
Contents

Foreword	xxi
About the Editor	xxii
Contributors	xxiii
Preface	xxv
Acknowledgments	xxix

Part 1 History/Lessons Learned

Chapter 1: Quality Thrust Ron Randall

1.1	Meaning of Quality	1-1
1.2	The Evolution of Quality	1-2
1.3	Some Quality Gurus and their Contributions	1-2
1.3.1	W. Edwards Deming	1-2
1.3.2	Joseph Juran	1-3
1.3.3	Philip B. Crosby	1-4
1.3.4	Genichi Taguchi	1-5
1.4	The Six Sigma Approach to Quality	1-6
1.4.1	The History of Six Sigma	1-6
1.4.2	Six Sigma Success Stories	1-7
1.4.3	Six Sigma Basics	1-7
1.5	The Malcolm Baldrige National Quality Award (MBNQA)	1-9
1.6	References	1-10

Chapter 2: Dimensional Management Robert H. Nickolaisen, P.E.

2.1	Traditional Approaches to Dimensioning and Tolerancing	2-1
2.1.1	Engineering Driven Design	2-2
2.1.2	Process Driven Design	2-2
2.1.3	Inspection Driven Design	2-2
2.2	A Need for Change	2-3
2.2.1	Dimensional Management	2-3
2.2.2	Dimensional Management Systems	2-3
2.2.2.1	Simultaneous Engineering Teams	2-4
2.2.2.2	Written Goals and Objectives	2-4
2.2.2.3	Design for Manufacturability (DFM) and Design for Assembly (DFA)	2-5
2.2.2.4	Geometric Dimensioning and Tolerancing (GD&T)	2-6
2.2.2.5	Key Characteristics	2-6
2.2.2.6	Statistical Process Control (SPC)	2-6
2.2.2.7	Variation Measurement and Reduction	2-7
2.2.2.8	Variation Simulation Tolerance Analysis	2-7
2.3	The Dimensional Management Process	2-8
2.4	References	2-10
2.5	Glossary	2-10

Chapter 3: Tolerancing Optimization Strategies..... Gregory A. Hetland, Ph.D.

3.1	Tolerancing Methodologies	3-1
3.2	Tolerancing Progression (Example # 1)	3-1
3.2.1	Strategy # 1 (Linear)	3-2
3.2.2	Strategy # 2 (Combination of Linear and Geometric)	3-5
3.2.3	Strategy # 3 (Fully Geometric)	3-6
3.3	Tolerancing Progression (Example # 2)	3-6
3.3.1	Strategy # 1 (Linear)	3-8
3.3.2	Strategy # 2 Geometric Tolerancing (\oplus) Regardless of Feature Size	3-11
3.3.3	Strategy # 3 (Geometric Tolerancing Progression At Maximum Material Condition)	3-12
3.3.4	Strategy # 4 (Tolerancing Progression “Optimized”)	3-13
3.4	Summary	3-15
3.5	References	3-15

Part 2 Standards

Chapter 4: Drawing Interpretation Patrick J. McCuiston, Ph.D

4.1	Introduction	4-1
4.2	Drawing History	4-2
4.3	Standards	4-2
4.3.1	ANSI	4-2
4.3.2	ISO	4-3
4.4	Drawing Types	4-3
4.4.1	Note	4-3
4.4.2	Detail	4-3
4.4.2.1	Cast or Forged Part	4-4
4.4.2.2	Machined Part	4-4
4.4.2.3	Sheet Stock Part	4-4
4.4.3	Assembly	4-4
4.5	Border	4-4
4.5.1	Zones and Center Marks	4-4
4.5.2	Size Conventions	4-13
4.6	Title Blocks	4-13
4.6.1	Company Name and Address	4-13
4.6.2	Drawing Title	4-13
4.6.3	Size	4-13
4.6.4	FSCM/CAGE	4-13
4.6.5	Drawing Number	4-14
4.6.6	Scale	4-14
4.6.7	Release Date	4-14
4.6.8	Sheet Number	4-14
4.6.9	Contract Number	4-14
4.6.10	Drawn and Date	4-14
4.6.11	Check, Design, and Dates	4-14
4.6.12	Design Activity and Date	4-15
4.6.13	Customer and Date	4-15
4.6.14	Tolerances	4-15
4.6.15	Treatment	4-15
4.6.16	Finish	4-15
4.6.17	Similar To	4-15
4.6.18	Act Wt and Calc Wt	4-15
4.6.19	Other Title Block Items	4-15
4.7	Revision Blocks	4-16
4.8	Parts Lists	4-16
4.9	View Projection	4-16

4.9.1	First-Angle Projection	4-16
4.9.2	Third-Angle Projection	4-16
4.9.3	Auxiliary Views	4-16
4.10	Section Views	4-16
4.10.1	Full Sections	4-19
4.10.2	Half Sections	4-19
4.10.3	Offset Sections	4-19
4.10.4	Broken-Out Section	4-19
4.10.5	Revolved and Removed Sections	4-22
4.10.6	Conventional Breaks	4-22
4.11	Partial Views	4-23
4.12	Conventional Practices	4-23
4.12.1	Feature Rotation	4-23
4.12.2	Line Precedence	4-23
4.13	Isometric Views	4-24
4.14	Dimensions	4-25
4.14.1	Feature Types	4-25
4.14.2	Taylor Principle / Envelope Principle	4-25
4.14.3	General Dimensions	4-26
4.14.4	Technique	4-27
4.14.5	Placement	4-27
4.14.6	Choice	4-28
4.14.7	Tolerance Representation	4-28
4.15	Surface Texture	4-28
4.15.1	Roughness	4-29
4.15.2	Waviness	4-29
4.15.3	Lay	4-29
4.15.4	Flaws	4-29
4.16	Notes	4-29
4.17	Drawing Status	4-30
4.17.1	Sketch	4-30
4.17.2	Configuration Layout	4-30
4.17.3	Experimental	4-30
4.17.4	Active	4-30
4.17.5	Obsolete	4-30
4.18	Conclusion	4-30
4.19	References	4-31

Chapter 5: Geometric Dimensioning and Tolerancing Walter M. Stites
 Paul Drake, P.E.

5.1	Introducing Geometric Dimensioning and Tolerancing (GD&T)	5-1
5.1.1	What is GD&T?	5-2
5.1.2	Where Does GD&T Come From?—References	5-2
5.1.3	Why Do We Use GD&T?	5-4
5.1.4	When Do We Use GD&T?	5-8
5.1.5	How Does GD&T Work?—Overview	5-9
5.2	Part Features	5-9
5.2.1	Nonsize Features	5-10
5.2.2	Features of Size	5-10
5.2.2.1	Screw Threads	5-11
5.2.2.2	Gears and Splines	5-11
5.2.3	Bounded Features	5-11
5.3	Symbols	5-11
5.3.1	Form and Proportions of Symbols	5-12
5.3.2	Feature Control Frame	5-14
5.3.2.1	Feature Control Frame Placement	5-14
5.3.2.2	Reading a Feature Control Frame	5-16
5.3.3	Basic Dimensions	5-17

5.3.4	Reference Dimensions and Data	5-18
5.3.5	“Square” Symbol	5-18
5.3.6	Tabulated Tolerances	5-18
5.3.7	“Statistical Tolerance” Symbol	5-18
5.4	Fundamental Rules	5-18
5.5	Nonrigid Parts	5-19
5.5.1	Specifying Restraint	5-20
5.5.2	Singling Out a Free State Tolerance	5-20
5.6	Features of Size—The Four Fundamental Levels of Control	5-20
5.6.1	Level 1—Size Limit Boundaries	5-20
5.6.2	Material Condition	5-23
5.6.2.1	Modifier Symbols	5-24
5.6.3	Method for MMC or LMC	5-25
5.6.3.1	Level 2—Overall Feature Form	5-26
5.6.3.2	Level 3—Virtual Condition Boundary for Orientation	5-33
5.6.3.3	Level 4—Virtual Condition Boundary for Location	5-34
5.6.3.4	Level 3 or 4 Virtual Condition Equal to Size Limit (Zero Tolerance).....	5-35
5.6.3.5	Resultant Condition Boundary	5-37
5.6.4	Method for RFS	5-38
5.6.4.1	Tolerance Zone Shape	5-38
5.6.4.2	Derived Elements	5-38
5.6.5	Alternative “Center Method” for MMC or LMC	5-43
5.6.5.1	Level 3 and 4 Adjustment—Actual Mating/Minimum Material Sizes	5-43
5.6.5.2	Level 2 Adjustment—Actual Local Sizes	5-45
5.6.5.3	Disadvantages of Alternative “Center Method”	5-46
5.6.6	Inner and Outer Boundaries	5-46
5.6.7	When do we use a Material Condition Modifier?	5-47
5.7	Size Limits (Level 1 Control)	5-48
5.7.1	Symbols for Limits and Fits	5-48
5.7.2	Limit Dimensioning	5-49
5.7.3	Plus and Minus Tolerancing	5-49
5.7.4	Inch Values	5-49
5.7.5	Millimeter Values	5-49
5.8	Form (Only) Tolerances (Level 2 Control)	5-50
5.8.1	Straightness Tolerance for Line Elements	5-51
5.8.2	Straightness Tolerance for a Cylindrical Feature	5-52
5.8.3	Flatness Tolerance for a Single Planar Feature	5-52
5.8.4	Flatness Tolerance for a Width-Type Feature	5-52
5.8.5	Circularity Tolerance	5-53
5.8.5.1	Circularity Tolerance Applied to a Spherical Feature	5-55
5.8.6	Cylindricity Tolerance	5-55
5.8.7	Circularity or Cylindricity Tolerance with Average Diameter	5-56
5.8.8	Application Over a Limited Length or Area	5-57
5.8.9	Application on a Unit Basis	5-57
5.8.10	Radius Tolerance	5-58
5.8.10.1	Controlled Radius Tolerance	5-59
5.8.11	Spherical Radius Tolerance	5-59
5.8.12	When Do We Use a Form Tolerance?	5-60
5.9	Datuming	5-61
5.9.1	What is a Datum?	5-61
5.9.2	Datum Feature	5-61
5.9.2.1	Datum Feature Selection	5-61
5.9.2.2	Functional Hierarchy	5-63
5.9.2.3	Surrogate and Temporary Datum Features	5-64
5.9.2.4	Identifying Datum Features	5-65
5.9.3	True Geometric Counterpart (TGC)—Introduction	5-67
5.9.4	Datum	5-69
5.9.5	Datum Reference Frame (DRF) and Three Mutually Perpendicular Planes	5-69

5.9.6	Datum Precedence	5-69
5.9.7	Degrees of Freedom	5-72
5.9.8	TGC Types	5-74
5.9.8.1	Restrained versus Unrestrained TGC	5-75
5.9.8.2	Nonsize TGC	5-75
5.9.8.3	Adjustable-size TGC	5-75
5.9.8.4	Fixed-size TGC	5-77
5.9.9	Datum Reference Frame (DRF) Displacement	5-80
5.9.9.1	Relative to a Boundary of Perfect Form TGC	5-81
5.9.9.2	Relative to a Virtual Condition Boundary TGC	5-83
5.9.9.3	Benefits of DRF Displacement	5-83
5.9.9.4	Effects of All Datums of the DRF	5-83
5.9.9.5	Effects of Form, Location, and Orientation	5-83
5.9.9.6	Accommodating DRF Displacement	5-83
5.9.10	Simultaneous Requirements	5-86
5.9.11	Datum Simulation	5-89
5.9.12	Unstable Datums, Rocking Datums, Candidate Datums	5-89
5.9.13	Datum Targets	5-91
5.9.13.1	Datum Target Selection	5-91
5.9.13.2	Identifying Datum Targets	5-92
5.9.13.3	Datum Target Dimensions	5-94
5.9.13.4	Interdependency of Datum Target Locations	5-95
5.9.13.5	Applied to Features of Size	5-95
5.9.13.6	Applied to Any Type of Feature	5-97
5.9.13.7	Target Set with Switchable Precedence	5-99
5.9.14	Multiple Features Referenced as a Single Datum Feature	5-100
5.9.14.1	Feature Patterns	5-100
5.9.14.2	Coaxial and Coplanar Features	5-103
5.9.15	Multiple DRFs	5-103
5.10	Orientation Tolerance (Level 3 Control)	5-103
5.10.1	How to Apply It	5-103
5.10.2	Datums for Orientation Control	5-104
5.10.3	Applied to a Planar Feature (Including Tangent Plane Application)	5-104
5.10.4	Applied to a Cylindrical or Width-Type Feature	5-106
5.10.4.1	Zero Orientation Tolerance at MMC or LMC	5-107
5.10.5	Applied to Line Elements	5-107
5.10.6	The 24 Cases	5-109
5.10.7	Profile Tolerance for Orientation	5-109
5.10.8	When Do We Use an Orientation Tolerance?	5-109
5.11	Positional Tolerance (Level 4 Control)	5-113
5.11.1	How Does It Work?	5-113
5.11.2	How to Apply It	5-114
5.11.3	Datums for Positional Control	5-116
5.11.4	Angled Features	5-117
5.11.5	Projected Tolerance Zone	5-117
5.11.6	Special-Shaped Zones/Boundaries	5-121
5.11.6.1	Tapered Zone/Boundary	5-121
5.11.6.2	Bidirectional Tolerancing	5-122
5.11.6.3	Bounded Features	5-126
5.11.7	Patterns of Features	5-127
5.11.7.1	Single-Segment Feature Control Frame	5-127
5.11.7.2	Composite Feature Control Frame	5-129
5.11.7.3	Rules for Composite Control	5-131
5.11.7.4	Stacked Single-Segment Feature Control Frames	5-134
5.11.7.5	Rules for Stacked Single-Segment Feature Control Frames	5-136
5.11.7.6	Coaxial and Coplanar Features	5-136
5.11.8	Coaxiality and Coplanarity Control	5-137

5.12 Runout Tolerance 5-138

5.12.1 Why Do We Use It? 5-138

5.12.2 How Does It Work? 5-138

5.12.3 How to Apply It 5-139

5.12.4 Datums for Runout Control 5-140

5.12.5 Circular Runout Tolerance 5-141

5.12.6 Total Runout Tolerance 5-143

5.12.7 Application Over a Limited Length 5-143

5.12.8 When Do We Use a Runout Tolerance? 5-144

5.12.9 Worst Case Boundaries 5-145

5.13 Profile Tolerance 5-145

5.13.1 How Does It Work? 5-145

5.13.2 How to Apply It 5-145

5.13.3 The Basic Profile 5-147

5.13.4 The Profile Tolerance Zone 5-147

5.13.5 The Profile Feature Control Frame 5-149

5.13.6 Datums for Profile Control 5-149

5.13.7 Profile of a Surface Tolerance 5-149

5.13.8 Profile of a Line Tolerance 5-149

5.13.9 Controlling the Extent of a Profile Tolerance 5-150

5.13.10 Abutting Zones 5-153

5.13.11 Profile Tolerance for Combinations of Characteristics 5-153

5.13.11.1 With Positional Tolerancing for Bounded Features 5-153

5.13.12 Patterns of Profiled Features 5-154

5.13.12.1 Single-Segment Feature Control Frame 5-154

5.13.12.2 Composite Feature Control Frame 5-154

5.13.12.3 Stacked Single-Segment Feature Control Frames 5-155

5.13.12.4 Optional Level 2 Control 5-155

5.13.13 Composite Profile Tolerance for a Single Feature 5-156

5.14 Symmetry Tolerance 5-156

5.14.1 How Does It Work? 5-157

5.14.2 How to Apply It 5-159

5.14.3 Datums for Symmetry Control 5-159

5.14.4 Concentricity Tolerance 5-160

5.14.4.1 Concentricity Tolerance for Multifold Symmetry about a Datum Axis 5-160

5.14.4.2 Concentricity Tolerance about a Datum Point 5-161

5.14.5 Symmetry Tolerance about a Datum Plane 5-161

5.14.6 Symmetry Tolerancing of Yore (Past Practice) 5-161

5.14.7 When Do We Use a Symmetry Tolerance? 5-162

5.15 Combining Feature Control Frames 5-162

5.16 “Instant” GD&T 5-163

5.16.1 The “Dimension Origin” Symbol 5-163

5.16.2 General Note to Establish Basic Dimensions 5-163

5.16.3 General Note in Lieu of Feature Control Frames 5-164

5.17 The Future of GD&T 5-164

5.18 References 5-166

Chapter 6: Differences Between US Standards and Other Standards Alex Krulikowski
..... Scott DeRaad

6.1 Dimensioning Standards 6-1

6.1.1 US Standards 6-2

6.1.2 International Standards 6-2

6.1.2.1 ISO Geometrical Product Specification Masterplan 6-4

6.2 Comparison of ASME and ISO Standards 6-5

6.2.1 Organization and Logistics 6-5

6.2.2 Number of Standards 6-5

6.2.3 Interpretation and Application 6-5

6.2.3.1	ASME.....	6-6
6.2.3.2	ISO	6-6
6.3	Other Standards	6-27
6.3.1	National Standards Based on ISO or ASME Standards	6-27
6.3.2	US Government Standards	6-28
6.3.3	Corporate Standards	6-28
6.3.4	Multiple Dimensioning Standards	6-29
6.4	Future of Dimensioning Standards	6-30
6.5	Effects of Technology	6-30
6.6	New Dimensioning Standards	6-30
6.7	References	6-30

Chapter 7: Mathematical Definition of Dimensioning and Tolerancing Principles.....
 Mark A. Nasson

7.1	Introduction	7-1
7.2	Why Mathematical Tolerance Definitions?	7-1
7.2.1	Metrology Crisis (The GIDEP Alert)	7-2
7.2.2	Specification Crisis	7-3
7.2.3	National Science Foundation Tolerancing Workshop	7-3
7.2.4	A New National Standard	7-4
7.3	What are Mathematical Tolerance Definitions?	7-4
7.3.1	Parallel, Equivalent, Unambiguous Expression	7-4
7.3.2	Metrology Independent	7-4
7.4	Detailed Descriptions of Mathematical Tolerance Definitions	7-4
7.4.1	Introduction	7-4
7.4.2	Vectors	7-5
7.4.2.1	Vector Addition and Subtraction	7-5
7.4.2.2	Vector Dot Products	7-6
7.4.2.3	Vector Cross Products	7-6
7.4.3	Actual Value / Measured Value	7-7
7.4.4	Datums	7-8
7.4.4.1	Candidate Datums / Datum Reference Frames	7-8
7.4.4.2	Degrees of Freedom	7-8
7.4.5	Form tolerances	7-9
7.4.5.1	Circularity	7-9
7.4.5.2	Cylindricity	7-12
7.4.5.3	Flatness	7-13
7.5	Where Do We Go from Here?	7-14
7.5.1	ASME Standards Committees	7-14
7.5.2	International Standards Efforts	7-14
7.5.3	CAE Software Developers	7-14
7.6	Acknowledgments	7-15
7.7	References	7-15

Chapter 8: Statistical Tolerancing..... Vijay Srinivasan, Ph.D

8.1	Introduction	8-1
8.2	Specification of Statistical Tolerancing	8-2
8.2.1	Using Process Capability Indices	8-2
8.2.2	Using RMS Deviation Index	8-4
8.2.3	Using Percent Containment	8-5
8.3	Statistical Tolerance Zones	8-5
8.3.1	Population Parameter Zones	8-6
8.3.2	Distribution Function Zones	8-7
8.4	Additional Illustrations	8-7
8.5	Summary and Concluding Remarks	8-9
8.6	References	8-10

Part 3 Design

Chapter 9: Traditional Approaches to Analyzing Mechanical Tolerance Stacks Paul Drake

9.1	Introduction	9-1
9.2	Analyzing Tolerance Stacks	9-1
9.2.1	Establishing Performance/Assembly Requirements	9-1
9.2.2	Loop Diagram	9-3
9.2.3	Converting Dimensions to Equal Bilateral Tolerances	9-5
9.2.4	Calculating the Mean Value (Gap) for the Requirement	9-7
9.2.5	Determine the Method of Analysis	9-8
9.2.6	Calculating the Variation for the Requirement	9-9
9.2.6.1	Worst Case Tolerancing Model	9-9
9.2.6.2	RSS Model.....	9-12
9.2.6.3	Modified Root Sum of the Squares Tolerancing Model.....	9-18
9.2.6.4	Comparison of Variation Models	9-22
9.2.6.5	Estimated Mean Shift Model	9-23
9.3	Analyzing Geometric Tolerances	9-24
9.3.1	Form Controls	9-25
9.3.2	Orientation Controls	9-26
9.3.3	Position	9-27
9.3.3.1	Position at RFS	9-27
9.3.3.2	Position at MMC or LMC	9-27
9.3.3.3	Virtual and Resultant Conditions	9-28
9.3.3.4	Equations	9-28
9.3.3.5	Composite Position	9-32
9.3.4	Runout	9-33
9.3.5	Concentricity/Symmetry.....	9-33
9.3.6	Profile	9-34
9.3.6.1	Profile Tolerancing with an Equal Bilateral Tolerance Zone	9-34
9.3.6.2	Profile Tolerancing with a Unilateral Tolerance Zone	9-35
9.3.6.3	Profile Tolerancing with an Unequal Bilateral Tolerance Zone	9-35
9.3.6.4	Composite Profile	9-36
9.3.7	Size Datums	9-36
9.4	Abbreviations	9-37
9.5	Terminology	9-39
9.6	References	9-39

Chapter 10: Statistical Background and Concepts Ron Randall

10.1	Introduction	10-1
10.2	Shape, Locations, and Spread	10-2
10.3	Some Important Distributions	10-2
10.3.1	The Normal Distribution	10-2
10.3.2	Lognormal Distribution	10-6
10.3.3	Poisson Distribution	10-8
10.4	Measures of Quality and Capability	10-10
10.4.1	Process Capability Index	10-10
10.4.2	Process Capability Index Relative to Process Centering (Cpk)	10-12
10.5	Summary	10-14
10.6	References	10-14
10.7	Appendix	10-15

Chapter 11: Predicting Assembly Quality (Six Sigma Methodologies to Optimize Tolerances) Dale Van Wyk

11.1 Introduction11-1

11.2 What is Tolerance Allocation?11-1

11.3 Process Standard Deviations11-2

11.4 Worst Case Allocation11-5

11.4.1 Assign Component Dimensions11-6

11.4.2 Determine Assembly Performance, P11-7

11.4.3 Assign the process with the largest si to each component11-8

11.4.4 Calculate the Worst Case Assembly, t_{wc6} 11-8

11.4.5 Is $P^{\geq} t_{wc6}$?11-9

11.4.6 Estimating Defect Rates11-10

11.4.7 Verification11-12

11.4.8 Adjustments to Meet Quality Goals11-13

11.4.9 Worst Case Allocation Summary11-13

11.5 Statistical Allocation11-13

11.5.1 Calculating Assembly Variation and Defect Rate11-15

11.5.2 First Steps in Statistical Allocation11-15

11.5.3 Calculate Expected Assembly Performance, P_g 11-15

11.5.4 Is $P^{\geq} P_g$?11-16

11.5.5 Allocating Tolerances11-17

11.5.6 Statistical Allocation Summary11-20

11.6 Dynamic RSS Allocation11-20

11.7 Static RSS analysis11-23

11.8 Comparison of the Techniques11-24

11.9 Communication of Requirements11-25

11.10 Summary11-26

11.11 Abbreviations11-26

11.12 References11-27

Chapter 12: Multi-Dimensional Tolerance Analysis (Manual Method) Dale Van Wyk

12.1 Introduction12-1

12.2 Determining Sensitivity12-2

12.3 A Technique for Developing Gap Equations12-4

12.4 Utilizing Sensitivity Information to Optimize Tolerances12-12

12.5 Summary12-13

Chapter 13: Multi-Dimensional Tolerance Analysis (Automated Method) Kenneth W. Chase, Ph.D.

13.1 Introduction13-1

13.2 Three Sources of Variation in Assemblies13-2

13.3 Example 2D Assembly – Stacked Blocks13-3

13.4 Steps in Creating an Assembly Tolerance Model13-4

13.5 Steps in Analyzing an Assembly Tolerance Model13-12

13.5.5.1 Percent rejects13-21

13.5.5.2 Percent Contribution Charts13-22

13.5.5.3 Sensitivity Analysis13-24

13.5.5.4 Modifying Geometry13-24

13.6 Summary13-26

13.7 References13-27

Chapter 14: Minimum-Cost Tolerance Allocation	Kenneth W. Chase, Ph.D.
14.1	Tolerance Allocation Using Least Cost Optimization 14-1
14.2	1-D Tolerance Allocation 14-1
14.3	1-D Example: Shaft and Housing Assembly 14-3
14.4	Advantages / Disadvantages of the Lagrange Multiplier Method 14-7
14.6	2-D and 3-D Tolerance Allocation 14-8
14.5	True Cost and Optimum Acceptance Fraction 14-8
14.7	2-D Example: One-way Clutch Assembly 14-9
14.7.1	Vector Loop Model and Assembly Function for the Clutch 14-10
14.8	Allocation by Scaling, Weight Factors 14-10
14.8.1	Proportional Scaling by Worst Case 14-11
14.8.2	Proportional Scaling by Root-Sum-Squares 14-11
14.8.3	Allocation by Weight Factors 14-11
14.9	Allocation by Cost Minimization 14-12
14.9.1	Minimum Cost Tolerances by Worst Case 14-13
14.9.2	Minimum Cost Tolerances by RSS 14-14
14.10	Tolerance Allocation with Process Selection 14-15
14.11	Summary 14-16
14.12	References 14-17
14.13	Appendix: Cost-Tolerance Functions for Metal Removal Processes 14-18
Chapter 15: Automating the Tolerancing Process	Charles Glancy
.....	James Stoddard
.....	Marvin Law
15.1	Background Information 15-2
15.1.1	Benefits of Automation 15-2
15.1.2	Overview of the Tolerancing Process 15-2
15.2	Automating the Creation of the Tolerance Model 15-3
15.2.1	Characterizing Critical Design Measurements 15-3
15.2.2	Characterizing the Model Function 15-4
15.2.2.1	Model Definition 15-4
15.2.2.2	Model Form 15-5
15.2.2.3	Model Scope 15-5
15.2.3	Characterizing Input Variables 15-6
15.3	Automating Tolerance Analysis 15-6
15.3.1	Method of System Moments 15-6
15.3.3	Distribution Fitting 15-8
15.3.2	Monte Carlo Simulation 15-8
15.4	Automating Tolerance Optimization 15-9
15.5	Automating Communication Between Design and Manufacturing 15-9
15.5.1	Manufacturing Process Capabilities 15-10
15.5.1.1	Manufacturing Process Capability Database 15-10
15.5.1.2	Database Administration 15-11
15.5.2	Design Requirements and Assumptions 15-11
15.6	CAT Automation Tools 15-12
15.6.1	Tool Capability 15-12
15.6.2	Ease of Use 15-12
15.6.3	Training 15-13
15.6.4	Technical Support 15-13
15.6.5	Data Management and CAD Integration 15-13
15.6.6	Reports and Records 15-13
15.6.7	Tool Enhancement and Development 15-14
15.6.8	Deployment 15-14
15.7	Summary 15-14
15.8	References 15-14

Chapter 16: Working in an Electronic Environment	Paul Matthews
16.1	Introduction 16-1
16.2	Paperless/Electronic Environment 16-2
16.2.1	Definition 16-2
16.3	Development Information Tools 16-3
16.3.1	Product Development Automation Strategy 16-3
16.3.2	Master Model Theory 16-4
16.3.3	Template Design 16-7
16.3.3.1	Template Part and Assembly Databases 16-7
16.3.3.2	Template Features 16-8
16.3.3.3	Templates for Analyses 16-9
16.3.3.4	Templates for Documentation 16-9
16.3.4	Component Libraries 16-9
16.3.5	Information Verification 16-10
16.4	Product Information Management 16-11
16.4.1	Configuration Management Techniques 16-11
16.4.2	Data Management Components 16-12
16.4.2.1	Workspace 16-12
16.4.2.2	Product Vault 16-12
16.4.2.3	Company Vault 16-12
16.4.3	Document Administrator 16-13
16.4.4	File Cabinet Control 16-13
16.4.5	Software Automation 16-13
16.5	Information Storage and Transfer 16-13
16.5.1	Internet 16-13
16.5.2	Electronic Mail 16-14
16.5.3	File Transfer Protocol 16-14
16.5.4	Media Transfer 16-15
16.6	Manufacturing Guidelines 16-15
16.6.1	Manufacturing Trust 16-15
16.6.2	Dimensionless Prints 16-15
16.6.2.1	Sheetmetal 16-16
16.6.2.2	Injection Molded Plastic 16-17
16.6.2.3	Hog Out Parts 16-17
16.6.2.4	Castings 16-18
16.6.2.5	Rapid Prototypes 16-18
16.7	Database Format Standards 16-19
16.7.1	Native Database 16-19
16.7.2	2-D Formats 16-19
16.7.2.1	Data eXchange Format (DXF) 16-19
16.7.2.2	Hewlett-Packard Graphics Language (HPGL) 16-20
16.8	3-D Formats 16-20
16.8.1	Initial Graphics Exchange Specification (IGES) 16-20
16.8.2	STandard for the Exchange of Product (STEP) 16-20
16.8.3	Virtual Reality Modeling Language (VRML) 16-20
16.8.4	STereoLithography (STL) 16-21
16.9	General Information Formats 16-21
16.9.1	Hypertext Markup Language (HTML) 16-21
16.9.2	Portable Document Format (PDF) 16-22
16.10	Graphics Formats 16-22
16.10.1	Encapsulated PostScript (EPS) 16-22
16.10.2	Joint Photographic Experts Group (JPEG) 16-22
16.10.3	Tagged Image File Format (TIFF) 16-22
16.11	Conclusion 16-23
16.12	Appendix A IGES Entities 16-23

Part 4 Manufacturing

Chapter 17: Collecting and Developing Manufacturing Process Capability Models..... Michael D. King

17.1	Why Collect and Develop Process Capability Models?	17-1
17.2	Developing Process Capability Models	17-2
17.3	Quality Prediction Models - Variable versus Attribute Information	17-3
17.3.1	Collecting and Modeling Variable Process Capability Models	17-3
17.3.2	Collecting and Modeling Attribute Process Capability Models	17-7
17.3.3	Feature Factoring Method	17-7
17.3.4	Defect Weighting Methodology	17-7
17.4	Cost and Cycle Time Prediction Modeling Variations	17-8
17.5	Validating and Checking the Results of Your Predictive Models	17-9
17.6	Summary	17-11
17.7	References	17-11

Part 5 Gaging

Chapter 18: Paper Gage Techniques Martin P. Wright

18.1	What is Paper Gaging?	18-1
18.2	Advantages and Disadvantages to Paper Gaging	18-2
18.3	Discrimination Provided By a Paper Gage	18-3
18.4	Paper Gage Accuracy	18-3
18.5	Plotting Paper Gage Data Points	18-4
18.6	Paper Gage Applications	18-4
18.6.1	Locational Verification	18-5
18.6.1.1	Simple Hole Pattern Verification	18-5
18.6.1.2	Three-Dimensional Hole Pattern Verification	18-8
18.6.1.3	Composite Positional Tolerance Verification	18-10
18.6.2	Capturing Tolerance From Datum Features Subject to Size Variation	18-12
18.6.2.1	Datum Feature Applied on an RFS Basis	18-12
18.6.2.2	Datum Feature Applied on an MMC Basis	18-12
18.6.2.3	Capturing Rotational Shift Tolerance from a Datum Feature Applied on an MMC Basis	18-16
18.6.2.4	Determining the Datum from a Pattern of Features	18-19
18.6.3	Paper Gage Used as a Process Analysis Tool	18-21
18.7	Summary	18-23
18.8	References	18-23

Chapter 19: Receiver Gages — Go Gages and Functional Gages.... James D. Meadows

19.1	Introduction	19-1
19.2	Gaging Fundamentals	19-2
19.3	Gage Tolerancing Policies	19-3
19.4	Examples of Gages	19-4
19.4.1	Position Using Partial and Planar Datum Features	19-4
19.4.2	Position Using Datum Features of Size at MMC	19-6
19.4.3	Position and Profile Using a Simultaneous Gaging Requirement	19-9
19.4.4	Position Using Centerplane Datums	19-12
19.4.5	Multiple Datum Structures	19-14
19.4.6	Secondary and Tertiary Datum Features of Size	19-17

19.5	Push Pin vs. Fixed Pin Gaging	19-20
19.6	Conclusion	19-20
19.7	References	19-20

Part 6 Precision Metrology

Chapter 20: Measurement Systems Analysis..... Gregory A. Hetland, Ph.D.

20.1	Introduction	20-1
20.2	Measurement Methods Analysis	20-2
20.2.1	Measurement System Definition (Phase 1)	20-2
20.2.1.1	Identification of Variables	20-2
20.2.1.2	Specifications of Conformance	20-3
20.2.1.3	Measurement System Capability Requirements	20-3
20.2.2	Identification of Sources of Uncertainty (Phase 2)	20-3
20.2.2.1	Machine Sources of Uncertainty	20-4
20.2.2.2	Software Sources of Uncertainty	20-4
20.2.2.3	Environmental Sources of Uncertainty	20-5
20.2.2.4	Part Sources of Uncertainty	20-5
20.2.2.5	Fixturing Sources of Uncertainty	20-5
20.2.2.6	Operator Sources of Uncertainty	20-6
20.2.3	Measurement System Qualification (Phase 3)	20-6
20.2.3.1	Plan the Capabilities Studies	20-6
20.2.3.2	Production Systems	20-7
20.2.3.3	Calibrate the System	20-7
20.2.3.4	Conduct Studies and Define Capabilities	20-8
20.2.4	Quantify the Error Budget (Phase 4)	20-8
20.2.4.1	Plan Testing (Isolate Error Sources)	20-8
20.2.4.2	Analyze Uncertainty	20-9
20.2.5	Optimize Measurement System (Phase 5)	20-9
20.2.5.1	Identify Opportunities	20-9
20.2.5.2	Attempt Improvements and Revisit Testing	20-9
20.2.5.3	Revisit Qualification	20-10
20.2.6	Implement and Control Measurement System (Phase 6)	20-10
20.2.6.1	Plan Performance Criteria	20-10
20.2.6.2	Plan Calibration and Maintenance Requirements	20-11
20.2.6.3	Implement System and Initiate Control	20-11
20.2.6.4	CMM Operator Competencies	20-11
20.2.6.5	Business Issue	20-12
20.3	CMM Performance Test Overview	20-17
20.3.1	Environmental Tests (Section 1)	20-17
20.3.1.1	Temperature Parameters	20-17
20.3.1.2	Other Environmental Parameters	20-20
20.3.2	Machine Tests (Section 2)	20-21
20.3.2.1	Probe Settling Time	20-21
20.3.2.2	Probe Deflection	20-24
20.3.2.3	Other Machine Parameters	20-27
20.3.2.4	Multiple Probes	20-27
20.3.3	Feature Based Measurement Tests (Section 3)	20-28
20.3.3.1	Number of Points Per Feature	20-30
20.3.3.2	Other Geometric Features	20-34
20.3.3.3	Contact Scanning	20-34
20.3.3.4	Surface Roughness	20-35
20.4	CMM Capability Matrix	20-35
20.5	References	20-38

Part 7 Applications

Chapter 21: Predicting Piecepart Quality Dan A. Watson, Ph.D.

21.1	Introduction	21-1
21.2	The Problem	21-2
21.3	Statistical Framework	21-3
21.3.1	Assumptions	21-3
21.3.2	Internal Feature at MMC	21-5
21.3.3	Internal Feature at LMC	21-7
21.3.4	External Features	21-8
21.3.5	Alternate Distribution Assumptions	21-8
21.4	Non-Size Feature Applications	21-9
21.5	Example	21-9
21.6	Summary	21-10
21.7	References	21-11

Chapter 22: Floating and Fixed Fasteners Paul Zimmermann

22.1	Introduction	22-1
22.2	Floating and Fixed Fasteners	22-1
22.2.1	What is a Floating Fastener?	22-4
22.2.2	What is a Fixed Fastener?	22-4
22.2.3	What is a Double-Fixed Fastener?	22-4
22.3	Geometric Dimensioning and Tolerancing (Cylindrical Tolerance Zone Versus +/- Tolerancing)	22-5
22.4	Calculations for Fixed, Floating and Double-fixed Fasteners	22-8
22.5	Geometric Dimensioning and Tolerancing Rules/Formulas for Floating Fastener	22-8
22.5.1	How to Calculate Clearance Hole Diameter for a Floating Fastener Application	22-8
22.5.2	How to Calculate Counterbore Diameter for a Floating Fastener Application	22-9
22.5.3	Why Floating Fasteners are Not Recommended	22-10
22.6	Geometric Dimensioning and Tolerancing Rules/Formulas for Fixed Fasteners	22-10
22.6.1	How to Calculate Fixed Fastener Applications	22-10
22.6.2	How to Calculate Counterbore Diameter for a Fixed Fastener Application	22-10
22.6.3	Why Fixed Fasteners are Recommended	22-11
22.7	Geometric Dimensioning and Tolerancing Rules/Formulas for Double-fixed Fastener	22-11
22.7.1	How to Calculate a Clearance Hole	22-11
22.7.2	How to Calculate the Countersink Diameter, Head Height Above and Head Height Below the Surface	22-11
22.7.3	What Are the Problems Associated with Double-fixed Fasteners?	22-13
22.8	Nut Plates: Floating and Nonfloating (see Fig. 22-14)	22-14
22.9	Projected Tolerance Zone	22-15
22.9.1	Comparison of Positional Tolerancing With and Without a Projected Tolerance Zone	22-16
22.9.2	Percent of Actual Orientation Versus Lost Functional Tolerance	22-18
22.10	Hardware Pages	22-18
22.10.1	Floating Fastener Hardware Pages	22-20
22.10.2	Fixed Fastener Hardware Pages	22-21
22.10.3	Double-fixed Fastener Hardware Pages	22-23
22.10.4	Counterbore Depths - Pan Head and Socket Head Cap Screws	22-25
22.10.5	Flat Head Screw Head Height - Above and Below the Surface	22-26
22.11	References	22-26

Chapter 23: Fixed and Floating Fastener Variation Chris Cuba

23.1 Introduction 23-1
 23.2 Hole Variation 23-2
 23.3 Assembly Variation 23-4
 23.4 Fixed and Floating Fasteners 23-4
 23.4.1 Fixed Fastener Assembly Shift 23-5
 23.4.2 Fixed Fastener Assembly Shift Using One Equation and Dimension Loop 23-6
 23.4.3 Fixed Fastener Equation 23-7
 23.4.4 Fixed Fastener Gap Analysis Steps 23-7
 23.4.5 Floating Fastener Gap Analysis Steps 23-8
 23.5 Summary 23-9
 23.6 References 23-10

Chapter 24: Pinned Interfaces Stephen Harry Werst

24.1 List of Symbols (Definitions and Terminology) 24-1
 24.2 Introduction 24-2
 24.3 Performance Considerations 24-2
 24.4 Variation Components of Pinned Interfaces 24-3
 24.4.1 Type I Error 24-3
 24.4.2 Type II Error 24-3
 24.5 Types of Alignment Pins 24-4
 24.6 Tolerance Allocation Methods - Worst Case vs. Statistical 24-6
 24.7 Processes and Capabilities 24-6
 24.8 Design Methodology 24-7
 24.9 Proper Use of Material Modifiers 24-10
 24.10 Temperature Considerations 24-11
 24.11 Two Round Pins with Two Holes 24-11
 24.11.1 Fit 24-12
 24.11.2 Rotation Errors 24-12
 24.11.3 Translation Errors 24-13
 24.11.4 Performance Constants 24-13
 24.11.5 Dimensioning Methodology 24-14
 24.12 Round Pins with a Hole and a Slot 24-14
 24.12.1 Fit 24-14
 24.12.2 Rotation Errors 24-16
 24.12.3 Translation Errors 24-17
 24.12.4 Performance Constants 24-17
 24.12.5 Dimensioning Methodology 24-17
 24.13 Round Pins with One Hole and Edge Contact 24-18
 24.13.1 Fit 24-19
 24.13.2 Rotation Errors 24-20
 24.13.3 Translation errors 24-20
 24.13.4 Performance Constants 24-20
 24.13.5 Dimensioning Methodology 24-20
 24.14 One Diamond Pin and One Round Pin with Two Holes 24-23
 24.14.1 Fit 24-23
 24.14.2 Rotation and Translation Errors 24-24
 24.14.3 Performance Constants 24-24
 24.14.4 Dimensioning Methodology 24-24
 24.15 One Parallel-Flats Pin and One Round Pin with Two Holes 24-26
 24.15.1 Fit 24-26
 24.15.2 Rotation and Translation Errors 24-27
 24.15.3 Performance Constants 24-27
 24.15.4 Dimensioning Methodology 24-28
 24.16 References 24-29

Chapter 25: Gage Repeatability and Reproducibility (GR&R) Calculations Gregory A. Hetland, Ph.D.

25.1	Introduction	25-1
25.2	Standard GR&R Procedure	25-1
25.3	Summary	25-7
25.4	References	25-7

Part 8 The Future

Chapter 26: The Future Several contributors

Figures	F-1
Tables	T-1
Index	I-1