Mechanical Properties of Metals
How strong is it?
Under what sort of deformation?
• Basic mechanical behavior of material
• Specimen is “pulled” in tension at a constant rate
• Load \((F)\) necessary to produce a given elongation \((\Delta L)\) is monitored
• Load vs elongation curve
• Converted to stress-strain curve
**Engineering Stress and Strain**

**Engineering Stress, \( \sigma \)**

\[
\sigma = \frac{F}{A_0}
\]

where \( F \) is the applied load and \( A_0 \) is the original cross-sectional area. Units: N/m\(^2\) or lb/in\(^2\)

**Engineering Strain, \( \varepsilon \)**

\[
\varepsilon = \frac{L_i - L_0}{L_0} = \frac{\Delta L}{L_0}
\]

where \( L_0 \) is the original length and \( L_i \) is the instantaneous. Unitless.
Stress Strain Curve

(Maximum) Tensile Strength

Fracture

Classification of the material

Figure by MIT OpenCourseWare.
Yielding occurs

- **Elastic** means reversible
- **Plastic** means permanent

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**Tensile Properties**

Yield strength

*Modulus of Elasticity or Youngs Modulus, $E$*

---

Graph showing stress-strain relationship with yield point $P$ and modulus of elasticity.

Figure by MIT OpenCourseWare.
Elastic Deformation

1. Initial
2. Small load
3. Unload

Elastic means reversible!

Hooke’s Law

\[ \sigma = E\varepsilon \]
Plastic Deformation

1. Initial

2. Small load
   - bonds stretch
   - planes shear

3. Unload
   - planes still sheared

$\delta_{\text{elastic + plastic}}$

$\delta_{\text{plastic}}$

Plastic means permanent!

$F$

$F$ vs $\delta$

Linear elastic

$\delta_{\text{plastic}}$
How does this occur?

Recall force is \(\frac{d(\text{energy})}{da}\)

Do we break all bonds at once?

Slipped Plane

Slip Plane

Slipped
Likely Process for Slipping

Dislocation Motion Along Slip Plane

• Requires only one broken bond at a given time
• Requires minimum energy
• Most plastic deformation occurs via dislocation motion along slip plane for metals and their alloys.
Ductility: degree of plastic deformation at fracture

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

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

Brittle Materials have a fracture strain of less than approx. 5%
Resilience

- **Resilience** is the capacity of material to absorb energy as elastic deformation and recover the energy.

- Characterized by modulus of resilience, $U_r$

$$U_r = \int_0^{\varepsilon_y} \sigma \, d\varepsilon$$

- If linear elastic region,

$$U_r = \frac{1}{2} \sigma_y \varepsilon_y$$

- These materials tend to have high yield strength and low modulus of elasticity.
Fracture Toughness

Energy required to fail $\rightarrow$ area under stress-strain curve. Material must be strong and ductile.

Engineering tensile stress, $\sigma$

Engineering tensile strain, $\varepsilon$

- Smaller toughness (ceramics)
- Larger toughness (metals, PMCs)
- Smaller toughness-unreinforced polymers
Think of a rose or banana dipped in liquid nitrogen

E, yield and tensile strength decrease with temperature
Ductility usually increases with temperature
Do you notice anything strange about the stress-strain curve after a material exceeds its Tensile Strength?
In elastic region, change in cross-sectional area and length are negligible.

As material deforms plastically, the initial cross-sectional area and length changes instantaneously.

\[ \sigma = \frac{F}{A_0} \]

\[ \varepsilon = \frac{\Delta L}{L_0} \]

\[ \sigma_T = \frac{F}{A_i} \]

\[ \varepsilon_T = \ln\left(\frac{L_i}{L_0}\right) \]

True stress and true strain are based on instantaneous cross-sectional area and instantaneous length.
If no volume occurs during deformation:

$$\sigma_T = \sigma (1 + \varepsilon)$$

$$\varepsilon_T = \ln(1 + \varepsilon)$$

After plastic deformation until necking:

$$\sigma_T = K \varepsilon^n_T$$ where $K$ and $n$ (strain hardening) are constants
Poisson’s Ratio, $\nu$

isotropic material

$$\nu = -\frac{\varepsilon_x}{\varepsilon_z} = -\frac{\varepsilon_y}{\varepsilon_z}$$

- Elastic strain in compression perpendicular to extension caused by tensile stress
- Cannot be directly obtained from stress-strain curve
- $\nu = 0.26$ to $0.35$ for common metal alloys
- $\nu < 0.25$ for ceramics
- $\nu$ has a maximum value of $0.50$ (no volume change)

$\varepsilon_x = \frac{\Delta l_x/2}{l_{0x}}$

$\varepsilon_y = \frac{\Delta l_y/2}{l_{0y}}$

Figure by MIT OpenCourseWare.
Shear Stress, $\tau$

$$\tau = \frac{F_s}{A_0}$$

where $F_s$ is the shear load and $A_0$ is the initial cross-sectional area parallel to the loading direction.

Shear Strain, $\gamma$

$$\gamma = \tan \theta$$

Shear Modulus, $G$

$$\tau = G\gamma$$

Figure by MIT OpenCourseWare.
Tensile Stress and Strain

\[ \sigma = \frac{F}{A_0} \]
\[ \varepsilon = \frac{L_i - L_0}{L_0} = \frac{\Delta L}{L_0} \]
\[ \sigma = E\varepsilon \]

Shear Stress and Strain

\[ \tau = \frac{F_s}{A_0} \]
\[ \gamma = \tan \theta \]
\[ \tau = G\gamma \]

\[ E = 2G(1+\nu) \]
Upon release of load during a stress-strain test, some fraction of the strain is recovered as elastic strain.

Reapplication of stress will traverse the same curve.

Note the increase in the yield stress – strain hardening.

Ductility decreases.

Figure by MIT OpenCourseWare.