3. Mechanical Properties of Materials

3.1 Stress-Strain Relationships
3.2 Hardness
3.3 Effect of Temperature on Properties
3.4 Fluid Properties
3.5 Viscoelastic Properties
Importance of Mechanical Properties

- Mechanical properties determine a material’s behavior when subjected to mechanical stresses
  - Properties include elastic modulus, ductility, hardness, and various measures of strength

- Mechanical properties desirable to the designer, such as high strength, usually make manufacturing more difficult

- Integration of design and manufacturing

- Tension, Compression and Shear tests
3.1 Stress-Strain Relationships

- **Tensile Properties**
  - Elastic modulus
  - Ductility
  - Hardness
  - Various measures of strength
    - Proportional limit
    - Elastic limit
    - Yield strength
    - Offset yield strength
    - Ultimate Tensile strength
    - Failure Strength

\[
TS = \frac{F_{max}}{A_o}
\]
Tensile Test

- Elastic
- Plastic Deformation
- Fracture

Measuring Force; Transducer
Measuring Displacement; extensometer, strain gauge

Gauge Length

necking
Stress and Strain Diagram

**Engineering Stress & Strain**
- Original Area, $A_o$

**True Stress and Strain**
- Instantaneous Current Area, $A$

Flow Curve: $\sigma = K \varepsilon^n$
- $\sigma$ = Stress
- $\varepsilon$ = Strain

- $S_y$: Yield Stress
- $S_u$: Ultimate Tensile Strength
- $S_f$: Fracture Stress

**Equations**

- Engineering Stress: $\sigma_e = \frac{F}{A_o}$, $e = \frac{\delta}{L_o}$
- True Stress: $\sigma = \frac{F}{A}$, $\varepsilon = \ln \frac{L_0}{L}$

At necking, $\sigma = K$
- $\sigma$ = Stress
- $\varepsilon$ = Strain

Reloading and Unloading regions are also shown.

**Graph**
- Stress vs. Strain plot
- Log-log scale for strain
- $10^{-3}, 10^{-2}, 10^{-1}$
Flow Curve

- The straight line in a log-log plot shows the relationship between true stress and true strain in the plastic region as

\[ \sigma = K \varepsilon^n \]

- where \( K \) = strength coefficient; and \( n \) = strain hardening exponent

- **strain hardening** - true stress increases continuously in the plastic region until necking.
Ultimate Tensile Strength

\[ P = \sigma A \]

\[ dP = \sigma dA + Ad\sigma \]

At Maximum load (necking), \( dP = 0 \)

\[ \frac{d\sigma}{\sigma} = - \frac{dA}{A} \quad \boxed{1} \]

For a constant volume process

\[ Al = \text{constant} \]

\[ Adl + ldA = 0 \]

\[ - \frac{dA}{A} = \frac{dl}{l} = d\epsilon \]

Flow Curve: \( \sigma = K \epsilon^n \)

Eq. (1) can be manipulated

\[ \sigma = \frac{d\sigma}{d\epsilon} \]

With the flow curve,

\[ K \epsilon^n = Kn \epsilon^{n-1} \]

\[ \therefore \epsilon = n \]
Characteristics

- Ductile and Brittle
- Perfectly elastic: $\sigma = E\varepsilon$
- Perfectly plastic: $\sigma = Y$
- Elastic and Perfectly Plastic
  - Flow curve: $K = Y$, $n = 0$
- Elastic and Strain hardening
  - Flow curve: $K > Y$, $n > 0$
- Nonlinear
- Temperature-dependent
Compression Properties

- Engineering stress, \( \sigma_e = \frac{F}{A_o} \)
- Engineering strain, \( e = \frac{h - h_o}{h_o} \)

Barreling due to the friction At the contact surfaces.

Use K and n from tensile tests

\[ \sigma = K \varepsilon^n \]
Bending and Testing of Brittle Materials

- Brittle Materials deform elastically until fracture
  - Failure occurs at the outer fibers of specimen when tensile strength are exceeded.
  - *Cleavage* - separation rather than slip occurs along certain crystallographic planes

- Three Point Bend Test
- (Four Point Bend Test)
- Transverse Rupture Strength (TRS)

\[ TRS = \frac{1.5FL}{bt^2} \]
Shear Properties

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

\[ \gamma = \frac{\delta}{b} \]

• For most materials, \( G \approx 0.4E \)
Hardness

- **Brinell Hardness Test**: 10mm diameter ball with a load of 500, 1000 or 3000kg
  \[ HB = \frac{2F}{\left(\pi D_b \left(D_b - \sqrt{D_b^2 - D_i^2}\right)\right)} \]

- **Rockwell Hardness Test**: A cone shape indenter; the depth of penetration is measured.

- **Vickers Hardness Test**: Pyramid shape indenter
  \[ HV = \frac{1.854F}{D^2} \]
Shear Plastic Stress-Strain Relationship

- Relationship similar to flow curve
- Shear stress at fracture = shear strength $S$
  - Shear strength can be estimated from tensile strength: $S \approx 0.7(TS)$
- Since cross-sectional area of test specimen in torsion test does not change, the engineering stress-strain curve for shear is similar to true stress-strain curve
Hardness

- Knoop hardness Test: Pyramid shape indenter
  \[ HK = \frac{14.2F}{D^2} \]

- Scleroscope: rebound height

- Durometer: The resistance to penetration (elastic deformation)

- Relationship between Hardness and Strength
  \[ TS = K_h(HB) \]
  where \( K_h = 500 \text{ in lb/in}^2 \)
  \[ = 3.45 \text{ in MPa} \]
Temperature Effect

- Effect the all properties
- Hot hardness
- Recrystallization ($0.5T_m$)
Recrystallization

- Most metals strain harden at room temperature
- Upon heating to sufficiently high temperature, strain hardening does not occur
  - *recrystallization* - Formation of new grains that are free of strain
  - *Recrystallization temperature* of a given metal = 0.5 $T_m$ measured on an absolute scale
- Recrystallization above the recrystallization temperature takes time.
- In manufacturing - recrystallization reduces forces and power. *Hot working* - Forming metals above recrystallization temperature
Fluid Flow in Manufacturing

- In many processes, materials converted from solid to liquid by heating.
  - Metals are cast in molten state
  - Glass is formed in a heated and highly fluid state
  - Polymers are almost always shaped as thick fluids
- Flow is a defining characteristic of fluids
  - Viscosity (the resistance to flow) is a measure of the internal friction when velocity gradients are present in the fluid
  - Reciprocal of viscosity is fluidity - the easiness of a fluid flows
Relation between Shear Stress and Strain rate

- Viscosity can be defined using two parallel plates separated by a distance $d$
- Shear viscosity is the fluid property that defines the relationship between $F/A$ and $dv/dy$ (shear rate);

$$
\tau = \frac{F}{A} = \eta \frac{dv}{dy} = \eta \dot{\gamma} \quad \text{or} \quad \tau = \eta \dot{\gamma}
$$

where $\eta$ = a constant of proportionality called the coefficient of viscosity, Pa-s

- For Newtonian fluids, viscosity is a constant
- For non-Newtonian fluids, it is not
Some Viscosity Data

<table>
<thead>
<tr>
<th>Materials</th>
<th>Viscosity Pa-s</th>
<th>Materials</th>
<th>Viscosity Pa-s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass @540C</td>
<td>$10^{12}$</td>
<td>Polymer @151C</td>
<td>115</td>
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<tr>
<td>Glass @815C</td>
<td>$10^5$</td>
<td>Polymer @205C</td>
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<td>Glass @1095C</td>
<td>$10^3$</td>
<td>Water @20C</td>
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<tr>
<td>Machine Oil</td>
<td>0.1</td>
<td>Water @100C</td>
<td>0.0003</td>
</tr>
</tbody>
</table>
Viscous behaviors

- A thermoplastic polymer melt is non-Newtonian
  - A fluid that exhibits this decreasing viscosity with increasing shear rate is called *pseudoplastic*

- This complicates analysis of polymer shaping processes such as injection molding
Viscoelastic Behavior

- Polymers
- The property of a material that determines the strain subjected to combination of stress and temperature over time.

\[ \sigma(t) = f(t) \varepsilon \]
Viscoelastic Behavior of Polymers

- **Viscoelastic** - Combination of viscosity and elasticity
- **Die swell** - In extrusion of polymers, the profile of extruded material grows in size after being squeezed through the smaller die opening
  - It “remembers” (Shape memory)