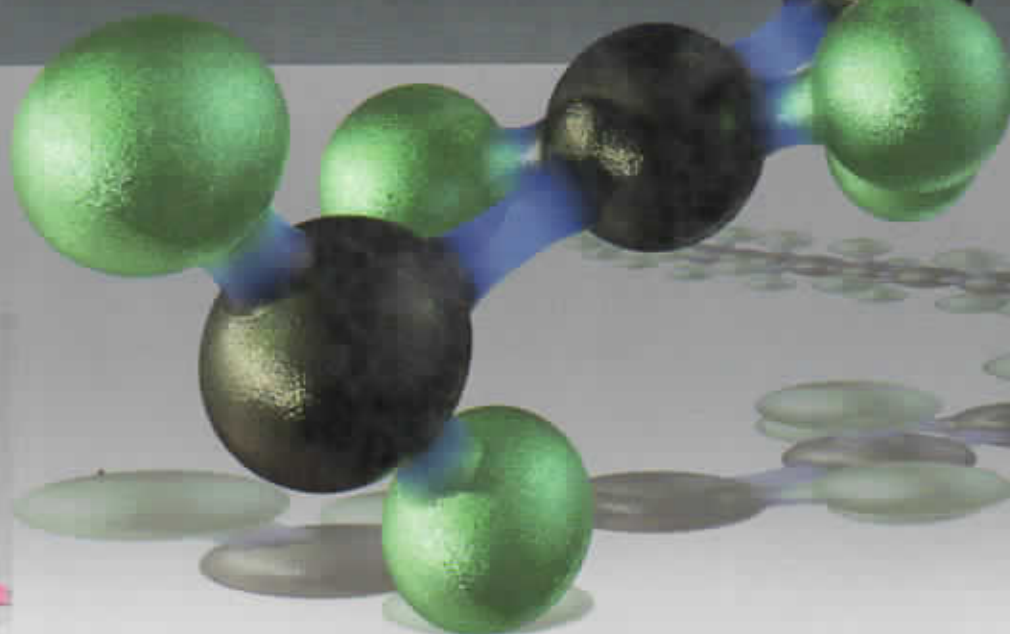


William D. Callister, Jr.

David G. Rethwisch

Fundamentals of  
**Materials Science  
and Engineering**

4th Edition



**SI Version**

## 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



<i>Important Terms and Concepts</i>	93
<i>References</i>	94
<i>Questions and Problems</i>	94
<i>Fundamentals of Engineering Questions and Problems</i>	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
<i>Summary</i>	128
<i>Equation Summary</i>	129
<i>Processing/Structure/Properties/Performance Summary</i>	130
<i>Important Terms and Concepts</i>	130
<i>References</i>	131
<i>Questions and Problems</i>	131
<i>Fundamentals of Engineering Questions and Problems</i>	133

#### **5. Imperfections in Solids 134**

Learning Objectives	135
5.1 Introduction	135
<b>POINT DEFECTS</b>	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
<b>MISCELLANEOUS IMPERFECTIONS</b>	147
5.7 Dislocations—Linear Defects	147
5.8 Interfacial Defects	150
5.9 Bulk or Volume Defects	153
5.10 Atomic Vibrations	153
<b>MICROSCOPIC EXAMINATION</b>	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
<i>Summary</i>	161
<i>Equation Summary</i>	163
<i>Processing/Structure/Properties/Performance Summary</i>	164
<i>Important Terms and Concepts</i>	165
<i>References</i>	165
<i>Questions and Problems</i>	165
<i>Design Problems</i>	169
<i>Fundamentals of Engineering Questions and Problems</i>	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
<i>Summary</i>	191
<i>Equation Summary</i>	192
<i>Processing/Structure/Properties/Performance Summary</i>	193
<i>Important Terms and Concepts</i>	194
<i>References</i>	195
<i>Questions and Problems</i>	195
<i>Design Problems</i>	198
<i>Fundamentals of Engineering Questions and Problems</i>	199

#### **7. Mechanical Properties 200**

Learning Objectives	201
7.1 Introduction	201
7.2 Concepts of Stress and Strain	202
<b>ELASTIC DEFORMATION</b>	205
7.3 Stress–Strain Behavior	205
7.4 Anelasticity	209
7.5 Elastic Properties of Materials	209
<b>MECHANICAL BEHAVIOR—METALS</b>	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

	<b>MECHANICAL BEHAVIOR—CERAMICS 223</b>				
7.10	Flexural Strength 223				
7.11	Elastic Behavior 224				
7.12	Influence of Porosity on the Mechanical Properties of Ceramics 224				
	<b>MECHANICAL BEHAVIOR—POLYMERS 226</b>				
7.13	Stress–Strain Behavior 226				
7.14	Macroscopic Deformation 228				
7.15	Viscoelastic Deformation 229				
	<b>HARDNESS AND OTHER MECHANICAL PROPERTY CONSIDERATIONS 233</b>				
7.16	Hardness 233				
7.17	Hardness of Ceramic Materials 238				
7.18	Tear Strength and Hardness of Polymers 239				
	<b>PROPERTY VARIABILITY AND DESIGN/SAFETY FACTORS 239</b>				
7.19	Variability of Material Properties 239				
7.20	Design/Safety Factors 242				
	<i>Summary 243</i>				
	<i>Equation Summary 246</i>				
	<i>Processing/Structure/Properties/Performance Summary 248</i>				
	<i>Important Terms and Concepts 249</i>				
	<i>References 250</i>				
	<i>Questions and Problems 250</i>				
	<i>Design Problems 258</i>				
	<i>Fundamentals of Engineering Questions and Problems 259</i>				
<b>8.</b>	<b><i>Deformation and Strengthening Mechanisms 260</i></b>				
	Learning Objectives 261				
8.1	Introduction 261				
	<b>DEFORMATION MECHANISMS FOR METALS 261</b>				
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				
	<b>MECHANISMS OF STRENGTHENING IN METALS 273</b>				
8.9	Strengthening by Grain Size Reduction 273				
8.10	Solid-Solution Strengthening 275				
8.11	Strain Hardening 276				
					<b>RECOVERY, RECRYSTALLIZATION, AND GRAIN GROWTH 279</b>
		8.12	Recovery 279		
		8.13	Recrystallization 280		
		8.14	Grain Growth 284		
			<b>DEFORMATION MECHANISMS FOR CERAMIC MATERIALS 285</b>		
		8.15	Crystalline Ceramics 285		
		8.16	Noncrystalline Ceramics 286		
			<b>MECHANISMS OF DEFORMATION AND FOR STRENGTHENING OF POLYMERS 287</b>		
		8.17	Deformation of Semicrystalline Polymers 287		
		8.18	Factors That Influence the Mechanical Properties of Semicrystalline Polymers 290		
			Materials of Importance—Shrink-Wrap Polymer Films 292		
		8.19	Deformation of Elastomers 293		
			<i>Summary 295</i>		
			<i>Equation Summary 298</i>		
			<i>Processing/Structure/Properties/Performance Summary 299</i>		
			<i>Important Terms and Concepts 302</i>		
			<i>References 302</i>		
			<i>Questions and Problems 302</i>		
			<i>Design Problems 307</i>		
			<i>Fundamentals of Engineering Questions and Problems 307</i>		
		<b>9.</b>	<b><i>Failure 308</i></b>		
			Learning Objectives 309		
		9.1	Introduction 309		
			<b>FRACTURE 310</b>		
		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		
			<b>FATIGUE 332</b>		
		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		
			<b>CREEP 342</b>		
		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**

	Learning Objectives	360
10.1	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 <sub>3</sub> 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**

	Learning Objectives	422
11.1	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**

- Learning Objectives 484
- 12.1 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**

- Learning Objectives 596
- 14.1 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  
*Summary 635*  
*Processing/Structure/Properties/Performance Summary 637*  
*Important Terms and Concepts 641*  
*References 642*  
*Questions and Problems 642*  
*Design Problems 644*  
*Fundamentals of Engineering Questions and Problems 645*
- 15. Composites 646**
- Learning Objectives 647  
 15.1 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 664  
 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  
*Summary 681*  
*Equation Summary 683*  
*Important Terms and Concepts 684*  
*References 684*  
*Questions and Problems 684*  
*Design Problems 687*  
*Fundamentals of Engineering Questions and Problems 688*
- 16. Corrosion and Degradation of Materials 689**
- Learning Objectives 690  
 16.1 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  
*Summary 724*  
*Equation Summary 726*  
*Important Terms and Concepts 728*  
*References 728*  
*Questions and Problems 728*  
*Design Problems 731*  
*Fundamentals of Engineering Questions and Problems 732*
- 17. Thermal Properties 733**
- Learning Objectives 734  
 17.1 Introduction 734  
 17.2 Heat Capacity 734  
 17.3 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**

	Learning Objectives	787
19.1	Introduction	787
	<b>BASIC CONCEPTS</b>	787
19.2	Electromagnetic Radiation	787
19.3	Light Interactions With Solids	789
19.4	Atomic and Electronic Interactions	790
	<b>OPTICAL PROPERTIES OF METALS</b>	791
	<b>OPTICAL PROPERTIES OF NONMETALS</b>	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
	<b>APPLICATIONS OF OPTICAL PHENOMENA</b>	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
	<b>ECONOMIC CONSIDERATIONS</b>	817
20.2	Component Design	818
20.3	Materials	818
20.4	Manufacturing Techniques	818
	<b>ENVIRONMENTAL AND SOCIETAL CONSIDERATIONS</b>	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***

Page numbers in *italics> refer to the glossary.*

- A**
- Abrasive ceramics, 566, 571
  - Abrasives, 869
  - Absorption coefficient, 797
  - Absorption of light:
    - in metals, 791–792
    - in nonmetals, 792–800
  - Absorptivity, 790
  - ABS polymer, 578
  - $A_m B_n X_p$  crystal structures, 57
  - Acceptors, 500, 869
  - Acetic acid, 106
  - Acetylene, 104
  - Acid rain, as corrosion environment, 714
  - Acids (organic), 106
  - Acid slags, 570
  - Acrylics, *see* Poly(methyl methacrylate)
  - Acrylonitrile, *see* Polyacrylonitrile (PAN)
  - Acrylonitrile-butadiene rubber, 581
  - Acrylonitrile-butadiene-styrene (ABS), 578
  - Activation energy, 869
    - for creep, 345
    - for diffusion, 180, 426
    - free, 425, 429
    - for viscous flow, 643
  - Activation polarization, 699–701, 869
  - Actuator, 11, 573
  - Addition polymerization, 627–628, 869
  - Additives, polymer, 630–631
  - Adhesives, 583–584, 869
  - Adhesive tape, 17
  - Adipic acid (structure), 630
  - Adsorption, 154
  - Advanced ceramics, 566, 573–576
  - Advanced materials, 10–12
  - Advanced polymers, 584–588
  - Age hardening, *see* Precipitation hardening
  - Air, as quenching medium, 609
  - AISI/SAE steel designation scheme, 547
  - Akermanite, 61
  - Alcohols, 106
  - Aldehydes, 106
  - Alkali metals, 25
  - Alkaline earth metals, 25
  - Allotropic transformation (tin), 67
  - Allotropy, 65, 869
  - Alloys, 5, 869. *See also* Solid solutions; specific alloys
    - atomic weight equations, 145
    - cast, 556
    - composition specification, 143–144
    - compositions for various, 857–858
    - costs, 859–861
    - defined, 140
    - density equations, 145
    - density values, 830–832
    - ductility values, 838–841
    - electrical resistivity values, 854–855
    - fracture toughness values, 319, 843–844
    - heat treatable, 556
    - high-temperature, 347
    - linear coefficient of thermal expansion values, 845–846
    - low expansion, 740
    - modulus of elasticity values, 833–835
    - Poisson's ratio values, 837
    - specific heat values, 851–852
    - strengthening, *see* Strengthening of metals
    - tensile strength values, 838–841
    - thermal conductivity values, 848–849
    - wrought, 556
    - yield strength values, 838–841
  - Alloy steels, 442, 544, 869
    - See also* Steels
  - Alnico, 771
  - $\alpha$ -Iron, *see* Ferrite ( $\alpha$ )
  - Alternating copolymers, 121, 122, 869
  - Alumina, *see* Aluminum oxide
  - Aluminosilicates, 620
  - Aluminum:
    - atomic radius and crystal structure, 47
    - bonding energy and melting temperature, 30
    - elastic and shear moduli, 206
    - electrical conductivity, 491
    - electrical wires, 494–496
    - for integrated circuit interconnects, 187–188
    - Poisson's ratio, 206
    - recrystallization temperature, 283
    - slip systems, 266
    - superconducting critical temperature, 778
    - thermal properties, 737
    - yield and tensile strengths, ductility, 217
  - Aluminum alloys, 558–559
    - fatigue behavior, 355
    - plane strain fracture toughness, 319, 843
    - precipitation hardening, 461–463
    - properties and applications, 559
  - Aluminum-copper alloys, phase diagram, 462
  - Aluminum-lithium alloys, 558, 559
  - Aluminum oxide:
    - electrical conductivity, 515
    - flexural strength, 217, 841



- Aluminum oxide (*Continued*)  
 hardness, 239  
 index of refraction, 793  
 modulus of elasticity, 206, 835  
 plane strain fracture toughness, 319, 844  
 Poisson's ratio, 206, 838  
 sintered microstructure, 626  
 stress-strain behavior, 225  
 thermal properties, 737  
 translucency, 4, 800  
 as whiskers and fibers, 664
- Aluminum oxide-chromium oxide  
 phase diagram, 392
- Ammonia, bonding energy and  
 melting temperature, 30
- Amorphous materials, 46,  
 91–92, 869
- Anelasticity, 209, 869
- Angle computation between two  
 crystallographic directions,  
 269
- Anions, 53, 869
- Anisotropy, 85–86, 869  
 of elastic modulus, 86, 210  
 magnetic, 767–769
- Annealing, 601, 602–604, 869  
 ferrous alloys, 602–604  
 glass, 618
- Annealing point, glass, 618, 869
- Annealing twins, 152
- Anodes, 691, 869  
 area effect, galvanic corrosion, 707  
 sacrificial, 716, 878
- Antiferromagnetism, 759, 869  
 temperature dependence, 763
- Aramid:  
 cost as a fiber, 863  
 fiber-reinforced polymer-matrix  
 composites, 667–668  
 melting and glass transition  
 temperatures, 868  
 properties as fiber, 664  
 repeat unit structure, 667, 866
- Argon, bonding energy and melt-  
 ing temperature, 30
- Aromatic hydrocarbons (chain  
 groups), 106, 467
- Arrhenius equation, 431
- Artificial aging, 464, 869
- Asphaltic concrete, 651
- ASTM standards, 202
- Atactic configuration, 118, 869
- Athermal transformation, 441, 869
- Atomic bonding, *see* Bonding
- Atomic mass, 18
- Atomic mass unit (amu), 19, 869
- Atomic models:  
 Bohr, 19–20, 21, 870  
 wave-mechanical, 20, 21, 880
- Atomic number, 18, 869
- Atomic packing factor, 48, 869
- Atomic point defects, 135–136,  
 137–139
- Atomic radii, of selected metals, 47
- Atomic structure, 18–26
- Atomic vibrations, 153, 735, 869
- Atomic weight, 19, 869  
 metal alloys, equations for, 145
- Atom percent, 144, 869
- Austenite, 398, 869  
 shape-memory phase  
 transformations, 457–458  
 transformations, 434–448  
 summary, 455–456
- Austenitic stainless steels, 548, 549
- Austenitizing, 603, 869
- Automobiles, rusted and stainless  
 steel, 689
- Automobile transmission, 170
- Auxetic materials, 210
- Average value, 240
- Avogadro's number, 19
- Avrami equation, 433, 465
- AX crystal structures, 56–57
- $A_mX_p$  crystal structures, 57
- B**
- Bainite, 438–439, 446, 456, 869  
 mechanical properties, 451
- Bakelite, *see* Phenol-formaldehyde  
 (Bakelite)
- Ball bearings, ceramic, 574, 576
- Band gap, 488–490
- Band gap energy, 869  
 determination of, 537  
 selected semiconductors, 497
- Bands, *see* Energy bands
- Barcol hardness, 239
- Barium ferrite (as magnetic  
 storage medium), 775
- Barium titanate:  
 crystal structure, 57, 525–526  
 as dielectric, 525  
 as ferroelectric, 525–526  
 as piezoelectric, 527, 575
- Base (transistor), 511–512
- Basic refractories, 570
- Basic slags, 570
- Beachmarks (fatigue), 338
- Bend strength, 224. *See also*  
 Flexural strength
- Beryllia, 571
- Beryllium-copper alloys, 556–557
- Beverage containers, 1, 816  
 corrosion of, 816  
 diffusion rate of  $CO_2$  through,  
 190–191  
 stages of production, 595
- Bifunctional repeat units, 109, 870
- Billiard balls, 542, 580
- Bimetallic strips, 733
- Binary eutectic alloys, 374–387
- Binary isomorphous alloys, 365–374  
 mechanical properties, 374  
 microstructure development,  
 equilibrium cooling, 371–372  
 microstructure development,  
 nonequilibrium cooling,  
 372–374
- Biodegradable beverage can, 816
- Biodegradable polymers/plastics,  
 824–825
- Biomass, 825
- Biomaterials, 11
- Biorenewable polymers/plastics,  
 824–825
- Block copolymers, 121, 122, 870
- Blowing, of glass, 617
- Blow molding, plastics, 634
- Body-centered cubic structure,  
 48–49, 870  
 Burgers vector for, 267  
 slip systems, 266  
 twinning in, 272
- Bohr atomic model, 19–20, 21, 870
- Bohr magneton, 756, 870
- Boltzmann's constant, 136, 870
- Bonding:  
 carbon-carbon, 108  
 cementitious, 572  
 covalent, 30–31, 52, 871  
 hybrid *sp*, 23  
 hydrogen, 32, 33, 874  
 ionic, 28–29, 52–53, 874  
 metallic, 31–32, 875  
 van der Waals, *see* van der Waals  
 bonding
- Bonding energy, 28, 870  
 and melting temperature for  
 selected materials, 30
- Bonding forces, 26–27
- Bond rupture, in polymers,  
 722–724



- Bone, as composite, 648
- Boron carbide:  
hardness, 239
- Boron:  
boron-doped silicon  
semiconductors, 501  
fiber-reinforced composites,  
668, 671  
properties as a fiber, 664
- Borosilicate glass:  
composition, 567  
electrical conductivity, 515  
viscosity, 616
- Borsic fiber-reinforced composites,  
672
- Bottom-up science, 12
- Bragg's law, 87–89, 870
- Branched polymers, 115, 116, 870
- Brass, 556, 557, 870  
annealing behavior, 282  
elastic and shear moduli, 206  
electrical conductivity, 491  
fatigue behavior, 355  
phase diagram, 388, 389  
Poisson's ratio, 206  
recrystallization temperature, 283  
stress corrosion, 713  
stress-strain behavior, 214  
thermal properties, 737  
yield and tensile strengths,  
ductility, 217
- Brazing, 600, 870
- Breakdown, dielectric, 511, 525
- Bridge, suspension, 200
- Brinell hardness tests, 234,  
235–236
- Brittle fracture, 215–216, 308, 310,  
312–315, 870  
ceramics, 322–326
- Brittle materials, thermal shock,  
745–746
- Bronze, 556, 557, 870
- Bronze age, 2
- Bronze, photomicrograph, coring,  
374
- Buckminsterfullerene, 65
- Burgers vector, 148, 870  
for FCC, BCC, and HCP, 267  
magnitude computation, 303
- Butadiene:  
degradation resistance, 722  
melting and glass transition  
temperatures, 868  
repeat unit structure, 122, 865
- Butane, 104–105
- C**
- Cadmium sulfide:  
color, 799  
electrical characteristics, 497
- Calcination, 572, 870
- Calendering, 676
- Capacitance, 517–518, 870
- Capacitors, 517–522
- Carbon:  
vs. graphite, 664, 667  
polymorphism, 65
- Carbon black, as reinforcement in  
rubbers, 581, 651
- Carbon-carbon composites,  
674, 870
- Carbon diffusion, in steels, 402, 453
- Carbon dioxide emissions, 154
- Carbon dioxide (pressure-  
temperature phase diagram),  
421
- Carbon fiber-reinforced polymer-  
matrix composites, 666–667,  
668
- Carbon fibers, 666–667  
properties as fiber, 664
- Carbon nanotubes, 12, 64
- Carburizing, 175, 177, 870
- Case-hardened gear, 170
- Case hardening, 170, 341, 342, 870
- Cast alloys, 556
- Casting techniques:  
metals, 598–599  
plastics, 634  
slip, 621–622  
tape, 626–627
- Cast irons, 400, 544, 549–555, 870  
annealing, 604  
compositions, mechanical  
properties, and applications,  
552  
graphite formation in, 550  
heat treatment effect on  
microstructure, 554  
phase diagram, 550, 554  
stress-strain behavior (gray), 251
- Catalysts, 154
- Catalytic converters  
(automobiles), 134, 154
- Cathodes, 692, 870
- Cathodic protection, 708,  
715–716, 870
- Cations, 53, 870
- Cemented carbide, 650–651
- Cementite, 398–400, 870  
decomposition, 550, 554  
proeutectoid, 405–406  
in white iron, 551, 553
- Cementitious bond, 572
- Cements, 566, 571–573, 870
- Ceramic ball bearings, 574, 576
- Ceramic-matrix composites,  
672–674, 870
- Ceramics, 6–7, 870. *See also* Glass  
advanced, 573–576  
application-classification scheme,  
566  
brittle fracture, 322–326  
coefficient of thermal expansion  
values, 737, 846–847  
color, 799  
corrosion, 720  
costs, 861–862  
crystal structures, 52–58  
summary, 58  
defects, 137–140  
defined, 6–7  
density computation, 58–59  
density values, 832  
elastic modulus values, 206,  
835–836  
electrical conductivity values for  
selected, 515  
electrical resistivity values,  
855–856  
fabrication techniques  
classification, 615  
flexural strength values, 217,  
841–842  
fractography of, 324–326  
fracture toughness values,  
319, 844  
impurities in, 142  
indices of refraction, 793  
as electrical insulators, 516, 525  
magnetic, 759–763  
mechanical properties of,  
223–226  
in MEMS, 574  
phase diagrams, 391–395  
piezoelectric, 11, 575  
plastic deformation, 285–286  
Poisson's ratio values, 206, 838  
porosity, 224–226, 625–626  
porosity, influence on properties,  
224–226  
silicates, 59–62  
specific heat values, 737, 853  
as superconductors, 778  
thermal conductivity values,  
737, 850



- Ceramics (*Continued*)  
 thermal properties, 737, 739, 742–743, 745  
 traditional, 573  
 traditional vs. new, 573  
 translucency and opacity, 800
- Cercor (glass-ceramic), 568
- Cermets, 650, 870
- Cesium chloride structure, 56
- Chain-folded model, 125–126, 870
- Chain-reaction polymerization, *see* Addition polymerization
- Chain stiffening/stiffness, 115, 467, 468
- Charge carriers:  
 majority vs. minority, 500  
 temperature dependence, 502–503
- Charpy impact test, 328–329, 870
- Chevron markings, 312
- Chips, semiconductor, 514
- Chlorine, bonding energy and melting temperature, 30
- Chloroprene, repeat unit structure, 122, 865
- Chloroprene rubber:  
 characteristics and applications, 581  
 melting and glass transition temperatures, 868
- Cis*, 119, 870
- Clay, characteristics, 620
- Clay products, 566, 569  
 drying and firing, 569, 622–624  
 fabrication, 620–622
- Cleavage (brittle fracture), 313
- Clinker, 572
- Close-packed ceramic crystal structures, 83–84
- Close-packed metal crystal structures, 81–83
- Coarse pearlite, 436–437, 446, 870
- Coatings (polymer), 583
- Cobalt:  
 atomic radius and crystal structure, 47  
 Curie temperature, 763  
 as ferromagnetic material, 758  
 magnetization curves (single crystal), 768
- Coercivity (coercive force), 765, 870
- Cold work, percent, 276
- Cold working, 870. *See also* Strain hardening
- Collector, 511–512
- Color, 870  
 metals, 791–792  
 nonmetals, 798–799
- Colorants, 631, 870
- Compacted graphite iron, 544, 551, 555
- Compliance, creep, 232
- Component, 360, 396, 870
- Composites:  
 aramid fiber-reinforced polymer, 667–668  
 carbon-carbon, 674, 870  
 carbon fiber-reinforced polymer, 666–667  
 ceramic-matrix, 672–674  
 classification scheme, 649  
 costs, 863  
 definition, 10, 648  
 dispersion-strengthened, 653  
 elastic behavior:  
 longitudinal, 657–658  
 transverse, 659–660  
 fiber-reinforced, *see* Fiber-reinforced composites  
 glass fiber-reinforced polymer, 665–666  
 hybrid, 674–675, 874  
 laminar, 649, 663, 677–678, 874  
 large-particle, 649–653  
 metal-matrix, 671–672  
 particle-reinforced, 649–653  
 production processes, 675–677  
 properties, glass-, carbon-, aramid-fiber reinforced, 668  
 rule of mixtures expressions, 650, 657, 660, 661, 662, 670  
 strength:  
 longitudinal, 661  
 transverse, 662  
 stress-strain behavior, 655–656  
 structural, 677–679
- Composition, 870  
 conversion equations, 144–145, 167  
 specification of, 143–144
- Compression molding, plastics, 632
- Compression tests, 204
- Compressive deformation, 203, 222
- Computers:  
 semiconductors in, 513–515  
 magnetic drives in, 773–775
- Concentration, 143, 870. *See also* Composition
- Concentration cells, 709
- Concentration gradient, 174, 870
- Concentration polarization, 701–702, 870
- Concentration profile, 174, 870
- Concrete, 651–653, 870  
 electrical conductivity, 515  
 plane strain fracture toughness, 319, 844
- Condensation polymerization, 629, 870
- Conducting polymers, 516–517
- Conduction:  
 electronic, 486  
 ionic, 486, 516
- Conduction band, 488, 871
- Conductivity, *see* Electrical conductivity; Thermal conductivity
- Configuration, molecular, 116–119
- Conformation, molecular, 114
- Congruent phase transformations, 391–392, 871
- Constitutional diagrams, *see* Phase diagrams
- Continuous casting, 599
- Continuous-cooling transformation diagrams, 445–448, 871  
 4340 steel, 448  
 1.13 wt% C steel, 478  
 0.76 wt% C steel, 445  
 for glass-ceramic, 568
- Continuous fibers, 654
- Conventional hard magnetic materials, 771
- Conversion factors, magnetic units, 755
- Cooling rate, of cylindrical rounds, 609
- Coordinates, point, 68–70
- Coordination numbers, 48, 50, 53–54, 871
- Copolymers, 108, 121–122, 871  
 styrenic block, 587–588
- Copper:  
 atomic radius and crystal structure, 47  
 diffraction pattern, 105  
 elastic and shear moduli, 206  
 electrical conductivity, 491  
 OFHC, 494  
 Poisson's ratio, 206  
 recrystallization, 283, 433  
 slip systems, 266  
 thermal properties, 737  
 yield and tensile strengths, ductility, 217



- Copper alloys, 556–557  
 properties and applications of, 557
- Copper-aluminum phase diagram, 462
- Copper-beryllium alloys, 494, 556–557  
 phase diagram, 481
- Copper-nickel alloys:  
 ductility vs. composition, 275, 375  
 electrical conductivity, 492  
 phase diagram, 365–366  
 tensile strength vs. composition, 275, 375  
 yield strength vs. composition, 275
- Copper-silver phase diagram, 375, 397
- Coring, 374
- CorningWare (glass-ceramic), 568
- Corrosion, 871  
 of beverage cans, 816  
 ceramic materials, 720  
 electrochemistry of, 691–696  
 environmental effects, 706  
 environments, 714–715  
 forms of, 707–714  
 galvanic series, 697, 698  
 overview of, 690  
 passivity, 705–706, 876  
 rates, 697–699  
 prediction of, 699–705
- Corrosion fatigue, 342, 871
- Corrosion inhibitors, 715
- Corrosion penetration rate, 698–699, 871
- Corrosion prevention, 715–716
- Corundum, 571. *See also*  
 Aluminum oxide  
 crystal structure, 104
- Cost of various materials, 859–863
- Coulombic force, 29, 871
- Covalency, degree of, 31
- Covalent bonding, 30–31, 52–53, 104, 871
- Crack configurations in ceramics, 324
- Crack critical velocity, 324
- Crack formation, 310  
 in ceramics, 324  
 fatigue and, 337  
 glass, 619
- Crack propagation, 310. *See also*  
 Fracture mechanics  
 in brittle fracture, 312–313  
 in ceramics, 322–326  
 in ductile fracture, 310–311  
 fatigue and, 337–339
- Cracks:  
 stable vs. unstable, 310
- Crack surface displacement modes, 318
- Crazing, 327
- Creep, 342–346, 871  
 ceramics, 347  
 influence of temperature and stress on, 344–345  
 mechanisms, 345  
 in polymers, 232, 347  
 stages of, 343–344  
 steady-state rate, 343  
 viscoelastic, 232
- Creep compliance, 232
- Creep modulus, 232
- Creep rupture tests, 343  
 data extrapolation, 346–347
- Crevice corrosion, 708–709, 871
- Cristobalite, 60–61, 395
- Critical cooling rate:  
 ferrous alloys, 446–448  
 glass-ceramics, 568
- Critical fiber length, 654–655
- Critical resolved shear stress, 268, 871  
 as related to dislocation density, 304
- Critical stress (fracture), 316
- Critical temperature, superconductivity, 776, 778
- Critical velocity (crack), 324, 325
- Crosslinking, 115, 116, 871  
 elastomers, 293–294  
 influence on viscoelastic behavior, 232  
 thermosetting polymers, 120
- Crystalline materials, 46, 85, 871  
 defects, 136–153  
 single crystals, 85, 878
- Crystallinity, polymers, 122–124, 871  
 influence on mechanical properties, 290–291
- Crystallites, 125, 871
- Crystallization, polymers, 464–465
- Crystallographic directions, 70–76  
 easy and hard magnetization, 767  
 families, 72  
 hexagonal crystals, 72–76
- Crystallographic planes, 76–80  
 atomic arrangements, 79  
 close-packed, ceramics, 83–84  
 close-packed, metals, 81–83  
 diffraction by, 87–89  
 families, 79  
 hexagonal crystals, 79–80
- Crystallographic point coordinates, 68–70
- Crystal structures, 46–50, 871. *See also* Body-centered cubic structure; Close-packed crystal structures; Face-centered cubic structure; Hexagonal close-packed structure  
 ceramics, 52–58  
 close-packed, ceramics, 83–84  
 close-packed, metals, 81–83  
 determination by x-ray diffraction, 87–91  
 selected metals, 47  
 types, ceramics, 52–58, 83–84  
 types, metals, 47–51, 81–83
- Crystallization (ceramics), 567, 620, 871
- Crystal systems, 65–66, 871
- Cubic crystal system, 65, 66
- Cubic ferrites, 759–762
- Cunife, 771, 772
- Cup-and-cone fracture, 311
- Curie temperature, 763, 871  
 ferroelectric, 526  
 ferromagnetic, 737
- Curing, plastics, 632
- Current density, 485
- Cyclic stresses, 333–334
- D**
- Damping capacity, steel vs. cast iron, 553
- Data scatter, 239–241
- Debye temperature, 736
- Decarburization, 175
- Defects, *see also* Dislocations  
 atomic vibrations and, 153  
 dependence of properties on, 135  
 in ceramics, 137–140, 142  
 interfacial, 150–153  
 point, 136–140, 877  
 in polymers, 143  
 surface, 153  
 volume, 153
- Defect structure, 137, 871
- Deformation:  
 elastic, *see* Elastic deformation  
 elastomers, 293–294  
 plastic, *see* Plastic deformation



- Deformation mechanism maps (creep), 345
- Deformation mechanisms (semicrystalline polymers),
  - elastic deformation, 287, 288
  - plastic deformation, 287, 289
- Degradation of polymers, 720–724, 871
- Degree of polymerization, 112, 871
- Degrees of freedom, 396
- Delayed fracture, 323
- Density:
  - computation for ceramics, 58–59
  - computation for metal alloys, 145
  - computation for metals, 51–52
  - computation for polymers, 124–125
  - of dislocations, 264
  - linear atomic, 80–81
  - planar atomic, 81
  - polymers (values for), 832–833
  - ranges for material types (bar chart), 5
  - relation to percent crystallinity for polymers, 123
  - values for various materials, 830–833
- Design, component, 818
- Design examples:
  - cold work and recrystallization, 283–284
  - conductivity of a *p*-type semiconductor, 506–507
  - cubic mixed-ferrite magnet, 762–763
  - creep rupture lifetime for an S-590 steel, 346–347
  - nonsteady-state diffusion, 183–184
  - spherical pressure vessel, failure of, 320–322
  - steel shaft, alloy/heat treatment of, 612–613
  - tensile-testing apparatus, 243
  - tubular composite shaft, 669–671
- Design factor, 242
- Design stress, 242, 871
- Dezincification, of brass, 711
- Diamagnetism, 756–757, 871
- Diamond, 63, 576–577
  - as abrasive, 571
  - bonding energy and melting temperature, 30
  - cost, 861
  - films, 576–577
  - hardness, 239
  - thermal conductivity value, 850
- Diamond cubic structure, 63
- Die casting, 599
- Dielectric breakdown, 511, 525
- Dielectric constant, 518, 871
  - frequency dependence, 524–525
  - relationship to refractive index, 793
  - selected ceramics and polymers, 519
- Dielectric displacement, 520, 871
- Dielectric loss, 525
- Dielectric materials, 516–517, 525, 871
- Dielectric strength, 525, 871
  - selected ceramics and polymers, 519
- Diffraction (x-ray), 87, 871
- Diffraction angle, 90
- Diffraction gratings, 90
- Diffusion, 171–172, 871
  - drive-in, 184–185
  - grain growth and, 284, 285
  - in ionic materials, 188
  - in integrated circuit interconnects, 187–188
  - in Si of Cu, Au, Ag, and Al, 188
  - interstitial, 173, 874
  - mechanisms, 172–173
  - and microstructure development, 372–374, 384
  - nonsteady-state, 175–179, 876
  - in polymers, 189–191
  - predeposition, semiconductors, 184–185
  - in semiconductors, 184–187
  - short-circuit, 188
  - steady-state, 173–175, 879
  - vacancy, 172–173, 188, 880
- Diffusion coefficient, 174, 871
  - relation to ionic mobility, 516
  - temperature dependence, 179–184
  - values for various metal systems, 179
- Diffusion couples, 171, 196
- Diffusion flux, 173, 871
  - for polymers, 189
- Digitization of information/signals, 774, 808
- Dimethyl ether, 106
- Dimethylsiloxane, 122, 581, 582, 865. *See also* Silicones; Silicone rubber
  - melting and glass transition temperatures, 868
- Diode, 509, 871
- Dipole moment, 519
- Dipoles:
  - electric, 32, 871
  - induced, 32
  - magnetic, 752–753
  - permanent, 33
- Directional solidification, 347
- Directions, *see* Crystallographic directions
- Discontinuous fibers, 654
- Dislocation density, 264, 302, 304, 871
- Dislocation etch pits, 260
- Dislocation line, 147, 148, 149, 871
- Dislocation motion, 262–263
  - caterpillar locomotion analogy, 263
  - in ceramics, 285–286
  - at grain boundaries, 273–274
  - influence on strength, 274
  - recovery and, 280
- Dislocations, 147–150, 871
  - in ceramics, 150, 264, 285–286
  - characteristics of, 264–265
  - interactions, 265
  - multiplication, 265
  - at phase boundaries, 450, 453
  - pile-ups, 274
  - plastic deformation and, 211–212, 261–271, 272
  - in polymers, 143, 150
  - strain fields, 264–265
- Dispersed phase, 648, 871
  - definition, 648
  - geometry, 648
- Dispersion (optical), 792
- Dispersion-strengthened composites, 653, 871
- Disposal of materials, 820–821
- Domain growth, 764–765
  - iron single crystal, 765
- Domains, 758, 764, 768, 872
- Domain walls, 764
- Donors, 500, 872
- Doping, 501, 504, 872
- Double bonds, 104
- Drain casting, 621
- Drawing:
  - glass, 617
  - influence on polymer properties, 291
  - metals, 598, 872
  - polymer fibers, 634, 872



- Drift velocity, electron, 490  
 Drive-in diffusion, 184–185  
 Driving force, 174, 872  
   electrochemical reactions, 694  
   grain growth, 284  
   recrystallization, 280  
   sintering, 626  
   steady-state diffusion, 174  
 Dry corrosion, 717  
 Dry ice, 421  
 Drying, clay products, 622–623  
 Ductile fracture, 215–216,  
   310–312, 872  
 Ductile iron, 551, 553, 872  
   compositions, mechanical  
   properties, and applications,  
   552  
 Ductile-to-brittle transition,  
   330–332, 872  
   polymers, 326  
   and temper embrittlement, 455  
 Ductility, 215–216, 872  
   fine and coarse pearlite, 450  
   precipitation hardened  
   aluminum alloy, 463  
   selected materials, 217, 838–843  
   spheroidite, 450  
   tempered martensite, 454  
 Durometer hardness, 236, 239
- E**
- Economics, materials selection:  
   considerations in materials  
   engineering, 817–818  
   tubular composite shaft, 669–671  
 Eddy currents, 770  
 Edge dislocations, 147, 262–263,  
   872. *See also* Dislocations  
   interactions, 264–265  
 E-glass, 664, 666  
 Elastic deformation, 205–211, 872  
 Elastic modulus, *see* Modulus of  
   elasticity  
 Elastic (strain) recovery, 222, 872  
 Elastomers, 227, 293–295, 580–582,  
   634, 872  
   in composites, 651  
   deformation, 293–294  
   thermoplastic, 587–588  
   trade names, properties, and  
   applications, 581  
 Electrical conduction:  
   in insulators and semiconductors,  
   489–490  
   in metals, 489  
   Electrical conductivity, 485, 491, 872  
     ranges for material types  
     (bar chart), 7  
     selected ceramics and polymers,  
     515  
     selected metals, 491  
     selected semiconductors, 497  
     temperature variation (Ge), 537  
     values for electrical wires, 495  
   Electrical resistivity, 485, 878. *See*  
     *also* Electrical conductivity  
   metals  
   influence of impurities, 493  
   influence of plastic deformation,  
   492, 493  
   influence of temperature,  
   492–493  
   values for various materials,  
   854–857  
   Electrical wires, aluminum and  
   copper, 494–496  
   Electric dipole moment, 519  
   Electric dipoles, *see* Dipoles  
   Electric field, 485, 490, 872  
   Electrochemical cells, 693–694  
   Electrochemical reactions, 691–696  
   Electrodeposition, 693  
   Electrode potentials, 693–694  
   values of, 695  
   Electroluminescence, 803, 872  
   Electrolytes, 693, 872  
   Electromagnetic radiation,  
   787–789  
   interactions with atoms/electrons,  
   790–791  
   Electromagnetic spectrum, 787–788  
   Electron band structure, *see*  
   Energy bands  
   Electron cloud, 31  
   Electron configurations, 22–25, 872  
   elements, 24  
   periodic table and, 25–26  
   stable, 23  
   Electronegativity, 25, 31, 872  
   influence on solid solubility, 141  
   values for the elements, 26  
   Electroneutrality, 137, 872  
   Electron gas, 489  
   Electronic conduction, 486, 516  
   Electronic polarization, 523, 575,  
   790, 794, 877  
   Electron microscopy, 157–158  
   Electron mobility, 490  
   influence of dopant content on,  
   504  
   influence of temperature on,  
   504–505  
   selected semiconductors, 497  
   Electron orbitals, 19  
   Electron probability distribution,  
   20, 21  
 Electrons, 18  
   conduction process, 498, 511–512  
   role, diffusion in ionic materials,  
   188  
   energy bands, *see* Energy bands  
   energy levels, 20–22  
   free, *see* Free electrons  
   scattering, 490–491, 735  
   in semiconductors, 496–502  
   temperature variation of  
   concentration, 502–503  
   spin, 22, 755–756  
   valence, 22  
 Electron states, 872  
 Electron transitions, 790–791  
   metals, 791–792  
   nonmetals, 792–794  
 Electron volt, 29, 872  
 Electropositivity, 25, 872  
 Electrorheological fluids, 11  
 Elongation, percent, 215  
   selected materials, 217, 838–843  
   selected metals, 217  
   selected polymers, 217  
 Embrittlement:  
   hydrogen, 713–714  
   temper, 455  
 Embryo, phase particle, 424–426  
 Emf series, 694–695, 872  
 Emitter, 511  
 Endurance limit, 335. *See also*  
   Fatigue limit  
 Energy:  
   activation, *see* Activation energy  
   bonding, 28–30, 870  
   current concerns about, 12,  
   820–821  
   free, 362, 363, 424–426, 873  
   grain boundary, 151  
   photon, 789  
   surface, 150  
   vacancy formation, 136  
 Energy band gap, *see* Band gap  
 Energy bands, 486–488  
   structures for metals, insulators,  
   and semiconductors, 488  
 Energy levels (states), 19–22,  
   486–487  
 Energy and materials, 820



- Energy product, magnetic, 770–771
- Engineering stress/strain, 203–204, 879
- Entropy, 293, 362, 424
- Environmental considerations and materials, 819–826
- Epoxies:
  - degradation resistance, 721
  - polymer-matrix composites, 668
  - repeat unit structure, 864
  - trade names, characteristics, and applications, 579
- Equilibrium:
  - definition of, 362
  - phase, 362–363, 872
- Equilibrium diagrams, *see* Phase diagrams
- Erosion-corrosion, 711–712, 872
- Error bars, 241
- Error function, Gaussian, 176
- Etching, 156
- Etch pits, 260
- Ethane, 104
- Ethers, 106
- Ethylene, 104
  - polymerization, 106–107
- Ethylene glycol (structure), 629
- Euro coins, alloys used for, 565
- Eutectic isotherm, 376
- Eutectic phase, 385, 872  $\Delta$
- Eutectic reactions, 376, 383, 872
  - iron-iron carbide system, 400
- Eutectic structure, 383, 872
- Eutectic systems:
  - binary, 374–387
  - microstructure development, 380–387
- Eutectoid, shift of position, 408
- Eutectoid ferrite, 404
- Eutectoid reactions, 390, 872
  - iron-iron carbide system, 400
  - kinetics, 434–436
- Eutectoid steel, microstructure changes/development, 401–403
- Exchange current density, 700
- Excited states, 791, 872
- Exhaustion, in extrinsic semiconductors, 502
- Expansion, thermal. *see* Thermal expansion
- Extrinsic semiconductors, 499–502, 872
  - electron concentration vs. temperature, 503
  - exhaustion, 502
  - saturation, 502
- Extrusion, 872
  - clay products, 621
  - metals, 598
  - polymers, 633
- F**
- Fabrication:
  - ceramics, 615–627
  - clay products, 620–624
  - fiber-reinforced composites, 675–677
  - metals, 597–601
- Face-centered cubic structure, 47–48, 872
  - anion stacking (ceramics), 83–84
  - Burgers vector for, 267
  - close packed planes (metals), 81–83
  - slip systems, 265–266
- Factor of safety, 242, 321
- Failure, mechanical, *see* Creep; Fatigue; Fracture
- Faraday constant, 696
- Fatigue, 332–342, 872
  - corrosion, 342
  - crack initiation and propagation, 337–339
  - cyclic stresses, 333–334
  - environmental effects, 341–342
  - low- and high-cycle, 336
  - polymers, 337
  - probability curves, 336
  - thermal, 341–342
- Fatigue damage, commercial aircraft, 308
- Fatigue life, 336, 872
  - factors that affect, 339–341
- Fatigue limit, 335, 872
- Fatigue strength, 335, 336, 872
- Fatigue testing, 334–335
  - S-N curves, 334–337, 355
- Feldspar, 620
- Fermi energy, 488, 501, 736, 872
- Ferrimagnetism, 759–763, 872
  - temperature dependence, 763
- Ferrite ( $\alpha$ ), 398–400, 872
  - eutectoid/proeutectoid, 404–405, 877
  - from decomposition of cementite, 550
- Ferrites (magnetic ceramics), 759–761, 872
  - Curie temperature, 763
  - as magnetic storage, 775
- Ferritic stainless steels, 548, 529
- Ferroelectricity, 525–526, 873
- Ferroelectric materials, 525–526
- Ferromagnetic domain walls, 153
- Ferromagnetism, 758–759, 873
  - temperature dependence, 763
- Ferrous alloys, 873. *See also* Cast irons; Iron; Steels
  - annealing, 601–604
  - classification, 401, 544
  - continuous-cooling transformation diagrams, 445–448
  - costs, 859–860
  - hypereutectoid, 405–408, 874
  - hypoeutectoid, 403–405, 874
  - isothermal transformation diagrams, 434–444
  - microstructures, 401–408
  - mechanical properties of, 448–452, 838–839
- Fiber efficiency parameter, 663, 685
- Fiberglass, 567
- Fiberglass-reinforced composites, 665–666
- Fiber-reinforced composites, 653–677, 873
  - continuous and aligned, 655–661
  - discontinuous and aligned, 662
  - discontinuous and randomly oriented, 662–663
  - fiber length effect, 654–655
  - fiber orientation/concentration effect, 655–663
  - fiber phase, 663–665
  - longitudinal loading, 655–659, 660–661
  - matrix phase, 665
  - processing, 675–677
  - reinforcement efficiency, 663
  - transverse loading, 659–660, 661
- Fibers, 582–583, 873
  - coefficient of thermal expansion values, 847
  - in composites, 649
    - continuous vs. discontinuous, 654–655
    - fiber phase, 663–665
    - length effect, 654–655
    - orientation and concentration, 655–663
  - costs, 863
  - density values, 833
  - elastic modulus values, 664, 836



- Fibers (*Continued*)  
 electrical resistivity values, 857  
 optical, 808–810  
 polymer, 582–583  
 properties of selected, 664  
 specific heat values, 853  
 spinning of, 634  
 tensile strength values, 664, 842  
 thermal conductivity values, 851
- Fick's first law, 174, 741, 873  
 for polymers, 189
- Fick's second law, 175–176, 749, 873
- Fictive temperature, 615
- Filament winding, 676–677
- Fillers, 630, 873
- Films:  
 diamond, 576, 577  
 polymer, 584  
 shrink-wrap (polymer), 292
- Fine pearlite, 436, 437, 448–449, 450, 452, 873
- Fireclay refractories, 570
- Firing, 570, 623–624, 873
- Flame retardants, 631, 873
- Flash memory, 483, 513
- Flash memory cards, 483
- Flexural deflection, equation for, 256
- Flexural strength, 223–224, 873  
 influence of porosity on,  
 ceramics, 224–226  
 values for selected ceramics,  
 217, 841–842
- Float process (sheet glass), 618
- Fluorescence, 801, 873
- Fluorite structure, 57
- Fluorocarbons, 108  
 trade names, characteristics, and  
 applications, 578
- Flux (clay products), 620, 623
- Foams, 584, 873
- Forces:  
 bonding, 26–28  
 coulombic, 29, 871
- Forging, 597, 598, 873
- Formaldehyde, 106
- Forming operations (metals),  
 597–598
- Forsterite, 61
- Forward bias, 510, 511, 873
- Fractographic investigations:  
 ceramics, 324–326  
 metals, 312
- Fractographs:  
 cup-and-cone fracture surfaces,  
 312
- fatigue striations, 338
- glass rod, 326
- intergranular fracture, 315
- transgranular fracture, 314
- Fracture, *see also* Brittle fracture:  
 Ductile fracture; Impact  
 fracture testing  
 delayed, 323  
 fundamentals of, 310  
 polymers, 326–327  
 types, 215–216, 310–314
- Fracture mechanics, 314, 873  
 applied to ceramics, 322–323  
 polymers, 328  
 use in design, 320–322
- Fracture profiles, 311
- Fracture strength, 214. *See also*  
 Flexural strength  
 ceramics, 223–224  
 distribution of, 323  
 influence of porosity, 224–226  
 influence of specimen size,  
 323, 663–664
- Fracture surface, ceramics, 325–326
- Fracture toughness, 218,  
 317–319, 873  
 ceramic-matrix composites,  
 673–674  
 ranges for material types  
 (bar chart), 7  
 testing, 319  
 values for selected materials,  
 319, 843–844
- Free electrons, 489, 873  
 contributions to heat capacity,  
 736  
 role in heat conduction, 741
- Free energy, 362, 424–426, 873  
 activation, 425, 430  
 volume, 424
- Freeze-out region, 502–503
- Frenkel defects, 137, 138, 873  
 equilibrium number, 139
- Full annealing, 446, 603, 873
- Fullerenes, 63, 65
- Functionality (polymers), 109
- Furnace heating elements, 494
- Fused silica, 92  
 characteristics, 567, 616  
 dielectric properties, 519  
 electrical conductivity, 515  
 flexural strength, 217  
 index of refraction, 793  
 modulus of elasticity, 206  
 thermal properties, 737
- G**
- Gadolinium, 758, 761
- Gallium arsenide:  
 cost, 861  
 electrical characteristics, 497, 498  
 for lasers, 807  
 for light-emitting diodes, 802, 815
- Gallium phosphide:  
 electrical characteristics, 497  
 for light-emitting diodes, 815
- Galvanic corrosion, 707–708, 873
- Galvanic couples, 693
- Galvanic series, 697, 698, 873
- Galvanized steel, 566, 716
- Garnets, 761
- Garnet single crystal, 85
- Gas constant, 136, 873
- Gating system, 599
- Gauge length, 202
- Gaussian error function, 176
- Gears (transmission), 170
- Gecko lizard, 17
- Geometrical isomerism, 118–119
- Germanium:  
 crystal structure, 63  
 electrical characteristics,  
 497, 503, 537
- Gibbs phase rule, 396–397, 873
- Gilding metal, 556
- Glass:  
 as amorphous material, 92–93  
 annealing, 604, 618, 869  
 blowing, 617  
 classification, 567  
 color, 799  
 commercial, compositions and  
 characteristics, 567  
 corrosion resistance, 720  
 cost, 861–862  
 dielectric properties, 519  
 electrical conductivity, 515  
 flexural strength, 206, 841  
 forming techniques, 617–618  
 fracture surface  
 (photomicrograph), 326  
 hardness, 239  
 heat treatment, 618–619  
 melting point, 616  
 modulus of elasticity, 206, 835  
 optical flint, 567  
 plane strain fracture toughness,  
 319, 844  
 refractive index, 793  
 sheet forming (float process), 618  
 soda-lime, composition, 567



- Glass (*Continued*)  
 softening point, 616  
 strain point, 616  
 stress-strain behavior, 225  
 structure, 93  
 surface crack propagation, 323  
 tempering, 618–619, 643  
 thermal properties, 737  
 viscous properties, 616  
 working point, 616, 881
- Glass-ceramics, 567–568, 873  
 composition (Pyroceram), 567  
 continuous-cooling  
 transformation diagram, 568  
 fabricating and heat treating,  
 619–620  
 flexural strength, 217, 841  
 modulus of elasticity, 206, 835  
 optical transparency, conditions  
 for, 800  
 properties and applications, 568
- Glass fibers, 666  
 fiberglass-reinforced composites,  
 665–666, 668  
 forming, 618  
 properties as fiber, 664
- Glass transition, polymers, 466
- Glass transition temperature,  
 466, 615, 873  
 factors that affect, polymers,  
 468–469  
 values for selected polymers,  
 467, 868
- Gold, 562  
 atomic radius and crystal  
 structure, 47  
 electrical conductivity, 491  
 slip systems, 266  
 thermal properties, 737
- Graft copolymers, 121, 122, 873
- Grain boundaries, 85, 150–151, 873
- Grain boundary energy, 151
- Grain growth, 284–285, 873
- Grains, 873  
 definition, 85  
 distortion during plastic  
 deformation, 270–271
- Grain size, 873  
 dependence on time, 284–285  
 determination of, 159–160  
 mechanical properties and, 285  
 reduction, and strengthening of  
 metals, 273–274  
 refinement by annealing, 603
- Grain size number (ASTM), 160
- Graphite, 63  
 in cast irons, 550  
 compared to carbon, 664,  
 666–667  
 cost, 862  
 from decomposition of  
 cementite, 550  
 electrical conductivity, 515  
 properties/applications, 576–577  
 properties as whisker, 664  
 as a refractory, 571  
 structure of, 63
- Gray cast iron, 550–553, 873  
 compositions, mechanical  
 properties, and applications,  
 552
- Green ceramic bodies, 622, 873
- Green design, 821
- Ground state, 22, 791, 873
- Growth, phase particle, 423,  
 430–432, 873  
 rate, 431  
 temperature dependence of rate,  
 432
- Gutta percha, 119
- H**
- Hackle region, 325–326
- Half-cells, standard, 694
- Half-reactions, 692
- Hall coefficient, 508
- Hall effect, 507–509, 873
- Hall-Petch equation, 274
- Hall voltage, 507
- Halogens, 25
- Hard disk drives, 773–775
- Hardenability, 604–608, 873
- Hardenability band, 607, 608
- Hardenability curves, 605–608
- Hard magnetic materials,  
 770–773, 873  
 properties, 772
- Hardness, 873  
 bainite, pearlite vs.  
 transformation temperature,  
 451  
 ceramics, 238–239  
 comparison of scales, 237  
 conversion diagram, 237  
 correlation with tensile strength,  
 238  
 fine and coarse pearlite,  
 spheroidite, 450  
 pearlite, martensite, tempered  
 martensite, 452  
 polymers, 239  
 tempered martensite, 452, 454
- Hardness tests, 233–237  
 summary of tests, 234
- Hard sphere model, 46
- Head-to-head configuration, 117
- Head-to-tail configuration, 117
- Heat affected zone, 600
- Heat capacity, 734–737, 873  
 temperature dependence, 736  
 vibrational contribution, 735
- Heat flux, 741
- Heat of fusion, latent, 425
- Heat transfer:  
 mechanism, 735, 741  
 nonsteady-state, 749
- Heat treatable, definition of, 556
- Heat treatments, 170. *See also*  
 Annealing; Phase  
 transformations  
 dislocation reduction, 264  
 glass, 618–619  
 hydrogen embrittlement, 714  
 intergranular corrosion and,  
 711  
 polymer morphology, 290  
 polymer properties, 292  
 for precipitation hardening,  
 459–461  
 recovery, recrystallization, and  
 grain growth during, 279–285  
 steel, 604–613
- Hertz, 789
- Heterogeneous nucleation, 423,  
 429–430
- Hexagonal close-packed structure,  
 49–50, 873  
 anion stacking (ceramics), 82  
 Burgers vector for, 267  
 close-packed planes (metals),  
 81–83  
 slip systems, 266  
 twinning in, 272
- Hexagonal crystal system, 65, 66  
 direction indices, 72–76  
 planar indices, 79–80
- Hexagonal ferrites, 761
- Hexane, 104
- High carbon steels, 547
- High-cycle fatigue, 336–337
- High polymers, 113, 874
- High-strength, low-alloy (HSLA)  
 steels, 546, 874
- High-temperature superconductors,  
 778



- Holes, 489, 497, 874  
 role, diffusion in ionic materials, 188  
 mobility:  
 influence of dopant concentration on, 504  
 influence of temperature on, 504–505  
 values for selected semiconductors, 497  
 temperature dependence of concentration (Si, Ge), 503
- Homogeneous nucleation, 424–429
- Homopolymers, 108, 874
- Honeycomb structure, 678–679
- Hooke's law, 205, 229
- Hot pressing, 626
- Hot working, 282, 597, 874. *See also* Heat treatments
- HSLA (high-strength, low-alloy) steels, 546, 874
- Hybrid composites, 674–675, 874
- Hydration, of cement, 572
- Hydrocarbons, 103–105
- Hydrogen:  
 diffusive purification, 174–175, 195  
 reduction, 699
- Hydrogen bonding, 30, 32, 33, 874  
 water expansion upon freezing, 34
- Hydrogen chloride, 33, 39
- Hydrogen electrode, 694
- Hydrogen embrittlement, 713–714, 874
- Hydrogen fluoride, 33, 39
- Hydrogen induced cracking, 713
- Hydrogen stress cracking, 713
- Hydroplastic forming, 621, 874
- Hydroplasticity, 620
- Hydrostatic powder pressing, 625
- Hypereutectoid alloys, 405–407, 874
- Hypoeutectoid alloys, 403–405, 874
- Hysteresis, 765
- Hysteresis, ferromagnetic, 874  
 soft and hard magnetic materials, 768, 770–771
- I**
- Ice, 34, 359, 364, 419
- Iceberg, 359
- Impact energy, 328, 874  
 fine pearlite, 449  
 temperature dependence:  
 high-strength materials, 331  
 low-strength FCC and HCP metals, 331  
 low-strength steels, 330, 331
- Impact fracture testing, 328–332
- Impact strength, polymers, 332
- Imperfections. *See* Defects; Dislocations
- Impurities:  
 in ceramics, 142  
 diffusion, 172  
 electrical resistivity, 493  
 in metals, 140–141  
 thermal conductivity, 742
- Incongruent phase transformation, 391
- Index of refraction, 792–793, 874  
 selected materials, 793
- Indices, Miller, 76, 875
- Indium antimonide, electrical characteristics, 497
- Induced dipoles, 32–33
- Inert gases, 23, 25
- Inhibitors, 715, 874
- Initial permeability, 765
- Injection molding, 663
- Ink-jet printer heads, 575
- Insulators (electrical), 874. *See also* Dielectric materials  
 ceramics and polymers as, 515, 525  
 color, 799  
 defined, 486  
 electron band structure, 488, 489–490  
 translucency and opacity, 800–801
- Integrated circuits, 514–515, 874  
 interconnects, 187–188  
 scanning electron micrograph, 483, 514
- Interatomic bonding, 28–32
- Interatomic separation, 27
- Interconnects, integrated circuits, 187–188
- Interdiffusion, 172, 874
- Interfacial defects, 150–153
- Interfacial energies, 153  
 for heterogeneous nucleation, 429
- Intergranular corrosion, 710, 874
- Intergranular fracture, 314, 315, 874
- Intermediate solid solutions, 387, 391, 874
- Intermetallic compounds, 389, 461, 874
- International Organization for Standardization (ISO), 821
- Interplanar spacing, cubic crystals, 89
- Interstitial diffusion, 172, 874
- Interstitial impurity defects, 141
- Interstitials:  
 in ceramics, 142  
 in polymers, 143  
 self-, 136, 878
- Interstitial solid solutions, 141, 874
- Intrinsic carrier concentration, 498  
 temperature dependence for Si and Ge, 503
- Intrinsic conductivity, 497
- Intrinsic semiconductors, 496–498, 874
- Invar, Material of Importance, 740  
 thermal properties, 737
- Invariant point, 364, 376, 874
- Inverse lever rule, 368. *See also* Lever rule
- Inverse spinel structure, 759
- Ion cores, 31
- Ionic bonding, 28–29, 874  
 in ceramics, 52
- Ionic character (percent), 31, 52
- Ionic conduction, 189, 486, 516
- Ionic polarization, 523, 877
- Ionic radii, 53–54, 55
- Iridium, 562
- Iron, *see also* Ferrous alloys; Steels  
 atomic radius and crystal structure, 47  
 bonding energy and melting temperature, 30  
 Curie temperature, 763  
 diffraction pattern, 90  
 electrical conductivity, 491  
 ferrite ( $\alpha$ ), 398, 400, 404, 873  
 as ferromagnetic material, 758  
 magnetic properties, 770  
 magnetization curves (single crystal), 767  
 polymorphism, 65  
 recrystallization temperature, 283  
 rolling texture, 769  
 slip systems, 266  
 stress-strain behavior (at three temperatures), 218  
 thermal properties, 737  
 yield and tensile strengths, ductility, 217
- Iron age, 2
- Iron-carbon alloys, *see* Ferrous alloys
- Iron-iron carbide alloys, 398–401



- Iron-silicon alloys, magnetic properties, 770  
 Material of Importance (use in transformer cores), 769  
 ISO (International Organization for Standardization), 821  
 Isobutane, 105  
 Isobutylene, 122  
 Isomerism, 105, 874  
   geometrical, 118–119, 120  
   stereoisomerism, 117–118, 120  
 Isomorphous systems, 365, 874  
   binary, *see* Binary isomorphous alloys  
 Isoprene, 118  
 Isostatic powder pressing, 625  
 Isostrain, in fiber-reinforced composites, 657  
 Isostress, in fiber-reinforced composites, 659  
 Isotactic configuration, 117, 120, 874  
 Isothermal, 874  
 Isothermal transformation  
   diagrams, 434–444, 874  
   4340 alloy steel, 443  
   0.76 wt% C steel, 442  
   0.45 wt% C steel, 477  
 Isotopes, 19, 874  
 Isotropic materials, 86, 663, 874  
 Izod impact test, 328–329, 874
- J**  
 Jominy end-quench test, 604–605, 874  
 Junction depth, diffusion, 185  
 Junction transistors, 511–512, 874
- K**  
 Kaolinite clay, 61–62, 620  
 Kevlar, *see* Aramid  
 Kinetics, 432–433, 874  
   crystallization of polymers, 464–465  
   oxidation, 719–720  
   phase transformations, 432–433  
 Knoop hardness, 234, 236  
 Kovar:  
   as low-expansion alloy, 740  
   thermal properties, 737
- L**  
 Ladder polymer, 724  
 Lamellae, 126  
 Laminar composites, 677–678, 874  
 Large-particle composites, 649–653, 875  
 Larson-Miller parameter, 346  
   plots of, 346, 357  
 Lasers, 804–808, 875  
   semiconductor, 805–807, 808  
   types, characteristics, and applications, 807  
 Laser beam welding, 601  
 Latent heat of fusion, 425  
 Latex, 583  
 Lattice parameters, 65, 66, 875  
 Lattices, 46, 875  
 Lattice strains, 264–265, 275–276, 463, 875  
 Lattice waves, 735  
 Laue photograph, 44, 91  
 Layered silicates, 61–62  
 Lay-up, in prepreg processing, 676  
 Lead, 564  
   atomic radius and crystal structure, 47  
   recrystallization temperature, 283  
   superconducting critical temperature, 778  
 Lead-free solders, 381  
 Lead-tin phase diagram, 377, 380–387  
 Lead titanate, 575  
 Lead zirconate, 527  
 Lead-zirconate-titanate, 526  
 Leak-before-break design, 321  
 Leathery region, polymers, 230–231  
 LEDs, *see* Light-emitting diodes  
 Lever rule, 368–369, 875  
 Life cycle analysis/assessment, 821  
 Light:  
   absorption, 794–797  
   reflection, 794  
   refraction, 792–793  
   scattering, 800  
   transmission, 798  
 Light-emitting diodes, 875  
   organic, 802  
   polymer, 802  
   semiconductor, 802  
 Lime, 573  
 Linear atomic density, 80–81  
 Linear coefficient of thermal expansion, 342, 738–740, 744, 745, 875  
   values for selected materials, 737, 845–848  
 Linear defects, 147–150  
 Linear polymers, 115, 875  
 Liquid crystal polymers, 585–586, 875  
 Liquidus line, 365, 366, 376, 875  
 Liquidus temperatures, Ge-Si system, 414  
 Lodestone (magnetite), 752, 759  
 Longitudinal direction, 655, 875  
 Longitudinal loading, composites, 655–658, 660–661  
 Lost-foam casting, 597, 599  
 Lost-wax casting, 599  
 Low-angle grain boundaries, *see* Small-angle grain boundaries  
 Low-carbon steels, 544–546  
 Low-cycle fatigue, 336  
 Lower critical temperature (ferrous alloys), 602–603, 875  
 Low-expansion alloys, 740  
   in wristwatches, 740  
 Lower yield point, 212, 213  
 Low-expansion alloys, 740  
 Luminescence, 801, 875
- M**  
 Macromolecules, 105, 875  
 Magnesia, *see* Magnesium oxide  
 Magnesium:  
   automobile wheel, 44  
   diffraction pattern, 44  
   elastic and shear moduli, 206  
   Poisson's ratio, 206  
   single crystal (cleaved), 44  
   slip systems, 266  
 Magnesium alloys, 560, 561  
 Magnesium fluoride, optical properties, 794  
 Magnesium-lead phase diagram, 389  
 Magnesium oxide:  
   bonding energy and melting temperature, 30  
   flexural strength, 217  
   index of refraction, 793  
   modulus of elasticity, 206  
   thermal properties, 737  
 Magnesium oxide-aluminum oxide phase diagram, 393  
 Magnetic anisotropy, 767–768  
 Magnetic ceramics, 759–762  
 Magnetic dipoles, 752–753  
 Magnetic domains, *see* Domains  
 Magnetic energy product, 770–771

- Magnetic field strength, 753–755, 875
- Magnetic field vectors, 753–755
- Magnetic flux density, 753, 755, 875  
critical values for  
  superconductors, 778
- Magnetic hard disk drives, 773–775
- Magnetic hysteresis, 764–766  
factors that affect, 767  
soft and hard magnetic materials, 768–773
- Magnetic induction, *see* Magnetic flux density
- Magnetic materials:  
  hard, 770–773  
  low thermal expansion characteristics, 740  
  neodymium-iron-boron alloys, 772–773  
  samarium-cobalt alloys, 772  
  soft, 768–770
- Magnetic moments, 755–756  
cations, 761
- Magnetic permeability, 754, 788, 792–793
- Magnetic recording, 773
- Magnetic storage, 773–776
- Magnetic susceptibility, 754, 875  
selected diamagnetic and paramagnetic materials, 757  
various units for, 755
- Magnetic tapes, 775–776
- Magnetic texture, 87, 769
- Magnetic units, conversion factors, 755
- Magnetism:  
  basic concepts, 752–756  
  electron spin and, 756
- Magnetite (lodestone), 752, 759
- Magnetization, 754, 755, 875  
easy and hard directions, 767  
saturation, 758, 761–762, 878
- Magnetocrystalline anisotropy, 767
- Magnetostrictive materials, 11
- Magnetorheological fluids, 11
- Majority charge carriers, 500
- Malleability, *see* Ductility
- Malleable cast iron, 551, 552, 554, 875  
compositions, mechanical properties, and applications, 552
- Manganese oxide, as antiferromagnetic material, 759
- Manufacturing techniques, economics, 818–819
- Martensite, 440–442, 446–447, 455–456, 875  
alloying to favor formation of, 447  
crystal structure, 441  
hardness, 452  
hardness vs. carbon content, 452  
shape-memory phase transformations, 457–458  
tempering of, 452–455
- Martensitic stainless steels, 548, 549
- Materials:  
  advanced, 10–12  
  by design, 12  
  classification of, 5–10  
  costs, 859–863  
  current and future needs, 12–13  
  disposal of, 820–821  
  economic considerations, 817–819  
  engineered, 819, 820  
  of the future, 11–12  
  historical development of, 2  
  nanoengineered, 11–12  
  nonrenewable sources of, 13, 820  
  smart, 11  
  total cycle, 819–820
- Materials engineering, 2–3, 202
- Materials of Importance:  
  aluminum electrical wires, 494–496  
  aluminum for integrated circuit interconnects, 187–188  
  biodegradable and biorenewable polymers/plastics, 824–825  
  carbon nanotubes, 64  
  carbonated beverage containers, 9  
  catalysts (and surface defects), 154  
  Invar and other low-expansion alloys, 740  
  an iron silicon alloy that is used in transformer cores, 769  
  lead-free solders, 381  
  light-emitting diodes, 802–803  
  metal alloys used for euro coins, 565  
  nanocomposites in tennis balls, 679–680  
  phenolic billiard balls, 580  
  piezoelectric ceramics, 575  
  shape-memory alloys, 456–459  
  shrink-wrap polymer films, 292  
  tin (its allotropic transformation), 67  
  water (its volume expansion upon freezing), 34
- Materials science, 2–4
- Matrix phase, 875  
definition, 648  
fiber-reinforced composites, 665
- Matthiessen's rule, 492, 875
- Mean stress (fatigue), 333–334, 339
- Mechanical properties, *see also* specific mechanical properties  
  grain size and, 274  
  variability, 239–241
- Mechanical twins, 152, 272. *See also* Twinning
- Mechanics of materials, 205
- Medium carbon steels, 544, 546–547
- Meissner effect, 777
- Melamine-formaldehyde, repeat unit structure, 864
- Melting (polymers), 465–466
- Melting point (temperature):  
  and bonding energy for selected materials, 30  
  ceramics, 616  
  factors that affect (polymers), 467–468  
  glasses, 875  
  polymers, 466, 467, 868
- Melt spinning, 634
- Memory, flash, 513
- Mercury:  
  bonding energy and melting temperature, 30  
  superconducting critical temperature, 778
- Mer unit, 106
- Metal alloys, *see* Alloys
- Metallic bonding, 31–32, 875
- Metallic glasses, 491
- Metallographic examination, 156
- Metal-matrix composites, 671–672, 875
- Metals, *see also* Alloys; Crystalline materials  
  corrosion, *see* Corrosion  
  costs, 859–861  
  crystal structures, *see* Crystal structures  
  defined, 5–6, 875  
  density values, 830–832  
  elastic modulus values, 206, 833–835  
  as electrical conductors, 486  
  electrical resistivity values, 854–855  
  electron band structure, 488  
  fabrication, 596–604



- Metals (*Continued*)
- fracture toughness for selected, 319, 843–844
  - linear coefficient of thermal expansion values, 737, 845–846
  - optical properties, 791–792
  - oxidation, 717–720
  - Poisson's ratio for selected, 206, 837–838
  - shear moduli, 206
  - specific heat values, 737, 851–852
  - strengthening, *see* Strengthening of metals
  - thermal conductivity values, 737, 848–849
- Metastability, 875
- of microstructures, 433–434
- Metastable states, 363
- Methane, 30–31, 104
- Methyl alcohol, 106
- Methyl group, 108
- Mica, 62
- dielectric constant and dielectric strength, 519
- Microconstituents, *see also* specific microconstituent phases:
- definition, 386, 875
  - in eutectic alloys, 385–387
  - in steel alloys, 401–408
- Microcracks, 315–317
- in ceramics, 322–323
- Microelectromechanical systems (MEMS), 11, 573–574, 875
- Microelectronics, 514–515
- Microindentation hardness tests, 236
- Micron, 155
- Microscopic techniques, useful resolution ranges, 159
- Microscopy, 155–159, 875
- Microstructure, 155, 875
- austenite, 400
  - bainite, 438
  - bonded ceramic abrasive, 572
  - brass during recrystallization and grain growth, 281
  - carbon-black-reinforced rubber, 651
  - carbon nanotube, 64
  - cast irons, 551, 554
  - cemented carbide, 651
  - coarse and fine pearlite, 437
  - compacted graphite iron, 551
  - cored structure, brass, 374
  - craze in poly(phenylene oxide), 327
  - development in eutectic alloys, 380–387
  - development in iron-carbon alloys, 401–408
  - development in isomorphous alloys:
    - equilibrium cooling, 371–372
    - nonequilibrium cooling, 372–374
  - eutectic (lead-tin), 384
  - ferrite ( $\alpha$ ), 400
  - glass-ceramic, 568
  - glass fracture surface, 326
  - gray cast iron, 551
  - hard disk drive, 775
  - hypereutectoid steel alloy, 406
  - hypoeutectoid steel alloy, 404
  - influence of cooling rate, 606
  - integrated circuit, 483, 514
  - magnetic tape storage, 775
  - martensite, 441
  - metastable, 363
  - microscopic examination, 153–159
  - pearlite, 402, 437
  - pearlite partially transformed to spheroidite, 440
  - polycrystalline metal before and after deformation, 271
  - porcelain, 624
  - precipitation-hardened aluminum alloy, 462
  - reversible-matrix, Al-Cu eutectic, 385
  - single-phase iron-chromium alloy, 157
  - sintered ceramic, 626
  - size ranges, various structural features, 159
  - spheroidite, 440
  - spherulite (natural rubber), 102
  - stress corrosion in brass, 713
  - TEM (high resolution)—single crystals of  $(\text{Ce}_{0.5}\text{Zr}_{0.5})\text{O}_2$ , 134, 154
  - tempered martensite, 453
- Microvoids, 310–311, 327
- Miller-Bravais index system, 72–73
- Miller indices, 76–78, 875
- Minority charge carriers, 500
- Mirror region (ceramics), 325–326
- Mist region (ceramics), 325–326
- Mixed dislocations, 147, 149, 262, 875. *See also* Dislocations
- Mobility, of charge carriers, 490–491, 875
- influence of dopant content, 504
  - influence of temperature, 504–505
  - ionic, 516
  - values for selected semiconductors, 497
- Modulus of elasticity, 205–208, 875
- anisotropy, 86
  - atomic bonding and, 207–208, 251–252
  - carbon nanotubes, 64
  - copper reinforced with tungsten, 650
  - influence of porosity on, in ceramics, 224–226
  - ranges for material types (bar chart), 6
  - relation to shear modulus, 210
  - selected ceramics, 206, 835–836
  - selected fiber-reinforcement materials, 664, 836
  - selected metals, 206, 833–835
  - selected polymers, 206, 836
  - temperature dependence:
    - elastomers, 293
    - metals, 208
    - and thermal fatigue, 342
    - and thermal stresses, 744
    - values for various materials, 833–837
- Modulus of resilience, 216, 218
- Modulus of rupture, 224. *See also* Flexural strength
- Mohs hardness scale, 233, 236, 237
- Molarity, 693, 875
- Molding, plastics, 632–634, 875
- Mole, 19, 875
- Molecular chemistry, polymers, 106–110, 875
- Molecular configurations, polymers, 116–120
- Molecular mass, 111
- Molecular materials, 35
- Molecular shape, polymers, 113–115
- Molecular structure, polymers, 115–116, 876
- Molecular weight, 876
- influence on polymer melting/glass transition temperatures, 468
  - influence on mechanical behavior, polymers, 290, 291
  - number-average, 111–113
  - weight-average, 111–113
- Molecular weight distribution, 111–112



- Molecules, polar, 33, 877  
 Molybdenum, 562  
   atomic radius and crystal structure, 47  
   density, 831  
   modulus of elasticity, 835  
   Poisson's ratio, 837  
   properties as wire, 664  
   slip systems, 266  
   thermal properties, 846, 849, 852  
   yield and tensile strengths, ductility, 217  
 Moment of inertia, 223, 256, 670  
 Monel, 564  
 Monoclinic crystal system, 66  
 Monomers, 106, 876  
 MOSFET transistors, 511, 512–513, 876  
 Mullite, 365, 570, 571  
   flexural strength, 217  
   modulus of elasticity, 206  
 Muntz metal, 556  
 Muscovite (mica), 62
- N**
- Nanocomposite barrier coatings, 679–680  
 Nanomaterials, 11–12  
 Nanotechnology, 12  
 Nanotubes, carbon, 12, 64  
 Natural aging, 464, 876  
 Natural rubber (polyisoprene), 118–119, 580, 581  
   degradation resistance, 722  
   melting and glass transition temperatures, 868  
   stress-strain behavior, 295  
   thermal properties, 737  
 NBR, *see* Nitrile rubber (NBR)  
 Necking, 213  
   complex stress state in, 220  
   criterion for, 255  
   in ductile fracture, 310–311  
   polymers, 228  
 Néel temperature, 763  
 Neodymium-iron-boron magnets, 772–773  
 Neoprene rubber, 581, 722  
 Nernst equation, 696  
 Network formers (glass), 93  
 Network modifiers (glass), 93  
 Network polymers, 115, 116, 876  
 Network solids, 65  
 Neutrons, 18
- Nichrome, 494  
 Nickel, 564  
   atomic radius and crystal structure, 47  
   Curie temperature, 763  
   elastic and shear moduli, 206  
   as ferromagnetic material, 758–759  
   magnetization curves (single crystal), 767  
   Poisson's ratio, 206  
   recrystallization temperature, 283  
   slip systems, 266  
   thermal properties, 737  
   thoria-dispersed (TD), 653  
   yield and tensile strengths, ductility, 217  
 Nickel ferrite, 761  
 Niobium, 562  
 Niobium alloys, as superconductors, 778  
 Nitinol, 456–457  
 Nitrile rubber (NBR), 122  
   characteristics and applications, 581  
   degradation resistance, 722  
 Noble metals, 562  
 Nodular iron, *see* Ductile iron  
 Noncrystalline materials, 46, 91–93, 876  
 Nondestructive evaluation, *see* Nondestructive testing  
 Nondestructive inspection, *see* Nondestructive testing  
 Nondestructive testing, 320  
 Nonequilibrium cooling, 408  
 Nonequilibrium phases, 432  
 Nonequilibrium solidification, 372–374  
 Nonferrous alloys, 556–566, 876.  
   *See also* specific nonferrous alloys  
 Nonsteady-state diffusion, 175–179, 876  
 Nonstoichiometry, 138  
 Normalizing, 446, 603, 876  
 Notches, effect of, 316  
 Notch toughness, 219, 328  
*n-p-n* Junction transistors, 511–512  
*n*-Type semiconductors, 499–500, 876  
 Nucleation, 423–430, 876  
   heterogeneous, 429–430  
   homogeneous, 424–429
- Nucleation rate, 427  
   temperature dependence, 427  
     homogeneous *vs.*  
     heterogeneous, 431  
 Nucleus, phase particle, 424  
 Number-average molecular weight, 111–113  
 Nylon, fatigue behavior, 337  
 Nylon 6,6: 110  
   degradation resistance, 721  
   density, 133, 833  
   dielectric constant and dielectric strength, 519  
   electrical conductivity, 515  
   mechanical properties, 206, 217  
   melting and glass transition temperatures, 467, 868  
   repeat unit structure, 110, 865  
   thermal properties, 737  
 Nylons, trade names, characteristics, and applications, 578
- O**
- Octahedral position, 83, 760, 876  
 Ohm's law, 484–485, 876  
 Oil, as quenching medium, 609  
 Opacity, 790, 876  
   in insulators, 800  
   in semiconductors, 794–795  
 Optical fibers, 574, 808–810, 876  
 Optical flint glass, composition and properties, 567, 793  
 Optical microscopy, 155–157  
 Optical properties, 787  
   of metals, 791–792  
   of nonmetals, 792–800  
 Ordered solid solution, 387, 556  
 Organic light-emitting diodes, 802  
 Orientation polarization, 523, 877  
 Orthorhombic crystal system, 65, 66  
 Osmium, 562  
 Overaging, 461, 876  
 Overvoltage, 699–702  
 Oxidation, 691–692, 876  
   kinetics, 719–720  
   metals, 717–720  
 Ozone, degradation of polymers, 722, 723
- P**
- Palladium, 174–175, 562  
 Paraffins, 104  
 Paramagnetism, 756–757, 876



- Parisons, 617, 634
- Particle-reinforced composites, 649–653, 876
- Pascal-second, 286
- Passivity, 705–706, 876
- Pauli exclusion principle, 22, 876
- Pearlite, 401–402, 876
- coarse, 436–437, 870
- colonies, 401
- as composite, 648
- fine, 436–437, 449, 873
- formation of, 401–402, 434–436, 446, 455
- hardness vs. transformation temperature, 451
- mechanical properties, 448–452
- Pentane, 104
- Performance (materials), 3
- Periclase, 569, 570, *see also* Magnesium oxide
- Periodic table, 25–26, 876
- Peritectic reaction, 390, 876
- Permalloy (45), magnetic properties, 770
- Permanent dipoles, 33, 523
- Permeability (in polymers), 189–191
- Permeability coefficient, 189
- Permeability, magnetic, 754–755, 788, 792–793, 876
- Permittivity, 299, 517–518, 788, 792–793, 876
- Perovskite structure, 57, 526, 778
- Perpendicular magnetic recording media, 751, 774–775
- PET, *see* Polyester(s)
- Phase boundaries, 151–152
- Phase diagrams, 876
- binary eutectic systems, 374–387
- binary isomorphous systems, 365–374
- ceramic systems, 391–395
- congruent phase transformations, 391
- definitions/basic concepts, 360–363
- eutectoid and peritectic reactions, 390
- intermediate phases in, 387, 389
- interpretation of, 367–371
- pressure-temperature (unary), 363–364
- specific:
- aluminum-copper, 418, 462
- aluminum-neodymium, 417
- aluminum oxide-chromium oxide, 392
- carbon dioxide (pressure-temperature), 421
- cast iron, 550
- copper-beryllium, 481
- copper-nickel, 366
- copper-silver, 375, 397
- copper-zinc, 388, 390
- halfniium-vanadium, 391
- iron-carbon (graphite), 550
- iron-iron carbide, 399
- lead-tin, 377, 380–387
- magnesium-lead, 389
- magnesium oxide-aluminum oxide, 393
- nickel-titanium, 392
- silica-alumina, 395
- sugar-water, 361
- tin-bismuth, 381
- titanium-copper, 418
- water (pressure-temperature), 359, 364, 419, 421
- water-sodium chloride, 378
- zirconia-calcia, 394
- ternary, 395
- Phase equilibria, 362–363, 876
- Phases, 362, 876
- Phase transformation diagrams:
- continuous-cooling, 871
- metals, 445–448, 478
- glass-ceramics, 568
- isothermal, 434–444, 874
- Phase transformation rate, 433
- martensitic transformation, 441
- temperature dependence, 431
- Phase transformations, 876
- athermal, 441
- classification, 423
- shape-memory effect, 457–458
- Phenol, 106
- Phenol-formaldehyde (Bakelite):
- in billiard balls, 542, 580
- dielectric constant and dielectric strength, 519
- electrical conductivity, 515
- mechanical properties, 206, 217
- repeat unit structure, 110, 864
- thermal properties, 737
- Phenolics, trade names, characteristics, and applications, 579
- Phenyl group, 105, 106
- Phonons, 735, 741, 742, 876
- Phosphorescence, 801, 876
- Photoconductivity, 801, 876
- Photomicrographs, 155, 876
- Photonic signal, 808
- Photons, 735, 789, 876
- Photovoltaic solar cell, 786
- Pickling, of steels, 714
- Piezoelectricity, 575, 876
- Piezoelectric ceramics, 527
- in ink-jet printer head, 575
- as Materials of Importance, 575
- properties and applications, 575
- in smart materials/systems, 11
- Pilling-Bedworth ratio, 718, 876
- selected metals, 718
- Pitting corrosion, 709–710, 876
- Plain carbon steels, 442, 544, 876
- Planar atomic density, 80–81
- Planck's constant, 789, 876
- Planes, *see* Crystallographic planes
- Plane strain, 317, 876
- Plane strain fracture toughness, 318, 876
- ceramic-matrix composites, 673–674
- selected materials, 319, 843–844
- Plaster of Paris, 571, 599, 621
- Plastic deformation, 211–222, 877
- ceramics, 286
- dislocation motion and, 261–272
- in fracture, 310
- influence on electrical conductivity, 492–493
- polycrystalline materials, 270–271
- semicrystalline polymers, 287, 289–290
- twinning, 272
- Plasticizers, 630, 877
- Plastics, 876
- characteristics and applications, 577–579
- in composites, 651
- forming techniques, 631–634
- Platinum, 652
- atomic radius and crystal structure, 47
- electrical conductivity, 491
- Plexiglass, *see* Poly(methyl methacrylate)
- Plywood, 678
- p-n-p* Junction transistors, 511–512
- p-n* Junctions:
- for light-emitting diodes, 802
- for rectification, 509–510
- Point coordinates, 68–70
- Point defects, 136–146, 877
- Poise, 286



- Poisson's ratio, 209–211, 877  
values for various materials, 206, 837–838
- Polarization, 519–520, 877. *See also*  
Electronic polarization; Ionic polarization; Orientation polarization
- Polarization (corrosion), 699–702, 877  
corrosion rates from, 703–705
- Polar molecules, 33, 877
- Polyacetylene, repeat unit structure, 516
- Polyacrylonitrile (PAN):  
carbon fibers, 667  
repeat unit structure, 122, 864
- Poly(alkylene glycol), as a quenching agent, 609
- Poly(amide-imide) (PAI), repeat unit structure, 864
- Polybutadiene, *see* Butadiene
- Poly(butylene terephthalate) (PBT), repeat unit structure, 865
- Polycarbonate:  
density, 833  
degradation resistance, 721  
mechanical properties, 206, 217, 836, 838, 842  
melting and glass transition temperatures, 467, 868  
plane strain fracture toughness, 319  
reinforced *vs.* unreinforced properties, 662  
repeat unit structure, 110, 865  
trade names, characteristics, and applications, 578
- Polychloroprene, *see* Chloroprene; Chloroprene rubber
- Polychlorotrifluoroethylene, repeat unit structure, 865
- Polycrystalline materials, 85, 86, 877  
plastic deformation, 270–271
- Poly(dimethyl siloxane), 582  
degradation resistance, 722  
repeat unit structure, 582, 865
- Polyester(s):  
degradation resistance (PET), 721  
density (PET), 833  
fatigue behavior (PET), 337  
magnetic storage tape, 776  
mechanical properties (PET), 206, 217, 836, 842  
melting and glass transition temperatures (PET), 467, 868  
in polymer-matrix composites, 668  
recycle code and products (PET), 823  
repeat unit structure (PET), 110, 865  
trade names, characteristics, and applications, 579
- Polyetheretherketone (PEEK), 669  
degradation resistance, 721  
melting and glass transition temperatures, 868  
repeat unit structure, 865
- Polyetherimide (PEI), 669
- Polyethylene, 107, 109  
crystal structure of, 123  
degradation resistance, 721  
density, 833  
dielectric constant and dielectric strength, 519  
electrical conductivity, 515  
fatigue behavior, 337  
index of refraction, 793  
mechanical properties, 206, 217, 836, 838, 842  
melting and glass transition temperatures, 467, 868  
recycle codes and products, 823  
single crystals, 126  
thermal properties, 737, 847, 850, 853  
trade names, characteristics, and applications, 578  
ultra-high-molecular-weight, *see* Ultra-high-molecular-weight polyethylene
- Poly(ethylene naphthalate), as magnetic storage tape, 776
- Poly(ethylene terephthalate) (PET), *see* Polyester(s)
- Poly(hexamethylene adipamide), *see* Nylon 6,6
- Polyimides:  
glass transition temperature, 868  
polymer-matrix composites, 666, 669  
repeat unit structure, 866
- Polyisobutylene:  
melting and glass transition temperatures, 868  
relaxation modulus, 257  
repeat unit structure, 118, 836
- Polyisoprene, *see* Natural rubber (polyisoprene)
- Poly(lactic acid), 825
- Polymer-matrix composites, 665–671, 877
- Polymerization, 106–108, 627–629  
degree of, 112
- Polymer light-emitting diodes, 802–803
- Polymers, 7–8, 106, 877. *See also* Plastics  
additives, 630–631  
classification (molecular characteristics), 120  
coefficient of thermal expansion values, 737, 847  
conducting, 516–517  
costs, 862–863  
crosslinking, *see* Crosslinking  
crystallinity, 122–127, 871  
crystallization, 464–465  
crystals, 125–127  
defined, 7–8, 106  
defects in, 143  
deformation (semicrystalline):  
elastic, 287, 288  
plastic, 287, 289–290  
degradation of, 720–724  
density, 123  
density values, 832–833  
diffusion in, 189–191  
ductility values, 217, 842  
elastic modulus values, 206, 836  
elastomers, 293–295, 580–582  
electrical properties, 515, 516–517, 519, 856  
fibers, 582–583  
fracture mechanics, 328  
fracture toughness values, 319, 844  
glass transition, 466–467  
glass transition temperatures, 466, 467, 868  
as insulators, 515, 525  
ladder, 724  
as light-emitting diodes, 802–803  
liquid crystal, 585–586  
mechanical properties, 226–228, 239  
factors that affect, 290–292  
values of, 206, 217, 836, 838, 842, 844  
melting of, 465–466  
melting temperatures, 467, 868  
miscellaneous applications, 583–584  
molecular chemistry, 106–110  
molecular configuration, 116–119  
molecular shape, 113–115  
molecular structure, 115–116



- Polymers (*Continued*)  
 molecular weight, 111–113  
 natural, 103  
 opacity and translucency, 800–801  
 Poisson's ratio values, 206, 838  
 radiation effects, 722–723  
 refraction indices, 793  
 semicrystalline, 123, 125–127, 287–292  
 specific heat values, 737, 853  
 spherulites in, 102, 126–127, 287, 292  
 stereoisomerism, 117–118  
 stress-strain behavior, 226–228  
 swelling and dissolution, 720–721  
 tensile strength values, 217, 842  
 thermal conductivity values, 737, 850–851  
 thermal properties, 737, 739, 743–744  
 thermoplastic, *see* Thermoplastic polymers  
 thermosetting, *see* Thermosetting polymers  
 types of, 103  
 viscoelasticity, 229–232  
 weathering, 724  
 yield strength values, 217, 842
- Poly(methyl methacrylate):  
 density, 833  
 electrical conductivity, 515  
 fatigue behavior, 337  
 index of refraction, 793  
 mechanical properties, 206, 217, 836, 838, 842  
 melting and glass transition temperatures, 868  
 plane strain fracture toughness, 319, 844  
 repeat unit structure, 110, 866  
 stress-strain behavior as function of temperature, 228  
 trade names, characteristics, and applications, 578
- Polymorphic transformations, in iron, 398–399
- Polymorphism, 65, 877
- Poly(paraphenylene terephthalamide), *see* Aramid
- Poly(phenylene oxide) (PPO), repeat unit structure, 866
- Poly(phenylene sulfide) (PPS), 669  
 melting and glass transition temperatures, 868  
 repeat unit structure, 866
- Polypropylene, 108  
 degradation resistance, 721  
 density, 133, 833  
 fatigue behavior, 337  
 index of refraction, 793  
 kinetics of crystallization, 465  
 mechanical properties, 206, 217, 836, 838, 842  
 melting and glass transition temperatures, 467, 868  
 plane strain fracture toughness, 844  
 recycle code and products, 823  
 repeat unit structure, 109, 866  
 thermal properties, 737, 847, 850, 853  
 trade names, characteristics, and applications, 579
- Polystyrene:  
 degradation resistance, 721  
 density, 833  
 dielectric properties, 519  
 electrical conductivity, 515  
 fatigue behavior, 337  
 index of refraction, 793  
 mechanical properties, 206, 217, 836, 838, 842  
 melting and glass transition temperatures, 467, 868  
 plane strain fracture toughness, 319, 844  
 repeat unit structure, 110, 867  
 thermal properties, 737, 847, 850, 853  
 trade names, characteristics, and applications, 579  
 viscoelastic behavior, 231–232
- Polytetrafluoroethylene, 108  
 degradation resistance, 721  
 density, 133, 833  
 dielectric constant and dielectric strength, 519  
 electrical conductivity, 515  
 fatigue behavior, 337  
 index of refraction, 793  
 mechanical properties, 206, 217, 836, 838, 842  
 melting and glass transition temperatures, 467, 868  
 repeat unit structure, 109, 867  
 thermal properties, 737, 847, 851, 853
- Poly(vinyl acetate), repeat unit structure, 867
- Poly(vinyl alcohol), repeat unit structure, 867
- Poly(vinyl chloride):  
 density, 833  
 mechanical properties, 206, 217, 836, 838, 842  
 melting and glass transition temperatures, 467, 868  
 recycle code and products, 823  
 repeat unit structure, 109, 867
- Poly(vinyl fluoride):  
 melting and glass transition temperatures, 868  
 repeat unit structure, 867
- Poly(vinylidene chloride):  
 melting and glass transition temperatures, 868  
 repeat unit structure, 867
- Poly(vinylidene fluoride):  
 glass transition temperature, 868  
 repeat unit structure, 867
- Porcelain, 621  
 dielectric constant and dielectric strength, 519  
 electrical conductivity, 515  
 microstructure, 624
- Porosity:  
 ceramics, 224–226  
 formation during sintering, 625–626  
 influence on flexural strength, ceramics, 224–226  
 influence on modulus of elasticity, ceramics, 225  
 influence on thermal conductivity, 743  
 optical translucency and opacity, 800  
 refractory ceramics, 570
- Portland cement, 572
- Portland cement concrete, 652
- Posttensioned concrete, 653
- Potassium chloride, bonding energy, determination of, 38
- Potassium niobate, 575
- Powder metallurgy, 600, 877
- Powder pressing, ceramics, 624–625
- Powder x-ray diffraction techniques, 89–91
- Precipitation-hardenable stainless steels, 548, 549



- Precipitation hardening, 459–464, 877  
 heat treatments, 459–461  
 mechanism, 461–464
- Prepreg production processes, 676, 877
- Pressing:  
 ceramics, powdered, 624–626  
 glass, 616
- Prestressed concrete, 652–653, 877
- Primary bonds, 28–32, 877
- Primary creep, 343
- Primary phase, 385, 77
- Principal quantum number, 21
- Principle of combined action, 648, 877
- Process annealing, 602, 877
- Processing, materials, 3
- Processing/structure/properties/  
 performance correlations:  
 glass-ceramics, 97, 300, 590,  
 591, 640  
 summary, 641  
 introduction, 13–15  
 polymer fibers, 37, 130, 249,  
 301, 475  
 summary, 641  
 silicon semiconductors, 36, 164,  
 193, 194, 531, 532, 533, 534  
 summary, 534  
 steels (iron-carbon alloys), 164,  
 165, 194, 248, 299, 300, 413,  
 473, 474  
 summary, 638, 639  
 topic timelines, 14–15
- Proeutectoid cementite, 405, 877
- Proeutectoid ferrite, 404, 877
- Propane, 104
- Properties, 877. *See also*  
 Processing/structure/  
 properties/performance  
 categories of, 3
- Proportional limit, 212, 877
- Protons, 18
- PTFE, *see* Polytetrafluoroethylene
- p*-Type semiconductors, 500–501,  
 877
- Pultrusion, 675
- Pyrex glass:  
 composition, 567  
 density, 832  
 fracture of soda-lime imitation,  
 746  
 electrical resistivity, 856  
 index of refraction, 793  
 mechanical properties, 835,  
 838, 841  
 plane strain fracture toughness,  
 844  
 thermal properties, 737, 846,  
 850, 853  
 thermal shock, 745
- Pyroceram:  
 composition, 567  
 density, 832  
 electrical resistivity, 856  
 flexural strength, 217  
 modulus of elasticity, 206  
 plane strain fracture toughness,  
 844  
 Poisson's ratio, 838  
 thermal properties, 846, 850, 853
- Q**
- Quantum mechanics, 19, 877
- Quantum numbers, 20–22, 877  
 magnetic, 22, 756
- Quartz, 60, 620–621, 624  
 index of refraction, 793  
 as piezoelectric material, 527
- Quenching media, 608–610
- R**
- Radiation effects, polymers,  
 722–723
- Random copolymers, 122, 877
- Range of stress, 333, 334
- Recombination, electron-hole,  
 510, 796, 802  
 in light-emitting diodes, 802
- Recovery, 279, 877
- Recrystallization, 280–284, 602, 877  
 effect on properties, 282  
 kinetics for copper, 433
- Recrystallization temperature,  
 280, 282–283, 877  
 dependence on alloy content,  
 280  
 dependence on percent cold  
 work, 280, 282  
 selected metals and alloys, 283
- Rectification, 509–510
- Rectifying junctions, 509, 877
- Recycling:  
 issues in materials science and  
 engineering, 821–824, 826  
 of beverage cans, 816  
 of composite materials, 826  
 of glass, 822  
 of metals, 822  
 of plastics and rubber, 822–823,  
 826
- Recycling codes and products,  
 823
- Reduction (electrochemical),  
 691, 877
- Reduction in area, percent, 216
- Reflection, 794, 877
- Reflectivity, 790, 798
- Refraction, 792–794, 877  
 index of, 792, 874
- Refractories (ceramics), 566,  
 569–571, 877  
 corrosion, 720
- Refractory metals, 562
- Reinforced concrete, 652–653, 877
- Reinforcement efficiency, table of,  
 663
- Relative permeability, 754, 755, 877
- Relative permittivity, *see* Dielectric  
 constant
- Relaxation frequency, 524, 877
- Relaxation modulus, 229–231, 877
- Relaxation time, 257
- Remanence (remanent induction),  
 765, 878
- Repeated stress cycle, 333
- Repeat units,  
 bifunctional and trifunctional,  
 109  
 table of, 109–110
- Residual stresses, 602, 878. *See also*  
 Thermal stresses  
 glass, 618  
 martensitic steels, 452
- Resilience, 216, 218, 878
- Resin, polymer, 665
- Resistance (electrical), 484
- Resistivity, 878. *See also* Electrical  
 resistivity
- Resolved shear stresses, 267, 878
- Retained austenite, 441
- Reverse bias, 510, 878
- Reversed stress cycle, 333
- Rhodium, 562
- Rhombohedral crystal system,  
 65, 66
- Rochelle salt, 526
- Rock salt structure, 56, 58
- Rockwell hardness tests, 233–235
- Rolling, of metals, 597–598, 878
- Rouge, 571
- Rovings, 675



- Rubbers, 115, 122  
 natural, *see* Natural rubber (polyisoprene)  
 synthetic, 122, 580–581, 582  
 trade names, characteristics, and applications, 581
- Rubbery region, polymers, 230, 231
- Ruby, *see also* Aluminum oxide lasers, 804–805  
 optical characteristics, 799
- Rule of mixtures, 878  
 composites, 650, 657–658, 660, 661, 662, 670  
 electrical resistivity, 493
- Rupture, 343, 878
- Rupture lifetime, 343, 344  
 extrapolation of, 346–347
- Rust, 692
- Ruthenium, 562
- S**
- Sacrificial anodes, 716, 878
- Safe stress, 242, 878
- Safety factors, 242, 321
- Samarium-cobalt magnets, 772
- Sand casting, 599
- Sandwich panels, 649, 678–679, 878
- Sapphire, *see also* Aluminum oxide optical transmittance, 799
- Saturated hydrocarbons, 104, 878
- Saturation, extrinsic semiconductors, 502
- Saturation magnetization, 758, 761–762, 764–765, 878  
 temperature dependence, 763
- SBR, *see* Styrene-butadiene rubber
- Scaling, 717
- Scanning electron microscopy, 158, 878
- Scanning probe microscopy, 12, 136, 158–159, 878
- Scanning tunneling microscope, 64
- Schmid factor, 303
- Schottky defect, 137–138, 188, 878  
 equilibrium number, 139–140
- Scission, 722, 878
- Scleroscope hardness, 236
- Screw dislocations, 147, 149, 262, 263, 878. *See also* Dislocations in polymers, 143
- Seawater, as corrosion environment, 714
- Secant modulus, 207
- Secondary bonds, 32–33, 878
- Secondary creep, 343–344
- Segregation, 374
- Selective leaching, 711, 878
- Self-diffusion, 172, 878
- Self-interstitials, 136, 878
- SEM, *see* Scanning electron microscopy
- Semiconductor devices, 509–515
- Semiconductor lasers, 805–807
- Semiconductors:  
 band structure, 48, 489–490  
 carbon nanotubes as, 64  
 in computers, 513  
 costs, 861, 862  
 defined, 10, 486, 878  
 diffusion in, 184–187  
 extrinsic, 499–502, 872  
 fullerenes as, 65  
 intrinsic, 496–498, 874  
 intrinsic carrier concentration, 498, 502  
 light absorption, 795–797  
*n*-Type, 499–501, 876  
*p*-Type, 500–501, 877  
 temperature dependence:  
   electron concentration, *n*-type Si, 503  
   electron mobility, Si, 504  
   hole mobility, Si, 504  
   intrinsic carrier concentration of Ge, 503  
   intrinsic carrier concentration of Si, 503
- Semicrystalline polymers, 123  
 deformation mechanisms:  
   elastic, 287, 288  
   plastic, 287, 289
- Sensors, 11, 573
- Severity of quench, 609
- Shape-memory:  
 alloys, 11  
 phase transformations, 456–459  
 thermoelastic behavior, 459
- Shear deformation, 203, 222
- Shear modulus, 208  
 relationship to elastic modulus, 210  
 selected metals, 206
- Shear strain, 203, 878
- Shear stress, 205, 878  
 resolved, 267  
 resolved from tensile stress, 205
- Shear tests, 204–205
- Sheet glass forming (float process), 618
- Shot peening, 341
- Shrinkage, clay products, 622–623
- Shrink-wrap polymer films, 292
- Silica, 60  
 crystalline and noncrystalline structures, 92  
 fibers for optical communications, 574, 808–810  
 fused, *see* Fused silica  
 as refractory, 570
- Silica-alumina phase diagram, 395
- Silica glasses, 92–93  
 viscosity, 616
- Silicates:  
 glasses, 92–93  
 layered, 61–62  
 tetrahedral structure, 60  
 types and structures, 59–62, 93
- Silicon:  
 bonding energy and melting temperature, 30  
 conduction in, 498  
 cost, 862  
 electrical characteristics, 497  
 electron concentration *vs.* temperature, *n*-type, 503  
 electron/hole mobility *vs.* impurity concentration, 504  
 electron/hole mobility *vs.* temperature, 504  
 fracture toughness, 574  
 intrinsic carrier concentration *vs.* temperature, 503  
 in MEMS, 574  
 vacancy (surface), 136
- Silicon carbide:  
 as abrasive, 571  
 flexural strength, 217, 842  
 hardness, 239  
 modulus of elasticity, 206, 835  
 properties as whiskers and fibers, 664  
 as refractory, 571
- Silicon dioxide, *see* Silica
- Silicone rubber, 581, 582  
 characteristics and applications, 581  
 degradation resistance, 722
- Silicon nitride:  
 ceramic ball bearings, 574, 576  
 compressive strength, 576  
 flexural strength, 217, 842  
 fracture strength distribution, 323  
 hardness, 239  
 modulus of elasticity, 206, 836  
 properties as a whisker, 664



- Silly putty, 229
- Silver, 562  
 atomic radius and crystal structure, 47  
 electrical conductivity, 491, 494  
 slip systems, 266  
 thermal properties, 737
- Simple cubic crystal structure, 98
- Single crystals, 85, 878  
 slip in, 267–270
- Sintered aluminum powder (SAP), 653
- Sintering, 625, 878
- SI units, 828–829
- Ski, cross-section, 646
- Slip, 212, 263, 878  
 compared to twinning, 273  
 polycrystalline metals, 270–271  
 single crystals, 267–270
- Slip casting, 621–622, 878
- Slip direction, 265
- Slip lines, 268, 270
- Slip plane, 262, 263, 265
- Slip systems, 265–267, 878  
 selected metals, 266
- Small-angle grain boundaries, 151, 275
- Smart materials, 11
- Societal considerations, materials science, 819–826
- Soda-lime glasses;  
 composition, 567  
 dielectric properties, 519  
 electrical conductivity, 515  
 hardness, 239  
 thermal properties, 737  
 thermal shock, 745  
 viscosity, 616
- Sodium chloride:  
 bonding energy and melting temperature, 30  
 ionic bonding, 29  
 structure, 56, 84
- Sodium-silicate glass, 93
- Softening point (glass), 616, 878
- Soft magnetic materials, 768–770, 878  
 properties, 770
- Soils, as corrosion environments, 715
- Solar panels, 786
- Soldering, 381, 600, 878
- Solders, lead-free, 381
- Solid-solution strengthening, 275–276, 374, 878
- Solid solutions, 140–141, 878  
 in ceramics, 142  
 intermediate, 387, 390, 874  
 interstitial, 141, 874  
 in metals, 140–141  
 ordered, 387, 556  
 terminal, 387, 879
- Solidus line, 366, 376, 878
- Solubility limit, 361, 878  
 factors that influence for solid phases, 141
- Solutes, 879  
 defined, 140
- Solution heat treatment, 460, 879
- Solvents, 879  
 defined, 140
- Solvus line, 376, 879
- Sonar, use of piezoelectric ceramics in, 575
- Specific heat, 734, 879  
 values for selected materials, 737, 851–854
- Specific modulus, 654, 879  
 selected fiber-reinforcement materials, 664
- Specific strength, 558, 654, 879  
 selected fiber-reinforcement materials, 664
- Sphalerite structure, 56, 58
- Spheroidite, 439–440, 879  
 hardness and ductility, 450
- Spheroidization, 603, 879
- Spherulites, in polymers, 102, 126–127, 879  
 alteration during deformation, 287–290  
 photomicrograph of polyethylene, 127  
 transmission electron micrograph, 102, 126
- Spinel, 58, 84, 393  
 flexural strength, 217  
 index of refraction, 793  
 modulus of elasticity, 206  
 structure, 84  
 thermal properties, 737
- Spin magnetic moment, 22, 756
- Spinnerets, 634
- Spinning, polymer fibers, 634–635, 879
- Stabilized zirconia, 394, 673
- Stabilizers, 631, 879
- Stacking faults, 153
- Stainless steels, 548–549, 879. *See also* Ferrous alloys; specific steels  
 compositions, properties, and applications for selected, 549  
 creep resistance, 347  
 electrical conductivity, 491  
 passivity, 705  
 thermal properties, 737  
 weld decay, 711
- Standard deviation, 240–241
- Standard emf series, 694–695
- Standard half-cells, 694, 879
- Static fatigue, 323
- Steady-state creep rate, 343
- Steady-state diffusion, 879
- Steatite, dielectric properties, 519
- Steels, 401. *See also* Alloy steels;  
 Stainless steels  
 AISI/SAE designation scheme, 547  
 classification, 442, 544  
 costs, 859–860  
 elastic and shear moduli, 206  
 electrical conductivity, 491  
 fatigue behavior (1045), 355  
 heat treatments, 604–613  
 impact energy, 328  
 magnetic properties, 772  
 overview of types, 543–549  
 plane strain fracture toughness, 319, 843  
 Poisson's ratio, 206  
 properties as wires (fiber reinforcement), 664  
 thermal properties, 737  
 yield and tensile strengths, ductility (1020), 217
- Step reaction polymerization, *see* Condensation polymerization
- Stereoisomerism, 879  
 polymers, 117–118
- Sterling silver, 140, 562
- Stiffness, *see* Modulus of elasticity
- Stoichiometry, 138, 879
- Stone age, 2
- Strain, 204. *See also* Stress-strain behavior  
 engineering, 204, 879  
 lattice, 264–265, 276, 463–464, 875  
 shear, 205, 878  
 true, 220, 880
- Strain hardening, 222, 223, 276–279, 597, 879  
 corrosion and, 707  
 influence on electrical resistivity, 492, 493



- Strain hardening (*Continued*)  
 influence on mechanical properties, 277, 278  
 recrystallization after, 280–282
- Strain-hardening exponent, 220, 278  
 determination of, 255  
 selected metal alloys, 221
- Strain point (glass), 616, 879
- Strength, 212  
 flexural, 223–224, 873  
 fracture, 214  
 ranges for material types (bar chart), 6
- Strengthening of metals:  
 grain size reduction, 273–275  
 mechanism, 273  
 solid-solution strengthening, 275–276  
 strain hardening, *see* Strain hardening
- Stress, *see also* Stress-strain behavior  
 critical (for fracture), 316  
 effect on creep, 344–345  
 engineering, 203, 879  
 mean (fatigue), 333, 334, 339, 340  
 normal (resolved from pure tensile), 205  
 range (fatigue), 333, 334  
 residual, *see* Residual stresses  
 safe, 242, 878  
 shear, 205, 267, 878  
 shear (resolved from pure tensile), 205  
 thermal, *see* Thermal stresses  
 true, 219, 880  
 working, 242
- Stress amplitude, 333, 334
- Stress concentration, 314–317, 328, 339, 879  
 polymers, 326
- Stress concentration factor, 316
- Stress corrosion cracking, 712–713, 879  
 in ceramics, 323
- Stress raisers, 315, 339, 879  
 in ceramics, 225, 322
- Stress ratio, 334
- Stress relaxation measurements, 230
- Stress relief annealing, 602, 879
- Stress state, geometric considerations, 205
- Stress-strain behavior:  
 brass, 214  
 cast iron, gray, 251  
 ceramics, 225  
 composite, fibrous (longitudinal), 656  
 elastic deformation, 205–207  
 natural rubber, vulcanized and unvulcanized, 295  
 nonlinear (elastic), 207  
 plastic deformation, 212–215  
 polymers, 226–228  
 shape-memory alloys, 459  
 steel alloy, 251  
 for steel, variation with percent cold work, 278  
 true, 220
- Striations (fatigue), 338–339
- Structural clay products, 569, 879
- Structural composites, 677–679, 879
- Structure, 3. *See also* Processing/structure/properties/performance correlations  
 atomic, 18–25  
 definition, 879
- Structures, crystal, *see* Crystal structures
- Styrene, 122
- Styrene-butadiene rubber (SBR), 122  
 characteristics and applications, 579  
 degradation resistance, 722
- Styrenic block copolymers, 584, 587–588
- Substitutional impurity defects, 141
- Substitutional solid solutions, 141, 879
- Superalloys, 562  
 compositions of selected, 564  
 creep resistance, 347  
 fiber reinforcement, 671
- Superconductivity, 776–779, 879  
 applications, 778–779
- Superconductors, 776  
 critical properties, 778  
 high-temperature, 778  
 types I and II, 777
- Supercooling, 428, 434, 879  
 degrees for homogeneous nucleation, 428
- Superficial Rockwell hardness tests, 233–235
- Superheating, 434, 879
- Super Invar, 737, 740  
 as low-expansion alloy, 740
- Supermalloy, magnetic properties, 770
- Surface energy, 150, 424
- Susceptibility, magnetic, 754
- Sustainability, 821
- Symbols, list, xxiii–xxv
- Syndiotactic configuration, 118, 879
- Synthetic rubbers, 122, 581, 722
- Systems:  
 definition, 361, 879  
 homogeneous *vs.* heterogeneous, 362
- T**
- Talc, 62
- Tangent modulus, 207
- Tantalum, 562
- Tape casting, 615, 626–627
- Tarnishing, 717
- Tear strength, polymers, 239
- Teflon, *see* Polytetrafluoroethylene
- TEM, *see* Transmission electron microscopy
- Temperature gradient, 741  
 thermal stresses, 745
- Temper designation, 558, 879
- Tempered martensite, 452–455, 879  
 hardness *vs.* carbon content, 452  
 mechanical properties *vs.* tempering temperature, 454  
 dependence on cylinder diameter, 612–613, 614
- Temper embrittlement, 455
- Tempering:  
 glass, 324, 618–619, 643  
 steels, 452–454
- Tennis balls (nanocomposites in), 679–680
- Tensile strength, 213–214, 879  
 carbon nanotubes, 64  
 correlation with hardness, 237–238  
 fibrous composites, 660–661  
 fine pearlite, 449  
 influence of recrystallization on, 282  
 precipitation hardened aluminum alloy, 463  
 ranges for material types (bar chart), 6  
 selected fiber-reinforcement materials, 664  
 selected metals, 838–841  
 selected polymers, 842  
 tempered martensite, 454  
 values for various materials, 217, 838–843



- Tensile test apparatus, 200, 202–204
- Tensile tests, 202–204. *See also* Stress-strain behavior
- Terephthalic acid (structure), 629
- Terminal solid solutions, 387, 879
- Ternary phase diagrams, 395
- Tertiary creep, 343, 344
- Tetragonal crystal system, 65, 66
- Tetrahedral position, 83, 760, 879
- Textile fibers, 582–583
- Texture:
  - magnetic, 87, 769
  - rolling (sheet, BCC iron), 769
- Thermal conduction, 735, 741
- Thermal conductivity, 741, 742–744
  - influence of impurities, 742
  - selected materials, 737, 848–851
- Thermal diffusivity, 749
- Thermal expansion, 738–740
  - linear coefficient of, 342, 738, 744–746, 880
  - relation to bonding, 738
  - selected materials, 737, 845–848
  - volume coefficient of, 738
- Thermal fatigue, 342, 880
- Thermally activated processes, 431, 880
- Thermal properties, 734. *See also* specific thermal properties
  - selected materials, 737, 845–854
- Thermal shock, 618, 739, 880
  - brittle materials, 745–746
  - maximum temperature change without, 750
- Thermal shock resistance, 745–746
- Thermal stresses, 341–342, 744–746, 880
  - avoidance at metal-to-glass junctions, 740
  - glass, 618
- Thermal tempering (glass), 618–619, 880
- Thermoelastic phenomenon, 459
- Thermoplastic elastomers, 587–588, 880
- Thermoplastic polymers, 120, 880
  - characteristics and applications, 578–579
  - degradation resistance, 721
  - forming techniques, 631–634
- Thermosetting polymers, 120, 880
  - characteristics and applications, 579
  - degradation resistance, 721
  - forming techniques, 631–634
- Thermostat (operation of), 733
- Thoria-dispersed (TD) nickel, 653
- Tie lines, 367, 880
- Tilt boundaries, 151, 152
- Time-temperature-transformation diagrams, *see* Isothermal transformation diagrams
- Tin, 564
  - allotropic transformation for, 67
  - crystal structures, 67
  - density, 832
  - electrical resistivity, 855
  - mechanical properties, 835, 838, 841
  - recrystallization temperature, 283
  - superconducting critical temperature, 778
  - thermal properties, 846, 849, 852
- Tin cans, 716
- Titanium:
  - atomic radius and crystal structure, 47
  - density, 831
  - elastic and shear moduli, 206
  - electrical resistivity, 855
  - Poisson's ratio, 206, 837
  - slip systems, 266
  - superconducting critical temperature, 778
  - thermal properties, 845, 849, 852
  - yield and tensile strengths, ductility, 217, 840
- Titanium alloys, 560–562, 563
  - compositions, 858
  - densities, 831
  - electrical resistivities, 855
  - mechanical properties, 834, 837, 840
  - plane strain fracture toughness, 319, 844
  - properties and applications of, 563
  - thermal properties, 845, 849, 852
- Titanium dioxide, crystal structure, 100
- Tool steels, 547–548
- Top-down science, 11
- Torque, 203
- Torsion, 204–205
- Torsional deformation, 203, 222
- Torsional tests, 204–205
- Toughness, 218–219, 880
- Tows, 675
- Trade names:
  - selected elastomers, 581
  - selected plastics, 578–579
- Trans*, 119, 880
- Transducers, 526, 575
- Transfer molding, plastics, 632
- Transformation rate, 431–433, 880
  - temperature dependence, 432
- Transformation toughening, 673
- Transformer cores, 769
- Transgranular fracture, 313–314, 880
- Transient creep, 343
- Transistors, 511–513
- Transition metals, 25
- Transition temperature, ductile-brittle, *see* Ductile-to-brittle transition
- Translucency, 790, 880
  - insulators, 800–801
- Transmission (of light), 798
- Transmission electron microscopy, 150, 157–158, 880
- Transmissivity, 790
- Transparency, 790, 880
- Transverse bending test, 223–224
  - equation for maximum deflection, 256, 670
- Transverse direction, 656, 880
- Transverse loading, composites, 659–660
- Triclinic crystal system, 66
  - anisotropy in, 86
- Tridymite, 60
- Trifunctional (polymers), 109, 880
- Trigonal crystal system, *see* Rhombohedral crystal system
- Triple point, 364
- True stress/strain, 219–221, 880
- T-T* diagrams, *see* Isothermal transformation diagrams



- Tungsten, 562  
 atomic radius and crystal structure, 47  
 bonding energy and melting temperature, 30  
 density, 831  
 elastic and shear moduli, 206  
 electrical resistivity, 855  
 Poisson's ratio, 206, 837  
 properties as wire, 664  
 recrystallization temperature, 283  
 slip systems, 266  
 superconducting critical temperature, 778  
 thermal properties, 737, 846, 849, 852  
 yield and tensile strengths, ductility, 841
- Tungsten carbide:  
 as abrasive, 571  
 hardness, 239
- Turbine blades, 347
- Twin boundaries, 152
- Twinning, 272  
 compared to slip, 273  
 role in shape-memory effect, 457–458
- Twins, 152
- U**
- Undercooling, *see* Supercooling
- UHMWPE (Ultra-high-molecular-weight polyethylene), 585, 880  
 properties as a fiber, 664
- Unary phase diagrams, 363–364
- Uniaxial powder pressing, 625
- Unidirectional solidification, 347
- Uniform corrosion, 707
- Unit cells, 46–47, 880. *See also*  
 Crystal structures  
 crystal systems, 65, 66
- Units:  
 electrical and dielectric parameters, 521  
 magnetic parameters, 755  
 SI, 828–829
- Unsaturated hydrocarbons, 104, 880
- UNS designation scheme, 547
- Upper critical temperature, 603, 880
- Upper yield point, 212, 213
- V**
- Vacancies, 136, 880  
 in ceramics, 137  
 diffusion, 172, 173, 178, 880  
 equilibrium number, 136  
 in polymers, 143
- Valence band, 488, 880
- Valence electrons, 22, 880
- van der Waals bonding, 32–33, 35, 880  
 in clays, 61  
 gecko lizards, 17  
 hydrocarbons, 104  
 in polymers, 116, 290
- Vermiculite, 679
- Vibrational heat capacity, 735
- Vibrations, atomic, 153, 735
- Vickers hardness tests, 234, 236
- Vinyl esters, polymer-matrix composites, 668
- Vinyls, 579
- Viscoelastic creep, 232
- Viscoelasticity, 209, 229–232, 880
- Viscoelastic relaxation modulus, 229–231, 877
- Viscosity, 286, 643, 880  
 temperature dependence for glasses, 616
- Viscous flow:  
 in ceramics, 286  
 in polymers, 230
- Visible spectrum, 788
- Vision (glass ceramic), 568
- Vitreous silica, *see* Fused silica
- Vitrification, 623, 880
- Volatile organic compound (VOC) emissions, 583, 680
- Volume defects, 153
- Volume expansion coefficient, 738
- Volume fraction (phase), 370
- Vulcanization, 116, 294, 880
- Vycor, 567
- W**
- Wallner line, 325
- Water:  
 as corrosion environment, 714  
 bonding energy and melting temperature, 30  
 desalination of, 190  
 hydrogen bonding in, 33, 34  
 phase diagram (pressure-temperature), 359, 364, 419  
 as quenching medium, 609  
 volume expansion upon freezing, 34
- Wave-mechanical atomic model, 20, 880
- Weathering, of polymers, 724
- Weight-average molecular weight, 111–112
- Weight percent, 143–145, 880
- Weld decay, 711, 881
- Welding, 600–601, 881
- Wetting, 429
- Whiskers, 317, 664, 881
- White cast iron, 551, 553–554, 881
- Whitewares, 566, 569, 620, 881
- Wiedemann-Franz constant, 742  
 values of, for metals, 737
- Wiedemann-Franz law, 742
- Wires, 664
- Wood:  
 as composite, 648  
 cost, 863  
 density, 833  
 electrical resistivity, 857  
 modulus of elasticity, 837  
 specific heat, 854  
 tensile strength, 843  
 thermal conductivity, 851  
 thermal expansion coefficient, 848
- Work hardening, *see* Strain hardening
- Working point (glass), 616, 881
- Working range (glass), 616
- Working stress, 242
- Wristwatches, low-expansion alloys in, 740
- Wrought alloys, 556, 881
- Wüstite, 138, 538
- X**
- X-ray diffraction, 44, 87–91
- X-rays, 787, 788
- Y**
- Yielding, 212, 881
- Yield point phenomenon, 212, 213
- Yield strength, 212, 214, 227, 881  
 dependence on grain size (brass), 274  
 fine pearlite, 449  
 selected metals, 838–841

Yield strength (*Continued*)  
 selected polymers, 842  
 tempered martensite, 454  
 values for various materials, 217,  
 319, 838–843  
 Young's modulus, *see* Modulus of  
 elasticity  
 Yttrium barium copper oxide, 778  
 Yttrium iron garnet (YIG), 761

## Z

### Zinc:

atomic radius and crystal  
 structure, 47  
 density, 832

electrical resistivity, 855  
 mechanical properties,  
 835, 838, 841  
 recrystallization temperature, 283  
 slip systems, 266  
 thermal properties, 846, 849, 852  
 Zinc alloys, 556  
 Zinc blende structure, 56, 58  
 Zinc telluride, electrical  
 characteristics, 497  
 Zirconia, 571  
 density, 832  
 electrical resistivity, 856  
 flexural strength, 217, 842  
 hardness, 239  
 modulus of elasticity, 206, 836

plane-strain fracture toughness,  
 844  
 Poisson's ratio, 838  
 as refractory, 571  
 stabilized, 394  
 transformation toughening, 673  
 Zirconia-calcia phase diagram,  
 394  
 Zirconium:  
 alloys, 566  
 density, 832  
 electrical resistivity, 855  
 mechanical properties,  
 835, 838, 841  
 slip systems, 266  
 thermal properties, 846, 849, 852