

Contents

LIST OF SYMBOLS xxiii

1. Introduction 1

- Learning Objectives 2
- 1.1 Historical Perspective 2
- 1.2 Materials Science and Engineering 3
- 1.3 Why Study Materials Science and Engineering? 5
- 1.4 Classification of Materials 5
- 1.5 Advanced Materials 11
- 1.6 Modern Materials' Needs 12
- References 13

2. Atomic Structure and Interatomic Bonding 15

- Learning Objectives 16
- 2.1 Introduction 16
- ATOMIC STRUCTURE 16
- 2.2 Fundamental Concepts 16
- 2.3 Electrons in Atoms 17
- 2.4 The Periodic Table 23
- ATOMIC BONDING IN SOLIDS 24
- 2.5 Bonding Forces and Energies 24
- 2.6 Primary Interatomic Bonds 26
- 2.7 Secondary Bonding or van der Waals Bonding 30
- 2.8 Molecules 32
- Summary 34
- Important Terms and Concepts 34
- References 35
- Questions and Problems 35

3. The Structure of Crystalline Solids 38

- Learning Objectives 39
- 3.1 Introduction 39
- CRYSTAL STRUCTURES 39
- 3.2 Fundamental Concepts 39
- 3.3 Unit Cells 40
- 3.4 Metallic Crystal Structures 41
- 3.5 Density Computations 45
- 3.6 Polymorphism and Allotropy 46

3.7	Crystal Systems	46
	CRYSTALLOGRAPHIC POINTS, DIRECTIONS, AND PLANES	49
3.8	Point Coordinates	49
3.9	Crystallographic Directions	51
3.10	Crystallographic Planes	55
3.11	Linear and Planar Densities	60
3.12	Close-Packed Crystal Structures	61

CRYSTALLINE AND NONCRYSTALLINE MATERIALS 63

3.13	Single Crystals	63
3.14	Polycrystalline Materials	64
3.15	Anisotropy	64
3.16	X-Ray Diffraction: Determination of Crystal Structures	66
3.17	Noncrystalline Solids	71
	<i>Summary</i>	72
	<i>Important Terms and Concepts</i>	73
	<i>References</i>	73
	<i>Questions and Problems</i>	74

4. Imperfections in Solids 80

	Learning Objectives	81
4.1	Introduction	81
	POINT DEFECTS 81	
4.2	Vacancies and Self-Interstitials	81
4.3	Impurities in Solids	83
4.4	Specification of Composition	85
	MISCELLANEOUS IMPERFECTIONS 88	
4.5	Dislocations—Linear Defects	88
4.6	Interfacial Defects	92
4.7	Bulk or Volume Defects	96
4.8	Atomic Vibrations	96
	MICROSCOPIC EXAMINATION 97	
4.9	General	97
4.10	Microscopic Techniques	98
4.11	Grain Size Determination	102
	<i>Summary</i>	104
	<i>Important Terms and Concepts</i>	105
	<i>References</i>	105
	<i>Questions and Problems</i>	106
	<i>Design Problems</i>	108

5. Diffusion 109

	Learning Objectives	110
5.1	Introduction	110
5.2	Diffusion Mechanisms	111
5.3	Steady-State Diffusion	112

5.4	Nonsteady-State Diffusion	114
5.5	Factors That Influence Diffusion	118
5.6	Other Diffusion Paths	125
	<i>Summary</i>	125
	<i>Important Terms and Concepts</i>	126
	<i>References</i>	126
	<i>Questions and Problems</i>	126
	<i>Design Problems</i>	129

6. Mechanical Properties of Metals 131

	Learning Objectives	132
6.1	Introduction	132
6.2	Concepts of Stress and Strain	133
	ELASTIC DEFORMATION 137	
6.3	Stress-Strain Behavior	137
6.4	Anelasticity	140
6.5	Elastic Properties of Materials	141
	PLASTIC DEFORMATION 143	
6.6	Tensile Properties	144
6.7	True Stress and Strain	151
6.8	Elastic Recovery after Plastic Deformation	154
6.9	Compressive, Shear, and Torsional Deformation	154
6.10	Hardness	155
	PROPERTY VARIABILITY AND DESIGN/SAFETY FACTORS 161	
6.11	Variability of Material Properties	161
6.12	Design/Safety Factors	163
	<i>Summary</i>	165
	<i>Important Terms and Concepts</i>	166
	<i>References</i>	166
	<i>Questions and Problems</i>	166
	<i>Design Problems</i>	172

7. Dislocations and Strengthening Mechanisms 174

	Learning Objectives	175
7.1	Introduction	175
	DISLOCATIONS AND PLASTIC DEFORMATION 175	
7.2	Basic Concepts	175
7.3	Characteristics of Dislocations	178
7.4	Slip Systems	179
7.5	Slip in Single Crystals	181
7.6	Plastic Deformation of Polycrystalline Materials	185
7.7	Deformation by Twinning	185

MECHANISMS OF STRENGTHENING IN METALS 188

- 7.8 Strengthening by Grain Size Reduction 188
- 7.9 Solid-Solution Strengthening 190
- 7.10 Strain Hardening 191

RECOVERY, RECRYSTALLIZATION, AND GRAIN GROWTH 194

- 7.11 Recovery 195
- 7.12 Recrystallization 195
- 7.13 Grain Growth 200
 - Summary* 201
 - Important Terms and Concepts* 202
 - References* 202
 - Questions and Problems* 202
 - Design Problems* 206

8. Failure 207

- Learning Objectives 208
- 8.1 Introduction 208
 - FRACTURE 208**
 - 8.2 Fundamentals of Fracture 208
 - 8.3 Ductile Fracture 209
 - 8.4 Brittle Fracture 211
 - 8.5 Principles of Fracture Mechanics 215
 - 8.6 Impact Fracture Testing 223
 - FATIGUE 227**
 - 8.7 Cyclic Stresses 228
 - 8.8 The *S-N* Curve 229
 - 8.9 Crack Initiation and Propagation 232
 - 8.10 Factors That Affect Fatigue Life 234
 - 8.11 Environmental Effects 237
 - CREEP 238**
 - 8.12 Generalized Creep Behavior 238
 - 8.13 Stress and Temperature Effects 239
 - 8.14 Data Extrapolation Methods 241
 - 8.15 Alloys for High-Temperature Use 242
 - Summary* 243
 - Important Terms and Concepts* 245
 - References* 246
 - Questions and Problems* 246
 - Design Problems* 250

9. Phase Diagrams 252

- Learning Objectives 253
- 9.1 Introduction 253
 - DEFINITIONS AND BASIC CONCEPTS 253**

- 9.2 Solubility Limit 254
- 9.3 Phases 254
- 9.4 Microstructure 255
- 9.5 Phase Equilibria 255
- 9.6 One-Component (or Unary) Phase Diagrams 256

BINARY PHASE DIAGRAMS 258

- 9.7 Binary Isomorphous Systems 258
- 9.8 Interpretation of Phase Diagrams 260
- 9.9 Development of Microstructure in Isomorphous Alloys 264
- 9.10 Mechanical Properties of Isomorphous Alloys 268
- 9.11 Binary Eutectic Systems 269
- 9.12 Development of Microstructure in Eutectic Alloys 276
- 9.13 Equilibrium Diagrams Having Intermediate Phases or Compounds 282
- 9.14 Eutectic and Peritectic Reactions 284
- 9.15 Congruent Phase Transformations 286
- 9.16 Ceramic and Ternary Phase Diagrams 287
- 9.17 The Gibbs Phase Rule 287
- THE IRON-CARBON SYSTEM 290**
- 9.18 The Iron-Iron Carbide ($\text{Fe-Fe}_3\text{C}$) Phase Diagram 290
- 9.19 Development of Microstructure in Iron-Carbon Alloys 293
- 9.20 The Influence of Other Alloying Elements 301
 - Summary* 302
 - Important Terms and Concepts* 303
 - References* 303
 - Questions and Problems* 304

10. Phase Transformations in Metals: Development of Microstructure and Alteration of Mechanical Properties 311

- Learning Objectives 312
- 10.1 Introduction 312
 - PHASE TRANSFORMATIONS 312**
 - 10.2 Basic Concepts 312
 - 10.3 The Kinetics of Phase Transformations 313
 - 10.4 Metastable versus Equilibrium States 324

MICROSTRUCTURAL AND PROPERTY CHANGES IN IRON-CARBON ALLOYS 324

- 10.5 Isothermal Transformation Diagrams 325
- 10.6 Continuous Cooling Transformation Diagrams 335
- 10.7 Mechanical Behavior of Iron-Carbon Alloys 339
- 10.8 Tempered Martensite 343
- 10.9 Review of Phase Transformations and Mechanical Properties for Iron-Carbon Alloys 346
 - Summary* 350
 - Important Terms and Concepts* 351
 - References* 352
 - Questions and Problems* 352
 - Design Problems* 356

11. Applications and Processing of Metal Alloys 358

- Learning Objectives 359
- 11.1 Introduction 359
 - TYPES OF METAL ALLOYS 359**
 - 11.2 Ferrous Alloys 359
 - 11.3 Nonferrous Alloys 372
 - FABRICATION OF METALS 382**
 - 11.4 Forming Operations 383
 - 11.5 Casting 384
 - 11.6 Miscellaneous Techniques 386
 - THERMAL PROCESSING OF METALS 387**
 - 11.7 Annealing Processes 388
 - 11.8 Heat Treatment of Steels 390
 - 11.9 Precipitation Hardening 402
 - Summary* 407
 - Important Terms and Concepts* 409
 - References* 409
 - Questions and Problems* 410
 - Design Problems* 411

12. Structures and Properties of Ceramics 414

- Learning Objectives 415
- 12.1 Introduction 415
 - CERAMIC STRUCTURES 415**
 - 12.2 Crystal Structures 415
 - 12.3 Silicate Ceramics 426
 - 12.4 Carbon 430
 - 12.5 Imperfections in Ceramics 434
 - 12.6 Diffusion in Ionic Materials 438

- 12.7 Ceramic Phase Diagrams 439
 - MECHANICAL PROPERTIES 442**
 - 12.8 Brittle Fracture of Ceramics 442
 - 12.9 Stress-Strain Behavior 447
 - 12.10 Mechanisms of Plastic Deformation 449
 - 12.11 Miscellaneous Mechanical Considerations 451
 - Summary* 453
 - Important Terms and Concepts* 454
 - References* 454
 - Questions and Problems* 455
 - Design Problems* 459

13. Applications and Processing of Ceramics 460

- Learning Objectives 461
- 13.1 Introduction 461
 - TYPES AND APPLICATIONS OF CERAMICS 461**
 - 13.2 Glasses 461
 - 13.3 Glass-Ceramics 462
 - 13.4 Clay Products 463
 - 13.5 Refractories 464
 - 13.6 Abrasives 466
 - 13.7 Cements 467
 - 13.8 Advanced Ceramics 468
 - FABRICATION AND PROCESSING OF CERAMICS 471**
 - 13.9 Fabrication and Processing of Glasses and Glass-Ceramics 471
 - 13.10 Fabrication and Processing of Clay Products 476
 - 13.11 Powder Pressing 481
 - 13.12 Tape Casting 484
 - Summary* 484
 - Important Terms and Concepts* 486
 - References* 486
 - Questions and Problems* 486
 - Design Problem* 488

14. Polymer Structures 489

- Learning Objectives 490
- 14.1 Introduction 490
- 14.2 Hydrocarbon Molecules 490
- 14.3 Polymer Molecules 492
- 14.4 The Chemistry of Polymer Molecules 493
- 14.5 Molecular Weight 497

14.6	Molecular Shape	500
14.7	Molecular Structure	501
14.8	Molecular Configurations	503
14.9	Thermoplastic and Thermosetting Polymers	506
14.10	Copolymers	507
14.11	Polymer Crystallinity	508
14.12	Polymer Crystals	512
14.13	Defects in Polymers	514
14.14	Diffusion in Polymeric Materials	515
	<i>Summary</i>	517
	<i>Important Terms and Concepts</i>	519
	<i>References</i>	519
	<i>Questions and Problems</i>	519

15. Characteristics, Applications, and Processing of Polymers 523

	Learning Objectives	524
15.1	Introduction	524
	MECHANICAL BEHAVIOR OF POLYMERS	524
15.2	Stress–Strain Behavior	524
15.3	Macroscopic Deformation	527
15.4	Viscoelastic Deformation	527
15.5	Fracture of Polymers	532
15.6	Miscellaneous Mechanical Characteristics	533
	MECHANISMS OF DEFORMATION AND FOR STRENGTHENING OF POLYMERS	535
15.7	Deformation of Semicrystalline Polymers	535
15.8	Factors That Influence the Mechanical Properties of Semicrystalline Polymers	538
15.9	Deformation of Elastomers	541
	CRYSTALLIZATION, MELTING, AND GLASS TRANSITION PHENOMENA IN POLYMERS	544
15.10	Crystallization	544
15.11	Melting	545
15.12	The Glass Transition	545
15.13	Melting and Glass Transition Temperatures	546
15.14	Factors That Influence Melting and Glass Transition Temperatures	547
	POLYMER TYPES	549
15.15	Plastics	549
15.16	Elastomers	552
15.17	Fibers	554
15.18	Miscellaneous Applications	555
15.19	Advanced Polymeric Materials	556

	POLYMER SYNTHESIS AND PROCESSING	560
15.20	Polymerization	561
15.21	Polymer Additives	563
15.22	Forming Techniques for Plastics	565
15.23	Fabrication of Elastomers	567
15.24	Fabrication of Fibers and Films	568
	<i>Summary</i>	569
	<i>Important Terms and Concepts</i>	571
	<i>References</i>	571
	<i>Questions and Problems</i>	572
	<i>Design Questions</i>	576

16. Composites 577

	Learning Objectives	578
16.1	Introduction	578
	PARTICLE-REINFORCED COMPOSITES	580
16.2	Large-Particle Composites	580
16.3	Dispersion-Strengthened Composites	584
	FIBER-REINFORCED COMPOSITES	585
16.4	Influence of Fiber Length	585
16.5	Influence of Fiber Orientation and Concentration	586
16.6	The Fiber Phase	595
16.7	The Matrix Phase	596
16.8	Polymer-Matrix Composites	597
16.9	Metal-Matrix Composites	603
16.10	Ceramic-Matrix Composites	605
16.11	Carbon–Carbon Composites	606
16.12	Hybrid Composites	607
16.13	Processing of Fiber-Reinforced Composites	607
	STRUCTURAL COMPOSITES	610
16.14	Laminar Composites	610
16.15	Sandwich Panels	611
	<i>Summary</i>	613
	<i>Important Terms and Concepts</i>	615
	<i>References</i>	616
	<i>Questions and Problems</i>	616
	<i>Design Problems</i>	619

17. Corrosion and Degradation of Materials 621

	Learning Objectives	622
17.1	Introduction	622
	CORROSION OF METALS	622
17.2	Electrochemical Considerations	623
17.3	Corrosion Rates	630

- 17.4 Prediction of Corrosion Rates 631
- 17.5 Passivity 638
- 17.6 Environmental Effects 640
- 17.7 Forms of Corrosion 640
- 17.8 Corrosion Environments 648
- 17.9 Corrosion Prevention 649
- 17.10 Oxidation 651

CORROSION OF CERAMIC MATERIALS 654

DEGRADATION OF POLYMERS 655

- 17.11 Swelling and Dissolution 655
- 17.12 Bond Rupture 657
- 17.13 Weathering 658
 - Summary 659
 - Important Terms and Concepts 660
 - References 661
 - Questions and Problems 661
 - Design Problems 644

18. Electrical Properties 665

Learning Objectives 666

- 18.1 Introduction 666
 - ELECTRICAL CONDUCTION 666
- 18.2 Ohm's Law 666
- 18.3 Electrical Conductivity 667
- 18.4 Electronic and Ionic Conduction 668
- 18.5 Energy Band Structures in Solids 668
- 18.6 Conduction in Terms of Band and Atomic Bonding Models 671
- 18.7 Electron Mobility 673
- 18.8 Electrical Resistivity of Metals 674
- 18.9 Electrical Characteristics of Commercial Alloys 677
 - SEMICONDUCTIVITY 679
- 18.10 Intrinsic Semiconduction 679
- 18.11 Extrinsic Semiconduction 682
- 18.12 The Temperature Dependence of Carrier Concentration 686
- 18.13 Factors That Affect Carrier Mobility 688
- 18.14 The Hall Effect 692
- 18.15 Semiconductor Devices 694

ELECTRICAL CONDUCTION IN IONIC CERAMICS AND IN POLYMERS 700

- 18.16 Conduction in Ionic Materials 701
- 18.17 Electrical Properties of Polymers 701
 - DIELECTRIC BEHAVIOR 702
- 18.18 Capacitance 703
- 18.19 Field Vectors and Polarization 704

- 18.20 Types of Polarization 708
- 18.21 Frequency Dependence of the Dielectric Constant 709
- 18.22 Dielectric Strength 711
- 18.23 Dielectric Materials 711

OTHER ELECTRICAL CHARACTERISTICS OF MATERIALS 711

- 18.24 Ferroelectricity 711
- 18.25 Piezoelectricity 712
 - Summary 713
 - Important Terms and Concepts 715
 - References 715
 - Questions and Problems 716
 - Design Problems 720



19. Thermal Properties W1

Learning Objectives W2

- 19.1 Introduction W2
- 19.2 Heat Capacity W2
- 19.3 Thermal Expansion W4
- 19.4 Thermal Conductivity W7
- 19.5 Thermal Stresses W12
 - Summary W14
 - Important Terms and Concepts W15
 - References W15
 - Questions and Problems W15
 - Design Problems W17



20. Magnetic Properties W19

Learning Objectives W20

- 20.1 Introduction W20
- 20.2 Basic Concepts W20
- 20.3 Diamagnetism and Paramagnetism W24
- 20.4 Ferromagnetism W26
- 20.5 Antiferromagnetism and Ferrimagnetism W28
- 20.6 The Influence of Temperature on Magnetic Behavior W32
- 20.7 Domains and Hysteresis W33
- 20.8 Magnetic Anisotropy W37
- 20.9 Soft Magnetic Materials W38
- 20.10 Hard Magnetic Materials W41
- 20.11 Magnetic Storage W44
- 20.12 Superconductivity W47
 - Summary W50
 - Important Terms and Concepts W52
 - References W52
 - Questions and Problems W53
 - Design Problems W56

 21. Optical Properties W57

Learning Objectives W58

21.1 Introduction W58

BASIC CONCEPTS W58

21.2 Electromagnetic Radiation W58

21.3 Light Interactions with Solids W60

21.4 Atomic and Electronic Interactions W61

OPTICAL PROPERTIES OF METALS W62**OPTICAL PROPERTIES OF NONMETALS W63**

21.5 Refraction W63

21.6 Reflection W65

21.7 Absorption W65

21.8 Transmission W68

21.9 Color W69

21.10 Opacity and Translucency in Insulators W71

APPLICATIONS OF OPTICAL PHENOMENA W72

21.11 Luminescence W72

21.12 Photoconductivity W72

21.13 Lasers W75

21.14 Optical Fibers in Communications W79

Summary W82

Important Terms and Concepts W83

References W84

Questions and Problems W84

Design Problem W85

 22. Materials Selection and Design Considerations W86

Learning Objectives W87

22.1 Introduction W87

MATERIALS SELECTION FOR A TORSIONALLY STRESSED CYLINDRICAL SHAFT W87

22.2 Strength Considerations—Torsionally Stressed Shaft W88

22.3 Other Property Considerations and the Final Decision W93

AUTOMOTIVE VALVE SPRING W94

22.4 Mechanics of Spring Deformation W94

22.5 Valve Spring Design and Material Requirements W95

22.6 One Commonly Employed Steel Alloy W98

FAILURE OF AN AUTOMOBILE REAR AXLE W101

22.7 Introduction W101

22.8 Testing Procedure and Results W102

22.9 Discussion W108

ARTIFICIAL TOTAL HIP REPLACEMENT W108

22.10 Anatomy of the Hip Joint W108

22.11 Material Requirements W111

22.12 Materials Employed W112

CHEMICAL PROTECTIVE CLOTHING W115

22.13 Introduction W115

22.14 Assessment of CPC Glove Materials to Protect Against Exposure to Methylene Chloride W115

MATERIALS FOR INTEGRATED CIRCUIT PACKAGES W119

22.15 Introduction W119

22.16 Leadframe Design and Materials W120

22.17 Die Bonding W121

22.18 Wire Bonding W124

22.19 Package Encapsulation W125

22.20 Tape Automated Bonding W127

Summary W129

References W130

Design Questions and Problems W131

 23. Economic, Environmental, and Societal Issues in Materials Science and Engineering W135

Learning Objectives W136

23.1 Introduction W136

ECONOMIC CONSIDERATIONS W136

23.2 Component Design W137

23.3 Materials W137

23.4 Manufacturing Techniques W137

ENVIRONMENTAL AND SOCIETAL CONSIDERATIONS W137

23.5 Recycling Issues in Materials Science and Engineering W140

Summary W143

References W143

Design Question W144

Appendix A The International System of Units A1**Appendix B Properties of Selected Engineering Materials A3**

B.1 Density A3

B.2 Modulus of Elasticity A6

B.3 Poisson's Ratio A10

B.4	Strength and Ductility	A11
B.5	Plane Strain Fracture Toughness	A16
B.6	Linear Coefficient of Thermal Expansion	A17
B.7	Thermal Conductivity	A21
B.8	Specific Heat	A24
B.9	Electrical Resistivity	A26
B.10	Metal Alloy Compositions	A29

Appendix C Costs and Relative Costs for Selected Engineering Materials A31

Appendix D Repeat Unit Structures for Common Polymers A37

Appendix E Glass Transition and Melting Temperatures for Common Polymeric Materials A41

Glossary G0

Answers to Selected Problems S1

Index I1

21.1	Introduction
21.2	Electromagnetic Radiation
21.3	Atomic and Electronic Interactions
21.4	Optical Properties of Materials
21.5	Refraction
21.6	Reflection
21.7	Absorption
21.8	Transmission
21.9	Color
21.10	Opacity and Transparency
21.11	Insulators
21.12	Applications of Optical Fibers
21.13	Lasers
21.14	Optical Fibers in Communications
21.15	Summary
21.16	Important Terms and Concepts
21.17	References
21.18	Questions and Problems
21.19	Design Problems
21.20	Summary
21.21	Important Terms and Concepts
21.22	References
21.23	Questions and Problems
21.24	Design Problem
21.25	Summary
21.26	Important Terms and Concepts
21.27	References
21.28	Questions and Problems
21.29	Design Problem
21.30	Summary
21.31	Important Terms and Concepts
21.32	References
21.33	Questions and Problems
21.34	Design Problem
21.35	Summary
21.36	Important Terms and Concepts
21.37	References
21.38	Questions and Problems
21.39	Design Problem
21.40	Summary
21.41	Important Terms and Concepts
21.42	References
21.43	Questions and Problems
21.44	Design Problem
21.45	Summary
21.46	Important Terms and Concepts
21.47	References
21.48	Questions and Problems
21.49	Design Problem
21.50	Summary
21.51	Important Terms and Concepts
21.52	References
21.53	Questions and Problems
21.54	Design Problem
21.55	Summary
21.56	Important Terms and Concepts
21.57	References
21.58	Questions and Problems
21.59	Design Problem
21.60	Summary
21.61	Important Terms and Concepts
21.62	References
21.63	Questions and Problems
21.64	Design Problem
21.65	Summary
21.66	Important Terms and Concepts
21.67	References
21.68	Questions and Problems
21.69	Design Problem
21.70	Summary
21.71	Important Terms and Concepts
21.72	References
21.73	Questions and Problems
21.74	Design Problem
21.75	Summary
21.76	Important Terms and Concepts
21.77	References
21.78	Questions and Problems
21.79	Design Problem
21.80	Summary
21.81	Important Terms and Concepts
21.82	References
21.83	Questions and Problems
21.84	Design Problem
21.85	Summary
21.86	Important Terms and Concepts
21.87	References
21.88	Questions and Problems
21.89	Design Problem
21.90	Summary
21.91	Important Terms and Concepts
21.92	References
21.93	Questions and Problems
21.94	Design Problem
21.95	Summary
21.96	Important Terms and Concepts
21.97	References
21.98	Questions and Problems
21.99	Design Problem
21.100	Summary