increase the wear resistance of parts, which of course depends on the wear resistance of materials, the geometry of parts, and the operative conditions of the machine or equipment. Optimum selection of materials for hardening and coating mating part surfaces with the desired surface finish and maintenance will help improve the wear and other competing failure resistance, reliability, and service life of industrial equipment.

10.5.1 Mating Part Surfaces and Wear Condition Monitoring and Maintenance Technology with the TI Model

A new approach undertaken in this book with help of the TI technique includes the design of experiment, analysis, and characterization of surface topographies as an integral part of the product of quality and reliability. Besides visual appearance, attention is focused particularly on the service and performance properties resulting from surface topography. This encompasses the production of, and stress-related changes to, surface finishing and topographies. Other central aspects include the optimization of tribosystems and the evaluation of materials' resistance to wear under diverse tribological conditions and applications. Prominent aims in this respect are to reduce the wear-related costs and assure long-term stability of the required product quality and reliability. The new approach will cover the following areas, among others:

- Wear and other competing failure mode analyses and component reduction of failure-related costs through critical part quality and process performance condition optimization
- In-service and laboratory reliability testing to solve defined wear and other competing failure problems
- Development of industrially oriented wear testing machines
- Analysis of material–part–equipment system wear resistance to enable the selection of suitably durable coating materials and provide manufacturing and maintenance support with TI tools and monitors
- Development, CM, and maintenance of tribological databases

This book is concerned with quality–reliability-oriented optimization of hard alloy–coated part, process, and equipment chains on the basis of extensive sampling of measured process and component condition data. Attention in this regard consequently focuses not on analytical knowledge of how the processes function but also on the supposition that it is possible to describe equipment and process behavior by means of its measurable input and output parameters during operations. This book therefore offers a mathematical and statistical technique for material/part evaluation, process/component CM, and failure with maintenance analysis with the help of the TI model.

10.5.2 Component and Process Reliability Condition Monitoring and Maintenance of a Tribosystem with the TI Model

Wear failure patterns in a tribosystem are a result of various interrelated factors. Quality factors of parts and process conditions on part surface interaction are valuable sources of information on wear mechanism and mode. The quality of components and process conditions can be used for wear failure analysis with the help of the TI model. It is used to solve the problem of wear analysis and its classification for further use as a database of an integrated reliability and maintenance monitoring service. Wear monitoring with the TI model is considered for providing long-term operation, with no failures, at optimum friction performance of a tribosystem. It provides design requirement for IRCMM of industrial equipment, because it is able to attain maximum reliability and service life with minimum failures at minimum life cycle/maintenance costs. Integrating reliability, CM and maintenance analysis of tribosystem combines fatigue and wear analysis into a consistent entity for the prediction of maximum achievable system reliability. This integration is applied in the early stages of design, throughout production and service operations. The approach puts together the optimum quality of components, the quality variation, the optimum process conditions, and the process variations (fatigue, wear, corrosion, creep, high temperature, and other modes of failures). This book presents a real-time technique for computing maximum achievable reliability prediction that accounts for usage uncertainties. The technique is appropriate for accumulative damage mechanisms such as wear, fatigue, corrosion, and high-temperature impact. These are true probabilistic forecasts that provide the entire distribution of time to failure. The analysis is carried out during friction and wear processes, which have their origins in the surface interactions between solid materials with many dynamically important details at the microscale. These details such as surface characteristics that include surface roughness, surface hardness, stress concentration factor, and surface wavelength will be framed in terms of quality–reliability–degradation–failure parameters. In this book, based on an initial data input of optimum hard alloy–coated part quality forecast, we use the multivariate regression model to compute a probability distribution for incremental damage over a time horizon of interest, such as the remaining life or reliability coefficient of the component of interest. The macroscale, physics-based wear models are graphically analyzed, making the computation of incremental damage very rapid. Combining these incremental probability estimates into a single probability distribution for the future remaining life can be determined with integrated reliability coefficient of parts and equipment and TI coefficients.

10.6 Wear and Wear Resistance Coefficient Testing with TI Coefficients

Since different types of wear occur in machinery, many different types of wear tests have been developed to evaluate the effects of wear on materials, parts, and surface treatments. Consequently, the selection of the right type of wear test for each investigation is important in order to achieve useful and meaningful engineering data. More than one type of wear can attack the same part, such as sliding wear on extrusion machine screws for plastics. Sometimes wear can operate in the presence of corrosive or chemically active environments, and synergistic chemomechanical effects are possible. Selection of an appropriate wear test method begins with an assessment of the type of wear involved in each problem area. Wear testing is performed for one or more of the following reasons, which includes screening materials, part surface treatments, or lubricants for a certain application and helping develop new wear-resistant materials, surface treatments, or lubricants; establishing the relationship between the manufacturing, processing, or finishing methods applied to a certain machine part and its wear performance; or better understanding and modeling of the fundamental nature of a certain type of wear. Surprisingly to some, the wear resistance of a given material is not a basic property, like elastic modulus or yield strength. Rather, the wear behavior of a material depends on the conditions of its use. Therefore, the first step in wear testing is to recognize how the results of the work will be used. Only then can the appropriate test method, testing parameters, and useful format for reporting the results be selected.

10.6.1 Component and Process Conditions of Industrial Equipment with a TI Model–Based Program

Before attempting to design an experiment, we must ensure that we have properly analyzed and understood the component reliability and process performance conditions to be modeled. The mating part contact surface environment is usually defined in terms of

- Contact pressure
- Contact speed
- Energy input
- Temperature
- Conditions of lubrication
- Others

None of these are completely straightforward to define, either for the practical contact or in the test machine model, and they are also not sufficient to define fully the nature of a mating part contacts.

When building a test model, considerations of scale are paramount. It is hazardous simply to attempt to define the real life of components without the knowledge of its reliability and service conditions (load, speed, temperature, etc.) and apply them to a small test piece on a test machine. The first major concern is to know where the temperatures are reached by the test specimens. This is possible with rotary cutting and turning machining with plasma flame of hard alloy–coated workpiece. The material and part quality multivariate regression model is used to determine optimum component and process conditions. This model is in turn used to model wear with the help of TI coefficients. The relationship will be such that the ratio of the surface quality factor, Q_f, to the wear coefficient, K_w, and to part/material quality, Y_i, will equate to the TI coefficient a_i. This condition can be expressed as

$$Y_i : Q_f : K_w = a_i \tag{10.8}$$

At minimum quality factor (Q_{min}) or minimum surface hardness (HRC_{min}), the wear failure temperature (f_t) is reached under this condition and can be measured with the TI coefficient sensor (TICS) during machining operation.

From our design of experiment and the multivariate regression model, the surface hardness of a hard alloy–coated part is expressed as

$$\begin{aligned} Y_4 = {} & 0.71 + 0.04X_1 - 0.15X_2 - 0.07X_3 + 0.004X_4 - 0.033X_5 + 0.089X_1X_2 \\ & + 0.032X_1X_3 - 0.032X_1X_4 - 0.024X_1X_5 + 0.111X_2X_3 - 0.108X_2X_4 \\ & - 0.023X_2X_5 - 0.131X_3X_4 + 0.059X_3X_5 - 0.057X_4X_5 + 0.068X_1^2 \\ & + 0.127X_2^2 + 0.051X_3^2 + 0.103X_4^2 + 0.043X_5^2 \end{aligned} \tag{10.9}$$

If large amounts of energy are being dissipated in small test specimens, with supporting structures that do not allow the heat to escape, the specimens may become unrepresentatively hot and the bulk temperature may exceed that which is experienced in practice. This is likely to produce transitions in wear or frictional response.

The temperature reached at the surface of the contact (the flash temperature) is strongly influenced by the width of the contact and flash temperature that is responsible for many wear and friction effects. The width of the part contact surfaces and the temperature flash can be determined by the degradation rate of the surface hardness or the wear coefficient (K_w) of the part surface.

The optimum variant of the hard alloy–coated surface hardness parameter is determined from Equation 10.9. The optimum machining condition that has provided the best desired range of the surface hardness values of 60–63 HRC is operating with current at the *–1 level*, which is 80 A. With the application of the TI model, this range of surface hardness can be scaled with the help of the TI coefficient for part surface hardness degradation (a_d = 0 – 1). With these data, the coated part load spectrum can be plotted and also with the TI coefficient for hard alloy–coated surface hardness degradation $aY_{d(HRC)}$ and quality degradation control (Q_d), which is with contact surface effect controls. Reliability degradation and failure during process operation with the TI coefficient is shown in Figure 10.2.

As the operating current increases, the material and part surface hardness also increase until the optimum reliability condition is obtained. When the process or equipment continues to operate, the component and system will start to degrade. The degradation trend is monitored to be able to identify the potential and functional failures. The control of current can therefore be used to determine and control the changes in wear resistance, reliability degradation, and wear failures. Arising from the graph, it is possible to set the maximum reliability and wear-resistant coefficient for a desired application as the most cost-effective value. These obtainable data can be sustained for a specific length of time with IRCMM with a TI model–based program. This program can used to assess and evaluate the materials and mating part surfaces. Apart from the component and process conditions, the material and part microstructure can also be assessed.

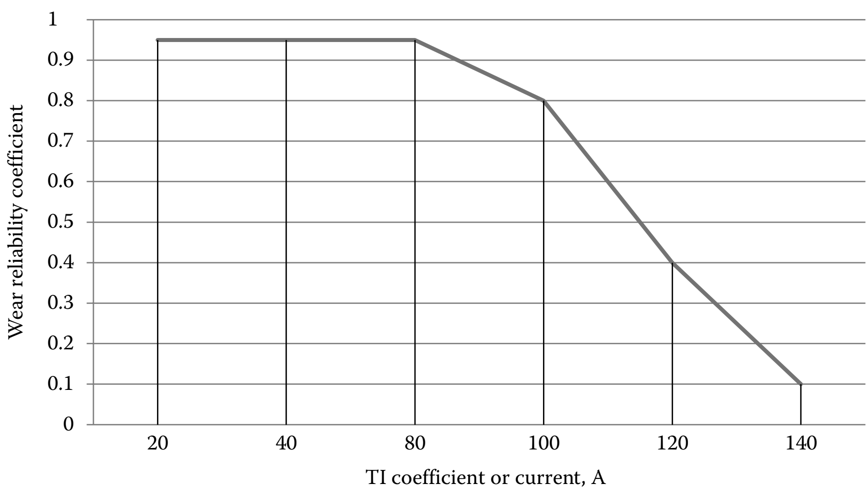

FIGURE 10.2
Wear reliability degradation and failure during process operation with TI coefficient.

The material structure and microstructure is another scale consideration that can be assessed with TI. Where the scale of the microstructure is much less than the contact area, the material can be considered to be homogeneous. But where the phase size is of the same order as the contact width, then the surface roughness on the counterface material and the properties of the different phases will influence the wear and friction behavior of the material.

The principal contact conditions are defined by the component (shape, surface condition, etc.) and some by the operating conditions (load, sliding speed), but others are less easy to define (lubrication conditions, contact pressure, wear mechanism) as these can vary during equipment operation and as the components wear out or as the surface hardness degrades.

The contact pressure (loading stress in the contact) is defined by the geometry of the contact, the applied load, and the material bulk properties. The geometry is defined by the shape of the two surfaces in contact, and any influence upon the shape by thermal distortion and wear will lead to high reliability degradation rates and failures. The load is influenced by the dynamics of the contact (stiffness of the material support and genuine load cycles) and other effects such as foreign bodies (abrasive particles, dirt, wear debris, etc.). The contact temperature results from the loading, the size, and the speed of relative motion and the thermal resistance of the two halves of the contact. While measuring the bulk temperature of a material poses little problem (apart from accessibility), the measurement of the contact temperature is another matter. The friction heating generates enormous transient temperatures in the contact (flash temperatures), which are surface effects only. These effects are based on surface hardness, surface stress, surface roughness, and surface wavelength, which eventually have become the root cause of reliability growth, degradation, and failures.

All wear processes are influenced by temperature, be they the formation of oxides on surfaces, the transformation of microstructure, the formation or breakdown of lubricant additive, the melting of the surface (the pressure and Velocity (PV) limit of the material), or thermal stress–induced failure. To be more specific, wear occurs in conjunction with the dissipation of frictional energy in the contact surfaces and this is always accompanied by a rise in temperature.

The frictional energy is generated by the combination of load and sliding speed and its distribution and dissipation is influenced by other contact conditions such as size and relative velocity. Different patterns of energy dissipation will give different wear patterns. Two more global parameters have been shown to be valuable in defining these conditions in sliding wear. These in fact become critical to the issue of simulation.

The friction power intensity (FPI) as presented by Matveesky is simply defined as the amount of energy pumped into the rubbing surfaces as they pass through the contact zone. The temperature achieved in the contact and in the bulk material is directly related to the FPI and the size and thermal characteristics of the materials and their supports. The FPI defines only the rate of energy generation and does not take into account the timescale over which this energy can be lost to the contacting materials. This timescale clearly has implications for the amount of damage caused in the contact [4]:

$$\text{Friction power intensity}: Q_F = \frac{mPV_s}{A} \quad \text{W/mm}^2 \tag{10.10}$$

where
m is friction coefficient
P is the normal load
V_s is the sliding speed
A is the apparent area of contact

Practical contacts have FPIs in the range of 5,000–20,000 W/mm^2.

The energy pulse (EP) is the product of the FPI and the contact transit time. The EP therefore takes into account the length of time during which the material is subjected to energy input during its transit in the contact zone, where t_t is the transit time in seconds [4]:

$$\text{EP} = \frac{mPV_s t_t}{A} \quad \text{J/mm}^2 \tag{10.11}$$

The EP can also be compared to the Archard wear law (DV = kPV_st_t/A mm^3). However, the EP equation uses the friction force rather than the applied load, which therefore justifies the use of rotary cutting with plasma spray for machining and for accelerated life test for components. This is perhaps more logical as it takes into account the rubbing conditions and since the friction coefficient can now be measured with the help of TI coefficients. This TI coefficient can therefore be used to determine the wear coefficient and reliability coefficient of components and systems. Fatigue and wear reliabilities (integrated reliability) can therefore be determined with the application of the TI technique.

Each EP is regarded as an incremental contribution to wear or surface damage in the contact. The sum of the EPs can therefore be used as a measure of the total wear. The amount of wear is directly related to the EP and lifetime reliability coefficient and this can be used to control and monitor the conditions of the component and system.

The correct analysis of the EP and its design into component or system reliabilities in real contact surfaces and subsequent modeling can significantly enhance the probability of achieving a satisfactory emulation of sliding and combined sliding and rolling contact applications. A multivariate regression model for such application has been developed in this book. This regression model provides initial data to the TI model for possible determination of optimum wear resistance coefficients (K_{wopt}), optimum component quality parameters (Y_{iopt}), optimum TI coefficients (a_{iopt}), optimum EP (EP_{opt}), optimum energy dissipation time (E_{topt}), optimum friction coefficient (F_{fopt}), and other optimum performance and service life variables. The wear resistance coefficient shows how many times the wear resistance of the given component surface part is higher or lower than the resistance of the base component material or optimum component quality condition that goes to make a new part or component. The quality factor and reliability coefficient values are established with the help of TI coefficients of components and materials under definite conditions of wear. The determination of wear conditions depends on the different patterns of wear through optimum EP, component wear resistance coefficient (K_w), component quality parameters (Y_i), and component reliability degradation (R_d) as well as power input in the part contact surfaces, initial optimum component condition parameters (Y_{i-1opt}), and TI coefficient for degradation (a_d).

Since the quantity of wear is proportional to the power (i.e., PV), then through mathematical modeling, the point on the part of a machine acted by minimum PV is taken as the reference quantity of wear for other parts of the machine, and this helps to determine the values of K_{w1}, K_{w2}, …, K_{wn}, where K_{w1} is the minimum wear resistance coefficient value (K_{wmin}), the minimum component condition parameter (Y_{imin}), or the minimum component reliability (R_{imin}), while K_{wn} is the maximum wear resistance coefficient value (K_{wmax}), the maximum component condition parameter (Y_{imax}), or the maximum component reliability (R_{imax}) for each respective mating pair. Wear, being the integral fraction of the power that runs through the component, whose coefficient depends on the material, geometric factors, and the surface treatment, the component reliabilities, and component condition parameters for the materials, parameters, and surface treatment can be determined with the help of the TI coefficient that runs through from the initial stage of design through production processes and service operations. The selected multiple component condition parameters (Y_i) for wear resistance and other failure-resistant mode designs would include the following:

Component condition parameters (Y_i)

- Surface roughness (R_a)
- Surface hardness (HRC)
- Surface wavelength (λ)
- Surface stress concentration factor (ε)
- Kinetic coefficient (k)

Process condition factors (X_i)

- Metallurgical process conditions (X_1)
- Coating deposition conditions (X_2)

- Surface finishing conditions (X_3)
- Machine/equipment conditions (X_4)
- Power conditions (X_5)
- Environmental conditions (X_6)

Modeling the conditions of a component for the different failure modes requires multiple optimization parameters (Y_i) and multiple factors (X_i). A single common trend for component/equipment failure resistance and reliability would involve the reliability parameter growth trend, the optimum reliability, and the component reliability degradation. The component condition parameter (Y_i) of an operating condition is directly proportional to the optimum initial component condition parameter (Y_{i-1}), that is, $Y_i = a \cdot Y_{i-1\text{opt}}$, where Y_{i-1}, is the initial optimum component parameter, Y_i is the component condition parameter of an operating process/equipment, and a is TI coefficient for component condition control. This same relationship is true for all parameters of a component condition like component wear resistance, corrosion resistance, temperature resistance, and reliability.

The TI coefficient $a_{i\text{opt}}$ can be used to determine and integrate $K_{i\text{w}}$ and $K_{i\text{f}}$ for all the components in the system, while the TI coefficient $b_{i\text{opt}}$ can be used to determine the optimum service lifetime ($T_{i\text{opt}}$). It can also be used to determine the optimum reliability of components and systems as well as reliability requirements. Integrated reliability of components and systems can therefore be determined with the application of the TI technique. An integrated reliability model can be used for the purpose of evaluating and assessing the component condition parameters and for the maintenance monitoring of components/systems.

This helps minimize frequent downtime of machine parts, machines, and finally the whole machine or equipment and hence increase component and system reliabilities.

The determination of wear and other failure resistance characteristics of machine joints and mechanisms is an important prerequisite for making optimum decisions for design, production, and construction and maintenance operations.

10.6.2 Wear and Competing Failure Test Analysis with the TI Model

Apart from wear failure mode analysis, there are multiple failure modes that can result in the failure of an individual component or unit. When performing integrated reliability degradation and failure analysis on a type of component, you can take the view of any individual unit or component that could fail due to any one of the possible failure modes, and since a component cannot fail more than one time in a nonrepairable system, there can only be one failure mode for each failed component. With this approach, the failure modes *compete* as to which one causes the failure for each particular component. This can be represented in a reliability block diagram as a series system of wear–corrosion–temperature failures in which a block represents each failure mode. Competing failure mode analysis, which segregates the analysis of failure modes and then combines the results to provide an overall reliability degradation and wear with other competing failure modes for the component in question, can be used to analyze data of this type.

In performing competing failure mode analysis, it is necessary to take the first step of analyzing data sets with more than one competing failure mode so as to perform a separate analysis for each failure mode. In the analysis for each failure mode, the failure times for the mode being analyzed are considered to be failures and the failure times for all other modes are considered to be suspensions. These are suspension times because the units would have continued to operate for some unknown amount of time if they had not been removed from the test when they failed due to another mode. Once the analysis for each individual failure mode has been completed in this manner, the resulting reliability degradation and failure equation for all modes is the product of the reliability equation for each individual failure mode. This is given by the following equation:

$$R_{\mathrm{d}(t)} = R_{\mathrm{d}1(t)} \cdot R_{\mathrm{d}2(t)} \cdots R_{\mathrm{d}n(t)} \tag{10.12}$$

where

n is the total number of failure modes under consideration

t is time

This is the product rule for the reliability of a series system with statistically independent components, which states that the reliability for a series system is equal to the product of the reliability values of the components that compose the system.

Applying the TI technique to the earlier equation, it can be written as follows:

$$R_{\mathrm{d}(a)} = R_{1(a)} \cdot R_{2(a)} \cdots R_{n(a)} \tag{10.13}$$

where

n is the total number of failure modes under consideration

a is the TI coefficient for component quality control

The coefficient is determined from the TI model, $Y_i = a{\cdot}Y_{i-1}{}^b$, where Y_i is the final quality parameter of a component, Y_{i-1} is the initial quality parameter of component, a is the TI coefficient for component quality control, and b is the TI coefficient for process condition control. Y_{i-1} can be determined experimentally with the regression equation for the different quality parameters of a component. When coefficient $b = 0$, $Y_i = a$, which means that at the beginning of any new component or equipment, the quality of a component is maximum, the coefficient is maximum, and the failure-resistant coefficient is also maximum, since there is no failure at this state if the installation and assembly of the equipment are carried out properly. The failure resistance coefficients (K_{fi}) of the different failure modes (wear [K_w], corrosion [K_c], temperature [K_t], fatigue [K_f], and others) can be determined with the TI coefficient a. The TI coefficients (a_i) of the different component quality parameters (Y_i) can also be determined, and as such, the product of the different coefficients is derived to be the resultant quality condition of a component. Converting component quality data to failure resistance-to-failure data and times-to-failure data is possible with TI coefficients.

When the TI coefficient $b = 1$, $Y_i = a \cdot Y_{i-1}$, where Y_{i-1}, which is the initial component quality condition and is also the failure resistance coefficient (K_{fi}) when the process condition is operating at optimal conditions. Under this optimal condition, $K_{fi(\text{opt})}$ and $Y_{i-1(\text{opt})}$ are optimal. With $Y_i = a \cdot Y_{i-1}$, $a = Y_i/Y_{i-1(\text{opt})}$, the ratio of quality output and quality input. The same applies to the ratio of failure resistance coefficient output to failure resistance coefficient input—$a = K_{fi}/K_{fi-1(\text{opt})}$. The change of Y_i with time and from an initial condition to a final condition of component is either condition growth or condition degradation. With this concept, reliability growth, reliability degradation, failure resistance trends, component health, and life data can be determined. The wear and competing failure mode analysis is shown in Figure 10.3.

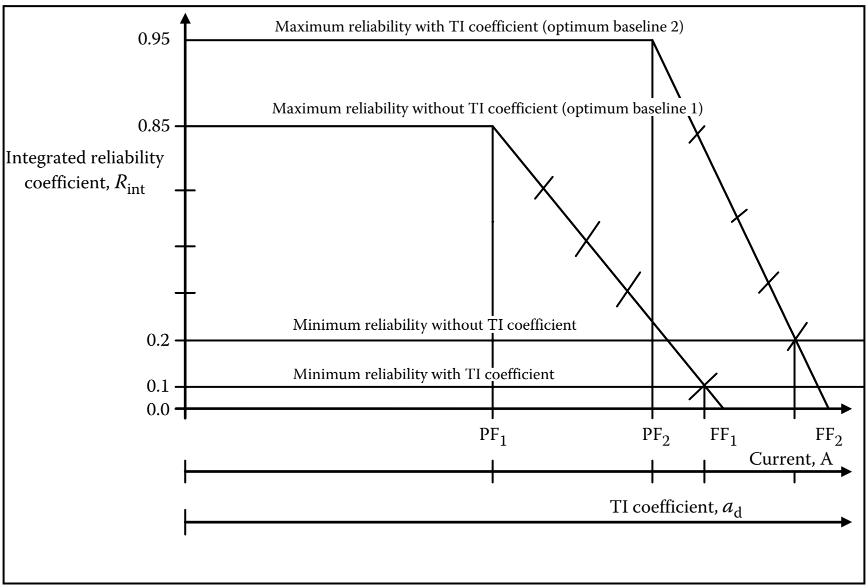

FIGURE 10.3
Integrated reliability curve for wear-resistant degradation and failures of equipment with TI coefficients.

10.7 Integrated Reliability Curve Analysis for Wear Resistance Degradation and Competing Failures of Equipment with the TI Model

Figure 10.3 shows a typical integrated reliability curve of the technological chains for wear- and other competing failure-resistant applications with the TI model. A suitable program is developed for optimum reliability selection of critical part/equipment and also for the detection of the root cause of potential failures with the TI model–based program, as shown in Figure 10.4. (The integrated reliability curve analysis with TI model based program for wear and other failure resistant application of equipment.) The reliability and wear and other failure test results with the TI model can therefore be used as reliability requirements for planning, maintenance, and management as well as for acquisition, analysis, communication, assessment, and display of data, as shown in Figure 10.5.

The results are used to further design data acquisition devices and data processing/transformation to design, set up reliability requirements, and integrate different generic failure modes for reliability condition monitoring and maintenance of processes, parts, and equipment, which can be buttressed with the following facts:

1. A typical integrated reliability curve and mechanism of a new rotating equipment for wear- and other competing failure-resistant applications is characterized with the following features: a system of parts that make the equipment work (P_i), inherited optimum wear-resistant shaft surface condition (P_{wk}), competing corrosion failure–resistant part conditions (P_{ck} and P_{tk}), and an IRCMM with a TI model–based program.
2. IRCMM with a TI model–based program is used to test for the optimum quality condition of the critical part with hard alloy–coated surface (Y_{opt}) within a specific optimum lifetime (T_{opt}). If it meets the equipment requirements (R_{opt}), it therefore means it would need to be sustained using an effective reliability condition monitoring and maintenance strategy that allows it to serve reliably for a desired period of time through the point, where it starts to degrade proportionally before it finally enters a failed state. The mean time to failure (MTTF) and the condition of failure (F_k) are measured.
3. IRCMM with a TI model–based program is used to test for the minimum quality condition of the critical part with hard alloy–coated surface (Y_{min}) within a specific desired lifetime (T_{fk}). If the test for failure is positive, then you can use the TI model to detect the mode of failures (F_{ik}) and the root cause of failure (Yi_{min}), the time of occurrence (t_i), the location of failure (e.g., processes, parts, parameters), and the rate of failure through reliability degradation (R_d, a_d).

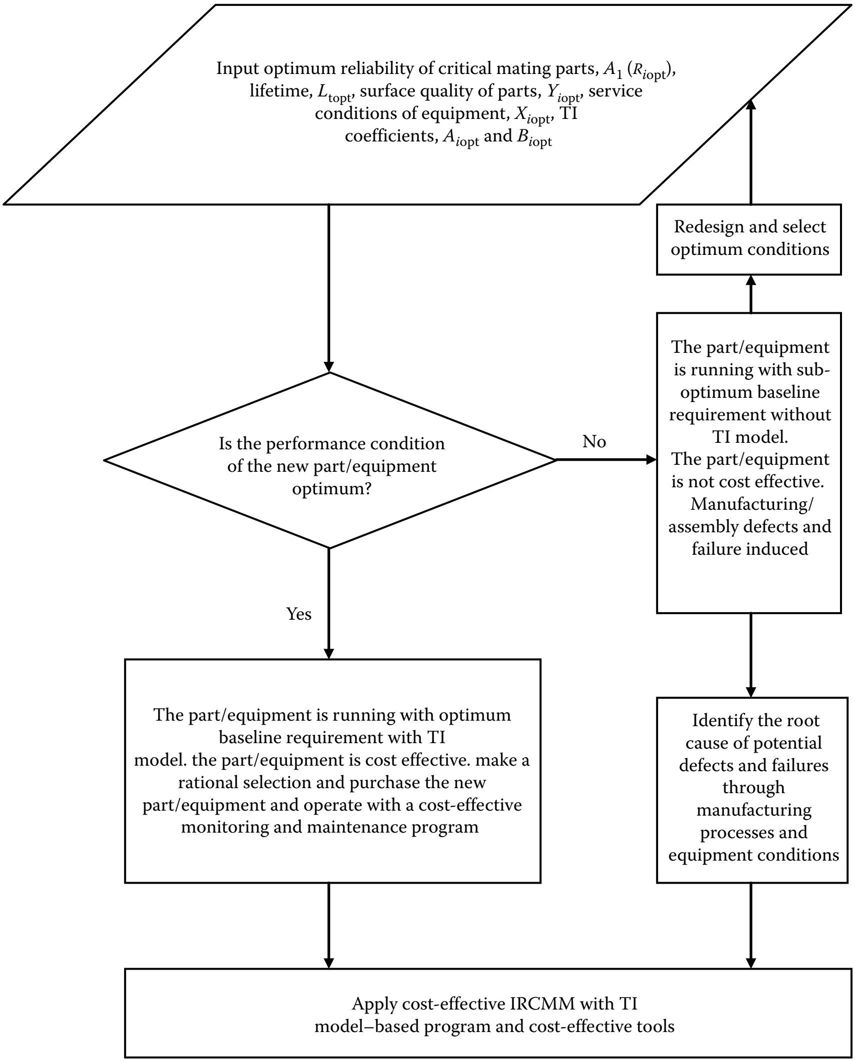

FIGURE 10.4
The optimum reliability selection of new critical part/equipment and detection of the root cause of potential wear failures with TI model–based program.

4. Integrated reliability CM with the TI model helps to detect and locate the different types of failure modes early to avoid mortality failures, random failures, and catastrophic damages.
5. Before a new equipment is bought and installed, the parts and equipment lifetime and reliability requirements in terms of optimum and minimum quality, mean time to failure, maintenance cost of equipment, and equipment lifetime need to be tested and verified with

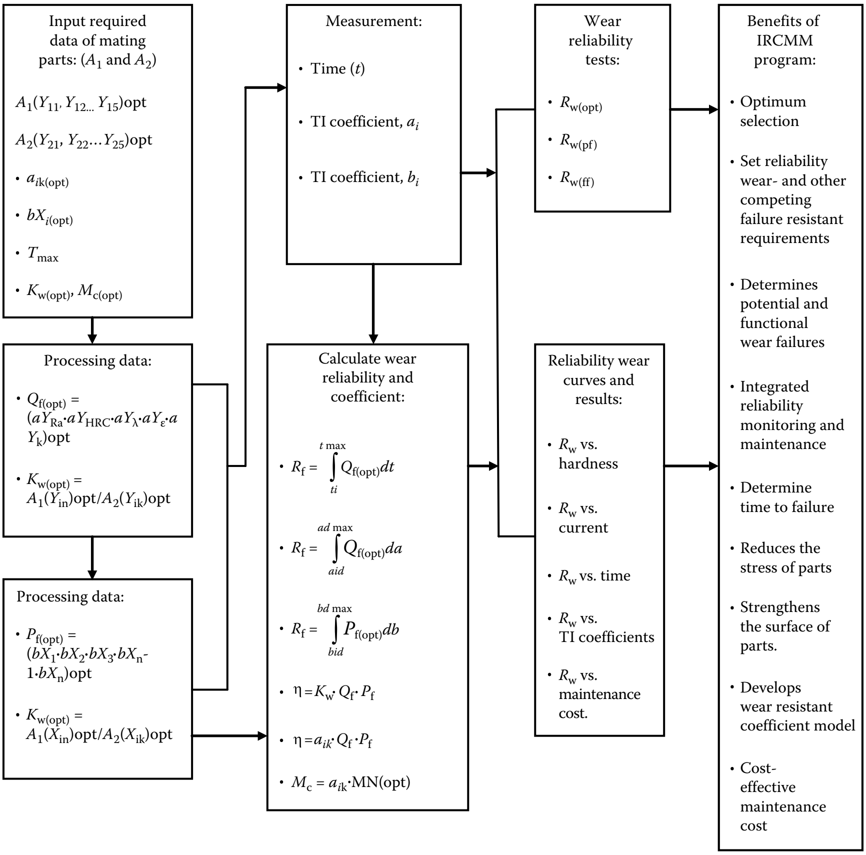

FIGURE 10.5
Reliability degradations and wear failure of parts/equipment assessment with TI model–based program.

the TI model ($Y_i = a_i \cdot Y_{i-1}^b$) and also using an integrated reliability monitor to effect a cost-effective change.

6. The integrated reliability monitor with a TI model–based program measures the TI coefficients that control reliability growth from minimum to maximum achievable reliability and reliability degradation from maximum achievable reliability to minimum reliability condition of the component and equipment.
7. The wear resistance coefficient (K_{iw}) and other competing failure resistance (K_{if}) are measured with the TICS, and data (a_i) are used to determine the maximum and minimum achievable reliability of parts and equipment.
8. The TI model is used to test and evaluate component and equipment reliabilities, component and equipment wear resistance coefficients,

and life cycle and maintenance cost of component and equipment and detect the root cause of degradations and failures.

9. The behavioral change of material and surface treatment depends on the conditions of its use (service conditions), where accurate reliability assessment is done to determine the reliability of component condition parameters and the useful baseline of its lifetime, which is now possible with the help of IRCMM with a TI model–based program.
10. This program is used to set up the targets and baseline requirements for reliability of materials and surface treatment of components/equipment conditions and provide a single metric to integrate design, production, and service operations together under one platform.
11. It is hazardous simply to attempt to determine the real life of component/equipment without the knowledge of its reliability and process performance condition parameters (load, speed, temperature, etc.) and apply them to a small test piece on a test machine.
12. The temperature of contact surfaces, material structure, material stress, microstructure, surface roughness on the counterface material, and properties/conditions of the different phases/operation parameters will influence wear and friction behavior of materials, which can be determined with TI coefficients.
13. The principal contact condition parameters are defined by the component (shape, surface conditions, etc.) and some by the operating conditions (load, sliding speed), but others are less easy to define (lubrication conditions, contact pressure, wear mechanism) as these can vary during machine cycle and as the components wear, due to the dissipation of frictional energy in the contact, which is always accompanied by a rise in temperature.
14. The EP equation uses the frictional force rather than the applied load, which of course is more logical as it takes into account the rubbing conditions and since the friction coefficient can now be measured with the help of TI coefficients to determine the wear resistance coefficients (W_{k}) and reliability coefficients ($R_{i\mathrm{k}}$) of components/systems.
15. The TI coefficient is used to define the friction coefficient, component wear resistance coefficient, as well as EP during process conditions and service conditions, which implies the integration of design, production, and service operations as well as component, process, and environment conditions with a single metric.
16. The reliability and wear and other failure test results with the TI model can be used as requirements for planning, maintenance, and management as well as for acquisition, analysis, communication, and display of data.

17. The TI model is used to further design data acquisition devices and data processing/transformation to design, production, and maintenance department for reliability requirements and for the integration of different generic failure modes for the reliability maintenance monitoring of processes, parts, and equipment.

10.8 Conclusions

1. The relationship between wear and the multiple variable factors that characterize the type and properties of material conditions, part surface conditions, process conditions, friction, lubrication, and others can now be determined with a multivariate regression model that has been developed in this book.
2. The multivariate regression model has helped to determine the reliability, performance, and lifetime requirements for hard alloy coating materials, hard alloy–coated part mating cylindrical surfaces, and the service conditions of desired equipment and optimize and predict component/system reliability.
3. The optimized component/system quality–reliability condition can be incorporated and integrated into process performance condition with the help of the TI model for the automation and implementation of IRCMM under a single platform.
4. The part and equipment's wear can be estimated by the total time, service condition of components/parts, and cost spent on restoring the performance (the length of service life) as well as by the probability of sustaining the original condition parameters of the equipment within the prescribed desired control limits during the specified service period.
5. The service life of most machines, mechanisms, and equipment is determined by the wear resistance of the hard-coated mating part surfaces.
6. Wear resistance is the property of a material that resists the degradations or changes in the dimensions of a machine part/equipment in a particular friction condition.
7. The increase in the wear resistance or the quality factor of a kinematic mating hard alloy–coated part surface, which can be used to determine the reliability coefficients of components/systems, mechanisms, and equipment, increases the durability coefficient of the kinematic mating hard alloy–coated part surfaces of machines, mechanisms, and systems.

8. The reliability coefficient of kinematic mating hard alloy–coated part surfaces of machines, mechanisms, and equipment is a function of all the failure resistances or the quality parameters of a particular hard alloy–coated cylindrical part surface, which can be used to fully assess component and system conditions, instead of the wear-resistant coefficient.
9. The quality factor, which is the function of all the quality parameters of a particular mating hard alloy–coated part surface, can be used to assess component/system conditions.
10. The surface quality parameters of the mating hard alloy–coated part are converted to equate the values of the TI coefficient for quality control, which in turn is used to determine the quality factor, reliability coefficient, and failure resistance coefficient.
11. The reliability and service life of equipment can also be determined by the wear rates of mating parts or by the reliability degradation rates of parts and can now be expressed in terms of power condition functions.
12. The integrated reliability coefficient is the integral function of mating parts' quality conditions, process condition, and power condition, whose coefficient depends on the material, geometric factors, process conditions, and surface treatment.
13. Integrated reliability analysis can be performed by constructing the specific curves from quality–reliability and performance–life data and using a practical understanding of wear and other competing failure mode characteristics, symptoms, and warning signs to form an opinion about the underlying failure condition for a tribosystem.
14. The author is focused on the development of automated methods of wear- and other competing failure-resistant analyses that use a data acquisition device to measure reliability growth and degradation as well as standardized rules for constructing curve diagrams to describe component and equipment reliability.
15. Before attempting to design an experiment for maximum wear-resistant coefficient, we must ensure that we have properly analyzed and understood the need to integrate reliability and condition monitoring with tribological systems, which is done with the TI model.
16. An integrated reliability test with the TI model will be used to assess and evaluate the component/equipment with wear- and other competing failure-resistant conditions.
17. A robust design with an integrated reliability nondestructive testing technique that provides accurate prediction of reliability growth and reliability degradations, wear, and other failure modes of components/equipment have been developed in this book.

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11

Integration of Reliability, Condition Monitoring, and Maintenance of Industrial Equipment

11.1 Existing Preventive and Predictive Maintenance Program of Equipment

It has been ascertained by researchers and consultants [1] that most organizations in the maintenance and reliability field have very weak preventive (PM) and predictive (PdM) maintenance programs that contain ambiguous and needless tasks at unnecessary frequencies. What makes this so shocking is that plant facilities send out their craftspeople to work thousands and thousands of hours each year, performing what should be the plant's most important work, armed with ineffective and inefficient PM tasks and standards. This trend will have to change with the application of integrated reliability condition monitoring and maintenance (IRCMM) with the technological inheritance (TI) model–based program since it helps select cost-effective maintenance strategies and manufacturing process conditions, predict maximum achievable reliability and minimum acceptable reliability, and detect failures throughout the life cycle of components and systems. It is used to measure component and system reliability, reliability growth and degradation, CM, condition- and time-based maintenance, as well as maintenance costs. It can also be used to integrate reliability, CM, and maintenance with a single TI coefficient metric under a single model-based program for task assessments and evaluations.

11.1.1 Reliability Condition Monitoring and Maintenance Tasking

How do you know that your PM program needs to be improved? First, look at the PMs themselves. Carefully review a stack of PM cards or sheets and their tasks. Are there tasks such as "Inspect the charge pumps" or "Check the crop shear bolts?" Tasks like these leave much to the imagination. In a real case of crop shear bolts, there were literally hundreds of bolts on this crop shear including base bolts, shear head bolts, frame bolts, housing bolts, adjustment bolts, and coupling bolts. With all the bolts involved, the craftsperson could easily spend 8 h checking the tightness of all the bolts with the proper torque wrenches (if they were available). Given that this was a weekly PM and just one of many assigned to the craftsperson during the weekly 8 h maintenance outage, not much was expected nor was much done. So why have the PM in the first place? If you do not know much about the equipment yourself, a second way to find out if your PM program needs improvement is to just ask the guys who have performed it. Print out, copy, and hand a group of knowledgeable craftspeople some of these questionable PMs and ask them "What does this mean?" You are likely to get as many different responses as personnel asked. In one training section, four craftspeople were asked to be honest and to write down how long it took them the last time they had performed a biweekly facility check that had a dozen tasks. The answers ranged from 30 min to 2 h [1]. Then, they were asked how long it would take to do various tasks. On the second task, "Check the valves and piping," one of them asked, "Which valves?" to which the trainer answered, "Since it doesn't specifically say, all of the facility product valves and piping would be assumed." One craftsperson responded that it would take 4–5 h to inspect all the valves to which another responded that it would take an entire day. The lesson here is that probably none of the craftspeople were even close to performing the right PM tasks that would prevent future failures. IRCMM with the TI model–based program can be used to determine the number of failures within a specific period of time, the component condition of failures, the rate of reliability degradation, and failure preventive and predictive strategies and select suitable tools and information as well as maintenance cost and quality–reliability assessments for improvements.

11.1.2 Getting Started on the Preventive Maintenance Improvement Process

The first step is determining where to get started. In most plants, there are several sources of information where the problems exist including equipment delay information, repair work orders, quality problems, and failure reports including mean time between failures (MTBF) statistics. If these plants' trouble spots also have weak PMs as judged earlier, you have found the place to get started. The IRCMM program provides an IRCMM diagram, which offers a step-by-step approach for a cost-effective maintenance strategy, as shown in Figure 11.3.

The next step is to form a team to work on the PM improvement process. As a minimum, the team should be made up of a craftsperson from each of the trades involved plus an operator or operating supervisor and either a maintenance supervisor, planner, or reliability engineer. The choice of craftspeople is most important. He or she should be very knowledgeable and preferably the person currently performing the PMs in the area. The operations person is important too in that there are usually cleaning or simple maintenance tasks that production can perform. The team will also need a leader to ensure the team makes progress. Each meeting will require a facilitator plus a competent notetaker.

11.1.3 Guidelines for Improving a Preventive and Predictive Maintenance Program

1. Make a list of the assets that you plan to analyze. Verify that the list is complete using drawings and/or field verifications.
2. Break each asset down to major systems/major components.
3. Utilize any appropriate information such as original equipment manufacturer (OEM) (vendor) manuals, drawings, training manuals, bills of material, and prior PMs.
4. Analyze each major system/component separately by using a particular form.
5. For each component, list any actual or likely future functional failures that may occur.
6. For each functional failure, develop one or more PM or PdM tasks that are appropriate. These tasks must either prevent or mitigate the consequences of the failure.
7. For each PM task, provide adequate detail:
    a. Task location questions
        i. Are directions needed to find it?
        ii. Does the location ID number on the PM card match the ID number on the machine or electrical device?
        iii. Is the nomenclature on the PM consistent with common plant language?
        iv. How many and where are the lubrication points or microswitches located? Are drawings needed so that the maintainer can locate all of these points?
    b. Task performance questions
        i. What are the safety requirements/permits, lock out/tag out, and personal protective equipment (PPE) required?
        ii. What tools and parts are required? Are there any additional parts that may be required if certain conditions are found? If so, list these part numbers as well.
        iii. Is there an order of steps that must be performed in sequence during disassembly/assembly?

iv. Explain the word "inspect" if it is used—what conditions are being inspected for?
v. What is oil or grease type and how much should be added?
vi. What are the alignment or gap settings?
vii. What is the bolt torque sequence and values?
viii. Should any readings be taken and recorded? If so, what is the acceptable range for these readings?
ix. When should the task be performed? Does the equipment have to be down?
x. If the PM task includes number of assets, is there an optimum order (route) that these tasks should be performed? (Examples: vibration, lube, infrared routes, integrated reliability maintenance monitoring)
xi. Who will perform the PM task? (Which craft, operations, or contractor?) Base this decision on the skills needed, efficiency, and ownership. Do operations own this process? Can they be trained to perform the PM or PdM?
xii. How long should the PM take to perform? Set a standard. If repairs are required, should they be performed immediately as part of the standard or should they be planned for the future?

c. Task frequency questions
   i. How quickly does the equipment deteriorate from a potential failure to a functional failure?
   ii. Is the frequency adequate to prevent the failure? Does the task interval include enough time to discover a potential failure and make repairs before the foundational failure can occur?
   iii. *Example*: The failure of a set of V belts of a critical conveyor system shuts down a plant for 2 h at a cost of $10,000. The belts of a critical conveyor system were very badly frayed indicating that a future failure is ready to occur over a period of time. Old Preventive Maintenance (PM) sheets were collected and it was found that not one of this weekly inspection task (task #11 of 16) was completed in a 6-month period during the weekly production changeover. The conditions for this task were poor, the area was hard to get to, it was very dirty and hot, and in addition, the solid steel guard that protected the belts was extremely heavy.

   Solution: The new PM task was to be performed once per year on its own separate PM card. The new tasking included changing all V belts, pulley alignment, and inspecting the condition of the pulleys for damage and looseness. Spare part numbers for the belts and pulleys were included on the PM card.

8. Make sure that the PM or PdMs developed are both cost- and time-effective. This can be accomplished by comparing the annual cost of failure that can be prevented to the annual cost of performing the PM/PdM. For example, a 500 hp motor "A" machine has an MTBF of 4 years if it is aligned and lubricated properly. If it functionally fails unexpectedly, "A" machine will lose 3 h of production that cannot be made up. In addition, the functional failure will cost about $1600 more to repair then if it were changed before the failure actually occurs. An existing cost-effective PdM program consisting of motor circuit analysis (MCA) and vibration analysis (VA) on the motor is estimated to detect and prevent 80% of functional failure of this motor. The quarterly MCA must be performed when "A" machine is down and takes one man-hour to perform, while the monthly VA takes 0.2 man-hours but can be performed while the line is running.
9. Notes

   One craft hour costs $30/h.

   During planned outages, craft hour is valued at $150/h.

   Downtime on "A" machine costs $4000/h.

   The annual cost of performing these PdMs is

   For MCA, 4 times × $150/h = $6000

   For VA, 12 times × 0.2 h × $30/h = $72

   The annual cost is $672.

   The annual savings that can be achieved is

   M_c × 0.8 × (3 h × $4000 + $1600) = $2720, a very acceptable ratio of annual savings to cost of more than 4–1
10. Finally, test the PM/PdM tasks that the team has developed by having someone not involved in the development to perform it. This validation is especially important when the team first starts developing new PM/PdM.
11. The common denominator for all of the PM programs is the scheduling guideline. All PM management programs assume that machines will degrade within the statistical time frame typical for its particular classification. For example, a single-stage, horizontal split-case centrifugal pump will normally run 18 months before its wear parts should be replaced. Using PM techniques, the pump would be removed from service and rebuilt after 17 months of operation. The problem with this approach is that the mode of operation or plant-specific variables directly affects the normal operating life of machinery. The MTBF will not be the same for a pump that is handling water and the one handling

abrasive slurries. The normal result of using MTBF statistics to schedule maintenance is either unnecessary or catastrophic failure. In the example, the pump need not be rebuilt after 17 months. Therefore, the labor and material used to make the repair are wasted. The second option using PM is even more costly. If the pump fails before 17 months, we are forced to repair using run-to-failure techniques. Analysis of maintenance costs has shown that a repair made in a reactive, that is, after failure, mode will normally be three times greater than the same repairs made on a scheduled basis.

12. PdM is a condition-driven PM program. Instead of relying on industrial or in-plant average-life statistics to schedule maintenance activities, PdM uses direct monitoring of the operating condition, efficiency, heat distribution, component performance, and other indicators to determine the actual mean time to failure or loss of efficiency that would be detrimental to plant operations for all critical systems in the plant or facility. PM is the means of improving productivity, component quality, and overall effectiveness of our manufacturing and production plants. PdM is not vibration monitoring, or thermal imaging, or lubricating oil analysis, or any of the other nondestructive testing techniques that are being marketed as predictive maintenance tools. Rather, it is a philosophy or attitude that simply stated uses the actual operating condition of plant equipment and systems to optimize total plant operation. A comprehensive PdM program utilizes a combination of the most cost-effective tools, that is, thermal imaging, vibration monitoring, tribology, and other nondestructive testing methods, to obtain the actual operating condition of critical plant systems and, based on the factual data, schedules all maintenance activities on an as-needed basis with the TI technique.
13. PdM has received a great deal of attention in the past 5 years or more. The US industry spent $200 billion in 1985 alone to maintain plants and equipment [2]. Studies show that the annual maintenance cost per horsepower (0.735 kW) using PM is between $11 and $13, but PdM reduces manual maintenance costs to $7 and $9 per horsepower (0.735 kW) [2]. PdM in today's state-of-the-art technologies, readily available user-friendly desktop computers, and increased sophistication of equipment monitoring instruments now makes it possible to have a reliable and cost-effective PdM program with the TI technique.
14. Improving the existing preventive and predictive program with the TI technique is possible with the IRCMM program.

11.2 Improving the Existing Preventive and Predictive Maintenance of Parts, Processes, and Equipment with an IRCMM Program

The conditions created by corporations struggling with consistent budget cuts, fueled by the lack of demand for their products, make it difficult to concentrate on the basic cornerstone of processes, parts, and equipment reliability like PdM and PM. Restructuring or restriction of staff, especially from those in the maintenance, engineering, and operations arenas, results in a loss of valuable and irreplaceable experience. The knowledge vacuum left will present itself in costly process interruptions, which can put the asset and personnel at risk. To help mitigate these types of events, companies must refocus their efforts to fully utilize their resources and constantly improve early asset failure recognition to maximize part, process, and equipment reliability. This can be done with the help of the TI technique that is used to determine the maximal achievable reliability with the help of the TI coefficient for quality growth control (a_g) and maximum acceptable failure coefficient with the TI coefficient for quality degradation control (a_d) of components during the manufacturing processes, which in turn is required to be sustained and as a control or monitoring limit during industrial equipment operations with the help of a cost-effective maintenance strategy within a specific time. This TI coefficient for quality degradation control, a_g, can be used to predict the time and conditions of failure and prevent the different failure modes through set threshold points for potential and functional failures that may occur in the component or system. For a continuous improvement of asset reliability, the technique helps integrate predictive maintenance tasks and equipment baselining during maintenance jobs, which is one way to maximize equipment availability. The production, maintenance, and reliability departments work in silos within a larger organization. Once maintenance work is complete, and before equipment is released back to manufacturing, mechanics should complete the following tasks to fully maximize asset availability:

- Integrated reliability readings
- Benchmark PdM readings
- Proactive maintenance
- TI coefficient for quality growth and degradation control

In the real world, precision maintenance is synonymous with asset reliability. Today, a wide range of companies are starting to recognize additional areas where process operators can participate proactively in reliability-based maintenance. As companies find ways to maximize resource utilization in these challenging times, integrating reliability-based maintenance and condition monitoring with the IRCMM program is highly essential. This new program is more cost-effective than the existing PM and PdM program.

11.3 New Concept of Preventive and Predictive Maintenance Program with a TI Model–Based Program

In any sustainable program with the TI model, as shown in Figure 11.1, you must start with knowing what you own. Everything must be surveyed and evaluated for its impact. The initial program must start out with a *pilot* area and the expansion of the program must be done in small chunks. Once a census of the part–process–equipment system is completed, a critical part–process–equipment system list can be developed through selecting parts, processes, and equipment based upon multiple

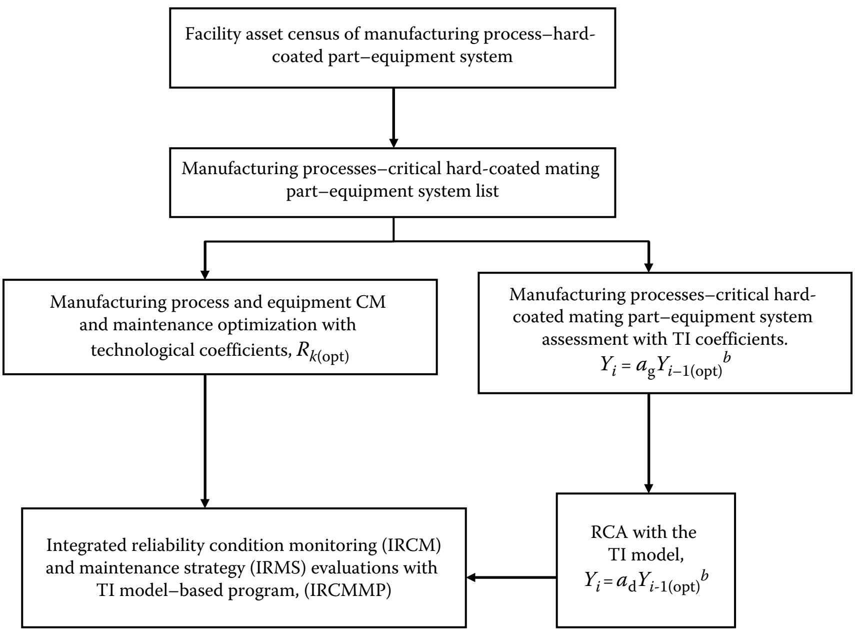

FIGURE 11.1
IRCMM map with TI model–based program.

criteria of component quality–performance–cost with a single metric known as the TI coefficient.

The next step is the component and system condition assessment with the TI coefficient, where the component and system condition is evaluated. The tests and inspections may be the ones selected for routine or proactive testing through reliability CM and maintenance practice development processes. The results should be kept on record, and equipment that is in poor condition should be scheduled for repair, replacement, and maintenance, at which time significant energy and reliability improvements can be considered.

System and component reliability CM assessment should be performed in parallel with maintenance optimization for the development of IRCMM practices. The optimization process is carried out with the TI model. The results are used for integration of reliability, CM, and maintenance as well as for root cause analysis and for the selection of suitable cost-effective integrated reliability monitoring and maintenance practices.

In order to track the IRCMM improvement process, all changes must be properly documented and approved before changes are made in the computerized maintenance management system (CMMS). Optimizing a plant's IRCMM program has many benefits including improving equipment reliability, improving production processes and operator's productivity, and reducing maintenance costs. In addition, operator morale improves when the craftspeople and operators feel that they are doing the right things and have key input into their plant's reliability improvement process. Optimizing and automating plant's maintenance parameters would further enhance the improvement of processes and equipment reliability CM and maintenance. The application of the TI model would help maximize the benefits and minimize the time and cost and integrate the reliability, monitoring, and maintenance of processes and equipment systems.

11.4 Integrated Reliability Monitoring and Maintenance Characteristics with a TI Model–Based Program

Industrial equipment reliability needs to be considered, thought about, and implemented from start to finish, that is, from concept and design through installation and on through operation of processes and equipment. Maximum achievable reliability has been designed into hard alloy–coated mating part surface and, in turn, into its desired equipment for wear- and other failure-resistant applications. Inherent reliability, which may be the maximum that a given hard-coated mating part can achieve, is largely determined by design, along with the quality of components (Y_i), assembly, installation, etc. Operational reliability, which is the actual level that the hard alloy–coated mating part or equipment achieves, is always less than inherent, but the difference can be enhanced by appropriate installation, operation, and maintenance practices to equate inherent reliability for a specific period of time. Both inherent and operational reliabilities must be carefully considered in order to achieve optimum performance with the help of the TI model. Realistic functional reliability requirements of equipment have been determined with a multivariate regression model in Chapter 6. A reliability specification of both components and the overall system has been developed to meet that functionality. Performance, reliability, quality, and health specifications have also been stated and appropriate testing done like in the case of reliability testing. Installation specifications also were identified and followed to meet the system reliability requirements. The optimum operating and maintenance requirements with the help of the TI technique were developed and trended to suit wear- and other failure-resistant applications. This reliability trend and the deviation from the trend are indicative of reliability growth and degradation and functional failures. The reliability trend curve can be read and interpreted from point to point from the initial to final stage of manufacturing and service operations. It offers cost-effective proactive maintenance, PM, and PdM solutions of components and processes before it enters a failed state or before catastrophic damages can occur. At this juncture, it will be necessary to look at how the process function–based maintenance and component-based maintenance are integrated in order to maximize component and system reliability.

11.4.1 Function-Based Maintenance Approach

The only occurrence that is likely to stop any machinery performing to the standard optimum values required by its users is some kind of failure. This suggests that maintenance achieves its objectives by adopting a suitable approach to the management of failure. However, before we can apply a suitable blend of failure management tools, we need to identify what failures can occur. Once each potential and functional failure has been identified, the next step is to try to identify all the events that are reasonably likely to cause each failed state. Most traditional lists of failure modes incorporate failures caused by deterioration or normal wear and tear. However, the list should include failures caused by human errors (on the part of operators and maintainers) and design flaws so that all reasonably likely causes of equipment and product failure can be identified and dealt with appropriately. It is also important to identify the cause of each failure in enough detail to ensure that time and efforts are not wasted trying to treat symptoms instead of causes. On the other hand, it is equally important to ensure that time is not wasted on the analysis itself by going into too much detail.

A detailed analysis of an average industrial undertaking is likely to yield between 3,000 and 10,000 possible failure modes. Each of these failures affects the organization in some way, but in each case, the effects are different. They may affect operations. They may also affect product quality, customer service, safety, or the environment. They will all take time and cost money to repair. It is these consequences that most strongly influence the extent to which we try to prevent each failure. In other words, if a failure has serious consequences, we are likely to go to great lengths to try to avoid it. On the other hand, if it has little or no effect, then we may decide to do no routine maintenance beyond basic cleaning and lubrication. A great strength of Reliability Condition Maintenance (RCM) is that it recognizes that the consequences of failures are far more important than their technical characteristics. In fact, it recognizes that the only reason for doing any kind of proactive maintenance is not to avoid failures per se but to avoid or at least to reduce the consequences of failure.

The RCM process classifies these failure consequences into four groups:

1. *Hidden or potential failure consequences*: Hidden failures have no direct impact, but they expose the organization to multiple failures with serious, often catastrophic, consequences (most of these failures are associated with protective devices that are not fail-safe).
2. *Safety and environmental consequences*: A failure has safety consequences if it could hurt or kill someone. It has environmental consequences if it could lead to a breach of any corporate, regional, national, or international environmental standard.
3. *Operational consequences*: A failure has operational consequences if it affects production (output, product quality, customer service, or operating costs in addition to the direct cost of repair).
4. *Nonoperational consequences*: Evident failures, which fail into this category, affect neither safety nor production, so they involve only the direct cost of repair.

The RCM process uses these categories as the basis of a strategic framework for maintenance decision-making. By forcing a structured review of the consequences of each failure mode in terms of the earlier categories, it integrates the operational, environmental, and safety objectives of the maintenance function.

This helps bring safety and the environment into the mainstream of maintenance management. The consequence evaluation process also shifts emphasis away from the idea that all failures are bad and must be prevented. In so doing, it focuses attention on the maintenance activities that have the most effect on the performance of the organization and diverts energy away from those that have little or no effects. It also encourages us to think more broadly about different ways of managing failure, rather than concentrate only on failure prevention. Failure management techniques are divided into two categories:

1. *Proactive tasks*: These are tasks undertaken before a failure occurs, in order to prevent the item from getting into a failed state. They embrace what is traditionally known as *PdM* and *PM*, RCM uses the terms scheduled restoration, scheduled discard, and on-condition maintenance.
2. *Default actions*: These deal with the failed state and are chosen when it is not possible to identify an effective proactive task. Default actions include failure finding, redesigning, and run to failure.

Many people still believe that the best way to optimize plant availability is to do some kind of proactive maintenance on a routine basis. Second-generation wisdom suggested that this should consist of overhauls of component replacements at fixed intervals. Classical thinking suggests that extensive records about failure will enable us to determine this life and so make plans to take preventive action shortly before the item is due to fail in the future. This model is true for certain types of simple equipment and for some complex items with dominant failure modes. In particular, wear-out characteristics are often found where equipment comes into direct contact with the product. Age-related failures are often associated with fatigue, corrosion, abrasion, and evaporation [2]. However, equipment in general is far more complex than it was 20 years ago. This has led to startling changes in the patterns of failure, as shown in Figure 1.1. The graphs show conditional probability of failure against operating age for a variety of electrical and mechanical items. Pattern A is the well-known bathtub curve. It begins with a high incidence of failure (known as infant mortality) followed by a constant or gradually increasing conditional probability of failure, then by a wear-out zone. Pattern B shows constant or slowly increasing conditional probability of failure, ending in a wear-out zone. Pattern C shows slowly increasing conditional probability of failure, but there is no identifiable wear-out age. Pattern D shows low conditional probability of failure when the item is new or just out of the shop, then a rapid increase to a constant level, while pattern E shows a constant conditional probability of failure at all ages (random failure). Pattern F starts with high infant mortality, which drops eventually to a constant or very slowly increasing conditional probability of failure. Studies done on civil aircraft showed that 4% of the items conformed to pattern A, 2% to B, 5% to C, 7% to D, 14% to E, and no fewer than 68% to pattern F. (The number of times these patterns occur in aircraft is not necessarily the same as in industry, but there is no doubt that as assets become more complex, we see more and more of patterns E and F.) These findings contradict the belief that there is always a connection between reliability and operating age.

This belief led to the idea that the more often an item is overhauled, the less likely it is to fail. Nowadays, this is seldom true. Unless there is a dominant age-related failure mode, age limits do little or nothing to improve the reliability of complex items. In fact, scheduled overhauls can actually increase overall failure rates by introducing infant mortality into otherwise stable systems. An awareness of these facts has led some organizations to abandon the idea of proactive maintenance altogether. In fact, this can be the right thing to do for failures with minor consequences. But when the failure consequences are significant, something must be done to prevent or predict the failures, or at least to reduce the consequences. This brings us back to the question of proactive tasks. As mentioned earlier, RCM divides proactive tasks into three categories:

1. Scheduled restoration tasks
2. Scheduled discard tasks
3. Scheduled on-condition tasks

11.4.1.1 Scheduled Restoration and Scheduled Discard Tasks

Scheduled restoration entails remanufacturing a component or overhauling an assembly at or before a specified age limit, regardless of its condition at the time. Similarly, scheduled discard entails discarding an item at or before a specified life limit, regardless of its condition at the time. Collectively, these two types of tasks are now generally known as PM. They used to be by far the most widely used form of proactive maintenance. However, for the reasons discussed earlier, they are much less widely used than they were 20 years ago. On-condition tasks, the continuing need to prevent certain types of failure, and the growing inability of classical techniques to do so are behind the growth of new types of failure management. The majority of these techniques rely on the fact that most failures give some warning of the fact that they are about to occur. These warnings are known as potential failures and are defined as identifiable physical conditions that indicate that a functional failure is about to occur or is in the process of occurring. New techniques are used to detect potential failures so that action can be taken to avoid the consequences that could occur if they degenerate into functional failures. They are called on-condition tasks because items are left in service on the condition that they continue to meet desired performance standards. (On-condition maintenance includes predictive maintenance, condition-based maintenance, and CM.) Used appropriately, on-condition tasks are a very good way of managing failures, but they can also be an expensive waste of time. The new program enables decisions in this area to be made with particular confidence. This book therefore introduces the new technique used to detect and monitor potential failures so as to avoid the consequences, which could occur if they degenerate into functional failures. This book adopts a new technique known as TI to detect potential failures and monitor the reliability of machineries throughout the technological and service operations, test the qualities of parts, and detect and predict any kind of failures from the initial to the final stage of a maintenance process. This technique is used to design the optimization of a maintenance route, life prediction, and life improvement and for the determination of optimum service life of machineries as well as for the optimum selection of tools, materials, parts, and processes in reliability maintenance organization. Optimizing a plant's PM/PdM program has many benefits including improving equipment reliability, improving production and craft productivity, and reducing maintenance costs. In addition, craft morale improves when the craftspeople feel that they are doing the right things and have key input into their plant's reliability improvement process.

The principal benefits of this book are to eliminate unnecessary scheduled maintenance and ensure proper cost-effective maintenance is performed on all components at all levels that have critical safety and mission failure potentials.

11.4.2 Component-Based Maintenance Approach

One alternative technique that can be used alongside with *classical RCM* is a *component-based* approach. The primary difference is that while RCM

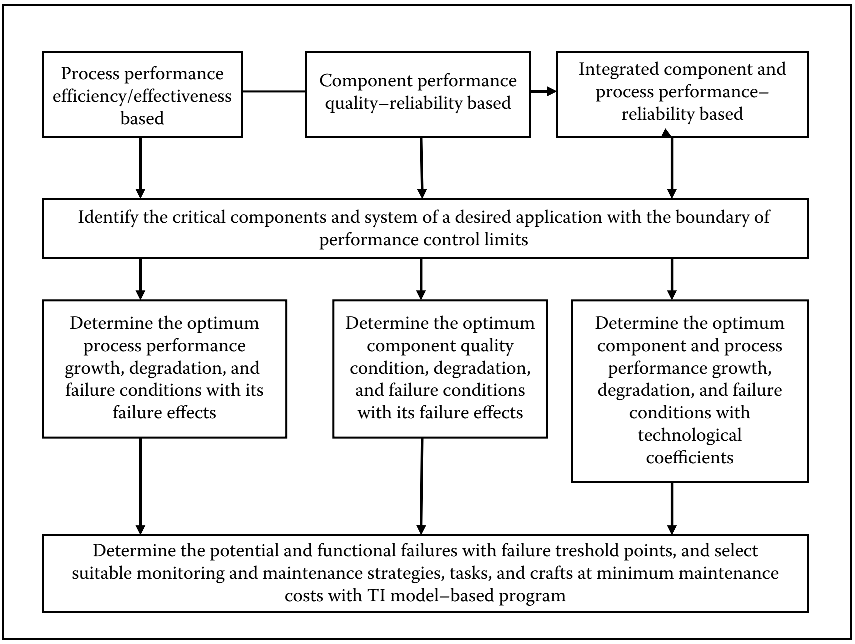

FIGURE 11.2
IRCMM of components and system with TI model–based program.

requires the rigorous documentation of the functions, functional failures, and failure effects, the component-based approach does not. It considers the hierarchical structure of the equipment system broken down to component level, where a *component* is the lowest practical level at which it is possible to implement a suitable failure management policy. The key to the credibility of this approach is the rigor of the decision diagram. The decision diagram that can be perfectly feasible for two or more methodologies to be used alongside each other in the same industrial setting will help enhance the integration and greater component/system reliability maintenance at minimum cost with TI model-based program, (Figure 11.2).

11.5 Integrating Component and Process Function Condition–Based Maintenance with the TI Model

There are two important factors to remember:

1. It is useful if the two methodologies share some common data fields. This should not be difficult to achieve since, at the very least, all monitoring and maintenance activities should be focused on component quality–reliability growth, reliability degradation, and failure mode condition trend. This trend is obvious in the operating life cycle of a component and system with the TI model-based program.
2. It would be wise to capture the results of all the analyses into one common data repository, which is structured in such a way that both approaches can be accommodated in parallel and still deliver the result of compiling the balanced monitoring and maintenance job plans. This simplifies making continuous improvements to the program.

It is worthy to note the *less critical* components or equipment systems where the benefit of conducting a full IRCMM analysis may be challenging, since taking the *component-based* approach will still provide all the rigor you need for a thorough, defendable monitoring and maintenance strategy, which could save you about a quarter of the total analysis and implementation time. Given that most analyses will involve a team of people, this translates into a significant cost benefit, as well as buying back some credibility in the eyes of management by demonstrating your flexibility to choose the right tools for the right occasion. IRCMM of manufacturing processes, parts, and equipment with the TI coefficient will provide suitable monitoring and maintenance strategies as well as the right tools for manufacturers, operators, and maintenance personnel, as seen in Table 11.1.

TABLE 11.1

IRCMM Strategies and Tools with the TI Coefficients

S. No.	Part, Process, and Equipment Conditions	Maintenance Strategies	Integrated Reliability Maintenance Monitoring Curve	TI Coefficient Trend	Monitoring and Maintenance Strategies and Tools
1.	$R_{ik} = 1.0$ $R_{k(\text{int})} = 1.0$	Proactive and predictive maintenance	Baseline is optimum and stable system with maximum useful life.	Optimum TI coefficient/curve trend with maximum achievable reliability, zero failure	Proactive, predictive, and online/cost-effective monitoring strategies with integrator/convertor devices; TI coefficient sensors and maintenance cost calculator
2.	$R_{ik} = 0$ $R_{k(\text{int})}$	Corrective maintenance and run-to-failure monitoring	Failed and high failure rate metric.	Minimum TI coefficient with highest failure rate with functional failures (FF)	Protection and high failure rate tools, no component/system required, portable and diagnostic technology
3.	$0 < R_i/R_{k(\text{int})} < 1$	Predictive and preventive maintenance	Increasing reliability growth, detection of defects, and potential failures (PF).	Positive TI coefficient with minimum or no failures and defects	Protection and online/offline reliability CM and maintenance strategy, diagnostic/portable integrator and calculator
4.	$1 < R_i/R_{k(\text{int})} < 0$	Predictive and preventive maintenance	Decreasing reliability degradation and potential failures (PF) and defects.	Negative TI curve trend	Protection and online/offline monitoring with diagnostic/portable technology for protection

Proportional hazards modeling is an effective approach to the problem of overload because it distills a large set of basic historical condition and failure data into an optimal decision recommendation founded upon the component/equipment's current state of health and reliability. This issue is possible by integrating reliability, CM, and maintenance of industrial equipment with the TI technique, which is done by applying a single metric of component and process condition reliability growth, degradations, and failures with the help of the TI model [3]:

$$Y_i = a_i Y_{i-1(\text{opt})}{}^{b}.$$

where

Y_i is the operating CM parameter of a component (machine part) (i is the number of CM parameters)
Y_1 is the surface roughness (Ra)
Y_2 is the surface hardness (HRC)
Y_3 is the surface wavelength (λ)
Y_4 is the stress concentration factor (ε)
Y_5 are other parameters
Y_{i-1} are the previous conditions of the component (machine part)
a_i is the TI coefficient for operating conditions of a particular part
$a_{n(\text{s/e})}$ is the TI coefficient for operating conditions of a particular system/equipment
n is the number of generic parts in a system or equipment
a_{y1} is the TI coefficient for operating conditions of a part surface roughness (Ra)
a_{y2} is the TI coefficient for operating conditions of a part surface hardness (HRC)
a_{y3} is the TI coefficient for operating conditions of part surface wavelength (λ)
a_{y4} is the TI coefficient for operating CM for part stress concentration factor (ε)
a_{y5} is the TI coefficient for operating conditions of part surface parameters
$a_{i\max/\text{opt}}$ is the TI coefficient for maximum/optimum operating conditions of a part
$a_{i\min}$ is the TI coefficient for minimum operating conditions of a part
b_i is the TI coefficient for manufacturing processes and equipment conditions
$b_{i\max/\text{opt}}$ is the TI coefficient for manufacturing processes and equipment conditions
$b_{i\min}$ is the TI coefficient for production processes and equipment operating condition parameters

$Y_{i-1(\mathrm{opt})}$ is determined through the already developed multivariate regression model with optimized surface quality conditions for critical parts ($Y_{i\mathrm{opt}}$) and process performance conditions ($X_{i\mathrm{opt}}$). These optimum conditions can be compared and converted to the component optimum quality factor (Q_{fopt}) and process optimum performance factor (P_{fopt}) with the optimum TI coefficients $a_{i\mathrm{opt}}$ and $b_{i\mathrm{opt}}$. This relationship for optimum component quality conditions can be expressed as

$$Y_{i\max} : Q_{\mathrm{f}\max} : a_{i\max} = 1.0 \tag{11.1}$$

$$Y_{i\min} : Q_{\mathrm{f}\min} : a_{i\min} = 0.0 \tag{11.2}$$

The relation for optimum process performance conditions can be expressed as

$$X_{i\max} : P_{\mathrm{f}\max} : b_{i\max} = 1.0 \tag{11.3}$$

$$X_{i\min} : P_{\mathrm{f}\min} : b_{i\min} = 0.0 \tag{11.4}$$

During component and process operations with time, the system performance starts to degrade until it enters a failure state (potential [PF] and functional failures [FF]). These performance degradations can be assessed with component reliability coefficients ($R_{ik(\mathrm{c})}$) and process reliability ($R_{ik(\mathrm{p})}$) as well as failure rates ($\gamma_{ik(\mathrm{f})}$).

The component quality condition can now be integrated into process performance condition with the help of the TI coefficient and model. The following models can be used to express integration:

$$Y_{i(\mathrm{int})} = aY_1 \cdot aY_2 \cdot aY_3 \cdot aY_n \tag{11.5}$$

$$X_{i(\mathrm{int})} = bX_1 \cdot aX_2 \cdot aX_3 \cdot aX_n \tag{11.6}$$

$$R_{k(\mathrm{int})} = Q_{\mathrm{f}} \cdot P_{\mathrm{f}} \tag{11.7}$$

$$F_{k(\mathrm{int})} = Q_{\mathrm{f(w)}} \cdot Q_{\mathrm{f(c)}} \cdot Q_{\mathrm{f(t)}} \cdot Q_{\mathrm{f(f)}} \tag{11.8}$$

$$F_{k(\mathrm{int})} = P_{\mathrm{f(w)}} \cdot P_{\mathrm{f(c)}} \cdot P_{\mathrm{f(t)}} \cdot P_{\mathrm{f(f)}} \tag{11.9}$$

$F_{k(\mathrm{int})}$ is the integrated failure of a component or system for wear (w), corrosion (c), temperature (t), fatigue (f), and other failure modes.

The TI coefficient calculator for component quality parameter controls is shown in Table 11.2.

TABLE 11.2

TI Coefficient Calculator for Integrating Component Quality Parameters

S. No. with Opt. Data	TI Coefficient Data, a_i	Y_1—Surface Roughness, Ra (μm)	Y_2—Surface Hardness, HRC (kg/mm^2)	Y_3—Surface Wavelength, λ (mm)	Y_4—Stress Concentration Factor, ε (%)	Y_5—Kinematic Coefficient, *K*	Y_{int}—Integrated Quality Parameters
1.	0.0	0.032	60	0.66	1.8	0.520	0.0
2.	0.1	0.410	6.3	0.10	0.46	0.066	0.1
3.	0.2	0.820	12.6	0.20	0.92	0.132	0.2
4.	0.3	1.230	18.9	0.30	1.38	0.198	0.3
5.	0.4	1.640	25.2	0.40	1.84	0.264	0.4
6.	0.5	2.050	31.5	0.50	2.30	0.330	0.5
7.	0.6	2.460	37.8	0.60	2.76	0.396	0.6
8.	0.7	2.87	44.1	0.70	3.22	0.462	0.7
9.	0.8	3.28	50.4	0.80	3.68	0.528	0.8
10.	0.9	3.69	56.7	0.90	4.14	0.594	0.9
11.	1.0	4.100	63	1.0	4.6	0.660	1.0

11.6 Integrating Reliability CM of Parts, Manufacturing Processes, and Equipment with a TI Model–Based Program

The reliability coefficient (R_{ik}) of the operating condition of a part is the desired condition parameter for a particular purpose (like wear resistance, corrosion resistance, temperature resistance, and fatigue resistance). Mathematically, it is expressed as $R_{ik} = f(a_{y1} \cdot a_{y2} \, \mathrm{L} \, a_{yn})$, where $i = 1 \ldots n$, which means that the TI coefficient for surface quality control, a, can be used to integrate reliability and CM of manufacturing processes and equipment. When the reliability coefficient, R_{ik}, is maximum or optimum, its TI coefficient, a_i, is also maximum or optimum, which is equal to 1.0, that is, $R_{ik\text{max/opt}} = a_{i\text{max/opt}} = Q_{\text{fmax/opt}} = 1.0$, and when reliability coefficient is minimum, the TI coefficient is minimum: $R_{ik\text{min}} = a_{i\text{min}} = Q_{\text{fmin}} = 0.0$. Between a control and the monitoring limits of $R_{ik(\text{min})}$ to $R_{k(\text{max})/\text{opt}}$ is the zone of part reliability growth, while between $R_{ik(\text{max})/\text{opt}}$ to $R_{ik(\text{min})}$ is the zone of part reliability degradation.

The part reliability coefficient, R_{ik}, for a particular failure mode, for example, wear resistance (w), can be expressed as $R_{ik(\text{w})}$ and subsequently for corrosion resistance part as $R_{ik(\text{c})}$, temperature resistance part as $R_{ik(\text{t})}$, fatigue resistance part as $R_{ik(\text{f})}$, and others. The TI coefficient for the different resistant parts can be represented as $a_{i(\text{w})}$, $a_{i(\text{c})}$, $a_{i(\text{t})}$, $a_{i(\text{f})}$, and other failure modes accordingly as shown in Table 11.3.

The maximum, minimum, and optimum TI coefficient a_i can be obtained experimentally, while the values between minimum and maximum can be measured with a TI coefficient sensor. The different failure mode mechanisms and trends can be constructed with TI models. With the help of the TI coefficient a, the different failure modes occurring in a particular part can be integrated using a single metric, integrated resistance to multiple failure modes (K_i), which is a function of $a_{i(\text{w})}$, $a_{i(\text{c})}$, $a_{i(\text{t})}$, $a_{i(\text{f})}$, and other failure modes. This implies, for example, that $K_i = a_{i(\text{w})} \cdot a_{i(\text{c})} \cdot a_{i(\text{t})} \cdot a_{i(\text{f})}$ in a critical part like the bearing of a rotating equipment.

TABLE 11.3

TI Coefficient of Component Failure Modes

S. No.	Failure Modes	TI Coefficient *a* for Part Surface Resistance
1.	Wear	$a_{i(\text{w})}$
2.	Corrosion	$a_{i(\text{c})}$
3.	Temperature	$a_{i(\text{t})}$
4.	Fatigue	$a_{i(\text{f})}$

For component reliability growth and reliability degradation, the TI model, $Y_i = a_i Y_{i-1}^{bi}$, can be applied.

The reliability coefficient of a system or equipment is therefore the integration of a generic group of component parts in the system or equipment: $R_{\text{sys(e)}} = (R_{in1} \cdot R_{in2} \cdot R_{ink})$, where $i = 1 \ldots k$, where i is the number of parts. When the reliability coefficient of the system or equipment is maximum/optimum or minimum, it will therefore be expressed as $R_{\text{sys(e)max/opt}} = a_{\text{sys(e)max/opt}} = 1$, while $R_{\text{sys(e)min}} = a_{\text{sys(e)min}} = 0$.

The integrated reliability of a component part/equipment (R_{in}) can be expressed as

$$R_{\text{in}} = R_{\text{f}} \cdot R_{\text{w}} \ldots R_{\text{n}}, \quad \text{for the component of parts}$$

$R_{\text{sys(e)}} = R_{\text{in(A)}} \cdot R_{\text{in(B)}} \cdot R_{\text{in(C)}}$ for systems and equipment with critical parts A, B, and C

The integrated resistance to failures (K_i) can be improved with PdM and PM with the help of integrated reliability monitoring of component and process/equipment condition parameters. Understanding the reliability growth trend during production and the reliability degradations during operations will definitely help control integrated resistance to failures as well as component and system reliability. Any deviation from the integrated reliability trend will definitely display the form of a failure mode, whether potential or functional. When it is a potential failure, efforts can still be taken to avoid it through effective maintenance strategy, and since the time of a functional failure is known with the TI model, the component and equipment can then be fully protected. The model can therefore be used to construct an integrated reliability maintenance monitoring curve/trend.

11.7 Integrated Reliability Monitoring and Maintenance Curve with the TI Model

It is important to note here that the use of an integrated reliability maintenance monitoring curve would be adjusted to the actual application, installation, mode of operation, and quality of maintenance for each production–monitoring–maintenance system, machine train, or related component. Like most of the other methods used in maintenance, the relationship between theory or ideal and the real world is practically nonexistent. The same is true for bathtub curves and time-based maintenance. The flat or low probability of failure zone duration is variable.

It is strictly dependent on the design, manufacturing, installation, application, maintenance, and especially the mode of operation. For example, when a system is applied, installed, operated, and maintained effectively with the help of the TI model–based program, the interval of low probability of degradation, damage, or failure on the IRCMM curves can be extended almost indefinitely. Moreover, the ability of using reliability CM and maintenance of processes and equipment to detect the first minor deviation from optimum operating condition permits personnel to make minor adjustments or repairs that can further extend the useful life of production systems. Before establishing monitoring intervals, you must first decide what results you want from your program. If you want to optimize performance, minimize costs, and extend the useful life of your critical production systems, you must base the interval and maintenance monitoring methods on a design, manufacturing, operation, installation system, and others. IRCMM with the TI model–based program reveals the necessary information about reliability, performance, quality, health of component parts, and conditions of processes and equipment. This vital information is applied in the component part and equipment design for an IRCMM of production processes and industrial equipment (Figures 11.3 through 11.5).

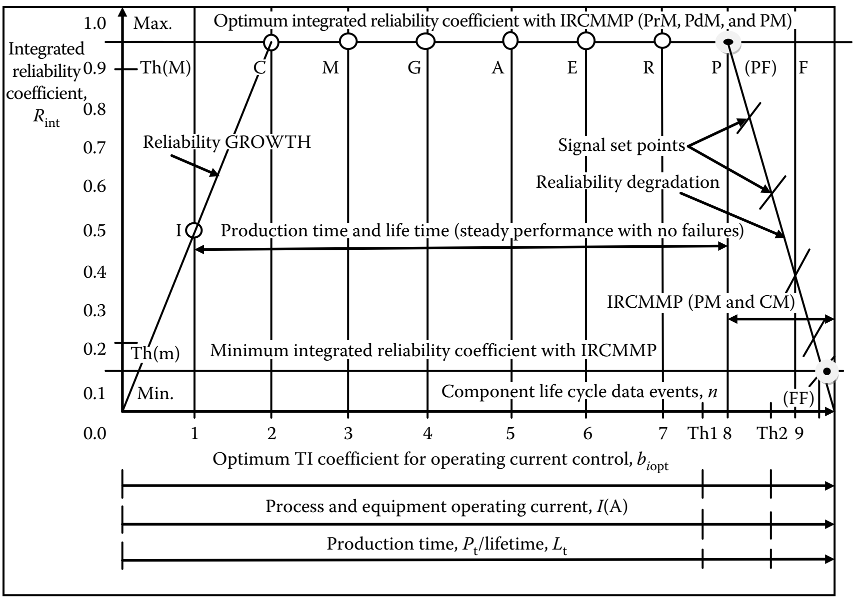

FIGURE 11.3
IRCMM curve for manufacturing processes and equipment with TI model–based program.

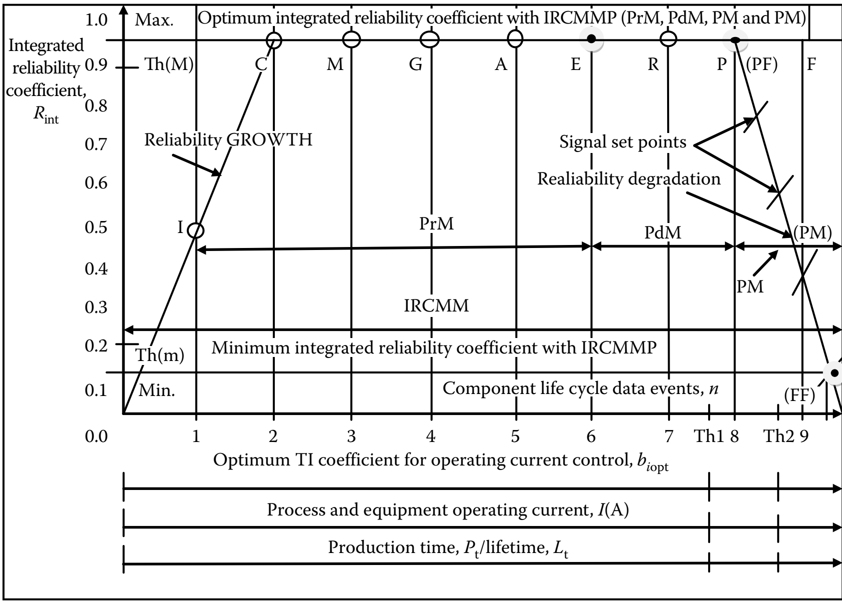

FIGURE 11.4
IRCMM curve for selecting a suitable maintenance strategy.

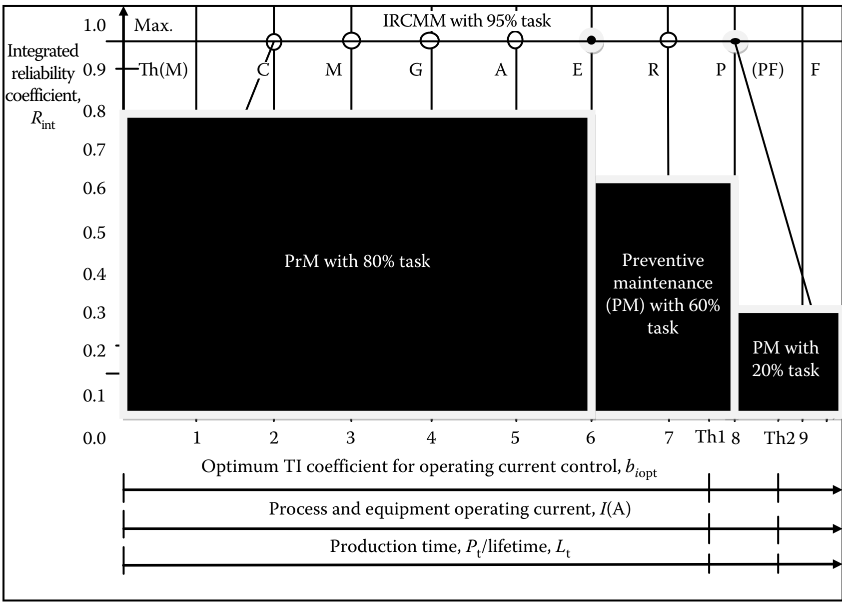

FIGURE 11.5
IRCMM curve with selected suitable maintenance strategy and tasks.

11.8 Developing Cost-Effective IRCMM Programs for Manufacturing Processes, Parts, and Industrial Equipment with the TI Model

Many companies' reliability activities have been performed primarily to satisfy internal procedures or customer requirements. Where reliability is actively considered in machine part design, it tends to be done relatively late in the development process. Some companies focus their efforts on developing reliability predictions when this effort instead could be better utilized understanding and mitigating failure modes, thereby developing improved part reliability. Organizations will go through repeated (and planned) design/build/test iterations to develop higher reliability parts, processes, and equipment. Overall, this focus is reactive in nature, and the time pressures to bring a part or equipment to market limit the reliability improvements that might be made. In an integrated reliability maintenance monitoring development environment, the orientation toward reliability has been changed and a more proactive approach utilized. Reliability engineers need to be involved in part design at an early stage of production to identify reliability issues and concerns and begin assessing reliability implications as the design concept emerges. Use of computer-aided engineering (CAE) analysis and simulation tools at an early stage in the design can improve component part and equipment reliability more inexpensively and in a shorter time than building and testing physical prototypes. Tools such as integrated reliability prediction models are more user friendly and less expensive. Design of experiments techniques can provide a structured, proactive approach to improving reliability and robustness as compared to unstructured, reactive design/build/test approaches. Further, these techniques consider the effect of component part, process, and equipment reliability parameters and also address the effect of interactions between parameters. Finally, companies should begin establishing a mechanism and curve trend to accumulate and apply *lessons learned* from the past related to reliability problems as well as other predictability and maintainability issues. These lessons learned can be very useful in avoiding making the same mistakes twice.

The application of integrated reliability maintenance monitoring curves and guidelines with the TI technique will definitely ensure a safe design process, part, and equipment at minimal cost. Such development philosophy aims to produce and maintain a processes, part, and equipment where no failures occur within its service life. Integrate reliability maintenance monitoring of processes, parts, and equipment aims to continually monitor the performance, service life, and reliability of the equipment and its service environment.

The data for continuous feedback, maintenance schedule, and component reliability maintenance performance, life and reliability characteristics are planned to exchange components that are nearing the end of their reliability life. If the component experiences excessive conditions, then immediate PM action can be taken. Many industrial equipment already have devices built into them to identify their locations and map their productivity. Large and specialized industrial equipment are relatively expensive; the additional cost of an in-build data acquisition unit is small in comparison. The value to the manufacturer, maintenance engineer, and end customer to be able to schedule PM from a reliability perspective when it is needed means reduced downtime and greater equipment availability. PM, unlike corrective maintenance, is the practice of replacing components or subsystems before they fail in order to promote continuous system operation. In many circumstances, it is financially more sensible to replace parts or components that have not failed at predetermined intervals rather than to wait for a system failure that may result in a costly disruption in operations. In general, a rational selection of a suitable maintenance strategy is done with an integrated reliability maintenance monitoring program. This program helps provide optimum integrated reliability maintenance monitoring characteristics with the TI technique. Since the TI technique is the transfer of component part condition parameters of a particular purpose like wear resistance (or corrosion, fatigue, and temperature resistance) from its initial stage to its final stage of production and operation system, it is therefore possible to determine the optimum TI coefficients, which would be used to select optimum parameters, detect failures, and predict and determine other vital characteristic parameters of parts, processes, and equipment (health, performance, and reliability) at any stage of operation in a technological process or in a maintenance route. The technique helps maximize the reliability characteristics of parts and minimize the negative traits, failure modes, and maintenance costs of parts and equipment. The coefficients are used to control the quality characteristics, performance, failures, and health of parts and control the reliability, conditions of the different operations, and maintenance strategies of the technological process. The integrated reliability maintenance–monitoring route with the TI technique can be optimized for component part, system, quality, time, and cost. The details will be discussed in the later chapters of this book.

11.9 Benefits of Integrating Reliability, CM, and Maintenance of Manufacturing Processes and Industrial Equipment with the TI Model

1. It offers a cost-effective integrated reliability monitoring and maintenance program with the TI technique that helps deliver traceable and transferable characteristics of continuous improvement and demonstrate functional control and CM of asset reliability growth/degradation in real time.

2. The program provides an integrated reliability monitoring and maintenance strategy that is coupled with an increase in the depth of PdM that enhances return on net asset (RONA).
3. It is beneficial in the provision of simple reliability devices and sensors that measure and report the manufacturing reliability growth, component quality, and component degradation/failure and life data in real time.
4. Reliability acquisition devices and sensors help identify the predominant reasons for nonstandard cycle time, which formulates action plans for correcting substandard reliability performance and improving asset reliability.
5. Integrated reliability monitoring and maintenance program with the TI technique is used to integrate reliability, maintenance, and CM under a single platform toward automation of the system.
6. The program is a computerized integrated data system that measures and records reliability performance characteristics of components and systems and correlates reliability growth and degradation trends with failure modes.
7. The TI technique is beneficial in providing the key metrics for reliability performance characteristics, which combines manufacturing process reliability with statistical process control and component CM.
8. The program is beneficial for monitoring the manufacturing process, part, and equipment reliability as well as asset health and failures in real time by automatically measuring the percentage and coefficient of input/output data of an asset function.
9. The program is also very useful in statistical manufacturing process, part, and equipment control/monitoring of all the asset functions, where the reliability performance is well contained within the specification limits between minimum and maximum for reliability growth or between maximum and minimum for reliability degradation.
10. Integrated reliability monitoring and maintenance with the TI coefficient creates a consistency of purpose for self-improvement by measuring the real-time condition reliability growth and degradation simulation of parts, manufacturing processes, and equipment.
11. Integrated reliability monitoring and maintenance program with the TI model–based simulation technique provides various charts, graphs, and curves that can be combined to create one number for each unit's aggregate functional reliability performance from design through manufacturing processes to service operations.

11.10 Conclusions

1. Most organizations in the maintenance and reliability field have a very weak PM and PdM program that contain ambiguous and needless tasks at unnecessary frequencies, because of the lack of a cost-effective monitoring and maintenance program for the maximum returns of net asset and reliability of equipment in plants.
2. In most plants, there are several sources of information where the existing problems include equipment delay information, maintenance work orders, quality data, and failure reports including MTBF statistics and PM and PdM strategies of industrial equipment.
3. IRCMM with the TI model–based program is used to select maintenance strategies, monitoring tools, and real-time data acquisition devices that provide accurate information to operators and maintenance personnel.
4. The new cost-effective program with the TI model provides a single metric for the assessment of parts, processes, and industrial equipment from concept and design through installation and operations of equipment toward maximum achievable reliability of components and systems at minimum life cycle costs.
5. The program is used to set up the desired control and reliability CM limits and develop cost-effective PM and PdM strategies for maximum achievable reliability at minimum life cycle and monitoring/maintenance costs.
6. The TI technique can therefore be used to integrate reliability, CM, and maintenance of parts, processes, and equipment and further enlarges and maximizes maintenance task interval from initial component condition to its final failure state condition at minimum monitoring and maintenance costs.
7. The integration of reliability, CM, and maintenance program with a single TI coefficient helps meet desired standards and baseline requirements of design, development, and maintenance and optimize the system.
8. The optimized reliability growth and degradation data are used to set up maximum reliability threshold points for the selection of maintenance strategies, parts, processes, equipment, and tools and set up minimum reliability threshold points that determine the functional failure state of parts and equipment.
9. The TI model is used to determine the component quality condition factor of the different failure modes that occurs in a particular component and the component reliability growth and degradation,

which is used to plot IRCMM distribution curves/mechanisms, and to assess parts, manufacturing processes, and industrial equipment.

10. The integrated reliability assessment of parts, manufacturing processes, and equipment with the help of the TI model offers the benefits of optimum selection, accurate detection of failures, and cost-effective integrated reliability test programs.
11. An integrated reliability test program with the TI model–based simulation technique provides the data to plot reliability curves/mechanisms during manufacturing processes and equipment operations and test for optimum reliability and failures of industrial equipment.
12. The role of integrating reliability, CM, and maintenance with the TI model on IRCMM helps maximize the control and monitoring limits of industrial equipment conditions, set up maximum and minimum threshold points, and test design, developments, monitoring, maintenance, and management of parts, processes, and equipment in the different industries of the future.

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12

Integrated Reliability of Equipment with a Technological Inheritance Model–Based Simulation Technique

12.1 Computer Simulation with the Technological Inheritance Model for Integrated Reliability Monitoring and Maintenance of Manufacturing Processes and Industrial Equipment System

A computer simulation with the technological inheritance (TI) model for integrated reliability monitoring and maintenance (IRCMM) of manufacturing processes and equipment is applied to provide the necessary real-time information about manufacturing processes and industrial equipment system behavior at a specific instance and over time. This involves how the reliability growth and optimum and degradation conditions of critical hard alloy–coated mating parts behave during manufacturing processes and equipment operations. This is useful for reliability testing, analysis, monitoring, and maintenance of components and systems where real-world concepts are represented by a TI model simulation. The computer simulation with the TI model and computer programs is discussed in this book. This type of simulation model for operations research is a symbolic model that is classified into two main groups, namely, the component quality model, which do not contain the element of probability like linear, non-linear, and dynamic programming, and the process performance models, which contain the element of probability like queuing theory, stochastic processes, reliability, and simulation techniques. Simulation techniques rely heavily on the element of randomness. This simulation model is used to study real-life systems that do not currently exist. In the case of this book, where one is interested in determining and controlling component reliability, process performance of a manufacturing process and equipment system for various values of its input parameters. The measurements of reliability coefficient and quality factor as well as process performance factor generation can be very useful in monitoring the part and equipment lifetime and failure characteristics as well as developing intelligent multivariate sensor devices for measuring and monitoring tool wear, workpiece quality, and machining process performance in the decision-making process.

12.2 Developing an Intelligent Multivariate Sensor for Measuring and Monitoring Tool Wear, Workpiece Quality, and Machining Process Performance

TI coefficient sensors (TICSs) will be used to measure the behavior of the tool wear, workpiece quality, and process performance conditions. Data acquisition (DAQ) hardware and software are needed to perform condition monitoring (CM) of manufacturing processes (coating deposition, machining, grinding, and others), parts (shaft, bearing, sleeve, and others), and equipment (turbine, compressor, pump, and others) and to identify problems before a failure occurs. Reliability CM and maintenance can prevent unscheduled outages, optimize component/system quality and performance, and reduce repair or maintenance costs. Developing an intelligent multivariate sensor and monitor with TI model-based simulation technique for measuring reliability growth and degradation coefficients to assess component and system conditions. This will help illustrate the flexibility and productivity provided by National Instrument (NI) DAQ hardware and TI software program for component and system monitoring. Using NI Labview, DAQ devices and a single number of TICSs can be used to develop a cost-effective system that will acquire multiple signals simultaneously. With NI DAQ devices and TI software program, it is possible to build a cost-effective, stand-alone, flexible measurement DAQ system for online tool wear, part quality, and equipment reliability monitoring. At this juncture, we therefore need to build an intelligent monitoring system for workpiece and equipment learning, which would result in the development of a smart tool that can acquire, analyze, and control the following signals with the following features:

- Rotary cutting process forces in three directions: X, Y, Z
- Process performance condition degradation ($P_{f(d)}$)
- Process machine power (P)
- Process performance factor (P_f)
- Workpiece surface quality factor (Q_f)

The following indicates the development of a DAQ system in the machining process operation of hard alloy–coated workpiece surface quality components, as shown in Figures 12.1 and 12.2:

1. *TICS setup*: A general-purpose 100–1000 kHz wide frequency sensor is used to capture the part surface quality factor (Q_f) and process performance factor (P_f) signals generated during machining operation. The sensor is connected through an SubMiniAture to Bayonet Neill Concelman (SMC–BNC) connector cable to a single-ended/differential, model 1220 C preamplifier with a selectable gain of 40/60 dB and powered by 28 V_{dc} through an external BNC-2110 noise-rejecting, part surface quality factor (Q_f) and process performance signal (P_f) to an NI Peripheral Component Interconnect (PCI)-6133 (16MS) S series multifunction DAQ board controlled by Labview software.

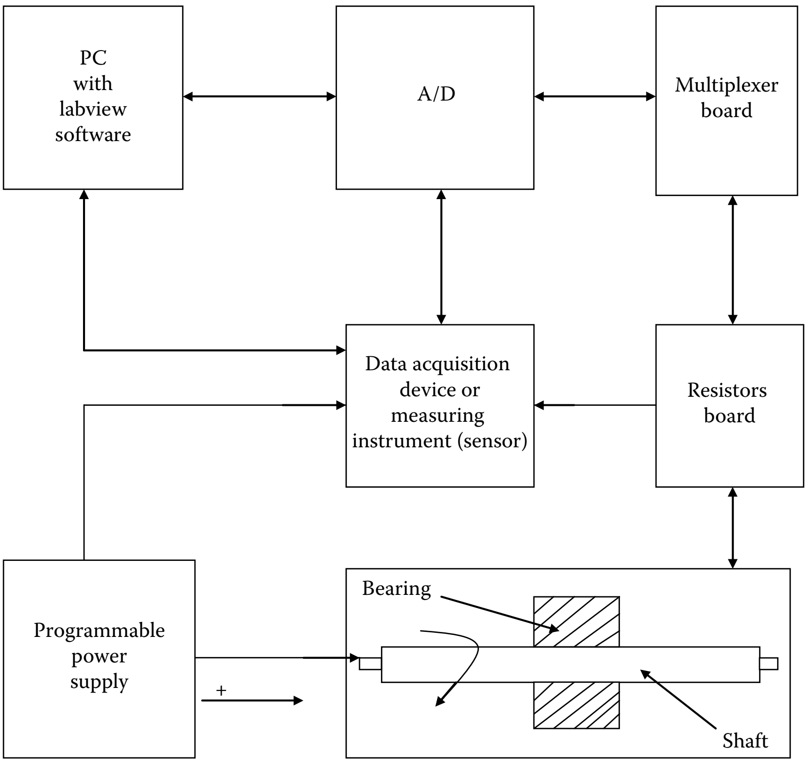

FIGURE 12.1
The layout of an automatic accelerated performance degradation testing device.

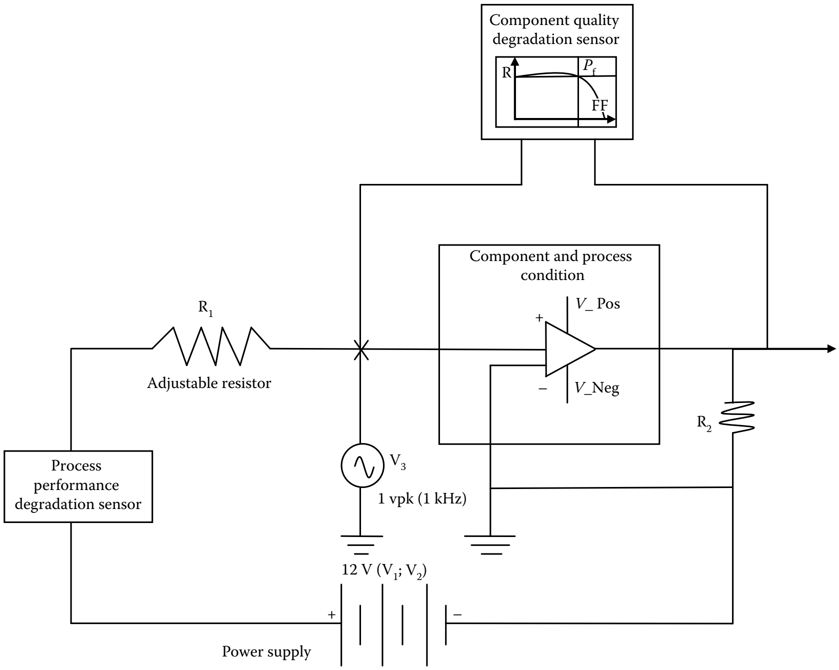

FIGURE 12.2
Adjustable resistor and degradation sensor circuit diagram for the performance degradation and failure test of components and systems.

2. *Process performance condition degradation sensor setup*: A high-sensitivity triaxial accelerometer simultaneously measured vibration in three mutually perpendicular axes (*X*, *Y*, *Z*) during a cutting operation and also due to the stress induced by operations. The internal charge amplifier converts the charge signal to a proportional high-level voltage signal at an output impedance of less than 500 Ω. The TICS is connected to a mistletoe (type 5134) coupler, which provided dc power and signal processing through adjustable gains and cutoff frequencies. The couple is connected to a BNC-2110 connector block, which fed the triaxial vibration signals to a PCI-6133 operated by Labview. Labview can conduct the setup digitally. An infinite impulse response (IIR) filter with an order of 29 and cutoff frequency of 3000 kHz for all *X*, *Y*, *Z* condition degradations in terms of vibration, stress, defects, and failure signals.
3. *Force sensor setup*: A quart three-component dynamometer to measure the three orthogonal components of a force. The force plate is connected a charge amplifier, which is connected through three BNC cables to a BNC-2110 connector block and a PCI-6133.

4. *Power spindle sensor setup*: Power sensor is used to measure the power consumed during the machining process. The true power measuring transducer MU3, in combination with the hall sensors required for current measurements, served as a complete sensor system for true power measurement of spindle motor power.
5. *Workpiece surface quality sensor setup*: The surface quality parameters of a workpiece (Y_i), comprising of surface hardness, surface roughness, surface stress, surface wavelength, and its kinematic coefficient that needs different sensors to measure each parameter will now require a single sensor as the TICS for quality conditions. With the TI model, it is now possible to build a single sensor that integrates all the parameters for a particular surface quality condition assessment of any critical hard alloy–coated part surface. The product of the TI coefficients of all the quality parameters will make up for the quality factor of the part, known as the workpiece TICS for the surface quality condition control (Q_f). This sensor is connected to the hard alloy–coated part surface to measure the highest quality value for wear-resistant applications that correlates with other components of the system. The TI coefficient for machining the process performance condition control, P_f, can be used to integrate all the performance parameters or all the sensors used to assess the process conditions (X_i), which is known as the process performance factor sensor (P_f). Optimization of the machining condition of a hard alloy–coated workpiece surface will provide the optimum surface quality parameter data, $Y_{i(opt)}$, of the surface finish of a critical part like a shaft (Table 12.1).

TABLE 12.1

Influence of Rotary Cutting and Turning Condition Factors on Hard Alloy–Coated Workpiece Surface Quality Parameters

Rotary Cutting and Turning Condition Factors	Degree of Influence on Kinematic Coefficient, K (%)	Degree of Influence on Surface Wavelength, λ (%)	Degree of Influence on Surface Roughness, R_a (%)	Degree of Influence on Surface Hardness, HRC (%)	Degree of Influence on Surface Stress, ε (%)
Operating current of plasma arc (X_1)	24.20	13.06	29.66	44.27	35.10
Distance between tool bit and plasmatron (X_2)	13.90	40.67	24.37	9.28	8.16
Feed rate (X_3)	33.85	25.37	13.77	14.76	25.99
Cutting speed (X_4)	22.52	11.94	19.03	28.96	30.34
Cutting depth (X_5)	5.53	8.96	13.17	2.73	0.41

12.2.1 Machining Process CM System of a Hard Alloy–Coated Workpiece Surface with a TI Model–Based Simulation

The machining process CM system consists of three major parts:

1. *The machine setup*: This comprises the workpiece, tool, and computer numerically controlled (CNC) machine.
2. *The indirect multivariate TICS system setup*: The system of condition degradation (triaxial vibration, stress, defect, failure system), force, power spindle, and workpiece quality surface can be integrated together with the two types of multivariate sensor features known as the process performance factor sensor and the workpiece surface quality factor sensor, which are used to assess components and systems with the help of the TI model. Each sensor has a charger and an amplifier.
3. *The DAQ system setup*: This system consists of the NI BNC connection box that can act as a gateway for all the signals generated by the two multivariate sensors after proper analog amplification. The connection box then sends all the signals to an NI DAQ board that could convert the signals from analog to digital with high sampling rate per channel. Labview can be used to properly filter and analyze all the digital signals.

High programming efficiency, performance, and cost savings are achievable using NI DAQ devices and Labview to build our cost-effective, stand-alone, flexible measurement DAQ system for online workpiece, process, and equipment monitoring with the use of multivariate workpiece quality factor sensor, multivariate process performance factor sensor, integrated reliability monitor, and life cycle/maintenance cost of manufacturing processes and equipment. Therefore, it is now possible to have events occurring at the same time, and as such, real numbers are generated and measured with the help of TICSs and monitors. The application of TI coefficients for system reliability CM and maintenance of hard alloy–coated surface machine parts, processes, and equipment in a manufacturing–equipment system technology can now be assessed with multivariate regression and TI models.

The following are multivariate regression models of a hard alloy–coated part surface condition for wear- and other competing failure-resistant applications:

$$\begin{aligned} Y_1 = {} & 5.25 + 2.26X_1 - 1.79X_2 + 1.07X_3 - 1.28X_4 - 1.08X_5 - 0.23X_1X_2 + 0.82X_1X_3 \\ & -3.07X_1X_4 - 1.38X_1X_5 + 0.29X_2X_3 - 0.56X_2X_4 + 0.25X_2X_5 + 0.26X_3X_4 \\ & +1.31X_3X_5 + 0.28X_4X_5 + 0.94X_1^2 + 0.99X_2^2 - 0.36X_3^2 + 0.99X_4^2 - 0.15X_5^2 \end{aligned} \quad (12.1)$$

$$Y_2 = 61.34 - 1.52X_1 - 0.35X_2 + 1.06X_3 + 0.73X_4 + 0.23X_5 + 0.22X_1X_2$$
$$+0.22X_1X_3 + 0.72X_1X_4 + 0.47X_1X_5 - 0.53X_2X_3 + 0.22X_2X_4 + 0.47X_2X_5$$
$$+0.97X_3X_5 - 0.77X_1^2 - 0.52X_2^2 - 1.67X_3^2 - 1.14X_4^2 - 0.64X_5^2 \quad (12.2)$$

$$Y_3 = 2.91 - 0.72X_1 - 0.24X_2 + 0.68X_3 + 0.79X_4 - 0.07X_5 - 0.27X_1X_2$$
$$+0.28X_1X_4 + 1.27X_1X_5 - 0.02X_2X_3 - 0.34X_2X_4 - 0.25X_2X_5 - 0.30X_3X_4$$
$$+0.21X_3X_5 + 0.30X_4X_5 - 1.11X_1^2 + 0.08X_2^2 + 0.09X_3^2 - 0.55X_4^2 - 0.34X_5^2$$
$$(12.3)$$

$$Y_4 = 0.71 + 0.04X_1 - 0.15X_2 - 0.07X_3 + 0.004X_4 - 0.033X_5 + 0.089X_1X_2$$
$$+0.032X_1X_3 - 0.032X_1X_4 - 0.024X_1X_5 + 0.111X_2X_3 - 0.108X_2X_4$$
$$-0.023X_2X_5 - 0.131X_3X_4 + 0.059X_3X_5 - 0.057X_4X_5 + 0.068X_1^2$$
$$+0.127X_2^2 + 0.051X_3^2 + 0.103X_4^2 + 0.043X_5^2 \quad (12.4)$$

$$Y_5 = 0.6598 - 0.0186X_1 + 0.01096X_2 + 0.0254X_3 - 0.0191X_4 + 0.00396X_5$$
$$-0.0021X_1X_2 + 0.00056X_1X_3 + 0.0068X_1X_4 - 0.0073X_1X_5 - 0.0026X_2X_3$$
$$+0.0042X_2X_4 + 0.0136X_2X_5 + 0.0263X_3X_4 - 0.0051X_3X_5 + 0.0069X_4X_5$$
$$-0.0103X_1^2 - 0.0096X_2^2 - 0.0236X_3^2 - 0.0235X_4^2 - 0.0261X_5^2 \quad (12.5)$$

$$Y_i = aY_{i-1[1]}^b$$

The optimum workpiece surface quality parameters (Y_i) are calculated from the previous multivariate regression model, and these optimum data are used as the initial data for implementing the TI model to predict reliability degradation and failures of components and systems.

The hard alloy–coated part surface quality condition factor, $Q_{f(mp)}$, is a function of Y_i:

$$Q_{f(mp)} = aY_1{}^*aY_2{}^*\ldots{}^*aY_m \quad (12.6)$$

where aY_i is the TI coefficient of the hard alloy part surface for reliability degradation and failure control, b_i is the TI coefficient of process performance, and $Q_{f(mp)}$ is the final surface quality condition factor of a machine part with mth number of surface quality condition parameters (Y_i) from a technological manufacturing process condition (X_i) with pth number of operations, including the machine part service conditions of an industrial equipment operation. $i = 1, 2, \ldots, m$ for the number of the machine part quality parameters and $i = 1, 2, \ldots, p$ for process condition parameters.

$Q_{f(m0)}$ is the initial surface quality condition factor of a machine part with mth number of surface condition parameters by the desired manufacturing process conditions for a particular failure-resistant purpose (e.g., wear resistance, corrosion resistance, fatigue resistance, temperature resistance, and its competing failure modes).

Q_{m0} is subject to changes and development (e.g., growth, defects, cracks, failures) with manufacturing processes until the condition reaches its maximum achievable desired specifications of $Q_{f(mp)opt}$, and when assembled into equipment, it becomes the initial component operating condition of the equipment, which also equals the initial component reliability of a new equipment. The component and system conditions with time undergo changes (e.g., degradations, defects, damages, failures) during the service operation of the equipment, processes, and parts. The component quality condition parameters (Y_i), failure-resistant conditions (F_i), vibration conditions (V_i), reliability conditions (R_i), etc., can be determined with the help of TI coefficients during operations.

The optimum quality conditions of the manufacturing processes for the production of a desired hard alloy–coated part surface and particular critical equipment have been determined in the previous chapter. Wear resistance and other competing failure-resistant coefficients of the hard alloy–coated part surface have also been determined with the help of TI coefficients. The optimum component and system reliability is also derived with the help of the TI model, which serves as the baseline requirements and performance control limits for testing, monitoring, maintenance, and designing of integrated reliability sensors, monitors, and other devices.

The TI model can also be used to integrate parameters, parts, manufacturing processes, and equipment. When the manufacturing processes and equipment are operating with optimum conditions, which can be expressed as $b_{iopt} = 1$, at this point, all the process condition factors (X_{iopt}) will also be operating at optimum conditions. When operating at minimum conditions, $b_i = 0$, all the process condition factors will also be operating at minimum conditions. When the optimized surface finished condition is sustained through assembly process into equipment, it therefore implies that all the component condition parameters are optimum, since the parts and the equipment are new. The manufacturing process or equipment performance factor (P_f) can be expressed as

$$P_f = bX_1{*}bX_2{*}\ldots{*}bX_p \tag{12.7}$$

Under optimum conditions, $b_i = 1.0$ and Equation 12.6a can be expressed in a linear form as: [1,10].

$$Y_i = aY_{i-1} \tag{12.8}$$

Equation 12.8 can therefore be used to assess and extrapolate the different equipment part surface qualities and also integrate parameters, processes, and equipment.

For the integration of machine/equipment part quality condition parameters (Y_i) with TI coefficients,

$$Q_f = a_1{*}a_2{*}\ldots{*}a_m \tag{12.9}$$

The integration condition is expressed as follows:

$$Y_{opt} : a_{opt} : Q_{f(opt)} : R_{k(opt)} = 1.0 \tag{12.10}$$

$$Y_{min} : a_{min} : Q_{f(min)} : R_{k(min)} = 0.0 \tag{12.11}$$

$$X_{opt} : b_{opt} : P_{f(opt)} : R_{k(opt)} = 1.0 \tag{12.12}$$

$$X_{min} : b_{min} : P_{f(min)} : R_{k(min)} = 0.0 \tag{12.13}$$

The reliability coefficient (R_k) of machine parts—A, B, C—for failure resistances can be assessed in terms of the process performance factor (P_f) and component quality factor (Q_f) of parts, while the reliability coefficients of parts (R_k) are expressed in terms of time and TI coefficient as

$$R_{ik} = \int_{t_i}^{t_{max}} Q_f \, dt \tag{12.14}$$

$$R_{ik} = \int_{a_i}^{a_{\max}} Q_f da \tag{12.15}$$

$$R_{ik} = \int_{t_i}^{t_{\max}} P_f dt \tag{12.16}$$

$$R_{ik} = \int_{b_i}^{b_{\max}} P_f db \tag{12.17}$$

When the process is running with optimal conditions within minimum and maximum time or TI coefficient interval, the reliability coefficient can be determined.

Q_f is the quality factor of parts A, B, C at any operating time, while P_f is the performance factor of the operation and R_{ik} is the reliability coefficient of the operating machine part. R_d is the reliability degradation of the machine parts, which is expressed as

$$R_d = \int_{a_{di}}^{a_{d\max}} Q_f da \tag{12.18}$$

$$R_d = \int_{b_{di}}^{b_{d\max}} P_f db \tag{12.19}$$

where

$a_{d(\max)}$ and $b_{d(\max)}$ are the maximum TI coefficients for component quality and process performance condition degradation control

a_{di} and b_{di} are the TI coefficients of the different component quality and process performance condition degradations with time, respectively

It is also possible to determine the component and equipment maintenance costs with the TI coefficient (a_i) and the component production cost, using the following equation:

$$M_c = a_i{*}P_c \tag{12.20}$$

where

M_c is the maintenance cost

P_c is the production cost or new cost of component/equipment

The machine/equipment part system reliability coefficient ($R_{k\text{sys}}$) of different parts is expressed as

$$R_{k\text{sys}} = R_{i1k} {}^* R_{i2k} {}^* \ldots {}^* R_{imk} \tag{12.21}$$

The maximum and minimum values of the part system ($R_{k\text{sys max}}$ and $R_{k\text{sys min}}$) can be determined from Equation 12.21, while the threshold points ($R_{k\text{sys max(th)}}$ and $R_{k\text{sys min(th)}}$) are set for IRCMM of parts, processes, and equipment. The component quality and process performance degradation are estimated with TI coefficients as well as component/system reliability with time and TI coefficients during manufacturing processes and equipment, as shown in Tables 12.2 and 12.3 and Figure 12.3.

The initial to final operations of the manufacturing processes for the production of a critical part hard coated surface in an equipment are as follows:

1. Me—metallurgical process
2. De—coating deposition process
3. Ma—machining process
4. Gr—grinding process
5. A—assembly
6. Ei—equipment initial operation
7. PF—potential failure
8. FF—functional failure

The TI model–based simulation program offers the following benefits:

- Reliability testing for system maximum achievable reliability and optimum reliability used for the selection of parameters, parts, processes, equipment, and maintenance practices
- Reliability testing for failures
- Reliability design of sensors, meters, and monitors
- Random number generation
- Reliability maintenance of components
- Selection monitoring
- Predictive monitoring and maintenance
- Preventive monitoring and maintenance
- Proactive monitoring and maintenance
- Component and maintenance costs
- Optimization of reliability, CM, and maintenance
- Process, part, and equipment assessment
- Root cause analysis

TABLE 12.2

Component Quality and Process Performance Degradation Estimation

Operating Component and Process Current, I (A)	**Component/ Performance Factor Degradation, $Q_f(d_1)/P_f(d_1)$**	**Component/ Performance Factor Degradation, $Q_f(d_2)/P_f(d_2)$**	**Component/ Performance Factor Degradation, $Q_f(d_3)/P_f(d_3)$**	**Component/ Performance Factor Degradation, $Q_f(d_4)/P_f(d_4)$**	**Component/ Performance Factor Degradation, $Q_f(d_5)/P_f(d_5)$**	**Component/ Performance Factor Degradation, $Q_f(d_6)/P_f(d_6)$**
	0.0	0.2	0.4	0.6	0.8	1.0
120	0.0	24.0	48.0	72.0	96.0	120.0
100	0.0	20.0	40.0	60.0	80.0	100.0
90	**0.0**	**18.0**	**36.0**	**54.0**	**72.0**	**90.0**
80	0.0	16.0	32.0	48.0	64.0	80.0
20	0.0	4.0	8.0	12.0	16.0	20.0

Note: The values that are in bold are optimum values.

TABLE 12.3
Component and System Reliability with Time and TI Coefficients

S. No.	Component and System Degradation Failures	TI for component/System Quality/Performance Degradation Control, a_i/Q_f or b_i/P_f	Process Performance Degradation (X_i) or Process Operating Current, I (A)	Lifetime (years)
1.	Low	1.0	20.0	0.0
2.	Low	0.8	18.0	2.0
3.	Low	0.6	36.0	4.0
4.	**Medium, PF**	**0.4**	**54.0**	**6.0**
5.	High	0.2	72.0	8.0
6.	**FF**	**0.0**	**90.0**	**10.0**

The developed multivariate quality regression model is used to determine and predict the optimum hard alloy–coated surface quality condition factor (Q_{mp}) of machine parts for maximum reliability requirements with the parameters (Y_i), where Y_1 in terms of the hard-coated surface is surface roughness, Y_2 is surface hardness, Y_3 is surface stress, Y_4 is surface wavelength, and Y_5 is the dynamic coefficient, and to simulate other untested quality parameters, parts, processes, and equipment.

The model-based simulation program has been used to determine wear and other competing failure modes like corrosion, temperature, and fatigue

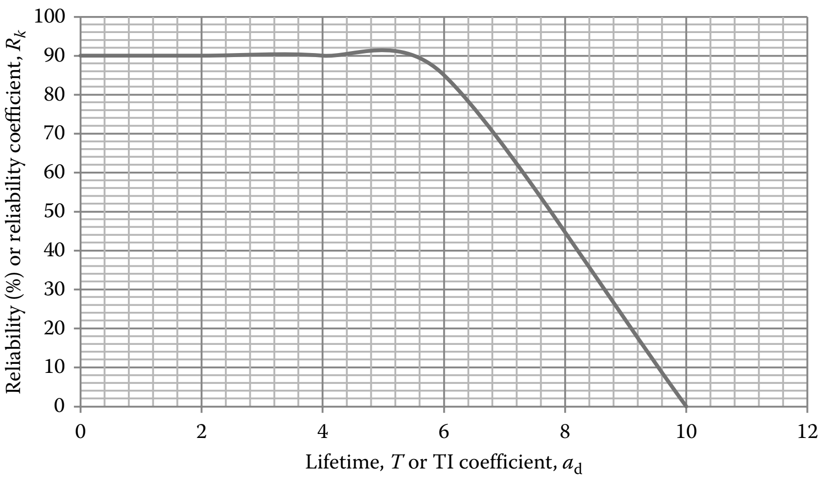

FIGURE 12.3
Component and system reliability with TI coefficient.

and can be used to simulate the behavior of components and systems during operation. The model-based simulation program can therefore be used to assess IRCMM of a particular group of hard-coated critical machine parts (e.g., bearings, shafts) and critical equipment (e.g., pumps, generators, machine tools) and can also be applied to simulate real-time operating conditions of parts, manufacturing processes, and equipment. This type of model-based program will help automate IRCMM of manufacturing processes, parts, and industrial equipment.

12.2.2 Object-Oriented Simulation Model in an Automatic Control Software Development Framework with the TI Technique

Computers are used to control industrial equipment, information devices, manufacturing processes, aircraft, office equipment, and others. The development of such mechatronic products requires the collaboration of mechanical designers, electronic system engineers, aerodynamic engineers, and software engineers. Whereas software development for mechatronic systems in industry benefits from advances in tools and supporting systems, in general, they still suffer from problems like a lack of integration across design domains, a lack of physical modeling, the need to handle irregular situation, and more importantly, a lack of automation. These problems can be solved with the application of a TI model and simulation program. The program envisions the use of a functional model as input to the control software generation process, specifying the required functionality of the components and systems being developed. The *function modeling* tool will create a formal representation of these functions, which will be used to generate the necessary behavior based on qualitative reasoning methods. At the same time, the function model will enable the mechatronic feature modeling tool to generate the product definition by using mechatronic features or function performers. The behavior description and the mechatronic feature model serve as an input for mechanical embodiment and electrical system design. At the end of the design process, the generated code can be verified at software and hardware level, using either the generated control models or the prototype of design, and analysis tools in an automated framework will support a more concurrent software design process in contrast to the sequential process often seen in practice, by automating the sharing of information across the design domains.

The need for a control model generator in the software development framework arises from the wish to be able to verify the software at earlier stages of development, before the real hardware has been built. A high-fidelity control model would enable the verification of the control software by using emulation or simulation methods, which, on the one hand, partially eradicate the need for more expensive equipment-based verification and, on the other hand, enable software verification at earlier stages of the development. A second point of interest is the integration of irregular situations and operating modes into the controller design development. Software development has to deal with irregular modes like initialization, monitoring, shutdown, maintenance, and calibration under a single integrated reliability platform.

The integrated reliability monitoring and maintenance automation of an industrial plant with the application of a TI software program can be considered as a synergic blend of man, machine, and methods in working activities whose execution leads to the production of desired outputs, starting with the available optimum inputs of parts and equipment reliability condition data, set points, and threshold values, as shown in Figure 12.4 that is derived from Equations 12.1 through 12.12:

R_{mp} is the reliability coefficient of parts or equipment.
$R_{mp(opt)}$ is the optimum reliability coefficient of parts from the preceding (e.g., finishing) process to the equipment.
a is the TI coefficient for part quality, failure, and reliability controls.
b is the TI coefficient for process condition controls.

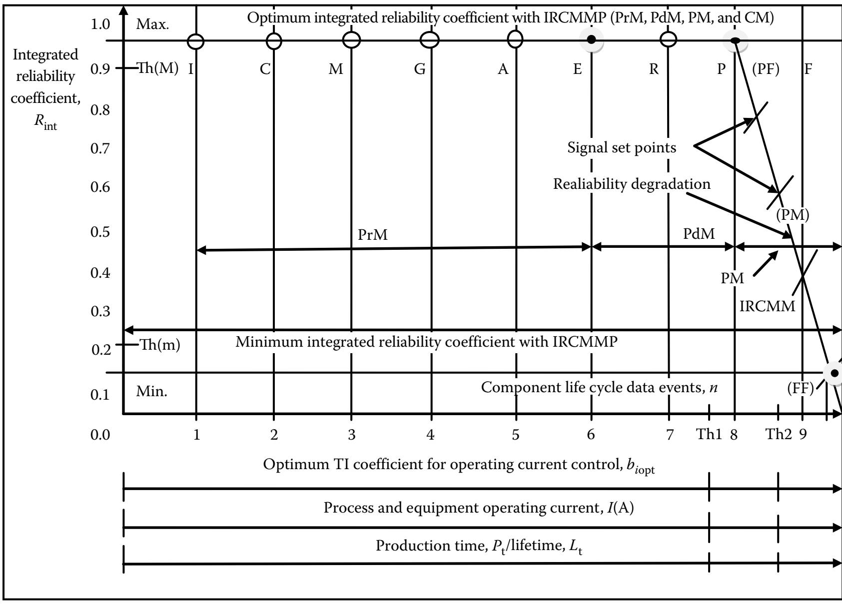

FIGURE 12.4
IRCMM curve with the TI model–based program.

The measurements of integrated reliability monitoring and maintenance characteristics for part, process, and equipment system are as follows:

- *Equipment operating control characteristics* with TI coefficients
  - U_{cl}—upper control limit = a_{max}
  - C_{ol}—optimum control limit = a_{opt}
  - C_l—center control limit = a_{mean}
  - L_{cl}—lower control limit = a_{min}
- *Parts and equipment reliability coefficients*
  - Maximum reliability coefficient = $R_{k\max}$
  - Optimum reliability coefficient = $R_{k\mathrm{opt}}$
  - Minimum reliability coefficient = $R_{k\min}$
  - Maximum reliability coefficient threshold = $R_{k\max(\mathrm{th})}$
  - Maximum reliability coefficient threshold = $R_{k\min(\mathrm{th})}$
- *TI coefficients*
  - a—TI coefficient for component quality (Y_i), failure (F_i), and reliability coefficient (R_{ik}) controls
  - b—TI coefficient of process and equipment condition (X_i) control
- *Machine part quality condition parameters* (Y_i)
  - Surface hardness (Y_1)
  - Surface roughness (Y_2)
  - Surface wavelength (Y_3)
  - Stress concentration factor (Y_4)
  - Kinematic/dynamic coefficient (Y_5)
  - Others (Y_6)
- *Industrial process, equipment, and instrument conditions*
- *Equipment conditions* (X_i)
  - Pressure
  - Time
  - Temperature
  - Speed
  - Power
  - Flow

    - Frequency
    - Pulse period
    - Others
- *Instruments and system network monitoring components*
    - DAQ hardware
    - Computers
    - Component reliability sensors
    - System reliability meters
    - Reliability, health, and maintenance cost monitors
    - Integrated reliability transmitters
    - Integrated reliability coefficient generators
    - Others
- *Critical machine parts with hard coating surfaces*
    - Shafts
    - Bearings
    - Gears
    - Seals
    - Others
- *Equipment*
    - Generators
    - Pumps
    - Motors
    - Compressors
    - Turbines
    - Others
- *Industrial common failure modes*
    - Wear
    - Corrosion
    - High temperature
    - Fatigue
    - Others
- *Industries of the future*
    - Agriculture
    - Power

- Chemical
- Oil
- Mining
- Others

- *Part, process, and equipment CM and maintenance requirements without the application of the TI technique*
  - Reliability = 90%
  - Confidence level = 95%
  - Lifetime = 5–10 years
  - MTBF = 18 months
- *Part, process, and equipment CM and maintenance requirements with the application of the TI technique*
  - Reliability = 95%
  - Quality factor = 95%
  - Confidence level = 95%
  - MTBF(R_t) = $R_{(t)}$ > 18 months
  - Lifetime (LT) = 5–10 years

Reliability test is carried out on the required part, process, and equipment to determine their optimum reliability under optimum operating conditions and to detect failures. The TICS is used to measure the TI coefficients for determining the component quality factor, process performance factor, reliability growth, and degradation and failures of components and systems during manufacturing and service operations. The reliability growth tends toward maximum reliability, life, and warranty period of time, while reliability degradation tends toward defects, potential failure, and functional failure at minimum warranty and maintenance costs. The maximum and minimum reliability thresholds are set for reliability desired tests and selections. The maximum reliability threshold point is used for the maximum and optimum selections of components and systems, while the minimum reliability threshold point is used to detect failure.

With the help of the integrated reliability monitor, it is possible for operators to see all that is happening to components and systems of a plant and gather real-time data for predictive, preventive, corrective, and proactive maintenance. The use of a model-based simulation program enhances the automation of IRCMM of parts, processes, and industrial equipment.

12.3 TI Model–Based Simulation Program for IRCMM of Parts and Equipment in the Industries of the Future

The model-based simulation program is used to monitor industrial parts and equipment from the initial stage of the manufacturing process to the final stage of operation, which includes industrial equipment. Machine part quality is tightly related to the quality during manufacturing processes used to produce them. The quality of parts produced by the same finishing manufacturing processes can result in different reliabilities of the same equipment. Also, within the software engineering community, a manner for *improving quality* is to improve software processes in order to improve software products. This implies the need for monitoring process execution, highlight process anomalies, and quickly proactively or with suitable planned time act on them.

Unfortunately, software processes are mainly human intensive, and dominated by cognitive activities, this makes each process execution a creative and unique activity. The predominant human factor implies differences in process performances and thus multiple outputs. The phenomenon known as *process diversity* [2,3,5] determines difficulty in predicting, monitoring, and improving a software process. This makes monitoring activities difficult to automate. For successful process and equipment monitoring, among others, there are mainly three software problems to address that make the monitoring activity difficult to automate.

12.3.1 Software Process Control Limits

It is difficult to characterize the behavior of the monitoring process through baselines useful for evaluating its performances. Given the heterogeneity of the operative contexts, the different maturity levels of the processes in use, and the differences of previous knowledge on the monitoring process, it is difficult to define an upper and lower limit for process performance variability. With the help of TI coefficients a and b, the software process and part condition limits can be determined.

12.3.2 Software Process Anomalies

There is difficulty in attributing meaning to *process anomalies* and in finding conceptual and operative tools for identifying them. In this book, both process anomalies and part condition variations can be determined with the help of TI coefficients and quality and performance threshold data. Once the threshold data points are reached, the set alarms go off to give warnings and relevant information to operators that relate this information to different personnel and departments for appropriate maintenance actions.

12.3.3 Software Sensibility

There is a need to adapt the sensibility of monitoring and maintenance activities to the continuous changing process performances and component qualities.

This book helps generalize and put together the experiences collected by the authors in these studies [2,5,6] to contribute to the discussion on these issues and to present solutions with the help of the TI model.

In order to do this, this book presents the structures, electrical circuits, and software programs in Figure 12.2.

Component reliability with the TI model is used to overcome the problems presented earlier within the software process performance control and component quality control limits.

12.3.3.1 Software Process and Component Control Limits

The existing solution to this problem is based on the statistical process control (SPC) [60], which has shown to be effective in manufacturing and recently also used in software contexts. It was developed by Shewhart in the 1920s and then used in many other contexts. It uses several *control charts* together with their indicators to establish operational limits for acceptable process variation. By using few data points, it is able to dynamically determine an upper and lower control limit of acceptable process performance variability. Such peculiarity makes SPC a suitable instrument to face problem 1. Process performance variations are mainly due to common cause variations (the result of normal interactions of people, machines, environment, techniques used, and so on) and assignable cause variations (arise from events that are not part of the process and make it unstable). A process can be described by measurable characteristics that vary in time due to common or assignable cause variations. If the variation in process performances is only due to common causes, the process is said to be stable and its behavior is predictable within a certain error range; otherwise an assignable cause (external to the process) is assumed to be present and the process is considered unstable. A control chart usually adopts an indicator of the process performance's central tendency (CL) and upper and lower control limits (UCLs and LCLs). Process performances are tracked overtime on a control chart, and if one or more of the values fall outside these limits, or exhibit a *nonrandom* behavior, an assignable cause is assumed to be present. Many control charts exist, but in software processes, due to the scarceness of data and since measurements often occur only as individual values, the most used ones are the XmR, that is, individual and moving range charts [7,8]. With the TI technique, optimum control limits and threshold points are set with optimum reliability values and maintained and monitored with set threshold points using indicators, alerts, and alarms to control the critical parts of industrial processes and equipment.

12.3.3.2 Process Anomalies

In the monitoring activity, a fundamental task is to point out process anomalies in order to quickly react to them. But what are process anomalies and how can we find them? The anomalies are in general some kind of noise in the process performances, the results of an unknown cause in action that implies unattended variation (for better or worse) and thus lower process predictability. In the software context, relevant examples in this sense are the introduction of a new case tool that speeds up the development; the use of a new testing or inspection technique that reduces the postrelease defects; the degradation of system maintainability due to the lack of documentation; the presence of an unknown bug in the hardware platform or in the operative system that leads to a crash of the application and unattended disservices; the involvement of low-profile programmers in the project team that determine lower productivity; an unexpected absence of a key person that implies project failure; and so on. Anomalies are consequences of the presence of causes in the process that determines unattended performance variations (for better or worse). The aim of the monitoring activity is to point out the anomalies and stimulate the search of the possible causes. The aim of software process improvement is to find the causes, eliminate them if detrimental, or otherwise, make them part of the process. There are many possible causes of variation such as their effect on process performances and, consequently, the observable anomalies. A standard mechanism is needed to be able to characterize an anomaly and, at the same time, to point it out. With the help of the TI technique, it is possible to identify potential problems and failures right from the initial stage of production and operation to the final stage. The failures are detected early enough and appropriate actions are taken to avoid catastrophic damages.

12.3.3.3 Software Sensibility

The concept of process diversity means that a process varies between different organizations, different projects, and also during the execution of a project [4]. This implies estimation model diversity [9]. The need for recalibrating a model is well known in the software estimation community. Process changes impact on the parameters and drivers predicted by the estimation models in use, and as a consequence, they determine estimation inaccuracy. Thus, even when the predictors and corrective parameters are adequately estimated at the beginning of the project, their values tend to change during execution as the context changes. Typical in this sense is the so-called maturity effect, that is, an improvement of human performances due to the experience collected during process execution: a better knowledge on the techniques in use, a better confidence with the development tool, etc.

Hence, even though a good initial estimation of the process performance is done, it will not prevent estimation errors during project execution.

A further confirmation in this sense comes from COCOMO II [9], which implies the use of different cost drivers for each development process stage (application composition, early design, post architecture). All these considerations imply the difficulty in correctly characterizing process behavior from the start to the end in terms of the upper and lower control limit. The process performance limits must be recalibrated according to relevant process performance changes pointed out by process anomalies. The sensibility of the monitoring activity has to be tuned continuously. The risk of not tuning sensibility is to miss anomalies as the result of using larger limits than necessary or having several false alarms. The existing monitoring activity based on SPC is carried out with control limits as baselines within which the process can vary. The latter is monitored according to specific characteristics (of the measurement object) selected by the SPC manager.

Given the characteristics of the monitoring activity, the inappropriateness of the SPC monitoring model, following to process changes, can be attributed to the following factors:

- *Control limits are no longer appropriate*: The central line is either too tight, too wide, or no longer representative of the average process performances.
- *Measurement object is no longer representative*: The measures used may no longer express the process and equipment variability.

In both cases, in order for SPC definitions to be updated, it is necessary to

1. Identify the part, process, and equipment events with the root cause of failure and failure modes that require such updates.
2. Identify the root cause and failure modes of parts and equipment.
3. Predict and prevent failure modes and consequences of parts and equipment.
4. Protect industrial products and equipment from catastrophic damages.
5. Determine the reliability of parts and equipment from the initial through production operations to final operations or events of plant equipment.
6. Select optimum conditions of parts, processes, instruments, and equipment.
7. Quickly intercept the situations in order to move on to the updates.

The new IRCMM model with the TI software program provides solution to all the previous updates through the correlation of the relationships between what has happened, what is happening in the parts and equipment, and what are the best actions to undertake.

12.4 TI Model–Based Software Program

In this section, a correlation–regression coefficient based on component and process condition parameters will serve as the metrics for integrated reliability monitoring and maintenance of industrial parts and equipment. According to this approach, each problem will be presented and discussed with the application of the TI model. Software process monitoring is a crucial activity in the context of software process improvement initiatives. This type of monitoring involves the measuring of quantifiable process, equipment, and part reliability characteristics over time and process conditions, pointing out anomalies such as reduction in the reliability, performance, and health values of components from the initial to the final stage of a technological process. The parts and equipment have been characterized before being monitored, by using reasonable experimental threshold values, one for the upper and one for the lower performance and reliability limits. When the observed performance and reliability fall outside these limits, someone can argue that there is something wrong in the process or equipment.

Moreover, part and equipment characterization require experimental and past knowledge. The part and equipment maturity, the project dimension, the number of people involved in a project, and their experience together with thousands of other factors can affect performance and reliability [6,7]. Thus, it is challenging to define an upper and lower control limit that is able to characterize part and equipment behavior. The best way is often to refer to expert judgment and use expert experience for estimating performances. Unfortunately, expert experience not necessarily includes the knowledge about the process in use. This implies that process and equipment monitoring seldom occurs. In this book, the multivariate statistical process and equipment monitoring with the help of a TI model–based software program has been applied as shown in Figures 10.1 and 10.2.

Multivariate statistical process and CM with the TI model provides a quick and effective solution that takes into account the conditions of processes and equipment as well as the reliability, performance, and health of part parameters monitoring sensibility, while the monitoring technique identifies the process anomalies through signals, distinguishes anomalies and identifies the most appropriate actions in order to update the definitions, and redefines the reliability maintenance monitoring model in use, being careful to preserve its sensibility.

The relationship between what happened, what happens within the process, and the reliability characteristics (Rm.p.k) of machine part and equipment can be assessed with the TI model. The reliability growth, degradation, and optimization as well as integrated reliability (R_{in}) can be determined with TI coefficients as well as integrated reliability (R_{in}), which is the product of reliability growth (R_g), degradation (R_d), and optimization (R_{opt}). Integrated reliability can represented as

$$R_{in} = R_g{}^*R_d{}^*R_{opt} \tag{12.14}$$

The mathematical model, the optimum values of the finishing process operation of a machine part or component (rotary shaft or bearing for rotating equipment), and the input data for monitoring process and equipment are known (Figure 10.3). The analysis for integrated reliability monitoring and maintenance curve of parts and equipment is highlighted in Figure 12.4. The optimum reliabilities of components A, B, C are used to determine the optimum control limits and threshold points of equipment and instruments for an IRCMM program. The component consists of parts, processes, equipment, and instruments for the integrated reliability monitoring and maintenance program. These components and its variations can be identified in the system through signals, which help distinguish among component anomalies and identify the most appropriate actions in order to update the definitions and redefine the integrated reliability monitoring and maintenance program in use while being careful to preserve its sensibility.

The simulation program for IRCMM of industrial parts and equipment with the TI model consists of the following:

1. Optimum selection of materials, parts, processes, equipment, instruments, and maintenance strategies/tools
2. Reliability testing and design of components and systems
3. Reliability CM of defects and failures
4. Maintenance of manufacturing processes and industrial equipment
5. Reliability multivariable network system
6. Determination of the optimum control limits for IRCMM of manufacturing processes and equipment
7. Management of IRCMM of manufacturing processes and industrial equipment with the TI model–based program

12.5 Determination of the Control Limits and Threshold Points with the TI Technique for IRCMM of Parts, Processes, and Equipment

The integrated reliability parameter control limits for DAQ devices and instruments as well as how rapidly the parameters vary between the limit depend on several factors including the component/system conditions, the environment, and the habits of the operators. The expected limit might be readily approximated, but there is an infinite number of possible parameters that can be measured at a given time. These unlimited possibilities are mapped to a finite set of values by DAQ hardware. The integrated reliability parameters being measured in a real-world DAQ experiment has an expected system control limit. The system control limits vary continuously between its low and high limits. The range of frequencies present in the signal being measured gives the control limit. The rate of change of this signal is related to the rate of change of these frequencies. Pulse amplitude is measured with respect to a specified reference like maximum achievable reliability with maximum voltage derived from the initial model parameters. The maximum time of failure is derived with maximum speed or acceleration of the component/system. Pulse amplitude also applies to the amplitude of frequency- and phase-modulated waveform envelope. The amplitude should therefore be modified and modulated by trending the data from minimum to maximum and from maximum to minimum reliability growth and degradation and frequency with the help of TI coefficients. The high frequency of an event like high reliability degradation coefficient, defects, cracks, and others of machine parts and high off/on cycles per time of a rotating part will lead to a greater likelihood of failure than with low frequency and low off/on cycles of a component and system. The number of times the event may occur within a particular time is the frequency of that event, and this can be counted or measured with a TICS. Frequency is defined as the number of cycles per unit time. Calculating the frequency of part reliability degradation, reliability growth, defects, and cracks is accomplished by counting the number of times it occurs within a specific time interval than dividing the count by the length of time interval. The inherent deficiency of a measuring mechanism introduces a great amount of noise to the signal. Therefore, the signature of a defective part is spread across a wide frequency band and can easily become masked by noise and low-frequency effects. One of the challenges is to enhance the weak signature at the early stage of defect development. A signal-enhancing technique is needed to provide more evident information for component/system performance assessment and prognostics. The TI technique is one of the progressive methods for signal processing. TICSs for a and b are used to measure the periodicity and positions of a signal. Optimizing the periodicity and position of a signal with the TI coefficient makes the weak periodic/position impulse signature successfully revealed and enhanced and helps detect the degradation or failure signature at an early stage, which gives more time for maintenance reaction and business decision-making and also provides proofs for prognostics. It helps to reduce noisy raw signal and enhance degradation detection and is a means of enhancing good baseline/control limits for reliability performance growth and degradation assessments for component/system and design modeling. The mathematical model of the manufacturing surface finish of hard-coated parts in rotating equipment with the TI technique provides the optimum baselines for the control limits of DAQ devices and instruments. It also provides the initial reliability monitoring, maintenance, design, and manufacturing process requirements for parts and equipment. The component and system integrated reliability trend from an initial reliability by metallurgical and deposition processes continues to increase or grow positively until it gets to maximum achievable values produced by a cost-effective machining process with the help of the TI technique. This integrated reliability trend describes the positive inheritance characteristics of hard-coated parts for wear, corrosion, and high-temperature resistance used to determine the optimum conditions of manufacturing processes, parts, equipment, and instruments. The optimum integrated reliability and quality condition requirements are used to set up control limits and threshold points for design and manufacturing of processes, equipment, and instruments, as shown in the Figure 12.3. With the integrated reliability graph, the optimum control levels of the conditions of the equipment, instruments, and parts are determined. This conditions also satisfies the following expression:

$$X_{i(\mathrm{opt})} : b_{\mathrm{p(opt)}} : b_{\mathrm{t(opt)}} : b_{\mathrm{e(opt)}} = 1.0 \tag{12.22}$$

where

- $X_{i\mathrm{opt}}$ is the optimum manufacturing process factor control level
- $b_{\mathrm{p(opt)}}$ is the TI coefficient for optimum conditions of processes
- $b_{\mathrm{t(opt)}}$ is the TI coefficient for optimum conditions of instruments
- $b_{\mathrm{e(opt)}}$ is the TI coefficient for optimum conditions of equipment
- Center level (CL) = 0.0
- Upper level (UCLy) = 1.0
- Optimum quality level (OPL) = 0.95
- Optimum performance level (OPL) = upper level (UCLx) = 1.0
- a is the TI coefficient for quality control
- b is the TI coefficient for process and equipment condition control
- b_p is the TI coefficient for different machine part performance condition control (b_p, $p = 1, 2, 3, \ldots, m$)
- b_t is the TI coefficient for instrument performance condition control (b_t, $t = 1, 2, 3, \ldots, l$)
- b_e is the TI coefficient for the different types of industrial process and equipment performance condition control (b_e, where $e = 1, 2, 3, \ldots, k$ number of equipment)

This model is therefore used to develop software programs for IRCMM of manufacturing processes and industrial equipment.

12.6 IRCMM of Manufacturing Processes and Equipment Distribution Curve with the TI Model

Optimum conditions of manufacturing processes for hard alloy surface machine part and critical industrial equipment have been determined with TI coefficients. The optimum condition data are scaled within a control level set between the limits of "0 and 1." The upper control level is set at +1, while the lower control level is at 0. This figure shows the relationship between the part conditions of initial to final operations. This figure highlights what is happening within industrial parts and equipment as well as what has happened and what would happen. It highlights optimum selection of manufacturing processes, acquisition of data, data measurements, monitoring parameters, methods of maintenance, and the integration of reliability, maintainability, and CM. The integrated reliability monitoring and maintenance of processes and critical equipment distribution curve can be expressed graphically in Figure 12.4 for industrial system automation, which can be managed through a TI software program and network system:

Optimum input reliability data—Ri,n,kopt
Current reliability data—Ri,n,k
Process and equipment reliability degradation, R_d
Process and equipment reliability growth, R_g
Performance factor of process and equipment, P_f
Quality factor of components, Q_f

The IRCMM curve with the TI model is shown in Figure 12.4. The optimum reliability coefficient and the minimum reliability coefficient values are derived from the mathematical models for the finished quality parameters of components A, B, C that are used to set the control limits for the reliability monitoring and maintenance of industrial equipment. These values are determined with the help of TI coefficients *a* and *b* for reliability and operating condition controls of equipment. The graphical plotting of these data for integrated reliability monitoring and maintenance of equipment is done to highlight the relationship between reliability, quality, and failure of parts for the different components (A, B, C) with the different conditions of operating equipment and instruments. The optimum TI coefficient values are used to construct equipment reliability baselines. The equipment baselines and variations are shown in Figure 12.4, which can be monitored with the help of TI coefficients at any time throughout the equipment, part, and instrument life. The relationship between *what happens* within the equipment with the reliability monitoring and maintenance actions and updates can be assessed with the TI model–based program. The relationship provides a predictive, preventive, and proactive chart and tool for monitoring and maintenance of equipment. This tool is used to detect, diagnose, predict, select, and integrate optimum reliability monitoring and maintenance of part, equipment, and instrument systems. The introduction of the integrated reliability monitoring and maintenance automation program with the TI technique will provide long-lasting effective solutions to the challenges of maintenance and monitoring processes. There are many aspects related to software process measurement such as the difficulty of collecting metrics, their reliability data, and their selection as measurement objects that leave a lot of space for subjective management decisions that can influence the success or failure of monitoring activities. In this sense, the author is introducing the most appropriate metrics for the automated monitoring of industrial equipment, optimum reliability, and the selection of measurement objects. The TI technique is a digital data-based methodology that integrates all the machine parts and equipment with instrument operations using the optimum reliability, quality, and performance values of the system. Today, digital computers and other microprocessor-based devices have replaced analog recording and display technologies in all but the simplest DAQ applications. While computers have had an undeniably positive impact on the practice of DAQ, they speak only a binary language of ones and zeroes. Manufacturing processes and natural phenomena, however, are still by their very nature analog. That is, natural processes tend to vary smoothly over time, not discontinuously changing states from black to white, from on to off. To be meaningfully recorded or manipulated by a computer then, analog measurements such as pressure, temperature, flow rate, surface roughness, surface hardness, surface wavelength, stress concentration factor, precision, and position can effectively be translated into digital representations by the TI technique. TI makes use of digital data to perform integrated reliability monitoring and maintenance functions for machine parts and equipment. A cost-effective integrated reliability monitoring and maintenance function is possible with an algorithm of the software program.

12.7 Algorithm for IRCMM of Machine Part, Manufacturing Process, and Equipment System with a TI Model–Based Simulation Program

An algorithm with TI coefficients is used to detect the high and low process and equipment integrated reliability variations and diagnose the cause of degradation/failure and provide corrective actions that help stabilize the system. It is also used to acquire data and analyze and transmit it to other computers. The algorithm is used to generate a string of random numbers in both deterministic and stochastic fashion. That is, given a starting value, known as the seed, the same sequence of random numbers can be produced each time as long as the seed remains the same. It is helpful in debugging a simulation program for producing the same sequence of events in order to verify the accuracy of the simulation. The algorithm for the design of integrated reliability monitor, TICSs, diagnostic transmitter, DAQ device, and controller as well as for CM and maintenance is based on TI model–based simulation.

The algorithm uses TI coefficients *a* and *b* for optimum integrated reliability monitoring and maintenance of machine parts, manufacturing processes, and industrial equipment. The algorithm for integrated reliability monitoring and maintenance of manufacturing processes, machine parts, and industrial equipment with TI coefficients is shown in Figure 12.5. The benefits of

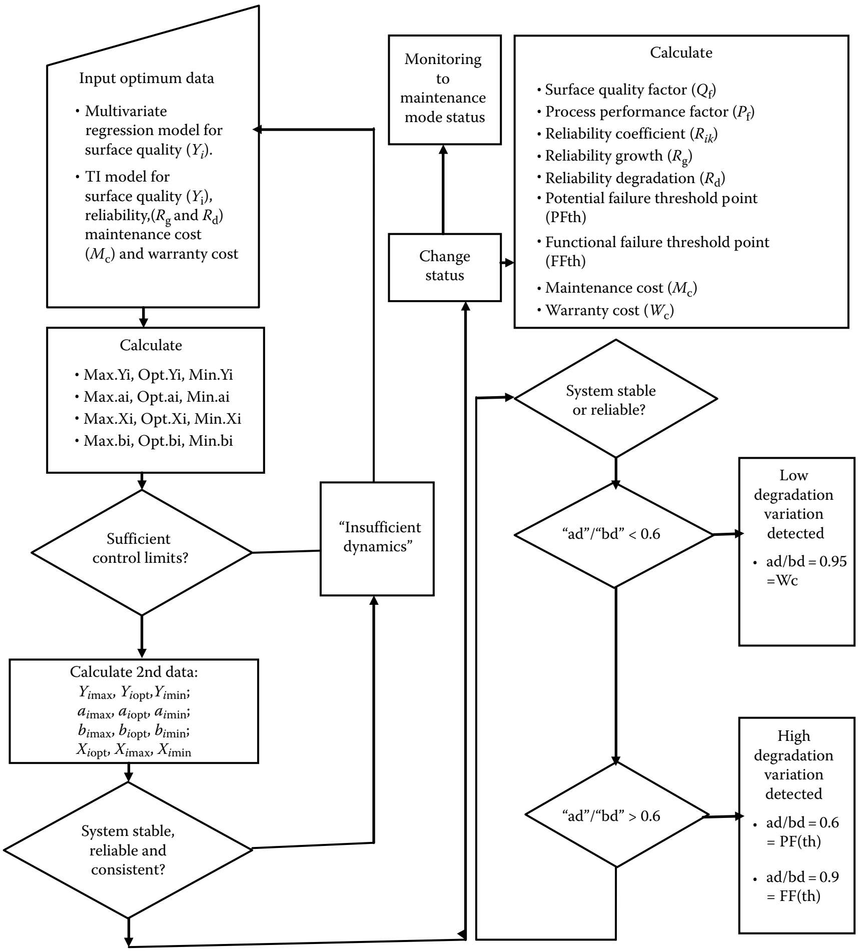

FIGURE 12.5
Simplified IRCMM with TI model–based flowchart.

the TI model–based algorithm for simulating integrated reliability monitoring and maintenance of machine parts, manufacturing processes, and equipment are as follows:

1. The TI model–based simulation technique provides a single metric known as TI coefficients *a* and *b* for the determination of component/system reliability factor (R_i), quality factor (Q_i), reliability growth (R_g), reliability degradation (R_d), and mean time to failure (MTTF), with hard-coated surface failure-resistant condition parameters (F_i) of machine parts.
2. The TI model–based simulation technique makes it possible to obtain optimum reliability and quality condition of parts as well as for the determination of reliability growth, degradation, and failure data and evaluation of components with multiple parameters during manufacturing processes prior to machine part release and assembly in a cost-effective manner.
3. The technique offers the opportunities and capabilities to test new and existing components for failures, maximum achievable reliability, quality, reliability growth, and degradation as well as MTTF and lifetime under normal operating conditions.
4. The TI model–based simulation technique is used for the analysis of reliability growth and degradation, which is one of the most cost-effective ways of overcoming the obstacles of obtaining information required to make effective business decisions regarding warranty periods/and or to demonstrate that components meet the reliability and quality specifications of the customers.
5. The technique simply employs the use of basic mathematical models to extrapolate over time the reliability growth and degradation measurements and conditions to the point at which the component is expected to fail.
6. The mathematical models are used to obtain standard reliability results like mean life, warranty time, and maintenance costs.
7. The model is used to develop the necessary tools and instruments with standard baseline requirements and calibrations for the measurements of reliability growth and degradation as well as quality coefficients of parts and equipment and also provides the desired software program that determines real-time reliability, life, and cost data for users and operators.
8. TI models are used for robust designs, reliability testing, and cost-effective maintenance strategies toward automation of integrated reliability monitoring and maintenance of parts, processes, and equipment.

9. The automation of integrated reliability monitoring and maintenance of parts, processes, and equipment is possible with the TI model–based simulation technique.
10. Integrated reliability monitoring and maintenance of manufacturing processes and industrial equipment can be derived from a reliability distribution curve and can be programmed through an algorithm and evaluated with the help of a TI software program.

12.8 Conclusions

1. The TI model–based simulation technique is the application of a mathematical model to provide the necessary information about manufacturing processes, parts, and industrial equipment system reliability CM and maintenance at specific instance and over time.
2. Quantifying the reliability and performance of manufacturing processes and equipment system for the various values of its input parameters is done with the quantified measurements of TI coefficients, which is very useful in monitoring the lifetime and failure characteristics as well as maintenance and management decision process.
3. The simulation model for manufacturing processes, parts, and equipment operations with TI coefficients is able to evenly produce numbers that follow a given theoretical mathematical model or empirical reliability distribution.
4. The mathematical model with TI coefficients represents multiple quality factors of critical part surface quality parameters (surface roughness, hardness, wavelength, stress concentration factor, and precision coefficient) for an IRCMM of a particular group of hard-coated critical machine parts (e.g., bearings, shafts) and critical equipment (e.g., pumps, generators, machine tools) that are applied to simulate real-time operating conditions of parts, manufacturing processes, and equipment.
5. The IRCMM automation of industrial plant with the application of the TI model–based simulation technique is considered as a synergic blend of man, machine, and methods in working activities whose execution leads to the manufacturing of desired part surface quality condition outputs, starting with a set optimum quality inputs of a particular critical part surface and equipment condition data, monitoring/maintenance conditions, set points, and threshold values.

6. The development of an object-oriented simulation model in an automatic control framework is possible with the help of the TI technique.
7. The multivariate statistical process with TI coefficients helps model the relationship between multiple quality condition parameters of an initial optimum operation and the final operation of a monitoring and maintenance system.
8. The optimum conditions scaled between zero minimum level and one maximum level for IRCMM of manufacturing processes, parts, and equipment is determined with the TI model–based simulation technique.
9. The reliability growth and degradation coefficients are used to plot the IRCMM distribution curve for the determination of component reliability, process performance, and health data as well as the monitoring levels (0, +1), the optimum operating condition levels of parts/equipment, and the baseline requirements for monitoring/maintenance design system.
10. The manufacturing process, part, and industrial equipment reliability CM and maintenance requirements as well as the reference set points and observations are always clearly displayed on an integrated reliability monitor, while the data collected from the reliability curve are used to determine process variations, potential/functional failures, errors, reliability growth/degradations, and the required suitable maintenance actions.
11. A cost-effective IRCMM curve can be programmed through an algorithm based on the TI model.

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13

Integrated Reliability with a Technological Inheritance Model–Based Program in the Industries of the Future

13.1 Role of Technological Inheritance–Model Based Programs for Integrated Reliability Condition Monitoring and Maintenance of Manufacturing Processes and Equipment

The critical part, process, and equipment failure of any technological system have the ability to bring plants and facilities to a halt and a catastrophic damage. It is therefore necessary to design maximum achievable reliability into critical manufacturing process, parts, and equipment and to have cost-effective maintenance strategies and shutdown protection programs in place to prevent catastrophic failures. It is a known fact that existing protection monitors and other existing monitoring and maintenance tools can only trip a relay on high vibration, but provides no insight into what the problem is all about. With the application of the technological inheritance (TI) model in an integrated reliability condition monitoring and maintenance (IRCMM) program, it is possible to have insights into failures, prevent failures, predict time of failures, diagnose the failures of parts and equipment, and attain maximum achievable reliability for longer lifetime of parts and equipment and provide insights into the root cause of failures. Integrated reliability condition monitors (IRCMs) and maintenance strategies can be used as proactive, predictive, and detective tools for fatigue, wear, corrosion, and temperature failures and can be used to develop maximum achievable reliability and maintain obsolete protection monitors, while today's plants are reengineering with the help of the TI model to integrate protection monitoring, prediction monitoring, performance monitoring, and integrated reliability condition monitoring (CM) under a single platform.

IRCMM with the help of the TI model enables smart field devices for integrating component reliability into process and equipment architecture in order to provide users and operators with the information needed to make decisions. The integration of component protection monitoring through the quality factor (Q_f) to process condition control through the performance factor (P_f) using the TI model allows for automated plant and equipment shutdown when required, as well as optimum reliability for warranty, manufacturing, and maintenance costs, while integrating component reliability degradation monitoring with operations during start-up means ramp rate optimization. With this type of integration, parts and equipment can continue performing within acceptable component quality parameters and process performance control limits at minimum life cycle costs. The IRCMM program is used for prediction, prevention, and performance monitoring as well as the maintenance of systems. Adding a prediction, prevention, and performance capability into a real-time operating system of hard alloy–coated mating parts for wear-, corrosion-, and temperature-resistant applications is the difference between saving the manufacturing and maintenance schedules. Prediction, prevention, and performance monitoring with real-time process, part, and equipment operating condition data offers full protection in a plant system. To measure, acquire, and monitor real-time component reliability, process and equipment performance data with component TI coefficient sensors (CTICSs) for process performance and reliability controls, reliability coefficient data acquisition hardware, integrated reliability monitor (IRM), and reliability maintenance strategy with software-defined measurement and instrumentation program for plant maintenance purposes are the essence of the TI model. The role of the TI model for IRCMM technology is therefore beneficial for optimum reliability selection, testing, design, monitoring, and maintenance of processes, parts, and equipment using suitable model-based defined measurement instruments, IRMs, and condition maintenance strategies that provide real-time data toward automation and sustainable development.

13.2 IRCMM Technology of Critical Parts, Processes, and Rotating Equipment

An integrated reliability condition monitor and maintenance technology is used for predicting, diagnosing, and detecting potential and functional failures in rotating equipment and can also be used to select suitable components and design optimal component reliability characteristics. The new integrated reliability monitor and maintenance technology provides information for cost-effective optimum selection, CM of failures, and optimum data for planning, designing, manufacturing, and maintenance. The monitor is also used to implement policies for plant and equipment life extension, refurbishment, and modernization toward a sustainable development in the industries of the future. The monitor determines system and component reliability growth and degradation, detects defects, and diagnoses the signs of commencing aging cycles of specific equipment, components, or parts of equipment during operations. The acquired data are stored and also supplied to a central processing unit that includes an export system, a model-based reliability and failure data bank, a predictor, a performance evaluator, and a system identifier. The results of the predictions, diagnoses, and detections are supplied to management terminals or other indicators for subsequent use.

The combination of prognostics, diagnostics, and detectors of the symptoms of existing faults and potential failures in mechanical rotating equipment and processes allows continuous online monitoring of systems to predict, detect, and diagnose failures at early stages before leading to catastrophic breakdown, which eventually assures safe and economic operations. The use of TI models for building the new IRMs and the maintenance technology of rotating mechanical components would help provide the operators of the equipment and processes with a warning data that indicate the time and conditions before failures and provide necessary information for suitable maintenance. The IRM and component maintenance device for failure detection, diagnosis, and prognostics as well as the achievement of maximum component and system reliability comprise of the following:

- A critical component and part surface that are susceptible to failure wear, corrosion, temperature, and fatigue modes
- A critical manufacturing process and equipment system for wear- and other failure-resistant applications
- An IRCMM system of critical mating hard alloy–coated part surfaces–manufacturing processes–equipment for wear- and other failure-resistant applications
- A system and component reliability condition monitor and condition maintenance data acquiring device with TICSs: calculators–regulators–alarm systems of instruments for component quality, process performance, reliability growth, degradation failure measurements, and its controls
- IRCMM data processing strategies for processing data received from the system reliability growth and degradation data acquisition device that relates to real-time operation of parts, processes, components, and equipment as well as a data processing device that includes failure detection, diagnosis, and prediction of components
- A component and process condition degradation failure technique for indicating a failure forecasted by a failure predicting device (failure indicator) and a device for controlling, monitoring, and maintaining as well as regulating further operations/performance (quality and performance regulator) of components in response to a failure being detected, diagnosed, and predicted by the IRMs and the instrumentation system

13.3 Instrumentation of IRCMM Technology with a TI Model–Based Program

While the IRM delivers field-based intelligence, instrumentation is the eyes and ears of processes, parts, and equipment through sensors, indicators, and regulators with the TI model. The TI model is used to design TICSs for measuring component and process reliability growth and degradation parameters. TICSs are both contact and noncontact measuring devices that directly measure the critical hard alloy–coated part reliability growth and degradation coefficients. It is also programmed to calculate the critical part reliability and surface quality characteristics in terms of its surface roughness, surface hardness, surface wavelength, stress concentration factor, and kinematic coefficient of mating parts and rotating equipment. These hard alloy–coated mating part surface quality parameters and process performance parameters form the root causes of success and failures of equipment. The control of the part surface quality and process performance parameter variations enhances the internal and external changes of equipment. The internal changes of the equipment are monitored before they become external systems. The innovative designs allow for instrumentation adjustments or changeouts with TICSs, convertors, and regulators when the equipment is running. Installation parts and standardized installation procedures and features are designed for high-temperature, harsh, or corrosive and wear environments. The instrument and measurement component characteristics for IRCMM can be optimally selected, designed, and determined with the help of TI coefficients in order to derive full benefits from the monitoring and maintenance of parts, processes, and industrial equipment. The instrumentation components and characteristics are as follows:

1. TICSs for integrated reliability growth and degradation controls
   a. Component quality factor (Q_{if})
   b. Process performance factor (P_{if})
   c. System reliability growth ($R_{kg(sys)}$)
   d. System reliability degradations ($R_{kd(sys)}$)
   e. Wear-resistant coefficient (K_w)
   f. Corrosion-resistant coefficient (K_c)
   g. Temperature-resistant coefficient (K_t)
   h. Mean time to failure (MTTF)
   i. Potential failure (PF)
   j. Functional failure (FF)
   k. Maintenance cost (M_c)
   l. Part, process, and equipment lifetime (L_{Ti})

2. The IRMs of parts, processes, and industrial equipment
   a. Reliability growth monitors (RGMs) for manufacturing processes
   b. Reliability degradation monitors (RDMs) for industrial equipment system
3. Integrated condition maintenance strategy
4. Integrated reliability data acquisition devices (RDADs)
5. Integrated reliability degradation and failure processors
6. Integrated reliability degradation and failure indicators
7. Integrated reliability degradation and failure regulators
8. Integrated reliability alerts and alarms
9. Industrial or personal computers
10. Maintenance cost calculators (MCCs)

The process and equipment reliability growth and degradation can be determined and monitored with TI coefficients a and b from one point to the other, part to part, process to process, and one operation to another as well as within the operation. With TI coefficients a and b, the parameters of the component, process, and equipment conditions can be determined with the TI model, $Y_i = a_i Y_{i-1}^b$ [1], when the component and process are running with optimal condition (i.e., TI coefficient for process condition variation, $b_{opt} = 1$).

This model is also used to determine component quality condition parameters, when the component is operating at optimum operating condition, where $b_i = 1.0$:

$$Y_i = a_i Y_{i-1(\mathrm{opt})} \tag{13.1}$$

where Y_i is the current operating component quality parameter (Y_i), while $Y_{i-1(\mathrm{opt})}$ is the initial component quality from the previous operation. a_i is the TI coefficient for quality degradation. b_i is the TI coefficient for process performance control. $Y_{i\mathrm{opt}}$ is the component optimum reliability, $R_{i\mathrm{opt}}$.

The model for process reliability $R_{k(\mathrm{p})}$ is expressed as

$$R_{k(\mathrm{p})} = \int_{t_{\min}}^{t_{\max}} P_{\mathrm{fopt}}\,dt \tag{13.2}$$

where $P_{\mathrm{fopt.}}$ is the optimum process performance condition factor, while $t_{\max}$ and $t_{\min}$ are the maximum and minimum time of operation, respectively.

The model for component reliability $R_{k(\mathrm{c})}$ is expressed as

$$R_{k(\mathrm{c})} = \int_{t_i}^{t_{\max}} Q_{\mathrm{fopt}}\,dt \tag{13.3}$$

The model for component reliability degradation is expressed in terms of the TI coefficient as

$$R_{dc} = \int_{a_{di}}^{a_{dmax}} Q_{fopt} da \tag{13.4}$$

The model for process reliability degradation is expressed in terms of the TI coefficient as

$$R_{dp} = \int_{b_{di}}^{b_{dmax}} Q_{fopt} db \tag{13.5}$$

The component condition degradations can be measured with the TI coefficient *a* within the operation and from one operation to the other. The process condition degradations can be measured with the TI coefficient *b* within the operation and from one operation to the other. With coefficient *b*, the parameters of the process conditions, X_i (pressure, speed, temperature, time, flow rate, power, and others), can be determined and also used to calculate the system performance factor (P_f), which is a function of b_i, where $b_{ip} = b_{x1}b_{x2}\ldots b_{xn}$.

By integrating system/component reliability degradation data with process automation, real-time decisions, maintenance actions, testing, and analysis can be carried out using diagnostic and cost-effective tools with the help of TI model–based programs.

Applying IRCMM with the TI model–based program for protection, prevention, prediction, and performance monitoring of parts, processes, and industrial equipment can be done cost-effectively using both offline and online monitoring tools.

13.3.1 IRCMM Tools with a TI Model–Based Program

In most existing protection systems where equipment anomaly occurs, operators usually trip off the equipment with little consideration for how this will impact the parts and equipment. It is unacceptable to trip off the equipment with total disregard for the parts and equipment. The trip off features and tools should be controlled and regulated with the help of process performance factor (P_f) or part quality factor (Q_f) tools, so that equipment and plant shutdown is safe and reliable. By integrating the part and equipment protection system with the process control system, the entire shutdown process is safely controlled. This type of integrated solution with TI models can be used for both online and offline monitoring of manufacturing processes, parts, and industrial equipment. With the help of TI models, you can customize acquisitions, access the built-in features of hardware devices, and incorporate the analysis and visualization features into the designs. The data can be analyzed and visualized and saved for postprocessing and make iterative updates to test setup baselines and reliability requirements on your analysis results. This type of reliability data acquisition tools allows you to use this program as a single, integrated environment to support the entire data acquisition, data analysis, and application development process. The TI model is also used to convert analog signal to digital and digital to analog. It can also be used to verify and validate models against real-time, measured data continuously as part of the system development process. When it comes to the application of IRCMM tools, integration of multiple parameters and factors is definitely useful. The use of a complement of proactive, predictive, and preventive tools can more effectively identify various failure modes much earlier than traditional protection maintenance programs. The powers of the tools are multiplied when they are used together under a single platform or as a network system. The need for an integrated approach of this book stems from three known facts about the nature of machinery failures and the ability of IRCMM tools to detect the onset of both potential and functional failures:

- Manufacturing process–part–equipment system failures that present themselves in a host of different failure modes like wear, corrosion, temperature, and fatigue.
- A single technology with the TI technique that can effectively detect all possible failure modes and attain component/system maximum achievable reliability.
- Some failures are detected earlier, while some are detected later, and the same is true of component quality from the initial to final operation on the technological chain, but with the application of the TI model, quality is controlled and failures are detected and captured throughout the life cycle of components.

The TI model is used in this book to detect, diagnose, and predict failures and predict optimum component/system reliability at any stage of design, manufacturing processes, and service operations. This is beneficial in the following ways:

1. Optimal reliability baseline and requirements set up to capture the right data surrounding the event with the TI model, where you can be assured the right component/system reliability data and the anomalous events will be captured by TICSs.
2. Online industrial equipment, part, and process reliability CM and maintenance system with the TI model–based program provides real-time continuous waveform recording to ensure events will not be missed throughout the life cycle of a critical hard alloy mating part surface.

3. With IRCMM with the TI model–based program that is always included in a field-based IRM, which also serves as a continuous data recorder of continuous-time waveforms simultaneously at all bearings and shafts.
4. An operating equipment view that supports real-time decisions during start-up. When you arrive on site and you learn it was manually done, it means the operator initiated trip off. The operator had real-time reliability data from the monitor and diagnostics from the process control that indicate the equipment should be brought down. Now the only question is, "How much damage was done, and can we restart the equipment?" With the help of multichannel, continuous data recording, you look at the quick views and extract the region of interest for more details. You review the data, compare with baseline requirements, and confirm that the reliability data trend is isolated to one bearing or shaft. The shaft centerline plots tell you the bearing clearance was exceeded or not. After fixing the issue, you will then give advice to restart the equipment. You can then watch the start-up for a real-time *inside the equipment* view scenario.
5. In this scenario, the integrated reliability monitor and maintenance technology with the TI model–based program allows the user to easily access critical information to make confident decisions.
6. Optimal selection and design of IRMs and condition maintenance strategy, instrument devices, and other relevant tools with the TI model–based program are beneficial for a sustainable instrument and data acquisition development.

13.3.2 Development of Instruments and Data Acquisition and Analysis and Presentation of Software for IRCMM Technology

Developing a software-defined measurement and instrumentation system is carried out with TI metrics a and b for real-time decisions during start-up and operations. These metrics are used to integrate data acquisition of component condition degradations or variations a and process condition degradations or variations b with analysis of TI models and presentation of the outputs. The integration provides superior software and hardware designs for optimum integrated reliability maintenance monitoring of production processes and industrial equipment.

A lot of works and guides have been written over the recent years addressing continuous process improvement and upgrade. However, very few address methodologies related to the improvement of the process and component conditions, which is due to the processing of the metrics used to measure the performance, quality, reliability, and degradation of a process, part, and equipment. The methodology applied in this book can be adopted by any process like manufacturing, maintenance, monitoring, management, software development, and financing. It is capable of improving the process and component conditions with the ability to process the metrics used to measure the performance, quality, reliability, and degradation of a process, part, and equipment. In order to assess if improvement, upgrade, and growth of a process or part (task) are needed, one or more metrics reflecting the performance, reliability, and health status of a particular task or object are highlighted and verified periodically. The metric value is compared to the corresponding reference used as the baseline requirements for that particular task function. The improvement, upgrade, growth, and degradation of the process and system or task are dependent on the result of this optimum reliability requirements and actual data event comparison:

- If the actual data value (R_{ik}) is equal to the reference reliability requirement value (R_{kopt}), then no corrective measure in the process or part is required; the system is said to be stable. The IRCMM with the TI model–based program is applied to verify and validate the optimum reliability of the component or system. The program is used to assess the reliability and failure conditions of components and system using TI coefficients and condition performance factors.
- If the performance (P_{f}) and reliability (Q_{f}) values fall below the desired requirement expectation, then corrective action in the process or part is required; the system is said to be below expectation, while the IRCMM with the TI model–based program is applied to select cost-effective maintenance strategies, components, and systems.
- If the metric value exceeds the reference reliability requirement expectation, then no corrective action is required in the process. However, the reference value can and should be changed accordingly to reflect the new baseline—*raising the bar*—the system is said to be above expectation, while the IRCMM with the TI model–based program is applied to provide the desired adjustments with TI coefficients.

In the case of this book, the TI coefficient a and b metric values are numerical and positive integers between 0 and +1, while there are metrics such as temperature, which would inherently include negative values in the Celsius and Fahrenheit scales, but with the use of TI coefficients, the negative values are taken care of. There are three types of *improvement* reliability values that can be generally considered in the IRCMM of industrial processes, parts, and equipment:

1. Positive reliability growth values where the improvement is expressed in ascending fashion (0 to +1) (e.g., component quality). This is positive TI, which in this book is a_{min} to a_{max}.

2. Degrading values where the process is expressed in descending fashion (+1 to 0) (e.g., process performance variations, component quality degradations). This is negative TI, which in this book is a_{max} to a_{min}.
3. Optimum values where the process, part, and equipment are expressed in optimum fashion (+1) (e.g., no process performance variations, no component growth or degradations, and cost-effective). This is an optimum TI, which in this book is a_{opt}.

Depending on the application, the improvement reliability value may be optimum, positive reliability growth, and negative reliability degrading values. The positive reliability growth value reaches an optimum baseline in the production/manufacturing lines. The negative reliability degradation metric value starts from the optimum values until it enters into the failure state of the component conditions. Optimum maintenance strategies are selected within the optimum reliability mode, when the TI coefficients are optimum. The measurement is carried out with the help of TICSs directly from the real-time operating equipment (Figure 13.1).

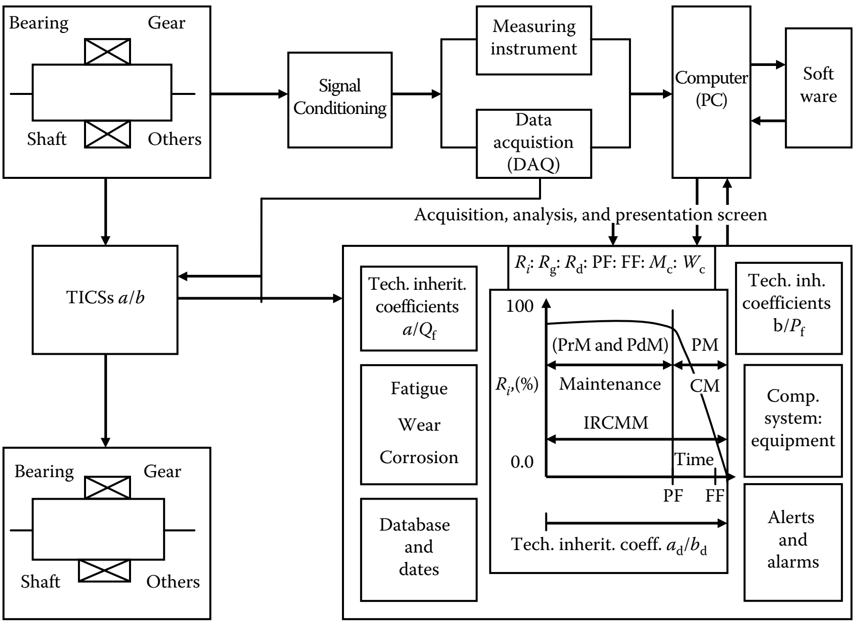

FIGURE 13.1
IRCMM of critical parts with TI model–based network system.

Vendors of data-acquisition-only software tend to be small in size compared with vendors of data acquisition/analysis/display software—this heightens the risk of obsolescence. If these drawbacks are not critical, then it is possible to select the best data analysis and presentation program without regard to data acquisition functionality with the help of an optimum selection software known as the TI software–defined measurement and instrumentation program. If a user must have an integration of acquisition/analysis/presentation data solution, then selection of the best developed software must be made from a more limited range of offerings or from the use of the integration of acquisition/analysis/presentation data with the TI model–based software program.

13.4 Integration of Acquisition, Analysis, and Presentation of Data with a TI Model–Based Software Program

The integration of acquisition, analysis, and presentation with the TI model–based software programs is possible with the application and combination of process monitoring, mathematical manipulation, and statistical analysis effectively to solve the problems of IRCMM systems. It is able to provide TI coefficients as reliability improvement values for continuous manufacturing process and service equipment reliability CM and maintenance systems. The metric selection adopted is with the help of TI coefficients. These coefficients consider a multiple set of reliability, quality, and performance metrics from the initial stage of manufacturing to the final stage of maintenance operation system. The metric values are numerical and positive integers between 0 and 1.

The reliability improvement metric value of continuous manufacturing processes and industrial equipment monitoring is of both ascending and descending values, where the quality, reliability, and process performance characteristics of the system change with time.

The TI metrics are used to determine the following:

- The cost-effectiveness of the IRCMM program of manufacturing processes, parts, and industrial equipment.
- Optimum selection of materials, parts, processes, equipment, and instrument system with the TI model–based program.
- Integration of acquisition/analysis/presentation data with the TI model–based software program.
- Design of software-defined measurement and instrumentation and hardware components for a continuous IRCMM of manufacturing processes and equipment. Once a decision has been made

as to what type of data analysis and presentation is required, the next step is to ensure a compatible interface with data acquisition instruments. Hardware solution accepts inputs from field devices and instruments and also converts these inputs into outputs compatible with the selected software. A model-based data acquisition, analysis and presentation program makes data available for data analysis and presentation, which is designed in this book with the help of the TI model for IRCMM of manufacturing process and industrial equipment network system, as shown in Figures 13.1 and 13.2.

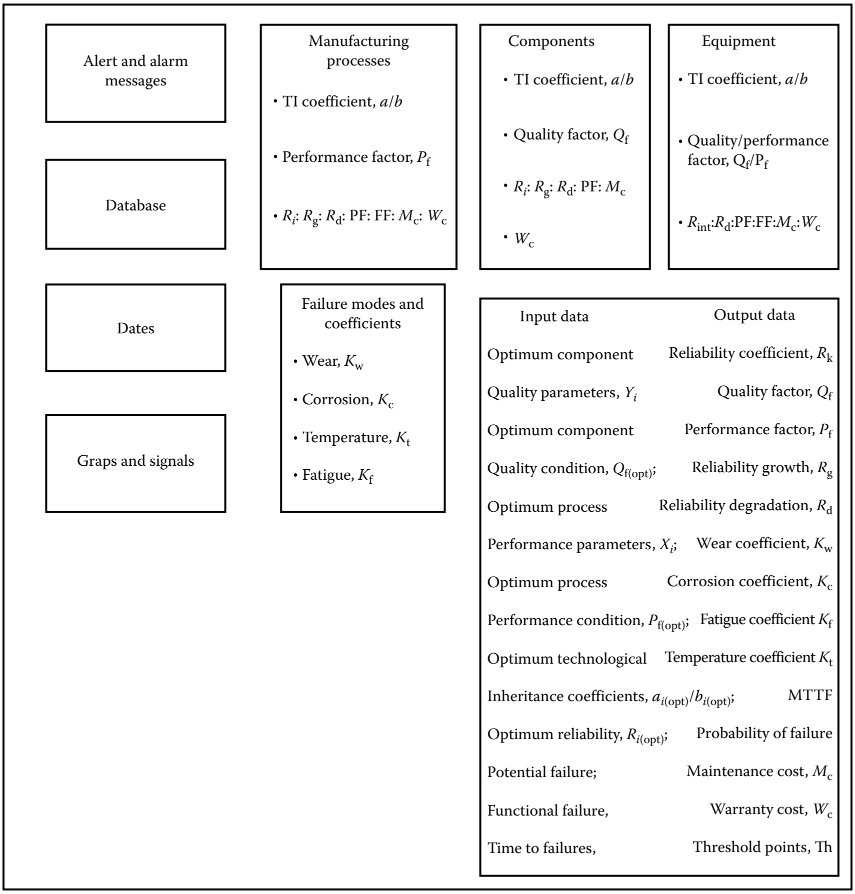

FIGURE 13.2
Component and system reliability information screen for IRCMM with the TI model–based network program.

13.5 IRCMM Tools with TI Coefficient Variation Control Limits

Although vibration analysis is the cornerstone of the existing reliability condition monitoring program, especially one where a large percentage of the asset base is rotating equipment, but vibration analysis uses different and multiple sensors to record the vibration signature from a machine or equipment. For a technician to determine if there is a defect in a rotating drive train, he or she must analyze the vibration signature. The TI model–based software program records the component quality factor (Q_f) and the process performance (P_f) and analyzes the component/system reliability coefficient and maintenance costs. Integrated reliability monitoring and maintenance with the TI model–based program consists mainly of the sensor–proactive and predictive maintenance strategy–IRM–computer–manufacturing process/industrial equipment system. An illustration of the IRCMM network structure is shown in Figures 13.1 through 13.4. The hardware structure and

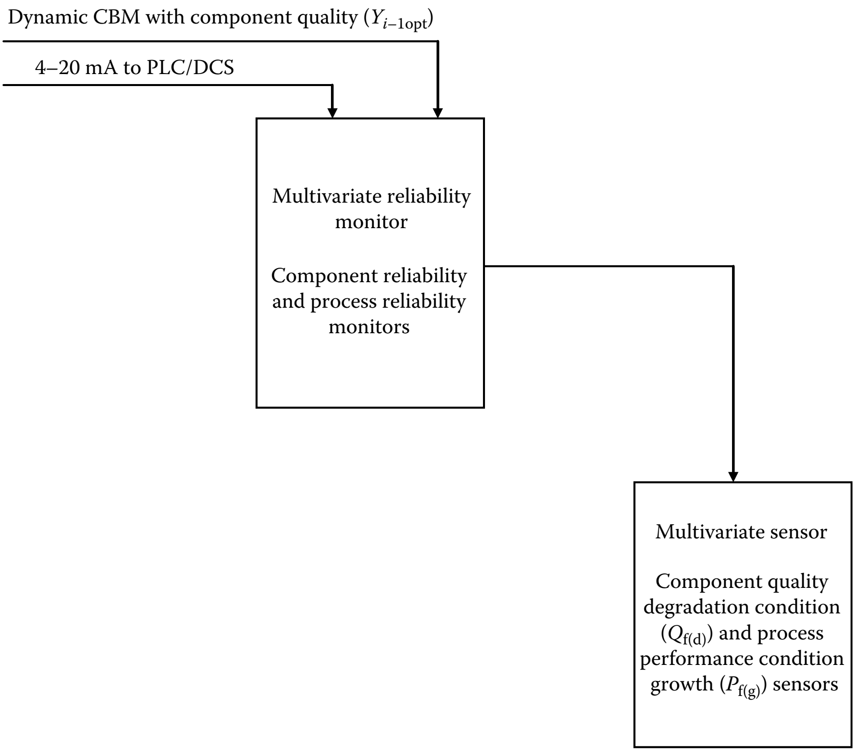

FIGURE 13.3
Tools for a multivariate reliability CM and maintenance program.

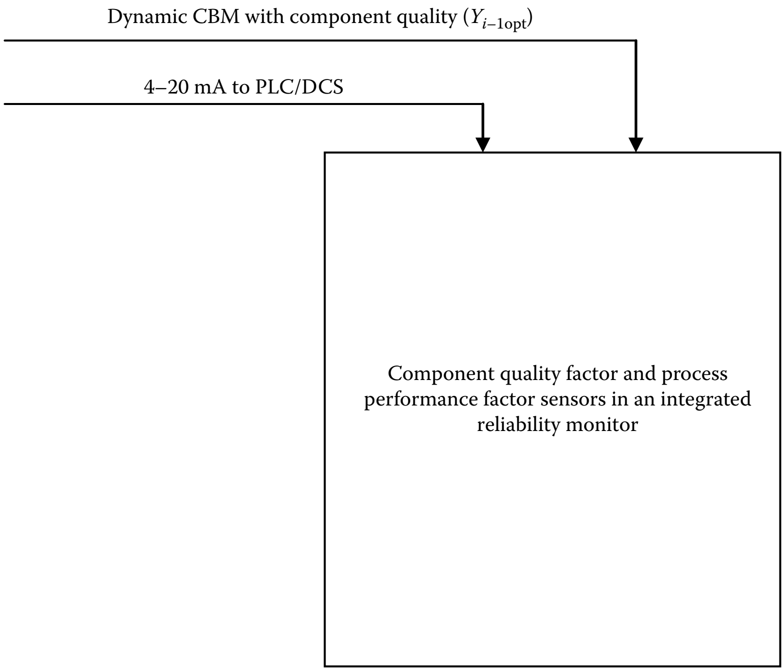

FIGURE 13.4
Integrated reliability monitor with component quality and performance factor sensors for a monitoring and maintenance program.

components can be selected optimally with the help of the TI model–based software, which can be highlighted as follows:

1. TICS for component quality control
2. TICS for process performance control
3. IRM
4. RGM
5. RDM
6. Integrated diagnostic maintenance strategy
7. Integrated indicator, regulator alarm device
8. RDAD
9. Industrial and personal reliability computer (RC)
10. TI model–based software
11. Integrated RDADs
12. Integrated reliability and failure processors (IRFPs)
13. Integrated reliability and failure indicators (IRFI)
14. MCCs

The software has to be coded with a C language or graphic programming, compiled by an open-source compiler and then programmed into the flash memory of the wireless reliability controller or reliability monitors. It realizes the following functions:

Sensor reading: The wireless integrated reliability monitor and maintenance strategy uses an I/O line to send an excitation voltage with an optimum value range to the sensor input. The sensor produces an output voltage that depends on the medium surrounding the sensor. The reading is then converted via the on-board analog to digital converter (ADC), stored, and also available for a continuous processing and transmission under a single platform or separate platform as the case may be.

Transmitting and receiving: The wireless reliability controller or monitor uses its I/O lines to transmit and receive data via the wireless transceiver. We designed and implemented our own bit-oriented protocol for the wireless communication, which has optimum features and network system.

Framing: All data being transmitted are broadcast in a single data frame. Using a frame delimiter, which is a unique sequence of bits that is guaranteed not to be seen inside a frame, identifies the beginning and end of each frame for a cost-effective integrated reliability maintenance monitoring of production processes and industrial equipment.

Process monitoring is the simplest and most widely used of the data analysis techniques. Typical application examples include monitoring the set point, the output, and the process variable versus the time to aid in loop tuning; plotting one analog variable versus a second analog variable; alarming variables when alarm points are reached, or when a variable exhibits certain behaviors such as a rapid change in value; filtering variables to eliminate noise problems; plotting historical data, including overlaying current data on historical data for analysis; and comparing sets of measured variables to desired results (whether manually entered or automatically generated).

The new on-line process performance monitoring tools with the TI model–based program (integrated multivariable sensors and transmitters [IMSTs] as well as the individual multivariable transmitters [MTs] and multivariable sensors [MSs]) with 4–20 mA signal network systems including the IRCM are designed to suit a desired application. For reliability growth, the tool is known as integrated reliability growth sensors and monitors (IRGSs and IRGMs), while the reliability degradation tool is called the integrated reliability degradation sensors and monitors (IRDSs and IRDMs). The individual monitors and sensors will be known as RGMs and reliability growth sensors (RGSs) accordingly. The individual reliability degradation tool will be known as RDMs and reliability degradation sensors (RDSs). The new network systems can be formed as follows:

1. Multivariate sensor–monitor
2. Multivariable reliability transmitter–monitor
3. Reliability sensor–monitor
4. Integrated reliability acquisition–IRGM/IRDM
5. Multivariate quality factor sensor–IRM–integrated reliability maintenance strategy (IRMS)–integrated reliability acquisition device system

The different new network systems can be compared with the existing ones in terms of maintenance costs, reliability, efficiency, and time of execution with the help of the TI model and coefficients, using a TI software program for a cost-effective integrated reliability monitoring of production processes and industrial equipment.

The TI technique therefore provides a standard role in the design of reliability growth and degradation monitor, reliability growth and degradation testing, and reliability CM and maintenance programs of the industries toward automation, continuity, and conversions at optimal life cycle/maintenance cost.

13.6 Integrated Reliability Condition Monitoring Tools and Features of Parts, Processes, and Industrial Equipment with a TI Model–Based Program

The ability of industrial equipment to adjust its own functionality according to its reliability, health, and lifetime status is an integral part of a self-maintenance paradigm. Self-maintenance requires both process functional intelligence and component reliability and health intelligence, which can be determined with the help of the TI model. With the TI model, it is possible to determine the maximum and minimum component and system condition parameters and control the condition variations at minimum cost.

Process functional intelligence provides the current operating condition information for the system reliability health and effectiveness assessment.

Component and system quality factor (Q_f) and process performance factor (P_f) intelligence evaluates the current reliability growth/degradation, life, and health status and predicts the likelihood of failures and successes. This information can be fed into a functional intelligence module—for example, integrated reliability controller, integrated reliability coefficient generator, IRMs, integrated reliability manager of manufacturing processes, and the equipment operation can be adjusted accordingly. The information can also be used to select cost-effective devices and instruments.

Adjusting operating condition parameters of processes and equipment is not the only way in which self-maintenance can be perceived. Acting a self-tuning or self-service function is another way to realize some degree of self-maintenance, which is possible with the help of the TI model.

Tuner adjustment and calibration can be triggered when reliability growth and degradation threshold data are detected. The purpose of self-maintenance is to keep the system running, providing enough time and data for maintenance personnel/operator so that they can be well equipped with the necessary information and to have sufficient time for the right maintenance. In the industry setting, the maintenance crew can conceivably fix the underlying problem proactively and at the appropriate times. In applications, such as in the aerospace industry, in which human intervention is not possible, a higher degree of self-maintenance is desired. In other industries where adequate time is needed, suitable time is provided for maintenance and repair schedules. A continuous reliability monitoring and maintenance with the help of the TI software program would provide the desired reliability and automatic proactive and predictive maintenance. This type of cost-effective integrated reliability monitoring and maintenance technology would require the following components:

- CTICSs
- Process TI coefficient sensor (PTICS)
- Component and process performance integrator (CPPI) and convertor (CPPC)
- IRGM
- IRDM
- Integrated reliability diagnostic maintenance strategy (IRDMS)
- RDAD
- RC
- IRFPs
- IRFIs
- Integrated reliability and failure regulator (IRFR)
- MCCs

13.7 Component and Process TICSs

Sensors have been relied upon and trusted to monitor systems. But what if a sensor fails? Such a failure could be complete or incipient, which will affect the readings issued from the sensor. There are currently two main approaches to solving this problem:

1. Hardware redundancy
2. Analytical redundancy

In the hardware redundancy approach, which is common in safety critical systems, such as nuclear power plants or airplanes, additional sensors are used to detect problems in one sensor or to provide a more accurate reading when one sensor fails by effectively replacing that sensor. The major downsides to this approach are the additional cost and the additional space required for extra sensors. The analytical redundancy approach uses the analytical or experimental model of a system to detect inconsistencies in the system's behavior, which could be generated by sensor failure. Few sensors are needed to build an analytically redundant system.

Simulating the analog and digital signals that go into the control unit and receiving signals from it as accurately as possible are two of the major challenges in designing such a system. The hardware used should have a sufficient number of input and output channels. The hardware also should be able to generate a wide variety of complex signals as accurately and deterministically as possible for the following:

- *Waveforms*: For component quality factor (Q_f) and process performance factor (P_f) sensors that can be use to simulate the load, material, and geometry of component, process, instrument, and equipment conditions
- *Counters*: Pulses, TI coefficient, and pulse width—modulated to simulate component and process condition parameters and wear, corrosion, and temperature resistance coefficients

With the help of the newly developed cost-effective integrated reliability monitoring and maintenance technology using the TI software program, the major design challenges facing online monitoring network techniques are solved with sufficient input and output channels as well as with standard process control loop network systems.

13.8 TI Coefficient Transfer Function for Communication Networks and Signal Processing

The TI coefficient transfer function is a mathematical representation, in terms of spatial or temporal frequency, of the relation between the input and output of a system.

It is mainly used in signal processing, communication theory, and control theory. Although most real systems have nonlinear input/output characteristics, many systems, when operated within nominal parameters, have behavior that is close enough to linear, which is an acceptable representation of the input/output behavior.

In the simplest form of continuous-time input $x(t)$ and output $y(t)$ signal, the transfer function is the linear mapping of the Laplace transform of the input, $X(s)$, to the output $Y(s)$.

$$Y(s) = H(s)X(s)$$

or

$$H(s) = Y(s)/X(s) = L\{y(t)\}/L\{x(t)\}$$

where $H(s)$ is the transfer function of the LTI system.

In discrete time systems, the function is similarly written as $H(z) = Y(z)/X(z)$, which is often referred to as the pulse transfer function. When the input $X(z)$ is replaced with the output $Y(z)$ from the previous operation of technological process ($X(z) = Y_{i-1}(z)$), while $H(z) = a_i$, for example, the component part output characteristics (Y_i) of a machining operation, it becomes the input characteristic, $Y_{i-1}(z)$, of a plant equipment, which can be expressed as $a_i(z) = Y_i(z)/Y_{i-1}(z)$. Through this expression, the positive and negative characteristics of a component part from a machining process will be transferred into the plant equipment. With the help of the TI coefficient a_i, the output characteristics can be controlled and monitored from the initial to final operation of a production process. Integrated reliability maintenance monitoring of component parts and plant equipment with the TI model–based network system is used to offer maximum benefits, which are as follows:

- The optimal value of the coefficient $a_{i\text{opt}}$ or quality factor $Q_{f\text{opt}}$ is the same for all generic process condition factors and component condition parameters of the same purpose. From Figure 13.1, a_{opt} is used to determine the system reliability requirement and the desired target requirements, $Y_{i(\text{opt})}$, $Y_{i(\text{min})}$, $Y_{i(\text{max})}$, for the design of IRCMM of components and plant equipment.
- It is used to control and monitor the output parameters of the component and system, using the expression $a_i(z) = Y_i(z)/Y_{i-1}(z)$.
- It is used to set the requirements, targets, and control limits of component parts, processes, and systems, where $Y_{i(\text{opt})} = Y_{i(\text{max})} = Y_{i-1(\text{opt})} = 1$.
- It is used to transfer the positive output and eradicate negative characteristics from the initial to final operation of a production process and in turn induce optimal characteristics into the plant equipment, $X(z) = Y_{i-1}(z)$.
- It can be used to convert a discrete time-domain signal into complex frequency-domain representation for the design of IRCMM of component and system.

- It is also used to integrate and transfer data from the point of acquisition through analysis to presentation under a single platform with integrated reliability maintenance monitoring technology.
- It is also used to determine and select cost-effective reliability CM and maintenance tools, instruments, and its technological system. This technology with the help of the TI coefficient transfer function is used for communication and signal purposes toward an integrated reliability monitoring and maintenance of production processes and industrial equipment. It performs both the functional and health intelligence activities of processes and industrial equipment. It is also used for optimum component selection and design of the software and hardware in the network system for IRCMM of production processes and industrial equipment.

The technology provides flexible signal conditioning interfaces, is compatible with industrial-standard protocols, and most importantly, is modular, flexible, and economical.

Integrated reliability monitoring and maintenance technology (IRMMT) helps acquire signals from TI sensors that analyze and present data accurately under a single platform.

It can generate different analog signals to simulate component condition quality parameters and its variations. It can generate digital signals for relays, switches, light emitting diode (LED), and also pattern/mechanism I/O. It can also use digital signals for timing applications such as pulse and frequency I/O. IRMMT devices can communicate through a common underlying software interface, which facilitates system integration. With the help of IRMMT, it is possible to choose the right programming environment that interacts with all the hardware in the system and to enable efficient programming and design or select suitable integrated reliability monitoring and maintenance devices. It is also quite possible to use the same computer or network system for both development and human–machine interface (HMI).

IRMMT applies proven diagnostic and prognostic techniques to obtain statistical failure and health values and is capable of measuring and quantifying low- and high-frequency acceleration forces, surface quality parameters, subsurface defects, ratios, coefficients, and control levels to provide meaningful values to machine parts, processes, environmental conditions, installation conditions, service life, and reliability of parts, processes, and equipment. The technology is a TI coefficient metric–based technique used for optimum selection, design, optimization, integration, maintenance, monitoring, and management of industrial equipment. The benefits of IRMMT are as follows:

- Selects the optimal quality parameters and reliability conditions of critical machine parts (e.g., bearings, shafts), processes (metallurgical, coating deposition, machining, grinding, etc.), and equipment (pumps, compressors, boilers, motors, etc.)

- Optimizes process conditions and sets the control limits for the reliability of parts, processes, and equipment
- It uses the optimum condition data to set the desired control limits for installation and functional processes and equipment
- Determines and measures the reliability growth and degradation of components and systems
- Monitors the reliability growth and degradation of components and systems
- Used to detect potential and functional failures early enough to prevent catastrophic damages to plants and equipment and predict the time and conditions of failures
- Determines the financial risk of inappropriate actions and the use of suboptimal systems
- Determines the total cost of failure and maintenance costs
- Provides accurate and useful real-time information
- Provides standard benchmark and requirements
- Optimum selection of model parameters, parts, processes, equipment, and instruments
- Design of hybrid software and hardware for integrated reliability monitoring and maintenance of production processes and industrial equipment

13.9 Cost-Effective Integrated Reliability Condition Degradation Monitor for the Detection of Distributed Defects and Failures in Parts and Industrial Equipment with a TI Network System

The detection of distributed defects of wear and competing failures relates to a TI model and IRDM designed for early detection of defects and failures in parts and industrial equipment. The problem with conventional techniques is that they usually detect too late, that is, after a failure has occurred. This problem can be solved with the understanding of a distributed defect and the transfer of these defects from one point to the other. A distributed defeat is one that occurs when a meshing gear produces a modulation in amplitudes of the components of vibration or reliability degradation signal, which has the same repetition rate as the meshing frequency and wavelength of the gears. Reliability degradation can be monitored and its corresponding values measured with a TICS embedded in an integrated reliability degradation monitor (IRDM), which is used to plot the component reliability degradation mechanism. The component reliability degradation mechanism has the frequency corresponding to the period of rotation of the gear and the wavelength of the meshing gear with the distributed effect. Detection of the modulation provides an indication of the existence, character, and extent of defect. The plotted mechanism by the monitor is used to detect and measure defects and failures and reliability degradation analysis and in making decisions for maintenance, design, and management.

The application of the TI model helps measure component reliability degradation, pulse periodicity, pulse width, defect amplitude modulation, and the frequency and wavelength of meshing gears or other rotating contact surfaces and determine the reliability performance, quality data, and time to failure of rotating parts and equipment. The IRDM with the quality factor sensor–based technique is used to detect the early bearing failures and determine the reliability degradations throughout the operations of rotating equipment. At this point, it is essential to note that sensor-based monitoring and signal denoising and extraction of the weak signature are crucial to bearing, shaft, and other critical part prognostics, since the inherent deficiency of the measuring mechanism often introduces a great amount of noise to the signal. In addition, the signature of a defective bearing and other critical part is spread across a wide frequency band and hence can easily become masked by noise and low-frequency effects, but TICS in an IRDM enhances the weak signature at the early stage of defect development and can also be controlled directly by the operator and through self-maintenance strategy. This signal enhancing technique and monitor provide more evident information for bearing, shaft, and other critical part reliability performance assessment, diagnostics, and prognostics.

The traditional approach for extracting signals from a noising background is to design an appropriate filter that removes the noise components and, at some time, lets the desired signal go through unchanged. Based on the noise type and application, different filters can be designed to conduct the denoising. With TICS that applies the TI model, the noise type, frequency, wavelength, stress, and other component quality data range are known and programmed with easy computations and determination of component reliability data. It also has time–frequency and quality condition inheritance capabilities. The IRDM is used to measure and detect smooth and single reliability degradation curves from raw noising signals of mechanical component failures, such as gears, shafts, and bearings, which are more impulse-like than smooth.

The TI technique seeks the optimal wavelet filter that can give out maximum reliability degradation values for the transformed signal. However, the defect signature of the bearing and critical parts is periodic impulses that can be measured at any time by a TICS. The periodicity, which plays an important role in fault identification, can be measured with such sensors and meters, which makes for optimum wavelet filter construction possible and cost-effective.

Another challenge of bearing and other critical part prognostics is how to cost-effectively evaluate the system performance based on the extracted features. One of the primary difficulties for effective implementation of critical part prognostics is the highly stochastic nature of defect growth. Even though a large variety of features can be extracted to describe the characteristics of signal from different aspects (such as root mean square [RMS], kurtosis, crest factor, cepstrum, and envelope spectrum), but previous works have shown that each feature is only effective for certain defects at certain stages. For example, spikiness of vibration signals indicated by crest factor and kurtosis implies incipient defects, whereas the high energy level given by the value of RMS indicates severe defects. A good performance assessment technique should take advantage of mutual information from multiple features, meters, and sensors for system reliability degradation assessment. The multivariate sensor and meter with the TI model is capable of measuring component defect growth and pulse period at the same time with a single metric. At this point, the application of the TI technique is therefore highly essential and justifiable, since it has the capability of multiple parameters, part and process integration, as well as their optimization capabilities. The TI model–based sensor–monitor network system can now be used to integrate multiple failure modes and determine and analyze the reliability degradations of different critical components within a particular period of time under a single platform. These real-time measurements and data can now be monitored and controlled from the initial stage of design and production to its final stage of service operations with the TI networking system. Within the control limits, any defect can be detected and prevented and can be predicted with the help of integrated reliability monitoring and maintenance with the TI networking program.

This program with the TI network system can be used also to diagnose the root cause of failure, determine the time and frequency of component/system failures, and determine the reliability degradation threshold data for different failure modes, as seen in Figures 13.3 and 13.4.

13.10 Real-Time Component and Process Data Acquisition and Automation with a TI Model–Based Software Program

Maximum benefits of predictive, preventive, and performance capabilities are possible with integrated reliability monitoring and maintenance data acquisition through the TI software–defined instrumentation technology.

With component and system integrated reliability as well as health feedback to process automation, operators can now know the effects their actions have on the quality, reliability, and heath of parts, processes, and rotating equipment. IRM, IRMS, CTICSs, PTICS, and reliability data acquisition hardware (RDAH) for reliability condition monitoring and maintenance application can be designed with the help of the TI model to provide real-time manufacturing processes and industrial equipment supervisory information and integrated reliability and health parameters to operators. If operators adjust the process or process upset occurrences, operators can see the live impact of different operating and environmental events on industrial equipment health and reliability.

For example, during start-up, if the equipment performance levels are not within acceptable limits, operators or process control can automatically adjust ramp rates by integrating machine part surface quality and reliability data that include environmental data into process automation with the TI model–based program. This will provide informed real-time decisions to set new industry standards and baselines for running dry and submerged applications of a plant system as well as the attainment of maximum achievable reliability of finished hard alloy surfaces of critical equipment parts.

13.11 IRCMM of Hard Alloy Critical Part Surfaces with a TI Model–Based Program in the Industries of the Future

The program is useful for running dry and submerged components in different existing industries as well as for the attainment of maximum achievable reliability for desired extreme applications. Examples of some critical components and equipment in existing critical plants and future industries are as follows:

- Power generation steam turbines
- Industrial drive gas turbines
- Hydroturbines
- Centrifugal compressors
- Screw compressors
- Fans, blowers, pumps, motors, and others

Examples of existing critical plant systems include:

13.11.1 Power Plant Monitoring

Since a power plant system can change sporadically, it needs to be monitored at all times. On the other hand, constantly measuring the system at a set interval can result in enormous amounts of data, much of which are repetitive and irrelevant. Change detection provides the best of both worlds by removing the repetitive data while still recording important system events. Using change detection, data are captured only when a rising or falling edge is detected on specified component quality parameter and process performance inputs. For example, any time a relay opens or closes, the states of all relays will be captured and saved in case they are needed at a later time.

The programmer has complete control over which lines are used to detect a change. The rising edge lines, and falling edge lines control, which is measured with TICSs that can be populated with any combination of input lines that physically exist on the device. In our own case of part surface quality factor, the optimum value ($Q_{i\text{opt}}$) and the minimum acceptable quality factor ($Q_{i\text{min}}$) data as well as the optimum/minimum process performance factor ($P_{ik\text{opt}}$ and $P_{ik\text{min}}$, respectively) are used as set threshold points for the rising edge and falling edge lines. Industrial environments can be electrically noisy. This noise can cause a variety of problems, one of which is unwanted readings. Any digital input device uses one or two voltage thresholds that represent the optimum and minimum quality factor threshold points to determine if the input is high or low. When the input voltage is above the high threshold, the device reads logic high. Conversely, if the voltage is below the low threshold, the device reads a logic low. If the noise is present, the input voltage could cross the thresholds unexpectedly, causing an incorrect high or low reading. In other case, a signal may appear to change state several times, when in reality it changed only once. For this reason, IRMs with TICSs are used to measure and observe the changes as well as to carry out necessary actions for maximum reliability coefficient at minimum cost. Hence, the need for integrated reliability monitoring and maintenance with the TI model–based program, which can cost-effectively be applied in the different industries.

13.11.2 Oil Refinery

In oil refineries, a key switch may be used to activate the flow of crude oil into a chamber for refinery. The switch, however, tends to exhibit a lot of bouncing. Much like a ball bouncing on a hard surface, one of the metal contacts will tend to bounce when it is forced into the contact. The repeated toggling of the signal would cause the pump it is controlling to rapidly switch on and off, which can accelerate wear on the pump and eventually lead to a premature failure. In addition, if you were using a device with change detection to acquire this signal, the input buffer would fill up unnecessarily. If input fillers are enabled on the device, it will eliminate the erroneous readings caused by the bouncing switch. It does this by ignoring any pulses that are too small in width. The device can then output filtered signal to the pump.

With programmable input filters, the user can programmatically select the minimum pulse width that is guaranteed to pass.

Any pulse that is greater than the specified minimum pulse is guaranteed to pass and any pulse that is less than half of the specified pulse width is guaranteed to be filtered. Pulses that fall between half of the pulse width and one entire pulse width may not pass.

When a computer is powered on, various components begin their own power-up routines to ensure that they reach a functional and expected state. If a digital output device is used inside the computer to control machinery or an industrial process, it is important that the digital outputs are also initialized to a known state. Changing the outputs typically requires that an application is running, but the device may be on for several minutes before the application can start. It is important here to note that integrated reliability monitoring and maintenance technology with the TI model–based program offers a possible way for the digital device itself to set its outputs as soon as it receives power.

13.11.3 Rolling Mill

In a rolling mill, heated steel is forced through rolling machinery to create steel beams of varying widths. A digital output line from a digital I/O device controls the rolling motor. When computer is powered on, the rolling motors must be turned off to prevent any steel from being wasted during start-up. If the digital I/O device does not provide a way to guarantee the initial outputs, the computer must completely boot and control the program, which must be started before known states are output on the channels. This lack of control could result in the waste of expensive raw materials and equipment damage. Glitch-free power-up states ensure that all digital outputs will begin a known state anytime the device is powered on. Because none of the machinery turns on unexpectedly, no steel is wasted.

On the event of an unexpected failure of some component of the system, the fail-safe mechanism will take over and place the system into a known state. An IRM with the TI model provides a means for detecting system errors and recovering from them safely.

13.11.4 Other Applications

This includes all the industries of the future where rotating equipment in dry running and submerged environment is critical. It is necessary to note here that most industrial applications connected to energy efficiency, renewable energy, metering, motor power control, and sensor interfacing are critical with high market demands. IRM with the TI software tool designed in this book can provide cost-effective, predictive, preventive, protective, and online reliability monitoring and maintenance for different industrial applications. The new integrated reliability monitoring and maintenance tool is a powerful way to regulate industrial equipment, reduce noise, limit machine damage, and prevent waste. With the newly designed software program, tool, and hardware with the TI technique, you can create a robust, industrial network system for optimum selections; design of IRMs, TICSs, and data acquisition hardware components; and instrumentation for integrated reliability monitoring and maintenance of parts, processes, and equipment.

13.12 Conclusions

1. The role of IRCMM with the TI software program offers a cost-effective engineering solution in today's plant, process, part, and equipment system reliability monitor, which include protection monitoring, prediction monitoring, performance monitoring, reliability growth/degradation monitoring, and online monitoring.
2. Online monitoring enables smart field devices like TICSs to be integrated in the digital plant architecture in order to provide users around the plant and across the enterprise with the information needed to make decisions.
3. Integrating industrial equipment protection monitoring to process control allows for automated plant shutdown when required while carrying out component reliability degradation monitoring and maintenance during start-up and real-time working conditions.
4. Prediction, prevention, reliability growth/degradation monitoring, and performance monitoring with real-time operating data are full protection for the bottom baseline of manufacturing processes, parts, and industrial equipment.
5. Maintenance personnel benefits from predictive, preventive, and reliability performance capabilities are maximized with the help of the TI model, which allows component/system reliability and health feedback to process automation for operators to know the effects their actions have on the reliability and heath of equipment in the industries of the future.
6. The IRM delivers field-based intelligence, while TICSs are used to measure part, process, and equipment reliability growth and degradation parameters.
7. Protection monitoring is controlled along with the process so that a plant shutdown is safe and equipment failure impact is minimal with an integrated equipment protection and process control system, where the process control condition is determined with the TI coefficient, while the condition variation is measured with TICSs.

8. IRCMM tools with the TI software program are a cost-effective online/offline predictive and proactive engineering solution in the different industries of the future.
9. The use of predictive and proactive tools with the TI software program can more effectively identify wear, corrosion, temperature, and fatigue failure modes much earlier than traditional predictive/proactive programs as the powers of the tools are multiplied when they are used together or as a network system.
10. A software solution process input data that make data available for data analysis and presentation are designed in this book with the help of the TI model–based software program for an IRCMM structure of manufacturing processes, parts, and industrial equipment.
11. The optimum selection and design of the hardware structure network system are carried out with the help of the TI model–based software program.
12. IRMs and cost-effective precision maintenance tools are used to monitor reliability growth/degradation and also for the detection of distributed defects and failures in critical parts and equipment and fix the failures with the help of the TI model–based program.

14

Integrated Reliability with a Technological Inheritance Model–Based Network Program in the Industries of the Future

14.1 Integrated Reliability Condition Monitoring and Maintenance Strategies

Integrated reliability condition monitoring and maintenance strategy (IRCMMS) is a hybrid hardware that performs multiple functions on a single platform for an optimum continuous reliability condition monitoring (CM) and maintenance of industrial equipment.

IRCMMS consists of the integrated reliability condition monitor (IRCM) and integrated maintenance strategy (IMS) with multiple distinct diagnostic and prognostic functions that can be used separately or in conjunction with each other to detect, deter, and alert users for wear-resistant conditions and other competing failure-resistant conditions that were previously undetectable or provide powerful troubleshooting and monitoring tools:

1. *Time stamp*: The IRCMMS features an operational clock whose purpose is fourfold:
    a. Provides user the total number of operating hours of the monitor
    b. Provides an elapsed *time since* event indication or time stamping for all monitors
    c. Provides a time corresponding to technological inheritance (TI) coefficients for component reliability degradation and failure controls a_d as well as component reliability growth and maximum achievable reliability, a_g
    d. Provides a time corresponding TI coefficients for process performance degradation and failure controls b_d as well as process performance growth and maximum achievable performance, b_g

All time values are nonvolatile and displayed in a suitable format. The time stamping capability significantly enhances the user's ability to troubleshoot measurement issues, particularly transient events that may be too fast to capture with distributed control system (DCS) or programmable logic controller (PLC) trending or historian capabilities.

2. *Integrated reliability condition growth monitor (IRCGM)/integrated reliability condition degradation monitor (IRCDM)* is used to detect changes in the system or component installation conditions of the monitor. This is done with a TI model (Y_i = a Y_{i-1}^b) of the quality–reliability chain and anomalies of an integrated operation system (with the statistical values of the TI coefficients a and b) under normal conditions and then comparing the reliability baseline/requirement values to current values over time. If a significant change in the current values is detected, the monitor will generate alerts or alarms, depending on the configuration. The condition is time stamped to suit desired TI coefficients and is also noted on the liquid crystal display (LCD). The statistical values are also available as secondary variables from the monitor, if the user is interested in their own analysis or in generating their own alarms or alerts.

   IRCMMS is a quality–reliability chain and condition based with the TI model analysis of hard alloy–coated mating part surface, processes, and systems that provide information on multiple key factors affecting industrial equipment maintenance costs:

   - Quality of components
   - Failure probability
   - Process performance conditions
   - Environmental conditions
   - Financial risk
   - Service life reducing forces
   - System reliability growth and degradation

   IRCMMS utilizes a single analytical TI model—$Y_i = a \cdot Y_{i-1}^b$—to assess the reliability growth and degradation, The discriminant parameters of a critical machine part or component and process conditions convert each of the input value, Y_{i-1}, to a and b numeric metric values of "0–1" for both the discriminant (Y_i) and process condition (X_i). The metric value of 1 indicates a near optimum discriminant state and the value near 0 is set to indicate the worst-case scenario (near failure state).

   When an optimum discriminant state (a_{opt}) of a critical part like bearing or shaft degrades, whether from lubrication film breakdown or subsurface fatigue, a common pattern of variation develops. Microscopic scoring or subsurface fatigue migration cracks begin to occur. Within this period, it may not be obvious and may not have caused any obvious damage. The failure within this period is known as potential failure with low variation, while the failure within a failed state is known to be functional with high variation. The functional failure occurs when a surface defect reaches a definite damage amount that is of catastrophic consequences. In this process, measurable acceleration impacts and high-frequency energy with specific characteristics of wear, corrosion, and high-temperature impacts and other modes of failure begin to develop.

The characteristics and pattern trend of these accelerations are observed and measured with a component degradation or process condition sensor (TI coefficient sensors [TICSs]) to describe a critical part, process, and system under investigation. The data collected under such investigation provide useful information for diagnostic and prognostic analysis for integrated reliability growth and degradation monitoring devices (IRCGM and IRCDM). It is true that there are many existing diagnostic or prognostic procedures with proven usefulness, but none are without some element of uncertainty. IRMMS is unique with a single standard metric of "0–1" for determining all the factors that affect the discriminant state of a component, process, and system. To improve on system reliability and performance, the system therefore must employ a single procedure that converts the compound quality index range from a_{opt} to a_{min} for the discriminant and b_{opt} to b_{min} for the process conditions that reflect the real-time values of the component, process, and system into a quantifiable metric of "0–1."

The results are used to calculate the failure probability, system reliability and service life, quality of components, maintenance costs, and other vital parameters. It is also used for continuous integrated reliability condition monitoring and maintenance (IRCMM) of industrial equipment with the help of the TI model.

3. *Advanced component and equipment alerts*: These alerts in IRCMMS are similar to the process pressure and temperature sensors alerts, with the addition of time stamping to document that start and elapsed time of the alert conditions is suitable to the TI coefficients. Upon detection of a process and equipment alert condition, an *alert* message is generated for maximum optimum and minimum reliability threshold points/levels. The LCD will also indicate the optimum and failure conditions.

4. *Variable data logging*: The IRCMMS logs the following values: minimum and maximum reliability, minimum and maximum quality, minimum and maximum lifetime, minimum and maximum maintenance costs, minimum and maximum operating current, minimum and maximum wear-resistant coefficients, minimum and maximum temperature, minimum and maximum power, and their total elapsed time

as well as their TI coefficients. Each of these is independently timed and TI coefficients are stamped.

5. *Advanced alerts and alarms*: IRCMMS contains the maximum and minimum reliability coefficient threshold points. The maximum reliability coefficient threshold point allows you to select the best material, part, process, and equipment monitoring and maintenance strategies that meet the desired applications. Also, the minimum reliability coefficient threshold point warns you about imminent functional failures. The threshold points prepare us ahead of time to prevent the impending failures. Alerts and alarms are set on these points with sounds and light indicators. Once the reliability conditions are reached, the alerts and alarms are triggered and set on for a specific period of time.
6. *Variable data logging* is provided in the monitor for real-time and future processing, analysis, and presentation at the required time when it is needed.
7. *Real-time information* may show up on the screen at the required time and would then be removed and stored later in the data storage section.
8. *The input data and parameter unit contains the following*:
   - Opt TI coefficient, $a_{i(\mathrm{opt})}$
   - Opt TI coefficient, $b_{i(\mathrm{opt})}$
   - Initial opt. component quality parameters, $Y_{i(\mathrm{opt})}$
   - Initial opt. process performance parameters, $X_{i(\mathrm{opt})}$
   - Opt component quality factor, $Q_{\mathrm{f(opt)}}$
   - Opt process performance factor, $P_{\mathrm{f(opt)}}$
   - TI model, $Y_i = a_i Y_{i-1(\mathrm{opt})^{b_i}}$
   - Materials
   - Parts
   - Manufacturing processes
   - Machines/equipment
9. *Software programs with TI model are available for the following*:
   - Optimum reliability selection
   - Reliability testing
   - Reliability CM
   - Reliability condition maintenance
   - Continuous management
10. *Instrumentation and computer networks involve the following*:
    - TICSs
    - PC networks

14.2 Working Conditions of the IRCMMS with the TI Coefficients

14.2.1 Component and Process Condition Variations

1. *The minimum/low failure mode and TI coefficient variation* captures the optimum control limits of the discriminant and the process conditions of all the low-frequency acceleration and energy inputs/output characteristics, including those caused by misalignment and rotational imbalance, up to approximately four times the rotational frequency. The variations are measured most accurately with the use of a TICS that reflects the real condition of the parts, processes, and systems. These values are scaled within the values of "0–1" with the help of TI coefficients a and b. TI coefficient a is for the component (e.g., bearings, shafts) optimum quality/reliability and degradation metric control, while b is the TI coefficient that controls the optimum process condition and performance variation metrics. The values of a and b, between the optimum metric and a definite threshold set point, are known as the low metric variation ($a_{opt} < a_{thmax} < a_{mean}$). Under this range, the frequency and energy from the optimum value are low. The values of these coefficients are used to determine, select, monitor, manage, test, and maintain industrial processes, parts, and equipment.
2. *The mean failure mode and TI coefficient variation* measures the average ratio between the peak value of low- and the initial value of high-frequency energy ($a_{min} < a_{mean} < a_{opt}/a_{thmax}$). The character of this value is such that it is very sensitive to microcracks in the bearings or shaft surfaces. It may be high on a new bearing or shaft and often declines after run-in and increases to higher values in the latter stages of failure. The microcracks can be detected early enough within this range, while appropriate measures and actions are taken with the help of integrated reliability monitors and maintenance strategy to prevent catastrophic damages and consequences.
3. *The high failure mode and TI coefficient variation* measures the high frequency and energy values of processes and equipment. Under this condition ($a_{mean} < a_{thmax} < a_{min}$), the component and product are characterized with general surface irregularities, surface roughness, and surface degradations that develop into wear, corrosion, high-temperature impacts and other modes of failure. With the help of TI coefficients a and b that measure the metric variation values, it is possible to detect the sources of failure and also determine the amount

of failure. The values can all be calculated, analyzed, and displayed in a time-stamped bar graph form with the help of a TI model that describes the relationship between the component optimum quality or reliability control data of the preceding process and the variation values of the operating process. A designed integrated variation sensor is used to measure the metric variations, while the integrated reliability monitor is used to monitor the system reliability, lifetime, and health, and the integrated reliability monitor and maintenance strategy is used to carry out appropriate monitoring and maintenance actions.

14.2.2 Applicable Monitoring and Maintenance Tasks

The TI technique is applicable in monitoring and maintenance analysis, using the coefficients to construct distribution curves and scale factors for the determination of monitoring and maintenance tasks. The scale factor is based on the ratio of the optimum or minimum conditions, which is expressed as

$$Y_{i\text{opt}} : a_{i\text{opt}} : Q_{\text{fopt}} : R_{ik(\text{opt})} = 1.0 \tag{14.1}$$

$$Y_{i\text{min}} : a_{i\text{min}} : Q_{\text{fmin}} : R_{ik(\text{opt})} = 0.0 \tag{14.2}$$

$$X_{i\text{opt}} : b_{i\text{opt}} : P_{\text{fopt}} : R_{ik(\text{opt})} = 1.0 \tag{14.3}$$

$$X_{i\text{min}} : b_{i\text{min}} : P_{\text{fmin}} : R_{ik(\text{min})} = 0.0 \tag{14.4}$$

If the input data are known (Y_i or X_i), then with the expressions in Equations 14.1 through 14.4, you can find the desired characteristics using the right scale factor of the distribution curve on the component or process conditions. Let us now address the effect of the scale factor in the different cases where the reliability coefficient, quality factor, and performance factor are evident and hidden:

1. *Initial component condition*: This is when the component condition is optimum after the finishing by manufacturers. At this stage, the TI coefficient $a_{i\text{opt}} = 1$, which is equal to the quality factor of $Q_{i\text{opt}} = 1$, for a particular critical part (e.g., shafts, bearings). When the optimum finished part is properly installed into critical rotating equipment (pump, turbine, compressor, etc.), the reliability, R_i, = 1, which is optimum. Selecting equipment and components with optimum, $a_{i\text{opt}}$, is cost-effective with the help of the TI model–based program. The maximum threshold point is set at this point for optimum selection and predictive maintenance.

2. *Intermediate component condition* is when the TI coefficients are represented as $a_{\min} < a_i < a_{\text{opt}}$ or $b_{\min} < b_i < b_{\text{opt}}$. It means that under this condition, the stresses on the components increase with time. This can be a result of induced defects from manufacturing that may lead to an early failure pattern. When this is a result of the defects introduced during the design and manufacturing processes, it is simply because the TI technique was not applied in all the different operations of design and manufacturing. With the use of the TI technique, an analysis of the root cause of the failure is carried out, while a suitable corrective action to improve quality and reliability is done.
3. *Final component condition* is when the TI coefficients are represented as $a_i = a_{\min} = 0$ or $b_i = b_{\min} = 0$. Under this condition, the component is in a failed state. This condition indicates a failure pattern (e.g., wear, corrosion, high temperature, and fatigue). Before this state is reached, the minimum threshold is set to guide against catastrophic danger. At this point, protective and preventive maintenance is done. Time–frequency-based maintenance strategies with the TI technique are applicable within a scale factor between 0 and 1. The lower the value of the scale factor, the more definite is the time of failure. When this is low, we can easily justify preventive time-based maintenance that will help to improve the performance and reliability. We can determine the maintenance interval by using the reliability distribution curve to determine the required survival probability at the time of maintenance intervention. Turning our attention to hidden failures next, we require a time-based test to identify whether the item is in a failed state. If the item has failed already, we have to carry out breakdown maintenance or corrective maintenance to bring it back in service. As you can see from the earlier discussion, only certain tasks are applicable in addressing the failures. The kind of failure, namely, whether it is evident (functional) or hidden (potential), and the shape of the reliability distribution curve will help determine the applicable task and verify the TI model–based program.

14.3 Application of the IRCMMS with a TI Model–Based Software Program

Due to the problems of power plants, plant managers have therefore decided to look for a new online technique that would not only monitor industrial processes and operations continuously but would also gather diagnostic data that are capable of revealing unrecognized internal problems in time for corrective actions to prevent a similar failure in the future.

In this day of advanced technology, it is both possible and essential to access decision-making information about the operating condition of critical equipment—not just a *trip* signal that comes only after significant internal damage has actually occurred. Some companies are putting productivity at risk by continuing to rely on *protection* systems for their critically important processes and equipment. Protection is vital, but it is only part of the complete maintenance solution for industrial processes and equipment.

The complete solution strategy for protecting critical machinery that covers three real-world scenarios is based on a continuous integrated reliability monitoring and maintenance with the TI software program, which uses five monitoring components.

These real-world scenarios are

- Unpredictable events
- Predictable events
- Controllable events

Unpredictable scenarios are events that happen suddenly and without warning. For example, a metallurgical imperfection or slug of water from the other boiler may cause a blade to snap suddenly. If such an event occurs, a decision to trip must come instantly and be integrated with process control to orchestrate the machine, area, or plant shutdown. In addition, machine health information gathered before and during the trip will aid the assessment of what happened.

Predictable events are machine malfunctions that are detected and tracked months in advance of a planned outage. Maintenance planners use this information to identify the area of the fault and fault type, gauge its severity, order parts, and plan the outage. When machine malfunctions in this category are monitored, business decisions can be made to continue running the machine and possibly damage the machine versus determining the optimal time for scheduling the outage, manpower, and parts. In parallel, the protection system involves monitoring for a sudden turn for the worse to protect from catastrophic failure.

Controllable events represent a class of scenarios that provide the largest return on investment for monitoring capital outlay. In addition, controllable scenarios provide the best opportunity to optimize industrial processes and equipment performances and reliabilities. For example, on an annually cold day, the operator ramps up a turbine and receives an oil whirl vibration alert from the predictive vibration monitoring system and simultaneously sees a low-temperature alarm from the process control system on the same bearing. This is a controllable scenario, and the operator knows exactly what to do. Reducing the revolutions per minute (RPM) of the turbine will immediately stop the oil whirl from damaging oil whirl condition when the turbine is brought back online. In controllable scenarios, an operator simultaneously has both machine reliability and process status/health and is able to avoid problems that would otherwise lead to degraded machine reliability.

The five monitoring components required for the complete solution of a continuous integrated reliability monitoring and maintenance of industrial processes and equipment are as follows:

- Protection monitoring
- Prediction monitoring
- Prevention monitoring
- Reliability monitoring
- Reliability growth and degradation monitoring
- Integrated reliability monitoring

Integrated reliability monitoring and maintenance of manufacturing processes and industrial equipment can now be best practiced using information gathered through online monitoring with the TI model–based program that integrates multiple monitoring components as shown in Figure 14.1.

14.4 Online Monitoring and Maintenance with a TI Model–Based Program

Continuous online monitoring of manufacturing processes and critical equipment represents technology well beyond systems that provide only periodic snapshots of an operation. Yet some critical situations can be averted only if a stream of data regarding the current condition of the equipment are available. Online monitoring with the TI software program can now make it possible to continuously obtain information about the reliability of a whole range of gas or steam turbines, generators, compressors, fans, motors, pumps, and the like. The cost-effective design, manufacturing processes, and industrial critical equipment that are essential to the success of the operation can be watched automatically with the help of the TI technique.

Some of the existing automated monitoring systems were dedicated to expensive steam-driven power-generating turbines. Data received directly from a machine are stored on a hard drive, buffered, and presented in a variety of plots that depict exactly what is occurring within that machine. Maintenance engineers and machine specialists suddenly had never-before-available information to use in analyzing changes in the machine's operation, but with the TI model, $Q_{i(\mathrm{N})} = aQ_{i-1}{}^{b}$, it is possible to make the component quality factors, $Q_{i(\mathrm{N})}$, valid for all N of both minimum and maximum component quality condition factor ($Q_{i\max}/Q_{i\min}$) variations. Ultimately we would like to

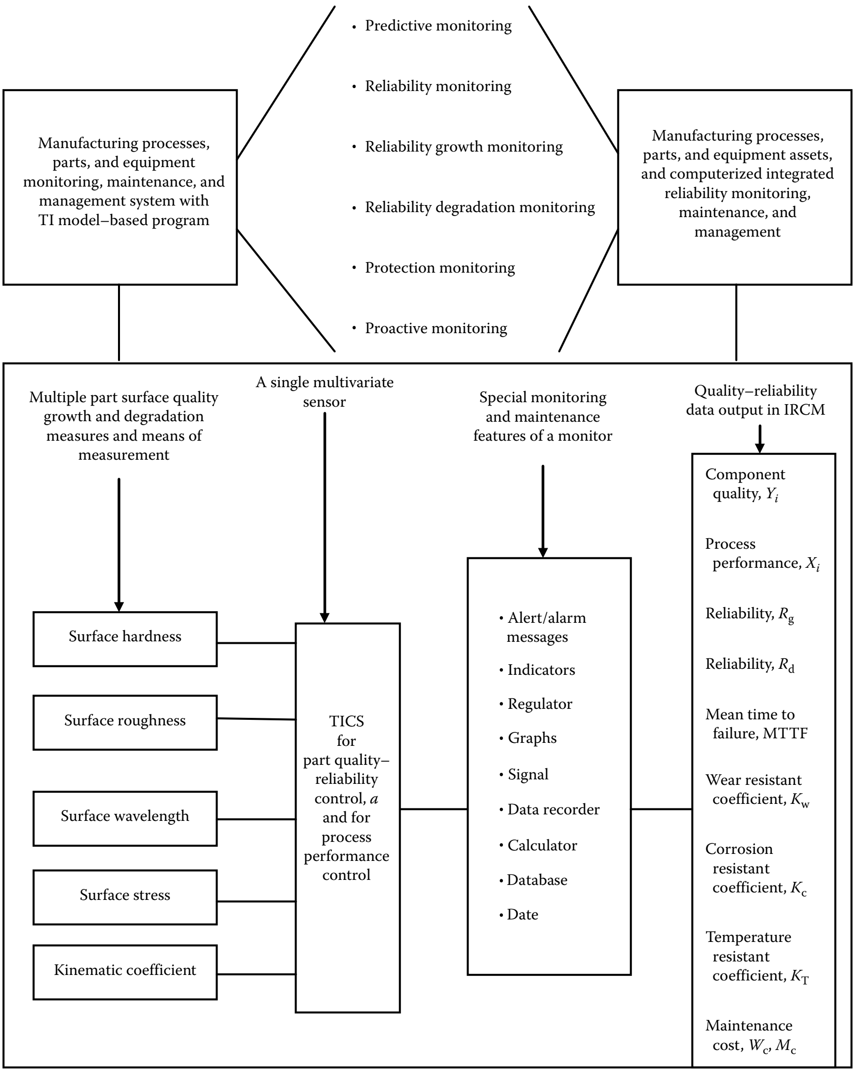

FIGURE 14.1
Online IRCMM networking structure with the TI model–based program.

get a quality factor or reliability (R_{ik}) distribution over N length of time or TI coefficient (a_i), indicating the probability of failure. For any given N, this can be computed from the reliability, R_{ik}, through integration of Q_{iopt}, with the TI coefficient (a_i):

$$R_{ik} = \int_{t_i}^{t_{max}} Q_f \, dt \tag{14.5}$$

where Q_f is the quality factor of components. In terms of the TI coefficient a_i, the reliability coefficient R_{ik} is expressed as

$$R_{ik} = \int_{a_i}^{a_{\max.}} Q_f \, da \qquad (14.6)$$

$$R_{ik} = \int_{b_i}^{b_{\max}} P_f \, db \qquad (14.7)$$

The computational complexity of each evaluation of this integral comes at a computational cost of designing a TICS that can measure a_i at any point of N distribution. This model can therefore be used to compute for the failure cost threshold, values of all component condition variations, and reliability growth/degradation thresholds. When N is over the highest point of a high metric variation, $a_{in} > a_{\min(N)\text{thresh}}$, the operation mode will be under *protection monitoring* that shuts down production processes and plant equipment. But when N is over the highest point, which is indicative of a low reliability variation, the operation mode is therefore said to be under *prediction monitoring*, where $a_{in} > a_{i(\text{maxthresh})}$ and $b_{in} > b_{i(\text{maxthresh})}$. When N is within the low metric variation, the operation is in the selection mode.

When the system is properly interpreted and assessed with TI coefficients a and b, the threshold signals are used to pinpoint the location, nature, and severity of developing problems like wear, corrosion, and high temperature as well as the optimum reliability growth during production processes. The different reliability parameters of component surface roughness, surface hardness, surface wavelength, stress concentration factor, dynamic coefficients, and relative inheritance ratio as inputs into the system can be transferred from one operation to the other as well as from one mode or point to the other in the same technological system. This sequential transfer of component condition parameters allows the parameter to be monitored accordingly and helps in locating the source and mode of failure and reliability growth, using the TI coefficient for reliability growth and degradation (a_d and a_g) to measure their values. The efficiency growth and the efficiency loss can be measured with the help of the TI coefficient for performance and efficiency loss control (b). The data from the automated monitoring system with the TI model–based program enable manufacturing processes and plant equipment personnel to predict, detect, and select with greater accuracy when a component will need maintenance to prevent damage and avoid lost production. Machinery management recognizes the significance of each machine in a production environment, focusing greater attention on those industrial equipment that, if stopped, would likely shut down all or a major section of the plant. Online monitoring with the TI technique assures that the condition of production processes and plant equipment is being assessed continuously.

14.5 Integrating Critical Component Reliability with a Process Control System Using the TI Model–Based Program

The TI technique can be applied to protect critical equipment and components that compare machine reliability with the component condition reliability model. Compressors, boilers, and stream or gas turbines are the most commonly modeled types of critical equipment, but a TI model can be computed on literally any machine in a plant. Equipment reliability deteriorates primarily due to fouling or buildup on blades and other surfaces, thus leading to less efficiency. The consequence is more energy usage and potential lost throughput.

Equipment reliability monitoring systems use existing process measurements, but with the TI model, equipment reliability and health can be integrated with process control to provide a truer picture of how well that equipment is actually performing. In other terms, actual process performance loss and component quality degradation versus design for the given operating conditions are determined. While plant personnel may be aware that the performance of a piece of equipment is below normal, they may not know the significant cost of lost/heat rate, excess energy usage, and system reliability. The knowledge of the component and process reliability coefficient and the subsequent TI coefficients can now help and lead to the understanding of the root cause of degradations and failures as well as the prediction of the maintenance costs.

The most important element of reliability monitoring is for experts and researchers to build a TI model to validate the large amount of input data. The model will be used to analyze system reliability and the health and failures of manufacturing processes and industrial critical equipment and formulate actionable recommendations with the results of the analysis. Reliability and maintenance specialists are able to identify lagging performance, failure modes, and the reliability of machineries that have not been recognized by either production or maintenance personnel.

The modeling input is the component quality condition parameters ($Y_{i-1\mathrm{opt}}$), from an optimum finished manufacturing process. These condition characteristics are passed on to the proceeding service operation (the equipment) to meet the desired optimum reliability and conditions of the equipment. Any variation from this optimum reliability value is determined by TI coefficient a, which controls the component reliability degradation, and equipment reliability b, which controls its efficiency loss and system reliability. The data can be analyzed either by on-site systems or remotely with off-site specialists. Analysis based on the TI model enables a specialist to select, detect, and predict with reasonable accuracy when a piece of equipment needs to be taken out of service for either the recovery of lost efficiency, a comprehensive overhaul, or a continuous reliability maintenance.

The future component and system reliability of manufacturing processes and industrial equipment can be evaluated based on real-time data to predict when the efficiency or process performance and the health or the component quality conditions of that unit will drop below a certain financial and reliability threshold point, which signals when it should be taken out of service or maintained proactively. In this way, component and system reliability values can be calculated with the formula of R_{ik} and TI coefficient data used for monitoring, which are complimentary to predictive maintenance as well as for predicting, detecting, selecting, and integrating model parameters. TI coefficients can also be used to determine the cost-effectiveness of maintenance operations, processes, tools, and management.

Integrating component reliability with process performance monitoring of an existing or any new production processes and plant equipment using the TI model can be demonstrated with a typical turbomachinery application. TICSs are mounted to bearings on a critically important machine that provides a continuous flow of component degradation measurements. A large turbogenerator may have about five bearings with one sensor at each bearing with other unique or without instrumentation—like speed sensors, differential expansion sensors, and case expansion sensors. There could be as many as different types of measurement at various locations down a machine train or dual measurements that can be carried out with an integrated reliability multivariable sensor that measures both a for measuring the quality–reliability of the parts and b for measuring the turbogenerator performance or power–reliability.

One cable leading from this type of sensor is connected to new online monitoring hardware (IRCMs), which is a complete online solution for a continuous CM of production processes and plant equipment. By measuring the detailed component degradation, in addition to maximum and minimum values of the degradation, the new turbomachinery protection system, which is intended as a retrofit on shutdown systems and has the ability to recognize developing machinery conditions and detect a severe condition requiring a shutdown, is necessary. In the rare unpredictable scenario of rapid catastrophic failure, the machine is protected when the generator reliability—$R_{ik(\mathrm{thmin})}$, $Q_{\mathrm{f(thmin)}}$, $P_{\mathrm{f(thmin)}}$, $Y_{i(\mathrm{thmin})}$, and $a_{i(\mathrm{thmin})}$—is reached.

Machinery and component condition quality parameters (Y_i) (component surface hardness, surface roughness, surface wavelength, stress concentration factor, relative speed coefficient, and others) are integrated with the plant's control system with the TI coefficient a. This coefficient is used to construct integrated reliability maintenance curves for production processes and industrial equipment as can be presented in an IRCM.

14.6 IRCMM Curves for Manufacturing Processes, Assembly Process, and Industrial Equipment

An excellent way to determine the maturity of the maintenance effort is not by looking at the age of the maintenance program, but where its focus is on the component part production reliability growth and equipment condition degradation curve *ICMGAERPF*, as shown in Figure 14.2. An organization that is constantly focused on point *F* and on staying clear of it will undoubtedly be a reactive culture. As the organization matures, the focus shifts from point *F* to point *P*. The organization then focuses its efforts on understanding how things fail and their ability to detect these failures early. Then another transition is made from the focus on point *P* to a focus on point *R*. These organizations use root cause analysis methods to eliminate or postpone point *P* and have applied best practices early on with fits,

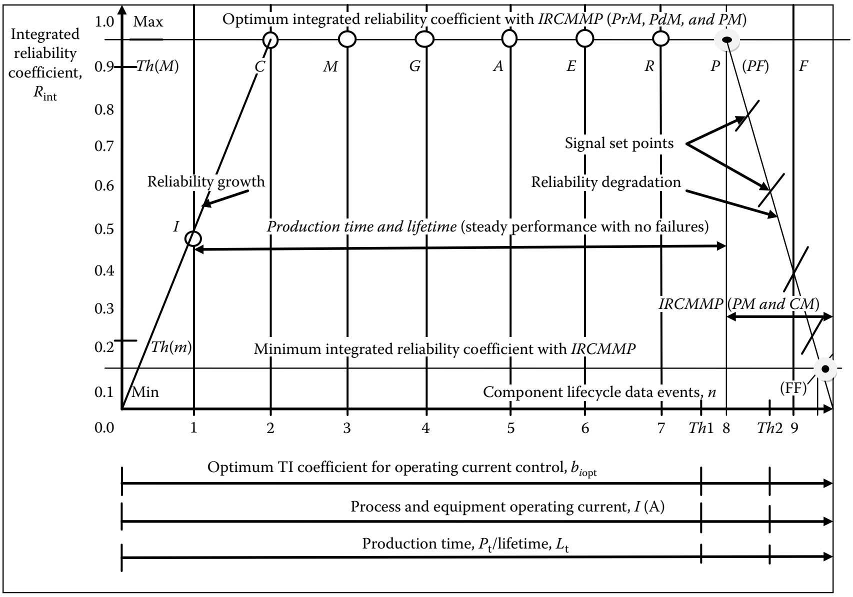

FIGURE 14.2
IRCMM curve for manufacturing processes and equipment with the TI model–based program. *Legend*: 1, Metallurgical process for part surface material, *I*; 2, coating deposition process for part workpiece, *C*; 3, workpiece surface machining process, *M*; 4, grinding process, *G*; 5, part–equipment assembly process, *A*; 6, – equipment process, *E*; 7, equipment run-in service data event, *R*; 8, equipment useful lifetime data event, *P*; 9, equipment wear-out data event, *F*; P_t, production time; L_t, lifetime; PF, potential failure; FF, functional failure; *Th*(*M*), maximum threshold point; *Th*(*m*), minimum threshold point; *Th*1, threshold point for potential failure; *Th*2, threshold point for functional failure; PrM, proactive maintenance; PdM, predictive maintenance; PM, preventive maintenance; CM, corrective maintenance; IRCMMP, integrated reliability condition monitoring and maintenance program.

tolerances, alignment standards, contamination control, induced manufacturing failures, and documented procedures. It is these groups who will see the step change in performance. Organizations that operate in a reactive mode typically spend all of their time reacting to failures. This behavior finds them with all of their focus around point *F* on the curve. For that organization to make a step change in performance, they will need to shift their focus to point *P*. As the organization shifts its focus to detecting defects early, they buy themselves a valuable commodity a maintenance organization can have—time. Time provides the ability to plan and schedule work at a substantially lower cost of execution. Detecting defects the moment they occur provides the maximum amount of time for the defect to be eliminated.

While detecting defects the moment they begin is not exactly possible, understanding the nature of the defects and how they are initiated and propagated is quite possible. A comprehensive inspection, reliability, and performance strategy performed at the correct interval or constantly will increase the conditional probability that the defects will be found very near their origination. Letting the defects progress down the curve or degrade changes the nature of the defect, making analysis more and more challenging and expensive as it crosses the threshold point minimum, th(min). Perhaps just as importantly, it makes the failure that much more expensive to correct.

The IRCMM curve program with the TI model from the initial operation to the final component part production operation will definitely increase the conditional probability and reduce maintenance cost. This program will help improve the component/system reliability and process performance conditions. With the application of the TI model, the optimal parameters of the initial component part conditions can be improved upon, maximized and optimized, while the optimized values of component/system quality–reliability and process performance–reliability can be sustained through an effective IRCMMS at minimum cost. This optimal condition of a particular finished equipment part is correctly transferred into the next operation—the equipment systems of a plant. Component production processes and equipment system conditions have been brought together under one platform with the help of the TI technique to form the IRCMM program.

The program is based on an IRCMM curve (Figure 14.2). The curve (ICMGAERPF) comprises of three main sections—the component reliability growth line (ICM), the optimum line (MGAER), and the equipment reliability degradation line (PF). The different lines represent the nature of component/system conditions. The first line (*I*–*M*) is the initial line of a component condition with reliability multiple parameters for wear, corrosion, fatigue, and temperature resistance purposes. Point *I* is the optimal material condition of the component part that suits the desired purpose (e.g., wear resistance), while point *M* is the improved component part condition by coating the part surface with hard alloyed materials. The component reliability growth from point *I* to *M* can be determined with the help of a reliability growth model, $Y_i = a \cdot Y_{i-1}^b$, where Y_i is the component/system quality parameter at point *M*, Y_{i-1} is the component/system at point *I*, *a* is the TI coefficient for component reliability growth control, and *b* is the TI coefficient of the coating deposition process condition. The same model is applied to obtain the initial component/system parameters at point *I*, where $Y_{i-1(\text{opt})}$ is the optimum value of the finished conditions of a component.

With the application of this model, through the manufacturing line, the component/system reliability continues to grow until it gets to maximum achievable reliability. From point *M* to *P*, the component part/system reliability can be sustained at optimum with the help of the reliability CM and maintenance program. At point *M*, it is important to note that hard alloyed coatings are difficult to machine to desired specifications by existing turning machine tools; a new method known as rotary turning with thermal spray designed by the author provides the optimum conditions for an improved reliability. The reliability continues to increase and improve with the right cost-effective finishing method. When grinding finishes the hard alloy–coated surface part, it is observed that at point *G*, the reliability decreases due to tensile stress induced into the machine part by using an existing method of grinding. This defect needs to be eliminated; if not, it will be transferred into the equipment system, which can cause a catastrophic failure during service operations at an early stage. The finishing is therefore done with the new method (RTPF) that can induce compression stress for a desired condition of a machine part. The reliability at this point becomes the maximum achievable reliability, where the process condition is optimized. The optimized parameters are passed on with a cost-effective reliability condition monitoring and maintenance strategy through the equipment system to point *P*. At this point, the wear, corrosion, fatigue, and temperature resistance conditions of the machine part are optimal, thereby causing the reliability and service life of component part/system to be optimal. This optimal level is sustained by a cost-effective integrated reliability monitoring and maintenance program.

The different lines of this cost-effective IRCMM curve represent the nature of component reliability growth and rotating equipment reliability degradation. The first P–F line is the philosophical progression of any given defect. Point *P* on the line represents the point in time when the defect enters the system. For example, point *P* could represent the exact moment in time where a particle of dirt comes between a rolling element and its raceway, producing a gouge in both components. No longer defect-free, the bearing's condition worsens as the defect matures, accelerating toward point *F* and the point of functional failure. Different points along the line indicate changes in the nature of the defect, which correlate to different inspection methods that can be used to identify the current status of the defect. The line *P*–*F* is due to negative TI.

The second is the MGAERP line, which is the optimum reliability baseline of manufacturing processes and equipment system. *M*–*G* is also the

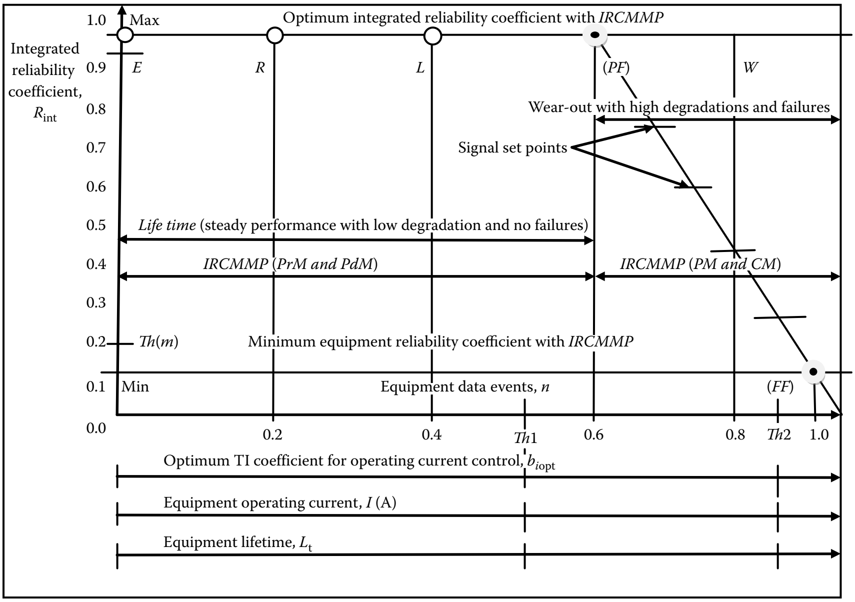

FIGURE 14.3
Equipment reliability CM and maintenance curve with the TI model–based program.

same baseline with *G–P* but from the manufacturing, assembly, and equipment operations that are failure-free. This is the line with the optimum quality and reliability of components. Point *M–P* is achievable with the help of the TI model. *I–M* is the initial line of a component with all necessary properties that can lead to maximum achievable quality and reliability. Points *I* to *M* are the lines known as positive TI for reliability growth. Figure 14.3 shows what the ERLPF lines provide when, for example, it is applied to two identical industrial equipment (e.g., pump) and four identical manufacturing lines (e.g., machining–grinding–assembly–equipment), which might look like when one machine is installed using precision measuring devices and well-trained crafts personnel applying IRCMM with the TI model–based program installed in one of the industrial equipment—1. The same well-trained personnel applies precision instruments for monitoring and maintenance procedures, but without the application of IRCMM with the TI model–based program installed in the other industrial equipment—2. Due to the fact that cost-effective IRCMM of manufacturing processes and industrial equipment and the TI model–based program operate with optimum condition throughout a critical part life cycle, the results offer optimum component/system reliability, lifetime, and cost-effectiveness, as shown in Figure 14.4. The TI model–based program is therefore more preferred to other existing monitoring and maintenance programs.

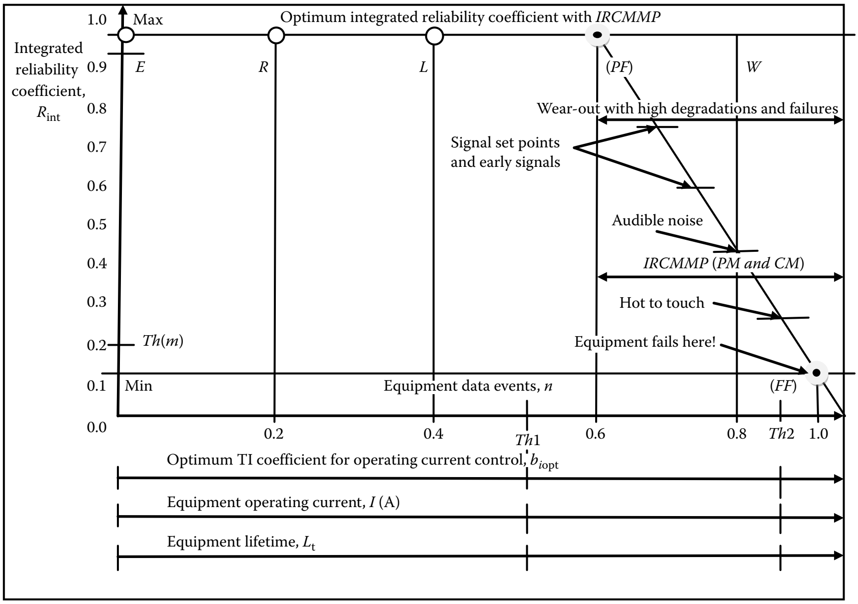

FIGURE 14.4
Equipment reliability condition degradation curve for IRCMM with the TI model–based program.

14.7 IRCMM for a Typical Turbine with the TI Model–Based Program

Motion control technology addresses two of the key issues that the wind power industry faces as it matures, moving offshore and the use of bigger turbines. But the clear focus is on the system reliability, which has become the number one design challenge that wind turbines must address. In addition to technology focus on gearboxes and generators, suppliers are looking at the entire drive train function system and how to use technologies such as gearbox health management tools, CM, ac brushless servomotors, and precision cooling systems to provide robustness and serviceability that the next generation of this alternative energy demands.

Instead of focusing solely on the gearbox as in the past, the TI software program focuses on electromechanical drive train with multiple functions. The feature is based on wind turbine drive train from where the rotor shaft connects to the gearbox and the other side where electrical energy comes out of the turbine, to boost system reliability and maintainability. The focus is on larger wind turbines (4…7 and up to 10 MW) developed for offshore operation and ways to keep the drive train stable by deploying optimum conditioning and cooling for the various key components such as bearing, gearbox, generator, and converter. It is a well-known fact that if the bearings and gearbox are well lubricated, are cooled with clean oil, have no moisture or humidity present, and employ a good filtration package, the gearbox is less likely to fail. If we can monitor the gearbox using a CM program that includes trends from component quality condition parameters (Y_i), component failure modes (F_i), and process condition characteristics (X_i) like temperature, pressures, speed, and others, like vibration and cleanliness of the oil and moisture, we can reliably predict failure or prevent failures by knowing what will happen in the gearbox over a time horizon. The component condition factor, which is the product of all the desired condition parameters, is represented in this book with a single metric, known as the TI coefficient for quality control (a_i). In the same model, the process condition parameters (X_i) are also represented by a single metric, called TI coefficient for process control (b_i) for an integrated reliability coefficient parameter (R_i).

These multiple condition parameters and the single parameters can be trended as well for integrated reliability monitoring and maintenance, which can be controlled remotely with the help of the TI software program. IRCMM with the TI model–based program can be applied in wind turbines remotely. With the trend moving toward larger turbines and offshore applications because of the availability and consistency of the wind, an important focus is on serviceability and service intervals of these offshore installations. This of course is driving suppliers to better control temperatures in the gearbox and to the optimization as well as monitoring of cleanliness of the oil in the system. To get service people on board in an offshore turbine, it normally means you need a ship or helicopter. As a result, suppliers are improving the lubrication systems and increasing the lifetime of the filters, so it is a maximum of once a year to 18 months service interval. With the TI software program, equipment lifetime and service interval can now be increased, and more importantly for maximum achievable reliability, designed components can be increased to optimum value. Users can now employ an online connection to assess when they need to schedule maintenance on turbines with the help of the TI models, tools, and programs. With the ability to program the measuring and monitoring devices, reaching a threshold of reliability coefficient level indicates it is time to change the element, adjust the settings, and carry out the desired maintenance strategy. Remote IRCMM with the TI model–based program also allows for preventive, predictive, and proactive maintenance events that reduce the cost of service.

If everything is running smoothly and there is no extensive wear on bearings, it is normally alright to use continuous real-time procedures, but performance is also dependent on the gearbox itself, vibration, alignment, loads, and other factors. The TI model–based software program has helped integrate multiple functions into a single platform that combines the component conditions, processes, and control parts of the total system, which also allows measurements to be trended on a continuous basis and specific commands to be used to prevent further damage, which is toward a sustainable development of reliability, maintenance, and management programs.

14.8 Conclusions

1. It has been ascertained in this book that the ability of manufacturing processes, parts, and industrial equipment to adjust its own functionality according to its reliability, health, and lifetime status is an integral part of a self-maintenance paradigm, which requires both process functional intelligence and component reliability intelligence that can be integrated and determined with the help of the TI model–based program.
2. IRCMM technology with process loop network system provides optimum reliability, health, lifetime, and automatic cost-effective precision maintenance.
3. IRCMM technology consists of functional multiple components under a single platform and program.
4. The main advantage of IRCMM technology over the existing vibration technology is its integration capability of reliability, CM, and maintenance and its cost-effective protection, prediction, and detection features as well as the optimum selection and testing devices with the TI model–based program.
5. IRCMM with the help of the TI model–based program is used to monitor the reliability growth and degradation of components/systems from the initial to final operation of a critical part during design and manufacturing of processes and industrial equipment.
6. IRCMM with the help of the TI model–based program can be used for optimum component/system selection and design of IRCMM tools in the network system for manufacturing processes, parts, and industrial equipment.
7. An integrated reliability monitor is a hybrid hardware that performs multiple functions on a single platform for reliability growth/degradation monitoring of manufacturing processes, parts, and industrial equipment.
8. Online monitoring and maintenance functions of IRCMM with the help of the TI model–based program now make it possible to continuously obtain information about component/system reliability, lifetime, and health of a whole range of gas or steam turbines, generators, compressors, fans, motors, pumps, and other critical equipment.

9. IRCMM with the help of the TI model–based program is used to construct integrated reliability–performance distribution curves/mechanisms of manufacturing process, part, and equipment system for the selection of maintenance tasks and strategies as well as for reliability condition monitoring and maintenance analysis.
10. IRCMM with the help of the TI model–based program is a complete solution strategy for protecting critical industrial equipment that covers three real-world scenarios, which are based on multiple reliability monitoring and maintenance functions.
11. IRCMM with the help of the TI model–based program offers multiple benefits that determine the desired level of monitoring and maintenance that is required to keep the system at a needed level of capacity, effectiveness, and reliability at minimum life cycle and maintenance costs in the industries of the future.

15

Integrated Reliability Management with a Technological Inheritance Model–Based Program in the Industries of the Future

15.1 Effective Reliability Condition Monitoring and Maintenance Management with a Technological Inheritance Model–Based Program

Effective reliability condition monitoring (CM) and maintenance management with the technological inheritance (TI) model–based program examines the role of monitoring and maintenance in minimizing the risk of safety, failures, environmental incidents, adverse effects, and loss of profitability. In addition to dealing with risk reduction tools, it also explains their applicability to specific situations, thereby enabling you to select the tool that best fits your requirements throughout the monitoring and maintenance process. Intended to bridge the gap between maintainers and reliability engineers, this book is sure to help businesses utilize their assets more effectively, safely, successfully, and profitably through optimum selections, reliability, and life cycle cost assessment with the TI software program.

Maintenance may mean different things to different people. Senior managers and accountants may see maintenance as a cost problem that should be minimized. At the working level, some people may see it as a set of preventive, corrective, or breakdown rectification activities. Some classify it as reactive or proactive work. To some others, it means predictive, planned, or unplanned activity. All these are merely the various dimensions of maintenance. They are valid descriptions but do not address its functional aspects. The author has looked at the role, dimensions, and functions of maintenance and its strategic contribution to the health of a business.

In this book, the author examined the role of monitoring and maintenance in preventing failure event escalation and how it helps retain the integrity and productive capacity of manufacturing processes and equipment over its life. The strategic role of maintenance is to help maximize the profitability of a business over its life. We looked at how appropriate maintenance strategies can help manage risk, failures, and component/ system reliability performance effectively with appropriate planning. Planning is the process of thinking through the execution of work. In the course of preparing a plan, we can identify potential pitfalls and find solutions in anticipation of the problems, thereby improving the quality and speed of execution. Planned maintenance is that which is correctly prepared sufficiently ahead of its execution. All preventive (PM) and predictive (PdM) maintenance strategies can be planned, scheduled, and proactively executed.

In most cases, we can plan corrective maintenance as well with the help of CM and with the use of TI coefficients, but there is less time available to schedule the work since the onset of failure has already occurred. The term scheduling means the allocation of suitable materials and resources as well as assigning a start and finish date to the work. When it comes to breakdown maintenance however, we do not know the exact scope and timing in advance. It is difficult to plan such work effectively, except in the most generic terms. Hence, breakdown maintenance tends to be less efficient in terms of resource utilization and control of duration.

People tend to regard PM and PdM as good while they frown on breakdown maintenance. This view is fashionable but incorrect. It has resulted in unnecessary maintenance expenditure and equipment downtime. There are many failure modes that have little or no effect in terms of consequences on the system or plant as a whole. In such cases, it is economical to allow the failures to take place before taking any action. PM became very popular after the Second World War, when the mass production industries enjoyed a period of rapid growth. It became fashionable to apply PM strategies as a matter of policy, even in industries where the economic logic was different. The result was that items of equipment became *due* for maintenance, even though they were performing perfectly well. There are situations where each of the strategies is appropriate and the author has based the selection on the most appropriate and effective way to reduce risks and failures with integrated reliability monitoring and maintenance management (IRMMM) program. Here, the consequences are negligible, the risk is low, and so a breakdown strategy can be appropriate. If there is a threat to safety, production, industrial equipment, or the environment, proactive, preventive, and predictive strategies are appropriate. This will therefore require an integration of reliability, monitoring, and maintenance strategies with a careful and cost-effective design through manufacturing processes to service operation systems. A cost-effective IRMMM of materials, parts, manufacturing processes, and equipment system is possible with TI coefficients, since the optimum baseline requirements are determined with TI coefficients for all generic components with $a_{i\text{opt}}$ and for all generic processes with $b_{i\text{opt}}$. With TI coefficients, it is possible to predict the different optimum component and process conditions as well as the failures from design, through manufacturing processes and service operations of the same generic network management system and application.

15.2 IRMMM for Manufacturing Processes and Industrial Equipment Systems

An IRMMM incorporates major effective maintenance improvements and integrates the different systems of design, manufacturing processes, and service operations together under one platform. This type of IRMMM can be implemented for any system defined as a hierarchical distributed network of intelligent elements (HDNIE), comprising primarily of the following:

1. Architecture of a material–part–process–equipment–sensor–device system for an industrial plant
2. Intelligent elements with TI coefficient metrics
3. A conceptual framework with measuring instruments and data acquisition devices (DAQs)
4. Ontology that defines optimum conditions, standard requirements, and protocols with TI models

The industrial plant is a system that comprises multiple subsystems (e.g., a system of multiple possibly interacting flow subsystems that include pumps, motors, boilers, tanks, sensors, and parts like bearings, seals, couplings, and valves). The term intelligent is used in the sense of artificial intelligence with the help of TI coefficients *a* and *b*. An intelligent element in this case is both physical and virtual, which is network enabled and is able to measure and manage data, information, and knowledge focused on determining its condition parameters and condition variations like reliability growth and degradations. Reliability signifies the functionality and system/component integrity of an engineering system, subsystem, or process leading to the determination of the health, growth, and

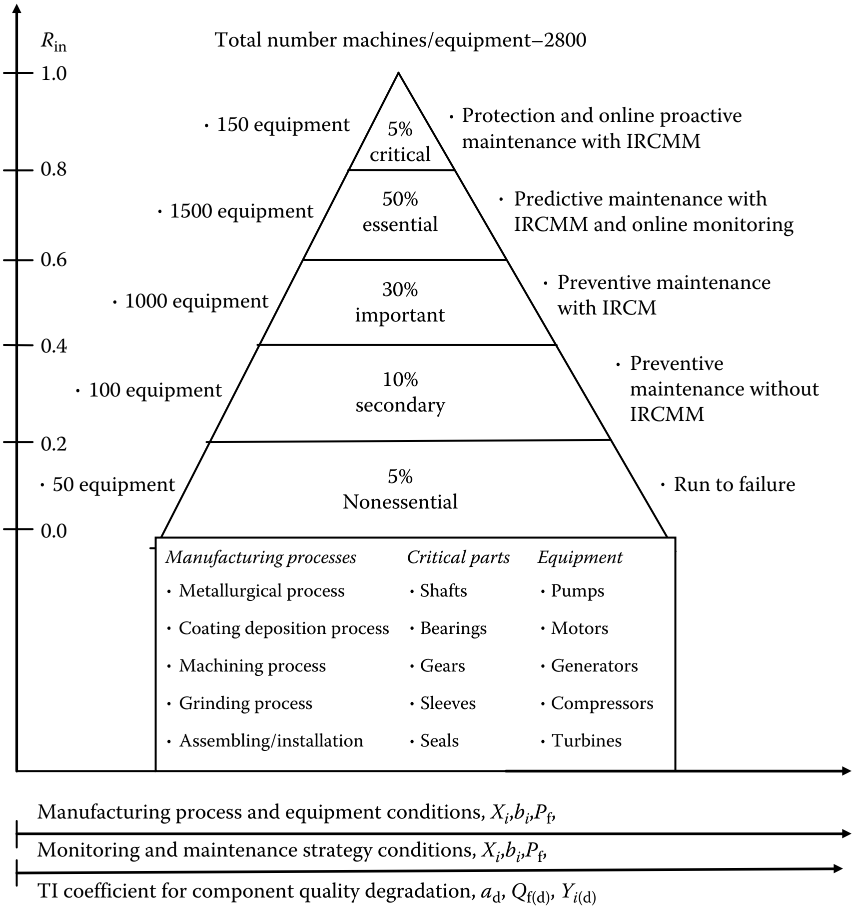

FIGURE 15.1
A typical industrial process plant and tasks for integrated reliability condition monitoring and maintenance (IRCMM) with TI model–based program.

failures of components/systems and processes. The processes signify manufacturing processes and service operation element where functionally related sensors are grouped. An element can signify a component (e.g., an actuator, sensors, a valve, equipment, bearing, seal, a process, controller, a subsystem, or a system) which is classified with TI coefficients. (Figure 15.1).

The term "integrated reliability monitoring and maintenance management system" is used to describe a capability that focuses on determining the optimum reliability, monitoring, and maintenance of every critical element in a complex system (detect anomalies, diagnose causes and prognosis of future anomalies, and provide data, information, and knowledge, not just data to control systems for safe and effective operation, but also for cost-effective maintenance). The purpose of an intelligent integration is to enable automated analysis of physical phenomena in imitation of human reasoning, including the use of qualitative methods and techniques. Intelligent integration is said to occur in a system in which all critical elements are intelligent and can acquire, maintain, and share knowledge and information. The elements of this type of plant system are considered to be intelligent in that they determine their own conditions within an integrated scheme that involves consideration of data, information, knowledge bases, and techniques that reside in all elements of the system. The conceptual framework of the HDNIE and the methodologies of implementing it enable the flow of information and knowledge among the elements so as to make possible the determination of integrated reliability parameters and monitoring and maintenance of the elements involved in the generic components. The necessary information and knowledge are made available to each affected element at the desired time, satisfying a need to present information overload while providing context-sensitive information at the proper level of detail. Provision of high-quality data is a central goal in designing this integrated reliability monitoring and maintenance management system (IRMMMS). In pursuit of this goal, functionally related individual and TI coefficient sensors are logically assigned to groups' denoted process and component. The HDNIE of this IRMMMS can be regarded as consisting of a framework containing object models—TI *models*—that encapsulate all elements of the system, their individual and relational knowledge bases, generic methods, and procedures based on models of applicable physics and communication processes (see Figure 14.1). The framework enables effective implementation of maintenance tasks through operators with the help of the following:

1. Accurate data, information, and knowledge from various components and systems
2. TI model–based software program that assists in rapid visualization of the component and process conditions
3. Analytical software tool that assists in reasoning about the conditions
4. Sharing of information via network communication hardware and software
5. Integrated reliability monitoring and maintenance programs that aid in making prompt decisions to remedy unacceptable conditions or improve integrated reliability throughout design, manufacturing processes, and equipment

15.3 IRMMM Tasks with a TI Software Program for Manufacturing Processes, Parts, Industrial Equipment, and Sensor System

The application of the TI model—software defined measurement and instrumentation in monitoring and maintenance analysis, using the TI coefficients to plot integrated reliability monitoring and maintenance distribution curves with TI coefficients for the selection of monitoring and maintenance tasks for all the intelligent elements of component and process system. Certain tasks are applicable in addressing failures. The kinds of failure, namely, whether it is functional or potential, and the shape of the distribution curve help determine the applicable task as well as the work volume. The tasks identified by such analysis would usually consist of some failure modes requiring preventive and predictive works, others requiring corrective work, and some others allowed to run to failure. We can work out the correct ratio for each system in a plant, through the determination of the ratio of maintenance work volume to the total for the continuous monitoring and improvement of manufacturing processes and industrial equipment. We can therefore monitor plant's component/system health and reliability continuously within the cycle of design, manufacturing process, and service operation. This enables us to improve the effectiveness of monitoring and maintenance operations. The TI model can be used to represent the monitoring and maintenance process in four phases. The first of these is the planning phase, where we think through the execution of the work. In this phase, we evaluate alternative monitoring and maintenance strategies in terms of the probability of success as well as costs and benefits. In the next phase, we schedule the work. At this point, we allocate resources and finalize the timing. In the third phase, we execute the work, and at the same time, we generate data. Some of these data are very useful in the next phase, namely, that of analysis, and we have discussed how the data needed are collected with reliability acquisition devices (RADs) in the previous chapters. The results of the analysis are useful in improving the planning of future work. This completes the continuous improvement cycle. Figure 9.10 shows the phases of the integrated reliability monitoring and maintenance cycle with the TI software program for manufacturing processes and industrial equipment. Effective management must focus on the improvement of all the phases of the monitoring and maintenance tasks. This can be managed with the help of good computerized integrated reliability monitoring and maintenance management (CIRMMM) with the TI network program. CIRMMM is also known as material–part–process–equipment–sensor system management. A CIRMMM software package maintains a computer database of information about an organization's maintenance operations. This information is intended to help maintenance workers do their jobs more effectively and to help management make decisions (e.g., calculating the cost of maintenance for each piece of part, process, and equipment used by the organization, possibly leading to better allocation of resources). The information may also be useful when dealing with third parties. A typical package deals with some or all of the following:

- Work order (WO): Scheduling jobs, assigning personnel, resuming materials, recording costs, and tracking relevant information such as the case of the problem (if any), downtime involved (if any), and recommendations for future actions
- PM
- PdM
- Proactive maintenance (PrM)
- Part, process, and equipment evaluation (PPEE)
- Monitoring and maintenance optimization (MMO)
- Root cause analysis (RCA)
- Inventory control (IC)
- Safety

A CIRMMM system truly can be a manager's best friend, by enabling engineers, technicians, operators, and maintenance personnel to gather and store vital information in its database and giving managers valuable data to analyze these systems to make smarter decisions. The key, however, to making smarter decisions involves

- Ensuring that everyone understand the importance of having meaningful data in the system
- Knowing how to use the CIRMMM data effectively
- Designing and implementing various codes into the system that allow a manager to access the data and make intelligent decisions (i.e., appropriate codes for problem, cause, and remedies)

Data entry and analysis

The following outlines some examples of reliability and health data to be entered in the system, the type of analysis, and expected or predicted results:

1. Predicted and actual reliability/health of parts, processes, and equipment with time/conditions
   Predicted data and time should be entered on as many WOs as possible. In integrated reliability monitoring and maintenance system, a RAD (integrated reliability sensor [IRS], reliability coefficient generator [RCG]) that measures reliability growth and degradation of parts,

processes, and equipment conditions is used. They can be applied as handheld or on a continuous basis. The integrated reliability sensor (IRS) measures and records continuously at all times, including random events with RCG and emergency repairs and breakdowns (WOs). The measured data are analyzed, presented, and distributed accordingly to the appropriate quarters by an integrated reliability growth monitor (IRGM) and an integrated reliability degradation monitor (IRDM).

All PM, PdM, PrM, and other planned WOs, however, can be assigned estimated/predicted data and times. If managed right, these should account for the majority of the WOs. Once a job is complete, actual data and time spent by each technician or by the system on the job should be entered into the system. It should reflect overtime, double, etc.

Component/system failures

- The type of failure we can see are as follows:
  - Wear
  - Corrosion
  - Heat
  - Looseness
  - Cracking
  - Noise
  - Vibration
- The causes of failure are as follows:
  - Lubrication
  - Seals
  - Balance
  - Alignment
  - Bearings
  - Shafts
  - Contaminations
- The machine part failure and quality condition parameters are as follows:
  - Surface roughness (R_a)
  - Surface hardness (HRC)
  - Surface wavelength (λ)
  - Stress concentration factor (ε)
  - Kinematic coefficient (k)

A computerized integrated reliability monitoring and maintenance management system (CIRMMMS) can report the variance, growth, and degradation in predicted versus actual parameters and time.

Managers should closely analyze any variance, growth, and degradation and identify the root cause—either the estimates/predicted are inaccurate or someone is not following the instructions, and therefore, actual data times are off. Also the sensor/meter used could be faulty. Based on the findings, data should be corrected. After a period of time, you will have a valuable database and time estimates.

Benefits

- Components (critical part surface) and equipment condition parameters with time are used to assess the reliability, lifetime, and health of processes and equipment.
- It allows comparison of two equipment, instruments, processes, and people doing identical jobs or operations (say PM, PdM, PrM). If a significant data variance, growth, degradation, or time difference is reported, a manager can analyze the reason and take corrective action.
- It helps in planning, scheduling, and setting up accurate reliability, lifetime, and health requirements.
- It enables better forecasting of manpower requirements.
- Based on overtime spent for a given time period and condition, it is easier to justify additional manpower.

2. Root cause

   Where applicable, for all unplanned jobs and operations (emergency, repair, breakdown, etc.), reliability, performance, and health data should be collected as to what the problem was, what caused it, and what was done to correct it. This involves designing a proper coding system—easy to use and understand, yet very powerful in terms of results—allowing data gathering and analysis with the help of TI models and integrated reliability maintenance–monitoring curve diagram.

   Analysis of data by managers will aid in finding the root causes of the problems. Breakdowns and failures are never planned and can cause significant loss of productivity and resources. Finding the root cause of a failure provides an organization with a solvable problem. Once the root cause is identified, a fix can be developed and implemented, preventing a recurring failure situation.

3. Warranty

   Warranty information should be entered into the system for each asset (equipment and/or facility) as to warranty period and nature of the warranty; the same applies to spare parts. Each time a WO is issued for an asset that is under warranty, CIRMMMS should flag a message stating this equipment is under warranty. The warranty can be calculated with TI models. This in turn gives managers a chance to make an intelligent decision—whether to go ahead with a repair. Such an approach can save hundreds of thousands of dollars over a period of time.

4. Backlog
   Managers should see to it that walk orders are being closed in the CIRMMMS within 24 h of the job completion. This will ensure that the data in the system are current. A report generated by CIRMMMS that shows *overdue WO* can be used to control the backlog. A controlled backlog is key to PrM.
5. Outside contractor
   Most maintenance operations use outside contractors to perform certain PdM, PM, repair, and other tasks. While the percentage may vary from operation, in some plants, up to 60% of total work might be done by outside contractors. An effective CIRMMMS should contain a database of these contractors. Each time a job is assigned to outside contractors, history should be captured in the system—just like your other WOs, except these are not outside contractors' performance and the quality of work, delivery dates promised and kept, etc., also should be gathered. Managers can analyze these data to
   - Gauge contractor performance and take corrective action if necessary
   - Justify additional in-house resources
6. WO priority
   Ideally each piece of component part and equipment should be assigned a level of criticality. For example, assign a number from 1 to 5 with 5 being most critical part or equipment. Each job then should be assigned a level of priority. For example, assign a number from 1 to 5—with 5 being the highest priority for that job. CIRMMMS can determine the priority of each WO based on equipment criticality and job priority. The planner can then plan and schedule WOs based on WO priority and the set baseline standards are derived with TI coefficients. The equipment with the highest criticality level is the one with the highest criticality index (a_i). Criticality index can be determined with the TI coefficient a, with values from 0 to 1, based on the desired reliability of component/equipment and probability of failure. The control limit of functionality for each level is determined with the TI coefficient b, which must be the same for all processes and equipment.
7. Labor skill
   You can enter the skill of each technician in the system based on the skill:
   - A WO can be assigned to proper personnel.
   - CIRMMMS can report if there is a certain skill set in-house, enabling the manager to make an informed decision on whether to seek outside help.

8. WO type
   Each WO should be assigned a WO type such as PdM, PM, PrM, repair, routine, and inspection. Doing so lets managers review jobs by WO type. For example, you may want to review how *repair* jobs have been done in the last 12 months. Further analysis can be done to see how many of these were for a particular piece of equipment. Ultimately, this knowledge can lead to a replacement versus repair decision.
9. WO material, labor, and tools
   A properly planned WO (PM or otherwise) contains information on what parts and tools are needed and what type of labor (plumbing, carpentry, etc.) is required to do the job. It helps managers eliminate unnecessary delays. Otherwise, technicians may get to a job site and discover that tools and materials to perform the task are missing, thus requiring an extra delay if parts are not in stock.
10. Trending of sensors/meter readings
    Monitoring and maintenance operations frequently gather readings on equipment such as boilers, chillers, pumps, turbines, and generators. In a paper-based system, forms are filled out and filed away—never to be seen again. Use your CIRMMMS to record and save readings of pressure, temperature, surface roughness, surface wavelength, and other component/system condition parameters. One of the purposes of these problems is to identify failures and determine component/system reliabilities, health, and lifetime.
11. Processes/equipment type
    Processes/equipment type and subtype information is very useful. It entails a one-time design and data entry efforts—while entering a new piece of equipment in the system—and is well worth the results. For example, an equipment type is *pump*, while subtype for pump could be hydraulics, pneumatic, electric, etc. There can be further subtypes to these. (This concept applies to spare parts as well.) Analysis of these data provides the following benefits:
    - A manager knows what he or she has in equipment and part inventory, for example, the number of pumps in the plant and then a breakdown by types of pumps (i.e., how many of these are hydraulic pumps).
    - It allows scheduling of PM by equipment types and subtypes.
12. Equipment manufacturer information
    For each piece of equipment in the system, enter the model and serial numbers. This information is invaluable when you need to find all equipment in-house by a certain manufacturer and model.
13. Attach documents
    You can attach Processing Development Environment (PDE), Computer-Aided Design (CAD), Word, Excel, video, digital pictures, and many

other types of documents to maintenance (equipment, parts, WO) records. This is a tremendous help in troubleshooting—if you have attached an Operator/Maintainer manual to the equipment record, it will be available to technicians at the point of performance—and in providing work instructions by attaching sketches and drawings to a WO.

14. Part lists
    Enter a list of parts required to maintain a piece of equipment. This is also referred to as *bill of material* (BOM). Information should include part number and description, as well as part suppliers' details. This information is very useful when you have an equipment breakdown and are looking for a particular part to fix it. Having the part information at your fingertips can save substantial time in locating the part and minimizing equipment downtime.
15. ABC part analysis
    You can categorize your parts into A, B, and C, where "A" parts are most expensive and critical and "C" are just the opposite. This helps managers focus their energy and resources on the right group of parts:
    - Start your cycle counting efforts with "A" parts.
    - Get rid of obsolete parts starting with "A" parts, as that is going to give you the most return on your investment.
    - Spending resources in trying to obtain better part pricing starting with "A" parts.

The following are the characteristics of "A" parts in CIRMMM:

1. A group of parts in the same industrial equipment (bearings, shafts, pipes, gears)
2. A group of parts with the same failure mode (wear, corrosion, temperature, fatigue)
3. A group of parts with the same failure resistance surface conditions (R_a, HRC)
4. A group of parts with the same failure resistance coefficient ($a_{i(\mathrm{kw})}$, $a_{i(\mathrm{kc})}$, $a_{i(\mathrm{kt})}$, $a_{i(\mathrm{f})}$)
5. A group of parts with the same production line (metallurgical, coating deposition, machining, grinding processes)
6. A group of parts with the same applications (power generation steam turbines, industrial drive gas turbines, hydroturbines, centrifugal compressors, fans, blowers, pumps, gears, and motors)
7. A group of parts with the same instrumentation (sensors, component quality factor sensor [CQS]/process performance factor sensor [PPS]; monitors, integrated reliability growth monitor [IRGM]/integrated reliability degradation monitor [IRDM])
8. A group of parts with the same management device (CIRMMM) (Figure 15.2)

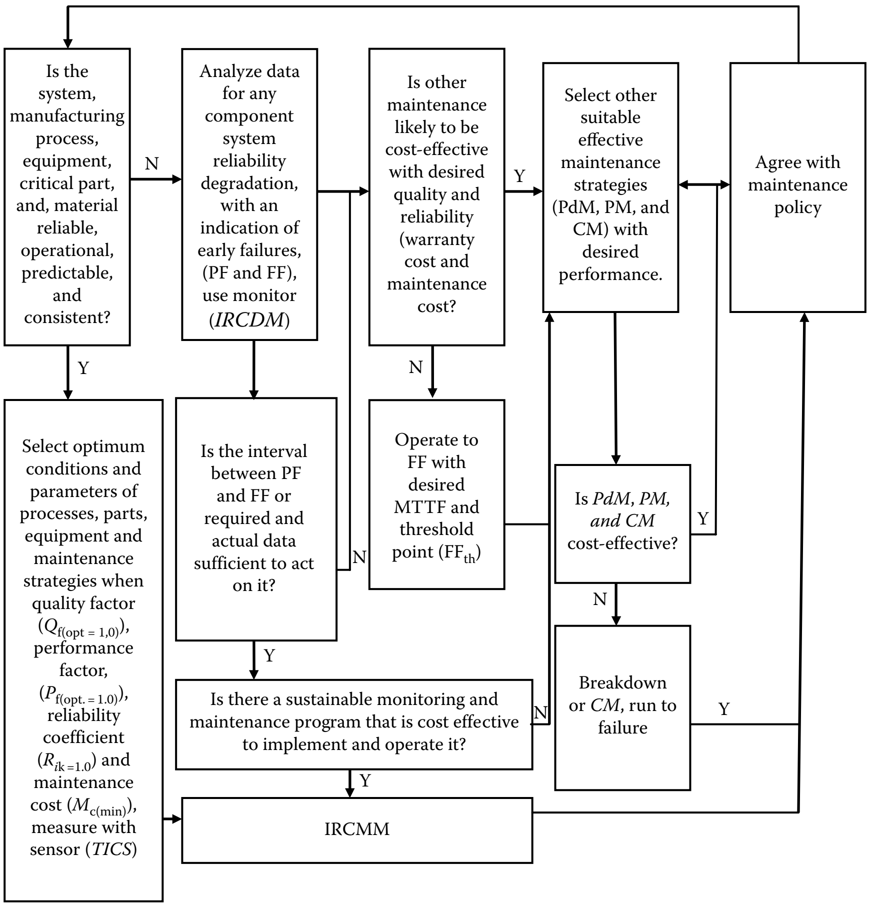

FIGURE 15.2
IRCMM decision diagram with TI model for parts, processes, and equipment.

15.4 IRCMM Technology of Manufacturing Processes, Parts, and Industrial Equipment with a TI Device Manager Software

In order to ensure that a device management software package is fully utilized, we employ a device manager whose job is to monitor the instrumentation, keep all configurations and calibrations current, and maintain the database. Based on information received from the field instrumentation network system from the TI coefficient for CQS and PPS, DAQ, IRM, IRGM, and IRDM, the device manager determines the integrated reliability monitoring and maintenance tasks and generates WOs as appropriate. He or she helps establish the PdM system and trains other maintenance personnel to use it. He or she is also responsible for continuously monitoring the reliability, health, and status of critical control points identified as essential to the safety, quality, and reliability performance of components as well as the lifetime of equipment. Monitoring these critical points of the different elements with parameters like reliability, health, failure, and maintenance costs and calibration certification using traceable procedures would allow changing the quality, reliability, and lifetime control procedure from fully analytical to a process instrumentation–based system. The reduction of in-process testing can save us enormous amounts of analytical testing time and dollars. Also the procedure of IRMMM with the TI technique through online monitoring will further enhance cost-effectiveness and development/maintenance executions.

It is essential in any plant that one individual be designated as asset manager. That person must be very knowledgeable about industrial processes, parts, equipment, and instrumentation used for process control as well as the intelligent device management software. This resource is too valuable to be ignored, which could happen if a specific person does not have this as a full-time responsibility with authority to take whatever action is necessary to protect the integrity of the processing system. Many potential problems are simply avoided because the device manager systematically checks every instrument on the network, looking for the warning signs that indicate an impending failure. When he catches a transmitter and monitor before it gets too far out of calibration or expires, he is helping maintain the reliability of the production system. If early action by the device manager avoids a plant shutdown, the savings is always substantial and profitable.

15.5 Functions of a Device Manager

The device manager can be used in multiple primary ways:

- Configuration management
- Calibration management
- Diagnostics and prognostics management
- Monitoring and maintenance management
- Asset evaluation management
- Documentation management

- Process, equipment, and instrument selection management
- System optimization management

Configuration management allows you to change, store, compare, and transfer device configurations. Tasks such as changing upper and lower range values, damping values, and setting up an Liquid Crystal Display (LCD) meter on devices are quick and easy. Swapping out devices and setting up the replacement device only require copying the configuration to another device. All device records are easily accessed and viewed on user-friendly screens.

Calibration management helps define test schemes, schedule calibrations, and manage calibration data. The test scheme includes the calibration interval, test point requirements, and accuracy, as well as both setup and cleanup instructions. Then, devices from your database can be grouped in calibration routes according to your choice of device type, machinery location, date, etc. Next, calibration routes are checked out manually to generate a paper calibration form, or checked out to a self-documenting calibrator. After the calibrations are performed, the as-found/as-left information is entered back into the device manager manually or checked in automatically using the calibrator interface. All past calibration records can be reviewed by accessing the calibration history for each device. After several calibrations are performed, you will begin to see a trend for this device displayed on a graph without having to search for old paper records. Calibration certificates can be printed and filed if a hard copy is required according to your procedures. All the test equipment calibrations can be managed so you know when it is time to send them to a certified testing lab. The information on your test equipment calibrations can also be stored and managed in a device manager. Flow verifications are also available to you to make sure your flow meters are configured properly. Flow verification can be performed using the *totalize* function on most flow meters and verifying its accuracy against a known process quantity. In addition, you can manage external lab test schemes associated with devices that are sent to a third party for calibration, such as test equipment and some flow devices.

Diagnostics, prognostics, monitoring, and maintenance let you quickly check the health of any connected device by viewing the status. The status screen shows overview, critical, and informational status messages that let you decide if any action needs to be taken. To increase overall process availability, a proactive method of diagnosing potential problems includes a critical device list in the alert monitor. The alert monitor can poll the devices on the list at set intervals and receive any active status alert messages. When a new message is received by the scan, a bell located at the bottom right-hand corner of your device manager screen will highlight to let you know that you need to investigate further. The alert monitor summary screen provides you with an overview of all alerts. Then, you can interrogate the device in question to get a complete understanding of the problem. After the problem is identified, a suited maintenance strategy is carried out, and then you can clear the message from the alert monitor summary screen.

Automatic documentation management will save you valuable time. The audit trail automatically generates a historical record for maintenance activities associated with each device connected to the device manager. Events recorded in the audit trail include application, calibration, configuration change, status alerts, and system maintenance. Audit trail records are tied to a plant location and to a specific device. The audit trail simplifies your job because as you perform tasks, it works in the background to automatically create the necessary documentation trail. You no longer need to search for records in a file cabinet. Simply look in the audit trail history to determine when, and by whom, a particular activity was performed.

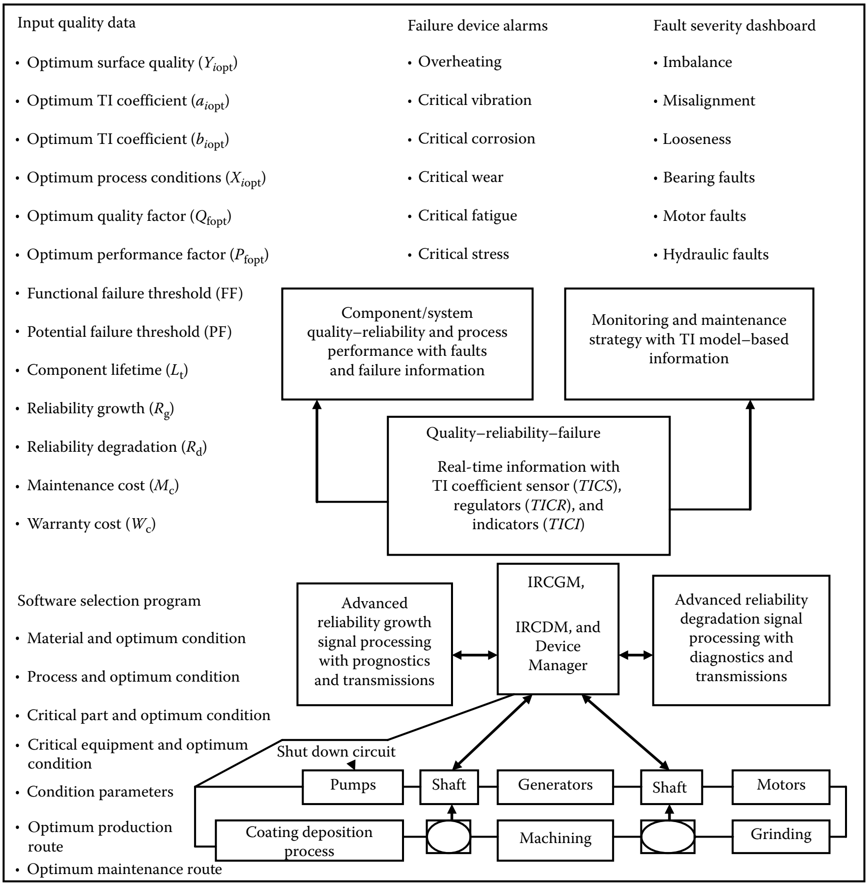

FIGURE 15.3
IRCMMM with a device manager of processes and equipment.

Process, equipment, and instrument selection management: With the help of TI coefficients, optimum model quality and performance parameters can be selected for materials, parts, process conditions, route technologies, valves, instruments, and equipment.

System optimization: TI coefficients are used to optimize model reliability, quality, and performance of processes and equipment (Figure 15.3).

15.6 Efficient Hardware System for the Management of Integrated Reliability Monitoring and Maintenance Technology

Mechanical equipment: Half of equipment failures that cause downtime typically involve mechanical equipment such as pumps, motors, compressors, and turbines. The TI model–based software combines online monitoring information with data from a wide range of analytical tools, so you can see which equipment will need service soon and which would not. Bearing failure, for example, is a common problem with rotating equipment. IRGM and IRDM technology with its device manager software can detect and identify the very high process and component condition variation that is associated with the earliest stages of bearing or shaft wear. You get maximum warning of future problems before increasing damage significantly increases the cost (and possibly the time) for repairs.

It helps in equipment balancing, which also plays an important role in PrM of rotating equipment. Used to ensure that shafts are coupled center to center and that vibration levels are low at operating speeds and loads, they can substantially extend equipment life and reduce maintenance costs.

Process equipment performance of larger process equipment such as boilers, compressors, heat exchangers, and distillation towers often degrades gradually. Repairs or overhauls can restore the loss efficiency, but at the cost of lost production while the equipment is out of service.

Integrated Reliability (IR) helps you pinpoint the right time to service such equipment.

Equipment reliability monitor software can be used to show the change in the reliability of component and equipment efficiency over time. It can calculate the financial impact of these changes so you can weigh the cost of suboptimal performance against the cost of shutting down for maintenance.

You can also use equipment reliability monitor to measure maintenance effectiveness, verifying that the equipment is again delivering the needed performance or even comparing the economic impact of different maintenance methods, such as in-place cleaning or complete equipment overhaul.

Enabling operators to do more, IRGM and IRDM increase operator productivity by reducing the time operators spend in reactive mode, scrambling to deal with unexpected situations and problem loops that threaten process stability and safety.

With fewer abnormal situations and better tools and guidance for dealing with those that do occur, operators can manage more loops in both local and remote locations and focus on improving and optimizing production and maintenance.

Abnormal situation prevention and management: Much of the gain comes from the maintenance improvements. Because many potential problems can be predicted (and the maintenance team notified) before they affect process performance, they never even hit the operator's dashboard. Integration of equipment and process information helps keep things running smoothly in situations like these, as intelligent TI automation systems monitor the signal status (something not every system can do) to constantly verify that the data are valid for use in control algorithms. If it is not, the systems can automatically modify control actions as appropriate.

Operators can also easily check equipment condition to anticipate and adjust for potential problems. The integration of process and plant equipment monitoring with the TI technique provides an integrated, high-level view of information from valves and instruments, rotating equipment, and process equipment in a single browser-based interface. This access to predictive diagnostics and other asset data also enables operators to determine when equipment health is (or, more likely, is not) causing process problems.

When process or equipment problems do occur, the alerts notify the right people without flooding operators with nuisance alarms. This capability relies on powerful software in our field devices, IRGM and IRDM software packages, and the integration of process and plant equipment monitoring management with the TI technique helps analyze the incoming information, categorize it by who should be told, prioritize it by severity and time criticality, and then not only tell the recipients what's wrong but also advise them what to do about it, in clear, everyday language.

With the advanced warning provided by predictive intelligence of the TI technique, combined with effective information integration for both control and equipment health information, operators and maintenance personnel have more information and more lead time to deal with potential problems. This reduces overall operations and maintenance cost and may reduce or eliminate staffing requirements at remote locations.

Better control: IRGM and IRDM also improve productivity by reducing process variability, so operators do not have to spend time managing problem loops manually.

This better control begins with the intelligent instruments and valves that form the foundation of IRGM and IRDM architecture. They include transmitters with fast dynamic response, digital valves that respond to signals of 1% or less, and the world's most accurate flow meters. IRGM and IRDM integrate equipment and process information to add rock-solid regulatory and advanced control. And because advanced controls such as model predictive control are embedded in the system controllers, they are easier to configure and use and have better availability than traditional host-based systems.

Process optimization: As operators shift their focus to improving process performance, the TI technique provides the tools that help them make it happen.

Model-based Data Toolkit (MDT) real-time optimizer software identifies optimum set points to achieve best performance without violating constraints. The advanced control of IRGM and IRDM optimizer is an integral part of the architecture, making implementation of optimum set points easy.

Instruments and valves: The proven reliability valve transmitters reduce maintenance needs right from the start. But process conditions and events can lead to problems in even the best equipment. That's when these devices' built-in performance monitoring and diagnostics help focus your maintenance efforts where they are most productive.

For example, transmitters can fail if the electronics are exposed to excessive temperatures. But built-in temperature monitoring and alarming in IRGM and IRDM instruments can alert you to the problem in time to find and remedy the cause.

Similarly, the sensor fouling detection diagnostic in our pH transmitters can trigger a maintenance request before fouling causes process problems or even automatically initiate cleaning of the sensor.

And valve diagnostics can tell you (while the valve is still in service) if conditions like seat wear, packing friction, or air-supply leakage are approaching the point where maintenance is needed.

The ability to forecast service needs can reduce the need for a large in-house spare part inventory. Knowing exactly which devices need work, and what kind of work, also lets maintenance technicians plan their work more efficiently taking the right tools and parts into the field, for example. Just as important, IRGM and IRDM can tell you which devices do not need maintenance, reducing unnecessary equipment checks, shortening shutdowns, and avoiding the cost and risk of unneeded PM. Experience has shown that monitoring the performance and condition of critical valves' diagnostic software can reduce their maintenance costs by 50%. Intelligent device manager software consolidates valve and instrument information for easy access, as well as providing a robust but user-friendly tool for many maintenance tasks from initial device configuration through troubleshooting and record keeping.

For example, the software's remote monitoring and diagnostic capabilities dramatically speed equipment checks. What might have been a

25 min check in the field becomes a 2 min task done online from the maintenance shop or control room without exposing workers to hazardous environments.

The device manager software also helps cut instrument calibration time. And its automatic documentation of maintenance tasks virtually eliminates the manual data entry that eats up so much wrench time.

Combined with new CIRMMMS work practices to reduce unproductive work, taking full advantage of these effective TI software–defined instrumentation tools over a broad spectrum of tasks can, on average, reduce maintenance time much more than traditional methods (Figures 15.4 and 15.5).

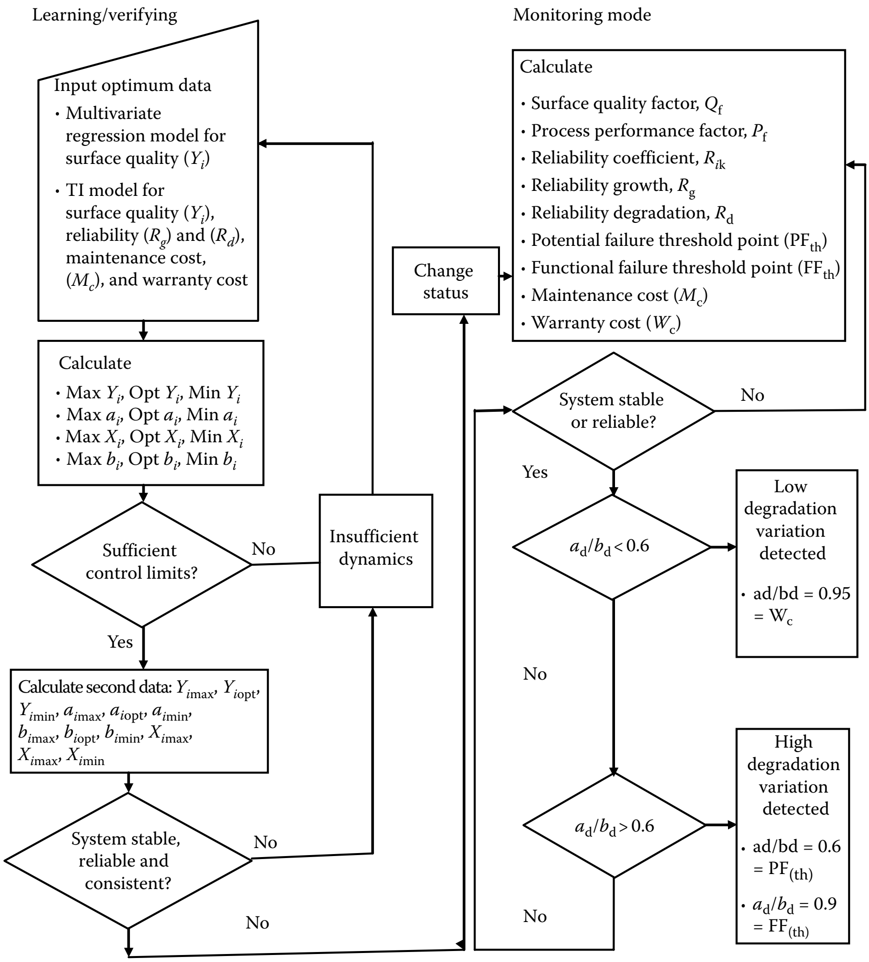

FIGURE 15.4
Simplified integrated reliability CM with model based flowchart.

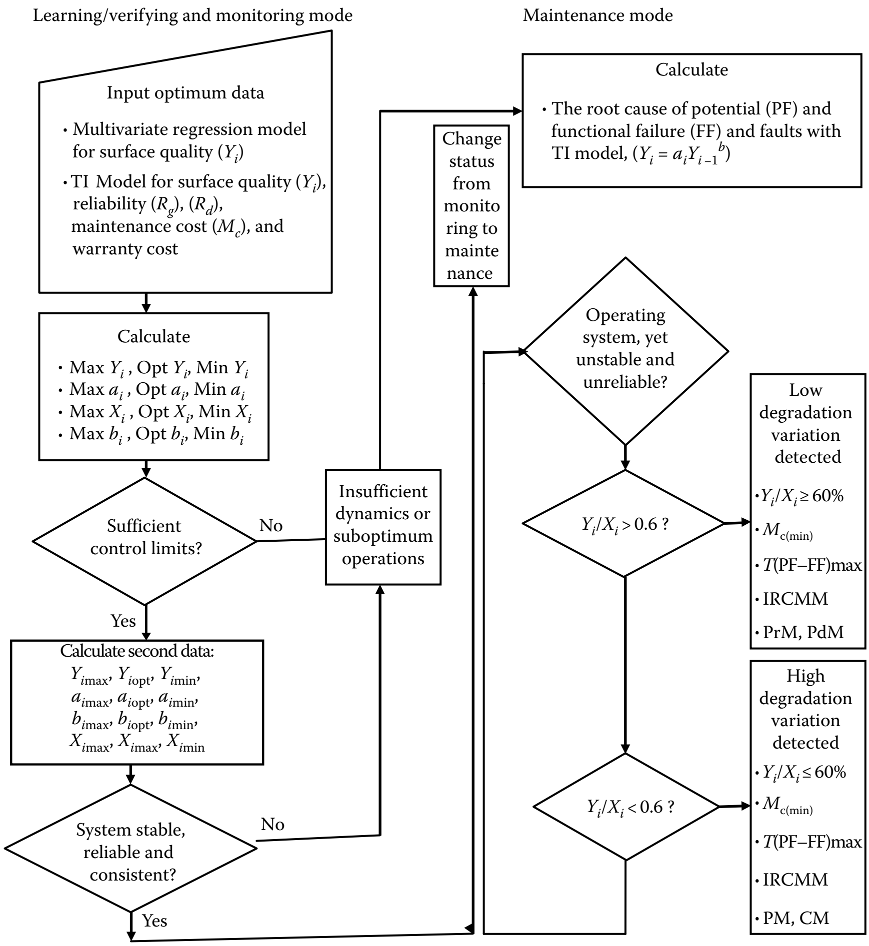

FIGURE 15.5
Simplified integrated reliability condition maintenance management with model-based flowchart.

15.6.1 Efficient Device Management Software for IRCMM Technology

Efficient device management software strives to maximize reliability and performance while minimizing maintenance and operating costs. Device management improvement is possible by integrating new advances in online optimum route-based CM and maintenance systems and flexible communication technologies. This results in the optimum delivery of relevant real-time information to people who operate and maintain plant equipment as well as those who produce the critical parts.

In reality, there are not enough time and personnel to manually monitor component parts, processes, and plant equipment, analyze data, and then effectively communicate the results. As a result, we react to surprise incidents and shutdowns or spend efforts on what should have been unnecessary maintenance.

Through process and component control system optimization and integration of component condition with process condition control, information can be targeted to the right system and end users.

IRMMT with the TI model–based software program provides relevant real-time reliability, performance, and quality information to the people who produce parts and operate and maintain the equipment (Figure 13.1). It goes beyond vibration shutdown protection to include part reliability monitoring that is integrated to the process condition control system and other equipment decision support systems from the initial to final stage of part and equipment life cycle.

Sensors mounted to the manufacturing processes and plant equipment train provide raw signals to a processing unit of parts, instruments, valves, and equipment. This unit analyzes the signals using techniques such as the new IRGM and IRDM to select and determine the optimum quality of parts, equipment conditions, and performance and perform data analysis, which then supplies diagnostic rules to determine the root cause and severity of abnormal situations. The information is integrated into the part, instrument, and equipment systems in the form of alarms with recommended corrective actions and fault status or dashboard screens. The advanced information of IRGM and IRDM can detect the early stages of most faults to allow for optimum maintenance planning and minimized component damages.

For critical faults that develop quickly, the monitoring system is equipped with shutdown protection, prevention, and prediction capabilities. The integrated reliability maintenance–monitoring program provides benefits to manufacturers, equipment operators, and the staff that maintain the equipment. Operators are immediately alerted to problems such as wear, corrosion, fatigue, stress, wear, cracks, vibrations, and cavitations. Without notification, these may remain hidden and cause process inefficiencies and equipment damages. Some problems can be eliminated or minimized by the operator adjusting the process and service conditions. With access to monitoring component and process condition parameters with TI coefficients, the operator may be able to tune the process for maximum or optimum reliability, health, performance, and efficiency of plant equipment.

Maximizing the effectiveness of the IRMMM system with TI model-based software will help alert operators/maintainers of eminent failures and catastrophic damages.

Reducing process and component condition variability also reduces workloads, because there are fewer problems to deal with. But today's short-staffed plants can have trouble finding the resources needed to make improvements, especially when adopting unfamiliar technologies or work practices.

With the TI model–based software that does not have to be a problem, IRMMT offers a wide range of services based on technological know-how and industrial experience, helping customers make the most of the quality, reliability, and performance improvement capabilities as well as management efficiency (Figure 15.6).

Integrated Reliability Growth Monitoring and Maintenance (IRGMM) and Integrated Reliability Degradation Monitoring Maintenance (IRDMM) systems can alert you to potential problems not only with field devices but also with other process and plant equipment.

For instance, statistical process monitoring can identify a wide variety of problems—from leaks in pipes to fouling in heat exchangers, filters, and similar equipment.

The advanced diagnostic capability of IRGMM and IRDMM devices allow up to multiple control or process variables to be monitored for changes with TI coefficients. Statistical process monitoring with the TI software program analyzes how these multiple user-selectable factors change in relation to each other to detect production processes and industrial equipment problems while maximizing the effectiveness of device management at minimum operating cost with the help of TI coefficients a_i and b_i in the different monitoring and maintenance routes of a critical part life cycle through design, manufacturing and service operations as shown in Figure 15.6.

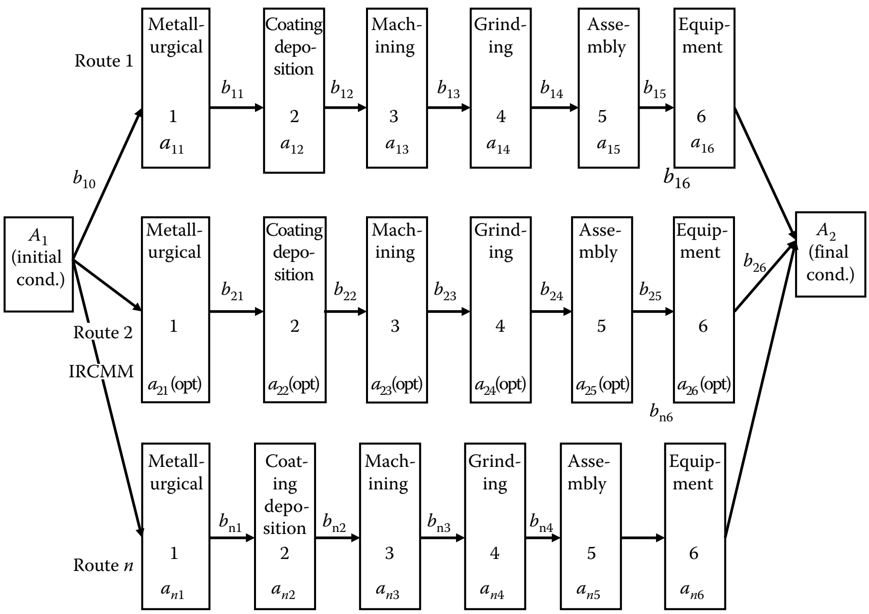

FIGURE 15.6
Selecting the most cost-effective CM and maintenance route chain of a particular critical part for failure resistant application with TI model-based program.

15.7 Management of IRCMM Technology with a TI Model–Based Program

The operation costs (also called variable costs) include repairs and maintenance, fuel, lubrication, and operator labor. Repair costs occur because of routine maintenance, wear and tear, and accidents. Repair costs of a particular type of equipment vary widely from industry to another with common problems of wear, corrosion, and high temperature.

The huge cost of repairing and maintaining industrial equipment is comprised of the expenditure on spare parts and materials. That is why one of the main ways of reducing repair and maintenance cost is the reduction of expenditure in spare parts as a result of development in reliability monitoring and maintenance of parts. Maximum reliability of parts provides for maximum availability of parts, processes, and equipment with minimum repair costs of equipment. Indirect expenditure can be reduced by a careful expenditure on tools, electrical energy, water, steam, and other materials, reduction in the administrative-controlling personnel and the expenditure for its repairs and maintenance, and reduction in the depreciation of the account on a unit component due to the increase in component output with one and the same manufacturing process. Direct expenditure can be reduced by increasing the reliability toward maximum achievable reliability of critical parts with the same manufacturing processes.

The expenditure on salaries for workers can be reduced systematically through technological development and device management of industrial processes and equipment as well as the increase in the labor productivity, which arises from the introduction of new technological processes, modification and changes in equipment, improvement in the monitoring techniques, management and cooperation of the different industries, and other activities with the application of the TI technique that considers all the factors influencing the monitoring and maintenance of processes and plant equipment control systems.

This technique is applied to maximize the reliabilities, qualities, and performances of processes and to control the process and component variations at minimum costs. The TI model–based software can therefore be used to minimize the component cost; the operation costs of parts, processes, and equipment; as well as the total ownership cost of parts, processes, and equipment. The TI model–based software is used for optimum selection, determination, and validation of a cost-effective integrated reliability monitoring and maintenance of parts, processes, and equipment as well as the life cycle and maintenance costs of critical parts. The determination and prediction of the real-time data of life cycle cost, maintenance cost, time of failures and reliability have helped to cost-effectively select, operate and maintain components and systems.

The operating conditions, component reliabilities and maintenance costs of critical parts, processes, and equipment can now be determined using the new integrated reliability monitoring and maintenance with the TI model–based program. This program is used for monitoring, maintenance and management throughout the life cycle of a critical part that follows cost effective routes throughout all desired manufacturing and equipment operations as seen in Figure 15.6. All the existing monitoring, maintenance and management technology and the new IRMMM of parts, processes, and equipment start from the same initial reliability, quality, and performance characteristics at point A_1 and ends at the final point A_2. The coefficients of TI, a and b, were used to construct the monitoring and maintenance routes (BlockSim R_1P_k, R_2P_k, ... R_nP_k) from point A_1 to A_2 as shown in Figure 15.6, where a is the TI coefficient that controls the reliability, performance, and qualities of parts, b is the TI coefficient that controls the conditions of parts, processes, and equipment, while k is the different manufacturing process and equipment conditions. n is the number of different routes for monitoring, maintenance and management of components/systems.

R_1P_k is the first monitoring, maintenance and management route technology of a critical surface finished part by grinding and industrial equipment for wear and other competing failure resistant applications.

R_2P_k is the second monitoring, maintenance and management route technology of a critical surface finished part by rotary turning with plasma spray and industrial equipment for wear and other competing failure resistant applications.

R_nP_k is the nth monitoring, maintenance and management route technology of a critical surface finished part by rotary turning with plasma spray and grinding and industrial equipment for wear and other competing failure resistant applications.

All the monitoring, maintenance and management routes started from the same initial hard alloy–coated surface quality parameters A_1 and ended with the same final optimum surface finish quality condition during manufacturing and starts with an optimum surface mating part in an equipment, but finally ends up with different surface conditions even with optimum equipment service operations A_2. The monitoring and maintenance route consists of parts, processes, equipment, instruments, and computers of different conditions for each component. TI coefficients a and b of the components must satisfy the optimum reliability criteria for selection, performance, and cost.

The coefficients of TI, a and b, were used to construct the different integrated reliability monitoring, maintenance and management routes from point A_1 to A_2, as shown in Figure 15.6.

With the help of TI coefficients, the most cost-effective integrated reliability monitoring and maintenance route technologies for parts, processes, and industrial equipment is determined with the help of a BlockSim, as shown in Figure 15.6. The most cost effective route is carried out to suit the different applications in three groups, which are as follows:

Group 1: Optimum Technological Route for wear resistant mating part surfaces in operating machine and equipment system.

Group 2: Optimum Technological Route for corrosion resistant mating part surfaces in operating machine and equipment system.

Group 3: Optimum Technological Route for high temperature resistant mating part surfaces in operating machine and equipment system.

Group 1 - is an optimum IRCMM route for wear resistant application, which consists of manufacturing and equipment operations of a critical mating part "A" from an initial A_1 to the final A_2 conditions.

A_1: The initial quality, (Y_{i-1}) - reliability, (R_{i-1}) chain of a critical mating part surface in a machine and equipment system.

a_i: TI coefficient for part surface quality condition control, which is measured with TI coefficient sensor, (TICS) and is used to calculate quality factor, (Q_f), reliability coefficient, (R_k), failure resistant coefficient (wear-K_w, corrosion-K_c, temperature-K_t), maintenance cost, (M_c) and others.

b_i: TI coefficient for process condition control, which is measured with a TI coefficient sensor, (TICS) and is used to calculate process performance factor, (P_f), reliability coefficient, (R_k), failure resistant coefficient (wear-K_w, corrosion-K_c, temperature-K_t), maintenance cost, (M_c) and others.

$a_{i\text{opt.}}$: Optimum TI coefficient for component/system quality condition control, which is expressed as:

$$a_{i\text{opt.}} = a_{i\text{max.}} = a_{1\text{max.}}\, a_{2\text{max.}} \ldots a_{n\text{max.}} = 1.0$$

$$a_{i\text{opt.}} = a_{i\text{min.}} = a_{1\text{min.}}\, a_{2\text{min.}} \ldots a_{n\text{min.}} = 0.0$$

where, $i = 1, 2 \ldots n$

$b_{i\text{opt.}}$: Optimum TI coefficient for process condition control, which is expressed as:

$$b_{i\text{opt.}} = b_{i\text{max.}} = b_{1\text{max.}}\, b_{2\text{max.}} \ldots b_{n\text{max.}} = 1.0$$

$$b_{i\text{opt.}} = b_{i\text{min.}} = b_{1\text{min.}}\, b_{2\text{min.}} \ldots b_{n\text{min.}} = 0.0$$

where, $i = 1, 2 \ldots n$ and this is used for optimum selections, detection of failures, prediction of the time of failures, for planning and management.

A_2: The final quality, (Y_i) - reliability, (R_i) chain of a critical mating part surface in a machine and equipment system.

A_i: The different critical part surface conditions in a machine, process and equipment system of a particular technological route.

CIRCMMMT: is a computerized IRCMM technology with TI model based software defined instrumentation program.

Group 2 - is an optimum IRCMM route for corrosion resistant application, which consists of manufacturing and equipment operations of a critical mating part A from an initial A_1 to the final A_2 conditions.
Group 3 - is an optimum IRCMM route for high temperature resistant application, which consists of manufacturing and equipment operations of a critical mating part A from an initial A_1 to the final A_2 conditions.

After the construction of a selection diagram for optimum technological routes of the different groups, integrated reliability condition monitoring and maintenance management technology (IRCMMMT) were assessed by using TI coefficients, a_i and b_i to evaluate the different distances between points A_1 and A_2 of the different critical part (A_i) surface conditions through manufacturing processes,(P), machine - equipment operations (e) and measuring instruments, (I): $b_i = b_p \cdot b_e \cdot b_I$, where b_p is the TI coefficient that controls the conditions of the production processes, be is the TI coefficient that controls the conditions of equipment, and b_I is the TI coefficient that controls the conditions of the instruments, while b_i is the TI coefficient of the routes. The shortest distance, which is the least value of b_i, represents the route that spent the least time and cost to obtain the desired qualities, performance, and reliability of the system or network. This is also the route that had the least expenditure for the maintenance monitoring of industrial processes and equipment, which represents the most cost-effective IRCMM route. The most cost-effective route for the reliability monitoring and maintenance of parts, processes, and equipment is selected as the best variant. The best integrated reliability monitoring and maintenance route variant is optimized with the help of the TI model–based software toward a sustainable development through TI coefficient for critical part surface quality control, "a_i" from initial to final operation in the monitoring and maintenance route. In this case, the longest distance within the desired time and cost is used to determine the best component quality and reliability in industrial engineering technology. This book offers an optimum integrated reliability monitoring and maintenance route with computerized integrated reliability condition monitoring and maintenance maintenance technology (CIRCMMMT) that have helped to integrate data acquisition, analysis, and presentation into a single unit for maximum benefits at minimum cost in the industries of the future (Figure 15.7).

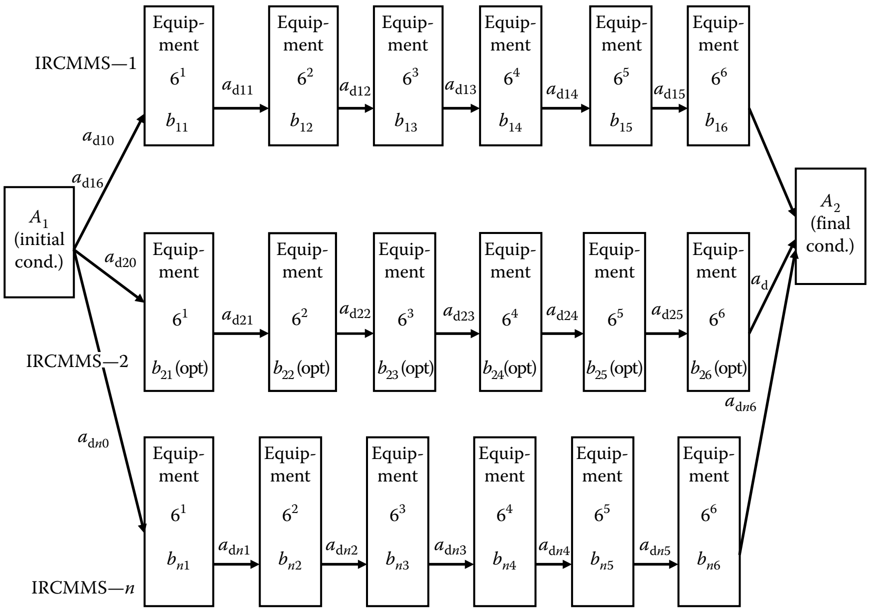

FIGURE 15.7
Determination of the most cost-effective IRCMM management of a particular critical part and equipment for failure-resistant application with TI model–based program.

15.8 Benefits of IRCMM Management Systems with a TI Software Program in the Industries of the Future

IRMMM with the TI software program helps to access and manage the full capacity of industrial processes and field devices. A device manager configures the process and field devices from the maintenance shop, stores device configurations in plant equipment database, performs device loop tests and calibrations, associates electronic drawings and notes with a particular device, imports or exports system data, and establishes multilevel password security quickly and easily, which offers the following benefits:

- Optimization of maintenance operations and cost-effectiveness: The device manager increases productivity by detecting and diagnosing potential plant equipment problems before they impact the process, reducing unnecessary and unproductive tasks. This is done right from the initial manufacturing processes of the critical parts of the system operations to the final operation including the production service field operations.

- Field device provides engineers and maintenance personnel with a consistent graphical and digital data looks during device configuration and maintenance. It offers operators intuitive graphics and digital data to aid in making timely, accurate decisions when abnormal operating conditions occur. The manager offers selection software to all the manufacturing, production, and maintenance departments using optimum process conditions, component conditions, and multivariate mathematical model field parameters.
- Optimization of component quality, process performance, and reliability system: In a perfect world, the process would be consistent, day in and day out. But the reality is that field device performance and component reliability, like most things, can degrade over time. Variability is a natural phenomenon that must be dealt with. With device manager, online device diagnostics and status information alert you to any device not performing as it should. You gain process and component consistency through properly performing field devices.
- Minimum commissioning time is the possibility of downloading configuration information from a single database to a new device using drag-and-drop techniques rather than keying in configuration parameters one at a time. The device manager also guides you through field device calibration processes, improving efficiency and accuracy.
- Efficient system availability and reliability using alert IRMs: The device manager's alert monitor is a reliability coefficient diagnostic tool used to observe field devices suspected of periodic or intermittent malfunction, one of the most difficult failure modes to troubleshoot. Use an IRM to watch for field device failure patterns. The IRM will identify potential problems before they occur, not after they have affected your process and the quality of parts. Increased process availability is about keeping production running on schedule, just the way you planned it. A device manager provides real-time online access to intelligent device diagnostics and alerts, so you always know how devices are performing and have valuable information about the health of the device. Predictive information can alert you to a device that is likely to fail, so you can replace it at a convenient time, rather than suffer from a costly unscheduled shutdown. Even during scheduled maintenance, time is of the essence. With a device manager, maintenance preparations can be performed ahead of time, stored in the PC, and then simply downloaded to the devices during the shutdown, increasing your efficiency, decreasing turnaround time, and maximizing process availability.
- Efficient startup and commissioning: A device manager helps maintenance staff to work more efficiently with lower costs and fewer

trips to the field. With a device manager, you will reduce operating and maintenance costs in installation, commissioning, and regular ongoing maintenance because the staff can perform these quickly and easily.

- Optimum selection of route technologies, parts, materials, and processes.
- Optimum selection of maintenance strategies and techniques.
- Optimum selection of valves, instruments, and equipment.
- Reduced and optimized maintenance costs: In today's competitive business climate, there is increasing pressure to reduce capital spending and engineering costs. Budgets are tighter, labor is more expensive, and resources of all kinds are at a premium. The manager reduces the engineering cost by optimizing the manufacturing process, service, and maintenance operations with the help of the TI software program.
- Integration of online monitoring of plant equipment system with IRMMT.
- Integration of online monitoring with process and equipment system with IRMMT.
- Efficient IRMMT for monitoring and maintaining plant equipment to perform the following:
  - Detect, diagnose, and predict wear, fatigue, high temperature, corrosion, and other modes of failure from a group of machine parts.
  - Track progressive failure, health, and reliability conditions of plant equipment.
  - Track progressive power efficiency of plant equipment.
  - Track the product durability and the reliability of plant equipment.
  - Select optimum materials, parts, processes, route technologies, maintenance strategies, instruments, and equipment.
- Safety and compliance: Today, more than ever before, you need an effective change management system in place to meet the requirements of the Food and Drug Administration (FDA), Occupational Safety and Health Administration (OSHA), International Standard Organization (ISO), Environmental Protection Agency (EPA), and general principles of process safety management. The task of documenting maintenance activities is consuming ever-larger percentages of your time and energy, not just for US companies, but worldwide. Ironically, it may take more time to do the required documentation than it does to perform the actual maintenance work.

When maintenance functions are performed using a device manager, records are automatically produced and logged in an audit trail. The documentation step is done simultaneously and accurately.

15.9 Conclusions

1. IRCMM management examines the role of the TI network program in minimizing the risk of safety, component/system failures, and loss of profitability as well as dealing with risk reduction tools that best fit maintenance requirements, overall equipment effectiveness, and maintenance strategies.
2. The optimum selection of tools, processes, parts, equipment, and maintenance strategies is done with the help of the TI software program.
3. The IRCMM tasks have been selected based on the level of reliability, CM, and maintenance of parts, processes, and equipment system with the use of reliability distribution curves that apply the TI model.
4. IRCMM management with the TI software program focuses on the improvement of all the phases of PdM and PrM processes during design, manufacturing processes, and equipment operations.
5. The program is used to develop a device manager whose job is to monitor the instrumentation, keep all configurations and calibrations current, and maintain the database of processes, parts, and industrial equipment through the checks and balances of the TICSs.
6. The device manager is also used for continuous monitoring of the failures, reliability growth/degradations, and status of critical control points identified as essential to the safety, protection, lifetime, and selection of optimum conditions of parts/equipment.
7. The device manager performs multiple primary functions for manufacturing processes, parts, and equipment in the following ways:
   - Configuration management
   - Calibration management
   - Diagnostics and prognostic management
   - Reliability growth and degradation management
   - Documentation management
   - Optimum component and system selection management

- Monitoring and maintenance management
- Root cause of failure and equipment reliability evaluation management
- Other forms of management

8. Researches have shown that half of equipment failures that cause downtime typically involve mechanical critical equipment such as pumps, motors, compressors, and turbines of the different industries of the future, and therefore, the application of IRCMM with the TI model–based program will maximize productivity and reliability while keeping the equipment in continuous service, using integrated reliability network to optimize reliability, lifetime, and overall effectiveness of manufacturing processes, parts, and industrial equipment.
9. The TI technique software program applies online monitoring information with IRMs, diagnostic/prognostic transmitters, and precision maintenance strategies with a cost-effective device manager so that you can see which manufacturing process, part, and equipment will need service soon and which would not.
10. Integrated reliability growth and degradation monitors are used to show the changes between the optimum and minimum component/system reliability condition data over time and can be used to calculate the financial impact of these changes so that you can weigh the cost of suboptimal reliability condition against the cost of shutting down for maintenance.
11. Device management improvement is possible by integrating new advances in online optimum IRCMM systems and flexible communication technologies with the TI model–based software program.
12. TICSs mounted to the part–equipment train provide raw signals to the processing unit of parts, instruments, valves, and equipment, while the unit analyzes the signals using IRMs and reliability diagnostic transmitters, which then supply diagnostic data to determine the root cause and severity of abnormal situations.
13. Integrated reliability monitoring and maintenance with the TI software program provides benefits to equipment and operators as well as to the staff that maintain the equipment so that they are immediately alerted to problems such as fatigue, stress, wear, cracks, vibrations, corrosion, cavitations, and high temperature.
14. The TI software program is applied to IRMMM in order to optimize reliability, lifetime, and life cycle costs of parts, processes, equipment, instruments, and maintenance strategies toward minimizing the maintenance cost and operation costs and monitoring the technology cost as well as the total ownership cost of processes, parts, and industrial equipment.

15. The best of the existing reliability monitoring and maintenance management route is optimized and compared with the new IRCMM management route technology with the TI software program for optimum selection of components/systems in the different industries of the future.
16. This book offers IRCMM management route with the TI software program as the best program, since it integrates reliability with CM and maintenance data acquisition, analysis, and presentation into a single unit for maximum benefits at minimum cost toward a sustainable development and management in the industries of the future.

Mechanical Engineering

INTEGRATED RELIABILITY
Condition Monitoring and Maintenance of Equipment

CONSIDER A VIABLE AND COST-EFFECTIVE PLATFORM FOR THE INDUSTRIES OF THE FUTURE (IOF)

Benefit from improved safety, performance, and product deliveries to your customers. Achieve a higher rate of equipment availability, performance, product quality, and reliability. *Integrated Reliability: Condition Monitoring and Maintenance of Equipment* incorporates reliable engineering and mathematical modeling to help you move toward sustainable development in reliability condition monitoring and maintenance. This text introduces a cost-effective integrated reliability growth monitor, integrated reliability degradation monitor, technological inheritance coefficient sensors, and a maintenance tool that supplies real-time information for predicting and preventing potential failures of manufacturing processes and equipment.

The author highlights five key elements that are essential to any improvement program: improving overall equipment and part effectiveness, quality, and reliability; improving process performance with maintenance efficiency and effectiveness; training all employees involved; including operators in the daily maintenance and upkeep of the equipment; and implementing early equipment management and maintenance prevention design. He offers a sustainable solution with integrated reliability condition monitoring and maintenance of manufacturing processes, parts, and equipment in the IOFs with a technological inheritance model-based program.

This book contains 15 chapters that include details on:

- Improving the material–part–equipment system life cycle, reliability conditions, and manufacturing process productivity for wear, corrosion, and temperature resistance applications
- Maximizing the component and system reliability growth of parts and equipment
- Minimizing reliability degradation within the framework of a condition-based maintenance
- Analyzing the reliability degradation, wear, and other competing failure modes of nickel-based hard alloy–coated part mating surface with a technological inheritance model-based program
- Introducing a cost-effective integrated reliability monitor and maintenance strategy with a technological inheritance model–based software program

Integrated Reliability: Condition Monitoring and Maintenance of Equipment addresses potential failures from an asset manager, maintenance user, and operator's standpoint, and highlights the solutions to common failures and reliability problems for equipment in the IOFs.

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