SUMMARY

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 Behavior

- 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 behavior, 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 (ν), represents the negative ratio of transverse and longitudinal strains (ϵ_x and ϵ_z, respectively)—Equation 6.8. Typical values of ν 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 a 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 behavior, 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 microindentation hardness testing techniques are the Knoop and Vickers tests. Small indenters and relatively light loads are employed for these two techniques. They are used to measure the hardnesses 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

(*continued*)

Symbol	*Meaning*
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

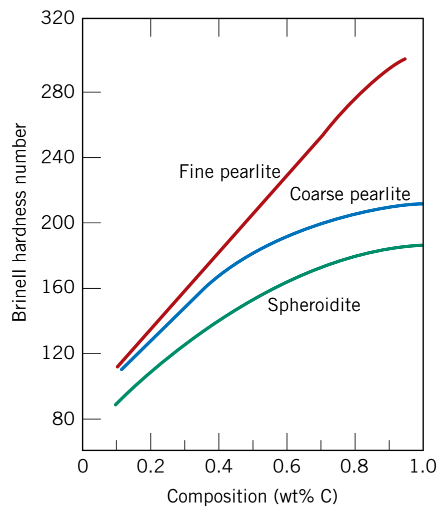
In this chapter, we defined and explained the types of deformation that metal alloys experience (elastic and plastic) as well as the associated properties (modulus of elasticity, yield strength, hardness, etc.). In order to improve the mechanical characteristics of metal alloys [e.g., steel (Chapter 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) → **Mechanical properties of iron–carbon alloys (Chapter 10)**

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

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



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