

Contents

Preface XV

List of Contributors XVII

Part I Powders 1

1	Powder Compaction by Dry Pressing	3
	<i>Rainer Oberacker</i>	
1.1	Introduction	3
1.2	Fundamental Aspects of Dry Pressing	3
1.2.1	Die or Mold Filling Behavior of Powders	4
1.2.1.1	Particle Packing: A Static View	5
1.2.1.2	Practical Aspects of Die Filling With Granulates	7
1.2.2	Compaction Behavior	8
1.2.2.1	Compaction of Monolithic Powders	8
1.2.2.2	Compaction of Granulated Powders	10
1.2.2.3	Understanding Powder Compaction by Advanced Modeling	14
1.3	Practice of Uniaxial Compaction	19
1.3.1	Die Filling	19
1.3.2	Tooling Principles and Pressing Tools	21
1.3.3	Powder Compaction Presses	23
1.4	Practice of Isostatic Compaction	25
1.4.1	Wet-Bag Isostatic Pressing	25
1.4.2	Dry-Bag Isostatic Pressing	28
1.5	Granulation of Ceramic Powders	29
1.5.1	Spray-Drying	30
1.5.2	Alternative Spray Granulation Methods	33
1.5.3	Characterization of Ceramic Granulates	34
	References	34
2	Tape Casting	39
	<i>Andreas Roosen</i>	
2.1	Use of the Tape Casting Process	39
2.2	Process Variations	41

2.3	Tape Casting Process	42
2.4	Components of the Slurry	44
2.4.1	Inorganic Raw Materials	45
2.4.2	Solvents	46
2.4.3	Organic Raw Materials	47
2.4.3.1	Dispersing Agents	47
2.4.3.2	Binder and Plasticizer	48
2.4.3.3	Other Additives	49
2.4.4	Interaction between Slurry Components	50
2.5	Preparation of the Slurry and its Properties	51
2.6	Tape Casting	52
2.6.1	Drying and Characteristics of the Green Tape	54
2.7	Machining, Metallization, and Lamination	55
2.8	Binder Burnout	56
2.9	Firing	56
2.10	Summary	58
	References	58
3	Hydrothermal Routes to Advanced Ceramic Powders and Materials	63
	<i>Wojciech L. Suchanek and Richard E. Riman</i>	
3.1	Introduction to Hydrothermal Synthesis	63
3.1.1	Fundamental Definitions	63
3.1.2	Process Development and Industrial Production	65
3.1.3	Hydrothermal Hybrid Techniques	67
3.1.4	Physical and Chemical Advantages of Hydrothermal Solutions	68
3.2	Engineering Ceramic Synthesis in Hydrothermal Solution	69
3.2.1	Phase Partitioning in Hydrothermal Systems	69
3.2.2	A Rational Approach for Engineering Hydrothermal Synthesis Methods	69
3.2.3	Thermodynamic Modeling	70
3.2.4	Examples of Synthesis Engineering	72
3.3	Materials Chemistry of Hydrothermal Ceramic Powders	74
3.3.1	Control of Chemical Composition	74
3.3.2	Physical Characteristics and their Control	77
3.4	Ceramics Processed from Hydrothermally Synthesized Powders	80
3.4.1	Synthesis of Modified Powders for Enhanced Sinterability	80
3.4.2	Powders for Sintered Dense Ceramics with Fine Grain Size	81
3.4.3	Sintered Porous Ceramics from Hydrothermally Synthesized Powders	85
3.4.4	Fabrication of Textured Ceramics from Hydrothermal Powders	86
3.4.5	<i>In-Situ</i> Hydrothermal Conversion and Hydrothermal Sintering	87
3.5	Summary	88
	References	88

4	Liquid Feed-Flame Spray Pyrolysis (LF-FSP) in the Synthesis of Single- and Mixed-Metal Oxide Nanopowders	97
	<i>Richard M. Laine</i>	
4.1	Introduction	97
4.2	Basic Concepts of Nanopowder Formation During LF-FSP	100
4.2.1	Particle Size Distributions	101
4.2.2	Phase Formation	102
4.2.3	Phase Characterization	103
4.3	Can Nanoparticles Be Prepared That Consist of Mixed Phases?	104
4.3.1	The TiO ₂ /Al ₂ O ₃ System	104
4.3.2	Changing Band Gaps	107
4.4	Which Particle Morphologies Can be Accessed?	107
4.5	Can Nanopowders Be Doped?	110
4.5.1	Sinter-Resistant Materials	110
4.5.2	Laser Paints	111
	References	116
5	Sol–Gel Processing of Ceramics	121
	<i>Nicola Hüsing</i>	
5.1	Introduction	121
5.2	Principles of Sol–Gel Processing	122
5.3	Porous Materials	126
5.4	Hybrid Materials	130
5.5	Bioactive Sol–Gel Materials	133
5.5.1	<i>In-Situ</i> Encapsulation of Biomolecules	133
5.5.2	Bioactive Materials	136
	References	137
Part II	Densification and Beyond	141
6	Sintering	143
	<i>Suk-Joong L. Kang</i>	
6.1	Sintering Phenomena	143
6.2	Solid-State Sintering	144
6.2.1	Sintering Models and Kinetics with No Grain Growth	144
6.2.1.1	Initial Stage Model and Kinetics	145
6.2.1.2	Intermediate and Final Stage Models and Kinetics	148
6.2.1.3	Grain Boundary Structure and Densification Kinetics	150
6.2.2	Grain Growth	150
6.2.2.1	Normal Grain Growth	151
6.2.2.2	Grain Growth in the Presence of Second-Phase Particles	152
6.2.2.3	Grain Growth with Boundary Segregation	152
6.2.2.4	Grain Growth Behavior with Boundary Structure	154
6.2.3	Microstructure Development	155
6.3	Liquid-Phase Sintering	156

6.3.1	Densification Models and Theories	157
6.3.1.1	Contact Flattening	159
6.3.1.2	Pore Filling	159
6.3.2	Grain Growth	161
6.3.3	Microstructure Development	163
6.4	Summary	164
	References	165
7	Hot Isostatic Pressing and Gas-Pressure Sintering	171
	<i>Michael J. Hoffmann, Stefan Fünfschilling, and Deniz Kahraman</i>	
7.1	Introduction	171
7.2	Sintering Mechanisms with Applied Pressure	172
7.3	Silicon Nitride Ceramics: Comparison of Capsule HIP and Sinter-HIP Technology	175
7.3.1	Capsule HIP	176
7.3.2	Sinter-HIP	177
7.3.3	Differences between Capsule-HIP and Sinter-HIP	181
7.4	Other Applications	182
7.4.1	Structural Ceramics	182
7.4.2	Post-HIPing of Oxide Ceramics for Optical Applications	182
	References	185
8	Hot Pressing and Spark Plasma Sintering	189
	<i>Mats Nygren and Zhijian Shen</i>	
8.1	Introduction	189
8.2	Advantages of Sintering Under a Uniaxial Pressure	190
8.3	Conventional Hot Presses	193
8.4	SPS Set-Up	194
8.5	Unique Features and Advantages of the SPS Process	196
8.6	The Role of High Pressure	197
8.7	The Role of Rapid and Effective Heating	199
8.8	The Role of Pulsed Direct Current	202
8.9	Microstructural Prototyping by SPS	203
8.9.1	Nanoceramics and Ceramics Nanocomposites	203
8.9.2	Self-Reinforced Ceramics	205
8.9.3	Superplasticity and Textured Ceramics	206
8.9.4	Non-Equilibrium Ceramic Composites	208
8.9.5	Ceramics with Macro- and Micro- Graded Structures	210
8.9.6	Hard-to-Make Ceramics	211
8.9.7	Defect-Engineered Ceramics	212
8.10	Potential Industrial Applications	213
	References	213

9 Fundamentals and Methods of Ceramic Joining 215*K. Scott Weil*

- 9.1 Introduction 215
- 9.2 Basic Phenomena in Ceramic Joining 216
 - 9.2.1 Mechanics 216
 - 9.2.1.1 The Strength of Ceramics 216
 - 9.2.1.2 Contact Stress 217
 - 9.2.1.3 Residual Stress 217
 - 9.2.1.4 Elastic Modulus Effects 219
 - 9.2.1.5 Other Effects 220
 - 9.2.1.6 Strength of Bonded Joints 220
 - 9.2.2 Adhesion and Wetting 221
 - 9.2.3 Diffusion 224
 - 9.2.4 Chemical Reaction 225
- 9.3 Methods of Joining 227
 - 9.3.1 Mechanical Joining 227
 - 9.3.2 Direct Bonding 231
 - 9.3.2.1 Solid-State Direct-Bonding Processes 231
 - 9.3.2.2 Liquid-State Direct-Bonding Processes 234
 - 9.3.3 Interlayer Bonding 235
 - 9.3.3.1 Solid-State Interlayer Bonding Processes 235
 - 9.3.3.2 Liquid-State Interlayer Bonding Processes 237
 - 9.4 Conclusions 243
 - References 243

10 Machining and Finishing of Ceramics 247*Eckart Uhlmann, Gregor Hasper, Thomas Hoghé, Christoph Hübert, Vanja Mihotovic, and Christoph Sammler*

- 10.1 Introduction 247
- 10.2 Face and Profile Grinding 248
 - 10.2.1 Process Description 248
 - 10.2.2 Machining of Ceramics 250
- 10.3 Current Status and Future Prospects 251
- 10.4 Double-Face Grinding with Planetary Kinematics 252
 - 10.4.1 Process Description 252
 - 10.4.2 Machining of Ceramics 254
 - 10.4.3 Current Status and Future Prospects 255
- 10.5 Ultrasonic-Assisted Grinding 256
 - 10.5.1 Process Description 256
 - 10.5.2 Machining of Ceramics 256
 - 10.5.3 Current Status and Future Prospects 258
- 10.6 Abrasive Flow Machining 261
 - 10.6.1 Process Description 261
 - 10.6.2 Machining of Ceramics 263

10.6.3	Current Status and Future Prospects	263
10.7	Outlook	264
	References	265

Part III Films and Coatings 267

11	Vapor-Phase Deposition of Oxides	269
	<i>Lambert Alff, Andreas Klein, Philipp Komissinskiy, and Jose Kurian</i>	
11.1	Introduction	269
11.1.1	Sputter Deposition	270
11.1.2	Pulsed-Laser Deposition	275
11.1.3	Oxide Molecular Beam Epitaxy	282
11.2	Summary	289
	References	289
12	Metal–Organic Chemical Vapor Deposition of Metal Oxide Films and Nanostructures	291
	<i>Sanjay Mathur, Aadesh Pratap Singh, Ralf Müller, Tessa Leuning, Thomas Lehnert, and Hao Shen</i>	
12.1	Introduction	291
12.2	Metal Oxide Film Deposition	300
12.2.1	Physical and Chemical Vapor Deposition Techniques	300
12.2.2	Chemical Vapor Deposition	302
12.2.2.1	Thermally Activated CVD (TA-CVD)	302
12.2.2.2	Plasma-Enhanced CVD (PE-CVD)	303
12.2.2.3	Molecule-Based CVD (MB-CVD)	304
12.2.3	Atomic Layer Deposition	304
12.2.4	Growth Dynamics	308
12.2.4.1	Amorphous Growth	309
12.2.4.2	Epitaxial Growth	309
12.2.4.3	Polycrystalline Growth	309
12.2.5	Mechanistic Aspects of CVD	310
12.3	The Precursor Concept in CVD	313
12.3.1	Precursor Requisites	313
12.3.2	Precursor–Material Relationship	314
12.3.3	Influence of Precursor Flow Rate on Microstructure and Growth	320
12.4	Metal Oxide Coatings	321
12.4.1	Monometallic Precursor (MO_x) Systems	321
12.4.2	Bimetallic Precursor ($\text{MM}'\text{O}_x$) Systems	324
12.4.3	Composites ($\text{MO}_x/\text{M}'\text{O}_y$) Systems	326
12.5	Summary	327
	References	330

Part IV Manufacturing Technology 337

13	Powder Characterization 339
	<i>Wolfgang Sigmund, Vasana Maneeratana, and Shu-Hau Hsu</i>
13.1	Introduction 339
13.1.1	Accuracy Versus Precision and Instrument Resolution 340
13.1.2	Sampling 341
13.2	Chemical Composition and Surface Characterization 343
13.2.1	Bulk Elemental Identification 344
13.2.1.1	Optical Absorption Spectroscopy 344
13.2.1.2	Electron and X-Ray Microanalysis 346
13.2.1.3	Infrared Spectroscopy 347
13.2.1.4	Raman Spectroscopy 348
13.2.1.5	Nuclear Magnetic Resonance Spectroscopy 348
13.2.1.6	Detailed Depth Profiling of Elemental Distribution within a Particle 348
13.2.2	Surface Characterization 349
13.2.2.1	Surface Chemistry Analysis 349
13.2.2.2	Vacuum Techniques 350
13.2.2.3	Specific Surface Area of Particles 351
13.2.2.4	Electrokinetic Potential or Zeta-Potential 353
13.2.3	Crystallographic Identification 353
13.3	Particle Sizing and Data Interpretation 354
13.3.1	Particles Types 354
13.3.2	Particle Shapes 355
13.3.3	General Methods 356
13.3.4	Light Scattering Techniques 357
13.3.5	Sedimentation Analysis 358
13.3.6	Coulter Counter 360
13.3.7	Image-Based Analysis 361
13.3.8	Sieve Analysis 362
13.3.8.1	Dry Sieving 363
13.3.8.2	Wet Sieving 363
13.4	Physical Properties 363
13.4.1	Particle Density 363
13.4.1.1	Particle Density Definition 364
13.4.1.2	Particle Density Measurement 365
13.4.2	Powder Porosity 366
13.5	Summary 367
	References 367
14	Process Defects 369
	<i>Keizo Uematsu</i>
14.1	Introduction 369
14.2	Bulk Examination Methods 370

14.3	Characterization Methods for Green Compact	371
14.3.1	Specimen Preparation	371
14.3.1.1	Ceramics	371
14.3.1.2	Green Compact	371
14.3.2	Observation with an Optical Microscope	373
14.3.2.1	Transmission Optical Microscopy	373
14.3.2.2	Polarized Light Microscopy	373
14.3.2.3	Infrared Transmission Microscopy	374
14.3.2.4	Confocal Fluorescent Scanning Laser Microscopy (CFSLM)	374
14.4	Process Defects in Ceramics	375
14.4.1	Short-Range Defects	375
14.4.1.1	Circumferential Cracks at the Granular Boundaries	377
14.4.1.2	Dimple Defects at the Centers of Granules	378
14.4.1.3	Coarse Particles/Aggregates	381
14.4.1.4	Defects Due to Inhomogeneous Distribution of Binder	383
14.4.2	Long-Range Defects	387
14.4.2.1	Particle Size Variation	387
14.4.2.2	Density Variation	387
14.4.2.3	Orientation of Particles	388
14.4.2.4	Anisotropic Packing	392
14.4.2.5	Long-Range Distribution of Additives	392
	References	393
15	Nonconventional Polymers in Ceramic Processing: Thermoplastics and Monomers	395
	<i>John W. Halloran</i>	
15.1	Introduction: Ceramic Green Bodies as Filled Polymers	395
15.2	Thermoplastics in Ceramic Processing	396
15.3	A Brief Review of Thermoplastics Used in Ceramic Forming	397
15.4	Melt Spinning of Fibers	397
15.5	Single-Component Extrusion and “Plastics Processing”	398
15.6	Thermoplastic Green Machining	400
15.7	Thermoplastic Coextrusion	401
15.8	Crystallinity in Thermoplastics	403
15.9	Compounding Thermoplastic Blends	404
15.10	Volumetric Changes in Thermoplastic–Ceramic Compounds	405
15.11	Polymer Formation by Polymerization of Suspensions in Monomers	407
15.12	Summary	410
	References	411
16	Manufacturing Technology: Rapid Prototyping	415
	<i>James D. McCaffin-Cawley</i>	
16.1	Introduction	415
16.2	Outline of Ceramic Processing	418

16.3	Solid Freeform Fabrication	422
16.4	Additive Prototyping Processes	422
16.4.1	Stereolithography-Based Methods	422
16.4.2	Flowable Powder Methods	423
16.4.3	Ink Jet Methods	426
16.4.4	Extrusion Methods	426
16.5	Sheet-Based Processes	427
16.6	Formative Prototyping Methods	427
16.7	Casting Methods	428
16.8	Plastic-Forming Methods	428
16.9	Subtractive Methods	429
16.9.1	Green (and Bisque) Machining	429
16.10	Examples of SFF	429
16.11	Summary	432
	References	432

Part V Alternative Strategies to Ceramics 439

17	Sintering of Nanograin Ceramics	441
	<i>I.-Wei Chen and Xiaohui Wang</i>	
17.1	Introduction	441
17.2	Background: What Went Wrong With Conventional Thinking?	442
17.3	Two-Step Sintering of Y_2O_3	445
17.4	Two-Step Sintering of Other Ceramics	451
17.5	Conclusions	453
	References	454
18	Polymer-Derived Ceramics	457
	<i>Emanuel Ionescu</i>	
18.1	Introduction	457
18.2	Preceramic Polymers	457
18.3	Polymer-to-Ceramic Transformation	459
18.4	Processing Techniques for PDCs	462
18.4.1	Polymer-Derived Ceramic Monoliths: Filler-Controlled Pyrolysis	462
18.4.2	Polymer-Derived Ceramic Coatings	464
18.4.3	Polymer-Derived Ceramic Fibers	466
18.4.3.1	Silicon Carbonitride	467
18.4.3.2	Silicon Borocarbonitride	467
18.4.4	Polymer-Derived Ceramic Foams	468
18.4.4.1	Direct-Foaming Techniques	468
18.4.4.2	Infiltration of Porous Performs	469
18.4.4.3	Sacrificial Fillers	469
18.5	High-Temperature Behavior of PDCs	470
18.5.1	Microstructure of PDCs	470

18.5.2	Energetics in SiOC and SiCN Systems	472
18.5.3	High-Temperature Stability of PDCs: Decomposition and Crystallization Processes	474
18.5.4	Oxidation Behavior of PDCs	476
18.6	Electrical Properties of PDCs	478
18.6.1	Electrical Properties of SiOC-Based Ceramics	479
18.6.2	Electrical Properties of SiCN-Based Ceramics	479
18.7	Magnetic Properties of PDCs	481
18.8	Polymer-Derived Ceramic Membranes	483
18.9	Microfabrication of PDC-Based Components for MEMS Applications	485
18.9.1	Direct Lithographic Methods	487
18.9.2	Micromolding Techniques	489
18.10	Summary and Outlook	491
	References	492
19	High-Pressure Routes to Ceramics	501
	<i>Dmytro A. Dzivenko and Ralf Riedel</i>	
19.1	Introduction	501
19.2	Static High-Pressure Techniques	502
19.2.1	Laser-Heated Diamond Anvil Cell (DAC)	503
19.2.2	Multianvil Apparatus	506
19.3	Shock-Wave Techniques	508
19.4	Synthesis of Cubic Silicon Nitride	511
	References	513

Index 519