

Third Edition

Modern Ceramic Engineering

Properties, Processing,
and Use in Design



David W. Richerson

Contents

Part I

Ceramics as Engineering Materials	1
---	---

Chapter 1

What Is a Ceramic?	3
1.1 Definitions of Ceramics	3
1.2 Material Types Generally Considered in the Ceramics Family	3
1.2.1 Polycrystalline Ceramics Fabricated by Sintering	3
1.2.2 Glass	4
1.2.3 Glass Ceramics	4
1.2.4 Single Crystals of Ceramic Compositions	4
1.2.5 Chemical Synthesis or Bonding	5
1.2.6 Natural Ceramics	5
1.3 So What Is a Ceramic?	5
References	6
Study Guide	6

Chapter 2

History of Ceramics	7
2.1 Ceramics in the Stone Age	7
2.1.1 Use of Natural Ceramics	7
2.1.2 Synthetic Stone: Clay Transformed by Fire	9
2.1.3 First Practical Use of Earthenware	9
2.1.4 Other Neolithic Ceramic Innovations	10
2.2 The Rise of Traditional Ceramic Industries	12
2.2.1 Ceramic Innovations during the Chalcolithic Period	12
2.2.2 Ceramics and the Metals Ages	13
2.2.3 The Emergence of Glass	13
2.2.4 Ceramics in Building	15
2.2.5 Ceramic Whitewares	17
2.3 From Traditional to Modern Ceramics	18
2.4 Summary	19
References	19
Study Guide	20

Chapter 3

Applications: Engineering with Ceramics	21
3.1 High-Temperature Applications	22
3.1.1 Ceramics in Metals Processing	22
3.1.2 Glass Production	25
3.1.3 Industrial Processes	25
3.1.4 Heat Engines	29
3.2 Wear and Corrosion Resistance Applications	36
3.2.1 Seals	36
3.2.2 Valves	39

3.2.3	Pumps	42
3.2.4	Bearings	42
3.2.5	Thread Guides	44
3.2.6	Ceramics in Papermaking	44
3.3	Cutting and Grinding	45
3.3.1	Ceramic Cutting Tool Inserts	46
3.3.2	Superhard Abrasives	49
3.3.3	Waterjet Cutting	50
3.4	Electrical Applications of Ceramics	50
3.4.1	Ceramic Electrical Insulators	51
3.4.2	Dielectric Ceramics	54
3.4.3	Semiconductors	55
3.4.4	Electrical Conductors	57
3.4.5	Ceramic Superconductors	59
3.5	Magnetic Ceramics	61
3.6	Optical Applications of Ceramics	61
3.6.1	Applications Based on Transparency	62
3.6.2	Applications Based on Phosphorescence and Fluorescence	66
3.7	Composites	68
3.8	Medical Applications of Ceramics	69
3.8.1	Replacement and Repair	69
3.8.2	Ceramics for Medical Diagnosis	73
3.8.3	Ceramics in Medical Treatment and Therapy	76
3.9	Energy Efficiency and Pollution Control	78
3.9.1	Energy Savings in the Home	78
3.9.2	Ceramics for Power Generation	81
3.9.3	Ceramics in the Transportation Sector	82
3.9.4	Other Uses of Ceramics for Energy Efficiency and Pollution Control	84
3.10	Military	84
3.11	Recreation	85
3.12	Summary	87
References	87	
Study Guide	88	

Chapter 5	Molecular Structures	
4.9.1	Hydrocarbons	
4.9.2	Addition Polymerization	
4.9.3	Condensation Polymerization	
4.9.4	Polymer Crystallization	
4.9.5	Cross-Linking and Brunching	
5.1	Isomorphism	
5.1.1	Homomorphism	
5.1.2	Heteromorphism	
5.1.3	Polymorphism	
5.2	Crystal Chemistry and Specific Crystal Structures	
5.2.1	Crystal Structure Notations	
5.2.1.1	Crystal Systems and Bravais Lattices	
5.2.1.2	Crystal Directions and Planes	
5.2.1.3	Structure, Composition, and Coordination Notations	
5.2.2	Crystal Chemistry of Ceramics	
5.2.2.1	Crystal Chemistry Concepts	
5.2.2.2	Crystal Chemical Substitutions	
5.2.3	Derivative Structures	
5.2.3.1	Metallic and Ceramic Crystal Structures	
5.3	Crystal Chemistry	
5.3.1	Metallic Crystal Structures	
5.3.2	Ceramic Structures with a Single Element	
5.3.3	Binary Ceramic Structures	
5.3.4	Ternary Ceramic Structures	
5.4	References	
5.5	Additional Recommended Reading	
5.6	Problems	
5.7	Study Guide	
Chapter 6	Phase Equilibria and Phase Equilibrium Diagrams	
6.1	Phase Equilibrium and Phase Equilibrium Diagrams	
6.1.1	Concept of Phase Equilibria	
6.1.2	The Phase Rule	
6.1.3	One-Component Phase Diagrams	
6.1.4	Two-Component Systems	
6.1.5	Intermediate Compounds	
6.1.6	Three-Component Systems	
6.2	Phase Equilibrium Diagram Composition Calculations	
6.2.1	Composition Conversions	
6.2.2	Binary Composition Calculations	
6.2.3	Ternary Composition Calculations	
6.3	Isothermal Crystallization Paths	
6.3.1	Binary Isothermal Analysis	
6.3.2	Ternary System Isothermal Analysis	
6.4	Nonisothermal Crystallization	

6.4.4	Elastic Constraint of a Polymorphic Transformation	179
6.4.5	Additional Information on Nonequilibrium	179
6.5	Stresses	179
6.6	Chemical Effects	180
6.7	Mechanically Induced Effects	182
6.8	9.1.6 Measurement of Creep	179
6.9	9.1.7 Creep Consideration for Component Design	179
7	Physical Properties	183
7.1	Density	183
7.1.1	1.1 Density	180
7.1.2	7.1.2 Melting Behavior	183
7.2	Thermal Properties	183
7.2.1	7.2.1 Heat Capacity	189
7.2.2	7.2.2 Thermal Conductivity	192
7.3	Thermal Expansion	198
7.3.1	7.3.1 Factors Influencing Thermal Expansion	200
7.3.2	7.3.2 References	207
7.3.3	7.3.3 Problems	209
7.4	Study Guide	209
8	Mechanical Behavior and Measurement	211
8.1	1. Elasticity	211
8.1.1	8.1.1 Modulus of Elasticity	211
8.1.2	8.1.2 Elastic Modulus Measurement	212
8.1.3	8.1.3 Poisson's Ratio	214
8.2	Strength	215
8.2.1	8.2.1 Theoretical Strength	216
8.2.2	8.2.2 Effects of Flaw Size	217
8.2.3	8.2.3 Strength Measurement	221
8.2.4	8.2.4 Strength Data for Ceramic Materials	228
8.3	Fracture Toughness	230
8.4	Ductile Versus Brittle Behavior	231
8.4.1	8.4.1 Mechanism of Plastic Deformation	232
8.4.2	8.4.2 Deformation Behavior of Metals	234
8.4.3	8.4.3 Deformation Behavior in Ceramics	235
8.4.4	8.4.4 Ceramics Deformation Summary	239
8.5	References	240
8.6	Additional Recommended Reading	241
8.7	Study Guide	241
9	Temperature and Environmental Effects on Properties	243
9.1	Creep	243
9.1.1	9.1.1 Effects of Temperature and Stress on Creep	244
9.1.2	9.1.2 Creep Mechanisms	244
9.2	Static Fatigue	244
9.3	Chemical Effects	244
9.4	Mechanically Induced Effects	244
9.4.1	9.4.1 Surface Flaw Formation	244
9.4.2	9.4.2 Removal of Surface Material	244
9.5	Thermal Shock	244
9.6	Problems	244
9.7	Study Guide	244
10	Electrical Behavior	244
10.1	10.1 Fundamentals and Definitions	244
10.2	10.2 Electronic Conductivity	244
10.3	10.3 Ionic Conductivity	244
10.4	10.3.1 Mechanisms of Ionic Conductivity	244
10.5	10.3.2 Ceramic Materials Exhibiting Ionic Conductivity	244
10.6	10.3.3 Applications of Zirconia Oxygen Ion Conductive Ceramics	244
10.7	10.3.4 Alternate Oxygen Ion Conductors	244
10.8	10.3.5 Sodium Ion Conductors and Applications	244
10.9	10.3.6 Lithium Ion Conduction and Applications	244
10.10	10.4 Conductive Polymers	244
10.11	10.5 Electrical Insulators	244
10.12	10.5.1 Applications of Electrical Insulators	244
10.13	10.6 Semiconductors	244
10.14	10.6.1 Mechanisms of Semiconduction	244
10.15	10.6.2 Applications of Ceramic Semiconductors	244
10.16	10.7 Superconductivity	244
10.17	10.7.1 Mechanism of Superconductivity	244
10.18	10.7.2 Characteristics of Superconductivity	244
10.19	10.7.3 Evolution of Superconductor Materials	244
10.20	10.7.4 Structure of High T_c Ceramic Superconductors	244
10.21	10.7.5 Characteristics of the 1:2:3 Ceramic Superconductor	244
10.22	10.7.6 Applications of Superconductors	244
10.23	10.8 References	244
10.24	10.9 Additional Recommended Reading	244
10.25	10.10 Problems	244
10.26	10.11 Study Guide	244
11	Dielectric, Magnetic, and Optical Behavior	244
11.1	11.1 Dielectric Properties	244
11.1.1	11.1.1 Polarization	244
11.1.2	11.1.2 Dielectric Constant	244

11.1.7	Pyroelectricity
11.1.8	Ferroelectricity

337

347

348

350

353

356

358

360

360

362

364

365

366

366

369

369

371

371

371

372

372

373

375

375

375

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

376

Chapter 16	547
Quality Assurance	547
16.1 In-Process QA	547
16.2 Specification and Certification	548
16.3 Proof Testing	550
16.4 Nondestructive Inspection	550
16.4.1 Penetrants	550
16.4.2 X-Ray Radiography	551
16.4.3 Computed Tomography	555
16.4.4 Ultrasonic NDI	555
16.4.5 Other NDI Techniques	560
16.5 Quality Problem Solving and Improvement	560
16.5.1 Nature of Variation in a Fabrication Process	560
16.5.2 SPC Tools and Techniques	561
16.5.3 Use of SPC Tools for Continuous Improvement	566
16.5.4 Quality Assurance Perspective of the End User	567
References	567
Additional Recommended Reading	568
Problems	569
Study Guide	569
Part IV	571
Design with Ceramics	571
Chapter 17	573
Design Considerations	573
17.1 Requirements of the Application	573
17.2 Property Limitations	574
17.3 Fabrication Limitations	574
17.4 Cost Considerations	576
17.5 Reliability Requirements	578
17.6 Summary	579
References	579
Study Guide	579
Chapter 18	581
Design Approaches	581
18.1 Empirical Design	581
18.2 Deterministic Design	581
18.3 Probabilistic Design	583
18.3.1 Weibull Statistics	584
18.3.2 Use of the Weibull Distribution in Design	588
18.3.3 Advantages of Probabilistic Design	590
18.3.4 Limitations of Probabilistic Design	590
References	590
Study Guide	590
Chapter 19	591
Fractography	591
19.1 Location of the Fracture Origin	591
19.2 Techniques of Fractography	591
19.3 Determining Failure Cause	591
Summary	591
References	591
Additional Recommended Reading	591
Problems	591
Study Guide	591
Chapter 20	593
Toughening of Ceramics	593
20.1.1 Modulus Transfer	593
20.1.2 Prestressing	593
20.1.3 Crack Deflection or Impediment	593
20.1.4 Crack Bridging	593
20.1.5 Pullout	593
20.1.6 Crack Shielding	593
20.1.7 Energy Dissipation	593
Examples of Toughened Ceramics	593
20.2.1 Self-Reinforced Ceramics	593
20.2.2 Transformation-Toughened Ceramics	593
20.2.3 Particulate-Reinforced Ceramics	593
20.2.4 Whisker-Reinforced Ceramics	593
20.2.5 Al_2O_3 Reinforced with SiC Whiskers	593
20.2.6 Si_3N_4 Reinforced with SiC and Si_3N_4 Whiskers	593
20.2.7 MoSi_2 and $\text{MoSi}_2\text{-WSi}_2$ Reinforced with SiC Whiskers	593
20.2.8 Fiber-Reinforced Ceramics	593
20.2.9 Examples of Ceramic Matrix Composites Reinforced with Ceramic Fit	593
20.2.10 Composites with Surface Compression	593
20.2.11 Fibrous Monolith	593
20.3 Summary	593
References	593
Study Guide	593
Appendix A	595
Glossary	595
Appendix B	596
Effective Ionic Radii for Cations and Anions	596