Chapter 6: Mechanical properties of metals

Outline
- Introduction
- Concepts of stress and strain
- Elastic deformation
  - Stress-strain behavior
  - Elastic properties of materials
- Plastic deformation
  - Yield and yield strength
  - Ductility
  - Resilience
  - Toughness

Concepts of stress and strain

- Tension, compression, shear, and torsion
# Stress-strain testing

- **Tension tests**
  - engineering stress
  - engineering strain
  \[
  \sigma = \frac{F}{A_0} \\
  \varepsilon = \frac{l_l - l_0}{l_0} = \frac{\Delta l}{l_0}
  \]

- **Compression tests**

- **Shear stress**
  - Shear and torsional tests
    - Shear stress
      \[
      \tau = \frac{F}{A_0} = G\gamma
      \]
    - Shear strain
      \[
      \gamma = \frac{\Delta x}{y} = \tan(\theta)
      \]

- **Geometric considerations of the stress state**
Elastic deformation

1. Initial
2. Small load
3. Unload

Elastic means reversible!

Linear elastic properties

- Modulus of Elasticity, $E$: (also known as Young's modulus)
- Hooke's Law:
  \[ \sigma = E \varepsilon \]
Stress-strain behavior

- Stress-strain for linear elastic deformation
- Stress-strain for non-linear elastic deformation

Modulus of elasticity $E$ is proportional to $(dF/dr)_r$.
Slope of stress strain plot (which is proportional to the elastic modulus) depends on bond strength of metal.
Other elastic properties

- **Elastic Shear modulus, $G$**:
  \[ \tau = G \gamma \]

- **Elastic Bulk modulus, $K$**:
  \[ P = - K \frac{\Delta V}{V_0} \]

- **Special relations for isotropic materials**:
  \[ G = \frac{E}{2(1 + \nu)} \quad K = \frac{E}{3(1 - 2\nu)} \]

Comparison of Young’s moduli

- $E_{\text{ceramics}} > E_{\text{metals}} >> E_{\text{polymers}}$

<table>
<thead>
<tr>
<th>Material</th>
<th>Young’s Modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diamond</td>
<td>1200</td>
</tr>
<tr>
<td>Carbon fibers only</td>
<td>900</td>
</tr>
<tr>
<td>Graphite</td>
<td>100</td>
</tr>
<tr>
<td>Concrete</td>
<td>80</td>
</tr>
<tr>
<td>Glass - soda</td>
<td>70</td>
</tr>
<tr>
<td>Steel, Ni</td>
<td>60</td>
</tr>
<tr>
<td>Moissanite</td>
<td>50</td>
</tr>
<tr>
<td>Al, Ti</td>
<td>40</td>
</tr>
<tr>
<td>Cr, Fe</td>
<td>30</td>
</tr>
<tr>
<td>Mg, Zn</td>
<td>20</td>
</tr>
<tr>
<td>Al, Cu</td>
<td>15</td>
</tr>
<tr>
<td>Si, Ge</td>
<td>10</td>
</tr>
<tr>
<td>Graphite</td>
<td>5</td>
</tr>
<tr>
<td>Glass - soda</td>
<td>4</td>
</tr>
<tr>
<td>Glass</td>
<td>3</td>
</tr>
<tr>
<td>Steel</td>
<td>2</td>
</tr>
<tr>
<td>Al</td>
<td>1</td>
</tr>
<tr>
<td>C</td>
<td>0.5</td>
</tr>
<tr>
<td>Wood, Al</td>
<td>0.4</td>
</tr>
<tr>
<td>Epoxy only</td>
<td>0.3</td>
</tr>
</tbody>
</table>

**Notes**:
- CFRE(|| fibers)*: Carbon fibers only
- GFRE(|| fibers)*: Graphite fibers only
- EPRE: Epoxy only
- CFRE: Carbon fibers only
- GFRE: Graphite fibers only
- HDPE: High-density polyethylene
- PTFE: Polytetrafluoroethylene
- PET: Polyethylene terephthalate
- PC: Polycarbonate
- PP: Polypropylene
- PS: Polystyrene
- PP: Polypropylene
Comparison of yield strength

<table>
<thead>
<tr>
<th>Material</th>
<th>σ_y (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PVC</td>
<td>Hard to measure, since in tension, fracture usually occurs before yield.</td>
</tr>
<tr>
<td>Nylon 6,6</td>
<td>70</td>
</tr>
<tr>
<td>LDPE</td>
<td>20</td>
</tr>
<tr>
<td>HDPE</td>
<td>40</td>
</tr>
<tr>
<td>PC</td>
<td>60</td>
</tr>
<tr>
<td>PET</td>
<td>100</td>
</tr>
<tr>
<td>Steel (1020)</td>
<td>200</td>
</tr>
<tr>
<td>Steel (4140)</td>
<td>300</td>
</tr>
<tr>
<td>Ti (5Al-2.5Sn)</td>
<td>400</td>
</tr>
<tr>
<td>Mo (pure)</td>
<td>500</td>
</tr>
<tr>
<td>Cu (71500)</td>
<td>600</td>
</tr>
<tr>
<td>Ti (pure)</td>
<td>700</td>
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<tr>
<td>Ta (pure)</td>
<td>800</td>
</tr>
<tr>
<td>Al (6061)</td>
<td>900</td>
</tr>
<tr>
<td>Al (6061)ag</td>
<td>1000</td>
</tr>
<tr>
<td>Steel (1020)hr</td>
<td>2000</td>
</tr>
<tr>
<td>Steel (4140)ag</td>
<td>3000</td>
</tr>
<tr>
<td>Steel (1020)cd</td>
<td>4000</td>
</tr>
<tr>
<td>Steel (4140)qt</td>
<td>5000</td>
</tr>
</tbody>
</table>

Elastic properties of materials

- Poisson's ratio
  
  \[ v = -\varepsilon_x / \varepsilon_z = -\varepsilon_y / \varepsilon_z \]

  - Metals: \( v \approx 0.33 \)
  - Ceramics: \( v \approx 0.25 \)
  - Polymers: \( v \approx 0.40 \)

Units:

- \( E \): [GPa] or [psi]
- \( v \): dimensionless
Plastic means permanent!

Plastic Deformation (Metals)

1. Initial
   - bonds
2. Small load
   - stretch & planes shear
   - $\delta_{\text{elastic + plastic}}$
3. Unload
   - planes still sheared
   - $\delta_{\text{plastic}}$

Plastic deformation: yield and yield strength

- Yielding
- Proportional limit
- Yield strength
Tensile strength

- Tensile strength: the stress at the maximum on the engineering stress-strain curve
- Metals: occurs when noticeable “necking” starts
- Ceramics: occurs when crack propagation starts
- Polymers: occurs when polymer backbones are aligned and about to break

Plastic (permanent) deformation

(At lower temperature: T < T_{melt}/3)

- Simple tension test:
  - Elastic + Plastic at larger stress
  - Elastic initially
  - Permanent (plastic) after load is removed
  - Plastic strain
Elastic and plastic deformations

- Stress-strain relations under uniaxial loading

![Diagram showing stress-strain curves for Ceramics, Steel, and Polymeric material.](image)

Ductility

- Ductility: a measure of the degree of plastic deformation that has been sustained at fracture

\[
\%EL = \left( \frac{L_f - L_0}{L_0} \right) \times 100
\]

\[
\%RA = \left( \frac{A_0 - A_f}{A_0} \right) \times 100
\]
Resilience

- Resilience: is the capacity of a material to absorb energy when it is deformed elastically and then, upon unloading, to have this energy recovered.

- Resilience formula:
  \[ U_r = \int_0^\varepsilon \sigma \, d\varepsilon \]

- Resilience equation:
  \[ U_r = \frac{1}{2} \sigma_0 \varepsilon_0 \]

- Resilience calculation:
  \[ U_r = \frac{1}{2} \sigma_0 \varepsilon_0 = \frac{1}{2} \sigma_0 \left( \frac{\varepsilon_0}{E} \right) = \frac{\sigma_0^2}{2E} \]
Toughness

- Energy to break a unit volume of material
- Approximate by the area under the stress-strain curve

Brittle fracture: elastic energy
Ductile fracture: elastic + plastic energy

Summary

- **Stress** and **strain**: These are size-independent measures of load and displacement, respectively.
- **Elastic** behavior: This reversible behavior often shows a linear relation between stress and strain. To minimize deformation, select a material with a large elastic modulus ($E$ or $G$).
- **Plastic** behavior: This permanent deformation behavior occurs when the tensile (or compressive) uniaxial stress reaches $\sigma_y$.
- **Toughness**: The energy needed to break a unit volume of material.
- **Ductility**: The plastic strain at failure.