

Contents

	Foreword	V
	Preface	XVII
	List of Contributors	XIX
1	Fibers for Ceramic Matrix Composites	1
	<i>Bernd Clausß</i>	
1.1	Introduction	1
1.2	Fibers as Reinforcement in Ceramics	1
1.3	Structure and Properties of Fibers	2
1.3.1	Fiber Structure	2
1.3.2	Structure Formation	3
1.3.3	Structure Parameters and Fiber Properties	4
1.4	Inorganic Fibers	7
1.4.1	Production Processes	7
1.4.1.1	Indirect Fiber Production	7
1.4.1.2	Direct Fiber Production	7
1.4.2	Properties of Commercial Products	9
1.4.2.1	Comparison of Oxide and Non-oxide Ceramic Fibers	9
1.4.2.2	Oxide Ceramic Filament Fibers	10
1.4.2.3	Non-oxide Ceramic Filament Fibers	11
1.5	Carbon Fibers	12
1.5.1	Production Processes	15
1.5.1.1	Carbon Fibers from PAN Precursors	15
1.5.1.2	Carbon Fibers from Pitch Precursors	17
1.5.1.3	Carbon Fibers from Regenerated Cellulose	17
1.5.2	Commercial Products	18
	Acknowledgments	19
2	Textile Reinforcement Structures	21
	<i>Thomas Gries, Jan Stüve, and Tim Grundmann</i>	
2.1	Introduction	21
2.1.1	Definition for the Differentiation of Two-Dimensional and Three-Dimensional Textile Structures	23
2.1.2	Yarn Structures	23

2.2	Two-Dimensional Textiles	24
2.2.1	Nonwovens	24
2.2.2	Woven Fabrics	25
2.2.3	Braids	27
2.2.4	Knitted Fabrics	28
2.2.5	Non-crimp Fabrics	29
2.3	Three-Dimensional Textiles	30
2.3.1	Three-Dimensional Woven Structures	30
2.3.2	Braids	32
2.3.2.1	Overbraided Structures	32
2.3.2.2	Three-Dimensional Braided Structures	34
2.3.3	Three-Dimensional Knits	37
2.3.3.1	Multilayer Weft-Knits	37
2.3.3.2	Spacer Warp-Knits	37
2.4	Preforming	38
2.4.1	One-Step/Multi-Step Preforming	38
2.4.2	Cutting	39
2.4.3	Handling and Draping	39
2.4.4	Joining Technologies	40
2.5	Textile Testing	41
2.5.1	Tensile Strength	41
2.5.2	Bending Stiffness	41
2.5.3	Filament Damage	42
2.5.4	Drapability	42
2.5.5	Quality Management	42
2.6	Conclusions	43
2.6.1	Processability of Brittle Fibers	43
2.6.2	Infiltration of the Textile Structure	43
2.6.3	Mechanical Properties of the Final CMC Structure	44
2.6.4	Productivity and Production Process Complexity	44
2.7	Summary and Outlook	44
	Acknowledgments	45
3	Interfaces and Interphases	49
	<i>Jacques Lamon</i>	
3.1	Introduction	49
3.2	Role of Interfacial Domain in CMCs	50
3.3	Mechanism of Deviation of Transverse Cracks	52
3.4	Phenomena Associated to Deviation of Matrix Cracks	53
3.5	Tailoring Fiber/Matrix Interfaces. Influence on Mechanical Properties and Behavior	55
3.6	Various Concepts of Weak Interfaces/Interphases	59
3.7	Interfacial Properties	61
3.8	Interface Control	64
3.9	Conclusions	66

4 Carbon/Carbons and Their Industrial Applications 69

Roland Weiß

- 4.1 Introduction 69
- 4.2 Manufacturing of C/Cs 69
 - 4.2.1 Carbon Fiber Reinforcements 71
 - 4.2.2 Matrix Systems 73
 - 4.2.2.1 Thermosetting Resins as Matrix Precursors 73
 - 4.2.2.2 Thermoplastics as Matrix Precursors 74
 - 4.2.2.3 Gas Phase Derived Carbon Matrices 75
 - 4.2.3 Redensification/Recarbonization Cycles 79
 - 4.2.4 Final Heat Treatment (HTT) 80
- 4.3 Industrial Applications of C/Cs 82
 - 4.3.1 Oxidation Protection of C/Cs 83
 - 4.3.1.1 Bulk Protection Systems for C/Cs 83
 - 4.3.1.2 Outer Multilayer Coatings 88
 - 4.3.1.3 Outer Glass Sealing Layers 90
 - 4.3.2 Industrial Applications of C/Cs 92
 - 4.3.2.1 C/Cs for High Temperature Furnaces 97
 - 4.3.2.2 Application for Thermal Treatments of Metals 102
 - 4.3.2.3 Application of C/C in the Solar Energy Market 105

5 Melt Infiltration Process 113

Bernhard Heidenreich

- 5.1 Introduction 113
- 5.2 Processing 114
 - 5.2.1 Build-up of Fiber Protection and Fiber/Matrix Interface 115
 - 5.2.2 Manufacture of Fiber Reinforced Green Bodies 117
 - 5.2.3 Build-up of a Porous, Fiber Reinforced Preform 118
 - 5.2.4 Si Infiltration and Build-up of SiC Matrix 119
- 5.3 Properties 121
 - 5.3.1 Material Composition 127
 - 5.3.2 Mechanical Properties 128
 - 5.3.3 CTE and Thermal Conductivity 130
 - 5.3.4 Frictional Properties 131
- 5.4 Applications 131
 - 5.4.1 Space Applications 131
 - 5.4.2 Short-term Aeronautics 133
 - 5.4.3 Long-term Aeronautics and Power Generation 133
 - 5.4.4 Friction Systems 134
 - 5.4.5 Low-Expansion Structures 135
 - 5.4.6 Further Applications 136
- 5.5 Summary 137

6 Chemical Vapor Infiltration Processes for Ceramic Matrix Composites: Manufacturing, Properties, Applications 141

Martin Leuchs

- 6.1 Introduction 141
- 6.2 CVI Manufacturing Process for CMCs 143
 - 6.2.1 Isothermal-Isobaric Infiltration 144
 - 6.2.2 Gradient Infiltration 145
 - 6.2.3 Discussion of the Two CVI-processes 146
- 6.3 Properties of CVI Derived CMCs 146
 - 6.3.1 General Remarks 146
 - 6.3.2 Mechanical Properties 148
 - 6.3.2.1 Fracture Mechanism and Toughness 148
 - 6.3.2.2 Stress-Strain Behavior 149
 - 6.3.2.3 Dynamic Loads 151
 - 6.3.2.4 High Temperature Properties and Corrosion 151
 - 6.3.2.5 Thermal and Electrical Properties 153
- 6.4 Applications and Main Developments 153
 - 6.4.1 Hot Structures in Space 153
 - 6.4.2 Gas Turbines 155
 - 6.4.3 Material for Fusion Reactors 156
 - 6.4.4 Components for Journal Bearings 156
- 6.5 Outlook 161

7 The PIP-process: Precursor Properties and Applications 165

Günter Motz, Stephan Schmidt, and Steffen Beyer

- 7.1 Si-based Precursors 165
 - 7.1.1 Introduction 165
 - 7.1.2 Precursor Systems and Properties 166
 - 7.1.3 Cross-Linking Behavior of Precursors 167
 - 7.1.4 Pyrolysis Behavior of Precursors 169
 - 7.1.5 Commercial Available Non-oxide Precursors 171
- 7.2 The Polymer Impregnation and Pyrolysis Process (PIP) 171
 - 7.2.1 Introduction 171
 - 7.2.2 Manufacturing Technology 173
 - 7.2.2.1 Preform Manufacturing 173
 - 7.2.2.2 Manufacturing of CMC 175
- 7.3 Applications of the PIP-process 180
 - 7.3.1 Launcher Propulsion 180
 - 7.3.2 Satellite Propulsion 182
- 7.4 Summary 184

8 Oxide/Oxide Composites with Fiber Coatings 187

George Jefferson, Kristin A. Keller, Randall S. Hay, and Ronald J. Kerans

- 8.1 Introduction 187
- 8.2 Applications 189

8.3	CMC Fiber-Matrix Interfaces	189
8.3.1	Interface Control	190
8.3.2	Fiber Coating Methods	191
8.3.3	CMC Processing	194
8.3.4	Fiber-Matrix Interfaces	195
8.3.4.1	Weak Oxides	195
8.3.4.2	Porous Coatings and Fugitive Coatings	197
8.3.4.3	Other Coatings	198
8.4	Summary and Future Work	198
9	All-Oxide Ceramic Matrix Composites with Porous Matrices	205
	<i>Martin Schmücker and Peter Mechnich</i>	
9.1	Introduction	205
9.1.1	Oxide Ceramic Fibers	206
9.1.2	“Classical” CMC Concepts	207
9.2	Porous Oxide/Oxide CMCs without Fiber/Matrix Interphase	208
9.2.1	Materials and CMC Manufacturing	210
9.2.2	Mechanical Properties	214
9.2.3	Thermal Stability	218
9.2.4	Other Properties	220
9.3	Oxide/Oxide CMCs with Protective Coatings	223
9.4	Applications of Porous Oxide/Oxide CMCs	226
10	Microstructural Modeling and Thermomechanical Properties	231
	<i>Dietmar Koch</i>	
10.1	Introduction	231
10.2	General Concepts of CMC Design, Resulting Properties, and Modeling	232
10.2.1	Weak Interface Composites WIC	232
10.2.2	Weak Matrix Composites WMC	237
10.2.3	Assessment of Properties of WIC and WMC	238
10.2.4	Modeling of the Mechanical Behavior of WMC	238
10.2.5	Concluding Remarks	243
10.3	Mechanical Properties of CMC	244
10.3.1	General Mechanical Behavior	244
10.3.2	High Temperature Properties	246
10.3.3	Fatigue	251
10.3.4	Concluding Remarks	255
	Acknowledgment	256
11	Non-destructive Testing Techniques for CMC Materials	261
	<i>Jan Marcel Hausherr and Walter Krenkel</i>	
11.1	Introduction	261
11.2	Optical and Haptic Inspection Analysis	263
11.3	Ultrasonic Analysis	262

11.3.1	Physical Principle and Technical Implementation	263
11.3.2	Transmission Analysis	264
11.3.3	Echo-Pulse Analysis	265
11.3.4	Methods and Technical Implementation	266
11.3.5	Ultrasonic Analysis of CMC	267
11.4	Thermography	268
11.4.1	Thermal Imaging (Infrared Photography)	269
11.4.2	Lockin Thermography	271
11.4.3	Ultrasonic Induced Thermography	272
11.4.4	Damage Detection Using Thermography	272
11.5	Radiography (X-Ray Analysis)	273
11.5.1	Detection of X-Rays	273
11.5.1.1	X-Ray Film (Photographic Plates)	274
11.5.1.2	X-Ray Image Intensifier	274
11.5.1.3	Solid State Arrays	275
11.5.1.4	Gas Ionization Detectors (Geiger Counter)	275
11.5.2	Application of Radiography for C/SiC Composites	275
11.5.3	Limitations and Disadvantages of Radiography	277
11.6	X-Ray Computed Tomography	277
11.6.1	Functional Principle of CT	277
11.6.2	Computed Tomography for Defect Detection	279
11.6.3	Micro-structural CT-Analysis	280
11.6.4	Process Accompanying CT-Analysis	282
11.7	Conclusions	283
12	Machining Aspects for the Drilling of C/C-SiC Materials	287
	<i>Klaus Weinert and Tim Jansen</i>	
12.1	Introduction	287
12.2	Analysis of Machining Task	288
12.3	Determination of Optimization Potentials	290
12.3.1	Tool	290
12.3.2	Parameters	294
12.3.3	Basic Conditions	294
12.4	Process Strategies	295
12.5	Conclusions	300
13	Advanced Joining and Integration Technologies for Ceramic Matrix Composite Systems	303
	<i>Mrityunjay Singh and Rajiv Asthana</i>	
13.1	Introduction	303
13.2	Need for Joining and Integration Technologies	304
13.3	Joint Design, Analysis, and Testing Issue	304
13.3.1	Wettability	305
13.3.2	Surface Roughness	306
13.3.3	Joint Design and Stress State	306

13.3.4	Residual Stress, Joint Strength, and Joint Stability	307
13.4	Joining and Integration of CMC–Metal Systems	309
13.5	Joining and Integration of CMC–CMC Systems	314
13.6	Application in Subcomponents	318
13.7	Repair of Composite Systems	321
13.8	Concluding Remarks and Future Directions	322
	Acknowledgments	323
14	CMC Materials for Space and Aeronautical Applications	327
	<i>François Christin</i>	
14.1	Introduction	327
14.2	Carbon/Carbon Composites	328
14.2.1	Manufacturing of Carbon/Carbon Composites	328
14.2.1.1	n-Dimensional Reinforcement	328
14.2.1.2	Three-Dimensional Reinforcement Preforms	329
14.2.1.3	Densification	333
14.2.2	Carbon/Carbon Composites Applications	335
14.2.2.1	Solid Rocket Motors (SRM) Nozzles	335
14.2.2.2	Liquid Rocket Engines (LRE)	337
14.2.2.3	Friction Applications	338
14.3	Ceramic Composites	338
14.3.1	SiC-SiC and Carbon-SiC Composites Manufacture	339
14.3.1.1	Elaboration	340
14.3.2	SiC-SiC and Carbon-SiC Composites Applications	340
14.3.2.1	Aeronautical and Space Applications	340
14.3.2.2	Liquid Rocket Engines Applications	341
14.3.3	A Breakthrough with a New Concept: The Self-Healing Matrix	343
14.3.3.1	Manufacturing of Ceramic Composites	343
14.3.3.2	The Self-Healing Matrix	344
14.3.3.3	Characterization	344
14.3.4	Representative Applications of These New Materials	347
14.3.4.1	Military Aeronautical Applications	347
14.3.4.2	Commercial Aeronautical Applications	349
15	CMC for Nuclear Applications	353
	<i>Akira Kohyama</i>	
15.1	Introduction	353
15.2	Gas Reactor Technology and Ceramic Materials	354
15.3	Ceramic Fiber Reinforced Ceramic Matrix Composites (CFRC, CMC)	356
15.4	Innovative SiC/SiC by NITE Process	358
15.5	Characteristic Features of SiC/SiC Composites by NITE Process	359
15.6	Effects of Radiation Damage	362
15.6.1	Ion-Irradiation Technology for SiC Materials	363
15.6.2	Micro-Structural Evolution and Swelling	364

15.6.3	Thermal Conductivity	366
15.6.4	Mechanical Property Changes	369
15.7	Mechanical Property Evaluation Methods	371
15.7.1	Impulse Excitation Method for Young's Modulus Determination	372
15.7.2	Bulk Strength Testing Methods for Ceramics	373
15.7.3	Test Methods for Composites	374
15.7.4	Development of Materials Database	378
15.8	New GFR Concepts Utilizing SiC/SiC Composite Materials	379
15.9	Concluding Remarks	381

16 CMCs for Friction Applications 385

Walter Krenkel and Ralph Renz

16.1	Introduction	385
16.2	C/SiC Pads for Advanced Friction Systems	385
16.2.1	Brake Pads for Emergency Brake Systems	388
16.2.2	C/SiC Brake Pads for High-Performance Elevators	388
16.3	Ceramic Brake Disks	391
16.3.1	Material Properties	392
16.3.2	Manufacturing	394
16.3.3	Braking Mechanism	396
16.3.4	Design Aspects	398
16.3.5	Testing	401
16.4	Ceramic Clutches	403

Index 409