Contents

LIST OF SYMBOLS xvii

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
Case Study—Liberty Ship Failures 6
1.4 Classification of Materials 7
Case Study—Carbonated Beverage Containers 12
1.5 Advanced Materials 14
1.6 Modern Materials' Needs 16
Summary 17
References 18
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-Material Classification Correlations 44
Summary 45
Equation Summary 46
List of Symbols 46
Important Terms and Concepts 46
References 47
Questions and Problems 47

3. The Structure of Crystalline Solids 49

Learning Objectives 50
3.1 Introduction 50
CRYSTAL STRUCTURES 50
3.2 Fundamental Concepts 50
3.3 Unit Cells 51
3.4 Metallic Crystal Structures 52
3.5 Density Computations 58
3.6 Polymorphism and Allotropy 58
Material of Importance—Tin (Its Allotropic Transformation) 59
3.7 Crystal Systems 60
CRYSTALLOGRAPHIC POINTS, DIRECTIONS, AND PLANES 62
3.8 Crystallographic Points 62
3.9 Crystallographic Directions 65
3.10 Crystallographic Planes 71
3.11 Linear and Planar Densities 77
3.12 Close-Packed Crystal Structures 78
CRYSTALLINE AND NONCRYSTALLINE MATERIALS 80
3.13 Single Crystals 80
3.14 Polycrystalline Materials 80
3.15 Anisotropy 82
3.16 X-Ray Diffraction: Determination of Crystal Structures 83
3.17 Noncrystalline Solids 88
Summary 89
Equation Summary 91
List of Symbols 91
Important Terms and Concepts 92
References 92
Questions and Problems 92

4. Imperfections in Solids 97

Learning Objectives 98
4.1 Introduction 98
POINT DEFECTS 98
4.2 Vacancies and Self-Interstitials 98
4.3 Impurities in Solids 100
4.4 Specification of Composition 103
MISCELLANEOUS IMPERFECTIONS 107
4.5 Dislocations—Linear Defects 107
4.6 Interfacial Defects 110
Materials of Importance—Catalysts (and Surface Defects) 113
4.7 Bulk or Volume Defects 114
4.8 Atomic Vibrations 114
MICROSCOPIC EXAMINATION 115
4.9 Basic Concepts of Microscopy 115
4.10 Microscopic Techniques 116
4.11 Grain-Size Determination 120
Summary 123
Equation Summary 124
List of Symbols 125
Important Terms and Concepts 125
References 125
Questions and Problems 126

5. Diffusion 129

Learning Objectives 130
5.1 Introduction 130
5.2 Diffusion Mechanisms 131
5.3 Fick's First Law 132
5.4 Fick's Second Law—Nonsteady-State Diffusion 134
5.5 Factors That Influence Diffusion 138
5.6 Diffusion in Semiconducting Materials 143
Materials of Importance—Aluminum for Integrated Circuit Interconnects 146
5.7 Other Diffusion Paths 147
Summary 147
Equation Summary 148
List of Symbols 149
Important Terms and Concepts 149
References 149
Questions and Problems 149

6. Mechanical Properties of Metals 154

Learning Objectives 155
6.1 Introduction 155
6.2 Concepts of Stress and Strain 156
ELASTIC DEFORMATION 160
6.3 Stress–Strain Behavior 160
6.4 Anelasticity 163
6.5 Elastic Properties of Materials 163
PLASTIC DEFORMATION 166
6.6 Tensile Properties 166
6.7 True Stress and Strain 173
6.8 Elastic Recovery After Plastic Deformation 176
6.9 Compressive, Shear, and Torsional Deformations 177
6.10 Hardness 177
PROPERTY VARIABILITY AND DESIGN/SAFETY FACTORS 183
6.11 Variability of Material Properties 183
6.12 Design/Safety Factors 185
Summary 189
Equation Summary 190
List of Symbols 191
Important Terms and Concepts 191
References 191
Questions and Problems 192

7. Dislocations and Strengthening Mechanisms 196

Learning Objectives 197
7.1 Introduction 197
DISLOCATIONS AND PLASTIC DEFORMATION 197
7.2 Basic Concepts 198
7.3 Characteristics of Dislocations 200
7.4 Slip Systems 201
7.5 Slip in Single Crystals 203
7.6 Plastic Deformation of Polycrystalline Materials 206
7.7 Deformation by Twinning 208
MECHANISMS OF STRENGTHENING IN METALS 209
7.8 Strengthening by Grain Size Reduction 209
7.9 Solid-Solution Strengthening 211
7.10 Strain Hardening 212
RECOVERY, RECRYSTALLIZATION, AND GRAIN GROWTH 215
7.11 Recovery 215
7.12 Recrystallization 216
7.13 Grain Growth 220
Summary 222
Equation Summary 224
List of Symbols 224
Important Terms and Concepts 224
References 224
Questions and Problems 225

8. Failure 227

Learning Objectives 228
8.1 Introduction 228

FRACTURE 229

8.2 Fundamentals of Fracture 229
8.3 Ductile Fracture 229
8.4 Brittle Fracture 231
8.5 Principles of Fracture Mechanics 233
8.6 Fracture Toughness Testing 242

FATIGUE 247

8.7 Cyclic Stresses 247
8.8 The *S–N* Curve 249
8.9 Crack Initiation and Propagation 253
8.10 Factors That Affect Fatigue Life 255
8.11 Environmental Effects 257

CREEP 258

8.12 Generalized Creep Behavior 258
8.13 Stress and Temperature Effects 259
8.14 Data Extrapolation Methods 262
8.15 Alloys for High-Temperature Use 263
Summary 264
Equation Summary 266
List of Symbols 267
Important Terms and Concepts 267
References 267
Questions and Problems 268

9. Phase Diagrams 271

Learning Objectives 272
9.1 Introduction 272

DEFINITIONS AND BASIC CONCEPTS 272

9.2 Solubility Limit 273
9.3 Phases 274
9.4 Microstructure 274
9.5 Phase Equilibria 274
9.6 One-Component (or Unary) Phase Diagrams 275

BINARY PHASE DIAGRAMS 276

9.7 Binary Isomorphous Systems 277
9.8 Interpretation of Phase Diagrams 279
9.9 Development of Microstructure in Isomorphous Alloys 283
9.10 Mechanical Properties of Isomorphous Alloys 286
9.11 Binary Eutectic Systems 286
9.12 Development of Microstructure in Eutectic Alloys 292
Materials of Importance—Lead-Free Solders 293
9.13 Equilibrium Diagrams Having Intermediate Phases or Compounds 299
9.14 Eutectoid and Peritectic Reactions 302
9.15 Congruent Phase Transformations 303
9.16 Ceramic and Ternary Phase Diagrams 304
9.17 The Gibbs Phase Rule 304

THE IRON–CARBON SYSTEM 307

9.18 The Iron–Iron Carbide (Fe–Fe_3C) Phase Diagram 307
9.19 Development of Microstructure in Iron–Carbon Alloys 310
9.20 The Influence of Other Alloying Elements 318
Summary 318
Equation Summary 320
List of Symbols 321
Important Terms and Concepts 321
References 322
Questions and Problems 322

10. Phase Transformations: Development of Microstructure and Alteration of Mechanical Properties 327

Learning Objectives 328
10.1 Introduction 328

PHASE TRANSFORMATIONS 328

10.2 Basic Concepts 328
10.3 The Kinetics of Phase Transformations 329
10.4 Metastable Versus Equilibrium States 340

MICROSTRUCTURAL AND PROPERTY CHANGES IN IRON–CARBON ALLOYS 341

10.5 Isothermal Transformation Diagrams 341
10.6 Continuous-Cooling Transformation Diagrams 352
10.7 Mechanical Behavior of Iron–Carbon Alloys 355
10.8 Tempered Martensite 359
10.9 Review of Phase Transformations and Mechanical Properties for Iron–Carbon Alloys 362
Materials of Importance—Shape-Memory Alloys 365
Summary 368
Equation Summary 369
List of Symbols 370
Important Terms and Concepts 370
References 370
Questions and Problems 371

11. Applications and Processing of Metal Alloys 375

Learning Objectives 376
11.1 Introduction 376

TYPES OF METAL ALLOYS 377

11.2 Ferrous Alloys 377
11.3 Nonferrous Alloys 389
Materials of Importance—Metal Alloys Used for Euro Coins 400

FABRICATION OF METALS 401

11.4 Forming Operations 401
11.5 Casting 403
11.6 Miscellaneous Techniques 404
11.7 3D Printing (Additive Manufacturing) 406

THERMAL PROCESSING OF METALS 410

11.8 Annealing Processes 410
11.9 Heat Treatment of Steels 412
11.10 Precipitation Hardening 422
Summary 429
Important Terms and Concepts 431
References 431
Questions and Problems 432

12. Structures and Properties of Ceramics 435

Learning Objectives 436
12.1 Introduction 436

CERAMIC STRUCTURES 436

12.2 Crystal Structures 437
12.3 Silicate Ceramics 445
12.4 Carbon 449
12.5 Imperfections in Ceramics 450
12.6 Diffusion in Ionic Materials 454
12.7 Ceramic Phase Diagrams 455

MECHANICAL PROPERTIES 458

12.8 Brittle Fracture of Ceramics 459
12.9 Stress–Strain Behavior 463
12.10 Mechanisms of Plastic Deformation 465
12.11 Miscellaneous Mechanical Considerations 467
Summary 469
Equation Summary 470
List of Symbols 471
Important Terms and Concepts 471
References 471
Questions and Problems 471

13. Applications and Processing of Ceramics 474

Learning Objectives 475
13.1 Introduction 475

TYPES AND APPLICATIONS OF CERAMICS 476

13.2 Glasses 476
13.3 Glass–Ceramics 476
13.4 Clay Products 478
13.5 Refractories 478
13.6 Abrasives 481
13.7 Cements 483
13.8 Ceramic Biomaterials 484
13.9 Carbons 485
13.10 Advanced Ceramics 488

FABRICATION AND PROCESSING OF CERAMICS 493

13.11 Fabrication and Processing of Glasses and Glass–Ceramics 494
13.12 Fabrication and Processing of Clay Products 498
13.13 Powder Pressing 503
13.14 Tape Casting 505
13.15 3D Printing of Ceramic Materials 506
Summary 508
Important Terms and Concepts 510
References 510
Questions and Problems 511

14. Polymer Structures 512

Learning Objectives 513
14.1 Introduction 513
14.2 Hydrocarbon Molecules 513
14.3 Polymer Molecules 516
14.4 The Chemistry of Polymer Molecules 516
14.5 Molecular Weight 520
14.6 Molecular Shape 523
14.7 Molecular Structure 525
14.8 Molecular Configurations 526
14.9 Thermoplastic and Thermosetting Polymers 529
14.10 Copolymers 530
14.11 Polymer Crystallinity 531
14.12 Polymer Crystals 535
14.13 Defects in Polymers 537
14.14 Diffusion in Polymeric Materials 538
Summary 540
Equation Summary 542
List of Symbols 542
Important Terms and Concepts 542
References 543
Questions and Problems 543

15. Characteristics, Applications, and Processing of Polymers 545

Learning Objectives 546
15.1 Introduction 546

MECHANICAL BEHAVIOR OF POLYMERS 546

15.2 Stress–Strain Behavior 546
15.3 Macroscopic Deformation 549
15.4 Viscoelastic Deformation 549
15.5 Fracture of Polymers 553
15.6 Miscellaneous Mechanical Characteristics 555

MECHANISMS OF DEFORMATION AND FOR STRENGTHENING OF POLYMERS 556

15.7 Deformation of Semicrystalline Polymers 556
15.8 Factors That Influence the Mechanical Properties of Semicrystalline Polymers 558
Materials of Importance—Shrink-Wrap Polymer Films 562
15.9 Deformation of Elastomers 562

CRYSTALLIZATION, MELTING, AND GLASS-TRANSITION PHENOMENA IN POLYMERS 564

15.10 Crystallization 565
15.11 Melting 566
15.12 The Glass Transition 566
15.13 Melting and Glass Transition Temperatures 566
15.14 Factors That Influence Melting and Glass Transition Temperatures 568

POLYMER TYPES 570

15.15 Plastics 570
Materials of Importance—Phenolic Billiard Balls 573
15.16 Elastomers 573
15.17 Fibers 575
15.18 Miscellaneous Applications 576
15.19 Polymeric Biomaterials 577
15.20 Advanced Polymeric Materials 579

POLYMER SYNTHESIS AND PROCESSING 583

15.21 Polymerization 583
15.22 Polymer Additives 585
15.23 Forming Techniques for Plastics 587
15.24 Fabrication of Elastomers 589
15.25 Fabrication of Fibers and Films 589
15.26 3D Printing of Polymers 591
Summary 593
Equation Summary 596
List of Symbols 596
Important Terms and Concepts 596
References 597
Questions and Problems 597

16. Composites 600

Learning Objectives 601
16.1 Introduction 601

PARTICLE-REINFORCED COMPOSITES 603

16.2 Large-Particle Composites 603
16.3 Dispersion-Strengthened Composites 607

FIBER-REINFORCED COMPOSITES 608

16.4 Influence of Fiber Length 608
16.5 Influence of Fiber Orientation and Concentration 609
16.6 The Fiber Phase 617
16.7 The Matrix Phase 619
16.8 Polymer-Matrix Composites 619
16.9 Metal-Matrix Composites 625
16.10 Ceramic-Matrix Composites 626
16.11 Carbon–Carbon Composites 628
16.12 Hybrid Composites 628
16.13 Processing of Fiber-Reinforced Composites 629

STRUCTURAL COMPOSITES 631

16.14 Laminar Composites 631
16.15 Sandwich Panels 633
Case Study—Use of Composites in the Boeing 787 Dreamliner 635
16.16 Nanocomposites 636
Summary 638
Equation Summary 641
List of Symbols 642
Important Terms and Concepts 642
References 642
Questions and Problems 643

17. Corrosion and Degradation of Materials 645

Learning Objectives 646
17.1 Introduction 646

CORROSION OF METALS 647

17.2 Electrochemical Considerations 647
17.3 Corrosion Rates 653
17.4 Prediction of Corrosion Rates 655
17.5 Passivity 662
17.6 Environmental Effects 663
17.7 Forms of Corrosion 663
17.8 Corrosion Environments 671

17.9 Corrosion Prevention 671
17.10 Oxidation 674

CORROSION OF CERAMIC MATERIALS 677

DEGRADATION OF POLYMERS 677

17.11 Swelling and Dissolution 678
17.12 Bond Rupture 680
17.13 Weathering 681
Summary 682
Equation Summary 684
List of Symbols 684
Important Terms and Concepts 685
References 685
Questions and Problems 686

18. Electrical Properties 688

Learning Objectives 689
18.1 Introduction 689

ELECTRICAL CONDUCTION 689

18.2 Ohm's Law 689
18.3 Electrical Conductivity 690
18.4 Electronic and Ionic Conduction 691
18.5 Energy Band Structures in Solids 691
18.6 Conduction in Terms of Band and Atomic Bonding Models 693
18.7 Electron Mobility 695
18.8 Electrical Resistivity of Metals 696
18.9 Electrical Characteristics of Commercial Alloys 699

SEMICONDUCTIVITY 699

18.10 Intrinsic Semiconduction 699
18.11 Extrinsic Semiconduction 702
18.12 The Temperature Dependence of Carrier Concentration 705
18.13 Factors That Affect Carrier Mobility 707
18.14 The Hall Effect 711
18.15 Semiconductor Devices 713

ELECTRICAL CONDUCTION IN IONIC CERAMICS AND IN POLYMERS 719

18.16 Conduction in Ionic Materials 720
18.17 Electrical Properties of Polymers 720

DIELECTRIC BEHAVIOR 721

18.18 Capacitance 721
18.19 Field Vectors and Polarization 723
18.20 Types of Polarization 726
18.21 Frequency Dependence of the Dielectric Constant 728
18.22 Dielectric Strength 729
18.23 Dielectric Materials 729

OTHER ELECTRICAL CHARACTERISTICS OF MATERIALS 729

18.24 Ferroelectricity 729
18.25 Piezoelectricity 730
Material of Importance—Piezoelectric Ceramic Ink-Jet Printer Heads 731
Summary 732
Equation Summary 735
List of Symbols 736
Important Terms and Concepts 736
References 737
Questions and Problems 737

19. Thermal Properties 741

Learning Objectives 742
19.1 Introduction 742
19.2 Heat Capacity 742
19.3 Thermal Expansion 746
Materials of Importance—Invar and Other Low-Expansion Alloys 748
19.4 Thermal Conductivity 749
19.5 Thermal Stresses 752
Summary 754
Equation Summary 755
List of Symbols 755
Important Terms and Concepts 756
References 756
Questions and Problems 756

20. Magnetic Properties 758

Learning Objectives 759
20.1 Introduction 759
20.2 Basic Concepts 759
20.3 Diamagnetism and Paramagnetism 763
20.4 Ferromagnetism 765
20.5 Antiferromagnetism and Ferrimagnetism 766
20.6 The Influence of Temperature on Magnetic Behavior 770
20.7 Domains and Hysteresis 771
20.8 Magnetic Anisotropy 774
20.9 Soft Magnetic Materials 775
Materials of Importance—An Iron–Silicon Alloy Used in Transformer Cores 776
20.10 Hard Magnetic Materials 777
20.11 Magnetic Storage 780
20.12 Superconductivity 783
Summary 786
Equation Summary 788
List of Symbols 788

Important Terms and Concepts 789
References 789
Questions and Problems 789

21. Optical Properties 792

Learning Objectives 793
21.1 Introduction 793
BASIC CONCEPTS 793
21.2 Electromagnetic Radiation 793
21.3 Light Interactions with Solids 795
21.4 Atomic and Electronic Interactions 796
OPTICAL PROPERTIES OF METALS 797
OPTICAL PROPERTIES OF NONMETALS 798
21.5 Refraction 798
21.6 Reflection 800
21.7 Absorption 800
21.8 Transmission 804
21.9 Color 804
21.10 Opacity and Translucency in Insulators 806
APPLICATIONS OF OPTICAL PHENOMENA 807
21.11 Luminescence 807
21.12 Photoconductivity 807
Materials of Importance—Light-Emitting Diodes 808
21.13 Lasers 810
21.14 Optical Fibers in Communications 814
Summary 816
Equation Summary 818
List of Symbols 819
Important Terms and Concepts 819
References 820
Questions and Problems 820

22. Environmental and Societal Issues in Materials Science and Engineering 822

Learning Objectives 823
22.1 Introduction 823
22.2 Environmental and Societal Considerations 823
22.3 Recycling Issues in Materials Science and Engineering 826
Materials of Importance—Biodegradable and Biorenewable Polymers/ Plastics 831
Summary 833
References 833
Design Questions 834

Appendix A The International System of Units (SI) A-1

Appendix B Properties of Selected Engineering Materials A-3

B.1 Density A-3
B.2 Modulus of Elasticity A-6
B.3 Poisson's Ratio A-10
B.4 Strength and Ductility A-11
B.5 Plane Strain Fracture Toughness A-16
B.6 Linear Coefficient of Thermal Expansion A-18
B.7 Thermal Conductivity A-21
B.8 Specific Heat A-24
B.9 Electrical Resistivity A-27
B.10 Metal Alloy Compositions A-30

Appendix C Costs and Relative Costs for Selected Engineering Materials A-32

Appendix D Repeat Unit Structures for Common Polymers A-37

Appendix E Glass Transition and Melting Temperatures for Common Polymeric Materials A-41

Glossary G-1

Answers to Selected Problems PA-1

Index I-1