

We express our appreciation to those who have made contributions to this edition. We are especially indebted to Michael Salkind of Kent State University, who provided assistance in updating and upgrading important material in several chapters. In addition, we appreciate Grant E. Head's expert programming skills, which he used in developing the *Virtual Materials Science and Engineering* software. In addition, we thank instructors who helped review the manuscript and reviewed and wrote content for *WileyPLUS*. We thank others who have made valuable contributions:

- Arvind Agarwal, *Florida International University*
- Sayavur I. Bakhtiyarov, *New Mexico Institute of Mining and Technology*
- Prabhakar Bandaru, *University of California-San Diego*
- Valery Bliznyuk, *Western Michigan University*
- Suzette R. Burckhard, *South Dakota State University*
- Stephen J. Burns, *University of Rochester*
- Audrey Butler, *University of Iowa*
- Matthew Cavalli, *University of North Dakota*
- Alexis G. Clare, *Alfred University*
- Stacy Gleixner, *San José State University*
- Ginette Guinois, *Dubois Agrinovation*
- Richard A. Jensen, *Hofstra University*
- Bob Jones, *University of Texas, Pan American*
- Molly Kennedy, *Clemson University*
- Kathleen Kitto, *Western Washington University*
- Chuck Kozlowski, *University of Iowa*
- Masoud Naghodolfeizi, *Fort Valley State University*
- Todd Palmer, *Penn State University*
- Oscar J. Parales-Perez, *University of Puerto Rico at Mayaguez*
- Bob Philipps, *Fujifilm USA*
- Don Rasmussen, *Clarkson University*
- Sandie Rawnsey, *Murdoch University*
- Wynn A. Ray, *San José State University*
- Hans J. Richter, *Seagate Recording Media*
- Joe Smith, *Black Diamond Equipment*
- Jeffrey J. Swab, *U.S. Military Academy*
- Cindy Waters, *North Carolina Agricultural and Technical State University*
- Yaroslava G. Yingling, *North Carolina State University*

We are also indebted to Jennifer Welter, Sponsoring Editor, for her assistance and guidance on this revision.

Last, but certainly not least, we deeply and sincerely appreciate the continual encouragement and support of our families and friends.

WILLIAM D. CALLISTER, JR.

DAVID G. RETHWISCH

LIST OF SYMBOLS xxiii

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
- 1.4 Classification of Materials 5
- Materials of Importance—Carbonated Beverage Containers 9
- 1.5 Advanced Materials 10
- 1.6 Modern Materials Needs 12
- 1.7 Processing/Structure/Properties/Performance Correlations 13
- Summary 15
- References 16
- Question 16

2. Atomic Structure and Interatomic Bonding 17

- Learning Objectives 18
- 2.1 Introduction 18
- ATOMIC STRUCTURE 18
- 2.2 Fundamental Concepts 18
- 2.3 Electrons in Atoms 19
- 2.4 The Periodic Table 25
- ATOMIC BONDING IN SOLIDS 26
- 2.5 Bonding Forces and Energies 26
- 2.6 Primary Interatomic Bonds 28
- 2.7 Secondary Bonding or van der Waals Bonding 32
- Materials of Importance—Water (Its Volume Expansion Upon Freezing) 34
- 2.8 Molecules 35
- Summary 35
- Equation Summary 36
- Processing/Structure/Properties/Performance Summary 36
- Important Terms and Concepts 37
- References 37

Questions and Problems 37

Fundamentals of Engineering Questions and Problems 39

3. Structures of Metals and Ceramics 40

- Learning Objectives 41
- 3.1 Introduction 41
- CRYSTAL STRUCTURES 42
- 3.2 Fundamental Concepts 42
- 3.3 Unit Cells 42
- 3.4 Metallic Crystal Structures 43
- 3.5 Density Computations—Metals 47
- 3.6 Ceramic Crystal Structures 48
- 3.7 Density Computations—Ceramics 54
- 3.8 Silicate Ceramics 55
- 3.9 Carbon 59
- Materials of Importance—Carbon Nanotubes 60
- 3.10 Polymorphism and Allotropy 61
- 3.11 Crystal Systems 61
- Material of Importance—Tin (Its Allotropic Transformation) 63
- CRYSTALLOGRAPHIC POINTS, DIRECTIONS, AND PLANES 64
- 3.12 Point Coordinates 64
- 3.13 Crystallographic Directions 66
- 3.14 Crystallographic Planes 72
- 3.15 Linear and Planar Densities 76
- 3.16 Close-Packed Crystal Structures 77
- CRYSTALLINE AND NONCRYSTALLINE MATERIALS 81
- 3.17 Single Crystals 81
- 3.18 Polycrystalline Materials 81
- 3.19 Anisotropy 81
- 3.20 X-Ray Diffraction: Determination of Crystal Structures 83
- 3.21 Noncrystalline Solids 87
- Summary 89
- Equation Summary 91
- Processing/Structure/Properties/Performance Summary 92

Important Terms and Concepts	93
References	94
Questions and Problems	94
Fundamentals of Engineering Questions and Problems	101

4. Polymer Structures 102

Learning Objectives	103
4.1 Introduction	103
4.2 Hydrocarbon Molecules	103
4.3 Polymer Molecules	105
4.4 The Chemistry of Polymer Molecules	106
4.5 Molecular Weight	111
4.6 Molecular Shape	113
4.7 Molecular Structure	115
4.8 Molecular Configurations	116
4.9 Thermoplastic and Thermosetting Polymers	120
4.10 Copolymers	121
4.11 Polymer Crystallinity	122
4.12 Polymer Crystals	125
Summary	128
Equation Summary	129
Processing/Structure/Properties/Performance Summary	130
Important Terms and Concepts	130
References	131
Questions and Problems	131
Fundamentals of Engineering Questions and Problems	133

5. Imperfections in Solids 134

Learning Objectives	135
5.1 Introduction	135
POINT DEFECTS	136
5.2 Point Defects in Metals	136
5.3 Point Defects in Ceramics	137
5.4 Impurities in Solids	140
5.5 Point Defects in Polymers	143
5.6 Specification of Composition	143
MISCELLANEOUS IMPERFECTIONS	147
5.7 Dislocations—Linear Defects	147
5.8 Interfacial Defects	150
5.9 Bulk or Volume Defects	153
5.10 Atomic Vibrations	153
MICROSCOPIC EXAMINATION	153
5.11 Basic Concepts of Microscopy	153
Materials of Importance—Catalysts (and Surface Defects)	154
5.12 Microscopic Techniques	155

5.13 Grain Size Determination	159
Summary	161
Equation Summary	163
Processing/Structure/Properties/Performance Summary	164
Important Terms and Concepts	165
References	165
Questions and Problems	165
Design Problems	169
Fundamentals of Engineering Questions and Problems	169

6. Diffusion 170

Learning Objectives	171
6.1 Introduction	171
6.2 Diffusion Mechanisms	172
6.3 Steady-State Diffusion	173
6.4 Nonsteady-State Diffusion	175
6.5 Factors That Influence Diffusion	179
6.6 Diffusion in Semiconducting Materials	184
Material of Importance—Aluminum for Integrated Circuit Interconnects	187
6.7 Other Diffusion Paths	188
6.8 Diffusion in Ionic and Polymeric Materials	188
Summary	191
Equation Summary	192
Processing/Structure/Properties/Performance Summary	193
Important Terms and Concepts	194
References	195
Questions and Problems	195
Design Problems	198
Fundamentals of Engineering Questions and Problems	199

7. Mechanical Properties 200

Learning Objectives	201
7.1 Introduction	201
7.2 Concepts of Stress and Strain	202
ELASTIC DEFORMATION	205
7.3 Stress–Strain Behavior	205
7.4 Anelasticity	209
7.5 Elastic Properties of Materials	209
MECHANICAL BEHAVIOR—METALS	211
7.6 Tensile Properties	212
7.7 True Stress and Strain	219
7.8 Elastic Recovery After Plastic Deformation	222
7.9 Compressive, Shear, and Torsional Deformation	222

MECHANICAL BEHAVIOR—CERAMICS 223

7.10 Flexural Strength	223
7.11 Elastic Behavior	224
7.12 Influence of Porosity on the Mechanical Properties of Ceramics	224

MECHANICAL BEHAVIOR—POLYMERS 226

7.13 Stress–Strain Behavior	226
7.14 Macroscopic Deformation	228
7.15 Viscoelastic Deformation	229

HARDNESS AND OTHER MECHANICAL PROPERTY CONSIDERATIONS 233

7.16 Hardness	233
7.17 Hardness of Ceramic Materials	238
7.18 Tear Strength and Hardness of Polymers	239

PROPERTY VARIABILITY AND DESIGN/SAFETY FACTORS 239

7.19 Variability of Material Properties	239
7.20 Design/Safety Factors	242
Summary	243
Equation Summary	246
Processing/Structure/Properties/Performance Summary	248
Important Terms and Concepts	249
References	250
Questions and Problems	250
Design Problems	258
Fundamentals of Engineering Questions and Problems	259

8. Deformation and Strengthening Mechanisms 260

8.1 Learning Objectives	261
Introduction	261
DEFORMATION MECHANISMS FOR METALS	261
8.2 Historical	262
8.3 Basic Concepts of Dislocations	262
8.4 Characteristics of Dislocations	264
8.5 Slip Systems	265
8.6 Slip in Single Crystals	267
8.7 Plastic Deformation of Polycrystalline Metals	270
8.8 Deformation by Twinning	272
MECHANISMS OF STRENGTHENING IN METALS	273
8.9 Strengthening by Grain Size Reduction	273
8.10 Solid-Solution Strengthening	275
8.11 Strain Hardening	276

RECOVERY, RECRYSTALLIZATION, AND GRAIN GROWTH 279

8.12 Recovery	279
8.13 Recrystallization	280
8.14 Grain Growth	284

DEFORMATION MECHANISMS FOR CERAMIC MATERIALS 285

8.15 Crystalline Ceramics	285
8.16 Noncrystalline Ceramics	286
MECHANISMS OF DEFORMATION AND FOR STRENGTHENING OF POLYMERS 287	287
Deformation of Semicrystalline Polymers	287
Factors That Influence the Mechanical Properties of Semicrystalline Polymers	290
Materials of Importance—Shrink-Wrap Polymer Films	292
Deformation of Elastomers	293
Summary	295
Equation Summary	298
Processing/Structure/Properties/Performance Summary	299
Important Terms and Concepts	302
References	302
Questions and Problems	302
Design Problems	307
Fundamentals of Engineering Questions and Problems	307

9. Failure 308

9.1 Learning Objectives	309
Introduction	309
FRACTURE	310
9.2 Fundamentals of Fracture	310
9.3 Ductile Fracture	310
9.4 Brittle Fracture	312
9.5 Principles of Fracture Mechanics	314
9.6 Brittle Fracture of Ceramics	322
9.7 Fracture of Polymers	326
9.8 Fracture Toughness Testing	328
FATIGUE	332
9.9 Cyclic Stresses	333
9.10 The S-N Curve	334
9.11 Fatigue in Polymeric Materials	337
9.12 Crack Initiation and Propagation	337
9.13 Factors That Affect Fatigue Life	339
9.14 Environmental Effects	341
CREEP	342
9.15 Generalized Creep Behavior	343

9.16	Stress and Temperature Effects	344
9.17	Data Extrapolation Methods	346
9.18	Alloys for High-Temperature Use	347
9.19	Creep in Ceramic and Polymeric Materials	347
	Summary	348
	Equation Summary	351
	Important Terms and Concepts	352
	References	352
	Questions and Problems	352
	Design Problems	357
	Fundamentals of Engineering Questions and Problems	357

10. Phase Diagrams 359

10.1	Learning Objectives	360
	Introduction	360
	DEFINITIONS AND BASIC CONCEPTS	360
10.2	Solubility Limit	361
10.3	Phases	362
10.4	Microstructure	362
10.5	Phase Equilibria	362
10.6	One-Component (or Unary) Phase Diagrams	363
	BINARY PHASE DIAGRAMS	365
10.7	Binary Isomorphous Systems	365
10.8	Interpretation of Phase Diagrams	367
10.9	Development of Microstructure in Isomorphous Alloys	371
10.10	Mechanical Properties of Isomorphous Alloys	374
10.11	Binary Eutectic Systems	374
10.12	Development of Microstructure in Eutectic Alloys	380
	Materials of Importance—Lead-Free Solders	381
10.13	Equilibrium Diagrams Having Intermediate Phases or Compounds	387
10.14	Eutectoid and Peritectic Reactions	390
10.15	Congruent Phase Transformations	391
10.16	Ceramic Phase Diagrams	391
10.17	Ternary Phase Diagrams	395
10.18	The Gibbs Phase Rule	396
	THE IRON-CARBON SYSTEM	398
10.19	The Iron-Iron Carbide (Fe-Fe ₃ C) Phase Diagram	398
10.20	Development of Microstructure in Iron-Carbon Alloys	401
10.21	The Influence of Other Alloying Elements	408
	Summary	409

	Equation Summary	411
	Processing/Structure/Properties/Performance Summary	412
	Important Terms and Concepts	412
	References	414
	Questions and Problems	414
	Fundamentals of Engineering Questions and Problems	420

11. Phase Transformations 421

11.1	Learning Objectives	422
	Introduction	422
	PHASE TRANSFORMATIONS IN METALS	422
11.2	Basic Concepts	423
11.3	The Kinetics of Phase Transformations	423
11.4	Metastable Versus Equilibrium States	433
	MICROSTRUCTURAL AND PROPERTY CHANGES IN IRON-CARBON ALLOYS	434
11.5	Isothermal Transformation Diagrams	434
11.6	Continuous-Cooling Transformation Diagrams	445
11.7	Mechanical Behavior of Iron-Carbon Alloys	448
11.8	Tempered Martensite	452
11.9	Review of Phase Transformations and Mechanical Properties for Iron-Carbon Alloys	455
	Materials of Importance—Shape-Memory Alloys	456
	PRECIPITATION HARDENING	459
11.10	Heat Treatments	459
11.11	Mechanism of Hardening	461
11.12	Miscellaneous Considerations	464
	CRYSTALLIZATION, MELTING, AND GLASS TRANSITION PHENOMENA IN POLYMERS	464
11.13	Crystallization	464
11.14	Melting	465
11.15	The Glass Transition	466
11.16	Melting and Glass Transition Temperatures	466
11.17	Factors That Influence Melting and Glass Transition Temperatures	467
	Summary	469
	Equation Summary	472
	Processing/Structure/Properties/Performance Summary	473
	Important Terms and Concepts	475
	References	475
	Questions and Problems	476

	Design Problems	480
	Fundamentals of Engineering Questions and Problems	481

12. Electrical Properties 483

12.1	Learning Objectives	484
	Introduction	484
	ELECTRICAL CONDUCTION	484
12.2	Ohm's Law	484
12.3	Electrical Conductivity	485
12.4	Electronic and Ionic Conduction	486
12.5	Energy Band Structures in Solids	486
12.6	Conduction in Terms of Band and Atomic Bonding Models	488
12.7	Electron Mobility	490
12.8	Electrical Resistivity of Metals	491
12.9	Electrical Characteristics of Commercial Alloys	494
	Materials of Importance—Aluminum Electrical Wires	494
	SEMICONDUCTIVITY	496
12.10	Intrinsic Semiconduction	496
12.11	Extrinsic Semiconduction	499
12.12	The Temperature Dependence of Carrier Concentration	502
12.13	Factors That Affect Carrier Mobility	503
12.14	The Hall Effect	507
12.15	Semiconductor Devices	509
	ELECTRICAL CONDUCTION IN IONIC CERAMICS AND IN POLYMERS	515
12.16	Conduction in Ionic Materials	516
12.17	Electrical Properties of Polymers	516
	DIELECTRIC BEHAVIOR	517
12.18	Capacitance	517
12.19	Field Vectors and Polarization	519
12.20	Types of Polarization	522
12.21	Frequency Dependence of the Dielectric Constant	524
12.22	Dielectric Strength	525
12.23	Dielectric Materials	525
	OTHER ELECTRICAL CHARACTERISTICS OF MATERIALS	525
12.24	Ferroelectricity	525
12.25	Piezoelectricity	526
	Summary	527
	Equation Summary	530
	Processing/Structure/Properties/Performance Summary	531
	Important Terms and Concepts	535

	References	535
	Questions and Problems	535
	Design Problems	539
	Fundamentals of Engineering Questions and Problems	540

13. Types and Applications of Materials 542

	Learning Objectives	543
13.1	Introduction	543
	TYPES OF METAL ALLOYS	543
13.2	Ferrous Alloys	543
13.3	Nonferrous Alloys	556
	Materials of Importance—Metal Alloys Used for Euro Coins	565
	TYPES OF CERAMICS	566
13.4	Glasses	567
13.5	Glass-Ceramics	567
13.6	Clay Products	569
13.7	Refractories	569
13.8	Abrasives	571
13.9	Cements	571
13.10	Advanced Ceramics	573
	Materials of Importance—Piezoelectric Ceramics	575
13.11	Diamond and Graphite	576
	TYPES OF POLYMERS	577
13.12	Plastics	577
	Materials of Importance—Phenolic Billiard Balls	580
13.13	Elastomers	580
13.14	Fibers	582
13.15	Miscellaneous Applications	583
13.16	Advanced Polymeric Materials	584
	Summary	588
	Processing/Structure/Properties/Performance Summary	590
	Important Terms and Concepts	592
	References	592
	Questions and Problems	592
	Design Questions	593
	Fundamentals of Engineering Questions and Problems	594

14. Synthesis, Fabrication, and Processing of Materials 595

14.1	Learning Objectives	596
	Introduction	596
	FABRICATION OF METALS	596

14.2	Forming Operations	597
14.3	Casting	598
14.4	Miscellaneous Techniques	600
	THERMAL PROCESSING OF METALS	601
14.5	Annealing Processes	601
14.6	Heat Treatment of Steels	604
	FABRICATION OF CERAMIC MATERIALS	613
14.7	Fabrication and Processing of Glasses and Glass-Ceramics	615
14.8	Fabrication and Processing of Clay Products	620
14.9	Powder Pressing	624
14.10	Tape Casting	626
	SYNTHESIS AND FABRICATION OF POLYMERS	627
14.11	Polymerization	627
14.12	Polymer Additives	630
14.13	Forming Techniques for Plastics	631
14.14	Fabrication of Elastomers	634
14.15	Fabrication of Fibers and Films	634
	<i>Summary</i>	635
	<i>Processing/Structure/Properties/Performance Summary</i>	637
	<i>Important Terms and Concepts</i>	641
	<i>References</i>	642
	<i>Questions and Problems</i>	642
	<i>Design Problems</i>	644
	<i>Fundamentals of Engineering Questions and Problems</i>	645

15. Composites 646

15.1	Learning Objectives	647
	Introduction	647
	PARTICLE-REINFORCED COMPOSITES	649
15.2	Large-Particle Composites	649
15.3	Dispersion-Strengthened Composites	653
	FIBER-REINFORCED COMPOSITES	653
15.4	Influence of Fiber Length	654
15.5	Influence of Fiber Orientation and Concentration	655
15.6	The Fiber Phase	663
15.7	The Matrix Phase	665
15.8	Polymer-Matrix Composites	665
15.9	Metal-Matrix Composites	671
15.10	Ceramic-Matrix Composites	672
15.11	Carbon-Carbon Composites	674
15.12	Hybrid Composites	674

15.13	Processing of Fiber-Reinforced Composites	675
	STRUCTURAL COMPOSITES	677
15.14	Laminar Composites	677
15.15	Sandwich Panels	678
	Materials of Importance—Nanocomposite Barrier Coatings	679
	<i>Summary</i>	681
	<i>Equation Summary</i>	683
	<i>Important Terms and Concepts</i>	684
	<i>References</i>	684
	<i>Questions and Problems</i>	684
	<i>Design Problems</i>	687
	<i>Fundamentals of Engineering Questions and Problems</i>	688

16. Corrosion and Degradation of Materials 689

16.1	Learning Objectives	690
	Introduction	690
	CORROSION OF METALS	691
16.2	Electrochemical Considerations	691
16.3	Corrosion Rates	697
16.4	Prediction of Corrosion Rates	699
16.5	Passivity	705
16.6	Environmental Effects	706
16.7	Forms of Corrosion	707
16.8	Corrosion Environments	714
16.9	Corrosion Prevention	715
16.10	Oxidation	717
	CORROSION OF CERAMIC MATERIALS	720
	DEGRADATION OF POLYMERS	720
16.11	Swelling and Dissolution	720
16.12	Bond Rupture	722
16.13	Weathering	724
	<i>Summary</i>	724
	<i>Equation Summary</i>	726
	<i>Important Terms and Concepts</i>	728
	<i>References</i>	728
	<i>Questions and Problems</i>	728
	<i>Design Problems</i>	731
	<i>Fundamentals of Engineering Questions and Problems</i>	732

17. Thermal Properties 733

17.1	Learning Objectives	734
17.2	Introduction	734
17.3	Heat Capacity	734
	Thermal Expansion	738

	Materials of Importance—Invar and Other Low-Expansion Alloys	740
17.4	Thermal Conductivity	741
17.5	Thermal Stresses	744
	<i>Summary</i>	746
	<i>Equation Summary</i>	747
	<i>Important Terms and Concepts</i>	748
	<i>References</i>	748
	<i>Questions and Problems</i>	748
	<i>Design Problems</i>	750
	<i>Fundamentals of Engineering Questions and Problems</i>	750

18. Magnetic Properties 751

	Learning Objectives	752
18.1	Introduction	752
18.2	Basic Concepts	752
18.3	Diamagnetism and Paramagnetism	756
18.4	Ferromagnetism	758
18.5	Antiferromagnetism and Ferrimagnetism	759
18.6	The Influence of Temperature on Magnetic Behavior	763
18.7	Domains and Hysteresis	764
18.8	Magnetic Anisotropy	767
18.9	Soft Magnetic Materials	768
	Materials of Importance—An Iron–Silicon Alloy That Is Used in Transformer Cores	769
18.10	Hard Magnetic Materials	770
18.11	Magnetic Storage	773
18.12	Superconductivity	776
	<i>Summary</i>	779
	<i>Equation Summary</i>	781
	<i>Important Terms and Concepts</i>	782
	<i>References</i>	782
	<i>Questions and Problems</i>	782
	<i>Design Problems</i>	785
	<i>Fundamentals of Engineering Questions and Problems</i>	785

19. Optical Properties 786

19.1	Learning Objectives	787
	Introduction	787
	BASIC CONCEPTS	787
19.2	Electromagnetic Radiation	787
19.3	Light Interactions With Solids	789
19.4	Atomic and Electronic Interactions	790
	OPTICAL PROPERTIES OF METALS	791
	OPTICAL PROPERTIES OF NONMETALS	792
19.5	Refraction	792

19.6	Reflection	794
19.7	Absorption	794
19.8	Transmission	798
19.9	Color	798
19.10	Opacity and Translucency in Insulators	800
	APPLICATIONS OF OPTICAL PHENOMENA	801
19.11	Luminescence	801
19.12	Photoconductivity	801
	Materials of Importance—Light-Emitting Diodes	802
19.13	Lasers	804
19.14	Optical Fibers in Communications	808
	<i>Summary</i>	810
	<i>Equation Summary</i>	812
	<i>Important Terms and Concepts</i>	813
	<i>References</i>	813
	<i>Questions and Problems</i>	814
	<i>Design Problem</i>	815
	<i>Fundamentals of Engineering Questions and Problems</i>	815

20. Economic, Environmental, and Societal Issues in Materials Science and Engineering 816

	Learning Objectives	817
20.1	Introduction	817
	ECONOMIC CONSIDERATIONS	817
20.2	Component Design	818
20.3	Materials	818
20.4	Manufacturing Techniques	818
	ENVIRONMENTAL AND SOCIETAL CONSIDERATIONS	819
20.5	Recycling Issues in Materials Science and Engineering	821
	Materials of Importance—Biodegradable and Biorenewable Polymers/Plastics	824
	<i>Summary</i>	826
	<i>References</i>	827
	<i>Design Questions</i>	827

Appendix A The International System of Units (SI) 828

	Appendix B Properties of Selected Engineering Materials	830
B.1	Density	830
B.2	Modulus of Elasticity	833
B.3	Poisson's Ratio	837
B.4	Strength and Ductility	838

B.5	Plane Strain Fracture Toughness	843
B.6	Linear Coefficient of Thermal Expansion	845
B.7	Thermal Conductivity	848
B.8	Specific Heat	851
B.9	Electrical Resistivity	854
B.10	Metal Alloy Compositions	857

Appendix C	Costs and Relative Costs for Selected Engineering Materials	859
-------------------	--	------------

Appendix D	Repeat Unit Structures for Common Polymers	864
-------------------	---	------------

Appendix E Glass Transition and Melting Temperatures for Common Polymeric Materials 868

Mechanical Engineering Online Support Module



Library of Case Studies



Glossary 869

Answers to Selected Problems 882

Index 886

List of Symbols

The number of the section in which a symbol is introduced or explained is given in parentheses.

A = area	\mathcal{E} = electric field intensity (12.3)
\AA = angstrom unit	E_f = Fermi energy (12.5)
A_i = atomic weight of element i (2.2)	E_g = band gap energy (12.6)
APF = atomic packing factor (3.4)	$E_r(t)$ = relaxation modulus (7.15)
a = lattice parameter: unit cell x -axial length (3.4)	%EL = ductility, in percent elongation (7.6)
a = crack length of a surface crack (9.5)	e = electric charge per electron (12.7)
at% = atom percent (5.6)	e^- = electron (16.2)
B = magnetic flux density (induction) (18.2)	erf = Gaussian error function (6.4)
B_r = magnetic remanence (18.7)	$\exp = e$, the base for natural logarithms
BCC = body-centered cubic crystal structure (3.4)	F = force, interatomic or mechanical (2.5, 7.2)
b = lattice parameter: unit cell y -axial length (3.11)	\mathcal{F} = Faraday constant (16.2)
\mathbf{b} = Burgers vector (5.7)	FCC = face-centered cubic crystal structure (3.4)
C = capacitance (12.18)	G = shear modulus (7.3)
C_i = concentration (composition) of component i in wt% (5.6)	H = magnetic field strength (18.2)
C'_i = concentration (composition) of component i in at% (5.6)	H_c = magnetic coercivity (18.7)
C_v, C_p = heat capacity at constant volume, pressure (17.2)	HB = Brinell hardness (7.16)
CPR = corrosion penetration rate (16.3)	HCP = hexagonal close-packed crystal structure (3.4)
CVN = Charpy V-notch (9.8)	HK = Knoop hardness (7.16)
%CW = percent cold work (8.11)	HRB, HRF = Rockwell hardness: B and F scales (7.16)
c = lattice parameter: unit cell z -axial length (3.11)	HR15N, HR45W = superficial Rockwell hardness: 15N and 45W scales (7.16)
c_v, c_p = specific heat at constant volume, pressure (17.2)	HV = Vickers hardness (7.16)
D = diffusion coefficient (6.3)	h = Planck's constant (19.2)
D = dielectric displacement (12.19)	(hkl) = Miller indices for a crystallographic plane (3.14)
DP = degree of polymerization (4.5)	I = electric current (12.2)
d = diameter	I = intensity of electromagnetic radiation (19.3)
d = average grain diameter (8.9)	i = current density (16.3)
d_{hkl} = interplanar spacing for planes of Miller indices h, k , and l (3.20)	i_c = corrosion current density (16.4)
E = energy (2.5)	
E = modulus of elasticity or Young's modulus (7.3)	