Chapter 6: Mechanical Properties: Part One

Learning Objectives

1. Technological significance
2. Terminology for mechanical properties
3. The tensile test: Use of the stress-strain diagram
4. Properties obtained from the tensile test
5. True stress and true strain
6. The bend test for brittle materials
7. Hardness of materials
8. Nanoindentation

9. Strain rate effects and impact behavior
10. Properties obtained from the impact test
11. Bulk metallic glasses and their mechanical behavior
12. Mechanical behavior at small length scales
Technological Significance

- Biocompatible titanium alloys used in bone implants must have enough strength and toughness to survive in the human body for many years without failure.
- Mechanical robustness of small devices fabricated using nanotechnology is important.
- Materials processing requires a detailed understanding of the mechanical properties of materials at different temperatures and conditions of loading.

Terminology for Mechanical Properties

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress</td>
<td>Force acting per unit area over which the force is applied.</td>
</tr>
<tr>
<td>Strain</td>
<td>Change in dimension per unit length.</td>
</tr>
<tr>
<td>Elastic strain</td>
<td>Fully recoverable strain resulting from an applied stress.</td>
</tr>
<tr>
<td>Young’s modulus or modulus of elasticity (E)</td>
<td>Slope of a tensile stress-strain curve in the linear regime (Figure 6-1 (b))</td>
</tr>
<tr>
<td>Elastomers</td>
<td>Materials that show large elastic deformations.</td>
</tr>
<tr>
<td>Shear modulus (G)</td>
<td>Slope of the linear part of the shear stress-shear strain curve.</td>
</tr>
<tr>
<td>Plastic deformation or strain</td>
<td>Permanent deformation of a material when a load is applied and then removed</td>
</tr>
<tr>
<td>Strain rate</td>
<td>Rate at which strain develops in or is applied to a material.</td>
</tr>
<tr>
<td>Impact loading</td>
<td>Rate of loading when materials are subjected to high strain rate.</td>
</tr>
</tbody>
</table>
### Terminology for Mechanical Properties

#### Viscous material
One in which the strain develops over a period of time and the material does not return to its original shape after the stress is removed.

#### Viscoelastic (or anelastic) material
A material with a response between that of a viscous material and an elastic material.

#### Stress relaxation
Decrease in stress for a material held under constant strain as a function of time, which is observed in viscoelastic materials.

#### Newtonian
Materials in which the shear stress and shear strain rate are linearly related.

### Viscosity (\(\eta\))
Measure of the resistance to flow.

**Viscosity is defined by** \(\tau = \eta \dot{\gamma}\)

#### Kinematic viscosity
\(\nu = \eta / \rho\)

#### Non-Newtonian materials
Materials with a nonlinear relationship between shear stress and shear strain rate. 

- **Shear thinning**
  Materials in which the apparent viscosity decreases with increasing rate of shear.

- **Shear thickening**
  Materials in which the apparent viscosity increases with increasing rate of shear.

### Figure 6.1
![Figure 6.1](image-url)
Terminology for Mechanical Properties

- **Bingham plastics**: 
  \[ \tau = \gamma \quad \text{(when } \gamma > \gamma_0) \]
  \[ \tau = \tau_0 + \eta \dot{\gamma} \quad \text{(when } \gamma < \gamma_0) \]

- **Apparent yield strength** \( \tau_0 \): Obtained by interpolating the shear stress–shear strain rate data to zero shear strain rate.

- **Thixotropic behavior**: Materials that show shear thinning and also an apparent viscosity that at a constant rate of shear decreases with time.

- **Rheopectic behavior**: Materials that show shear thickening and also an apparent viscosity that at a constant rate of shear increases with time.
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The Tensile Test: Use of the Stress–Strain Diagram

- **Load**: The force applied to a material during testing.
- **Strain gage or extensometer**: A device used for measuring strain.
- **Glass-transition temperature (T_g)**: Temperature below which a ductile material behaves as if it is brittle.

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The Tensile Test: Use of the Stress–Strain Diagram

- **Engineering stress** (\( \sigma \)) = \( \frac{F}{A} \)
- **Engineering strain** (\( \varepsilon \)) = \( \frac{\Delta l}{l_o} \)

Where:
- \( A_o \) = original cross-sectional area of the specimen before the test begins.
- \( l_o \) = original length between the gage marks.
- \( \Delta l \) = change in the length after a force of \( F \) is applied.

**Units**:
- Common units for stress are pounds per square inch (psi) and MegaPascals (MPa).
- Units for strain include inches/inches, m/m, and cm/cm or strain may be written as unitless.
Properties Obtained from the Tensile Test

- **Yield strength**
  - Elastic limit
    - The magnitude of stress at which plastic deformation commences.
  - Proportional limit
    - Level of stress above which the relationship between stress and strain is not linear.
- **Offset strain value**
  - Value of strain (e.g., 0.002) used to obtain the offset yield stress value.

- **Offset yield strength**
  - Stress value obtained graphically that describes the stress that causes no more than a specified amount of plastic deformation (usually 0.002).
- **Yield point phenomenon**
  - Abrupt transition from elastic deformation to plastic flow which occurs in some materials.

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**Figure 6.8**

<table>
<thead>
<tr>
<th>Stress</th>
<th>0.1% Offset UTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>150 MPa</td>
</tr>
</tbody>
</table>

**Upper yield point**

<table>
<thead>
<tr>
<th>Stress</th>
<th>0.2% Offset UTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>170 MPa</td>
</tr>
</tbody>
</table>
Properties Obtained from the Tensile Test

- **Elastic properties**
  - Hooke’s law
    - The linear relationship between stress and strain in the elastic portion of the stress-strain curve.
    - Denoted by the ratio $E = \frac{S}{e}$.
  - Stiffness
    - Measure of a material’s resistance to elastic deformation.
    - Stiffness of a component is directly proportional to its Young’s modulus.

- **Poisson’s ratio ($\nu$)**
  - The negative of the ratio between the lateral and longitudinal strains in the elastic region.
  - Denoted by the ratio $\nu = \frac{-e_{lateral}}{e_{longitudinal}}$.
  - Modulus of resilience
    - The maximum elastic energy absorbed by a material when a load is applied.
The Tensile Test: Use of the Stress–Strain Diagram

- **Tensile toughness**: Energy absorbed by a material prior to fracture.
- **Ductility**: The ability of a material to be permanently deformed without breaking when a force is applied.

\[
\text{% Elongation} = \frac{\Delta L}{L_i} \times 100
\]

\[
\text{% Reduction in area} = \frac{A_0}{A_f} \times 100
\]

**Ductility**: The ability of a material to be permanently deformed without breaking when a force is applied.

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Figure 6.13

The effect of temperature (a) on the stress–strain curve and (b) on the tensile properties of an alloy.

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True Stress and True Strain

\[\sigma = \frac{F}{A} \]

\[\varepsilon = \ln \left( \frac{A}{A_0} \right) \]

where:
- \(A\) = instantaneous area over which the force \(F\) is applied.
- \(A_0\) = instantaneous sample length.
- \(A_0\) = initial length.

After necking begins:

\[\varepsilon = \ln \left( \frac{A}{A_f} \right)\]

Instantaneous area is the cross-sectional area of the neck.
The Bend Test for Brittle Materials

- Flexural strength for a three-point bend test:
  \[ f_{\text{bend}} = \frac{3FL}{2bh^2} \]

- Flexural modulus:
  \[ E_{\text{bend}} = \frac{FL}{4wh^3} \]

- The maximum stress or flexural stress for a four-point bend test:
  \[ \sigma_{\text{bend}} = \frac{6FL}{wh^2} \]
Hardness of Materials

- **Hardness test**: Measure of resistance to penetration of the surface of a material by a hard object.

- **Bulk hardness** of materials measured using loads > 2N.

\[
H_B = \frac{2F}{\pi d (D - \sqrt{D^2 - d^2})}
\]

where:
- \( F \) = applied load in kilograms.
- \( D \) = diameter of the indenter in millimeters.
- \( d \) = diameter of the impression in millimeters.

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Figure 6.19 - Indenters for the Brinell and Rockwell Hardness Tests

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Nanoindentation

- Nanoindentation is hardness testing performed at the nanometer length scale.

- The reduced elastic modulus \( E_r \) is related to the unloading stiffness \( S \) according to

\[
E_r = \frac{\sqrt{\pi}}{2B} \frac{S}{\sqrt{4B}}
\]

where \( B \) is a constant for the shape of the indenter (\( B \approx 1.34 \) for a Berkovich indenter).

\[
B = 1 - \frac{\nu^2}{E_i} - \frac{1 - \nu_i^2}{E_i}
\]

where:
- \( E \) = elastic modulus of the material being indented
- \( \nu \) = Poisson's ratio of the material being indented
- \( E_i \) = elastic modulus of the indenter
- \( \nu_i \) = Poisson's ratio of the indenter
Figure 6.20 - Indentation in a Bulk Metallic Glass

Figure 6.21

Figure 6.23
Strain Rate Effects and Impact Behavior

<table>
<thead>
<tr>
<th>Property</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impact test</td>
<td>Measures the ability of a material to absorb the sudden application of a load without breaking.</td>
</tr>
<tr>
<td>Impact energy</td>
<td>Energy required to fracture a standard specimen when the load is applied suddenly.</td>
</tr>
<tr>
<td>Impact toughness</td>
<td>Ability of a material to withstand an impact blow.</td>
</tr>
<tr>
<td>Tensile toughness</td>
<td>Energy absorbed by a material subjected to tension prior to fracture.</td>
</tr>
<tr>
<td>Fracture toughness</td>
<td>Resistance of a material to failure in the presence of a flaw.</td>
</tr>
</tbody>
</table>

Properties Obtained from the Impact Test

- **Ductile to brittle transition temperature (DBTT)**
  - Temperature below which a material behaves in a brittle manner in an impact test.
- **Notch sensitivity**
  - Evaluated by comparing the absorbed energies of notched versus unnotched specimens.
- **Use of impact properties**
  - Absorbed energy and the DBTT are very sensitive to loading conditions.

Figure 6.26

The area under the true stress-strain curve is related to the fracture toughness. Although material B has a lower yield strength, it absorbs more energy than material A. The energies from these tests may not be the same as those obtained from impact tests.
Figure 6.27
A schematic diagram of the compressive stress-strain behavior of various engineering materials including metallic glasses. Softening flow is observed in the metallic glass.

Figure 6.29

Key Terms
- Stress
- Strain
- Elastic strain
- Young's modulus or modulus of elasticity (E)
- Shear modulus (G)
- Plastic deformation
- Plastic strain
- Strain rate
- Impact loading
- Viscoelastic
- Stress relaxation
- Shear thinning
- Apparent viscosity
- Bingham plastics
- Yield strength
- Thixotropic behavior
- Rheoplastic behavior
- Load
- Glass-transition
- Temperature
- Engineering stress
Key Terms

- Engineering strain
- Elastic limit
- Proportional limit
- Offset strain value
- Offset yield strength
- Yield strength
- Plastic strain
- Yield point phenomenon
- Tensile strength
- Ultimate tensile strength
- Necking

- Hooke’s law
- Poisson’s ratio
- Modulus of resilience
- Tensile toughness or Work of fracture
- Ductility
- Percent elongation
- Percent reduction in area
- True stress
- True strain

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Key Terms

- Bend test
- Elastic limit
- Flexural strength or Modulus of rupture
- Residual modulus
- Hardness test
- Macrohardness
- Impact energy

- Impact toughness
- Tensile toughness
- Fracture toughness
- Ductile to brittle transition temperature
- Notch sensitivity
- Modulus of resilience

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