

TRIBOLOGY OF CERAMICS AND COMPOSITES

A Materials Science Perspective



BIKRAMJIT BASU MITJAN KALIN





CONTENTS

PREFACE

FORE	EWORD BY PROF. IAN HUTCHINGS	xxi	
FORE	EWORD BY PROF. KARL-HEINZ ZUM GAHR	xxiii	
ABOU	UT THE AUTHORS	xxv	
SEC	CTION I FUNDAMENTALS		
CHAP	TER 1 INTRODUCTION	3	
	References 6		
CHAP	TER 2 OVERVIEW: TRIBOLOGICAL MATERIALS	7	
2.1	Introduction 7		
2.2	Definition and Classification of Ceramics 8		
2.3	Properties of Structural Ceramics 9		
2.4	Applications of Structural Ceramics 11		
2.5	Closing Remarks 14		
	References 16		
CHAP	TER 3 OVERVIEW: MECHANICAL PROPERTIES OF CERAMICS	18	
3.1	Theory of Brittle Fracture 18		
3.2	Cracking in Brittle Materials 23		
3.3	Definition and Measurement of Basic Mechanical Properties 24		
	3.3.1 Hardness 24		
	3.3.2 Compressive Strength 27		
	3.3.3 Flexural Strength 28		
	3.3.4 Elastic Modulus 30		
	3.3.5 Fracture Toughness 31		
3.4	Toughening Mechanisms 33		
3.5	Closing Remarks 37		
	References 37		

xvii

CHAPTE	R 4 SU	RFACES AND CONTACTS	39
4.1	Surface	Roughness 39	
4.2		Topography and Asperities 41	
4.3	Real Co	ontact Area 42	
4.4	Contact	Load Distribution and Hertzian Stresses 44	
4.5	Closing	Remarks 47	
	Referen	ces 48	
СНАРТЕ		ICTION	49
5.1	Introduc		
5.2		f Friction 49	
5.3		Mechanisms 51	
5.4		of Common Engineering Materials 54	
5.5	-	Remarks 58	
	Referen	ces 59	
CHART	n c ED	CICTIONAL HEATING AND CONTACT TEMPERATURE	60
CHAPTI			60
6.1		gical Process and Contact Temperature 60	
6.2	-	t of "Bulk" and "Flash" Temperature 61	
6.3		ance and Relevance of Some Ready-to-Use Analytical Models 63	
6.4		of Some Frequently Employed Ready-to-Use Models 64	
	6.4.1	Assumptions in Various Models 65	
	6.4.2	Model Descriptions and Implications 65	
		6.4.2.1 Archard Model 66	
	Referen	6.4.2.2 Kong–Ashby Model 67	
	Keleleli	1000	
CHAPTI	ER 7 WE	EAR MECHANISMS	70
7.1	Introduc	ction 70	
7.2		cation of Wear Mechanisms 72	
	7.2.1	Adhesive Wear 73	
	7.2.2	Abrasive Wear 75	
		7.2.2.1 Abrasion of Composites 77	
	7.2.3	Fatigue Wear 78	
	7.2.4	Oxidation and Tribochemical Wear 80	
	7.2.5	Fretting Wear 81	
		7.2.5.1 Fretting Modes 82	
		7.2.5.2 Mechanics of Elastic Contacts under Fretting Conditions	34
		7.2.5.3 Mechanics of Elastic-Plastic Contacts under Fretting	
		Conditions 86	
		7.2.5.4 Fretting Regimes 86	
		7.2.5.5 Determination of Fretting Regimes 89	
		7.2.5.6 Fretting Maps 89	
		7.2.5.7 Velocity Accommodation in Fretting 91	
		7.2.5.8 Friction Logs 92	
	7.2.6	Solid Particle Erosion 92	
		7.2.6.1 Erosion of Ductile Materials 94	

7.2.6.2 Erosion of Brittle Materials 96

7.3	Closing Remarks 98 References 99	
СНАРТ	ER 8 LUBRICATION	101
8.1 8.2	Lubrication Regimes 101 Stribeck Curve 107 References 109	
SEC	TION II FRICTION AND WEAR OF STRUCTURAL CERAMICS	
CHAPT	ER 9 OVERVIEW: STRUCTURAL CERAMICS	113
9.1	Introduction 113	
9.2	Zirconia Crystal Structures and Transformation Characteristics of Tetragonal Zirconia 114	
9.3	Transformation Toughening 116 9.3.1 Micromechanical Modeling 116	
9.4	Stabilization of Tetragonal Zirconia 117	
9.5	Different Factors Influencing Transformation Toughening 118 9.5.1 Grain Size 119 9.5.2 Yttria Content 121 9.5.3 Yttria Distribution 122	
9.6	Stress-Induced Microcracking 125	
9.7	Development of SiAlON Ceramics 126	
9.8	Microstructure of S-sialon Ceramics 127	
9.9	Mechanical Properties and Crack Bridging of SiAlON Ceramic 129	
9.10	Properties of Titanium Diboride Ceramics 132 References 138	
СНАРТ	ER 10 CASE STUDY: TRANSFORMATION-TOUGHENED ZIRCONIA	142
10.1	Background 142	<u> </u>
10.2	Wear Resistance 144	
10.3	Morphological Characterization of the Worn Surfaces 146	
10.4	Zirconia Phase Transformation and Wear Behavior 149	
10.5	Wear Mechanisms 152	
10.6 10.7	Relationship among Microstructure, Toughness, and Wear 154	
10.7	Influence of Humidity on Tribological Properties of Self-Mated Zirconia 156 Wear Mechanisms in Different Humidity 157	
10.9	Tribochemical Wear in High Humidity 160	
10.10	Closing Remarks 163	
	References 164	
СНАРТ	ER 11 CASE STUDY: SIALON CERAMICS	167
11.1	Introduction 167	
11.2	Materials and Experiments 168	

Tribological Properties of Compositionally Tailored Sialon versus β -Sialon 172

Tribological Properties of S-Sialon Ceramic 179

11.3

11.4

X CONTENTS

15.2

Materials and Experiments 235

11.5	Concluding Remarks 182 References 183	
СНАРТ	TER 12 CASE STUDY: MAX PHASE—TI ₃ SIC ₂	185
12.1	Background 185	
12.2	Frictional Behavior 188	
12.3	Wear Resistance and Wear Mechanisms 188	
12.4	Raman Spectroscopy and Atomic Force Microscopy Analysis 190	
12.5	Transition in Wear Mechanisms 193	
12.6	Summary 194 References 195	
СНАРТ	TER 13 CASE STUDY: TITANIUM DIBORIDE CERAMICS	
AND	COMPOSITES	197
13.1	Introduction 197	
13.2	Materials and Experiments 198	
13.3	Tribological Properties of TiB ₂ -MoSi ₂ Ceramics 200	
	13.3.1 Friction and Wear 200	
	13.3.2 Wear and Dissipated Energy 202	
	13.3.3 Wear and Abrasion Parameter 203	
12.4	13.3.4 Material Removal Mechanisms 204	
13.4 13.5	Tribological Properties of TiB ₂ –TiSi ₂ Ceramics 204 Closing Remarks 206	
13.3	References 208	
SEC	TION III FRICTION AND WEAR OF BIOCERAMICS AND	
*CONCRETEDEDE	OCOMPOSITES	
СНАРТ	TER 14 OVERVIEW: BIOCERAMICS AND BIOCOMPOSITES	213
14.1	Introduction 213	
14.2	Some Useful Definitions and Their Implications 215	
	14.2.1 Biomaterials 215	
	14.2.2 Biocompatibility 216 14.2.3 Host Response 216	
14.3	Experimental Evaluation of Biocompatibility 217	
14.4	Wear of Implants 221	
14.5	Coating on Metals 223	
14.6	Glass-Ceramics 224	
14.7	Biocompatible Ceramics 226	
	14.7.1 Bioinert Ceramics 226	
	14.7.2 Calcium Phosphate-Based Biomaterials 226	
14.8	Outlook 228	
	References 229	
CHAP	TER 15 CASE STUDY: POLYMER-CERAMIC BIOCOMPOSITES	233
15.1	Introduction 233	233
13.1	Infroduction 255	

15.3	Frictional Behavior 237 Wear-Resistance Properties 240
15.4	Wear Mechanisms 242
15.5	Correlation among Wear Resistance, Wear Mechanisms, Material Properties, and
15.6	Contact Pressure 247
157	Concluding Remarks 248
15.7	References 249
	References 243
CHAPT	ER 16 CASE STUDY: NATURAL TOOTH AND DENTAL RESTORATIVE
	RIALS 25
16.1	Introduction 251
16.2	Materials and Methods 254
10.2	16.2.1 Preparation of Human Tooth Material 254
16.3	Tribological Tests on Tooth Material 255
16.4	Production and Characterization of Glass-Ceramics 255
16.5	Wear Experiments on Glass-Ceramics 256
16.6	Microstructure and Hardness of Human Tooth Material 257
16.7	Tribological Properties of Human Tooth Material 260
10.7	16.7.1 Friction Behavior 260
	16.7.2 Wear Mechanisms 262
16.8	Wear Properties of Glass-Ceramics 262
16.9	Discussion of Wear Mechanisms of Glass-Ceramics 266
16.10	Comparison with Existing Glass-Ceramic Materials 271
16.11	Concluding Remarks 273
10.11	References 274
CHAPT	ER 17 CASE STUDY: GLASS-INFILTRATED ALUMINA 27
17.1	Introduction 276
17.2	Materials and Experiments 277
17.3	Frictional Properties 278
17.4	Wear Resistance and Wear Mechanisms 278
17.5	Wear Debris Analysis and Tribochemical Reactions 282
17.6	Influence of Glass Infiltration on Wear Properties 283
17.7	Concluding Remarks 284
	References 285
СНАРТ	ER 18 TRIBOLOGICAL PROPERTIES OF CERAMIC BIOCOMPOSITES 28
18.1	Background 287
18.2	Tribological Properties of Mullite-Reinforced Hydroxyapatite 288
18.3	Friction and Wear Rate 288
	18.3.1 Effect of Simulated-Body-Fluid Medium on Wear of Mullite-Reinforced
	Hydroxyapatite 289
	18.3.2 Surface Topography of Mullite-Reinforced Hydroxyapatite after Fretting
	Wear 293
	18.3.3 Frictional Behavior 293
	18.3.4 Wear Micromechanisms of Hydroxyapatite-Based Materials in Simulated
	Body Fluid 296

••	
XII	CONTENTS

Concluding Remarks 298

18.4

22.1 22.2

	ER 19 OVERVIEW: NANOCERAMIC COMPOSITES	307
19.1	Introduction 307	
19.2	Processing of Bulk Nanocrystalline Ceramics 309	
19.3	Overview of Developed Nanoceramics and Ceramic Nanocomposites 309	
	19.3.1 Monolithic Nanoceramics 311	
	19.3.2 Alumina-Based Nanocomposites 313	
	19.3.3 Tungsten Carbide-Based Nanocomposites 314	
	19.3.4 Zirconia-Based Nanocomposites 317	
19.4	Overview of Tribological Properties of Ceramic Nanocomposites 318	
19.5	Concluding Remarks 320	
	References 322	
СНАРТ	TER 20 CASE STUDY: NANOCRYSTALLINE YTTRIA-STABILIZED	
TETR	AGONAL ZIRCONIA POLYCRYSTALLINE CERAMICS	32
20.1	Introduction 325	
20.2	Materials and Experiments 327	
20.3	Tribological Properties 329	
20.4	Tribomechanical Wear of Yttria-Stabilized Zirconia Nanoceramic with Varying	
	Yttria Dopant 330	
20.5	Comparison with Other Stabilized Zirconia Ceramics 335	
20.6	Concluding Remarks 335	
	References 336	
СНАРТ	TER 21 CASE STUDY: NANOSTRUCTURED TUNGSTEN	
CARB	IDE-ZIRCONIA NANOCOMPOSITES	33
21.1	Introduction 338	
21.2	Materials and Experiments 339	
21.3	Friction and Wear Characteristics 340	
21.4	Wear Mechanisms 345	
	Explanation of High Wear Resistance of Ceramic Nanocomposites 347	
21.5	Concluding Remarks 349	
21.5 21.6		
	References 349	

Development of Metal Matrix Composites 353

Development of Cermets 356

References 358

423

CHAPTE R <i>EINF</i>	CASE STUDY: MAGNESIUM-SILICON CARBIDE PARTICULATE-CORCED COMPOSITES	362
23.1	Introduction 362	
23.2	Materials and Experiments 363	
23.3	Load-Dependent Friction and Wear Properties 363	
23.4	Fretting-Duration-Dependent Tribological Properties 366	
23.5	Tribochemical Wear of Magnesium-Silicon Carbide Particulate-Reinforced	
	Composites 371	
23.6	Concluding Remarks 375	
	References 376	
CHAPTE	ER 24 CASE STUDY: TITANIUM CARBONITRIDE-NICKEL-	
BASEL	O CERMETS	377
24.1	Introduction 377	
24.2	Materials and Experiments 379	
24.3	Energy Dissipation and Abrasion at Low Load 381	
24.4	Influence of Type of Secondary Carbides on Sliding Wear of Titanium	
	Carbonitride–Nickel Cermets 386	
	24.4.1 Wear Mechanisms 387	
24.5	Tribochemical Wear of Titanium Carbonitride–Based Cermets 387	
	24.5.1 Evolution of Tribochemistry and Contact Temperature 387	
24.6	Influence of Tungsten Carbide Content on Load-Dependent Sliding Wear	
	Properties 393	
24.7	High Temperature Wear of Titanium Carbonitride–Nickel Cermets 397	
	24.7.1 Wear Mechanisms 398	
	24.7.2 Discussion of High-Temperature Oxidation and Its Relation to Material	
	Removal 401	
	24.7.3 Thermal Oxidation 402	
	24.7.4 Influence of Different Secondary Carbide Addition 403	
24.8	Summary of Key Results 403	
	References 404	
CHAPTE	ER 25 CASE STUDY: (W,Ti)C-CO CERMETS	407
25.1	Introduction 407	
25.2	Materials and Experiments 408	
25.3	Microstructure and Mechanical Properties 409	
25.4	Wear Properties 410	
25.5	Correlation between Mechanical Properties and Wear Resistance 413	
25.6	Concluding Remarks 418	
	References 419	
	TION VI FRICTION AND WEAR OF CERAMICS IN A OGENIC ENVIRONMENT	
		oertililii

CHAPTER 26 OVERVIEW: CRYOGENIC WEAR PROPERTIES OF MATERIALS

Designing a High-Speed Cryogenic Wear Tester 425

26.1

26.2

Background 423

xiv	CONTENTS	
26.3	Summary of Results Obtained with Ductile Metals 427	
	26.3.1 Self-Mated Steel 427	
	26.3.2 Titanium/Steel Couple 430	
	26.3.3 Copper/Steel Sliding System 433	
26.4	Summary 437	
	References 437	
СНАР	IER 27 CASE STUDY: SLIDING WEAR OF ALUMINA IN A CRYOGENIC	
ENVI	RONMENT	439
27.1	Background 439	
27.2	Materials and Experiments 440	
27.3	Tribological Properties of Self-Mated Alumina 442	
27.4	Genesis of Tribological Behavior in a Cryogenic Environment 449	
•	27.4.1 Friction of Self-Mated Alumina in LN2 449	
	27.4.2 Brittle Fracture and Wear of Self-Mated Alumina in LN2 450	
27.5	Concluding Remarks 452	
	References 452	
СНАР	TER 28 CASE STUDY: SLIDING WEAR OF SELF-MATED TETRAGONAL	
	ONIA CERAMICS IN LIQUID NITROGEN	454
28.1	Introduction 454	
28.2	Materials and Experiments 456	
28,3	Friction of Self-Mated Y-TZP Material in LN2 456	
28.4	Cryogenic Wear of Zirconia 459	
28.5	Cryogenic Sliding-Induced Zirconia Phase Transformation 460	
28.6	Wear Mechanisms of Zirconia in LN2 464	
28.7	Concluding Remarks 466	
	References 467	
CHAD	TER 29 CASE STUDY: SLIDING WEAR OF SILICON CARBIDE	
	CRYOGENIC ENVIRONMENT	469
29.1	Introduction 469	
29.1	Materials and Experiments 470	
29.3	Friction and Wear Properties 470	
29.3	Thermal Aspect and Limited Tribochemical Wear 473	
29.5	Tribomechanical Stress-Assisted Deformation and Damage 479	
29.6	Comparison with Sliding Wear Properties of Oxide Ceramics 481	
29.7	Concluding Remarks 482	
27.1	References 483	
CE/	CTION VII WATER-LUBRICATED WEAR OF CERAMICS	
		enegle.
	TER 30 FRICTION AND WEAR OF OXIDE CERAMICS IN AN AQUEOUS RONMENT	487
30.1	Background 487	

Tribological Behavior of Alumina in an Aqueous Solution 488

30.2

	30.2.1 Electrochemical Properties and Wear Characterization of Self-Mated	
	Alumina 491	
	30.2.2 Surface Roughness and Frictional Behavior 492	
30.3	Tribological Behavior of Self-Mated Zirconia in an Aqueous Environment 49	93
	30.3.1 Zirconia Transformation and Wear 497	
	30.3.2 Electrochemical Aspect of Wear 498	
30.4	Concluding Remarks 499	
	References 500	

SECTION VIII CLOSURE

CHAPTER 31 PERSPECTIVE FOR DESIGNING MATERIALS FOR TRIBOLOGICAL APPLICATIONS

505

INDEX 509