Smith, *Foundations of Materials Science and Engineering*, *3e* Glossary

Chapter 1: Introduction to Materials Science and Engineering

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

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.

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

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

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.

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.

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).

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

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

Chapter 2: Atomic Structure and Bonding

Sec. 2.1
Atom: the basic unit of an element that can undergo chemical change.

Sec. 2.2
Atomic number: the number of protons in the nucleus of an atom of an element.

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

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

Sec. 2.3

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

Ground state: the quantum state with the lowest energy.

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

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

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.

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.

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.

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

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

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

Anion: an ion with a negative charge.

Cation: an ion with a positive charge.

Sec. 2.5

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.

Sec. 2.6

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.

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*.

Sec. 2.7

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

Positive-ion core: an atom without its valence electrons.

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.

Sec. 2.8

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.

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.

Chapter 3: Crystal Structures and Crystal Geometry

Sec. 3.1

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.

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

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

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

Sec. 3.3

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.

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 closepacked planes in the FCC crystal structure is *ABCABC. . . .*

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. . . .*

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

Sec. 3.5

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.

Sec. 3.6

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.

Sec. 3.9

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

Planar density r_p: the equivalent number of atoms whose centers are intersected by a selected area divided by the selected area.

Linear density r_l: the number of atoms whose centers lie on a specific direction on a specific length of line in a unit cube.

Sec. 3.10

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.

Chapter 4: Solidification, Crystalline Imperfections, and Diffusion in Solids

Sec. 4.1

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

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.

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.

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.

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.

Grain: a single crystal in a polycrystalline aggregate.

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

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.

Sec. 4.2

Polycrystalline structure: a crystalline structure that contains many grains.

Sec. 4.3

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

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

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.

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

Sec. 4.4

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

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.

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

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

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.

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

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

Sec. 4.5

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

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

Sec. 4.6

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.

Self-diffusion: the migration of atoms in a pure material.

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

Volume diffusion: atomic migration in the grain interiors of a polycrystalline aggregate.

Grain boundary diffusion: atomic migration at the grain boundaries of a polycrystalline aggregate.

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.

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.

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.

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

Chapter 5: Mechanical Properties of Metals I

Sec. 5.1

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

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.

Percent cold reduction:

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

Annealing: a heat treatment given to a metal to soften it.

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.

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

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

Sec. 5.2

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.

Engineering stress s: average uniaxial force divided by original cross-sectional area ($s = F/A_0$).

Engineering strain e: change in length of sample divided by the original length of sample ($e = Dl/l_0$).

Shear stress t : shear force S divided by the area A over which the shear force acts ($t = S/A$).

Shear strain g: shear displacement a divided by the distance h over which the shear acts ($g = a/h$).

Sec. 5.3

Engineering stress-strain diagram: experimental plot of engineering stress versus engineering strain; s is normally plotted as the y axis and e as the x axis.

Modulus of elasticity E: stress divided by strain (s/e) in the elastic region of an engineering stress-strain diagram for a metal ($E = s/e$).

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.

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

Sec. 5.4

Hardness: a measure of the resistance of a material to permanent deformation.

Sec. 5.5

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

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

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

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.

Sec. 5.6

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.

Sec. 5.7

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.

Chapter 6: Mechanical Properties of Metals II

Sec. 6.1

Recovery: the first stage in the removal of the effects of cold working when a coldworked metal is slowly heated with increasing temperature. During recovery, internal stresses are relieved and some dislocation rearrangement into lower-energy configurations takes place. Some dislocations are annihilated.

Recrystallization: the process whereby a cold-worked metal is heated to a sufficiently high temperature for a long enough time to form a new strain-free grain structure. During recrystallization the dislocation density of the metal is greatly reduced.

Sec. 6.2

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

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

Sec. 6.3

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

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.

Sec. 6.4

Fatigue crack growth rate *da/dN*: The rate of crack growth extension caused by constant-amplitude fatigue loading.

Sec. 6.5

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.

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.

Chapter 7: Polymeric Materials

Sec. 7.1

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.

Sec.7.2

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

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.

Mer: a repeating unit in a chain polymer molecule.

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

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

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.

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

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

Homopolymer: a polymer consisting of only one type of monomeric unit.

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

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.

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.

Sec. 7.3

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

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.

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.

Sec. 7.4

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.

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.

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

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

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

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

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.

Sec. 7.5

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.

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.

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

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.

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.

Sec. 7.6

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

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.

Sec. 7.9

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.

***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.

***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.

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.

Chapter 8: Phase Diagrams

Sec. 8.1

System: a portion of the universe that has been isolated so that its properties can be

studied.

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

Phase: a physically homogeneous and distinct portion of a material system.

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.

Sec. 8.2

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, $P + F = C + 1$.

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.

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$_3$C system is a two-component system; the Fe-Ni system is also a two-component system.

Sec. 8.3

Isomorphous system: a phase diagram in which there is only one solid phase; that is, there is only one solid-state structure.

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

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

Sec. 8.4

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. To use this rule, one takes the ratio of the segment of the tie line opposite the phase of interest and on the opposite side of the alloy or composition of interest over the whole tie line.

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 the lever rule.

Sec. 8.6

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.

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.

Invariant reactions: equilibrium phase transformations involving zero degrees of freedom.

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.

Hypoeutectic composition: one that is to the left of the eutectic point.
Hypereutectic composition: one that is to the right of the eutectic point.
Proeutectic phase: a phase that forms at a temperature above the eutectic temperature.
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.

Sec. 8.7
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.

Sec. 8.8
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).

Sec. 8.10
Terminal phase: a solid solution of one component in another for which one boundary of the phase field is a pure component.
Intermediate phase: a phase whose composition range is between those of the terminal phases.

Chapter 9: Engineering Alloys

Sec. 9.2
Austenite (*g* phase in Fe-Fe$_3$C 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.
***a* ferrite** (*a* phase in the Fe-Fe$_3$C phase diagram): an interstitial solid solution of carbon in BCC iron; maximum solid solubility of carbon in BCC iron is 0.02 percent.
Cementite: the intermetallic compound Fe$_3$C; a hard and brittle substance.
Pearlite: a mixture of *a* ferrite and cementite (Fe$_3$C) phases in parallel plates (lamellar structure) produced by the eutectoid decomposition of austenite.
Eutectoid *a* ferrite: *a* ferrite that forms during the eutectoid decomposition of austenite; the *a* ferrite in pearlite.
Eutectoid cementite (Fe$_3$C): cementite which forms during the eutectoid decomposition of austenite; the cementite in pearlite.
Eutectoid (plain-carbon steel): a steel with 0.8 percent C.
Hypoeutectoid (plain-carbon steel): a steel with less than 0.8 percent C.
Hypereutectoid (plain-carbon steel): a steel with 0.8 to 2.0 percent C.
Proeutectoid *a* ferrite: *a* ferrite that forms by the decomposition of austenite at temperatures above the eutectoid temperature.
Proeutectoid cementite (Fe$_3$C): cementite that forms by the decomposition of austenite

at temperatures above the eutectoid temperature.

Sec. 9.3

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

Bainite: a mixture of *a* ferrite and very small particles of Fe_3C particles produced by the decomposition of austenite; a nonlamellar eutectoid decomposition product of austenite.

Spheroidite: a mixture of particles of cementite (Fe_3C) in an *a* ferrite matrix.

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.

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.

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.

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.

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

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

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.

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

Sec. 9.4

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.

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.

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.

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.

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.

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 heattreated 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.

Chapter 10: Ceramic Materials

Sec. 10.1

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

Sec. 10.2

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.

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

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.

Octahedral interstitial site in the FCC crystal structure: the space enclosed when the nuclei of six surrounding atoms (ions) form an octahedron.

Tetrahedral interstitial site in the FCC crystal structure: the space enclosed when the nuclei of four surrounding atoms (ions) form a tetrahedron.

Sec. 10.4

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

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

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.

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.

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

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.

Sec. 10.6

Dielectric: an electrical insulator material.

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

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).

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.

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

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

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

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.

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.

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.

Sec. 10.8

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

Sec. 10.9

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

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-modifying oxide: 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.

Glass 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 .

Glass reference points (temperatures).

Working point: at this temperature the glass can easily be worked.

Softening point: at this temperature the glass flows at an appreciable rate.

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

Strain point: at this temperature the glass is rigid.

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.

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.

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.

Chapter 11: Composite Materials

Sec. 11.1
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.

Sec. 11.2
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.

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.

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.

Roving: a collection of bundles of continuous fibers twisted or untwisted.

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.

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.

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.

Specific tensile strength: the tensile strength of a material divided by its density.

Specific tensile modulus: the tensile modulus of a material divided by its density.

Sec. 11.3

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

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.

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.

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

Sec. 11.4

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.

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.

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.

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.

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.

Sec. 11.5

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.

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.

Sec. 11.6
Concrete (portland cement type): a mixture of portland cement, fine aggregate, coarse aggregate, and water.
Portland cement: a cement consisting predominantly of calcium silicates that react with water to form a hard mass.
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).
Hydration reaction: reaction of water with another compound. The reaction of water with portland cement is a hydration reaction.
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.
Reinforced concrete: concrete containing steel wires or bars to resist tensile forces.
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.

Sec. 11.7
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.

Sec. 11.8
Wood: a natural composite material consisting mainly of a complex array of cellulose fibers in a polymeric material matrix made up primarily of lignin.
Lignin: a very complex cross-linked three-dimensional polymeric material formed from phenolic units.
Sapwood: the outer part of the tree stem of a living tree that contains some living cells that store food for the tree.
Heartwood: the innermost part of the tree stem that in the living tree contains only dead cells.
Cambium: the tissue that is located between the wood and bark and is capable of repeated cell division.
Softwood trees: trees that have exposed seeds and arrow leaves (needles). Examples are pine, fir, and spruce.
Hardwood trees: trees that have covered seeds and broad leaves. Examples are oak, maple, and ash.
Parenchyma: food-storing cells of trees that are short with relatively thin walls.
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.
Tracheids (longitudinal): the predominating cell found in softwoods; tracheids have the

function of conduction and support.

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

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

Lumen: the cavity in the center of a wood cell.

Chapter 12: Corrosion

Sec. 12.1

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

Sec. 12.2

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

Cathode: the metal electrode in an electrolytic cell that accepts electrons.

Sec. 12.3

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

Galvanic cell: two dissimilar metals in electrical contact with an electrolyte.

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.

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.

Sec. 12.4

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*).

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

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

Sec. 12.5

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

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

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

Stress corrosion: preferential corrosive attack of a metal under stress in a corrosive environment.
Selective leaching: the preferential removal of one element of a solid alloy by corrosion processes.

Sec. 12.6
Pilling-Bedworth (P.B.) ratio: the ratio of the volume of oxide formed to the volume of metal consumed by oxidation.

Sec. 12.7
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.
Anodic protection: the protection of a metal that forms a passive film by the application of an externally impressed anodic current.

Chapter 13: Electrical Properties of Materials

Sec. 13.1
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*).*
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 r_e: a measure of the difficulty of electric current's passage through a *unit* volume of material. For a volume of material, $r_e = RA/l$, where R = resistance of material, Ω; l = its length, m; A = its cross-sectional area, m^2. In SI units , r_e = ohm-meters ($\Omega \cdot$ m)
Electrical conductivity s_e: a measure of the ease with which electric current passes through a unit volume of material. Units: $(\Omega \cdot m)^{-1}$. s_e is the inverse of s_e.
Electrical conductor: a material with a high electrical conductivity. Silver is a good conductor and has a $s_e = 6.3 \times 10^7$ $(\Omega \cdot m)^{-1}$.
Electrical insulator: a material with a low electrical conductivity. Polyethylene is a poor conductor and has a s_e = 10-15 to 10-17 $(\Omega \cdot m)^{-1}$.
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 $s_e = 4.3 \times 10^{-4}$ $(\Omega \cdot m)^{-1}$ at 300 K.
Electric current density J: the electric current per unit area. SI units: amperes/meter^2 (A/m^2).

Sec. 13.2
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.

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.

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.

Sec. 13.3

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.

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

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

Sec. 13.4

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.

Donor levels: in the band theory, local energy levels near the conduction band.

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.

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

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.

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.

Sec. 13.5

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

Bias: voltage applied to two electrodes of an electronic device.

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.

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.

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

Bipolar transistor: a three-element, two-junction semiconducting device. The three basic elements of the transistor are the emitter, base, and collector. Bipolar junction transistors (BJTs) can be of the npn or pnp types. The emitter-base junction is forward-

biased and the collector-base junction reverse-biased so that the transistor can act as a current amplification device.

Chapter 14: Optical Properties and Superconducting Materials

Sec. 14.3
Index of refraction: the ratio of the velocity of light in vacuum to that through another medium of interest.

Sec. 14.4
Absorptivity: the fraction of the incident light that is absorbed by a material.

Sec. 14.5
Luminescence: absorption of light or other energy by a material and the subsequent emission of light of longer wavelength.
Fluorescence: absorption of light or other energy by a material and the subsequent emission of light within 10^{-8} s of excitation.
Phosphorescence: absorption of light by a phosphor and its subsequent emission at times longer than 10^{-8} s.

Sec. 14.6
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.
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.

Sec. 14.7
Optical communication: a method of transmitting information by the use of light.
Light attenuation: decrease in intensity of the light.
Optical waveguide: a thin-clad fiber along which light can propagate by total internal reflection and refraction.

Sec. 14.8
Superconducting state: a solid in the superconducting state that shows no electrical resistance.
Critical temperature T_c: the temperature below which a solid shows no electrical resistance.
Critical current density J_c: the current density above which superconductivity disappears.
Critical field H_c: the magnetic field above which superconductivity disappears.
Meissner effect: the expulsion of the magnetic field by a superconductor.
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.

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

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

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

Chapter 15: Magnetic Materials

Sec. 15.1

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

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).

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 $\mu_0 M$. ($\mu_0 = 4p \times 10^{-4}$ T $\cdot$ m/A.)

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

Relative permeability m_r: the ratio of the permeability of a material to the permeability of a vacuum; $\mu_r = \mu/\mu 0$.

Magnetic susceptibility c_m: the ratio of M (magnetization) to H (applied magnetic field); $c_m = M/H$.

Sec. 15.2

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

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

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.

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 $\cdot$ m^2 .

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.

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.

Sec. 15.3

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

Sec. 15.4

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

Sec. 15.5

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.

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

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.

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

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.

Sec. 15.6

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

Saturation induction B_s or saturation magnetization M_s: the maximum value of induction *Bs* or magnetization *Ms* for a ferromagnetic material.

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

Coercive force Hc: the applied magnetic field required to decrease the magnetic induction of a magnetized ferro- or ferrimagnetic material to zero.

Sec. 15.7

Soft magnetic material: a magnetic material with a high permeability and low coercive force.

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.

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

Iron-silicon magnetic 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.

Nickel-iron magnetic 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.

Sec. 15.8

Hard magnetic material: a magnetic material with a high coercive force and a high saturation induction.

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 .

Alnico magnetic 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.

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 a' precipitate in alnico 5 alloy is elongated and aligned by this type of heat treatment.

Rare earth magnetic 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.

Iron-chromium-cobalt magnetic 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.

Sec. 15.9

Soft ferrites: ceramic compounds with the general formula MO · Fe$_2$O$_3$, 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.

Normal spinel structure: a ceramic compound having the general formula MO · M$_2$O$_3$. 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.

Inverse spinel structure: a ceramic compound having the general formula MO · M$_2$O$_3$. 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.

Hard ferrites: ceramic permanent magnetic materials. The most important family of these materials has the basic composition MO · Fe$_2$O3 , 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.