

Handbook of Machining with Grinding Wheels

Ioan D. Marinescu
Mike Hitchiner
Eckart Uhlmann
W. Brian Rowe
Ichiro Inasaki

AVAILABLE THROUGH THE ABRASIVES MALL
www.abrasivesmall.com/bkgrdwl.html

CRC PRESS
2006
ISBN 1-57444-671-1

Preface

Grinding, once considered primarily a finishing operation involving low rates of removal, has evolved as a major competitor to cutting, as the term “abrasive machining” suggests. This is what Milton Shaw, the man who is considered the great pioneer and father of American grinding, said about 10 years ago. Shaw led the development of grinding in the United States over the last 50 years.

We named this book *Handbook of Machining with Grinding Wheels* because the borders between grinding and other operations such as superfinishing, lapping, polishing, and flat honing are no longer distinct. Machining with grinding wheels extends from high-removal rate processes into the domains of ultra-high accuracy and superfinishing. This book aims to explore some of the new “transition operations,” and for this reason we chose this title.

This book presents a wide range of abrasive machining technology in fundamental and application terms. The emphasis is on why things happen as they do, rather than a how-to-do-it approach. The topics covered in this book cover a range of abrasive machining processes with grinding wheels, making this probably the most complete book regarding all kinds of grinding operations.

The aim of this book is to present a unified approach to machining with grinding wheels that will be useful in solving new grinding problems of the future. It should be of value to engineers and technicians involved in solving problems in industry and to those doing research on machining with grinding wheels in universities and research organizations.

The team of authors are famous researchers who have devoted their entire lives doing research in this field and who are still actively contributing to new research and development. The authors represent a large region of the world where abrasive machining with grinding wheels are most advanced: United States, Great Britain, Japan, and Germany. I thank my co-authors for taking time from their busy activities to write and review this book over a period of 2 years.

...

The main purpose of this book is to present abrasive-machining processes as a science more than an art. Research and development on abrasive-machining processes have greatly increased the level of science compared to 25 years ago when many aspects of abrasive machining processes still depended largely on the expertise of individual technicians, engineers, and scientists.

The book has two parts: “The Basic Process of Grinding” and “Application of Grinding Processes.” This structure allows us to present more about *understanding of grinding behavior* in the first part and more about *industrial application* in the second part,

Ioan D. Marinescu Toledo, 2006

The Authors

Ioan D. Marinescu is a professor of mechanical, industrial, and manufacturing engineering at the University of Toledo. He is also the director of the Precision Micro-Machining Center of the College of Engineering (www.eng.utoledo.edu/pmmc) of the same university. He has a Ph.D. in manufacturing processes, an honorary doctorate from University of Iasi, Romania, and is a member of numerous international professional organizations: **JSPE, SME, ASME, ASPE, CIRP, IDA, ASAT**, and NAMRI.

Professor Marinescu is author of more than 15 books and over 300 technical and scientific papers. He has given lectures and workshops in more than 40 countries around the world. Also, he is the executive director and cofounder of the American Society for Abrasive Technology.

Ten years ago, Dr. Marinescu founded his own company, Advanced Manufacturing Solutions Co., LLC, a company that specializes in consulting, R&D, manufacturing, and trade (www.interams.com). He is the president and CEO of this company.

Mike Hitchiner obtained his doctorate in 1982 at the University of Oxford for research in grinding and machining with cubic boron nitride (CBN) and diamonds. After another 3 years of university research in diamonds and CBN, he joined Saint-Gobain Abrasives (SGA) and its affiliate companies in 1985. He worked initially on conventional abrasive grain manufacture and advanced ceramics before becoming R&D manager for vitrified CBN in Europe in 1987. In 1989, he joined Universal Superabrasives (SGA) as technology manager for vitrified CBN for the U.S. market. More recently, he has broadened his responsibilities as the technology manager for precision grinding applications for North America, as well as projects throughout Asia and Europe.

Eckart Uhlmann is the director of the Fraunhofer-Institute for Production Systems and Design Technology IPK and professor of machine tools and manufacturing technology at the Institute for Machine Tools and Factory Management of the Technical University in Berlin, Germany. He received his doctorate in engineering on “Creep Feed Grinding of High-Strength Ceramic Materials.” Prior to his academic career, he served several years as vice-president and director of research and development at Hermes Schleifmittel GmbH & Co., Hamburg, Germany. In addition to being a consultant for various German and international companies, Dr. Uhlmann holds many professional memberships, including the Berlin Wissenschaftskommission, the Verein Deutscher Ingenieure, and the International Institution for Production Engineering Research. He also holds an honorary doctorate from Kolej Universiti Teknikal Kebangsaan, Malaysia.

W. Brian Rowe gained 6 years of experience with Austin Motor Company, Birmingham, England, and another 6 years with Wickman Machine Tools, Coventry, England. He studied at the University of Aston in Birmingham earning an honors degree in mechanical and production engineering in 1961. He earned a Ph.D. for research on the mechanics of centerless grinding at Manchester University in 1964 and became a doctor of science in 1976 for his wider research on tribology. He became the head of mechanical engineering in 1973 at Liverpool Polytechnic (later to become Liverpool John Moores University) and eventually became assistant rector responsible for corporate academic development, strategic planning, and for development of research. In 1992, he relinquished his administrative responsibilities in order to focus on research. As director of the Advanced Manufacturing Technology Research Laboratory (AMTREL), he built up a significant team of researchers that worked closely with industry in the United Kingdom. AMTREL has made

TABLE OF CONTENTS

Part I

The Basic Process of Grinding	I
Chapter 1	
Introduction	3
1.1 From Craft to Science	3
1.2 Basic Uses of Grinding	4
1.2.1 High Accuracy Required	4
1.2.2 High Removal Rate Required	4
1.2.3 Machining of Hard Materials	4
1.3 Elements of the Grinding System	4
1.3.1 The Basic Grinding Process	4
1.3.2 Four Basic Grinding Operations	5
1.4 The Importance of the Abrasive	6
1.5 Grinding Wheels for a Purpose	7
1.6 Problem-Solving	7
1.6.1 Part I	7
1.6.2 Part II	8
References	8
Chapter 2 Grinding Parameters	9
2.1 Introduction	9
2.1.1 Wheel Life	9
2.1.2 Redress Life	10
2.1.3 Cycle Time	10
2.2 Process Parameters	11
2.2.1 Uncut Chip Thickness or Grain Penetration Depth	11
2.2.2 Wheel Speed	11
2.2.3 Work Speed	11
2.2.4 Depth of Cut	11
2.2.5 Equivalent Wheel Diameter	11
2.2.6 Active Grit Density	12
2.2.7 Grit Shape Factor	12
2.2.8 Force per Grit	12
2.2.9 Specific Grinding Energy	12
2.2.10 Specific Removal Rate	12
2.2.11 Grinding Power	13
2.2.12 Tangential Grinding Force	14
2.2.13 Normal Grinding Force	14
2.2.14 Coefficient of Grinding	14
2.2.15 Surface Roughness	15
2.2.16 R_T Roughness	15
2.2.17 R_a Roughness	15
2.2.18 R_q Roughness	15
2.2.19 Material or Bearing Ratio	15
2.2.20 Peak Count	15
2.2.21 Comparison of Roughness Classes	15
2.2.22 Factors That Affect Roughness Measurements	15
2.2.23 Roughness Specifications on Drawings	16
2.2.24 Stock Removal Parameter	17
2.2.25 Decay Constant τ	17
2.2.26 G-Ratio	17
2.2.27 P-Ratio	18
2.2.28 Contact Length	18
2.2.29 Geometric Contact Length	18
2.2.30 Real Contact Length	18

2.3	Grinding Temperatures	18
2.3.1	Surface Temperature T	18
2.3.2	Maximum Workpiece Surface Temperature	19
2.3.3	The CFactor	19
2.3.4	The Transient Thermal Property	19
2.3.5	Workpiece Partition Ratio R	19
2.3.6	Effect of Grinding Variables on Temperature	19
2.3.7	Heat Convection by Coolant and Chips	20
2.3.8	Control of Thermal Damage	20
	Appendix 2.1 Drawing Form and Profile Tolerancing	21
	References	21
Chapter 3 Material Removal Mechanisms		23
3.1	Significance	23
3.1.1	Introduction	23
3.1.2	Defining Basic Behavior	23
3.2	Grinding Wheel Topography	24
3.2.1	Introduction	24
3.2.2	Specification of Single Cutting Edges	24
3.3	Determination of Grinding Wheel Topography	25
3.3.1	Introduction	25
3.3.2	Static Methods	25
3.3.3	Dynamic Methods	26
3.3.4	Kinematic Simulation Methods	26
3.3.5	Measurement of Grinding Wheel Topography	27
3.3.6	Roughness Measures	27
3.3.7	Qualitative Assessment	28
3.3.8	Counting Methods	28
3.3.9	Piezo and Thermoelectric Measurements	28
3.3.10	Photoelectric Method	28
3.3.11	Mirror Workpiece Method	28
3.3.12	Workpiece Penetration Method	28
3.4	Kinematics of the Cutting Edge Engagement	29
3.5	Fundamental Removal Mechanisms	31
3.5.1	Microplowing, Chipping, and Breaking	31
3.6	Material Removal in Grinding of Ductile Materials	32
3.7	Surface Formation in Grinding of Brittle-Hard Materials	35
3.7.1	Indentation Tests	35
3.7.2	Scratch and Grinding Behavior of Brittle-Hard Materials	35
3.7.2.1	Fine-Grained Materials	36
3.7.2.2	Coarse-Grained Materials	36
3.8	Energy Transformation	41
	References	42
Chapter 4 Grinding Wheels		45
4.1	Introduction	45
4.1.1	Developments in Productivity	45
4.1.2	System Development	45
4.1.3	Conventional and Superabrasive Wheel Design	45
4.2	Wheel Shape Specification	46
4.2.1	Basic Shapes	46
4.2.2	Hole Tolerances	48
4.2.3	Side and Diameter Tolerances	49
4.3	Wheel Balance	49
4.3.1	Introduction to Wheel Balance	49
4.3.2	Static and Dynamic Unbalance	50
4.3.3	Automatic Wheel Balancers	52
4.3.4	Dynamic Balancing in Two Planes	52

4.3.5	Coolant Unbalance	53
4.4	Design of High-Speed Wheels	54
4.4.1	Trend toward Higher Speeds	54
4.4.2	How Wheels Fail	54
4.4.3	Hoop Stress and Radial Stress	54
4.4.4	Reinforced Wheels	55
4.4.5	Segmented Wheels	56
4.4.6	Segment Design	56
4.4.7	Abrasive Layer Depth	57
4.4.8	Recent Development of High-Speed Conventional Wheels	58
4.4.9	Safety of Segmented Wheel Designs	59
4.4.10	Speed Rating of Grinding Wheels	60
4.5	Bond Life	61
4.6	Wheel Mount Design	61
4.6.1	A Conventional Wheel Mount	62
4.6.2	Use of Blotters	62
4.6.3	Clamping Forces	62
4.6.3.1	Clamping Force to Compensate for the Weight of the Wheel	62
4.6.3.2	Clamping Force for Unbalance of the Wheel	63
4.6.3.3	Clamping Force for Motor Power Surge	63
4.6.3.4	Clamping Force for Reaction of Wheel to Workpiece	63
4.6.4	High-Speed Wheel Mounts	64
4.6.5	The Single-Piece Wheel Hub	64
4.6.6	Direct Mounting on the Spindle	64
4.6.7	CFRP Wheel Hubs	66
4.6.8	Electroplated Wheels	66
4.6.9	Aluminum Hubs	68
4.6.10	Junker Bayonet Style Mounts	68
4.6.11	HSK Hollow Taper Mount	68
4.6.12	Titanium Hub Design	70
4.7	Wheel Design and Chatter Suppression	71
4.7.1	The Role of Damping	71
4.7.2	Forced and Self-Excited Vibrations	71
4.7.2.1	Forced Vibrations	71
4.7.2.2	Self-Excited Vibration	71
4.7.3	Damped Wheel Designs and Wheel Compliance	72
4.7.4	Wheel Frequency and Chatter	73
4.7.5	Summary	73
	References	73
Chapter 5	The Nature of the Abrasive	75
5.1	Introduction	75
5.2	Silicon Carbide	75
5.2.1	Development of SiC	75
5.2.2	Manufacture of SiC	75
5.2.3	Hardness of SiC	75
5.3	Alumina (Alox)-Based Abrasives	76
5.4	Electrofused Alumina Abrasives	76
5.4.1	Manufacture	76
5.4.2	Brown Alumina	77
5.4.3	White Alumina	77
5.4.4	Alloying Additives	78
5.4.5	Pink Alumina	78
5.4.6	Ruby Alumina	79
5.4.7	Zirconia-Alumina	79
5.4.8	Single Crystal White Alumina	79
5.4.9	Postfusion Processing Methods	79
5.4.10	Postfusion Heat Treatment	79
5.4.11	Postfusion Coatings	79

5.5	Chemical Precipitation and/or Sintering of Alumina	79
5.5.1	Importance of Crystal Size	79
5.5.2	Microcrystalline Grits	80
5.5.3	Seeded Gel Abrasive	80
5.5.4	Application of SG Abrasives	80
5.5.5	Sol Gel Abrasives	80
5.5.6	Comparison of SG and Cubitron Abrasives	81
5.5.7	Extruded SG Abrasive	81
5.5.8	Future Trends for Conventional Abrasives	82
5.6	Diamond Abrasives	82
5.6.1	Natural and Synthetic Diamonds	82
5.6.2	Origin of Diamond	83
5.6.3	Production Costs	83
5.6.4	Three Forms of Carbon	84
5.6.5	The Shape and Structure of Diamond	85
5.6.6	Production of Synthetic Diamond	85
5.6.7	Controlling Stone Morphology	85
5.6.8	Diamond Quality Measures	86
5.6.9	Diamond Coatings	86
5.6.10	Polycrystalline Diamond (PCD)	87
5.6.11	Diamond Produced by Chemical Vapor Deposition (CVD)	88
5.6.12	Structure of CVD Diamond	88
5.6.13	Development of Large Synthetic Diamond Crystals	88
5.6.14	Demand for Natural Diamond	89
5.6.15	Forms of Natural Diamond	89
5.6.16	Hardness of Diamond	89
5.6.17	Wear Resistance of Diamond	90
5.6.18	Strength of Diamond	90
5.6.19	Chemical Properties of Diamond	90
5.6.20	Thermal Stability of Diamond	91
5.6.21	Chemical Affinity of Diamond	92
5.6.22	Effects of Chemical Affinity in Manufacture	92
5.6.23	Effects of Chemical Affinity in Grinding	92
5.6.24	Grinding Steels and Cast Irons with Diamond	92
5.6.25	Thermal Properties	92
5.7	CBN	93
5.7.1	Development of CBN	93
5.7.2	Shape and Structure of CBN	93
5.7.3	Types of CBN Grains	94
5.7.4	CBN	95
5.7.5	Sources and Costs of CBN	95
5.7.6	Wurtzitic Boron Nitride	95
5.7.7	Hardness of CBN	96
5.7.8	Wear Resistance of CBN	96
5.7.9	Thermal and Chemical Stability of CBN	97
5.7.10	Effect of Coolant on CBN	97
5.7.11	Effect of Reactivity with Workpiece Constituents	98
5.7.12	Thermal Properties of CBN	98
5.8	Grain Size Distributions	98
5.8.1	The ANSI Standard	98
5.8.2	The FEPA Standard	99
5.8.3	Comparison of FEPA and ANSI Standards	99
5.8.4	US Grit Size Number	99
5.9	Future Grain Developments	99
5.10	Postscript	99
	References	100
	Chapter 6 Specification of the Bond	103

6.1	Introduction	103
6.2	Single-Layer Wheels	103
6.3	Electroplated (EP) Single-Layer Wheels	103
6.3.1	Structure of an EP Layer	103
6.3.2	Product Accuracy	103
6.3.3	Wear Resistance of the Bond	103
6.3.4	Grit Size and Form Accuracy	104
6.3.5	Wheel Wear Effects in Grinding	104
6.3.6	Size and Form-Holding Capability	105
6.3.7	Wheel Break-In Period	105
6.3.8	Summary of Variables Affecting Wheel Performance	107
6.3.9	Effect of Coolant on Plated Wheels	107
6.3.10	Reuse of Plated Wheels	107
6.4	Brazed Single-Layer Wheels	107
6.5	Vitrified Bond Wheels for Conventional Wheels	108
6.5.1	Application of Vitrified Bonds	108
6.5.2	Fabrication of Vitrified Bonds	108
6.5.3	Structure and Grade of Conventional Vitrified Wheels	109
6.5.4	Mixture Proportions	110
6.5.5	Structure Number	110
6.5.6	Grade of Conventional Vitrified Wheels	110
6.5.7	Fracture Wear Mode of Vitrified Wheels	111
6.5.8	High Porosity Vitrified Wheels	112
6.5.9	Multiple Pore Size Distributions	113
6.5.10	Ultrahigh Porosity Vitrified Wheels	113
6.5.11	Combining Grade and Structure	113
6.5.12	Lubricated Vitrified Wheels	113
6.6	Vitrified Bonds for Diamond Wheels	114
6.6.1	Introduction	114
6.6.2	Hard Work Materials	114
6.6.3	Low Chemical Bonding	114
6.6.4	High Grinding Forces	114
6.6.5	Diamond Reactivity with Air at High Temperatures	114
6.6.6	Porous Vitrified Diamond Bonds	115
6.7	Vitrified Bonds for CBN	115
6.7.1	Introduction	115
6.7.2	Requirements for Vitrified CBN Bonds	116
6.7.3	CBN Wheel Structures	116
6.7.4	Grades of CBN Wheels	116
6.7.5	Firing Temperature	116
6.7.6	Thermal Stress	118
6.7.7	Bond Mix for Quality	118
6.8	Resin Bond Wheels	118
6.9	Plastic Bonds	119
6.10	Phenolic Resin Bonds	119
6.10.1	Introduction	119
6.10.2	Controlled Force Systems	119
6.10.3	Abrasive Size	120
6.10.4	Benefits of Resilience	120
6.10.5	Phenolic Resin Bonds for Superabrasive Wheels	121
6.10.6	Wheel Marking Systems for Resin Bonds	121
6.11	Polyimide Resin Bonds	121
6.11.1	Introduction	121
6.11.2	Cost Developments and Implications	121
6.11.3	Induced Porosity Polyimide	121
6.12	Metal Bonds	122
6.12.1	Introduction	122
6.12.2	Bronze Alloy Bonds	122
6.12.3	Porous Metal Bonds	122
6.12.4	Crush-Dressing	122

6.12.5 High-Porosity Impregnated Metal Bonds	124
6.13 Other Bond Systems	124
6.13.1 Rubber	124
6.13.2 Shellac	124
6.13.3 Silicate	124
References	124
Chapter 7 Dressing	127
7.1 Introduction	127
7.2 Traverse Dressing of Conventional Vitrified Wheels with Stationary Tools	127
7.2.1 Nomenclature	127
7.2.2 Single-Point Diamonds	128
7.2.3 Diamond Size	128
7.2.4 Scaif Angle	129
7.2.5 Cooling	129
7.2.6 Dressed Topography	130
7.2.7 Dressing Feed and Overlap Ratio	130
7.2.8 Dressing Depth	131
7.2.9 Dressing Forces	131
7.2.10 Dressing Tool Wear	131
7.2.11 Rotationally Adjustable Tools	132
7.2.12 Profile Dressing Tools	132
7.2.13 Synthetic Needle Diamonds	133
7.2.14 Natural Long Diamond Blade Tools	134
7.2.15 Grit and Cluster Tools	135
7.2.16 Form Blocks	135
7.3 Traverse Dressing of Superabrasive Wheels with Stationary Tools	137
7.3.1 Introduction	137
7.3.2 Jig Grinding	137
7.3.3 Toolroom Grinding	137
7.4 Uniaxial Traverse Dressing of Conventional Wheels with Rotary Diamond Tools	138
7.4.1 Introduction	138
7.4.2 Crush or Dressing Speed Ratio	138
7.4.3 Single-Ring Diamond and Matrix Diamond Discs	139
7.4.4 Dressing Conditions for Disc Dressers	140
7.4.5 Synthetic Diamond Discs	141
7.4.6 Sintered and Impregnated Rolls	141
7.4.7 Direct-Plated Diamond Rolls	141
7.4.8 Cup-Shaped Tools	141
7.5 Uniaxial Traverse Dressing of Vitrified CBN Wheels with Rotary Diamond Tools	142
7.5.1 Introduction	142
7.5.2 Dressing Depth	142
7.5.3 Crush Ratio	143
7.5.4 The Dressing Affected Layer	143
7.5.5 Touch Dressing	144
7.5.6 Truer Design for Touch Dressing	147
7.5.7 Impregnated Truers	147
7.5.8 Traverse Rotary Truers Using Needle Diamonds	149
7.6 Cross-Axis Traverse Dressing with Diamond Discs	149
7.6.1 Introduction	149
7.6.2 TraverseRate	150
7.7 Diamond Form-Roll Dressing	150
7.7.1 Manufacture and Design	150
7.7.2 Reverse Plating	153
7.7.3 Infiltrated Rolls	153
7.7.4 Reverse Plated Rolls	154
7.7.5 Dress Parameters for Form Rolls	154
7.7.6 Dress Parameters for Form CBN Wheels	158
7.7.7 Handling Diamond Rolls	159
7.8 Truing and Conditioning of Superabrasive Wheels	160

References	165
Chapter 8 Grinding Dynamics	167
8.1 Introduction	167
8.1.1 Loss of Accuracy and Productivity	167
8.1.2 A Need for Chatter Suppression	167
8.2 Forced and Regenerative Vibrations	167
8.2.1 Introduction	167
8.2.2 Forced Vibration	168
8.2.3 Regenerative Vibration	168
8.3 The Effect of Workpiece Velocity	168
8.4 Geometrical Interference between Grinding Wheel and Workpiece	170
8.5 Vibration Behavior of Various Grinding Operations	170
8.6 Regenerative Self-Excited Vibrations	172
8.6.1 Modeling of Dynamic Grinding Processes	172
8.6.2 Grinding Stiffness and Grinding Damping	172
8.6.3 Contact Stiffness	174
8.6.4 Dynamic Compliance of the Mechanical System	175
8.6.5 Stability Analysis	176
8.7 Suppression of Grinding Vibrations	178
8.7.1 Suppression of Forced Vibrations	178
8.7.2 Suppression of Self-Excited Chatter Vibrations	179
8.8	Conclusions
References	183
Chapter 9 Grinding Wheel Wear	185
9.1 Three Types of Wheel Wear	185
9.1.1 Introduction	185
9.2 Wheel Wear Mechanisms	185
9.2.1 Abrasive Wheel Wear	185
9.2.2 Adhesive Wheel Wear	185
9.2.3 Tribochemical Wheel Wear	186
9.2.4 Surface Disruptions	186
9.2.5 Diffusion	186
9.3 Wear of the Abrasive Grains	186
9.3.1 Types of Grain Wear	186
9.3.2 A Combined Wear Process	186
9.3.3 Grain Hardness and Temperature	187
9.3.4 Magnitude of the Stress Impulses	187
9.3.5 Growth of Grain Flats	187
9.3.6 Grain Splintering	188
9.3.7 Grain Break-Out	189
9.3.8 Bond Softening	189
9.3.9 Effect of Single Grain Forces	189
9.3.10 Wear by Deposition	191
9.4 Bond Wear	191
9.4.1 Introduction	191
9.4.2 Balancing Grain and Bond Wear	191
9.5 Assessment of Wheel Wear	192
9.5.1 Microtopography	192
9.5.2 Profile Wear	192
References	193
Chapter 10 Coolants	195
10.1 Introduction	195
10.2 Basic Properties of Grinding Fluids	195
10.2.1 Basic Properties	195
10.2.2 Basic Requirements	195
10.2.3 Secondary Requirements	195
10.3 Types of Grinding Fluids	196
10.4 Base Materials	197

10.4.1 Introduction	197
10.4.2 Water-Based and Oil-Based Fluids	198
10.4.3 Rinsing Capacity	198
10.4.4 Lubricating Capability	199
10.5 Additives	199
10.6 Application Results	201
10.7 Environmental Aspects	201
10.8 The Supply System	201
10.8.1 Introduction	201
10.8.2 Alternative Cooling Lubricant Systems	202
10.8.3 Fluid Supply System Requirements	
10.9 Grinding Fluid Nozzles	203
10.9.1 Basic Types of Nozzle System	203
10.9.2 The Jet Nozzle	204
10.9.3 The Shoe Nozzle	204
10.9.4 Through-the-Wheel Supply	205
10.9.5 Minimum Quantity Lubrication Nozzles	205
10.9.6 Auxiliary Nozzles	206
10.10 Influence of the Grinding Fluid in Grinding	206
10.10.1 Conventional Grinding	206
10.10.2 Influence of the Fluid in Grinding Brittle-Hard Materials	207
10.10.3 High-Speed and High-Performance Grinding	209
References	213
Chapter 11 Monitoring of Grinding Processes	217
11.1 The Need for Process Monitoring	217
11.1.1 Introduction	217
11.1.2 The Need for Sensors	217
11.1.3 Process Optimization	217
11.1.4 Grinding Wheel Wear	217
11.2 Sensors for Monitoring Process Variables	218
11.2.1 Introduction	218
11.2.2 Force Sensors	219
11.2.3 Power Measurement	222
11.2.4 Acceleration Sensors	223
11.2.5 AE Systems	223
11.2.6 Temperature Sensors	226
11.3 Sensor for Monitoring the Grinding Wheel	228
11.3.1 Introduction	228
11.3.2 Sensors for Macrogeometrical Quantities	230
11.3.3 Sensors for Microgeometrical Quantities	230
11.4 Sensors for Monitoring the Workpiece	233
11.4.1 Introduction	233
11.4.2 Contact-Based Workpiece Sensors for Macrogeometry	233
11.4.3 Contact-Based Workpiece Sensors for Microgeometry	234
11.4.4 Contact-Based Workpiece Sensors for Surface Integrity	235
11.4.5 Noncontact-Based Workpiece Sensors	237
11.5 Sensors for Peripheral Systems	240
11.5.1 Introduction	240
11.5.2 Sensors for Monitoring of the Conditioning Process	240
11.5.3 Sensors for Coolant Supply Monitoring	242
References	244
Chapter 12 Economics of Grinding	247
12.1 Introduction	247
12.2 A Grinding Cost Comparison Based on an Available Grinding Machine	247
12.2.1 Introduction	247
12.2.2 Aeroengine Shroud Grinding Example	247
12.3 A Cost Comparison Including Capital Investment	249
12.3.1 Introduction	249
12.3.2 Automotive Camlobe Grinding Example	249

12.4 Cost Comparison Including Tooling	250
12.4.1 Introduction	250
12.4.2 Effect of Tooling Costs in Camlobe Grinding	250
12.5 Grinding as a Replacement for Other Processes	251
12.5.1 Introduction	251
12.5.2 Fine Grinding as a Replacement for Lapping	251
12.5.3 High-Speed Grinding with Electroplated CBN Wheels	
to Replace Turn Broaching	252
12.6 Multitasking Machines for Hard-Turning with Grinding	252
12.7 Summary	253
References	253

Part 11

Application of Grinding Processes

255

Chapter 13 Grinding of Ductile Materials 257

13.1 Introduction	257
13.1.1 Grindability	257
13.1.2 Effect of Chip Form	257
13.1.3 Chemical Reactivity	257
13.2 Cast Irons	258
13.2.1 Gray Cast Iron	258
13.2.2 White Cast Iron	258
13.2.3 Malleable Cast Iron	259
13.2.4 Nodular or Ductile Cast Iron	259
13.3 Steels	259
13.3.1 Plain Carbon Steels	259
13.3.2 Alloy Steels	260
13.3.3 Tool Steels	260
13.3.4 Stainless Steels	262
13.4 Heat-Resistant Superalloys	263
13.4.1 Precipitation-Hardened Iron-Based Alloys	264
13.4.2 Nickel-Based Alloys	264
13.4.3 Cobalt-Based Alloys	264
13.4.4 Titanium	264
References	265
Chapter 14 Grinding of Ceramics	267

14.1 Introduction	267
14.1.1 Use of Ceramic Materials	267
14.1.2 Machining Hard Ceramics	267
14.1.3 Wheel-Dressing Requirements	267
14.1.4 ELID Grinding	268
14.1.5 Advantages of ELID	268
14.2 Background on Ceramic Materials	268
14.2.1 History	268
14.2.2 Structure	268
14.2.3 Ceramic Groups	269
14.2.4 Ceramic Product Groups	269
14.2.5 Application of ZTA Ceramics	270
14.2.6 Grinding of Ceramics	270
14.3 Diamond Wheels for Grinding Ceramics	271
14.3.1 The Type of Diamond Abrasive	271
14.3.2 Types of Diamond Wheel	271
14.3.3 Wheel Truing and Dressing	273
14.4 Physics of Grinding Ceramics	274
14.5 ELID Grinding of Ceramics	278
14.5.1 Mechanism of ELID Grinding Technique	278

14.5.2	Research Studies on ELID	280
14.5.3	Summary on ELID Grinding	282
	References.....	282
Chapter 15 Grinding Machine Technology		285
15.1	The Machine Base	285
15.1.1	Introduction	285
15.1.2	Cast Iron Bases	285
15.1.3	Reuse of Cast Bases	285
15.1.4	Welded Bases	285
15.1.5	Machine Tools	
15.1.6	Large Mass Bases	287
15.1.7	Tuned Mass Dampers	287
15.1.8	Composite Material Bases	287
15.1.9	Granite Bases	288
15.2	Foundations	288
15.3	Guideways	290
15.3.1	Introduction	290
15.3.2	Definition of Axes	290
15.4	Slideway Configurations	290
15.4.1	Introduction	290
15.4.2	The Flat and Vee Way	291
15.4.3	The Double Vee Slideway	291
15.4.4	Dovetail Slideway	291
15.4.5	Plain Slideway Materials	293
15.5	Hydrostatic Slideways	294
15.5.1	Hydrostatic Bearing Principle	294
15.5.2	Plane-Pad Hydrostatic Slideway Configurations	294
15.5.3	Plane-Pad Hydrostatic Flowrate	294
15.5.4	Hydrostatic Slideway Materials and Manufacture	294
15.5.5	Round Hydrostatic Slideways	295
15.5.6	Diaphragm-Controlled Hydrostatic Slideways	295
15.5.7	Self-Compensating Hydrostatic Slideways	296
15.6	Recirculating Rolling Element Slideways	297
15.7	Linear Axis Drives and Motion Control	299
15.7.1	Introduction	299
15.7.2	Hydraulic Drives	299
15.7.3	Electrohydraulic Drives	299
15.7.4	Ac Servo- and Ballscrew Drives	299
15.8	Elements of AC Servodrive Ballscrew Systems	299
15.8.1	The Baliscrew	299
15.8.2	The Ballnut	301
15.8.3	AC Servomotors	302
15.8.4	Encoders	303
15.8.5	Resolvers	305
15.9	Linear Motor Drive Systems	305
15.9.1	Introduction	305
15.9.2	A Linear Motor System	305
15.9.3	Laser Interferometer Encoders for Linear Motor Drives	306
15.10	Spindle Motors and Grinding Wheel Drives	307
15.11	Drive Arrangements for Large Conventional Wheels	307
15.11.1	Rolling Element Spindle Bearings for Large Wheels	307
15.11.2	Hydrodynamic Spindle Bearings for Large Wheels	309
15.11.3	Hydrostatic Spindle Bearings for Large Wheels	310
15.12	Drive Arrangements for Small Wheel Spindle Units	312
15.12.1	Introduction	312
15.12.2	Rolling Bearing Spindles with Belt Drive for Small Wheels	312
15.12.3	High-Speed Spindles for Small Wheels	313
15.12.3.1	Direct Drive Motors	313

15.12.3.2	Dynamic Balancing of High-Speed Spindles	313
15.12.3.3	Oil-Mist Lubrication for High-Speed Spindles	313
15.12.3.4	Adjustment of Bearing Preload for High-Speed Spindles	313
15.12.4	Use of Ceramic Balls for High-Speed Spindles	314
15.12.5	Liquid Cooled High-Speed Spindles	314
15.12.6	Floating Rear Bearing for High-Speed Spindles	314
15.13	Spindles for High-Speed Grinding	315
15.13.1	Introduction	315
15.13.2	Spindle Bearings for High-Speed Grinding of Hardened Steel	315
15.13.3	Spindle Bearings for HEDG	315
15.13.4	Spindle Cooling for High-Speed Grinding	315
15.13.5	Spindle Bearings for Very Small High-Precision High-Speed Wheels	316
15.13.6	Active Magnetic Bearings for High-Speed Wheels	316
15.14	Miscellaneous Wheel Spindles and Drives	316
15.14.1	Hydraulic Spindle Drives	316
15.14.2	Air Motors and Bearings	316
15.15	Rotary Dressing Systems	317
15.15.1	Pneumatic Drives	317
15.15.2	Hydraulic Drives	317
15.15.3	Electric Drives	318
15.16	Power and Stiffness Requirements for Rotary Dressers	319
15.17	Rotary Dressing Spindle Examples	320
15.17.1	Introduction	320
15.17.2	DFW-ACI Air-Driven Spindle	320
15.17.3	ECI Hydraulic Spindle	320
15.17.4	DFW-HI Heavy-Duty Hydraulic Spindle for Internal Grinders	321
15.17.5	DFW-HO Five-Eighths Heavy-Duty Hydraulic Spindle Typically Used for Centerless Wheels	322
15.17.6	DFW-HO Variable-Speed Hydraulic Dresser	322
15.17.7	DFW-HHD Hydraulic Heavy-Duty Plunge Dresser	322
15.17.8	DFW-HTG Heavy-Duty Hydraulic Spindle	322
15.17.9	DFW-NTG Belt-Drive Spindle	324
15.17.10	DFW-VF44 AC Servo HF Spindle	325
15.17.11	DFS-VS8 DC Servo Variable-Speed Dresser	325
15.18	Dressing Infeed Systems	325
15.18.1	Introduction	325
15.18.2	Single Hydraulically Driven Carrier	326
15.18.3	Mini Double-Barrel Infeed	327
15.18.4	Double-Barrel Infeed Carrier	327
15.18.5	Double-Barrel Plunge-Form Dresser	328
15.18.6	Triple-Barrel Infeed Carrier with Hydraulic-Mechanical Compensator	329
15.18.7	Stepping Motor Carrier	329
15.18.8	Stepping Motor Carrier for a Cylindrical Grinder	329
15.18.9	Combination Stepper Motor and DC Traverse Motor	331
15.18.10	Plunge-Roll Infeed System for a Creep-Feed Grinder	331
15.18.11	Servomotor Infeed and Double-Barrel Carrier Dresser	331
15.18.12	Two-Axis CNC Profile Dresser	332
References	336
Chapter 16	Surface Grinding	341
16.1	Types of Surface Grinding Process	341
16.2	Basics of Reciprocating Grinding	341
16.2.1	Process Characterization	341
16.2.1.1	Real Depth of Cut	341
16.2.1.2	Speed Ratio	343
16.2.1.3	Specific Removal Rate	343
16.2.1.4	Upcut and Downcut Grinding	343
16.2.1.5	Nonproductive Time	343
16.2.2	Influences of Grinding Parameters on Grinding Performance	343

16.2.2.1	The Influence of Cutting Speed (Wheel Speed)	343
16.2.2.2	The Influence of Feedrate (Workspeed)	344
16.2.2.3	The Influence of Infeed	344
16.2.2.4	The Influence of the Interrupted Cut	344
16.2.2.5	Reciprocating Grinding without Cross-Feed	345
16.2.2.6	Multiple Small Parts	345
16.2.3	Economics	346
16.3	Basics of Creep Grinding	346
16.3.1	Introduction	346
16.3.2	Process Characterization	346
16.3.3	High-Efficiency Deep Grinding	347
16.3.4	The Influence of the Set Parameters in Creep Feed Grinding	348
16.3.4.1	The Influence of Cutting Speed v	348
16.3.4.2	The Influence of Infeed, a , and Feedrate, v_f	348
16.3.4.3	The Influence of Dressing Conditions	348
16.3.4.4	The Influence of Grinding Wheel Specification	348
16.3.4.5	The Influence of Up- and Down-Cut Grinding	349
16.3.4.6	Process	349
16.3.4.7	Work Results	351
16.3.4.8	Grinding Wheels	351
16.3.4.9	Grinding Wheel Wear	351
16.3.5	Requirements for Creep Feed Grinding Machines	352
16.3.6	Typical Applications	352
16.3.7	Economics of Creep Feed Grinding	353
16.4	Basics of Speed-Stroke Grinding	353
16.5	Successful Application of Creep Feed Grinding	356
16.5.1	Creep Feed Grinding with Vitrified Wheels Containing Alox and Silicon Carbide	356
16.5.2	Coolant Application in CF Grinding	356
16.5.2.1	Film Boiling	356
16.5.2.2	Coolant Delivery System	356
16.5.3	Continuous Dress Creep Feed	364
16.5.3.1	The Viper Process	364
16.5.4	Creep Feed Grinding with CBN	366
16.5.4.1	Electroplated CBN	368
16.5.4.2	Vitrified CBN	370
16.5.4.3	Process Selection	371
16.6	Face Grinding	381
16.6.1	Introduction	381
16.6.2	Rough Grinding with Segmented Wheels	383
16.6.3	Rough Machining/Finish Grinding	387
16.6.4	Single-Sided Face Grinding on Small-Surface Grinders	387
16.6.5	High-Precision Single-Sided Disc Grinding	387
16.6.6	Double-Disc Grinding	390
16.7	Fine Grinding	401
16.7.1	Principles and Limitations of Lapping	401
16.7.2	Double-Sided Fine Grinding	403
16.7.3	Comparison of Fine Grinding with Double-Disc Grinding	406
Appendix 16.1	Lapping Kinematics	407
A16.1.1	Introduction	407
A16.1.2	Kinematical Fundamentals	408
A16.1.3	Analysis of Path Types and Velocities	408
A16.1.4	Kinematic Possibilities of Machines	410
References	412
Chapter 17	External Cylindrical Grinding	417
17.1	The Basic Process	417
17.1.1	Introduction	417
17.1.2	Work Drives	417

17.1.3	The Tailstock	417
17.1.4	Wheel Speeds	418
17.1.5	Stock Removal	419
17.1.6	Angle-Approach Grinding	420
17.1.7	Combined Infeed with Traverse	420
17.2	High-Speed Grinding	421
17.2.1	Introduction	421
17.2.2	Energy and Temperatures in High-Speed Grinding	421
17.2.2.1	The C_a -Factor	422
17.2.2.2	Peclet Number L and Workspeed	423
17.2.2.3	Contact Angle θ	423
17.2.2.4	Heat Convection by Coolant and Chips	424
17.2.3	Coolant Drag and Nozzle Design in High-Speed Grinding	428
17.2.4	Maximum Removal Rates	429
17.2.5	Peel Grinding	430
17.3	Automotive Camlobe Grinding	431
17.4	Punch Grinding	439
17.5	Crankshaft Grinding	442
17.6	Roll Grinding	447
	References	450
	Chapter 18 Internal Grinding	453
18.1	Introduction	453
18.2	The Internal Grinding Process	453
18.3	Abrasive Type	455
18.3.1	Grain Selection	455
18.3.2	Impact on Grind Configuration	456
18.3.4	Quill Designs for CBN	457
18.4	Process Parameters	458
18.4.1	Wheel Speed	458
18.4.2	Workspeed	459
18.4.3	Oscillation	459
18.4.4	Incoming Part Quality	459
18.4.5	Dressing	459
18.4.6	Grinding Cycles	461
18.4.7	Automatic Compensation of Process Variations	462
18.5	Machine Tool Selection	466
18.5.1	Introduction	466
18.5.2	Fuel Injection	467
18.5.3	Automotive Components (Lifters, Tappets, UJ Cups, Plain Bearings)	468
18.5.4	Machine Layout	468
18.5.5	Wheel Speeds	468
18.5.6	Work-Spindle Runout	468
18.5.7	Work-Loading Mechanisms	469
18.5.8	Coolant	469
18.5.9	Gauging	469
18.5.10	Flexible Multipurpose Grinders	470
18.6	Troubleshooting	474
	References	476
	Chapter 19 Centerless Grinding	479
19.1	The Importance of Centerless Grinding	479
19.2	Basic Process	480
19.2.1	External Centerless Grinding	480
19.2.2	Approximate Guide to Work-Height	480
19.2.3	Internal Centerless Grinding	481
19.2.4	Shoe Centerless Grinding	481
19.2.5	Roundness and Rounding Geometry	481
19.2.6	System Interactions	484
19.3	Basic Relationships	485

19.3.1	Depth of Cut	485
19.3.2	Removal Rate	485
19.3.3	Power	485
19.3.4	Specific Energy	486
19.3.5	Contact Length	486
19.3.5.1	Geometric Contact Length	486
19.3.5.2	Dynamic Contact Length	486
19.3.6	Equivalent Grinding Wheel Diameter	487
19.3.7	Equivalent Chip Thickness	487
19.3.8	Grinding Ratio	487
19.4	Feed Processes	487
19.4.1	Plunge Feed	487
19.4.2	Through-Feed	489
19.5	Centerless Wheels and Dressing Geometry	490
19.5.1	The Grinding Wheel	490
19.5.2	Grinding Wheel Dressing	490
19.5.3	The Control Wheel	491
19.5.4	Control Wheel Dressing	492
19.5.4.1	Dressing Geometry	492
19.5.4.2	Control Wheel Runout	493
19.6	The Workrest	493
19.7	Speed Control	494
19.7.1	Spinning Out of Control	494
19.7.2	Failure to Turn	495
19.8	Machine Structure	496
19.8.1	The Basic Machine Elements	496
19.8.2	The Grinding Force Loop	496
19.8.3	Structural Layout	498
19.8.3.1	Low Workspeeds	499
19.8.3.2	High Workspeeds	499
19.8.4	Spindle Bearings	499
19.9	High Removal Rate Grinding	501
19.9.1	Introduction	501
19.9.2	Routes to High Removal Rate	502
19.9.2.1	Increasing the Number of Active Grits	502
19.9.2.2	Increasing Removal Rate per Grit	502
19.9.2.3	Longer Redress Life	502
19.9.2.4	Improved Abrasive	502
19.9.2.5	Grinding Trials	503
19.9.2.6	Improved Grinding Machines and Auxiliary Equipment	503
19.9.3	Process Limits	504
19.9.3.1	Effect of Infeed Rate	504
19.9.3.2	Effect of Wheel Speed	505
19.9.3.3	Effect of Workspeed	505
19.9.4	Specific Energy as a Measure of Efficiency	506
19.10	Economic Evaluation of Conventional and CBN Wheels	506
19.10.1	Introduction	506
19.10.2	Cost Relationships	507
19.10.3	Wheel Cost/Part	507
19.10.4	Labor Cost/Part	507
19.10.5	Machine Cost/Part	509
19.10.6	Total Variable Cost/Part	509
19.10.7	Experiment Design	510
19.10.7.1	Stage 1. Basic Trials	510
19.10.7.2	Stage 2. Select Best Conditions and Confirm	510
19.10.7.3	Stage 3. Cost Comparisons	511
19.10.8	Machine Conditions and Cost Factors	512
19.10.9	Materials, Grinding Wheels, and Grinding Variables	512
19.10.9.1	AISI 52100 Steel	512
19.10.9.2	Inconel 718 Trials	513

19.10.10	Direct-Effect Charts	514
19.10.11	Redress Life and Cost Comparisons	515
19.10.11.1	AISI 52100	515
19.10.11.2	Inconel 718	515
19.10.12	Effects of Redress Life	515
19.10.13	Economic Conclusions	516
19.11	The Mechanics of Rounding	516
19.11.1	Avoiding Convenient Waviness	516
19.11.1.1	Rules for Convenient Waviness	517
19.11.2	Theory of the Formation of the Workpiece Profile	518
19.11.3	Workpiece Movements	519
19.11.4	The Machining-Elasticity Parameter	521
19.11.5	The Basic Equation for Rounding	522
19.11.6	Simulation	523
19.11.7	Roundness Experiments and Comparison with Simulation	525
19.12	Vibration Stability	527
19.12.1	Definitions	527
19.12.1.1	Marginal Stability	527
19.12.1.2	A Stable System	527
19.12.1.3	An Unstable System	527
19.12.1.4	Chatter	527
19.12.1.5	Forced Vibration	528
19.12.2	A Model of the Dynamic System	528
19.12.3	Nyquist Test for Stability	530
19.12.4	The Depth of Cut Function	53
19.12.5	The Geometric Function	531
19.12.6	Machine and Wheel Compliances	534
19.12.6.1	Static Compliance	534
19.12.6.2	Dynamic Compliances	535
19.12.6.3	Added Static Compliance	536
19.13	Dynamic Stability	537
19.13.1	Threshold Conditions	537
19.13.2	Dynamic Stability Charts	539
19.13.3	Up Boundaries	539
19.13.4	Down Boundaries	540
19.14	Avoiding Critical Frequencies	541
19.14.1	Vibration Frequencies at Threshold Conditions	541
19.14.2	Selection of Work Rotational Speed	541
19.14.3	Selection of Grinding Wheel Rotational Speed	542
19.14.4	Selection of Dresser Speed	542
19.14.5	Speed Rules	542
19.15	Summary and Recommendations for Rounding	543
19.16	Process Control	543
	References	546
Chapter 20	Ultrasonic Assisted Grinding	549
20.1	Introduction	549
20.2	Ultrasonic Technology and Process Variants	549
20.3	Ultrasonic-Assisted Grinding with Workpiece Excitation	552
20.4	Peripheral Grinding with Radial Ultrasonic Assistance	552
20.5	Peripheral Grinding with Axial Ultrasonic Assistance	555
20.6	Ultrasonic-Assisted Grinding with Excitation of the Wheel	557
20.6.1	Ultrasonic-Assisted Cross-Peripheral Grinding	557
20.6.2	Ultrasonic-Assisted Face Grinding	558
20.7	Summary	561
	References	562
	Appendix 1: Glossary	563
	Appendix 2: Notation and Use of SI Units	591
	Use of Units	591
	Examples of Correct and Incorrect Practice	591
	Factors for Conversion between SI Units and British Units (Values Rounded)	592
	Index	593

A

Abrasives 6, 75-102

Aluminum oxide 75, 76-80, 97, 356, 424, 425, 444, 455, 506 Bond 103-127
 Ceramic 80-82 Coated 86, 345 Cubic boron nitride 45, 75, 93-98, 104, 108, 115, 206, 366, 370, 384, 385, 419, 423, 424, 425, 434, 439,454,456,463,506
 Diamond 75, 82-93, 114, 271, 345 Natural 82, 91 PCD 87, 115 Synthetic 82
 Grains, grit. See Grain, Grit Characteristics. Silicon carbide 75, 97, 356, 506 SG
 75, 80-82, 366, 385, 444, 455 **Accuracy 484** Alignment 290, 447, 474, 475, 497, 501 Axis errors 290 Bearing ratio 15 Flatness 389, 398, 403, 405 Form 106
 Gauging. See Grinding Process Capability and Monitoring. Grind pattern 15, 16
 Lead errors 300 Limits 511 Lobing (See roundness and waviness) 483 Peak count
 15 Profile 192 Radius 419 Repeatability 9 Roughness 11-16, 105, 157, 208, 224, 238, 257, 276, 351,353,354,421,475,491,500,510,513, 555,558 Roundness 185, 419, 453, 459, 466, 467, 476, 481, 499,500,510,516,522,543 Run-out 185, 417, 468, 493 Size 185, 453, 500, 510 Straightness 356, 419, 453, 456, 476
 Tolerance 368, 389, 393, 400, 406, 453, 458, 485 Waviness 516, 528, 529

C

Compliance See system stiffness **Conditioning** See dressing **Coolant** See fluids
Costs See grinding parameters Cycles See grinding cycles

D

Dressing 127-167, 267, 273, 394, 419, 459, 475,490,492,498,503,543

Brake 161, 273
 Conditioning 127, 160, 163, 164, 217, 240, 273, 490
 Continuous 156, 192, 364, 433
 Cooling 129
 Cross-axis 149, 151
 Crushing 122
 Depth 127, 131, 137, 140, 142
 ELID 267, 271, 272, 278, 280
 Feedrate 127, 130, 131, 140, 150, 158, 508
 Force 156
 Form/ Profile 132, 142, 150, 152, 155, 158
 Height 492
 Overlap ratio 127, 130, 140, 508
 Scaif angle 129
 Speed
 Dressing speed ratio 138, 139, 142, 542
 Time 162
 Tools 127, 274
 Cup 141, 149, 460
 Disk 139, 460, 512
 Impregnated 135, 141, 147, 491
 Plate 135
 Roll 140, 150, 159, 160, 460
 Single-point 128, 132, 460, 491
 Stick 127, 163, 273, 394, 490
 Tool-life 10, 144
 Touch-dressing 144, 147, 158, 241, 512
 Traverse 127, 137, 491
 Truing 127, 273, 274, 279, 490
 Wear 131

E

ELID See Dressing and Grinding Processes.

F

Fluids and coolants 195-217, 372, 469, 503

Air barrier 204
 Additives 197, 198, 199, 200, 211, 212
 Emulsion 196, 206, 208, 209, 213, 356, 368, 422, 424,476
 Environment 201
 Esters 197, 212
 Explosions, Fires 203, 362
 Filters 203
 Fluid force 14,429
 Lubrication 34,199,201,206,211,313
 Mineral oil 197, 206, 208, 209, 213, 356, 362, 368, 424,426,439, 593

Nozzles 203-206, 210, 243

Flood 204, 210, 243
 Jet 204, 243, 358, 361
 MQL 205
 Shoe 204, 243, 428
 Slot 361
 Power 428, 429
 Properties 196, 197, 198, 199
 Requirements 195
 Supply 202, 203, 205, 242, 349, 351, 356, 358, 362, 366, 397
 Synthetic 197, 209
 Unbalance 53
 Velocity 204, 428
 Viscosity 197, 212, 361

Force See System force and Grinding force

G

Grain, grit characteristics

active grain density 12, 19, 421 active surface roughness 144 contact
 time 424 flats 19, 112, 187, 423 force 12, 189, 349, 353, 354, 421
 hardness 6, 90, 97, 187, 271 protrusion 39, 189, 191, 279 size 79,
 98-99, 100, 104, 456 shape 12, 23, 25, 78, 81-96, 120, 187 spacing
 25, 82, 156 speed 556 wear 90, 96, 185-195

Grindability 207, 257

Grinding chips 33, 257, 353 Shape parameters aspect ratio 257
 cross-sectional area 30, 278 length 29, 277 thickness 29-32, 349
 volume 277

Grinding Contact Contact angle 423 Contact length 486 Geometric 18,
 29, 277, 349, 486 Dynamic/Deformed 18, 486 Real 18 Surface Contact
 surface 423 Finish surface 423 Time 424

Grinding Feed Cycle 460, 461, 488, 500 Finishing 462 Plunge 462
 Roughing 462 Spark-out 17, 462, 489, 521 Through-feed 489 Time
 10, 11, 468, 507

Grinding parameters 9 Costs 247-255, 485, 506 Coolant 201, 248

Dressing tool 248
 Inspection 248
 Filter 248
 Labor 248, 507
 Machine 249, 312, 509
 Tooling 247
 Wheel 248, 434, 455, 507
 Depth of cut 11, 20, 341, 347, 425, 485, 528, 530, 531
 Real341,347,521
 Set 341, 521
 Equivalent chip thickness 12, 487, 504
 Equivalent diameter 11, 29, 418, 420, 455, 487
 Feed, feed-rate 344, 346, 485, 489, 504
 Forces 14, 114, 157, 201, 206, 208, 210, 220, 244,
 349,428,463,494,497,557,560

Force ratio 14
 G-ratio 17, 18, 174, 211, 257, 345, 366, 455, 487,
 510,514

Infeed 344, 346, 349

Interrupted cut 344, 354

Oscillation 459

P-ratio 18

Power 13, 132, 220, 222, 405, 418, 422, 429, 446, 461,
 466,467,485,491,521

Productivity 167, 485, 497

Redress life 10, 168, 502, 511, 515

Removal rate 12, 210, 343, 347, 366, 370,427, 429,435,
 485,501,504,550,555,559,560

Specific Grinding Energy 12, 221, 222, 353, 354, 421,
 424,427,486,505,506,510

Chips 20

Fluid 20

Wheel 20

Workpiece 20

Total 12, 20

Speed ratio 30, 343, 349, 418

Stock removal parameter 17, 257, 463

Tangent angle 482, 518, 527, 533

Through-feed angle 489, 492

Uncut chip thickness 11, 343, 353, 381, 421
Upcut and downcut 343, 349, 351, 363, 364
Wheel-speed 343,426,428,435,445,458, 505,541,542
Work-height 482, 483
Work-rest angle 482, 483, 493, 527, 533
Workspeed 344, 425, 459, 489, 494, 499, 505, 541, 542

Grinding Processes

Angle-approach 417, 420, 472
Bore 453, 472, 473
Cam 146,164,249,250,251,417,430,431
Crankshaft 146, 234, 252, 389, 390, 427, 430, 442, 444
Center 480
Centerless 308, 479-549
 Plunge 487
 Through-feed 489
 Shoe 471, 481, 482
Contour 444, 453, 454
Cut-off 20
Cylindrical 6, 29, 170, 171, 417-453
Creep-feed 346, 356, 366, 425
Deep 188, 422
Double-side 390
Drill-flute 20 ELID 278, 280 Face 6, 208, 381, 454, 473 Fine 251, 401 Gear 222, 234, 236 HEDG 315, 347, 368, 370 High-speed 209, 252, 347, 421, 427, 501 Internal 150, 170, 188, 248, 417, 453-479
Multitasking 252, 366, 453, 473, 474, 475 Orbital 385 Peel 430
Peripheral 6, 341 Plunge 417 Profile 234, 248, 417, 425 Punch 439
Reciprocating 289, 341, 345, 349 Roll 418, 447 Slideway 291
Speed-stroke 353 Superfinishing 387, 390 Surface 6, 29, 170, 274, 341-417 Traverse 171, 178, 417 Ultrasonic 549-559 Universal 417
Vertical 292, 298, 474 Viper 364, 365, 374-376, 384, 391

Grinding process capability and monitoring 217-247,545

Acoustic emission 223, 224, 230, 241, 242, 460, 466 limit chart 419, 501, 504 monitoring 223, 448, 545 optimization and compensation 217, 233, 462, 463, 464, 465,543 sensors 217-247, 303, 419, 436, 465, 469, 545 trials 503 simulation 519, 523

H

Heat See Thermal characteristics

M

Machinability See Materials and properties

Machine tool structures and elements 285-341,469,498,505 Axes 290, 473 Base, bed 285 Bearings air, aerostatic 316, 467 hybrid 312 hydrodynamic 309, 467, 499 hydrostatic 293, 294, 310, 311, 467, 498, 499 magnetic 316, 398 plain 293 rolling 293, 297, 298, 307, 314, 467, 499 Control wheels 491 Dressers 127-167, 317 Cup 141 Disk 139, 140 Drives and motors, 299-316, 353

 Infeeds 325-336
 Roll 140
 Rotary 138, 317-325

 Foundations 288

 Guideways 290-298

 Lead-screws 299

 Requirements 352

 Sensors See Grinding Process Capability and Monitoring

 Slideways 290-298

 Spindles 307, 313, 315, 352, 353, 380, 381, 383, 393, 457,467,499

 Tailstock 417, 438

 Turret 471, 472

 Wheel-head 307, 313, 315

 Work-head and work-drives 417, 419

 Work-rest 439, 481, 493,

Materials and Properties 257-267

Alloys 13, 263, 352, 368, 374, 426, 458, 513

Burrs, 257, 459

Ceramics 42, 209, 267-285, 549, 553

Deformation

 Brittle 31, 35, 38, 274, 276

 Cracks 235, 476

 Cutting 31, 36, 276, 364

Ductile 32, 38, 39, 257-267, 276

Elastic 42, 367

Plastic 32, 276, 364

Ploughing 31, 364

Smooth contact 174

Rough contact 18, 174, 486

Density 458

Diffusion 186

Ductile 257-267

Elastic modulus 18

Granite 288

Hardness

 Knoop 188, 262

 Mobs 271

Irons 13, 92, 258, 426, 433, 435, 443

Machinability 207, 257

Monocrystalline silicon 38

Polymer matrix composite 288

Steels 13, 92, 259, 260, 389, 426, 433,

435,512

Stress

 Impulse 187, 224

 Residual 212, 220, 235, 257

S

System characteristics 167-185, 484, 528, 529

Compliance(s), stiffness(es) 14, 169, 172,173, 175, 179, 182,497,498,503,534,535,536

Damping 71, 172, 175, 180, 182, 287, 498, 535

Deflection(s) 175, 185, 464, 500, 521, 528

Force(s) 528

Machining-elasticity parameter 500, 521

Natural frequencies and resonance 169, 170, 176, 524, 535,541

Stiffness - See also compliances

Roots 176, 177, 528

Transfer functions 529-536

Vibration 167, 519, 550

 Chatter 71, 132, 167, 191, 466, 476, 519, 527

 Frequency 176, 528, 538, 542

 Growth rate 178, 528, 533, 535

 Wheel regenerative 168, 172, 173, 176

 Work regenerative 168, 172, 176, 519

 Stability 169, 176, 527

 Limit 169, 170, 175, 528, 530, 537, 539

 Parameter 532

Forced 71, 167, 168, 528

Phase 529, 538

 In-phase 536

 Quadrature 536

Resonance. See Natural frequencies and resonance.

Suppression 167, 178, 180

T

Temperature 18-21, 187,200,201,206,222, 226,228,355,421,422,433,553

Background 19

Boiling 356, 424

Chip melting 20, 32, 424

Damage 222, 224, 232

Finish 422

Maximum 422, 424, 425, 426

Thermal

Conduction 41

C-factors 19, 422

Convection 19, 422

h-factors 20

Damage 20, 222, 224, 225, 232, 236, 252, 418, 436, 465,475,504

Heat flux 41, 222

Partition ratio 19, 423

Peclet number 423

Properties 92, 98

Beta (p) 19, 423, 424
Conductivity 19, 423
Density 19, 423
Diffusivity 419
Specific heat capacity 19, 423
Stress 38, 118, 208, 212, 349, 557

Thermocouple 227

Truing See Dressing

U

Units See Appendix

V

Vibration See System characteristics

W

Wear 90, 969 105, 185-195, 528, 555

Abrasive 185
Adhesive 185
Break-out 189
Corrosion 187

Cracks 186, 275
Deposition 191
Flat 186, 555
Fracture 111, 143, 185, 186, 223
Micro-fracture 112, 143, 196, 188, 555
Rate 174, 212, 456, 528
Tribochemical 186

Wheel 45, 492

Abrasive depth 57
Balancing 49-54, 179, 223, 313
Bond 103-127
Bond life 61, 103, 189, 191, 354, 391
Bursting 54-59
Clamping 62
Compliance/stiffness 73, 169, 174, 175
Control and regulating 481, 491, 492
Conventional 46, 58, 108
Cup 368
Damped 72
Diamond 271
Failure 59
Geometric interference 170, 523, 542
Glazing 112, 191, 437, 475, 502
Grade 9, 109, 116, 438
High-speed 45, 54, 64
Life 9, 10, 11, 370, 435, 437, 446, 560
Loading 463, 476
Lubricated 113
Metal-bond 122, 126, 272, 279, 398
Mounts 53, 61, 64, 68
Plated 45-46, 66, 103, 251, 252, 368, 371, 426, 439
Porosity 112, 118, 366, 513
Reinforced 55-56
Resin 118-122, 271, 391, 433
Roughness 27
Run-out 168, 351, 468
Self-dressing
Segmented 56, 59, 146, 383
Shapes 45
Sharpness 185, 463, 557
Specification 46, 109, 117, 120
Speed 11, 45, 54, 60, 65, 183, 348, 378, 418, 425, 426,
445, 467, 468, 503, 542
Speed rating 60
Stresses 54
Structure 109, 116
Stiffness, compliance 169, 174, 175
Tolerances 48
Topography 24, 25, 28, 130, 189, 192, 217, 224, 229,
231, 241
Unbalance 168

Vitrified 108-118, 271, 370, 431
Wear 111, 104, 185-195, 210, 217, 351, 352, 354, 434,
454, 456, 463, 528, 555

Work

Feeding and holding 394, 396, 398, 467, 469, 470, 471,
479, 480, 543
Speed 11, 19, 168, 183, 425, 430, 435, 459, 468
Spinning 494
Work-height 480, 482, 483
Work-material 13, 14