Ch 1: Introduction

November 5, 2014 10:24 AM

- **Materials Science and Engineering**
    - There are six different property classifications of materials that determine their applicability: mechanical, electrical, thermal, magnetic optical, and deteriorative.
    - One aspect of materials science is the investigations of relationships that exist between the structures and properties of materials. By *structure*, we mean how some internal component(s) of the material is (are) arranged. In terms of (and with increasing) dimensionality, structural elements include subatomic, atomic, microscopic, and macroscopic.
    - With regard to the design, production, and utilization of materials, there are four elements to consider - processing, structure, properties, and performance. The performance of a material depends on its properties, which in turn are a function of its structure(s); furthermore, structure(s) is (are) determined by how the material was processed.
    - Three important criteria in materials selection are in-service conditions to which the material will be subjected, any deterioration of material properties during operation, and economics or cost of the fabricated piece.
- **Classification of Materials**
    - On the basis of chemistry and atomic structure, materials are classified into three general categories: metals (metallic elements), ceramics (compounds between metallic and non-metallic elements), and polymers (compounds composed of carbon, hydrogen, and other non-metallic elements). In addition, composites are composted of at least two different material types.
- **Advanced Materials**
    - Another materials category is advanced materials that are used in high-tech applications, including semiconductors (having electrical conductivities intermediate between those of conductors and insulators), biomaterials (which must be compatible with body tissues), smart materials (those that sense and respond to changes in their environments in predetermined manners), and nanomaterials (those that have structural features on the order of a nanometer, some of which may be designed on the atomic/molecular level).

Ch 2: Atomic Structure and Interatomic Bonding

November 5, 2014 10:41 AM

- **Electrons in Atoms**
    - The two atomic models are Bohr and wave mechanical. Whereas the Bohr model assumes electrons to be particles orbiting the nucleus in discrete paths, in wave mechanics we consider them to be wavelike and treat electron position in terms of a probability distribution.
    - The energies of electrons are *quantized* - that is, only specific values of energy are allowed.
    - The four electron quantum numbers are n, l, m_l, and m_s. They specify, respectively, electron orbital size, orbital shape, number of electron orbitals, and spin amount.
    - According to the Pauli exclusion principle, each electron state can accommodate no more than two electrons, which must have opposite spins.
- **The Periodic Table**
    - Elements in each of the columns (or groups) of the periodic table have distinctive electron configurations. For example:
        - Group 0 elements (the inert gases) have filled electron shells.
        - Group IA elements (the alkali metals) have one electron greater than a filled electron shell.
- **Bonding Forces and Energies**
    - *Bonding force* and *bonding energy* are related to one another according to Equations 2.5a and 2.5b.
    - Attractive, repulsive, and net energies for two atoms or ions depend on interatomic separation per the schematic plot of Figure 2.10*b*.
    - From a plot of interatomic separation versus force for two atoms/ions, the equilibrium separation corresponds to the value at zero force.
    - From a plot of interatomic separation versus potential energy for two atoms/ions, the bonding energy corresponds to the energy value at the minimum of the curve.
- **Primary Interatomic Bonds**
    - For ionic bonds, electrically charged ions are formed by the transference of valence electrons from one atom type to another.
    - The attractive force between two isolated ions that have opposite charges may be computed using Equation 2.13.
    - There is a sharing of valence electrons between adjacent atoms when bonding is covalent.
    - Electrons orbitals for some covalent bonds may overlap or hybridize. Hybridization of *s* and *p* orbitals to from sp^3 and sp^2 orbitals in carbon was discussed. Configurations of these hybrid orbitals were also noted.
    - With metallic bonding, the valence electrons from a "sea of electrons" that is uniformly dispersed around the metal ion cores and acts as a form of glue for them.
- **Secondary Bonding or van der Waals Bonding**
    - Relatively weak van der Waals bonds result from attractive force between electric dipoles, which may be induced or permanent.
    - For hydrogen bonding, highly polar molecules form when hydrogen covalently bonds to a non-metallic element such as fluorine.
- **Mixed Bonding**
    - In addition to van der Waals bonding and the primary bonding types, covalent-ionic, covalent-metallic, and metallic-ionic mixed bonds exist.
    - The percent ionic character (%IC) of a bond between two elements (A and B) depends on their electronegativities (X's) according to Equation 2.16.
- **Bonding Type-Materials Classification Correlations**
    - Correlations between bonding type and material class were noted:
        - Polymers - covalent
        - Metals - metallic
        - Ceramics - ionic/mixed ionic-covalent
        - Molecular solids - van der Waals
        - Semi-metals - mixed covalent-metallic
        - Intermetallics - mixed metallic-ionic

Equation Summary

Equation Number	Equation	Solving For	Page Number
2.5a	$E = \int F\,dr$	Potential energy between two atoms	31
2.5b	$F = \frac{dE}{dr}$	Force between two atoms	31
2.9	$E_A = -\frac{A}{r}$	Attractive energy between two atoms	32
2.11	$E_R = \frac{B}{r^n}$	Repulsive energy between two atoms	33
2.13	$F_A = \frac{1}{4\pi\epsilon_0 r^2}(\lvert Z_1 \rvert e)(\lvert Z_2 \rvert e)$	Force of attraction between two isolated ions	35
2.16	$\%\mathrm{IC} = \{1 - \exp[-(0.25)(X_\mathrm{A} - X_\mathrm{B})^2]\} \times 100$	Percent ionic character	43

List of Symbols

Symbol	Meaning
A, B, n	Material constants
E	Potential energy between two atoms/ions
E_A	Attractive energy between two atoms/ions
E_R	Repulsive energy between two atoms/ions
e	Electronic charge
ϵ_0	Permittivity of a vacuum
F	Force between two atoms/ions
r	Separation distance between two atoms/ions
X_A	Electronegativity value of the more electronegative element for compound BA
X_B	Electronegativity value of the more electropositive element for compound BA
Z_1, Z_2	Valence values for ions 1 and 2

Processing/Structure/Properties/Performance Summary

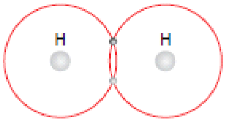
WileyPLUS

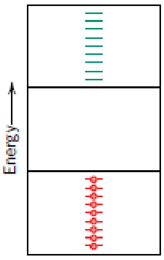
Tutorial Video: Bonding and Properties

In this chapter, we noted that the electron configuration of an atom influences the type of bonds that it forms with other atoms. Bonding type also affects other structural elements of the material: for silicon, its electron band structure (Chapter 18); for polymeric materials (i.e., fibers), their molecular structures (Chapter 14). These relationships are represented in the following concept maps.

Silicon Semiconductors (Structure)

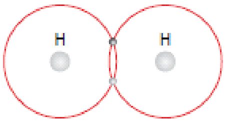
Electron configuration (Chapter 2) $1s^2 2s^2 2p^6 3s^2 3p^2$ → **Covalent bonding** (Chapter 2) → **Intrinsic electron band structure** (Chapter 18)

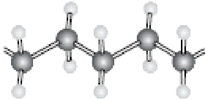




Polymer Fibers (Structure)

Electron configurations: C, H (Chapter 2) $1s^2 2s^2 2p^2$, $1s^1$ → **Covalent bonding** (Chapter 2) → **Polymer molecules** (Chapter 14)





Important Terms and Concepts

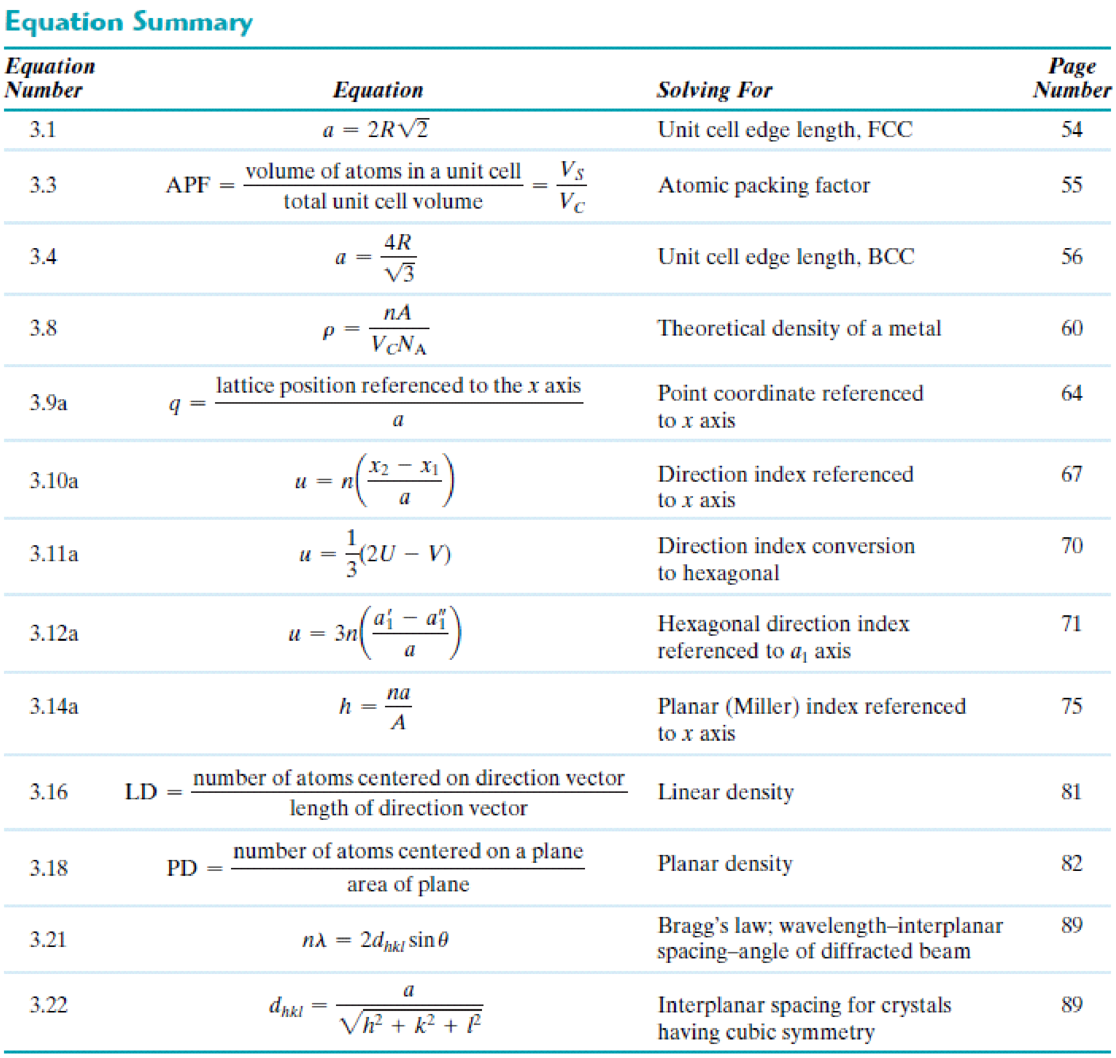
atomic mass unit (amu)
atomic number (Z)
atomic weight (A)
Bohr atomic model
bonding energy
coulombic force
covalent bond
dipole (electric)
electron configuration
electronegative
electron state
electropositive
ground state
hydrogen bond
ionic bond
isotope
metallic bond
mole
Pauli exclusion principle
periodic table
polar molecule
primary bond
quantum mechanics
quantum number
secondary bond
valence electron
van der Waals bond
wave-mechanical model

Ch 3: The Structure of Crystalline Solids

November 5, 2014 11:09 AM

- **Fundamental Concepts**
    - Atoms in crystalline solids are positioned in orderly and repeated patterns that are in contrast to the random and disordered atomic distribution found in noncrystalline or amorphous materials.
- **Unit Cells**
    - Crystal structures are specified in terms of parallelepiped unit cells, which are characterized by geometry and atom positions within.
- **Metallic Crystal Structures**
    - Most common metals exist in at least one of three relatively simple crystal structures:
        - Face-centered cubic (FCC), which has a cubic unit cell (Figure 3.1).
        - Body-centered cubic (BCC), which also has a cubic unit cell (Figure 3.2).
        - Hexagonal close-packed (HCP), which as a unit cell of hexagonal symmetry, (Figure 3.4*a*).
    - Unit cell edge length (a) and atomic radius ® are related according to:
        - Equation 3.1 for face-centered cubic.
        - Equation 3.4 for body-centered cubic.
    - Two features of a crystal structure are:
        - Coordination number - the number of nearest-neighbour atoms.
        - Atomic packing factor (APF) - the fraction of solid sphere volume in the unit cell.
- **Density Computations**
    - The theoretical density of a metal (ρ) is a function of the number of equivalent atoms per unit cell, the atomic weight, unit cell volume, and Avogadro's number (Equation 3.8).
- **Polymorphism and Allotropy**
    - *Polymorphism* is when a specific material can have more than one crystal structure.
    - *Allotropy* is polymorphism for elemental solids.
- **Crystal Systems**
    - The concept of a crystal system is used to classify crystal structures on the basis of unit cell geometry - that is, unit cell edge lengths and interaxial angles. There are seven crystal systems: cubic, tetragonal, hexagonal, orthorhombic, rhombohedral (trigonal), monoclinic, and triclinic.
- **Point Coordinates | Crystallographic Directions | Crystallographic Planes**
    - Crystallographic points, direction, and planes are specified in terms of indexing schemes. The basis for the determination of each index is a coordinate axis system defined by the unit cell for that particular crystal structure.
        - The location of a point within a unit cell is specified using coordinates that are fractional multiples of the cell edge lengths (Equations 3.9a-3.9c).
        - Directional indices are computed in terms of differences between vector head and tail coordinates (Equations 3.10a-3.10c)
        - Planar (or Miller) indices are determined from the reciprocals of axial intercepts (Equations 3.14a-3.14c).
    - For hexagonal unit cells, a four-index scheme for both directions and planes if found to be more convenient. Directions may be determined using Equations 3.11a-3.11d and 3.12a-3.12d.
- **Linear and Planar Densities**
    - Crystallographic directional and planar equivalencies are related to atomic linear and planar densities, respectively
        - *Linear density* (for a specific crystallographic direction) is defined as the number of atoms per unit length whose centers lie on the vector for this direction (Equation 3.16).
        - *Planar density* (for a specific crystallographic plane) is taken as the number of atoms per unit area that are centered on the particular plane (Equation 3.18).
    - For a given crystal structure, planes having identical atomic packing yet different Miller indices belong to the same family.
- **Close-Packed Crystal Structures**
    - Both FCC and HCP crystal structures may be generated by the stacking of close packed planes of atoms on top of one another. With this scheme *A*, *B*, and *C* denote possible atom positions on a close-packed plane.
        - The stacking sequence for HCP is *ABABAB*...

        - The stacking sequence for FCC is *ABCABCABC*…
    - Close-packed planes for FCC and HCP are {111} and {0001}, respectively.
- **Single Crystals | Polycrystalline Materials**
    - *Single crystals* are materials in which the atomic order extends uninterrupted over the entirety of the specimen; under some circumstances, single crystal may have flat faces and regular geometric shapes.
    - The vast majority of crystalline solids, however, are *polycrystalline*, being composed of many small crystals or grains having different crystallographic orientations.
    - A *grain boundary* is the boundary region separating two grains where there is come atomic mismatch.
- **Anisotropy**
    - *Anisotropy* is the directionality dependence of properties. For isotropic materials, properties are independent of the direction of measurement.
- **X-Ray Diffraction: Determination of Crystal Structures**
    - *X-ray diffractometry* is used for crystal structure and interplanar spacing determinations. A beam of x-rays directed on a crystalline material may experience diffraction (constructive interference) as a result of its interaction with a series of parallel atomic planes.
    - Bragg's law specifies the condition for diffraction of x-rays (Equation 3.21).
- **Noncrystalline Solids**
    - Noncrystalline solid materials lack a systematic and regular arrangement of atoms or ions over relatively large distances (on an atomic scale). Sometimes the term *amorphous* is also used to describe these materials.



Equation Summary

Equation Number	*Equation*	*Solving For*	*Page Number*
3.1	$a = 2R\sqrt{2}$	Unit cell edge length, FCC	54
3.3	$\text{APF} = \dfrac{\text{volume of atoms in a unit cell}}{\text{total unit cell volume}} = \dfrac{V_S}{V_C}$	Atomic packing factor	55
3.4	$a = \dfrac{4R}{\sqrt{3}}$	Unit cell edge length, BCC	56
3.8	$\rho = \dfrac{nA}{V_C N_A}$	Theoretical density of a metal	60
3.9a	$q = \dfrac{\text{lattice position referenced to the } x \text{ axis}}{a}$	Point coordinate referenced to x axis	64
3.10a	$u = n\left(\dfrac{x_2 - x_1}{a}\right)$	Direction index referenced to x axis	67
3.11a	$u = \dfrac{1}{3}(2U - V)$	Direction index conversion to hexagonal	70
3.12a	$u = 3n\left(\dfrac{a_1' - a_1''}{a}\right)$	Hexagonal direction index referenced to a_1 axis	71
3.14a	$h = \dfrac{na}{A}$	Planar (Miller) index referenced to x axis	75
3.16	$\text{LD} = \dfrac{\text{number of atoms centered on direction vector}}{\text{length of direction vector}}$	Linear density	81
3.18	$\text{PD} = \dfrac{\text{number of atoms centered on a plane}}{\text{area of plane}}$	Planar density	82
3.21	$n\lambda = 2d_{hkl}\sin\theta$	Bragg's law; wavelength–interplanar spacing–angle of diffracted beam	89
3.22	$d_{hkl} = \dfrac{a}{\sqrt{h^2 + k^2 + l^2}}$	Interplanar spacing for crystals having cubic symmetry	89

List of Symbols

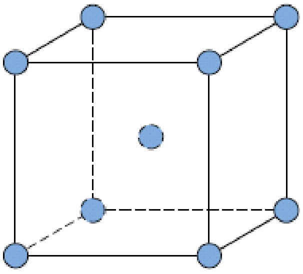
Symbol	*Meaning*
a	Unit cell edge length for cubic structures; unit cell x-axial length
a'_1	Vector head coordinate, hexagonal
a''_1	Vector tail coordinate, hexagonal
A	Atomic weight
A	Planar intercept on x axis
d_{hkl}	Interplanar spacing for crystallographic planes having indices h, k, and l
n	Order of reflection for x-ray diffraction
n	Number of atoms associated with a unit cell
n	Normalization factor—reduction of directional/planar indices to integers
N_A	Avogadro's number (6.022×10^{23} atoms/mol)
R	Atomic radius
V_C	Unit cell volume
x_1	Vector tail coordinate
x_2	Vector head coordinate
λ	X-ray wavelength
ρ	Density; theoretical density

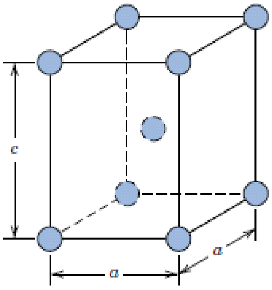
Processing/Structure/Properties/Performance Summary

In this chapter, we discussed crystal structure, the body-centered cubic crystal structure, and the ability of a metal to experience a change in its crystal structure (polymorphism). A knowledge of these concepts helps us understand the transformation of BCC iron to martensite (which has another crystal structure) in Chapter 10. This relationship is represented by the following concept map:

Iron–Carbon Alloys (Steels) (Structure)

Crystal structure for Fe (BCC) (Chapter 3) → **Crystal structure for martensite** (Chapter 10)

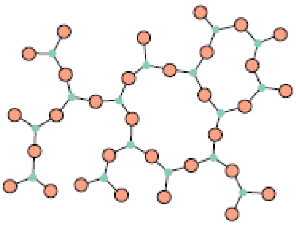


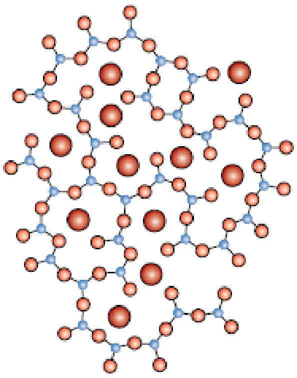


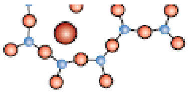
Also discussed was the notion of a noncrystalline material. Glass–ceramics (Chapter 13) are formed as noncrystalline silica glasses (Chapter 12), which are then heat-treated so as to become crystalline in nature. The following concept map notes this relationship:

Glass–Ceramics (Structure)

Structure of noncrystalline solids (Chapter 3) → **Structure of silica glasses** (Chapter 12) → **Structure of glass–ceramics (fine-grained, polycrystalline)** (Chapter 13)







Important Terms and Concepts

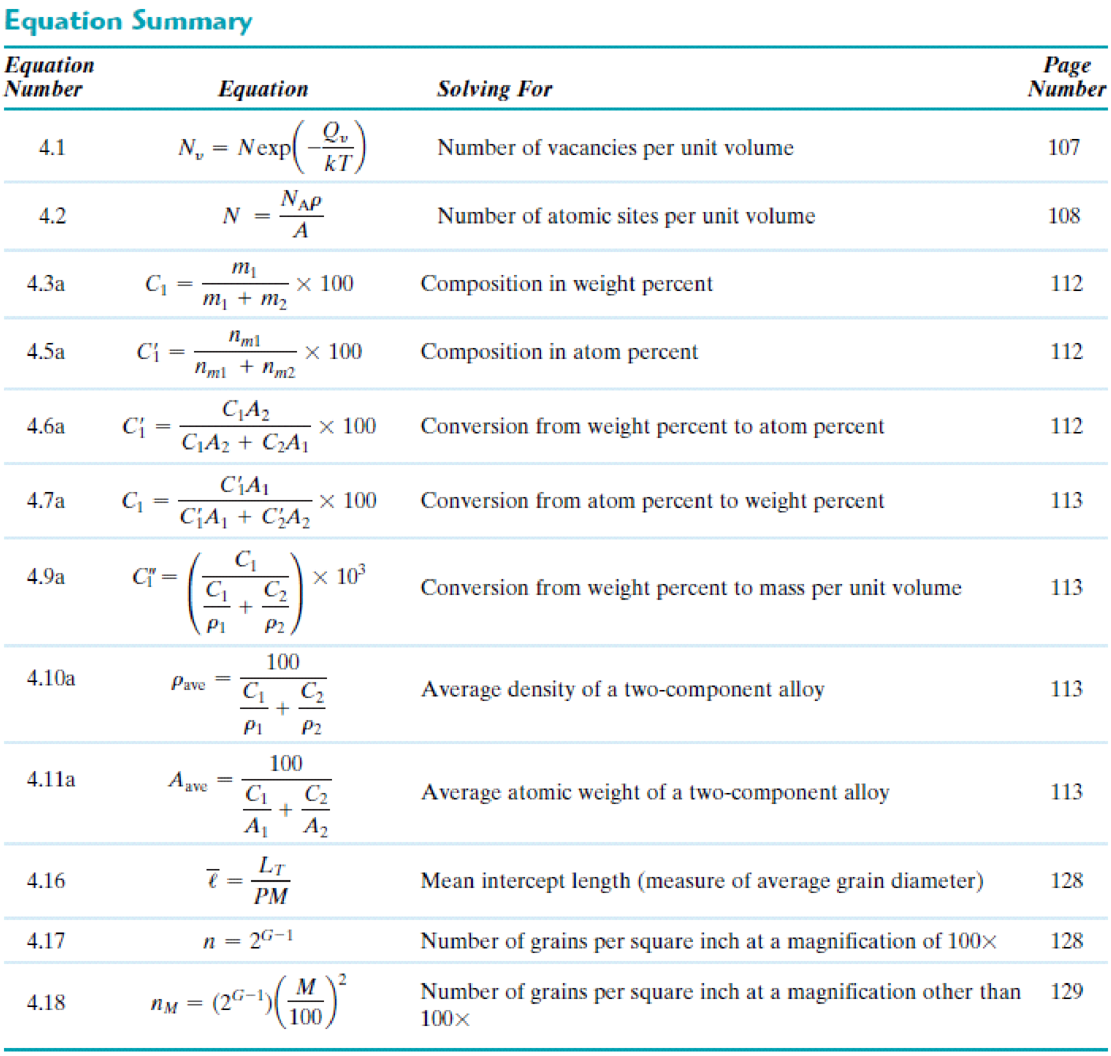
allotropy
amorphous
anisotropy
atomic packing factor (APF)
body-centered cubic (BCC)
Bragg's law
coordination number
crystalline
crystal structure
crystal system
diffraction
face-centered cubic (FCC)
grain
grain boundary
hexagonal close-packed (HCP)
isotropic
lattice
lattice parameters
Miller indices
noncrystalline
polycrystalline
polymorphism
single crystal
unit cell

Ch 4: Imperfections in Solids

November 5, 2014 6:58 PM

- **Vacancies and Self-Interstitials**
  - Point defects are those associated with one or two atomic positions; these include vacancies (or vacant lattice sites) and self-interstitials (host atoms that occupy interstitial sites).
  - The equilibrium number of vacancies depends on temperature according to Equation 4.1.
- **Impurities in Solids**
  - An *alloy* is a metallic substance that is composed of two or more elements.
  - A solid solution may form when impurity atoms are added to a solid, in which case the original crystal structure is retained and no new phases are formed.
  - For substitutional solid solutions, impurity atoms substitute for host atoms.
  - Interstitial solid solutions form for relatively small impurity atoms that can occupy interstitial sites among the host atoms.
  - For substitutional solid solutions, appreciable solubility is possible only when atomic diameters and electronegativities for both atom types are similar, when both elements have the same crystal structure, and when the impurity atoms have a valence that is the same as or greater than the host material.
- **Specification of Composition**
  - Composition of an alloy may be specified in weight percent (on the basis of mass fraction, Equations 4.3a and 4.3b) or atom percent (on the basis of mole or atom fraction, Equations 4.5a and 4.5b).
  - Expressions were provided that allow conversion of weight percent to atom percent (Equation 4.6a) and vice versa (Equation 4.7a).
  - Computation of average density and average atomic weight for a two-phase alloy is possible using other equations cited in this chapter (Equations 4.10a, 4.10b, 4.11a, and 4.11b).
- **Dislocations - Linear Defects**
  - *Dislocations* are one-dimensional crystalline defects of which there are two pure types: edge and screw.
    - An *edge* may be thought of in terms of the lattice distortion along the end of an extra half-plane of atoms.
    - A *screw* is as a helical planar ramp.
    - For *mixed* dislocations, components of both pure edge and screw are found.
  - The magnitude and direction of lattice distortion associated with a dislocation are specified by its Burgers vector.
  - The relative orientations Burgers vector and dislocation lines are (1) perpendicular for edge, (2) parallel for screw, and (3) neither perpendicular nor parallel for mixed.
- **Interfacial Defects**
  - Within the vicinity of a grain boundary (which is several atomic distances wide), there is some atomic mismatch between two adjacent grains that have different crystallographic orientations.
  - For a high-angle grain boundary, the angle of misalignment between grains is relatively large; this angle is relatively small for small-angle grain boundaries.
  - Across a twin boundary, atoms on one side reside in mirror-image positions of atoms on the other side.
- **Microscopic Techniques**
  - The microstructure of a material consists of defects and structural elements that are of microscopic dimensions. *Microscopy* is the observation of microstructure using some type of microscope.
  - Both optical and electron microscopes are employed, usually in conjunction with photographic equipment.
  - Transmissive and reflective modes are possible for each microscope type; preference is dictated by the nature of the specimen a well as the structural element or defect to be examined.
  - In order to observe the grain structure of a polycrystalline material using an optical microscope, the specimen surface must be ground and polished in order to produce a very smooth and mirror-like finish. Some type of chemical reagent (or etchant) must then be applied in order to either reveal the grain boundaries or produce a variety of light reflectance characteristics for the constituent grains.
  - The two types of electron microscopes are transmission (TEM) and scanning (SEM).
    - For TEM, an image is formed from an electron beam that, although passing through the specimen, is scattered and/or defracted.
    - SEM employs an electron beam that raster-scans the specimen surface; an image is produced from back-scattered or reflected electrons.

  - A scanning probe microscope employs a small and sharp-tipped probe that raster-scans the specimen surface. Out-of-plane deflections of the probe result from interactions with surface atoms. A computer-generated and three-dimensional image of the surface results having nanometer resolution.
- **Grain-Size Determination**
  - With the intercept method used to measure grain size, a series of straight-line segments are drawn on the photomicrograph. The number of grain boundaries that are intersected by these lines are counted, and the *mean intercept length* (a measure of grain diameter) is computed using Equation 4.16.
  - Comparison of a photomicrograph (taken at magnification of 100x) with ASTM standard comparison charts may be used to specify grain size in terms of grain-size number.
  - The average number of grains per square inch at a magnification of 100x is related to grain-size number according to Equation 4.17; for magnifications other than 100x, Equation 4.18 is used.
  - Grain-size number and mean intercept length are related per Equations 4.19a and 4.19b.



Equation Summary

Equation Number	*Equation*	*Solving For*	*Page Number*
4.1	$N_v = N\exp\left(-\frac{Q_v}{kT}\right)$	Number of vacancies per unit volume	107
4.2	$N = \frac{N_A\rho}{A}$	Number of atomic sites per unit volume	108
4.3a	$C_1 = \frac{m_1}{m_1 + m_2} \times 100$	Composition in weight percent	112
4.5a	$C_1' = \frac{n_{m1}}{n_{m1} + n_{m2}} \times 100$	Composition in atom percent	112
4.6a	$C_1' = \frac{C_1A_2}{C_1A_2 + C_2A_1} \times 100$	Conversion from weight percent to atom percent	112
4.7a	$C_1 = \frac{C_1'A_1}{C_1'A_1 + C_2'A_2} \times 100$	Conversion from atom percent to weight percent	113
4.9a	$C_1'' = \left(\frac{C_1}{\frac{C_1}{\rho_1} + \frac{C_2}{\rho_2}}\right) \times 10^3$	Conversion from weight percent to mass per unit volume	113
4.10a	$\rho_{\text{ave}} = \frac{100}{\frac{C_1}{\rho_1} + \frac{C_2}{\rho_2}}$	Average density of a two-component alloy	113
4.11a	$A_{\text{ave}} = \frac{100}{\frac{C_1}{A_1} + \frac{C_2}{A_2}}$	Average atomic weight of a two-component alloy	113
4.16	$\bar{\ell} = \frac{L_T}{PM}$	Mean intercept length (measure of average grain diameter)	128
4.17	$n = 2^{G-1}$	Number of grains per square inch at a magnification of 100×	128
4.18	$n_M = (2^{G-1})\left(\frac{M}{100}\right)^2$	Number of grains per square inch at a magnification other than 100×	129

List of Symbols

Symbol	***Meaning***
A	Atomic weight
G	ASTM grain-size number
k	Boltzmann's constant (1.38×10^{-23} J/atom·K, 8.62×10^{-5} eV/atom·K)
L_T	Total line length (intercept technique)
M	Magnification
m_1, m_2	Masses of elements 1 and 2 in an alloy
N_A	Avogadro's number (6.022×10^{23} atoms/mol)
n_{m1}, n_{m2}	Number of moles of elements 1 and 2 in an alloy
P	Number of grain boundary intersections
Q_v	Energy required for the formation of a vacancy
ρ	Density

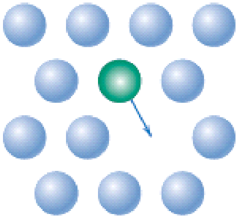
Processing/Structure/Properties/Performance Summary

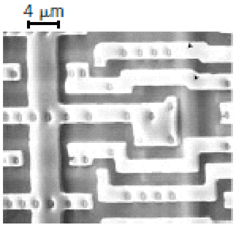
In this chapter, we discussed several schemes used to specify concentration of one element in another; equations were also provided to convert from one scheme to another. During the processing of silicon to form integrated circuit components (Chapters 5 and 18), it is imperative that specification and control of impurity concentration be extremely precise. These relationships are represented in the following concept map:

Silicon Semiconductors (Processing)

Specification of composition (Chapter 4) → **Diffusion in semiconductors** (Chapter 5) → **Fabrication of integrated circuits** (Chapter 18)

$$C_1 = \frac{m_1}{m_1 + m_2} \times 100$$

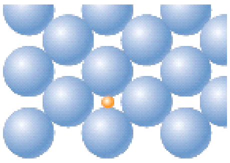


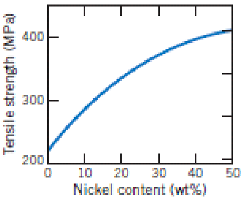


The concept of a solid solution was also discussed. One form of solid solution in an iron–carbon alloy, or steel (martensite), derives its high strength and hardness from the formation of an interstitial solid solution (carbon dissolved in iron). The following concept map represents this relationship:

Iron–Carbon Alloys (Steels) (Processing)

Concept of solid solution (Chapter 4) → **Solid solution strengthening** (Chapters 7 & 10)

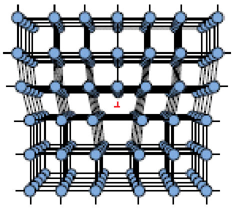




With a knowledge of the characteristics of dislocation defects, we are able to understand the mechanisms by which metals [i.e., iron–carbon alloys (steels)] permanently deform (Chapter 7), and, in addition, techniques that are used to improve the mechanical properties of these materials. The following concept map notes this relationship:

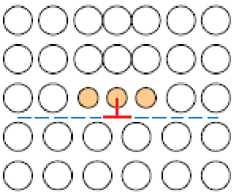
Iron–Carbon Alloys (Steels) (Properties)

Concept of dislocation defects (Chapter 4)



→

Strengthening mechanisms (Chapters 7 & 10)



Important Terms and Concepts

alloy
atomic vibration
atom percent
Boltzmann's constant
Burgers vector
composition
dislocation line
edge dislocation
grain size
imperfection
interstitial solid solution
microscopy
microstructure
mixed dislocation
photomicrograph
point defect
scanning electron microscope (SEM)
scanning probe microscope (SPM)
screw dislocation
self-interstitial
solid solution
solute
solvent
substitutional solid solution
transmission electron microscope (TEM)
vacancy
weight percent

Ch 5: Diffusion

November 5, 2014 6:59 PM

- **Introduction**
    - Solid-state diffusion is a means of mass transport within solid materials by stepwise atomic motion.
    - The term *interdiffusion* refers to the migration of impurity atoms; for hose atoms, the term *self-diffusion* is used.
- **Diffusion Mechanisms**
    - Two mechanisms for diffusion are possible: vacancy and interstitial.
        - *Vacancy diffusion* occurs via the exchange of an atom residing on a normal lattice site with an adjacent vacancy.
        - For *interstitial diffusion*, an atom migrates from one interstitial position to an empty adjacent one.
    - For a given host metal, interstitial atomic species generally diffuse more rapidly.
- **Fick's First Law**
    - *Diffusion flux* is defined in terms of mass of diffusing species, cross-sectional area, and time according to Equation 5.1.
    - Diffusion flux is proportional to the negative of the concentration gradient according to Fick's first law, Equation 5.2.
    - *Concentration profile* is represented as a plot of concentration versus distance into the solid material.
    - *Concentration gradient* is the slope of the concentration profile curve at some specific point.
    - The diffusion condition for which the flux is independent of time is known as *steady state*.
    - The driving force for steady-state diffusion is the concentration gradient (dC/dx).
- **Fick's Second Law - Nonsteady-State Diffusion**
    - For nonsteady-state diffusion, there is a net accumulation or depletion of diffusing species, and the flux is dependent on time.
    - The mathematics for nonsteady state in a single (x) direction (and when the diffusion coefficient is independent of concentration) may be described by Fick's second law, Equation 5.4b.
    - For a constant surface composition boundary condition, the solution to Fick's second law (Equation 5.4b) is Equation 5.5, which involves the Gaussian error function (erf).
- **Factors That Influence Diffusion**
    - The magnitude of the diffusion coefficient is indicative of the rate of atomic motion and depends on both host and diffusing species as well as on temperature.
    - The diffusion coefficient is a function of temperature according to Equation 5.8.
- **Diffusion in Semiconducting Materials**
    - The two hear treatments that are used to diffuse impurities into silicon during integrated circuit fabrication are predeposition and drive-in.
        - During predeposition, impurity atoms are diffused into silicon, often from a gas phase, the partial pressure of which is maintained constant.
        - For the drive-in step, impurity atoms are transported deeper into the silicon so as to provide a more suitable concentration distribution without increasing the overall impurity content.
    - Integrated circuit interconnects are normally made of aluminum - instead of metals such as copper, silver, and gold that have higher electrical conductivities - on the basis of diffusion considerations. During high-temperature heat treatments, interconnect metal atoms diffuse into the silicon; appreciable concentrations will compromise the chip's functionality.

Equation Summary

Equation Number	Equation	Solving For	Page Number
5.1	$J = \dfrac{M}{At}$	Diffusion flux	143
5.2	$J = -D\dfrac{dC}{dx}$	Fick's first law	143
5.4b	$\dfrac{\partial C}{\partial t} = D\dfrac{\partial^2 C}{\partial x^2}$	Fick's second law	145
5.5	$\dfrac{C_x - C_0}{C_s - C_0} = 1 - \operatorname{erf}\left(\dfrac{x}{2\sqrt{Dt}}\right)$	Solution to Fick's second law—for constant surface composition	146
5.8	$D = D_0 \exp\left(-\dfrac{Q_d}{RT}\right)$	Temperature dependence of diffusion coefficient	149

List of Symbols

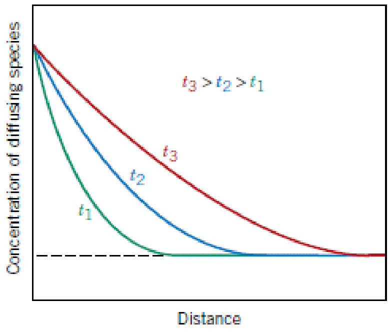
Symbol	Meaning
A	Cross-sectional area perpendicular to direction of diffusion
C	Concentration of diffusing species
C_0	Initial concentration of diffusing species prior to the onset of the diffusion process
C_s	Surface concentration of diffusing species
C_x	Concentration at position x after diffusion time t
D	Diffusion coefficient
D_0	Temperature-independent constant
M	Mass of material diffusing
Q_d	Activation energy for diffusion
R	Gas constant (8.31 J/mol·K)
t	Elapsed diffusion time
x	Position coordinate (or distance) measured in the direction of diffusion, normally from a solid surface

Processing/Structure/Properties/Performance Summary

Diffusion in semiconducting materials was discussed in Section 5.6. For both predeposition and drive-in treatments, diffusion is nonsteady-state—solutions to Fick's second law were provided for both. Nonsteady-state diffusion and these treatments are two of the processing components for silicon, as noted in the following concept map:

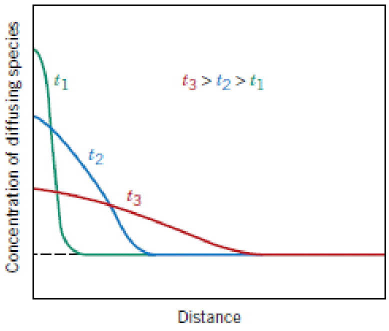
Silicon
Semiconductors
(Processing)

Nonsteady-state diffusion
(Chapter 5)



$$\frac{C_x - C_0}{C_s - C_0} = 1 - \operatorname{erf}\left(\frac{x}{2\sqrt{Dt}}\right)$$

Diffusion in semiconductors
(Chapter 5)



$$C(x, t) = \frac{Q_0}{\sqrt{\pi D t}} \exp\left(-\frac{x^2}{4Dt}\right)$$

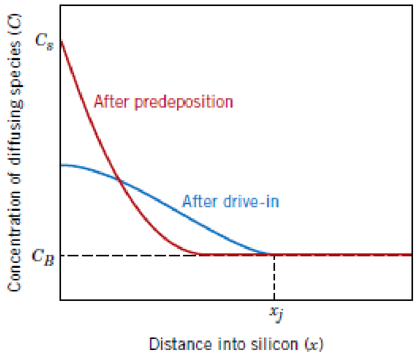
In the design of heat treatments to be used for introducing impurities into semiconductors (i.e., doping, Chapter 18) and, in the production of steel alloys (Chapter 10), an understanding of the temperature dependence of the diffusion coefficient (i.e., Equation 5.8) is essential. The following concept maps illustrate the preceding relationships for these two materials.

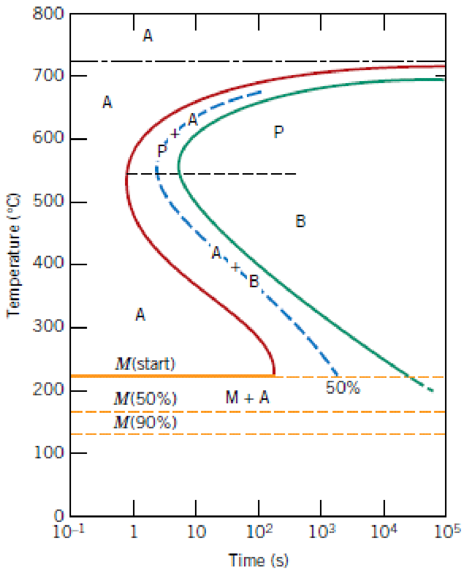
Silicon Semiconductors (Processing)

Temperature dependence of diffusion coefficient
(Chapter 5)

$$D = D_0 \exp\left(-\frac{Q_d}{RT}\right)$$

Diffusion in semiconductors (impurity doping)
(Chapters 5 & 18)





Iron–Carbon Alloys (Steels) (Processing)

Temperature dependence of diffusion coefficient
(Chapter 5)

$$D = D_0 \exp\left(-\frac{Q_d}{RT}\right)$$

Isothermal transformation diagrams
(Chapter 10)

Tempering (tempered martensite)
(Chapter 10)

martensite (BCT, single phase) →

tempered martensite (α + Fe_3C phases)

Important Terms and Concepts

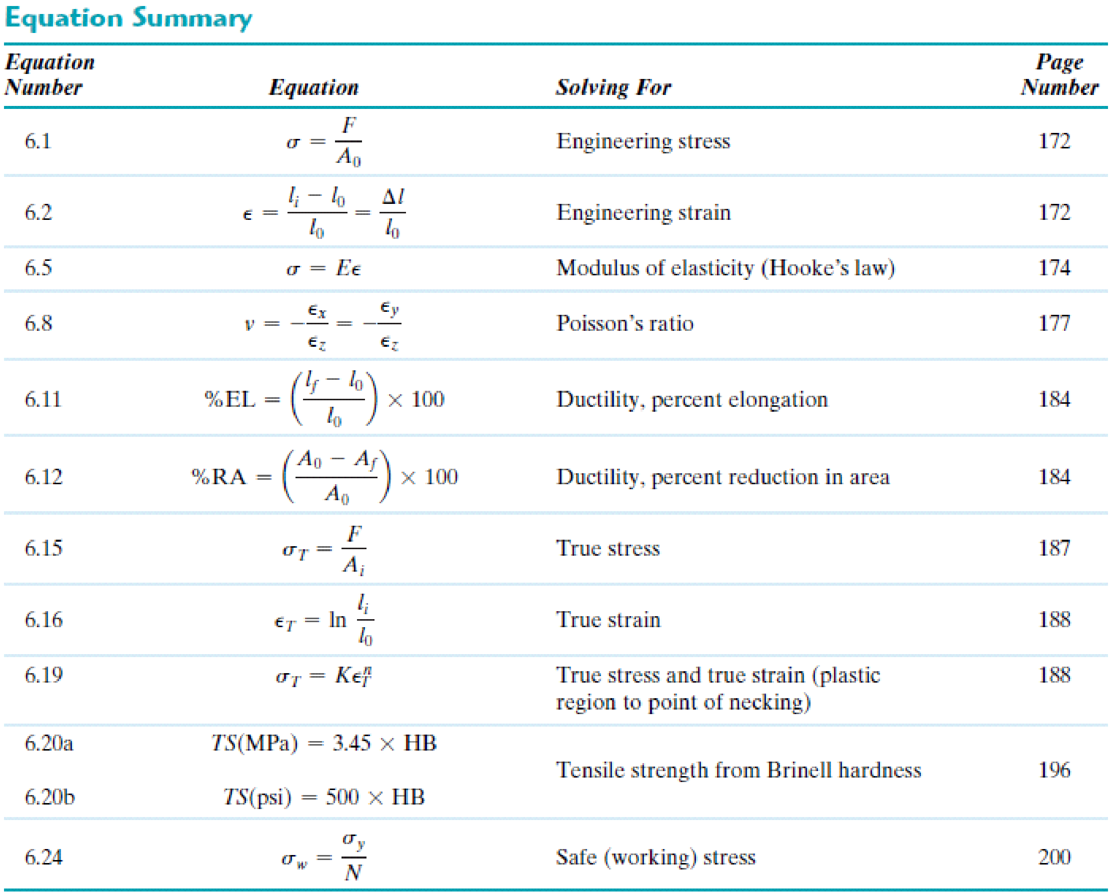
activation energy
carburizing
concentration gradient
concentration profile
diffusion
diffusion coefficient
diffusion flux
driving force
Fick's first law
Fick's second law
interdiffusion (impurity diffusion)
interstitial diffusion
nonsteady-state diffusion
self-diffusion
steady-state diffusion
vacancy diffusion

Ch 6: Mechanical Properties of Metals

November 5, 2014 12:25 PM

- **Introduction**
    - Three factors that should be considered in designing laboratory tests to assess the mechanical characteristics of materials for service use are the nature of the applied load (i.e., tension, compression, shear), load duration, and environmental conditions.
- **Concepts of Stress and Strain**
    - For loading in tension and compression:
        - Engineering stress (σ) is defined as the instantaneous load divided by the original specimen cross-sectional area (Equation 6.1).
        - Engineering strain (ε) is expressed as the change in length (in the direction of load application) divided by the original length (Equation 6.2).
- **Stress-Strain Behaviour**
    - A material that is stressed first undergoes elastic, or nonpermanent, deformation.
    - When most materials are deformed elastically, stress and strain are proportional - that is, a plot of stress versus strain is linear.
    - For tensile and compressive loading, the slope of the linear elastic region of the stress-strain curve is the modulus of elasticity (E), per Hooke's law (Equation 6.5).
    - For a material that exhibits nonlinear elastic behaviour, tangent and secant moduli are used.
    - On an atomic level, elastic deformation of a material corresponds to the stretching of interatomic bonds and corresponding slight atomic displacements.
    - For shear elastic deformations, shear stress (τ) and shear strain (γ) are proportional to one another (Equation 6.7). The constant of proportionality is the shear modulus (G).
    - Elastic deformation that is dependent on time is termed *anelastic*.
- **Elastic Properties of Materials**
    - Another elastic parameter, Poisson's ratio (v), represents the negative ratio of transverse and longitudinal strains (ε_x and ε_z, respectively) (Equation 6.8). Typical values of *v* for metals lie within the range of about 0.25 to 0.35.
    - For an isotropic material, shear and elastic moduli and Poisson's ratio are related according to Equation 6.9.
- **Tensile Properties**
    - The phenomenon of yielding occurs at the onset of plastic or permanent deformation.
    - Yield strength is indicative of the stress at which plastic deformation begins. For most materials, yield strength is determined from a stress-strain plot using the 0.002 strain offset technique.
    - Tensile strength is taken as the stress level at the maximum point on the engineering stress-strain curve; it represents the maximum tensile stress that can be sustained by a specimen.
    - For most metallic materials, at the maxima on their stress-strain curves, a small constriction or "neck" begins to form at some point on the deforming specimen. All subsequent deformation ensues by the narrowing of this neck region, at which point fracture ultimately occurs.
    - *Ductility* is a measure of the degree to which a material plastically deforms by the time fracture occurs.
    - Quantitatively, ductility is measured in terms of percents elongation and reduction in area.
        - Percent elongation (%EL) is a measure of the plastic strain at fracture (Equation 6.11).
        - Percent reduction in area (%RA) may be calculated according to Equation 6.12.
    - Yield and tensile strengths and ductility are sensitive to any prior deformation, the presence of impurities, and/or any heat treatment. Modulus of elasticity is relatively insensitive to these conditions.
    - With increasing temperature, values of elastic modulus and tensile and yield strengths decrease, whereas the ductility increases.
    - *Modulus of resilience* is the strain energy per unit volume of material required to stress as material to the point of yielding - or the area under the elastic portion of the engineering stress-strain curve. For a metal that displays linear-elastic behaviour, its value may be determined using Equation 6.14.
    - A measure of toughness is the energy absorbed during the fracture of a material, as measured by the area under the entire engineering stress-strain curve. Ductile metals are normally tougher than brittle ones.
- **True Stress and Strain**
    - *True stress* (σ_T) is defined as the instantaneous applied load divided by the instantaneous cross-sectional area (Equation 6.15).

  - *True strain* (ε_T) is equal to the natural logarithm of the ratio of instantaneous and original specimen lengths per Equation 6.16.
  - For some metals, from the onset of plastic deformation to the onset of necking, true stress and true strain are related by Equation 6.19.
- **Elastic Recovery after Plastic Deformation**
  - For a specimen that has been plastically deformed, elastic strain recovery occurs if the load is released. This phenomenon is illustrated by the stress-strain plot of Figure 6.17.
- **Hardness**
  - Hardness is a measure of a material's resistance to localized plastic deformation.
  - The two most common hardness testing techniques are the Rockwell and Brinell tests.
    - Several scales are available for the Rockwell test; for the Brinell test, there is a single scale.
    - Brinell hardness is determined from indentation size; the Rockwell test is based on the difference in indentation depth from the imposition of minor and major loads.
  - The two micro-indentation hardness testing techniques are the Knoop and Vickers tests. Small indenters are relatively light loads are employed for these two techniques. They are also used to measure the hardness of brittle materials (such as ceramics) and also of very small specimen regions.
  - For some metals, a plot of hardness versus tensile strength is linear - that is, these two parameters are proportional to one another.
- **Variability of Material Properties**
  - Five factors that can lead to scatter in measured material properties are the following: test method, variations in specimen fabrication procedure, operator bias, apparatus calibration, and inhomogeneities and/or compositional variations from sample to sample.
  - A typical material property is often specified in terms of an average value ($\bar{x}$), whereas magnitude of scatter may be expressed as a standard deviation (s). Equations 6.21 and 6.22, respectively, are used to calculate values for these parameters.
- **Design/Safety Factors**
  - As a result of uncertainties in both measured mechanical properties and in-service applied stresses, design or safe stresses are normally utilized for design purposes. For ductile materials, safe (or working) stress (σ_w) is dependent on yield strength and factor of safety as described in Equation 6.24.



Equation Summary

Equation Number	*Equation*	*Solving For*	*Page Number*
6.1	$\sigma = \frac{F}{A_0}$	Engineering stress	172
6.2	$\epsilon = \frac{l_i - l_0}{l_0} = \frac{\Delta l}{l_0}$	Engineering strain	172
6.5	$\sigma = E\epsilon$	Modulus of elasticity (Hooke's law)	174
6.8	$\nu = -\frac{\epsilon_x}{\epsilon_z} = -\frac{\epsilon_y}{\epsilon_z}$	Poisson's ratio	177
6.11	$\%\text{EL} = \left(\frac{l_f - l_0}{l_0}\right) \times 100$	Ductility, percent elongation	184
6.12	$\%\text{RA} = \left(\frac{A_0 - A_f}{A_0}\right) \times 100$	Ductility, percent reduction in area	184
6.15	$\sigma_T = \frac{F}{A_i}$	True stress	187
6.16	$\epsilon_T = \ln \frac{l_i}{l_0}$	True strain	188
6.19	$\sigma_T = K\epsilon_T^n$	True stress and true strain (plastic region to point of necking)	188
6.20a	$TS(\text{MPa}) = 3.45 \times \text{HB}$	Tensile strength from Brinell hardness	196
6.20b	$TS(\text{psi}) = 500 \times \text{HB}$		
6.24	$\sigma_w = \frac{\sigma_y}{N}$	Safe (working) stress	200

List of Symbols

Symbol	*Meaning*
A_0	Specimen cross-sectional area prior load application
A_f	Specimen cross-sectional area at the point of fracture
A_i	Instantaneous specimen cross-sectional area during load application
E	Modulus of elasticity (tension and compression)
F	Applied force
HB	Brinell hardness
K	Material constant
l_0	Specimen length prior to load application
l_f	Specimen fracture length
l_i	Instantaneous specimen length during load application
N	Factor of safety
n	Strain-hardening exponent
TS	Tensile strength
ϵ_x, ϵ_y	Strain values perpendicular to the direction of load application (i.e., the transverse direction)
ϵ_z	Strain value in the direction of load application (i.e., the longitudinal direction)
σ_y	Yield strength

Processing/Structure/Properties/Performance Summary

In this chapter, we defined and explained the types of deformation that metal alloys experience (elastic and plastic) as well as the associated properties (modulus of elasticity, yield strength, hardness, etc.). In order to improve the mechanical characteristics of metal alloys [e.g., steel (Chapter 10)], it is first necessary to understand what these properties represent. The following concept map illustrates this relationship for these materials.

Iron–Carbon Alloys
(Steels)
(Properties)

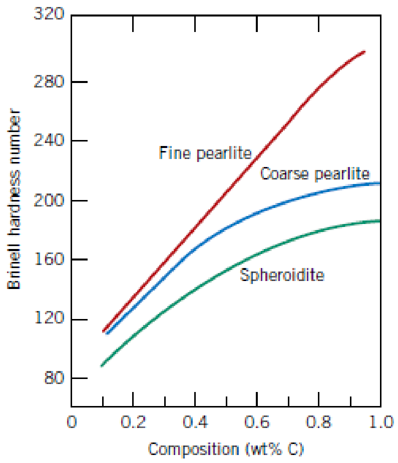
Definitions of mechanical properties
(Chapter 6)

$$\sigma = \frac{F}{A_0}$$

$$\epsilon = \frac{l_i - l_0}{l_0} = \frac{\Delta l}{l_0}$$

→

Mechanical properties of iron–carbon alloys
(Chapter 10)



Important Terms and Concepts

anelasticity
design stress
ductility
elastic deformation
elastic recovery
engineering strain
engineering stress
hardness
modulus of elasticity
plastic deformation
Poisson's ratio
proportional limit
resilience
safe stress
shear
tensile strength
toughness
true strain
true stress
yielding
yield strength

Ch 7: Dislocations and Strengthening Mechanisms

November 5, 2014 6:58 PM

- **Basic Concepts**
    - On a microscopic level, plastic deformation corresponds to the motion of dislocations in response to an externally applied shear stress. An edge dislocation moves by the successive and repeated breaking of atomic bonds and shifting by interatomic distances of half planes of atoms.
    - For edge dislocations, dislocation line motion and direction of the applied shear stress are parallel; for screw dislocations, these directions are perpendicular.
    - *Dislocation density* is the total dislocation length per unit volume of material. Its units are per square millimeter.
    - For an edge dislocation, tensile, compressive, and shear strains exist in the vicinity of the dislocation line. Shear lattice strains only are found for pure screw dislocations.
- **Slip System**
    - The motion of dislocations in response to an externally applied shear stress is termed *slip*.
    - Slip occurs on specific crystallographic planes, and within these planes only in certain directions. A slip system represents a slip plane-slip direction combination.
    - Operable slip system depend on the crystal structure of the material. The *slip plane* is that plane that has the densest atomic packing, and the *slip direction* is the direction within this plane that is most closely packed with atoms.
    - The slip system for the FCC crystal structure is {111}{110}; for BCC, several are possible: {110}{111}, {211}{111}, and {321}{111}.
- **Slip in Single Crystals**
    - *Resolved shear stress* is the shear stress resulting from an applied tensile stress that is resolved onto a plane that is neither parallel nor perpendicular to the stress direction. Its value is dependent on the applied stress and orientations of plane and direction according to Equation 7.2.
    - *Critical resolved shear stress* is the minimum resolved shear stress required to initiate dislocation motion (or slip) and depends on yield strength and orientation of slip components per Equation 7.4.
    - For a single crystal that is pulled in tension, small steps form on the surface that are parallel and loop around the circumference of the specimen.
- **Plastic Deformation of Polycrystalline Materials**
    - For polycrystalline metals, slip occurs within each grain along those slip systems that are most favourably oriented with the applied stress. Furthermore, during the deformation, grains change shape and extend in those directions in which there is gross plastic deformation.
- **Deformation by Twinning**
    - Under some circumstances, limited plastic deformation may occur in BFF and HCP metals by mechanical twinning. The application of a shear force produces slight atomic displacements such that on one side of a plane (i.e., a twin boundary), atoms are located in mirror-image positions of atoms on the other side.
- **Mechanisms of Strengthening in Metals**
    - The ease with which a metal is capable of plastic deformation is a function of dislocation mobility - that is, restricting dislocation motion leads to increased hardness and strength.
- **Strengthening by Grain Size Reduction**
    - *Grain boundaries* are barriers to dislocation motion for two reasons:
        - When crossing a grain boundary, a dislocation's direction of motion must change.
        - There is a discontinuity of slip planes within the vicinity of a grain boundary.
    - A metal that has small grains is stronger than one with large grains because the former has more grain boundary area and, thus, more barriers to dislocation motion.
    - For most metals, yield strength depends on the average grain diameter according to the Hall-Petch equation, Equation 7.7.
- **Solid-Solution Strengthening**
    - The strength and hardness of a metal increase with increase of concentration of impurity atoms that go into solid solution (both substitutional and interstitial).
    - Solid-solution strengthening results from lattice strain interactions between impurity atoms and dislocations; these interactions produce a decrease in dislocation mobility.
- **Strain Hardening**

    - *Strain hardening* is the enhancement in strength (and decrease of ductility) of a metal that is deformed plastically.
    - Degree of plastic deformation may be expressed as percent cold work, which depends on original and deformed cross-sectional areas as described by Equation 7.8.
    - Yield strength, tensile strength, and hardness of a metal increase with increasing percent cold work (Figures 7.19a and 7.19b); ductility decreases (Figure 7.19c).
    - During plastic deformation, dislocation density increases, the average distance between adjacent dislocations decreases, and - because dislocation-dislocation strain field interactions, are, on average, repulsive - dislocation mobility becomes more restricted; thus, the metal becomes harder and stronger.
- **Recovery**
    - During recovery:
        - There is some relief of internal strain energy by dislocation motion.
        - Dislocation density decreases, and dislocations assume low-energy configurations.
        - Some material properties revert back to their precold-worked values.
- **Recrystallization**
    - During recrystallization:
        - A new set of strain-free and equiaxed grains form that have relatively low dislocation densities.
        - The metal becomes softer, weaker, and more ductile.
    - The driving force for recrystallization is the difference in internal energy between strained and recrystallized material.
    - For a cold-worked metal that experience recrystallization, as temperature increases (at constant heat-treating time), tensile strength decreases and ductility increases (per Figure 7.22).
    - The recrystallization temperature of a metal alloy is that temperature at which recrystallization reaches completion in 1 h.
    - Two factors that influence the recrystallization temperature are percent cold work and impurity content.
        - Recrystallization temperature decreases with increasing percent cold work.
        - It rises with increasing concentration of impurities.
    - Plastic deformation of a metal above its recrystallization temperature is *hot working*; deformation below it recrystallization temperature is termed *cold working*.
- **Grain Growth**
    - *Grain growth* is the increase in average grain size of a polycrystalline materials, which proceeds by grain boundary motion.
    - The driving force for grain growth is the reduction in total grain boundary energy.
    - The time dependence of grain size is represented by Equation 7.9.

Equation Summary

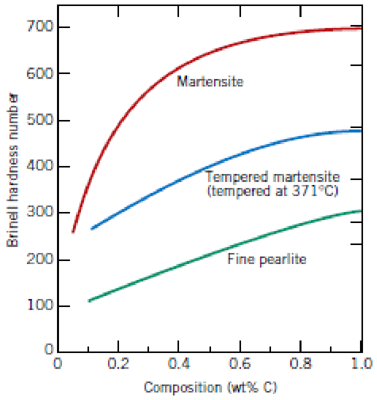
Equation Number	Equation	Solving For	Page Number
7.2	$\tau_R = \sigma \cos\phi \cos\lambda$	Resolved shear stress	223
7.4	$\tau_{\text{crss}} = \sigma_y(\cos\phi \cos\lambda)_{\max}$	Critical resolved shear stress	224
7.7	$\sigma_y = \sigma_0 + k_y d^{-1/2}$	Yield strength (as a function of average grain size)—Hall–Petch equation	230
7.8	$\%\text{CW} = \left(\dfrac{A_0 - A_d}{A_0}\right) \times 100$	Percent cold work	232
7.9	$d^n - d_0^n = Kt$	Average grain size (during grain growth)	240

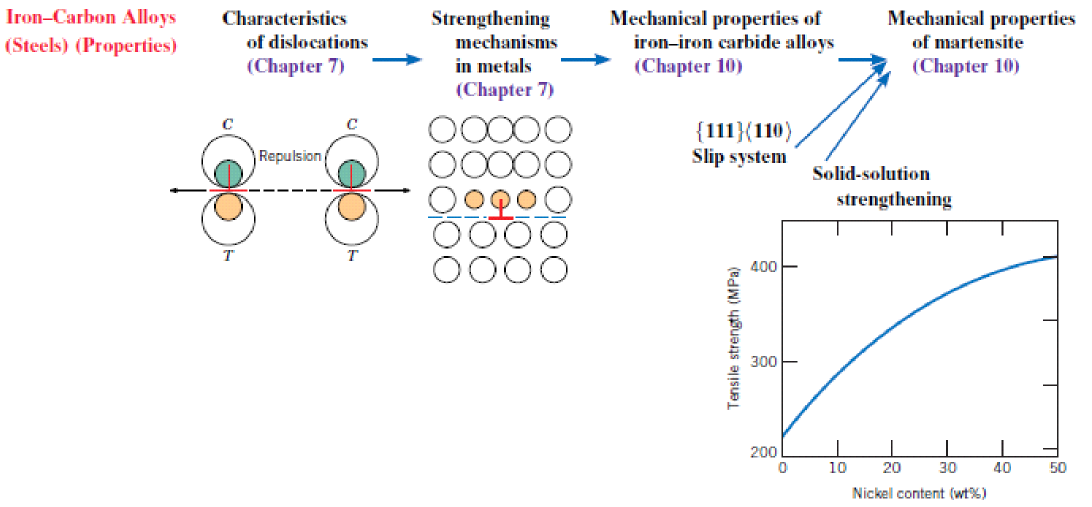
List of Symbols

Symbol	Meaning
A_0	Specimen cross-sectional area prior to deformation
A_d	Specimen cross-sectional area after deformation
d	Average grain size; average grain size during grain growth
d_0	Average grain size prior to grain growth
K, k_y	Material constants
t	Time over which grain growth occurred
n	Grain size exponent—for some materials has a value of approximately 2
λ	Angle between the tensile axis and the slip direction for a single crystal stressed in tension (Figure 7.7)
ϕ	Angle between the tensile axis and the normal to the slip plane for a single crystal stressed in tension (Figure 7.7)
σ_0	Material constant
σ_y	Yield strength

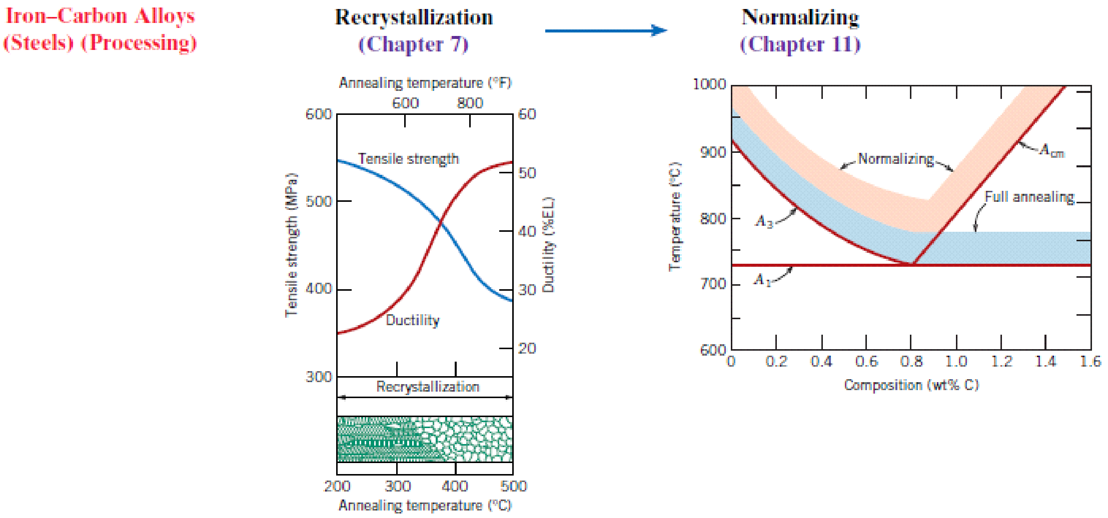
Processing/Structure/Properties/Performance Summary

An understanding of the strengthening mechanisms for metals necessarily requires some knowledge concerning (1) the correlation of dislocation motion with plastic deformation, (2) the characteristics of these defects (i.e., surrounding strain fields and strain-field interactions), and (3) crystallographic aspects (i.e., the concept of slip systems). The high hardness (and lack of ductility) of one phase found in steel (martensite, Section 10.7) is explained by a solid-solution strengthening effect and, in addition, to the presence of few slip systems. The following concept map represents these relationships.





Other heat treatments are designed to recrystallize metal alloys that have been strain hardened, to render them softer and more ductile and to develop more desirable grain structures. Two such treatments are described in Section 11.7—process annealing and, for steels, normalizing. The preceding relationships are indicated in the following concept map.



Important Terms and Concepts

cold working
critical resolved shear stress
dislocation density
grain growth
lattice strain
recovery
recrystallization
recrystallization temperature
resolved shear stress
slip
slip system
solid-solution strengthening
strain hardening

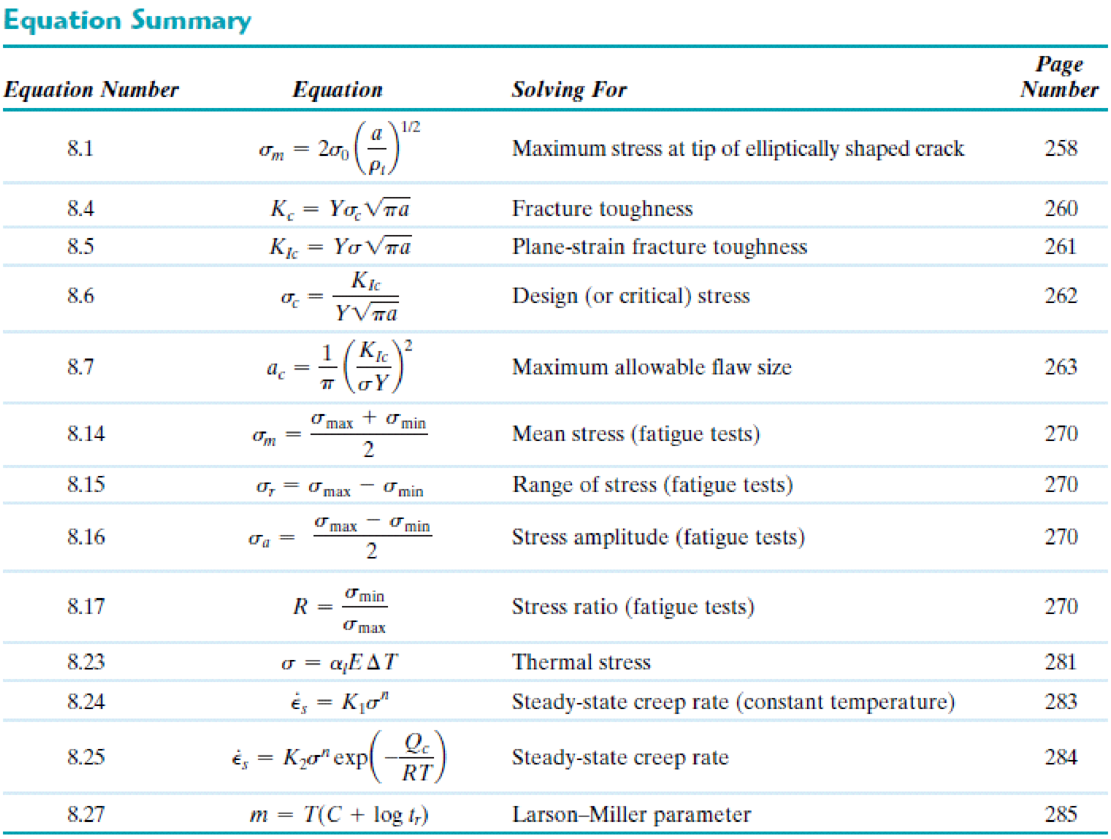
Ch 8: Failure

November 5, 2014 3:52 PM

- **Introduction**
    - The three usual causes of failure are:
        - Improper materials selection and processing
        - Inadequate component design
        - Component misuse
- **Fundamentals of Fracture**
    - Fracture in response to tensile loading and at relatively low temperatures may occur by ductile and brittle modes.
    - Ductile fracture is normally preferred because:
        - Preventative measures may be taken inasmuch as evidence of plastic deformation indicates that fracture is imminent.
        - More energy is required to induce ductile fracture than for brittle fracture.
    - Cracks in ductile materials are said to be *stable* (i.e., resist extension without an increase in applied stress).
    - For brittle materials, cracks are *unstable* - that is, crack propagation, once started, continues spontaneously without an increase in stress level.
- **Ductile Fracture**
    - For ductile metals, two tensile fracture profiles are possible:
        - Necking down to a point fracture when ductility is high (Figure 8.1a).
        - Only moderate necking with a cup-and-cone fracture profile (Figure 8.1b) when the material is less ductile.
- **Brittle Fracture**
    - For *brittle fracture*, the fracture surface is relatively flat and perpendicular to the direction of the applied tensile load (Figure 8.1c).
    - *Transgranular* (through-grain) and *intergranular* (between-grain) crack propagation paths are possible for polycrystalline brittle materials.
- **Principles of Fracture Mechanics**
    - The significant discrepancy between actual and theoretical fracture strengths of brittle materials is explained by the existence of small flaws that are capable of amplifying an applied tensile stress in their vicinity, leading ultimately to crack formation. Fracture ensues when the theoretical cohesive strength is exceeded at the tip of one of these flaws.
    - The maximum stress that may exist at the tip of a crack (oriented as in Figure 8.8a) is dependent on crack length and tip radius, as well as on the applied tensile stress according to Equation 8.1.
    - Sharp corners may also act as points of stress concentration and should be avoided when designing structures that are subjected to stresses.
    - There are three crack displacement modes (Figure 8.10): opening (tensile), sliding, and tearing.
    - A condition of plane strain is found when specimen thickness is much greater than crack length - that is, there is no strain component perpendicular to the specimen faces.
    - The fracture toughness of a material is indicative of its resistance to brittle fracture when a crack is present. For the plane strain situation (and mode I loading), it is dependent on applied stress, crack length, and the dimensionless scale parameter Y as represented in Equation 8.5
    - K_{Ic} is the parameter normally cited for design purposes; its value is relatively large or ductile materials (and small for brittle ones) and is a function of microstructure, strain rate, and temperature.
    - With regard to designing against the possibility of fracture, consideration must be given to material (its fracture toughness), the stress level, and the flaw size detection limit.
- **Fracture Toughness Testing**
    - Three factors that may cause a metal to experience a ductile-to-brittle transition are exposure to stresses at relatively low temperatures, high strain rates, and the presence of a sharp notch.
    - Qualitatively, the fracture behaviour of materials may be determined using the Charpy and the Izod impact testing techniques (Figure 8.12).
    - On the basis of the temperature dependence of measured impact energy (or the appearance of the fracture surface), it is possible to ascertain whether a material experiences a ductile-to-brittle transition and, if it does, the temperature range over which such a transition occurs.

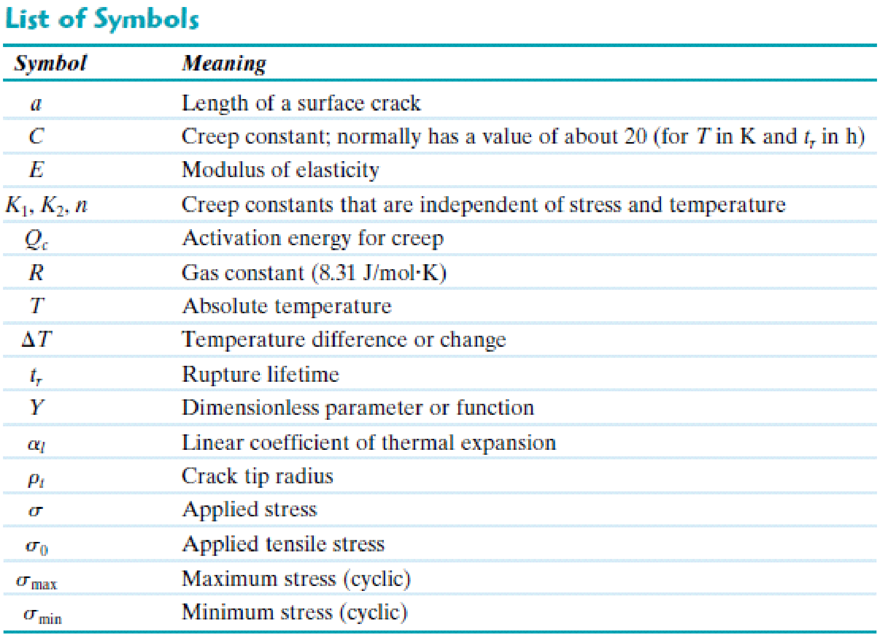
  - Low-strength steel alloys typify this ductile-to-brittle behaviour and, for structural applications, should be used as temperatures in excess of the transition range. Furthermore, low-strength FCC metals, most HCP metals, and high-strength materials do not experience this ductile-to-brittle transition.
  - For low-strength steel alloys, the ductile-to-brittle transition temperature may be lowered by decreasing grain size and lowering carbon content.
- **Fatigue**
  - Fatigue is a common type of catastrophic failure in which the applied stress level fluctuates with time; it occurs when the maximum stress level may be considerably lower than the static tensile or yield strength.
- **Cyclic Stresses**
  - Fluctuating stresses are categorized into three general stress-versus-time cycle modes: reversed, repeated, and random (Figure 8.17). Reversed and repeated modes are characterized in terms of mean stress, range of stress, and stress amplitude.
- **The S-N Curve**
  - Test data are plotted as stress (normally, stress amplitude) versus the logarithm of the number of cycles to failure.
  - For many metals and alloys, stress decreases continuously with increasing number of cycles at failure; fatigue strength and fatigue life are parameters used to characterize the fatigue behaviour of these materials (Figure 8.19b).
  - For other metals (e.g., ferrous and titanium alloys), at some point, stress ceases to decrease with, and becomes independent of, the number of cycles; the fatigue behaviour of these materials is expressed in terms of fatigue limit (Figure 8.19a).
- **Crack Initiation and Propagation**
  - Fatigue cracks normally nucleate on the surface of a component at some point of stress concentration.
  - Two characteristic fatigue surface features are beachmarks and striations.
    - *Beachmarks* form on components that experience applied stress interruptions; they normally may be observed with the naked eye.
    - Fatigue *striations* are of microscopic dimensions, and each is thought to represent the crack tip advance distance over a single load cycle.
- **Factors That Affect Fatigue Life**
  - Measures that may be taken to extend fatigue life include the following:
    - Reducing the mean stress level.
    - Eliminating sharp surface discontinuities.
    - Improving the surface finish by polishing.
    - Imposing surface residual compressive stresses by shot peening.
    - Case hardening by using a carburizing or nitriding process.
- **Environmental Effects**
  - Thermal stresses may be induced in components that are exposed to elevated temperature fluctuations and when thermal expansion and/or contraction is restrained; fatigue for these conditions is termed *thermal fatigue*
  - The presence of chemically active environment may lead to a reduction in fatigue life for corrosion fatigue. Measures that may be taken to prevent this type of fatigue include the following:
    - Application of a surface coating.
    - Use of a more corrosion-resistant material.
    - Reducing the corrosiveness of the environment.
    - Reducing the applied tensile stress level.
    - Imposing residual compressive stresses on the surface of the specimen.
- **Generalized Creep Behaviour**
  - The time-dependent plastic deformation of metals subjected to a constant load (or stress) and at temperature greater than about $0.4T_m$ is termed *creep*.
  - A typical creep curve (strain versus time) normally exhibits three distinct regions (Figure 8.29): transient (or primary), steady-state (or secondary), and tertiary.
  - Important design parameters available from such a plot include the steady-state creep rate (slope of the linear region) and rupture lifetime (Figure 8.29).
- **Stress and Temperature Effects**
  - Both temperature and applied stress level influence creep behaviour. Increasing either of these parameters produces the following effects:
    - An increase in the instantaneous initial deformation.

        - An increase in the steady-state creep rate.
        - A decrease in the rupture lifetime.
    - An analytical expression was presented that relates $\dot{\varepsilon}_s$ to both temperature and stress - see Equation 8.25.
- **Data Extrapolation Methods**
    - Extrapolation of creep test data to lower-temperature/longer-time regimes is possible using a plot of logarithm of stress versus the Larson-Miller parameter for the particular alloy (Figure 8.33).
- **Alloys for High-Temperature Use**
    - Metal alloys that are especially resistant to creep have high elastic moduli and melting temperatures; these include the superalloys, the stainless steels, and the refractory metals. Various processing techniques are employed to improve the creep properties of these materials.



Equation Summary

Equation Number	*Equation*	*Solving For*	*Page Number*
8.1	$\sigma_m = 2\sigma_0\left(\frac{a}{\rho_t}\right)^{1/2}$	Maximum stress at tip of elliptically shaped crack	258
8.4	$K_c = Y\sigma_c\sqrt{\pi a}$	Fracture toughness	260
8.5	$K_{Ic} = Y\sigma\sqrt{\pi a}$	Plane-strain fracture toughness	261
8.6	$\sigma_c = \frac{K_{Ic}}{Y\sqrt{\pi a}}$	Design (or critical) stress	262
8.7	$a_c = \frac{1}{\pi}\left(\frac{K_{Ic}}{\sigma Y}\right)^2$	Maximum allowable flaw size	263
8.14	$\sigma_m = \frac{\sigma_{\max} + \sigma_{\min}}{2}$	Mean stress (fatigue tests)	270
8.15	$\sigma_r = \sigma_{\max} - \sigma_{\min}$	Range of stress (fatigue tests)	270
8.16	$\sigma_a = \frac{\sigma_{\max} - \sigma_{\min}}{2}$	Stress amplitude (fatigue tests)	270
8.17	$R = \frac{\sigma_{\min}}{\sigma_{\max}}$	Stress ratio (fatigue tests)	270
8.23	$\sigma = \alpha_l E \Delta T$	Thermal stress	281
8.24	$\dot{\epsilon}_s = K_1\sigma^n$	Steady-state creep rate (constant temperature)	283
8.25	$\dot{\epsilon}_s = K_2\sigma^n \exp\left(-\frac{Q_c}{RT}\right)$	Steady-state creep rate	284
8.27	$m = T(C + \log t_r)$	Larson–Miller parameter	285



List of Symbols

Symbol	*Meaning*
a	Length of a surface crack
C	Creep constant; normally has a value of about 20 (for T in K and t_r in h)
E	Modulus of elasticity
K_1, K_2, n	Creep constants that are independent of stress and temperature
Q_c	Activation energy for creep
R	Gas constant (8.31 J/mol·K)
T	Absolute temperature
ΔT	Temperature difference or change
t_r	Rupture lifetime
Y	Dimensionless parameter or function
α_l	Linear coefficient of thermal expansion
ρ_t	Crack tip radius
σ	Applied stress
σ_0	Applied tensile stress
$\sigma_{\max}$	Maximum stress (cyclic)
$\sigma_{\min}$	Minimum stress (cyclic)

Important Terms and Concepts

σ_0	Applied tensile stress
σ_{max}	Maximum stress (cyclic)
σ_{min}	Minimum stress (cyclic)

Important Terms and Concepts

brittle fracture
case hardening
Charpy test
corrosion fatigue
creep
ductile fracture
ductile-to-brittle transition
fatigue
fatigue life
fatigue limit
fatigue strength
fracture mechanics
fracture toughness
impact energy
intergranular fracture
Izod test
plane strain
plane strain fracture toughness
stress raiser
thermal fatigue
transgranular fracture