

Contents

LIST OF SYMBOLS xxi

1. Introduction 1

- Learning Objectives 2
- 1.1 Historical Perspective 2
- 1.2 Materials Science and Engineering 2
- 1.3 Why Study Materials Science and Engineering? 4
- Case Study—Liberty Ship Failures 5
- 1.4 Classification of Materials 6
- Case Study—Carbonated Beverage Containers 11
- 1.5 Advanced Materials 12
- 1.6 Modern Materials' Needs 14
- 1.7 Processing/Structure/Properties/Performance Correlations 15
- Summary 17
- References 17
- Questions 18

2. Atomic Structure and Interatomic Bonding 19

- Learning Objectives 20
- 2.1 Introduction 20
- ATOMIC STRUCTURE 20
- 2.2 Fundamental Concepts 20
- 2.3 Electrons in Atoms 22
- 2.4 The Periodic Table 28
- ATOMIC BONDING IN SOLIDS 30
- 2.5 Bonding Forces and Energies 30
- 2.6 Primary Interatomic Bonds 32
- 2.7 Secondary Bonding or van der Waals Bonding 39
- Materials of Importance—Water (Its Volume Expansion Upon Freezing) 42
- 2.8 Mixed Bonding 43
- 2.9 Molecules 44
- 2.10 Bonding Type-Materials Classification Correlations 44
- Summary 45

- Equation Summary 46
- List of Symbols 46
- Processing/Structure/Properties/Performance Summary 47
- Important Terms and Concepts 47
- References 47
- Questions and Problems 48
- Fundamentals of Engineering Questions and Problems 50

3. The Structure of Crystalline Solids 51

- Learning Objectives 52
- 3.1 Introduction 52
- CRYSTAL STRUCTURES 52
- 3.2 Fundamental Concepts 52
- 3.3 Unit Cells 53
- 3.4 Metallic Crystal Structures 54
- 3.5 Density Computations 60
- 3.6 Polymorphism and Allotropy 60
- Materials of Importance—Tin (Its Allotropic Transformation) 61
- 3.7 Crystal Systems 62
- CRYSTALLOGRAPHIC POINTS, DIRECTIONS, AND PLANES 64
- 3.8 Point Coordinates 64
- 3.9 Crystallographic Directions 67
- 3.10 Crystallographic Planes 75
- 3.11 Linear and Planar Densities 81
- 3.12 Close-Packed Crystal Structures 82
- CRYSTALLINE AND NONCRYSTALLINE MATERIALS 84
- 3.13 Single Crystals 84
- 3.14 Polycrystalline Materials 84
- 3.15 Anisotropy 86
- 3.16 X-Ray Diffraction: Determination of Crystal Structures 87
- 3.17 Noncrystalline Solids 92
- Summary 93
- Equation Summary 95
- List of Symbols 96

<i>Processing/Structure/Properties/Performance</i>	
<i>Summary</i>	96
<i>Important Terms and Concepts</i>	97
<i>References</i>	97
<i>Questions and Problems</i>	97
<i>Fundamentals of Engineering Questions and Problems</i>	104

4. Imperfections in Solids 105

	Learning Objectives	106
4.1	Introduction	106
	POINT DEFECTS	106
4.2	Vacancies and Self-Interstitials	106
4.3	Impurities in Solids	108
4.4	Specification of Composition	111
	MISCELLANEOUS IMPERFECTIONS	115
4.5	Dislocations—Linear Defects	115
4.6	Interfacial Defects	118
	Materials of Importance—Catalysts (and Surface Defects)	121
4.7	Bulk or Volume Defects	122
4.8	Atomic Vibrations	122
	MICROSCOPIC EXAMINATION	123
4.9	Basic Concepts of Microscopy	123
4.10	Microscopic Techniques	124
4.11	Grain-Size Determination	128
	<i>Summary</i>	131
	<i>Equation Summary</i>	132
	<i>List of Symbols</i>	133
	<i>Processing/Structure/Properties/Performance Summary</i>	134
	<i>Important Terms and Concepts</i>	135
	<i>References</i>	135
	<i>Questions and Problems</i>	135
	<i>Design Problems</i>	138
	<i>Fundamentals of Engineering Questions and Problems</i>	139

5. Diffusion 140

	Learning Objectives	141
5.1	Introduction	141
5.2	Diffusion Mechanisms	142
5.3	Fick's First Law	143
5.4	Fick's Second Law—Nonsteady-State Diffusion	145
5.5	Factors That Influence Diffusion	149
5.6	Diffusion in Semiconducting Materials	154
	Material of Importance—Aluminum for Integrated Circuit Interconnects	157

5.7	Other Diffusion Paths	158
	<i>Summary</i>	158
	<i>Equation Summary</i>	159
	<i>List of Symbols</i>	160
	<i>Processing/Structure/Properties/Performance Summary</i>	160
	<i>Important Terms and Concepts</i>	162
	<i>References</i>	162
	<i>Questions and Problems</i>	162
	<i>Design Problems</i>	166
	<i>Fundamentals of Engineering Questions and Problems</i>	167

6. Mechanical Properties of Metals 168

	Learning Objectives	169
6.1	Introduction	169
6.2	Concepts of Stress and Strain	170
	ELASTIC DEFORMATION	174
6.3	Stress–Strain Behavior	174
6.4	Anelasticity	177
6.5	Elastic Properties of Materials	177
	PLASTIC DEFORMATION	180
6.6	Tensile Properties	180
6.7	True Stress and Strain	187
6.8	Elastic Recovery After Plastic Deformation	190
6.9	Compressive, Shear, and Torsional Deformation	191
6.10	Hardness	191
	PROPERTY VARIABILITY AND DESIGN/SAFETY FACTORS	197
6.11	Variability of Material Properties	197
6.12	Design/Safety Factors	199
	<i>Summary</i>	203
	<i>Equation Summary</i>	205
	<i>List of Symbols</i>	205
	<i>Processing/Structure/Properties/Performance Summary</i>	206
	<i>Important Terms and Concepts</i>	206
	<i>References</i>	207
	<i>Questions and Problems</i>	207
	<i>Design Problems</i>	213
	<i>Fundamentals of Engineering Questions and Problems</i>	214

7. Dislocations and Strengthening Mechanisms 216

	Learning Objectives	217
7.1	Introduction	217
	DISLOCATIONS AND PLASTIC DEFORMATION	217

7.2	Basic Concepts	218
7.3	Characteristics of Dislocations	220
7.4	Slip Systems	221
7.5	Slip in Single Crystals	223
7.6	Plastic Deformation of Polycrystalline Materials	226
7.7	Deformation by Twinning	228
	MECHANISMS OF STRENGTHENING IN METALS	229
7.8	Strengthening by Grain Size Reduction	229
7.9	Solid-Solution Strengthening	231
7.10	Strain Hardening	232
	RECOVERY, RECRYSTALLIZATION, AND GRAIN GROWTH	235
7.11	Recovery	235
7.12	Recrystallization	236
7.13	Grain Growth	240
	<i>Summary</i>	242
	<i>Equation Summary</i>	244
	<i>List of Symbols</i>	244
	<i>Processing/Structure/Properties/Performance Summary</i>	245
	<i>Important Terms and Concepts</i>	246
	<i>References</i>	246
	<i>Questions and Problems</i>	246
	<i>Design Problems</i>	250
	<i>Fundamentals of Engineering Questions and Problems</i>	250

8. Failure 251

	Learning Objectives	252
8.1	Introduction	252
	FRACTURE 253	
8.2	Fundamentals of Fracture	253
8.3	Ductile Fracture	253
8.4	Brittle Fracture	255
8.5	Principles of Fracture Mechanics	257
8.6	Fracture Toughness Testing	265
	FATIGUE 270	
8.7	Cyclic Stresses	270
8.8	The <i>S-N</i> Curve	272
8.9	Crack Initiation and Propagation	276
8.10	Factors That Affect Fatigue Life	278
8.11	Environmental Effects	280
	CREEP 281	
8.12	Generalized Creep Behavior	281
8.13	Stress and Temperature Effects	282
8.14	Data Extrapolation Methods	285
8.15	Alloys for High-Temperature Use	286
	<i>Summary</i>	287

<i>Equation Summary</i>	290
<i>List of Symbols</i>	290
<i>Important Terms and Concepts</i>	291
<i>References</i>	291
<i>Questions and Problems</i>	291
<i>Design Problems</i>	295
<i>Fundamentals of Engineering Questions and Problems</i>	296

9. Phase Diagrams 297

	Learning Objectives	298
9.1	Introduction	298
	DEFINITIONS AND BASIC CONCEPTS 298	
9.2	Solubility Limit	299
9.3	Phases	300
9.4	Microstructure	300
9.5	Phase Equilibria	300
9.6	One-Component (or Unary) Phase Diagrams	301
	BINARY PHASE DIAGRAMS 302	
9.7	Binary Isomorphous Systems	303
9.8	Interpretation of Phase Diagrams	305
9.9	Development of Microstructure in Isomorphous Alloys	309
9.10	Mechanical Properties of Isomorphous Alloys	312
9.11	Binary Eutectic Systems	312
9.12	Development of Microstructure in Eutectic Alloys	318
	Materials of Importance—Lead-Free Solders	319
9.13	Equilibrium Diagrams Having Intermediate Phases or Compounds	325
9.14	Eutectoid and Peritectic Reactions	328
9.15	Congruent Phase Transformations	329
9.16	Ceramic and Ternary Phase Diagrams	330
9.17	The Gibbs Phase Rule	330
	THE IRON-CARBON SYSTEM 333	
9.18	The Iron-Iron Carbide ($\text{Fe-Fe}_3\text{C}$) Phase Diagram	333
9.19	Development of Microstructure in Iron-Carbon Alloys	336
9.20	The Influence of Other Alloying Elements	344
	<i>Summary</i>	344
	<i>Equation Summary</i>	346
	<i>List of Symbols</i>	347
	<i>Processing/Structure/Properties/Performance Summary</i>	347
	<i>Important Terms and Concepts</i>	349

References	349
Questions and Problems	349
Fundamentals of Engineering Questions and Problems	355

10. Phase Transformations: Development of Microstructure and Alteration of Mechanical Properties 356

Learning Objectives	357
10.1 Introduction	357
PHASE TRANSFORMATIONS	357
10.2 Basic Concepts	357
10.3 The Kinetics of Phase Transformations	358
10.4 Metastable Versus Equilibrium States	369
MICROSTRUCTURAL AND PROPERTY CHANGES IN IRON-CARBON ALLOYS	370
10.5 Isothermal Transformation Diagrams	370
10.6 Continuous-Cooling Transformation Diagrams	381
10.7 Mechanical Behavior of Iron-Carbon Alloys	384
10.8 Tempered Martensite	388
10.9 Review of Phase Transformations and Mechanical Properties for Iron-Carbon Alloys	391
Materials of Importance—Shape-Memory Alloys	394
Summary	397
Equation Summary	398
List of Symbols	399
Processing/Structure/Properties/Performance Summary	399
Important Terms and Concepts	401
References	402
Questions and Problems	402
Design Problems	406
Fundamentals of Engineering Questions and Problems	406

11. Applications and Processing of Metal Alloys 408

Learning Objectives	409
11.1 Introduction	409
TYPES OF METAL ALLOYS	410
11.2 Ferrous Alloys	410
11.3 Nonferrous Alloys	422
Materials of Importance—Metal Alloys Used for Euro Coins	433
FABRICATION OF METALS	434
11.4 Forming Operations	434

11.5 Casting	436
11.6 Miscellaneous Techniques	437
THERMAL PROCESSING OF METALS	439
11.7 Annealing Processes	439
11.8 Heat Treatment of Steels	441
11.9 Precipitation Hardening	451
Summary	458
Processing/Structure/Properties/Performance Summary	460
Important Terms and Concepts	460
References	463
Questions and Problems	463
Design Problems	464
Fundamentals of Engineering Questions and Problems	466

12. Structures and Properties of Ceramics 467

Learning Objectives	468
12.1 Introduction	468
CERAMIC STRUCTURES	468
12.2 Crystal Structures	469
12.3 Silicate Ceramics	477
12.4 Carbon	481
12.5 Imperfections in Ceramics	482
12.6 Diffusion in Ionic Materials	486
12.7 Ceramic Phase Diagrams	487
MECHANICAL PROPERTIES	490
12.8 Brittle Fracture of Ceramics	491
12.9 Stress-Strain Behavior	495
12.10 Mechanisms of Plastic Deformation	497
12.11 Miscellaneous Mechanical Considerations	499
Summary	501
Equation Summary	503
List of Symbols	503
Processing/Structure/Properties/Performance Summary	503
Important Terms and Concepts	504
References	505
Questions and Problems	505
Design Problems	509
Fundamentals of Engineering Questions and Problems	509

13. Applications and Processing of Ceramics 510

Learning Objectives	511
13.1 Introduction	511
TYPES AND APPLICATIONS OF CERAMICS	512

13.2	Glasses	512
13.3	Glass–Ceramics	512
13.4	Clay Products	514
13.5	Refractories	514
13.6	Abrasives	516
13.7	Cements	517
13.8	Carbons	518
13.9	Advanced Ceramics	521
	FABRICATION AND PROCESSING OF CERAMICS	525
13.10	Fabrication and Processing of Glasses and Glass–Ceramics	526
13.11	Fabrication and Processing of Clay Products	531
13.12	Powder Pressing	535
13.13	Tape Casting	537
	<i>Summary</i>	538
	<i>Processing/Structure/Properties/Performance Summary</i>	540
	<i>Important Terms and Concepts</i>	542
	<i>References</i>	543
	<i>Questions and Problems</i>	543
	<i>Design Problem</i>	544
	<i>Fundamentals of Engineering Questions and Problems</i>	544

14. Polymer Structures 545

	Learning Objectives	546
14.1	Introduction	546
14.2	Hydrocarbon Molecules	546
14.3	Polymer Molecules	549
14.4	The Chemistry of Polymer Molecules	549
14.5	Molecular Weight	553
14.6	Molecular Shape	556
14.7	Molecular Structure	558
14.8	Molecular Configurations	559
14.9	Thermoplastic and Thermosetting Polymers	562
14.10	Copolymers	563
14.11	Polymer Crystallinity	564
14.12	Polymer Crystals	568
14.13	Defects in Polymers	570
14.14	Diffusion in Polymeric Materials	571
	<i>Summary</i>	573
	<i>Equation Summary</i>	575
	<i>List of Symbols</i>	575
	<i>Processing/Structure/Properties/Performance Summary</i>	575
	<i>Important Terms and Concepts</i>	576
	<i>References</i>	576
	<i>Questions and Problems</i>	577
	<i>Fundamentals of Engineering Questions and Problems</i>	579

15. Characteristics, Applications, and Processing of Polymers 580

	Learning Objectives	581
15.1	Introduction	581
	MECHANICAL BEHAVIOR OF POLYMERS	581
15.2	Stress–Strain Behavior	581
15.3	Macroscopic Deformation	584
15.4	Viscoelastic Deformation	584
15.5	Fracture of Polymers	588
15.6	Miscellaneous Mechanical Characteristics	590
	MECHANISMS OF DEFORMATION AND FOR STRENGTHENING OF POLYMERS	591
15.7	Deformation of Semicrystalline Polymers	591
15.8	Factors That Influence the Mechanical Properties of Semicrystalline Polymers	593
	Materials of Importance—Shrink-Wrap Polymer Films	597
15.9	Deformation of Elastomers	597
	CRYSTALLIZATION, MELTING, AND GLASS-TRANSITION PHENOMENA IN POLYMERS	599
15.10	Crystallization	600
15.11	Melting	601
15.12	The Glass Transition	601
15.13	Melting and Glass Transition Temperatures	601
15.14	Factors That Influence Melting and Glass Transition Temperatures	603
	POLYMER TYPES	605
15.15	Plastics	605
	Materials of Importance—Phenolic Billiard Balls	607
15.16	Elastomers	608
15.17	Fibers	610
15.18	Miscellaneous Applications	610
15.19	Advanced Polymeric Materials	612
	POLYMER SYNTHESIS AND PROCESSING	616
15.20	Polymerization	616
15.21	Polymer Additives	618
15.22	Forming Techniques for Plastics	620
15.23	Fabrication of Elastomers	622
15.24	Fabrication of Fibers and Films	622
	<i>Summary</i>	624
	<i>Equation Summary</i>	626
	<i>List of Symbols</i>	626
	<i>Processing/Structure/Properties/Performance Summary</i>	626

<i>Important Terms and Concepts</i>	629
<i>References</i>	629
<i>Questions and Problems</i>	629
<i>Design Questions</i>	633
<i>Fundamentals of Engineering Question</i>	633

16. Composites 634

Learning Objectives	635
16.1 Introduction	635
PARTICLE-REINFORCED COMPOSITES	637
16.2 Large-Particle Composites	637
16.3 Dispersion-Strengthened Composites	641
FIBER-REINFORCED COMPOSITES	642
16.4 Influence of Fiber Length	642
16.5 Influence of Fiber Orientation and Concentration	643
16.6 The Fiber Phase	651
16.7 The Matrix Phase	653
16.8 Polymer-Matrix Composites	653
16.9 Metal-Matrix Composites	659
16.10 Ceramic-Matrix Composites	660
16.11 Carbon-Carbon Composites	662
16.12 Hybrid Composites	662
16.13 Processing of Fiber-Reinforced Composites	663
STRUCTURAL COMPOSITES	665
16.14 Laminar Composites	665
16.15 Sandwich Panels	667
Case Study—Use of Composites in the Boeing 787 Dreamliner	669
16.16 Nanocomposites	670
Summary	673
Equation Summary	675
List of Symbols	676
Important Terms and Concepts	676
References	676
Questions and Problems	676
Design Problems	679
Fundamentals of Engineering Questions and Problems	680

17. Corrosion and Degradation of Materials 681

Learning Objectives	682
17.1 Introduction	682
CORROSION OF METALS	683
17.2 Electrochemical Considerations	683
17.3 Corrosion Rates	689
17.4 Prediction of Corrosion Rates	691

17.5 Passivity	698
17.6 Environmental Effects	699
17.7 Forms of Corrosion	699
17.8 Corrosion Environments	707
17.9 Corrosion Prevention	707
17.10 Oxidation	709

CORROSION OF CERAMIC MATERIALS 712

DEGRADATION OF POLYMERS 713

17.11 Swelling and Dissolution	713
17.12 Bond Rupture	715
17.13 Weathering	716
Summary	717
Equation Summary	719
List of Symbols	719
Important Terms and Concepts	720
References	720
Questions and Problems	721
Design Problems	723
Fundamentals of Engineering Questions and Problems	724

18. Electrical Properties 725

Learning Objectives	726
18.1 Introduction	726
ELECTRICAL CONDUCTION	726
18.2 Ohm's Law	726
18.3 Electrical Conductivity	727
18.4 Electronic and Ionic Conduction	728
18.5 Energy Band Structures in Solids	728
18.6 Conduction in Terms of Band and Atomic Bonding Models	730
18.7 Electron Mobility	732
18.8 Electrical Resistivity of Metals	733
18.9 Electrical Characteristics of Commercial Alloys	736
Materials of Importance—Aluminum Electrical Wires	736
SEMICONDUCTIVITY	738
18.10 Intrinsic Semiconduction	738
18.11 Extrinsic Semiconduction	741
18.12 The Temperature Dependence of Carrier Concentration	744
18.13 Factors That Affect Carrier Mobility	745
18.14 The Hall Effect	749
18.15 Semiconductor Devices	751
ELECTRICAL CONDUCTION IN IONIC CERAMICS AND IN POLYMERS	757
18.16 Conduction in Ionic Materials	758

18.17	Electrical Properties of Polymers	758
	DIELECTRIC BEHAVIOR	759
18.18	Capacitance	759
18.19	Field Vectors and Polarization	761
18.20	Types of Polarization	764
18.21	Frequency Dependence of the Dielectric Constant	766
18.22	Dielectric Strength	767
18.23	Dielectric Materials	767
	OTHER ELECTRICAL CHARACTERISTICS OF MATERIALS	767
18.24	Ferroelectricity	767
18.25	Piezoelectricity	768
	Materials of Importance—Piezoelectric Ceramic Ink-Jet Printer Heads	769
	Summary	770
	Equation Summary	773
	List of Symbols	774
	Processing/Structure/Properties/Performance Summary	774
	Important Terms and Concepts	778
	References	778
	Questions and Problems	778
	Design Problems	782
	Fundamentals of Engineering Questions and Problems	783

19. Thermal Properties 785

	Learning Objectives	786
19.1	Introduction	786
19.2	Heat Capacity	786
19.3	Thermal Expansion	790
	Materials of Importance—Invar and Other Low-Expansion Alloys	792
19.4	Thermal Conductivity	793
19.5	Thermal Stresses	796
	Summary	798
	Equation Summary	799
	List of Symbols	799
	Important Terms and Concepts	800
	References	800
	Questions and Problems	800
	Design Problems	802
	Fundamentals of Engineering Questions and Problems	802

20. Magnetic Properties 803

	Learning Objectives	804
20.1	Introduction	804
20.2	Basic Concepts	804

20.3	Diamagnetism and Paramagnetism	808
20.4	Ferromagnetism	810
20.5	Antiferromagnetism and Ferrimagnetism	811
20.6	The Influence of Temperature on Magnetic Behavior	815
20.7	Domains and Hysteresis	816
20.8	Magnetic Anisotropy	819
20.9	Soft Magnetic Materials	820
	Materials of Importance—An Iron-Silicon Alloy Used in Transformer Cores	821
20.10	Hard Magnetic Materials	822
20.11	Magnetic Storage	825
20.12	Superconductivity	828
	Summary	831
	Equation Summary	833
	List of Symbols	833
	Important Terms and Concepts	834
	References	834
	Questions and Problems	834
	Design Problems	837
	Fundamentals of Engineering Questions and Problems	837

21. Optical Properties 838

	Learning Objectives	839
21.1	Introduction	839
	BASIC CONCEPTS	839
21.2	Electromagnetic Radiation	839
21.3	Light Interactions with Solids	841
21.4	Atomic and Electronic Interactions	842
	OPTICAL PROPERTIES OF METALS	843
	OPTICAL PROPERTIES OF NONMETALS	844
21.5	Refraction	844
21.6	Reflection	846
21.7	Absorption	846
21.8	Transmission	850
21.9	Color	850
21.10	Opacity and Translucency in Insulators	852
	APPLICATIONS OF OPTICAL PHENOMENA	853
21.11	Luminescence	853
21.12	Photoconductivity	853
	Materials of Importance—Light-Emitting Diodes	854
21.13	Lasers	856
21.14	Optical Fibers in Communications	860

Summary	862
Equation Summary	864
List of Symbols	865
Important Terms and Concepts	865
References	865
Questions and Problems	866
Design Problem	867
Fundamentals of Engineering Questions and Problems	867

22. Economic, Environmental, and Societal Issues in Materials Science and Engineering 868

Learning Objectives	869
22.1 Introduction	869
ECONOMIC CONSIDERATIONS	869
22.2 Component Design	870
22.3 Materials	870
22.4 Manufacturing Techniques	870
ENVIRONMENTAL AND SOCIETAL CONSIDERATIONS	871
22.5 Recycling Issues in Materials Science and Engineering	873
Materials of Importance—Biodegradable and Biorenewable Polymers/Plastics	876
Summary	878
References	879
Design Questions	879

Appendix A The International System of Units (SI) 880

Appendix B Properties of Selected Engineering Materials 882

B.1	Density	882
B.2	Modulus of Elasticity	885
B.3	Poisson's Ratio	889
B.4	Strength and Ductility	890
B.5	Plane Strain Fracture Toughness	895
B.6	Linear Coefficient of Thermal Expansion	897
B.7	Thermal Conductivity	900
B.8	Specific Heat	903
B.9	Electrical Resistivity	906
B.10	Metal Alloy Compositions	909

Appendix C Costs and Relative Costs for Selected Engineering Materials 911

Appendix D Repeat Unit Structures for Common Polymers 916

Appendix E Glass Transition and Melting Temperatures for Common Polymeric Materials 920

Glossary 921

Answers to Selected Problems 934

Index 939