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PREFACE TO THE ADAPTED EDITION

Materials play a very important role in the development process. Materials define all eras such as Stone Age, Iron Age, Bronze Age and the contemporary Smart and Nano-materials Age. The materials scenario is fast changing and development of new materials are being reported very rapidly. These developments are taking place so as to meet the ever-increasing demand for newer and better quality products, greater efficiency, increased service life and stringent reliability requirements. In view of these requirements of today's technological society, the importance of the knowledge of materials science and engineering has increased considerably. Fast computers, prostheses and implants, supersonic aircrafts, space shuttles, long-range surface-to-surface, air-to-air and surface-to-air missiles, satellites and televisions, teleconferencing, etc., would not have been possible but for the development of newer materials having low density (light materials), high strength and high stiffness, frictionless surfaces, corrosion resistance, very low wear, etc.

Hence, proper exposure of students to the field of Materials Science and Engineering is a must. The present book *Materials Science and Engineering* is primarily meant to provide the students with a strong foundation for better understanding of the structure and property relationship in materials, understanding mechanical behaviors such as fatigue behavior, fracture behavior, creep behavior, deformation behavior, corrosion behavior; and processing and performance of materials, engineering and biomedical applications of materials, etc.

Whenever a part or product has to be developed or designed, the first step is always proper selection of the material to be used. A wide choice of materials such as metallic materials, polymeric materials, ceramic materials, composite materials, electronic materials, biomaterials, smart materials, nano-materials, etc., are available to a design engineer and proper selection of a material would be possible only if there exists proper understanding of various materials. All these materials as well as topics such as buckyball, carbon nanotubes, MEMS (micro-electro-mechanical systems), etc., are duly covered in this book.

Details of experimental techniques used for identification and characterization purposes as well as those techniques which are used for mechanical testing of various materials are properly described. Description of non-destructive testing (NDT) techniques also finds due place for the benefit of students.

The present book provides details of topics such as hydrogen embrittlement, ductile-to-brittle transition and in-service embrittlement, stress corrosion cracking, cathodic and anodic protection methods for corrosion control, fracture modes and failure theories, biomedical applications of engineering materials and important properties of selected materials.

A number of solved numerical problems have been included in the book to help the students in their learning and understanding process. Also, a number of unsolved numerical and descriptive problems have been given at the end of every chapter for developing problem-solving skills. Answers to selected problems have also been provided. In accordance with the present engineering practices and contemporary technological requirements, SI units have been used throughout the book.

One chapter on Optical Properties and Superconductive Materials and the other chapter on Magnetic Properties have been uploaded at the website for the book. Students interested in these topics may use the following link to reach this dedicated site.

http://www.mhhe.com/smith/ms4esi

RAVI PRAKASH

June 11, 2008

PREFACE

Materials Science and Engineering, Fourth Edition, is designed for a first course in materials science and engineering for engineering students. Understanding that this might be a student's first exposure to materials science, the book presents essential topics in a clear, concise manner, without extraneous details to overwhelm newcomers. Industrial examples and photographs used throughout the book give students a look at the many ways material science and engineering are applied in the real world.

NEW FEATURES OF THE FOURTH EDITION

In addition to its already renowned student-friendly writing style and applications to industry, the fourth edition offers new features including a thorough coverage of modern materials science topics that prepare students for life outside the classroom. The new sections are:

- New reference to smart materials/devices, MEMs, and nanomaterials (1.1)
- New reference to superalloys and their biomedical applications (1.3)
- Added discussion of engineering plastics and applications in automobiles (1.3.2)
- Added discussion of engineering ceramics and applications (1.3.3)
- Added discussion of composite materials (1.3.4)
- New coverage of smart materials and nanomaterials (1.5)
- New section featuring a simplified case study in selection of materials for the frame and forks of a bicycle (1.6)
- New coverage of amorphous materials was added in Chapter 3
- Added references to long and short range order (SRO also known as amorphous materials) (3.1)
- Chapter 4 has been split into chapters 4 and 5 for the fourth edition so diffusion can be covered in a stand-alone chapter
- Coverage of microscopes added to the end of Chapter 4
- Added coverage of planar defects and twin boundaries (4.4.3)
- New section on volume defects (4.4.4)
- New section on experimental techniques for identification of microstructure and defects (4.5)
- Added coverage of fine-grained metals and the Hall–Petch equation in Chapter 6

- New case study in failure and coverage of recent advances in improving mechanical performance in Chapter 7
- Added coverage of failure and fracture of metals (7.1)
- New section on ductile-to-brittle transition temperature (7.1.4)
- New section on recent advances and future directions in improving the mechanical performance of metals (7.7)
- New coverage of cooling curves in Chapter 8
- Added coverage of intermediate compounds (8.11.1)
- Three new sections devoted to advanced alloys and their application in biomedical engineering have been added to Chapter 9
- New section devoted to biomedical applications of polymeric materials added to Chapter 10
- New section with coverage of bucky balls and carbon nanotubes (11.2.12)
- New section on ceramic coatings and surface engineering (11.9)
- New section on ceramics in biomedical applications (11.10)
- New section on nanotechnology and ceramics (11.11)
- New section on bone: a natural composite material (12.11)
- New section on hydrogen damage (13.5.11)
- New section on nanoelectronics (14.9)
- New appendix featuring extensive materials properties reference

Other New Features:

- Learning objectives have been added to every chapter
- Icons have been added to highlight the supplemental media resources

- Many new chapter openers and interior photos are included

Retained Features:

- Over 1200 end-of-chapter problems and over 180 materials selection and design problems are offered
- Over 140 example problems
- Modern applications of materials
- A concise, readable style is used throughout; readers are given understandable explanations without excessive detail

Online Learning Center

Web support is provided for the book at the website. Visit this site for book and supplement information, errata, author information, and resources for further study or reference.

ACKNOWLEDGMENTS

The co-author, Javad Hashemi, would like to acknowledge the everlasting love, support, encouragement, and guidance of his mother, Sedigheh, throughout the course of his life and career. He dedicates this textbook to her, to the love of his life, Eva, to the most precious gifts of his life, Evan and Jonathon, to his siblings, and last but not least to the memory of his father.

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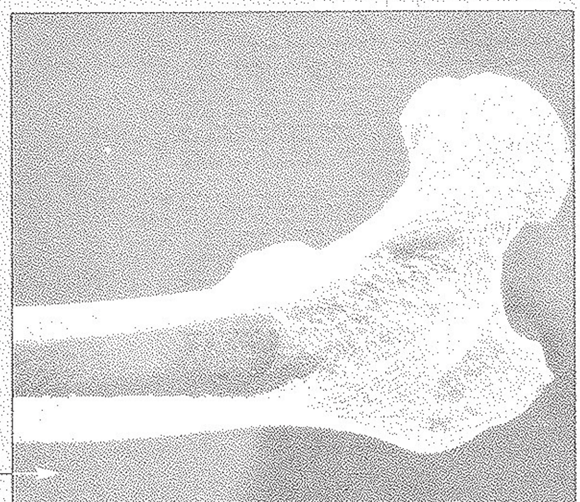
JAVAD HASHEMI

GUIDED TOUR

Modern materials science topics have been added throughout the text including:

- Smart materials/devices, MEMs and nanomaterials
- Biomedical applications
- Chapter 4 has been split into two chapters to allow diffusion to be covered alone
- Three new sections devoted to advanced alloys and their application in biomedical engineering
- Ceramics coverage has been expanded to include nanotechnology and ceramics

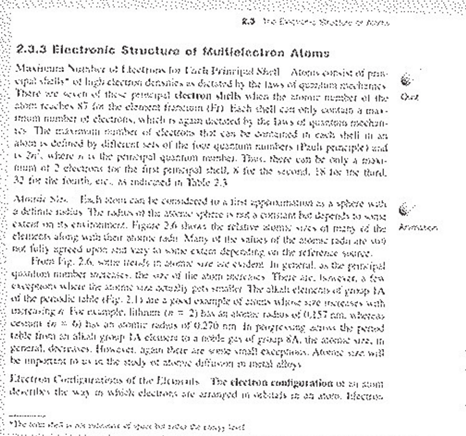


Materials selection and design problems follow the end-of-chapter problems. These problems challenge students to create engineering solutions through materials selection and process design.

198 **CHAPTER 5** Thermally Activated Processes and Diffusion in Solids

5.8 MATERIALS SELECTION AND DESIGN PROBLEMS

1. In integrated circuits, dissimilar metal wires such as gold and aluminum are joined at the cross section to form a bonded interface. At elevated temperatures, the interface starts to move or shift in the direction of one of the metals, called the Kirkendall effect. (*a*) Can you explain this phenomenon? (*b*) Is the direction of the shift random? (*c*) What are the negative effects of this process?
2. (*a*) Design a process that would be used to make a solid steel component out of fine steel powder. The density of the formed solid should be very close to the density of the physical metal. (*b*) Explain how this process works at both macro and micro levels. (*c*) What are some of the obstacles that you may encounter in your process?
3. Explain what happens if carbon steel is exposed to an oxygen-rich atmosphere at elevated temperatures inside a furnace.
4. Based on the data in Table 5.2, is it easier for carbon atoms to diffuse in the structure of BCC iron or FCC iron? What is the physical reason for this?
5. Classify the mechanism of diffusion in all 12 solute/solvent pairs given in Table 5.2 (interstitial or substitutional). Compare the diffusivity values and draw a conclusion.
6. The activation energy for the diffusion of hydrogen in steel at room temperature is 3600 cal/mol, which is significantly lower than that of, for example, carbon at 20,900 cal/mol. Investigate the effect of diffused hydrogen on the mechanical behavior of steel.
7. Investigate the role of solid state diffusion in manufacturing of ceramic components using the powder metallurgy process.



2.3 The Electronic Structure of Atoms

2.3.3 Electronic Structure of Multielectron Atoms

Maximum Number of Electrons for Each Principal Shell Atoms consist of principal shells* of high electron densities as dictated by the laws of quantum mechanics. There are seven of these principal **electron shells** when the atomic number of the atom reaches 87 for the element francium (Fr). Each shell can only contain a maximum number of electrons, which is again dictated by the laws of quantum mechanics. The maximum number of electrons that can be contained in each shell in an atom is defined by different sets of the four quantum numbers (Pauli principle) and is $2n^2$, where n is the principal quantum number. Thus, there can be only a maximum of 2 electrons for the first principal shell, 8 for the second, 18 for the third, 32 for the fourth, etc., as indicated in Table 2.3.

Quiz

Atomic Size Each atom can be considered to a first approximation as a sphere with a definite radius. The radius of the atomic sphere is not a constant but depends to some extent on its environment. Figure 2.6 shows the relative atomic sizes of many of the elements along with their atomic radii. Many of the values of the atomic radii are still not fully agreed upon and vary to some extent depending on the reference source.

Animation

From Fig. 2.6, some trends in atomic size are evident. In general, as the principal quantum number increases, the size of the atom increases. There are, however, a few exceptions where the atomic size actually gets smaller. The alkali elements of group 1A of the periodic table (Fig. 2.1) are a good example of atoms whose size increases with increasing n. For example, lithium ($n = 2$) has an atomic radius of 0.157 nm, whereas cesium ($n = 6$) has an atomic radius of 0.270 nm. In progressing across the period table from an alkali group 1A element to a noble gas of group 8A, the atomic size, in general, decreases. However, again there are some small exceptions. Atomic size will be important to us in the study of atomic diffusion in metal alloys.

Electron Configurations of the Elements The **electron configuration** of an atom describes the way in which electrons are arranged in orbitals in an atom. Electron

*The term shell is not a volume of space but rather the energy level.

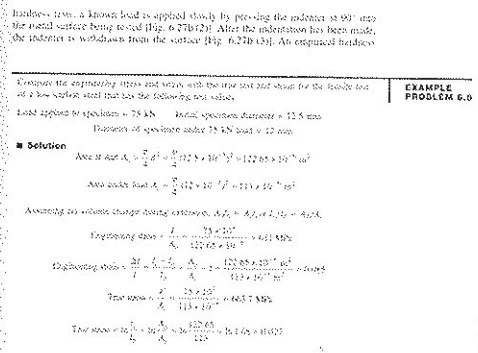
Icons have been added to highlight the media supplement resources.

LEARNING OBJECTIVES

By the end of this chapter, students will be able to. . .

1. Describe what crystalline and noncrystalline (amorphous) materials are.
2. Learn how atoms and ions in solids are arranged in space and identify the basic building blocks of solids.
3. Describe the difference between atomic structure and crystal structure for solid material.
4. Distinguish between crystal structure and crystal system.
5. Explain why plastics cannot be 100% crystalline in structure.
6. Explain polymorphism or allotropy in materials.
7. Compute the densities for metals having body-centered, and face-centered cubic structures.
8. Describe how to use the x-ray diffraction method for material characterization.
9. Write the designation for atom position, direction indices, and Miller indices for cubic crystals. Specify what are the three densely packed structures for most metals. Determine Miller-Bravais indices for hexagonal-closed packed structure. Be able to draw directions and planes in cubic and hexagonal crystals.

Learning Objectives have been added to each chapter to guide students' comprehension of the material.



6.4 Hardness and Hardness Testing   227

hardness tests, a known load is applied slowly by pressing the indenter at 90° into the metal surface being tested [Fig. 6.27b (2)]. After the indentation has been made, the indenter is withdrawn from the surface [Fig. 6.27b (3)]. An empirical hardness

EXAMPLE PROBLEM 6.6

Compute the engineering stress and strain, with the true stress and strain for the tensile test of a low-carbon steel that has the following test values.

Load applied to specimen = 75 kN   Initial specimen diameter = 12.5 mm

Diameter of specimen under 75 kN load = 12 mm

■ **Solution**

Assuming no volume change during extension, $A_0 l_0 = A_i l_i$ or $l_i/l_0 = A_0/A_i$

SI Units have been used throughout the book.

Greek Alphabet

Name	Lowercase	Capital	Name	Lowercase	Capital
Alpha	α	A	Nu	ν	N
Beta	β	B	Xi	ξ	Ξ
Gamma	γ	Γ	Omicron	o	O
Delta	δ	Δ	Pi	π	Π
Epsilon	ϵ	E	Rho	ρ	P
Zeta	ζ	Z	Sigma	σ	Σ
Eta	η	H	Tau	τ	T
Theta	θ	Θ	Upsilon	υ	Υ
Iota	ι	I	Phi	ϕ	Φ
Kappa	κ	K	Chi	χ	X
Lambda	λ	Λ	Psi	ψ	Ψ
Mu	μ	M	Omega	ω	Ω

SI Unit Prefixes

Multiple	Prefix	Symbol
10^{-12}	pico	p
10^{-9}	nano	n
10^{-6}	micro	μ
10^{-3}	milli	m
10^{-2}	centi	c
10^{-1}	deci	d
10^{1}	Deca	Da
10^{2}	Hecto	H
10^{3}	kilo	k
10^{6}	Mega	M
10^{9}	Giga	G
10^{12}	Tera	T

Example: 1 kilometer = 1 km = 10^3 meters.

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GLOSSARY

A

absorptivity the fraction of the incident light that is absorbed by a material.

acceptor levels in the band theory, local energy levels close to the valence band.

activation energy the additional energy required above the average energy for a thermally activated reaction to take place.

advanced ceramics new generation of ceramics with improved strength, corrosion resistance, and thermal shock properties, also called engineering or structural ceramics.

aggregate inert material mixed with portland cement and water to produce concrete. Larger particles are called coarse aggregate (e.g., gravel), and smaller particles are called fine aggregate (e.g., sand).

air-entrained concrete concrete in which there exists a uniform dispersion of small air bubbles. About 90 percent of the air bubbles are 100 μm or less.

alloy a mixture of two or more metals or a metal (metals) and a nonmetal (nonmetals).

alnico (aluminum-nickel-cobalt) alloys a family of permanent magnetic alloys having the basic composition of Al, Ni, and Co, and about 25 to 50 percent Fe. A small amount of Cu and Ti is added to some of these alloys.

α ferrite (α phase in the Fe-Fe_3C phase diagram) an interstitial solid solution of carbon in BCC iron; maximum solid solubility of carbon in BCC iron is 0.02 percent.

amorphous lacking in long range atomic order

amorphous metal metals with a noncrystalline structure also called glassy metal. These alloys have high elastic strain threshold.

anion an ion with a negative charge.

annealing a heat treatment given to a metal to soften it.

annealing a heat treatment process applied to a cold worked metal to soften it.

annealing point at this temperature stresses in the glass can be relieved.

anode the metal electrode in an electrolytic cell that dissolves as ions and supplies electrons to the external circuit.

anodic protection the protection of a metal that forms a passive film by the application of an externally impressed anodic current.

antiferromagnetism a type of magnetism in which magnetic dipoles of atoms are aligned in opposite directions by an applied magnetic field so that there is no net magnetization.

aramid fibers fibers produced by chemical synthesis and used for fiber-reinforced plastics. Aramid fibers have an aromatic (benzene ring type) polyamide linear structure and are produced commercially by the Du Pont Co. under the trade name of Kevlar.

Arrhenius rate equation an empirical equation that describes the rate of a reaction as a function of temperature and an activation energy barrier.

asphalt a bitumen consisting mainly of hydrocarbons having a wide range of molecular weights. Most asphalt is obtained from petroleum refining.

asphalt mixes mixtures of asphalt and aggregate that are used mainly for road paving.

atactic stereoisomer this isomer has pendant groups of atoms *randomly arranged* along a vinyl polymer chain. Example: atactic polypropylene.

atom the basic unit of an element that can undergo chemical change.

atomic mass unit (u) mass unit based on the mass of exactly 12 for $^{12}_{6}C$.

atomic number the number of protons in the nucleus of an atom of an element.

atomic orbital the region in space about the nucleus of an atom in which an electron with a given set of quantum numbers is most likely to be found. An atomic orbital is also associated with a certain energy level.

atomic packing factor (APF) the volume of atoms in a selected unit cell divided by the volume of the unit cell.

austempering a quenching process whereby a steel in the austenitic condition is quenched in a hot liquid (salt) bath at a temperature just above the M_s of the steel, held in the bath until the austenite of the steel is fully transformed, and then cooled to room temperature. With this process a plain-carbon eutectoid steel can be produced in the fully bainitic condition.

austenite (γ phase in Fe-Fe_3C phase diagram) an interstitial solid solution of carbon in FCC iron; the maximum solid solubility of carbon in austenite is 2.0 percent.

austenitizing heating a steel into the austenite temperature range so that its structure becomes austenite. The austenitizing temperature will vary depending on the composition of the steel.

Avogadro's number 6.023×10^{23} atoms/mol; the number of atoms in one relative gram-mole or mole of an element.

B

bainite a mixture of α ferrite and very small particles of Fe_3C particles produced by the decomposition of austenite; a nonlamellar eutectoid decomposition product of austenite.

bias voltage applied to two electrodes of an electronic device.

biodegradable polymer a type of polymer that is absorbed by the human body after it serves its purpose; for instance, absorbable sutures.

biopolymer polymers that are used inside the human body for various surgical applications.

bipolar junction transistor a three-element, two-junction semiconducting device. The three basic elements of the transistor are the emitter, base, and collector. Bipolar junction transistors can be of the npn or pnp types. The emitter-base junction is forward-biased and the collector-base junction is reverse-biased so that the transistor can act as a current amplification device.

blends mixture of two or more polymers, also called polymer alloys.

blistering a type of damage due to diffusion of atomic hydrogen into internal pores in a metal creating high internal pressure resulting in rupture.

blow molding a method of fabricating plastics in which a hollow tube (parison) is forced into the shape of a mold cavity by internal air pressure.

body-centered cubic (BCC) unit cell a unit cell with an atomic packing arrangement in which one atom is in contact with eight identical atoms located at the corners of an imaginary cube.

Bohr magneton the magnetic moment produced in a ferro- or ferrimagnetic material by one unpaired electron without interaction from any others; the Bohr magneton is a fundamental unit. 1 Bohr magneton = 9.27×10^{-24} A · m^2.

bone the structural material of the human body.

bone remodelling the ability of bone to alter its size and structure based on external stress.

brittle fracture a mode of fracture characterized by rapid crack propagation. Brittle fracture surfaces of metals are usually shiny and have a granular appearance.

buckyball also called Buckminister Fullerene is soccer ball shaped molecule of carbon atoms (C_{60}).

buckytube a tubular structure made of carbon atoms covalently bonded together.

bulk polymerization the direct polymerization of liquid monomer to polymer in a reaction system in which the polymer remains soluble in its own monomer.

C

cambium the tissue that is located between the wood and bark and is capable of repeated cell division.

cancellous (trabecular) bone the bone material that is porous and soft comprising the internal structure of the bone.

capacitance a measure of the ability of a capacitor to store electric charge. Capacitance is measured in farads; the units commonly used in electrical circuitry are the picofarad (1 pF = 10^{-12} F) and the microfarad (1 μF = 10^{-6} F).

capacitor an electric device consisting of conducting plates or foils separated by layers of dielectric material and capable of storing electric charge.

carbon fibers (for a composite material) carbon fibers produced mainly from polyacrylonitrile (PAN) or pitch that are stretched to align the fibrillar network structure within each carbon fiber and which are heated to remove oxygen, nitrogen, and hydrogen from the starting or precursor fibers.

cathode the metal electrode in an electrolytic cell that accepts electrons.

cathodic polarization the slowing down or the stopping of cathodic reactions at a cathode of an electrochemical cell due to (1) a slow step in the reaction sequence at the-metal-electrolyte interface (*activation polarization*) or (2) a shortage of reactant or accumulation of reaction products at the metal-electrolyte interface (*concentration polarization*).

cathodic protection the protection of a metal by connecting it to a sacrificial anode or by impressing a DC voltage to make it a cathode.

cation an ion with a positive charge.

cementite the intermetallic compound Fe_3C; a hard and brittle substance.

ceramic materials inorganic, nonmetallic materials that consist of metallic and nonmetallic elements bonded together primarily by ionic and/or covalent bonds.

ceramic materials materials consisting of compounds of metals and nonmetals. Ceramic materials are usually hard and brittle. Examples are clay products, glass, and pure aluminum oxide that has been compacted and densified.

chain polymer a high-molecular-mass compound whose structure consists of a large number of small repeating units called *mers*. Carbon atoms make up most of the mainchain atoms in most polymers.

chain polymerization the polymerization mechanism whereby each polymer molecule increases in size at a rapid rate once growth has started. This type of reaction occurs in three steps: (1) chain initiation, (2) chain propagation, and (3) chain termination. The name implies a chain reaction and is usually initiated by some external source. Example: the chain polymerization of ethylene into polyethylene.

chemically tempered glass glass that has been given a chemical treatment to introduce large ions into its surface to cause compressive stresses at its surface.

***cis*-1,4 polyisoprene** the isomer of 1,4 polyisoprene that has the methyl group and hydrogen on the same side of the central double bond of its mer. Natural rubber consists mainly of this isomer.

coercive force H_c the applied magnetic field required to decrease the magnetic induction of a magnetized ferro- or ferrimagnetic material to zero.

cold working of metals permanent deformation of metals and alloys below the temperature at which a strain-free microstructure is produced continuously (recrystallization temperature). Cold working causes a metal to be strain-hardened.

collagen the organic component of the bone.

columnar grains long, thin grains in a solidified polycrystalline structure. These grains are formed in the interior of solidified metal ingots when heat flow is slow and uniaxial during solidification.

composite material a materials system composed of a mixture or combination of two or more micro- or macroconstituents that differ in form and chemical composition and are essentially insoluble in each other.

composite materials materials that are mixtures of two or more materials. Examples are fiberglass-reinforcing material in a polyester or epoxy matrix.

compression molding a thermoset molding process in which a molding compound (which is usually heated) is first placed in a molding cavity. Then the mold is closed and heat and pressure are applied until the material is cured.

concrete (portland cement type) a mixture of portland cement, fine aggregate, coarse aggregate, and water.

conduction band the unfilled energy levels into which electrons can be excited to become conductive electrons. In semiconductors and insulators there is an energy gap between the filled lower valence band and the upper empty conduction band.

continuous-cooling transformation (CCT) diagram a time-temperature-transformation diagram that indicates the time for a phase to decompose into other phases continuously at different rates of cooling.

cooling curve plots of temp. vs time acquired during solidification of a metal. It provides phase change information as temperature is lowered.

coordination number (CN) the number of equidistant nearest neighbors to an atom or ion in a unit cell of a crystal structure. For example, in NaCl, CN = 6 since six equidistant Cl^- anions surround a central Na^+ cation.

copolymer a polymer chain consisting of two or more types of monomeric units.

copolymerization the chemical reaction in which high-molecular-mass molecules are formed from two or more monomers.

cored structure a type of microstructure that occurs during rapid solidification or nonequilibrium cooling of a metal.

corrosion the deterioration of a material resulting from chemical attack by its environment.

cortical (compact) bone dense bone comprising the outer structure.

covalent bond a primary bond resulting from the sharing of electrons. In most cases the covalent bond involves the overlapping of half-filled orbitals of two atoms. It is a directional bond. An example of a covalently bonded material is diamond.

creep time-dependent deformation of a material when subjected to a constant load or stress.

creep rate the slope of the creep-time curve at a given time.

critical current density J_c the current density above which superconductivity disappears.

critical field H_c the magnetic field above which superconductivity disappears.

critical radius r^* of nucleus the minimum radius that a particle of a new phase formed by nucleation must have to become a stable nucleus.

critical (minimum) radius ratio the ratio of the central cation to that of the surrounding anions when all the surrounding anions just touch each other and the central cation.

creep (stress)-rupture strength the stress that will cause fracture in a creep (stress-rupture) test at a given time and in a specific environment at a particular temperature.

critical temperature T_c the temperature below which a solid shows no electrical resistance.

cross-linking the formation of primary valence bonds between polymer chain molecules. When extensive cross-linking occurs as in the case of thermosetting resins, cross-linking makes one supermolecule of all the atoms.

crystal a solid composed of atoms, ions, or molecules arranged in a pattern that is repeated in three dimensions.

crystal structure a regular three-dimensional pattern of atoms or ions in space.

crystallinity (in polymers) the packing of molecular chains into a stereoregular arrangement with a high degree of compactness. Crystallinity in polymeric materials is never 100 percent and is favored in polymeric materials whose polymer chains are symmetrical. Example: high-density polyethylene can be 95 percent crystalline.

curie temperature the temperature at which a ferromagnetic material when heated completely loses its ferromagnetism and becomes paramagnetic.

curie temperature (of a ferroelectric material) the temperature at which a ferroelectric material on cooling undergoes a crystal structure change that produces spontaneous polarization in the material. For example, the Curie temperature of $BaTiO_3$ is 120°C.

D

deformation twinning a plastic deformation process that occurs in some metals and under certain conditions. In this process a large group of atoms are displaced together to form a region of a metal crystal lattice that is a mirror image of a similar region along a twinning plane.

degree of polymerization the molecular mass of a polymer chain divided by the molecular mass of its mer.

degrees of freedom F the number of variables (temperature, pressure, and composition) that can be changed *independently* without changing the phase or phases of the system.

diamagnetism a weak, negative, repulsive reaction of a material to an applied magnetic field; a diamagnetic material has a small negative magnetic susceptibility.

dielectric an electrical insulator material.

dielectric constant the ratio of the capacitance of a capacitor using a material between the plates of a capacitor compared to that of the capacitor when there is a vacuum between the plates.

dielectric strength the voltage per unit length (electric field) at which a dielectric material allows conduction, that is, the maximum electric field that a dielectric can withstand without electrical breakdown.

diffusivity a measure of the rate of diffusion in solids at a constant temperature. Diffusivity D can be expressed by the equation $D = D_0 e^{-Q/RT}$, where Q is the activation energy and T is the temperature in Kelvins. D_0 and R are constants.

dislocation a crystalline imperfection in which a lattice distortion is centered around a line. The displacement distance of the atoms around the dislocation is called the *slip* or *Burgers vector* **b**. For an *edge dislocation* the slip vector is perpendicular to the dislocation line, while for a *screw dislocation* the slip vector is parallel to the dislocation line. A *mixed dislocation* has both edge and screw components.

domain wall energy the potential energy associated with the disorder of dipole moments in the wall volume between magnetic domains.

donor levels in the band theory, local energy levels near the conduction band.

dry pressing the simultaneous uniaxial compaction and shaping of ceramic granular particles (and binder) in a die.

ductile cast irons iron-carbon-silicon alloys with 3.0 to 4.0 percent C and 1.8 to 2.8 percent Si. Ductile cast irons contain large amounts of carbon in the form of graphite nodules (spheres) instead of flakes as in the case of gray cast iron. The addition of magnesium (about 0.05 percent) before the liquid cast iron is poured enables the nodules to form. Ductile irons are in general more ductile than gray cast irons.

ductile fracture a mode of fracture characterized by slow crack propagation. Ductile fracture surfaces of metals are usually dull with a fibrous appearance.

ductile to brittle transition (DBT) observed reduced ductility and fracture resistance of a material when temperature is low.

E

eddy-current energy losses energy losses in magnetic materials while using alternating fields; the losses are due to induced currents in the material.

e-glass fibers fibers made from E (electrical) glass, which is a borosilicate glass and which is the most commonly used glass for fibers for fiberglass-reinforced plastics.

elastic deformation if a metal deformed by a force returns to its original dimensions after the force is removed, the metal is said to be elastically deformed.

elastomer a material that at room temperature stretches under a low stress to at least twice its length and then quickly returns to almost its original length upon removal of the stress.

electric current the time rate passage of charge through material; electric current i is the number of coulombs per second that passes a point in a material. The SI unit for electric current is the ampere (1 A = 1 C/s).

electric current density J the electric current per unit area. SI units: amperes/meter^2 (A/m^2).

electrical conductivity σ_e a measure of the ease with which electric current passes through a unit volume of material. Units: $(\Omega \cdot m)^{-1}$. σ_e is the inverse of ρ_e.

electrical conductor a material with a high electrical conductivity. Silver is a good conductor and has a $\sigma_e = 6.3 \times 10^7 (\Omega \cdot m)^{-1}$.

electrical insulator a material with a low electrical conductivity. Polyethylene is a poor conductor and has a $\sigma_e = 10^{-15}$ to $10^{-17} (\Omega \cdot m)^{-1}$.

electrical resistance R the measure of the difficulty of electric current's passage through a volume of material. Resistance increases with the length and increases with decreasing cross-sectional area of the material through which the current passes. SI unit: ohm (Ω).

electrical resistivity ρ_e a measure of the difficulty of electric current's passage through a *unit* volume of material. For a volume of material, $\rho_e = RA/l$, where R = resistance of material, Ω; l = its length, m; A = its cross-sectional area, m^2. In SI units, ρ_e = ohm-meters (Ω · m).

electromotive force series an arrangement of metallic elements according to their standard electrochemical potentials.

electron a negative charge carrier with a charge of 1.60×10^{-19} C.

electron configuration the distribution of all the electrons in an atom according to their atomic orbitals.

electron shell a group of electrons with the same principal quantum number n.

electronic materials materials used in electronics, especially microelectronics. Examples are silicon and gallium arsenide.

embryos small particles of a new phase formed by a phase change (e.g., solidification) that are not of critical size and that can redissolve.

energy-band model in this model the energies of the bonding valence electrons of the atoms of a solid form a band of energies. For example, the 3*s* valence electrons in a piece of sodium form a 3*s* energy band. Since there is only one 3*s* electron (the 3*s* orbital can contain two electrons), the 3*s* energy band in sodium metal is half-filled.

engineering strain ϵ change in length of sample divided by the original length of sample ($\epsilon = \Delta l/l_0$).

engineering stress σ average uniaxial force divided by original cross-sectional area ($\sigma = F/A_0$).

engineering stress-strain diagram experimental plot of engineering stress versus engineering strain; σ is normally plotted as the y axis and ϵ as the x axis.

equiaxed grains grains that are approximately equal in all directions and have random crystallographic orientations.

equilibrium a system is said to be in equilibrium if no macroscopic changes take place with time.

equilibrium phase diagram a graphical representation of the pressures, temperatures, and compositions for which various phases are stable at equilibrium. In materials science the most common phase diagrams involve temperature versus composition.

eutectic composition the composition of the liquid phase that reacts to form two new solid phases at the eutectic temperature.

eutectic point the point determined by the eutectic composition and temperature.

eutectic reaction (in a binary phase diagram) a phase transformation in which all the liquid phase transforms on cooling into two solid phases isothermally.

eutectic temperature the temperature at which a eutectic reaction takes place.

eutectoid (plain-carbon steel) a steel with 0.8 percent C.

eutectoid α **ferrite** α ferrite that forms during the eutectoid decomposition of austenite; the α ferrite in pearlite.

eutectoid cementite (Fe_3C) cementite that forms during the eutectoid decomposition of austenite; the cementite in pearlite.

exchange energy the energy associated with the coupling of individual magnetic dipoles into a single magnetic domain. The exchange energy can be positive or negative.

extrusion a plastic forming process in which a material under high pressure is reduced in cross section by forcing it through an opening in a die.

extrusion the forcing of softened plastic material through an orifice, producing a continuous product. Example: plastic pipe is extruded.

F

face-centered cubic (FCC) unit cell a unit cell with an atomic packing arrangement in which 12 atoms surround a central atom. The stacking sequence of layers of close-packed planes in the FCC crystal structure is *ABCABC*. . . .

fatigue the phenomenon leading to fracture under repeated stresses having a maximum value less than the ultimate strength of the material.

fatigue crack growth rate da/dN the rate of crack growth extension caused by constant-amplitude fatigue loading.

fatigue failure failure that occurs when a specimen undergoing fatigue fractures into two parts or otherwise has been significantly reduced in stiffness.

fatigue life the number of cycles of stress or strain of a specific character that a sample sustains before failure.

ferrimagnetism a type of magnetism in which the magnetic dipole moments of different ions of an ionically bonded solid are aligned by a magnetic field in an antiparallel manner so that there is a net magnetic moment.

ferroelectric material a material that can be polarized by applying an electric field.

ferromagnetic material one that is capable of being highly magnetized. Elemental iron, cobalt, and nickel are ferromagnetic materials.

ferromagnetism the creation of a very large magnetization in a material when subjected to an applied magnetic field. After the applied field is removed, the ferromagnetic material retains much of the magnetization.

ferrous metals and alloys metals and alloys that contain a large percentage of iron such as steels and cast irons.

fiber-reinforced plastics composite materials consisting of a mixture of a matrix of a plastic material such as a polyester or epoxy strengthened by fibers of high strength such as glass, carbon, or aramid. The fibers provide the high strength and stiffness, and the plastic matrix bonds the fibers together and supports them.

Fick's first law of diffusion in solids the flux of a diffusing species is proportional to the concentration gradient at constant temperature.

Fick's second law of diffusion in solids the rate of change of composition is equal to the diffusivity times the rate of change of the concentration gradient at constant temperature.

filament winding a process for producing fiber-reinforced plastics by winding continuous reinforcement previously impregnated with a plastic resin on a rotating mandrel. When a sufficient number of layers have been applied, the wound form is cured and the mandrel removed.

filler a low-cost inert substance added to plastics to make them less costly. Fillers may also improve some physical properties such as tensile strength, impact strength, hardness, wear resistance, etc.

firing (of a ceramic material) heating a ceramic material to a high enough temperature to cause a chemical bond to form between the particles.

float glass flat glass that is produced by having a ribbon of molten glass cool to the glass-brittle state while floating on the top of a flat bath of molten tin and under a reducing atmosphere.

fluorescence absorption of light or other energy by a material and the subsequent emission of light within 10^{-8} s of excitation.

fluxoid a microscopic region surrounded by circulating supercurrents in a type II superconductor at fields between H_{c2} and H_{c1}.

forging a primary processing method for working metals into useful shapes in which the metal is hammered or pressed into shape.

forward bias bias applied to a pn junction in the conducting direction; in a pn junction under forward bias, majority-carrier electrons and holes flow toward the junction so that a large current flows.

frenkel imperfection a point imperfection in an ionic crystal in which a cation vacancy is associated with an interstitial cation.

functionality the number of active bonding sites in a monomer. If the monomer has two bonding sites, it is said to be *bifunctional*.

G

galvanic cell two dissimilar metals in electrical contact with an electrolyte.

galvanic (seawater) series an arrangement of metallic elements according to their electrochemical potentials in seawater with reference to a standard electrode.

Gibbs phase rule the statement that at equilibrium the number of phases plus the degrees of freedom equals the number of components plus 2. $P + F = C + 2$. In the condensed form with pressure ≈ 1 atm, $P + F = C + 1$.

glass a ceramic material that is made from inorganic materials at high temperatures and is distinguished from other ceramics in that its constituents are heated to fusion and then cooled to the rigid condition without crystallization.

glass enamel a glass coating applied to a glass substrate.

glass-forming oxide an oxide that forms a glass easily; also an oxide that contributes to the network of silica glass when added to it, such as B_2O_3.

glass reference points (temperatures)

glass transition temperature the center of the temperature range where a heated thermoplastic upon cooling changes from a rubbery, leathery state to that of brittle glass.

glass transition temperature the center of the temperature range in which a noncrystalline solid changes from being glass-brittle to being viscous.

glaze a glass coating applied to a ceramic substrate.

grain a single crystal in a polycrystalline aggregate.

grain boundary a surface imperfection that separates crystals (grains) of different orientations in a polycrystalline aggregate.

grain growth the third stage in which new grains start to grow in an equiaxed manner.

grain-size number a nominal (average) number of grains per unit area at a particular magnification.

graphite a layered structure of carbon atoms covalently bonded to three others inside the layer. Various layers are the bonded through secondary bonds.

gray cast irons iron-carbon-silicon alloys with 2.5 to 4.0 percent C and 1.0 to 3.0 percent Si. Gray cast irons contain large amounts of carbon in the form of graphite flakes. They are easy to machine and have good wear resistance.

ground state the quantum state with the lowest energy.

H

Hall–petch relationship an empirical equation that relates the strength of a metal to its grain size.

hand lay-up the process of placing (and working) successive layers of reinforcing material in a mold by hand to produce a fiber-reinforced composite material.

hard ferrites ceramic permanent magnetic materials. The most important family of these materials has the basic composition $MO \cdot Fe_2O_3$, where M is a barium (Ba) ion or a strontium (Sr) ion. These materials have a hexagonal structure and are low in cost and density.

hard magnetic material a magnetic material with a high coercive force and a high saturation induction.

hardenability the ease of forming martensite in a steel upon quenching from the austenitic condition. A highly hardenable steel is one that will form martensite throughout in thick sections. Hardenability should not be confused with hardness. Hardness is the resistance of a material to penetration. The hardenability of a steel is mainly a function of its composition and grain size.

hardness a measure of the resistance of a material to permanent deformation.

hardwood trees trees that have covered seeds and broad leaves. Examples are oak, maple, and ash.

heartwood the innermost part of the tree stem that in the living tree contains only dead cells.

Heisenberg's uncertainty principle the statement that it is impossible to determine accurately at the same time the position and momentum of a small particle such as an electron.

heterogeneous nucleation (as pertains to the solidification of metals) the formation of very small regions (called *nuclei*) of a new solid phase at the interfaces of solid impurities. These impurities lower the critical size at a particular temperature of stable solid nuclei.

hexagonal close-packed (HCP) unit cell a unit cell with an atomic packing arrangement in which 12 atoms surround a central identical atom. The stacking sequence of layers of close-packed planes in the HCP crystal structure is *ABABAB*. . . .

high resolution transmission electron microscope (HRTEM) a Technique based on TEM but with significantly higher resolution by using significantly thinner samples.

hole a positive charge carrier with a charge of 1.60×10^{-19} C.

homogeneous nucleation (as pertains to the solidification of metals) the formation of very small regions of a new solid phase (called *nuclei*) in a pure metal that can grow until solidification is complete. The pure homogeneous metal itself provides the atoms that make up the nuclei.

homogenization a heat treatment process given to a metal to remove undesirable cored structures.

homopolymer a polymer consisting of only one type of monomeric unit.

hot working of metals permanent deformation of metals and alloys above the temperature at which a strain-free microstructure is produced continuously (recrystallization temperature).

hybrid orbital an atomic orbital obtained when two or more nonequivalent orbitals of an atom combine. The process of the rearrangement of the orbitals is called *hybridization*.

hydration reaction reaction of water with another compound. The reaction of water with portland cement is a hydration reaction.

hydrogel a soft polymeric material that absorbs water and swells to a specific level.

hydrogen bond a special type of intermolecular permanent dipole attraction that occurs between a hydrogen atom bonded to a highly electronegative element (F, O, N, or Cl) and another atom of a highly electronegative element.

hydrogen embrittlement loss of ductility in a metal due to interaction of the alloying element in the metal with atomic or molecular hydrogen.

hydrophilic polymer polymers the absorb water; like water.

hydroxyapatite the inorganic constituent of the bone.

hypereutectic composition one that is to the right of the eutectic point.

hypereutectoid (plain-carbon steel) a steel with 0.8 to 2.0 percent C.

hypoeutectic composition one that is to the left of the eutectic point.

hypoeutectoid (plain-carbon steel) a steel with less than 0.8 percent C.

hysteresis energy loss the work or energy lost in tracing out a *B-H* hysteresis loop. Most of the energy lost is expended in moving the domain boundaries during magnetization.

hysteresis loop the *B* versus *H* or *M* versus *H* graph traced out by the magnetization and demagnetization of a ferro- or ferrimagnetic material.

I

index of refraction the ratio of the velocity of light in vacuum to that through another medium of interest.

indices for cubic crystal planes (Miller indices) the reciprocals of the intercepts (with fractions cleared) of a crystal plane with the *x*, *y*, and *z* axes of a unit cube are called the Miller indices of that plane. They are designated *h*, *k*, and *l* for the *x*, *y*, and *z* axes, respectively, and are enclosed in parentheses as (*hkl*). Note that the selected crystal plane must *not* pass through the origin of the *x*, *y*, and *z* axes.

indices of direction in a cubic crystal a direction in a cubic unit cell is indicated by a vector drawn from the origin at one point in a unit cell through the surface of the unit cell; the position coordinates (*x*, *y*, and *z*) of the vector where it leaves the surface of the unit cell (with fractions cleared) are the indices of direction. These indices, designated *u*, *v*, and *w* are enclosed in brackets as [*uvw*]. Negative indices are indicated by a bar over the index.

injection molding a molding process whereby a heat-softened plastic material is forced by a screw-drive cylinder into a relatively cool mold cavity that gives the plastic the desired shape.

intergranular corrosion preferential corrosion occurring at grain boundaries or at regions adjacent to the grain boundaries.

intermediate oxides an oxide that may act either as a glass former or as a glass modifier, depending on the composition of the glass. Example, Al_2O_3.

intermediate phase a phase whose composition range is between those of the terminal phases.

intermetallics stochiometric compounds of metallic elements with high hardness and high temp strength, but brittle.

interstitial diffusion the migration of interstitial atoms in a matrix lattice.

interstitial solid solution a solid solution formed in which the solute atoms can enter the interstices or holes in the solvent-atom lattice.

interstitialcy (self-interstitial) a point imperfection in a crystal lattice where an atom of the same kind as those of the matrix lattice is positioned in an interstitial site between the matrix atoms.

intrinsic semiconductor a semiconducting material that is essentially pure and for which the energy gap is small enough (about 1 eV) to be surmounted by thermal excitation; current carriers are electrons in the conduction band and holes in the valence band.

invariant reactions equilibrium phase transformations involving zero degrees of freedom.

invariant reactions those reactions in which the reacting phases have fixed temperature and composition. The degree of freedom, F_1 is zero at these reaction points.

inverse spinal structure a ceramic compound having the general formula $MO \cdot M_2O_3$. The oxygen ions in this compound form an FCC lattice, with the M^{2+} ions occupying octahedral sites and the M^{3+} ions occupying both octahedral and tetrahedral sites.

ion-concentration cell galvanic cell formed when two pieces of the same metal are electrically connected by an electrolyte but are in solutions of different ion concentrations.

ionic bond a primary bond resulting from the electrostatic attraction of oppositely charged ions. It is a nondirectional bond. An example of an ionically bonded material is a NaCl crystal.

ionization energy the energy required to remove an electron from its ground state in an atom to infinity.

iron-chromium-cobalt alloys a family of permanent magnetic alloys containing about 30% Cr–10 to 23% Co and the balance iron. These alloys have the advantage of being cold-formable at room temperature.

iron-silicon alloys Fe–3 to 4% Si alloys that are soft magnetic materials with high saturation inductions. These alloys are used in motors and low-frequency power transformers and generators.

isomorphous system a phase diagram in which there is only one solid phase, i.e., there is only one solid-state structure.

isostatic pressing the simultaneous compaction and shaping of a ceramic powder (and binder) by pressure applied uniformly in all directions.

isotactic isomer this isomer has pendant groups of atoms all on the *same side* of a vinyl polymer chain. Example: isotactic polypropylene.

isothermal transformation (IT) diagram a time-temperature-transformation diagram that indicates the time for a phase to decompose into other phases isothermally at different temperatures.

J

jominy hardenability test a test in which a 1 in. (2.54 cm) diameter bar 4 in. (10.2 cm) long is austenitized and then water-quenched at one end. Hardness is measured along the side of the bar up to about 2.5 in. (6.35 cm) from the quenched end. A plot called the *Jominy hardenability curve* is made by plotting the hardness of the bar against the distance from the quenched end.

L

laminate a product made by bonding sheets of a material together, usually with heat and pressure.

laminate ply (lamina) one layer of a multilayer laminate.

Larsen Miller parameter a time-temperature parameter used to predict stress rupture due to creep.

laser acronym for *l*ight *a*mplification by *s*timulated *e*mission of *r*adiation.

laser beam a beam of monochromatic, coherent optical radiation generated by the stimulated emission of photons.

lattice point one point in an array in which all the points have identical surroundings.

lever rule the weight percentages of the phases in any two-phase region of a binary phase diagram can be calculated using this rule if equilibrium conditions prevail.

light attenuation decrease in intensity of the light.

lignin a very complex cross-linked three-dimensional polymeric material formed from phenolic units.

linear density ρ_l the number of atoms whose centers lie on a specific direction on a specific length of line in a unit cube.

liquidus the temperature at which liquid starts to solidify under equilibrium conditions.

low angle boundary (Tilt) an array of dislocations forming angular mismatch inside a crystal.

lower critical field H_{c1} the field at which magnetic flux first penetrates a type II superconductor.

lumen the cavity in the center of a wood cell.

luminescence absorption of light or other energy by a material and the subsequent emission of light of longer wavelength.

M

M_f the temperature at which the austenite in a steel finishes transforming to martensite.

M_s the temperature at which the austenite in a steel starts to transform to martensite.

magnetic anneal the heat treatment of a magnetic material in a magnetic field that aligns part of the alloy in the direction of the applied field. For example, the α' precipitate in alnico 5 alloy is elongated and aligned by this type of heat treatment.

magnetic domain a region in a ferro- or ferrimagnetic material in which all magnetic dipole moments are aligned.

magnetic field H the magnetic field produced by an external applied magnetic field or the magnetic field produced by a current passing through a conducting wire or coil of wire (solenoid).

magnetic induction B the sum of the applied field H and the magnetization M due to the insertion of a given material into the applied field. In SI units, $B = \mu_0(H + M)$.

magnetic permeability μ the ratio of the magnetic induction B to the applied magnetic field H for a material; $\mu = B/H$.

magnetic susceptibility χ_m the ratio of M (magnetization) to H (applied magnetic field); $\chi_m = M/H$.

magnetization M a measure of the increase in magnetic flux due to the insertion of a given material into a magnetic field of strength H. In SI units the magnetization is equal to the permeability of a vacuum (μ_0) times the magnetization, or $\mu_0 M$. ($\mu_0 = 4\pi \times 10^{-4}$ T · m/A.)

magnetocrystalline anisotropy energy the energy required during the magnetization of a ferromagnetic material to rotate the magnetic domains because of crystalline anisotropy. For example, the difference in magnetizing energy between the hard [111] direction of magnetization and the [100] easy direction in Fe is about 1.4×10^4 J/m^3.

magnetostatic energy the magnetic potential energy due to the external magnetic field surrounding a sample of a ferromagnetic material.

magnetostriction the change in length of a ferromagnetic material in the direction of magnetization due to an applied magnetic field.

magnetostrictive energy the energy due to the mechanical stress caused by magnetostriction in a ferromagnetic material.

majority carriers the type of charge carrier most prevalent in a semiconductor; the majority carriers in an n-type semiconductor are conduction electrons, and in a p-type semiconductor they are conduction holes.

malleable cast irons iron-carbon-silicon alloys with 2.0 to 2.6 percent C and 1.1 to 1.6 percent Si. Malleable cast irons are first cast as white cast irons and then are heat-treated at about 940°C (1720°F) and held about 3 to 20 h. The iron carbide in the white iron is decomposed into irregularly shaped nodules or graphite.

martempering (marquenching) a quenching process whereby a steel in the austenitic condition is hot-quenched in a liquid (salt) bath at above the M_s temperature, held for a time interval short enough to prevent the austenite from transforming, and then allowed to cool slowly to room temperature. After this treatment the steel will be in the martensitic condition, but the interrupted quench allows stresses in the steel to be relieved.

martensite a supersaturated interstitial solid solution of carbon in body-centered tetragonal iron.

materials substances of which something is composed or made. The term *engineering materials* is sometimes used to refer specifically to materials used to produce technical products. However, there is no clear demarcation line between the two terms, and they are used interchangeably.

materials engineering an engineering discipline that is primarily concerned with the use of fundamental and applied knowledge of materials so that they can be converted into products needed or desired by society.

materials science a scientific discipline that is primarily concerned with the search for basic knowledge about the internal structure, properties, and processing of materials.

maximum energy product $(BH)_{max}$ the maximum value of B times H in the demagnetization curve of a hard magnetic material. The $(BH)_{max}$ value has SI units of J/m^3.

Meissner effect the expulsion of the magnetic field by a superconductor.

mer a repeating unit in a chain polymer molecule.

metallic bond a primary bond resulting from the sharing of delocalized outer electrons in the form of an electron charge cloud by an aggregate of metal atoms. It is a nondirectional bond. An example of a metallically bonded material is elemental sodium.

metallic Glass metals with an amorphous atomic structure.

metallic materials (metals and metal alloys) inorganic materials that are characterized by high thermal and electrical conductivities. Examples are iron, steel, aluminum, and copper.

microelectromechanical systems (MEMs) any miniaturized device that performs sensing and/or actuating function.

microfibrils elementary cellulose-containing structures that form the wood cell walls.

micromachine MEMs that perform a specific function or task.

minority carriers the type of charge carrier in the lowest concentration in a semiconductor. The minority carriers in n-type semiconductors are holes, and in p-type semiconductors they are electrons.

modulus of elasticity E stress divided by strain (σ/ϵ) in the elastic region of an engineering stress-strain diagram for a metal ($E = \sigma/\epsilon$).

monomer a simple molecular compound that can be covalently bonded together to form long molecular chains (polymers). Example: ethylene.

monotectic reaction (in a binary phase diagram) a phase transformation in which, upon cooling, a liquid phase transforms into a solid phase and a new liquid phase (of different composition than the first liquid phase).

motif a group of atoms that or (basis) are organized relative to each other and are associated with corresponding lattice points.

multidirectional laminate a fiber-reinforced-plastic laminate produced by bonding together layers of fiber-reinforced sheets with some of the directions of the continuous fibers of the sheets being at different angles.

N

nanocrystalline metals metals with grain size smaller than 100 nm.

nanomaterials materials with a characteristic length scale smaller than 100 nm.

network modifiers an oxide that breaks up the silica network when added to silica glass; modifiers lower the viscosity of silica glass and promote crystallization. Examples are Na_2O, K_2O, CaO, and MgO.

nickel-iron alloys high-permeability soft magnetic alloys used for electrical applications where a high sensitivity is required such as for audio and instrument transformers. Two commonly used basic compositions are 50% Ni–50% Fe and 79% Ni–21% Fe.

nonferrous metals and alloys metals and alloys that do not contain iron, or if they do contain iron, it is only in a relatively small percentage. Examples of nonferrous metals are aluminum, copper, zinc, titanium, and nickel.

non–steady-state conditions for a diffusing system the concentration of the diffusing species changes with time at different places in the system.

normal spinel structure a ceramic compound having the general formula $MO \cdot M_2O_3$. The oxygen ions in this compound form an FCC lattice, with the M^{2+} ions occupying tetrahedral interstitial sites and the M^{3+} ions occupying octahedral sites.

n-type extrinsic semiconductor a semiconducting material that has been doped with an n-type element (e.g., silicon doped with phosphorus). The n-type impurities donate electrons that have energies close to the conduction band.

nuclei small particles of a new phase formed by a phase change (e.g., solidification) that can grow until the phase change is complete.

number of components of a phase diagram the number of elements or compounds that make up the phase-diagram system. For example, the Fe-Fe_3C system is a two-component system; the Fe-Ni system is also a two-component system.

O

octahedral interstitial site the space enclosed when the nuclei of six surrounding atoms (ions) form an octahedron.

optical-fiber communication a method of transmitting information by the use of light.

optical waveguide a thin-clad fiber along which light can propagate by total internal reflection and refraction.

oxygen-concentration cell galvanic cell formed when two pieces of the same metal are electrically connected by an electrolyte but are in solutions of different oxygen concentration.

P

paramagnetism a weak, positive, attractive reaction of a material to an applied magnetic field; a paramagnetic material has a small positive magnetic susceptibility.

parenchyma food-storing cells of trees that are short with relatively thin walls.

passivation the formation of a film of atoms or molecules on the surface of an anode so that corrosion is slowed down or stopped.

pauli exclusion principle the statement that no two electrons can have the same four quantum numbers.

pearlite a mixture of α ferrite and cementite (Fe_3C) phases in parallel plates (lamellar structure) produced by the eutectoid decomposition of austenite.

percent cold reduction

$$\% \text{ cold reduction} = \frac{\text{change in cross-sectional area}}{\text{original cross-sectional area}} \times 100\%$$

peritectic reaction (in a binary phase diagram) a phase transformation in which, upon cooling, a liquid phase combines with a solid phase to produce a new solid phase.

permanent dipole bond a secondary bond created by the attraction of molecules that have permanent dipoles. That is, each molecule has positive and negative charge centers separated by a distance.

phase a physically homogeneous and distinct portion of a material system.

phosphorescence absorption of light by a phosphor and its subsequent emission at times longer than 10^{-8} s.

photon a particle of radiation with an associated wavelength and frequency. Also referred to as a *quantum* of radiation.

piezoelectric ceramics materials that produce an electric field when subjected to mechanical force (and vice versa).

piezoelectric effect an electromechanical effect by which mechanical forces on a ferroelectric material can produce an electrical response and electrical forces produce a mechanical response.

pilling-Bedworth (P.B.) ratio the ratio of the volume of oxide formed to the volume of metal consumed by oxidation.

pitting corrosion local corrosion attack resulting from the formation of small anodes on a metal surface.

plain-carbon steel an iron-carbon alloy with 0.02 to 2 percent C. All commercial plain-carbon steels contain about 0.3 to 0.9 percent manganese along with sulfur, phosphorus, and silicon impurities.

planar density ρ_p the equivalent number of atoms whose centers are intersected by a selected area divided by the selected area.

plasticizers chemical agents added to plastic compounds to improve flow and processibility and to reduce brittleness. Example: plasticized polyvinyl chloride.

pn junction an abrupt junction or boundary between p- and n-type regions within a single crystal of a semiconducting material.

polarization the alignment of small electric dipoles in a dielectric material to produce a net dipole moment in the material.

polycrystalline structure a crystalline structure that contains many grains.

polymeric materials materials consisting of long molecular chains or networks of low-weight elements such as carbon, hydrogen, oxygen, and nitrogen. Most polymeric materials have low electrical conductivities. Examples are polyethylene and *polyvinyl chloride* (PVC).

polymerization the chemical reaction in which high-molecular-mass molecules are formed from monomers.

polymorphism (as pertains to metals) the ability of a metal to exist in two or more crystal structures. For example, iron can have a BCC or an FCC crystal structure, depending on the temperature.

population inversion condition in which more atoms exist in a higher-energy state than in a lower one. This condition is necessary for laser action.

porcelain enamel a glass coating applied to a metal substrate.

portland cement a cement consisting predominantly of calcium silicates that react with water to form a hard mass.

positive-ion core an atom without its valence electrons.

prepreg a ready-to-mold plastic resin-impregnated cloth or mat that may contain reinforcing fibers. The resin is partially cured to a "B" stage and is supplied to a fabricator who uses the material as the layers for a laminated product. After the layers are laid up to produce a final shape, the layers are bonded together, usually with heat and pressure, by the curing of the laminate.

prestressed concrete reinforced concrete in which internal compressive stresses have been introduced to counteract tensile stresses resulting from severe loads.

pretensioned (prestressed) concrete prestressed concrete in which the concrete is poured over pretensioned steel wires or rods.

primary phase a solid phase that forms at a temperature above that of an invariant reaction and is still present after the invariant reaction is completed.

proeutectic phase a phase that forms at a temperature above the eutectic temperature.

proeutectoid α ferrite α ferrite that forms by the decomposition of austenite at temperatures above the eutectoid temperature.

proeutectoid cementite (Fe_3C) cementite that forms by the decomposition of austenite at temperatures above the eutectoid temperature.

p-type extrinsic semiconductor a semiconducting material that has been doped with a p-type element (e.g., silicon doped with aluminum). The p-type impurities provide electron holes close to the upper energy level of the valence band.

pultrusion a process for producing a fiber-reinforced-plastic part of constant cross section continuously. The pultruded part is made by drawing a collection of resin-dipped fibers through a heated die.

Q

quantum mechanics a branch of physics in which systems under investigation can have only discrete allowed energy values that are separated by forbidden regions.

quantum numbers the set of four numbers necessary to characterize each electron in an atom. These are the principal quantum number n, the orbital quantum number l, the magnetic quantum number m_l, and the spin quantum number m_s.

R

radius ratio (for an ionic solid) the ratio of the radius of the central cation to that of the surrounding anions.

rare earth alloys a family of permanent magnetic alloys with extremely high energy products. $SmCo_5$ and $Sm(Co, Cu)_{7.4}$ are the two most important commercial compositions of these alloys.

recovery the first stage in the annealing process that results in removal of residual stresses and formation of low energy dislocation configurations.

recrystallization the second stage of the annealing process in which new grains start to grow and dislocation density decreases significantly.

rectifier diode a pn junction diode that converts alternating current to direct current (AC to DC).

refractory (ceramic) material a material that can withstand the action of a hot environment.

reinforced concrete concrete containing steel wires or bars to resist tensile forces.

relative permeability α_r the ratio of the permeability of a material to the permeability of a vacuum; $\mu_r = \mu/\mu_0$.

remanent induction B_r the value of B or M in a ferromagnetic material after H is decreased to zero.

reverse bias bias applied to a pn junction so that little current flows; in a pn junction under reverse bias, majority-carrier electrons and holes flow away from the junction.

roving a collection of bundles of continuous fibers twisted or untwisted.

S

sapwood the outer part of the tree stem of a living tree that contains some living cells that store food for the tree.

saturation induction B_s the maximum value of induction B_s or magnetization M_s for a ferromagnetic material.

scanning electron microscope (SEM) an instrument used to examine the surface of a material at very high magnifications by impinging electrons.

scanning probe microscopy (SPM) microscopy techniques such as STM and AFM that allow mapping of the surface of a material at the atomic level.

schottky imperfection a point imperfection in an ionic crystal in which a cation vacancy is associated with an anion vacancy.

selective leaching the preferential removal of one element of a solid alloy by corrosion processes.

self-diffusion the migration of atoms in a pure material.

semiconductor a material whose electrical conductivity is approximately midway between the values for good conductors and insulators. For example, pure silicon is a semiconducting element and has $\sigma_e = 4.3 \times 10^{-4}\ (\Omega \cdot m)^{-1}$ at 300 K.

semicrystalline materials with regions of crystalline structure dispersed in the surrounding, amorphous region; for instance some polymers.

s-glass fibers fibers made from S glass, which is a magnesia-alumina-silicate glass and which is used for fibers for fiberglass-reinforced plastics when extra-high-strength fibers are required.

shape memory alloys metal alloys that recover a previously defined shape when subjected to an appropriate heat treatment process.

shape-memory alloys materials that can be deformed but return to their original shape upon an increase in temperature.

shear strain γ shear displacement a divided by the distance h over which the shear acts ($\gamma = a/h$).

shear stress τ shear force S divided by the area A over which the shear force acts ($\tau = S/A$).

sheet-molding compound (SMC) a compound of plastic resin, filler, and reinforcing fiber used to make fiber-reinforced-plastic composite materials. SMC is usually made with about 25 to 30 percent fibers about 1 in. (2.54 cm) long, of which fiberglass is the most commonly used fiber. SMC material is usually pre-aged to a state so that it can support itself and then cut to size and placed in a compression mold. Upon hot pressing, the SMC cures to produce a rigid part.

sintering (of a ceramic material) the process in which fine particles of a ceramic material become chemically bonded together at a temperature high enough for atomic diffusion to occur between the particles.

slip the process of atoms moving over each other during the permanent deformation of a metal.

slip casting a ceramic shape-forming process in which a suspension of ceramic particles and water are poured into a porous mold and then some of the water from the cast material diffuses into the mold, leaving a solid shape in the mold. Sometimes excess liquid within the cast solid is poured from the mold, leaving a cast shell.

slip system a combination of a slip plane and a slip direction.

slipbands line markings on the surface of a metal due to slip caused by permanent deformation.

smart materials materials with the ability to sense and respond to external stimuli.

soft ferrites ceramic compounds with the general formula $MO \cdot Fe_2O_3$, where M is a divalent ion such as Fe^{2+}, Mn^{2+}, Zn^{2+}, or Ni^{2+}. These materials are ferrimagnetic and are insulators and so can be used for high-frequency transformer cores.

soft magnetic material a magnetic material with a high permeability and low coercive force.

softening point at this temperature the glass flows at an appreciable rate.

softwood trees trees that have exposed seeds and arrow leaves (needles). Examples are pine, fir, and spruce.

solid solution an alloy of two or more metals or a metal(s) and a nonmetal(s) that is a single-phase atomic mixture.

solid-solution hardening (strengthening) strengthening a metal by alloying additions that form solid solutions. Dislocations have more difficulty moving through a metal lattice when the atoms are different in size and electrical characteristics, as is the case with solid solutions.

solidus the temperature during the solidification of an alloy at which the last of the liquid phase solidifies.

solution polymerization in this process a solvent is used that dissolves the monomer, the polymer, and the polymerization initiator. Diluting the monomer with the solvent reduces the rate of polymerization, and the heat released by the polymerization reaction is absorbed by the solvent.

solvus a phase boundary below the isothermal liquid + proeutectic solid phase boundary and between the terminal solid solution and two-phase regions in a binary eutectic phase diagram.

space lattice a three-dimensional array of points each of which has identical surroundings.

specific tensile modulus the tensile modulus of a material divided by its density.

specific tensile strength the tensile strength of a material divided by its density.

spheroidite a mixture of particles of cementite (Fe_3C) in an α ferrite matrix.

spray lay-up a process in which a spray gun is used to produce a fiber-reinforced product. In one type of spray-up process, chopped fibers are mixed with plastic resin and sprayed into a mold to form a composite material part.

stacking fault a surface defect formed due to improper (out of place) stacking of atomic planes.

steady-state conditions for a diffusing system there is no change in the concentration of the diffusing species with time at different places in the system.

stepwise polymerization the polymerization mechanism whereby the growth of the polymer molecule proceeds by a stepwise intermolecular reaction. Only one type of reaction is involved. Monomer units can react with each other or with any size polymer molecule. The active group on the end of a monomer is assumed to have the same reactivity no matter what the polymer length is. Often a by-product such as water is condensed off in the polymerization process. Example: the polymerization of nylon 6,6 from adipic acid and hexamethylene diamine.

stereoisomers molecules that have the same chemical composition but different structural arrangements.

stereospecific catalyst a catalyst that creates mostly a specific type of stereoisomer during polymerization. Example: the Ziegler catalyst used to polymerize propylene to mainly the isotactic polypropylene isomer.

strain hardening (strengthening) the hardening of a metal or alloy by cold working. During cold working, dislocations multiply and interact, leading to an increase in the strength of the metal.

strain point at this temperature the glass is rigid.

stress corrosion preferential corrosive attack of a metal under stress in a corrosive environment.

stress shielding a condition in which the applied implant is carrying a significant portion of load carried by a fractured bone. It has negative side effects.

substitutional diffusion the migration of solute atoms in a solvent lattice in which the solute and solvent atoms are approximately the same size. The presence of vacancies makes the diffusion possible.

substitutional solid solution a solid solution in which solute atoms of one element can replace those of solvent atoms of another element. For example, in a Cu–Ni solid solution the copper atoms can replace the nickel atoms in the solid-solution crystal lattice.

superalloys metal alloys with improved performance at elevated temperatures and high stress levels.

superconducting state a solid in the superconducting state that shows no electrical resistance.

superplasticity the ability of some metals to deform plastically by 1000–2000% at high temperatures and low loading rates.

suspension polymerization in this process water is used as the reaction medium, and the monomer is dispersed rather than being dissolved in the medium. The polymer products are obtained in the form of small beads that are filtered, washed, and dried in the form of molding powders.

syndiotactic isomer this isomer has pendant groups of atoms *regularly alternating* in positions on both sides of a vinyl polymer chain. Example: syndiotactic polypropylene.

system a portion of the universe that has been isolated so that its properties can be studied.

T

tempering (of a steel) the process of reheating a quenched steel to increase its toughness and ductility. In this process martensite is transformed into tempered martensite.

terminal phase a solid solution of one component in another for which one boundary of the phase field is a pure component.

tetrahedral interstitial site the space enclosed when the nuclei of four surrounding atoms (ions) form a tetrahedron.

thermal arrest a region of the cooling curve for a pure metal where temperature does not change with time (plateaue) representing the freezing temperature.

thermally tempered glass glass that has been reheated to near its softening temperature and then rapidly cooled in air to introduce compressive stresses near its surface.

thermistor a ceramic semiconductor device that changes in resistivity as the temperature changes and is used to measure and control temperature.

thermoplastic (noun) a plastic material that requires heat to make it formable (plastic) and upon cooling, retains its shape. Thermoplastics are composed of chain polymers with the bonds between the chains being of the secondary permanent dipole type. Thermoplastics can be repeatedly softened when heated and harden when cooled. Typical thermoplastics are polyethylenes, vinyls, acrylics, cellulosics, and nylons.

thermosetting plastic (thermoset) a plastic material that has undergone a chemical reaction by the action of heat, catalysis, etc., leading to a cross-linked network macromolecular structure. Thermoset plastics cannot be remelted and reprocessed since when they are heated they degrade and decompose. Typical thermoset plastics are phenolics, unsaturated polyesters, and epoxies.

tie line a horizontal working line drawn at a particular temperature between two phase boundaries (in a binary phase diagram) to be used to apply the lever rule. Vertical lines are drawn from the intersection of the tie line with the phase boundaries to the horizontal composition line. A vertical line is also drawn from the tie line to the horizontal line at the intersection point of the tie line with the alloy of interest to use with the lever rule.

tow (of fibers) a collection of numerous fibers in a straight-laid bundle, specified according to the number of fibers it contains—e.g., 6000 fibers/tow.

tracheids (longitudinal) the predominating cell found in softwoods; tracheids have the function of conduction and support.

***trans*-1,4 polyisoprene** the isomer of 1,4 polyisoprene that has the methyl group and hydrogen on opposite sides of the central double bond of its mer.

transducer a device that is actuated by power from one source and transmits power in another form to a second system. For example, a transducer can convert input sound energy into an output electrical response.

transfer molding a thermoset molding process in which the molding compound is first softened by heat in a transfer chamber and then is forced under high pressure into one or more mold cavities for final curing.

transmission electron microscope (TEM) an instrument used to study, the internal defect structures based on passage of electron through a thin films of materials.

twin boundary a mirror image misorientation of the crystal structure which is considered a surface defect.

twist boundary an array of screw dislocations creating mismatch inside a crystal.

type I superconductor one that exhibits complete magnetic-flux repulsion between the normal and superconducting states.

type II superconductor one in which the magnetic flux gradually penetrates between the normal and superconducting states.

U

ultimate tensile strength (UTS) the maximum stress in the engineering stress-strain diagram.

unidirectional laminate a fiber-reinforced-plastic laminate produced by bonding together layers of fiber-reinforced sheets that all have continuous fibers in the same direction in the laminate.

unit cell a convenient repeating unit of a space lattice. The axial lengths and axial angles are the lattice constants of the unit cell.

upper critical field H_{c2} the field at which superconductivity disappears for a type II superconductor.

V

vacancy a point imperfection in a crystal lattice where an atom is missing from an atomic site.

vacuum bag molding a process of molding a fiber-reinforced-plastic part in which sheets of transparent flexible material are placed over a laminated part that has not been cured. The sheets and the part are sealed, and a vacuum is then applied between the cover sheets and the laminated part so that entrapped air is mechanically worked out of the laminate. Then the vacuum-bagged part is cured.

valence band the energy band containing the valence electrons. In a conductor the valence band is also the conduction band. The valence band in a conducting metal is not full, and so some electrons can be energized to levels within the valence band and become conductive electrons.

valence electrons electrons in the outermost shells that are most often involved in bonding.

viscoelasticity the type of mechanical response in a material that depends on loading rate or strain rate.

vitrification melting or formation of a glass; the vitrification process is used to produce a viscous liquid glass in a ceramic mixture upon firing. Upon cooling, the liquid phase solidifies and forms a vitreous or glassy matrix that bonds the unmelted particles of the ceramic material together.

volume density ρ_v mass per unit volume; this quantity is usually expressed in Mg/m^3 or g/cm^3.

vulcanization a chemical reaction that causes cross-linking of polymer chains. Vulcanization usually refers to the cross-linking of rubber molecular chains with sulfur, but the word is also used for other cross-linking reactions of polymers such as those that occur in some silicone rubbers.

W

weld decay corrosion attack at or adjacent to a weld as the result of galvanic action resulting from structural differences in the weld.

white cast irons iron-carbon-silicon alloys with 1.8 to 3.6 percent C and 0.5 to 1.9 percent Si. White cast irons contain large amounts of iron carbide that make them hard and brittle.

wire drawing a process in which wire stock drawn through one or more tapered dies to the desired cross section.

wood a natural composite material consisting mainly of a complex array of cellulose fibers in a polymeric material matrix made up primarily of lignin.

wood ray a ribbonlike aggregate of cells extending radially in the tree stem; the tissue of the ray is primarily composed of food-storing parenchyma cells.

wood vessel a tubular structure formed by the union of smaller cell elements in a longitudinal row.

working point at this temperature the glass can easily be worked.

Y

yield strength the stress at which a specific amount of strain occurs in the engineering tensile test. In the U.S. the yield strength is determined for 0.2 percent strain.

ANSWERS TO SELECTED PROBLEMS

Chapter 2

2.6. 1.82×10^{21} atoms Au

2.8. 6.27×10^{21} atoms Mo

2.9. Atomic % Sn = 65.4 at%
Atomic % Pb = 34.6 at%

2.12. Cu_3Au

2.15. $\Delta E = 6.56 \times 10^{-19}$ J = 4.1 eV

2.17. **a.** $\Delta E = 0.66$ eV $= 1.06 \times 10^{-19}$ J
b. $\upsilon = 1.6 \times 10^{14}$ Hz **c.** $\lambda = 1876$ nm

2.19. $E = 9.30 \times 10^{-15}$ J
$\upsilon = 1.40 \times 10^{19}$ Hz

2.30. **b.**

Mo	[Kr] $4d^5\,5s^1$
Mo^{3+}	[Kr] $4d^3$
Mo^{4+}	[Kr] $4d^2$
Mo^{6+}	[Kr] $4d^3$

2.38. $F_{\text{attractive}} = 9.16 \times 10^{-9}$ N

2.39. $E_{K^+Br^-} = -6.26 \times 10^{-19}$ J

2.42. $r_{Sr^{2+}} = 0.135$ nm

2.53. % covalent bonding = 47.75%
% metallic bonding = 52.25%

2.64. While a 2 − 6 compound typically has a higher ionic character than a 3 − 5, the relatively high electronegativity of phosphorous causes InP to be more ionic in nature.

Chapter 3

3.11. 0.330 nm

3.13. 0.186 nm

3.16. 0.144 nm

3.18. 0.387 nm

3.25. $0.106\ nm^3$

3.26. 0.273 nm

3.31. **a.** Position Coordinates: (0, 0, 0), (1, 0, 0)
b. Position Coordinates: (0, 0, 0), (1, 1, 0)
c. Position Coordinates: (0, 0, 0), (1, 1, 1)

3.35. $[\bar{1}4\bar{1}]$

3.46. (100), (010), (001), $(\bar{1}00)$, $(0\bar{1}0)$, $(00\bar{1})$

3.48. **a.** (1, 0, 0), (1, 0, 1), (1, 1, 0), (1, 1, 1) (1, ½, ½)
b. (1, 0, 0), (1, 0, 1), (0, 1, 0), (0, 1, 1), (½, ½, 0), (½, ½, 1)
c. (1, 0, 0), (0, 0, 1), (0, 1, 0), (½, 0, ½), (½, ½, 0), (0, ½, ½)

3.49. $(6\bar{3}4)$

3.51. $(23\bar{4})$

3.52. $(\bar{1}\,\bar{1}2)$

3.54. $(\bar{1}2\bar{2})$

3.57. **a.** 0.224 nm **b.** 0.112 nm
c. 0.100 nm

3.58. **a.** 0.502 nm **b.** 0.217 nm

3.63. Miller-Bravais Indices for Planes Shown in Figure P3.63(a).
The Miller indices of plane *a* are $(0\bar{1}10)$.
The Miller indices of plane *b* are $(10\bar{1}2)$.
The Miller indices of plane *c* are $(\bar{2}200)$.
Miller-Bravais Indices for the Planes Shown in Figure P3.63(b).
The Miller indices of plane *a* are $(01\bar{1}0)$.
The Miller indices of plane *b* are $(1\bar{1}01)$.
The Miller indices of plane *c* are $(1\bar{1}01)$.

3.65. $[\bar{1}\,\bar{1}21]$, $[\bar{2}111]$, $[\bar{1}2\bar{1}1]$,
$[11\bar{2}1]$, $[2\bar{1}\,\bar{1}1]$, $[1\bar{2}11]$

3.67. For Fig. P3.67(*a*), the Miller-Bravais direction indices indicated are $[\bar{2}111]$ and $[11\bar{2}1]$. Those associated with Fig. P3.67(*b*) are $[\bar{1}101]$ and $[10\bar{1}1]$.

3.71. 180.09 g/mol

3.74. **a.** 1.20×10^{13} atoms/mm²
b. 8.50×10^{12} atoms/mm²
c. 1.963×10^{13} atoms/mm²

3.76. **a.** 3.29×10^6 mm **b.** 2.33×10^6 mm
c. 3.80×10^6 mm

3.80. −4.94%

3.86. 0.3303 nm

3.89. **a.** 0.50 ⇒ BCC **b.** 0.3296 nm
c. niobium (Nb)

3.91. **a.** 0.75 ⇒ FCC **b.** 0.38397 nm
c. iridium (Ir)

Chapter 4

4.7. $r^* = 1.11 \times 10^{-7}$ cm
4.10. 327 atoms
4.19. **a.** low **c.** moderate **e.** low
4.21. 0.036 nm
4.28. 10.23
4.31. 9.64

Chapter 5

5.3. **a.** 2.77×10^{24} vacancies/m^3
b. 2.02×10^{-5} vacancies/atom
5.13. 56.6 min.
5.16. 0.394 wt %
5.17. 340 min. = 5.67 h
5.19. 1.03 mm
5.20. 1.98×10^{-4} cm
5.23. 0.707 μm
5.25. $D = 1.71 \times 10^{-15}$ m^2/s
5.26. $D = 8.64 \times 10^{-14}$ m^2/s
5.29. 139.3 kJ/mol

Chapter 6

6.6. 0.0669 cm
6.13. 80.8%
6.19. $\sigma = 962$ MPa
6.20. $\sigma = 954$ MPa
6.23. Engineering strain $\varepsilon = 0.175$
6.39. The four principal slip planes are: (111); $(\bar{1}11)$; $(1\bar{1}1)$; $(11\bar{1})$.
The three slip directions are: $[\bar{1}10]$; $[01\bar{1}]$; $[\bar{1}01]$.
6.46. **a.** 30.6 MPa **b.** 0
6.48. $\sigma = 2.08$ MPa
6.49. **a.** 1.94 MPa **b.** 1.94 MPa
c. 0
6.52. **a.** 34.7 MPa **b.** 0
c. 34.7 MPa

Chapter 7

7.12. 0.76 mm
7.13. 3.90 mm
7.19. **a.** (199.8 MP) **b.** (99.9 MP)
c. (72.3 MP) **d.** −0.16
7.24. $\sigma = 149$ MPa
7.31. 1419 h
7.33. the stress is approximately 96 MPa
7.34. 186.2 h

Chapter 8

8.16. **a.** Weight of liquid phase = 364 g
Weight of proeutectic α = 136 g
b. Weight of liquid phase = 251 g
Weight of proeutectic α = 249 g
c. 307.5 g
d. 192.5 g
8.17. 83.3% Sn and 16.7% Pb
8.24. 66.7%
8.26. Wt % liquid = 14.3%
Wt % δ = 85.7%
8.29. **a.** Wt % α = 47.4%
Wt % L_1 = 52.6%
b. Wt % α = 72.2%
Wt % L_1 = 27.8%
c. Wt % α = 88.5%
Wt % L_2 = 11.5%
d. Wt % α = 90%
Wt % β = 10%
8.31. 10.8% Pb and 89.2% Cu

Chapter 9

9.12. Wt % austenite = 80.8%
Wt % proeutectoid ferrite = 19.2%
9.14. 0.49% C
9.17. Wt % austenite = 98.3%
Wt % cementite = 1.7%
9.19. 1.08% C
9.20. 1.32% C
9.24. 0.232% C
9.68. about 53 RC
9.69. **a.** 40 RC **b.** 34 RC
9.73. 12°C/sec
9.80. The constituents of the microstructure will be bainite, martensite and austenite.
9.96. 9.2%

Chapter 10

10.1. 14,643 mers
10.4. 98 mers
10.6. Mole fraction of polystyrene = 0.541
Mole fraction of polyacrylonitrile = 0.459
10.7. Mole fraction of polyacrylonitrile = 0.324
Mole fraction of polybutadiene = 0.382
Mole fraction of polystyrene = 0.294
10.9. 1.24 g S

10.13. 1.69%
10.17. Wt % S = 6.56%
10.18. **a.** 61.7 days **b.** 4.0 MPa
10.20. 37.65 kJ/mol
10.22. **a.** 35.7 days **b.** 65.95 days

Chapter 11

11.7. 0.414
11.10. 4.87 g/cm^3
11.13. **a.** 4.96 g/cm^3 **b.** 7.27 g/cm^3
11.14. **a.** 0.577 **b.** 0.524
11.16. 2.95 g/cm^3
11.18. 6.32 g/cm^3
11.21. 18.1 O^{2-} or 9.1 Th^{4+} ions/nm^2
11.27. 6.03 g/cm^3
11.93. 736.7°C

Chapter 12

12.20. **a.** Wt % carbon fibers = 76.0%
Wt % epoxy resin = 24.0%
b. 1.60 g/cm^3
12.23. 239.6 GPa
12.26. The strength of the composite material = 30.48 GPa
The fraction of the load carried by the Kevlar 49 fibers = 0.988
12.29. 9.40 GPa
12.81. 0.306
12.82. 222.2 GPa

Chapter 13

13.12. −0.314 V
13.13. −0.403 V
13.17. 0.07 *M*
13.19. −0.046 V
13.26. 23.5 min
13.28. $1.07 \times 10^{-2} \frac{g}{min}$
13.31. 4.52×10^{-7} A/cm^2
13.34. 8.34×10^{-7} A/cm^2
13.64. 23.6 h
13.75. 0.65 A

Chapter 14

14.7. 0.127 m
14.14. $2.36 \times 10^{-6}\ \Omega \times$ cm
14.15. −146.5°C
14.29. $0.45\ \Omega \cdot m$
14.32. $17.4\ (\Omega \cdot m)^{-1}$
14.39. **a.** 7.51 cm^3 **b.** $6.61 \times 10^{-3}\ \Omega \cdot m$
14.44. **a.** 6.17×10^{18} electrons/cm^3
b. 1.24×10^{-4}
14.70. **a.** i. InSb = 0.994
ii. InP = 0.979
b. i. InSb = 0.006
ii. InP = 0.021
14.78. 3675