

CONTENTS

List of Symbols xvii

1/INTRODUCTION 1

- 1.1 Historical Perspective 2
- 1.2 Materials Science and Engineering 2
- 1.3 **Classification** of Materials 3
- 1.4 Modern Materials Needs 5

2/ATOMIC STRUCTURE AND INTERATOMIC BONDING 7

- 2.1 Introduction 8
- Atomic Structure 8
- 2.2 Fundamental Concepts 8
- 2.3 Electrons in Atoms 9
- 2.4 The Periodic Table 15
- Atomic Bonding in Solids 16
- 2.5 Bonding Forces and Energies 16
- 2.6 Primary Interatomic Bonds 19
- 2.7 Secondary Bonding or van der Waals Bonding 23
- 2.8 Molecules 25
- Summary 25
- Important Terms and Concepts 26
- References 26
- Questions and Problems 26

3/THE STRUCTURE OF CRYSTALLINE SOLIDS 30

- 3.1 Introduction 31
- Crystal Structures 31
- 3.2 Fundamental Concepts 31
- 3.3 Unit Cells 31

- 3.4 Metallic Crystal Structures 32
- 3.5 Density Computations 37
- 3.6 Polymorphism and Allotropy 38
- 3.7 Crystal Systems 38
- Crystallographic Directions and Planes 40
- 3.8 Crystallographic Directions 40
- 3.9 Crystallographic Planes 44
- 3.10 Linear and Planar Atomic Densities 48
- 3.11 Close-Packed Crystal Structures 49
- Crystalline and Noncrystalline Materials 52
- 3.12 Single Crystals 52
- 3.13 Polycrystalline Materials 53
- 3.14 Anisotropy 54
- 3.15 X-Ray Diffraction: Determination of Crystal Structures 54
- 3.16 Noncrystalline Solids 59
- Summary 60
- Important Terms and Concepts 61
- References 62
- Questions and Problems 62

4/IMPERFECTIONS IN SOLIDS 71

- 4.1 Introduction 72
- Point Defects 72
- 4.2 Vacancies and Self-Interstitials 72
- 4.3 Impurities in Solids 74
- Miscellaneous Imperfections 76
- 4.4 Dislocations—Linear Defects 76
- 4.5 Interfacial Defects 80
- 4.6 Bulk or Volume Defects 83
- 4.7 Atomic Vibrations 83

Microscopic Examination	84
4.8 General	84
4.9 Microscopy	85
4.10 Grain Size Determination	88
Summary	89
Important Terms and Concepts	90
References	90
Questions and Problems	90

5/DIFFUSION 94

5.1 Introduction	95
5.2 Diffusion Mechanisms	96
5.3 Steady-State Diffusion	98
5.4 Nonsteady-State Diffusion	100
5.5 Factors That Influence Diffusion	104
5.6 Other Diffusion Paths	106
5.7 Materials Processing and Diffusion	106
Summary	106
Important Terms and Concepts	107
References	107
Questions and Problems	107

6/MECHANICAL PROPERTIES OF METALS 112

6.1 Introduction	113
6.2 Concepts of Stress and Strain	113
Elastic Deformation	117
6.3 Stress–Strain Behavior	117
6.4 Anelasticity	119
6.5 Elastic Properties of Materials	121
Plastic Deformation	123
6.6 Tensile Properties	124
6.7 True Stress and Strain	131
6.8 Elastic Recovery During Plastic Deformation	134
6.9 Compressive, Shear, and Torsional Deformation	134
6.10 Hardness	134
6.11 Variability of Material Properties	141
6.12 Safety Factors	142
Summary	144
Important Terms and Concepts	144
References	145
Questions and Problems	145

7/DISLOCATIONS AND STRENGTHENING MECHANISMS 155

7.1 Introduction	156
Dislocations and Plastic Deformation	156
7.2 Basic Concepts	156
7.3 Characteristics of Dislocations	159
7.4 Slip Systems	160
7.5 Slip in Single Crystals	162
7.6 Plastic Deformation of Polycrystalline Materials	165
7.7 Deformation by Twinning	166
Mechanisms of Strengthening in Metals	168
7.8 Strengthening by Grain Size Reduction	168
7.9 Solid-Solution Hardening	169
7.10 Strain Hardening	172
Recovery, Recrystallization, and Grain Growth	176
7.11 Recovery	176
7.12 Recrystallization	176
7.13 Grain Growth	181
Summary	183
Important Terms and Concepts	184
References	184
Questions and Problems	184

8/FAILURE 189

8.1 Introduction	190
Fracture	190
8.2 Fundamentals of Fracture	190
8.3 Ductile Fracture	191
8.4 Brittle Fracture	193
8.5 Principles of Fracture Mechanics	196
8.6 Impact Fracture Testing	205
Fatigue	209
8.7 Cyclic Stresses	210
8.8 The S–N Curve	210
8.9 Crack Initiation and Propagation	214
8.10 Crack Propagation Rate	218
8.11 Factors That Affect Fatigue Life	224
8.12 Environmental Effects	226
Creep	227
8.13 Generalized Creep Behavior	227
8.14 Stress and Temperature Effects	229
8.15 Data Extrapolation Methods	231

8.16 Alloys for High-Temperature Use	232
Summary	233
Important Terms and Concepts	235
References	235
Questions and Problems	236

9/PHASE DIAGRAMS 246

9.1 Introduction	247
Definitions and Basic Concepts	247
9.2 Solubility Limit	247
9.3 Phases	248
9.4 Microstructure	249
9.5 Phase Equilibria	249
Equilibrium Phase Diagrams	250
9.6 Binary Isomorphous Systems	251
9.7 Binary Eutectic Systems	258
9.8 Equilibrium Diagrams Having Intermediate Phases or Compounds	270
9.9 Eutectoid and Peritectic Reactions	272
9.10 Congruent Phase Transformations	274
9.11 Ceramic and Ternary Phase Diagrams	275
9.12 The Gibbs Phase Rule	275
The Iron–Carbon System	277
9.13 The Iron–Iron Carbide ($\text{Fe}-\text{Fe}_3\text{C}$) Phase Diagram	278
9.14 Development of Microstructures in Iron–Carbon Alloys	281
9.15 The Influence of Other Alloying Elements	289
Summary	290
Important Terms and Concepts	291
References	291
Questions and Problems	291

10/PHASE TRANSFORMATIONS IN METALS: DEVELOPMENT OF MICROSTRUCTURE AND ALTERATION OF MECHANICAL PROPERTIES 301

10.1 Introduction	302
Phase Transformations	302
10.2 Basic Concepts	302

10.3 The Kinetics of Solid-State Reactions	302
10.4 Multiphase Transformations	304
Microstructural and Property Changes in Iron–Carbon Alloys	305
10.5 Isothermal Transformation Diagrams	305
10.6 Continuous Cooling Transformation Diagrams	319
10.7 Mechanical Behavior of Iron–Carbon Alloys	322
10.8 Tempered Martensite	326
10.9 Review of Phase Transformations for Iron–Carbon Alloys	329
Summary	330
Important Terms and Concepts	331
References	331
Questions and Problems	331

11/THERMAL PROCESSING OF METAL ALLOYS 338

11.1 Introduction	339
Annealing Processes	339
11.2 Process Annealing	339
11.3 Stress Relief	339
11.4 Annealing of Ferrous Alloys	340
Heat Treatment of Steels	342
11.5 Hardenability	342
11.6 Influence of Quenching Medium, Specimen Size, and Geometry	347
Precipitation Hardening	351
11.7 Heat Treatments	351
11.8 Mechanism of Hardening	354
11.9 Miscellaneous Considerations	357
Summary	357
Important Terms and Concepts	358
References	358
Questions and Problems	358

12/METAL ALLOYS 362

12.1 Introduction	363
Fabrication of Metals	363
12.2 Forming Operations	364
12.3 Casting	365
12.4 Miscellaneous Techniques	366

Ferrous Alloys	367		
12.5 Steels	368		
12.6 Cast Irons	372		
Nonferrous Alloys	379		
12.7 Copper and Its Alloys	379		
12.8 Aluminum and Its Alloys	380		
12.9 Magnesium and Its Alloys	383		
12.10 Titanium and Its Alloys	385		
12.11 The Refractory Metals	385		
12.12 The Superalloys	385		
12.13 The Noble Metals	387		
12.14 Miscellaneous Nonferrous Alloys	387		
Summary	387		
Important Terms and Concepts	388		
References	388		
Questions and Problems	389		
14.7 Compositions of Clay Products		439	
14.8 Fabrication Techniques		439	
14.9 Drying and Firing		441	
Refractories		443	
14.10 Fireclay Refractories		444	
14.11 Silica Refractories		445	
14.12 Basic Refractories		445	
14.13 Special Refractories		445	
Other Applications and Processing Methods		445	
14.14 Abrasives		445	
14.15 Powder Pressing		447	
14.16 Cements		450	
14.17 Advanced Ceramics		451	
Summary		453	
Important Terms and Concepts		454	
References		454	
Questions and Problems		455	

13/STRUCTURES AND PROPERTIES

OF CERAMICS 392

13.1 Introduction	393	
Ceramic Structures	393	
13.2 Crystal Structures	393	
13.3 Silicate Ceramics	405	
13.4 Imperfections in Ceramics	409	
13.5 Ceramic Phase Diagrams	413	
Mechanical Properties	416	
13.6 Brittle Fracture of Ceramics	417	
13.7 Stress–Strain Behavior	419	
13.8 Mechanisms of Plastic Deformation	421	
13.9 Miscellaneous Mechanical Considerations	422	
Summary	423	
Important Terms and Concepts	424	
References	424	
Questions and Problems	425	

14/APPLICATIONS AND PROCESSING

OF CERAMICS 430

14.1 Introduction	431	
Glasses	431	
14.2 Glass Properties	432	
14.3 Glass Forming	435	
14.4 Heat Treating Glasses	437	
14.5 Glass–Ceramics	437	
Clay Products	438	
14.6 The Characteristics of Clay	439	

15/POLYMER STRUCTURES 458

15.1 Introduction	459	
15.2 Hydrocarbon Molecules	459	
15.3 Polymer Molecules	461	
15.4 The Chemistry of Polymer Molecules	462	
15.5 Molecular Weight	465	
15.6 Molecular Shape	469	
15.7 Molecular Structure	470	
15.8 Molecular Configurations	472	
15.9 Copolymers	474	
15.10 Polymer Crystallinity	476	
15.11 Polymer Crystals	478	
Summary	482	
Important Terms and Concepts	482	
References	483	
Questions and Problems	483	

16/CHARACTERISTICS, APPLICATIONS, AND PROCESSING OF POLYMERS 487

16.1 Introduction	488	
Mechanical and Thermomechanical Characteristics	488	
16.2 Stress–Strain Behavior	488	
16.3 Deformation of Semicrystalline Polymers	491	

16.4	Melting and Glass Transition Phenomena	494
16.5	thermoplastic and Thermosetting Polymers	496
16.6	Viscoelasticity	497
16.7	Deformation of Elastomers	502
16.8	Fracture of Polymers	503
16.9	Miscellaneous Characteristics	504
	Polymer Applications and Processing	506
16.10	Polymerization	506
16.11	Polymer Additives	508
16.12	Polymer Types	509
16.13	Plastics	510
16.14	Elastomers	515
16.15	Fibers	518
16.16	Miscellaneous Applications	519
	Summary	520
	Important Terms and Concepts	521
	References	521
	Questions and Problems	522

17/COMPOSITES 528

17.1	Introduction	529
	Particle-Reinforced Composites	531
17.2	Large-Particle Composites	531
17.3	Dispersion-Strengthened Composites	536
	Fiber-Reinforced Composites	536
17.4	Influence of Fiber Length	537
17.5	Influence of Fiber Orientation and Concentration	539
17.6	The Fiber Phase	545
17.7	The Matrix Phase	546
17.8	Fiberglass-Reinforced Composites	547
17.9	Miscellaneous Fiber-Reinforced Plastic Matrix Composites	548
17.10	Metal Matrix-Fiber Composites	548
17.11	Hybrid Composites	549
17.12	Processing of Fiber-Reinforced Composites	549
	Structural Composites	553
17.13	Laminar Composites	553
17.14	Sandwich Panels	554
	Summary	555
	Important Terms and Concepts	556
	References	556
	Questions and Problems	557

18/CORROSION AND DEGRADATION OF MATERIALS 562

18.1	Introduction	563
	Corrosion of Metals	563
18.2	Electrochemical Considerations	563
18.3	Corrosion Rates	570
18.4	Prediction of Corrosion Rates	572
18.5	Passivity	579
18.6	Environmental Effects	580
18.7	Forms of Corrosion	581
18.8	Corrosion Environments	589
18.9	Corrosion Prevention	589
18.10	Oxidation	592
	Corrosion of Ceramic Materials	595
	Degradation of Polymers	595
18.11	Swelling and Dissolution	596
18.12	Bond Rupture	597
18.13	Weathering	598
	Summary	599
	Important Terms and Concepts	600
	References	600
	Questions and Problems	601

19/ELECTRICAL PROPERTIES 606

19.1	Introduction	607
	Electrical Conduction	607
19.2	Ohm's Law	607
19.3	Electrical Conductivity	607
19.4	Electronic and Ionic Conduction	608
19.5	Energy Band Structures in Solids	609
19.6	Conduction in Terms of Band and Atomic Bonding Models	612
19.7	Electron Mobility	614
19.8	Electrical Resistivity of Metals	615
19.9	Electrical Characteristics of Commercial Alloys	618
	Semiconductivity	618
19.10	Intrinsic Semiconduction	618
19.11	Extrinsic Semiconduction	621
19.12	The Temperature Variation of Conductivity and Carrier Concentration	626
19.13	Semiconductor Devices	630
	Electrical Conduction in Ionic Ceramics and in Polymers	637
19.14	Conduction in Ionic Materials	638
19.15	Electrical Properties of Polymers	638

Dielectric Behavior	639
19.16 Capacitance	639
19.17 Field Vectors and Polarization	641
19.18 Types of Polarization	645
19.19 Frequency Dependence of the Dielectric Constant	647
19.20 Dielectric Strength	648
19.21 Dielectric Materials	648
Other Electrical Characteristics of Materials	649
19.22 Ferroelectricity	649
19.23 Piezoelectricity	650
Summary	651
Important Terms and Concepts	652
References	652
Questions and Problems	653

20/THERMAL PROPERTIES 659

20.1 Introduction	660
20.2 Heat Capacity	660
20.3 Thermal Expansion	663
20.4 Thermal Conductivity	665
20.5 Thermal Stresses	669
Summary	671
Important Terms and Concepts	671
References	672
Questions and Problems	672

21/MAGNETIC PROPERTIES 676

21.1 Introduction	677
21.2 Basic Concepts	677
21.3 Diamagnetism and Paramagnetism	682
21.4 Ferromagnetism	684
21.5 Antiferromagnetism and Ferrimagnetism	685
21.6 The Influence of Temperature on Magnetic Behavior	689
21.7 Domains and Hysteresis	690
21.8 Soft Magnetic Materials	693
21.9 Hard Magnetic Materials	695
21.10 Magnetic Storage	696
21.11 Superconductivity	697
Summary	701
Important Terms and Concepts	702
References	703
Questions and Problems	703

22/OPTICAL PROPERTIES 708

22.1 Introduction	709
Basic Concepts	709
22.2 Electromagnetic Radiation	709
22.3 Light Interactions with Solids	711
22.4 Atomic and Electronic Interactions	711
Optical Properties of Metals	713
Optical Properties of Nonmetals	714
22.5 Refraction	714
22.6 Reflection	716
22.7 Absorption	716
22.8 Transmission	719
22.9 Color	720
22.10 Opacity and Translucency in Insulators	722
Applications of Optical Phenomena	723
22.11 Luminescence	723
22.12 Photoconductivity	723
22.13 Lasers	724
Summary	726
Important Terms and Concepts	727
References	727
Questions and Problems	728

Appendix A/ THE INTERNATIONAL SYSTEM OF UNITS (SI) 731

Appendix B/ ELECTRON CONFIGURATIONS OF THE ELEMENTS 733

Appendix C/ PROPERTIES OF SELECTED ENGINEERING MATERIALS 737

GLOSSARY 745

ANSWERS TO SELECTED PROBLEMS 761

INDEX 767