Chapter 8: Mechanical Properties of Metals

- **ISSUES TO ADDRESS**
  - Stress and strain: What are they and why are they used instead of load and deformation?
  - Elastic behavior: When loads are small, how much deformation occurs? What materials deform least?
  - Plastic behavior: At what point does permanent deformation occur? What materials are most resistant to permanent deformation?
  - Toughness and ductility: What are they and how do we measure them?

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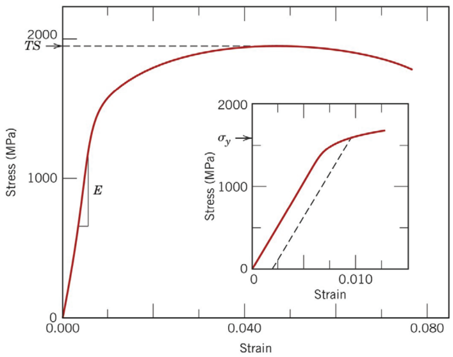
Model H300KU Universal Testing Machine by Tinius Olsen



8.1 Introduction

- **Mechanical behavior of a material reflects its response or deformation in relation to an applied load or force.**

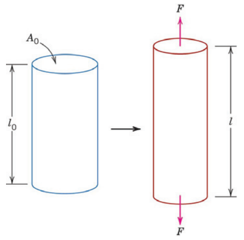
- **Key mechanical design properties: stiffness, strength, hardness, ductility and toughness**

- **ASTM (American Society for Testing and Materials) Standards (http://www.astm.org)**

- **Role of engineers**
  - Structural engineers: to determine stresses and stress distributions within members that are subjected to well-defined loads.
  - Materials and metallurgical engineers: to produce and to fabricate materials to meet service requirements as predicted by these stress analyses.

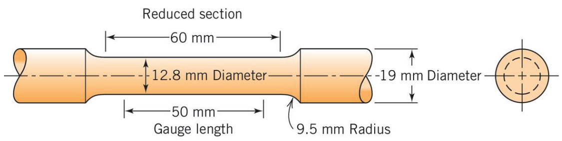
8.2 Concepts of Stress and Strain

- Tension Test (Tensile Test)

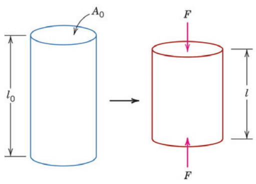


$$\sigma = \frac{F}{A_0}$$

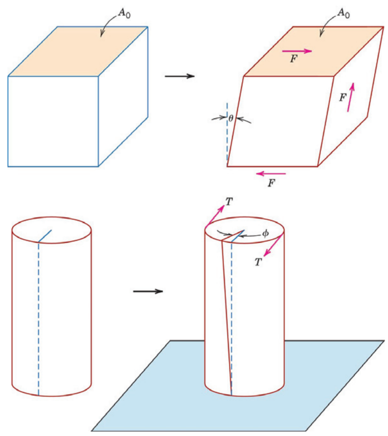
$$\varepsilon = \frac{\Delta l}{l_0}$$



- Compression Test

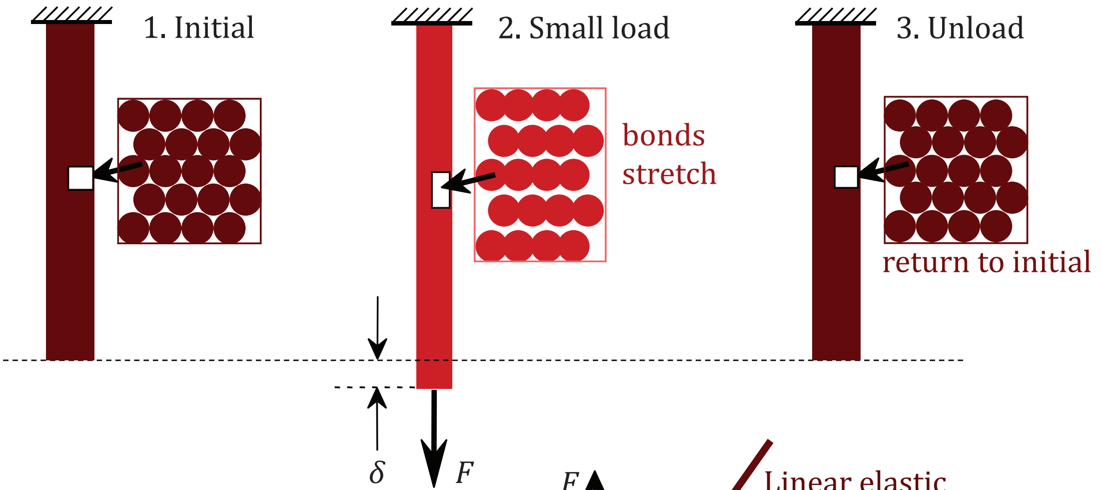


- Shear and Torsional Tests

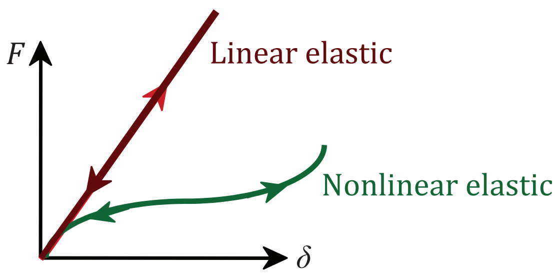


- Geometric Considerations of the Stress State
  - von Mises stress: a representative of general stress states

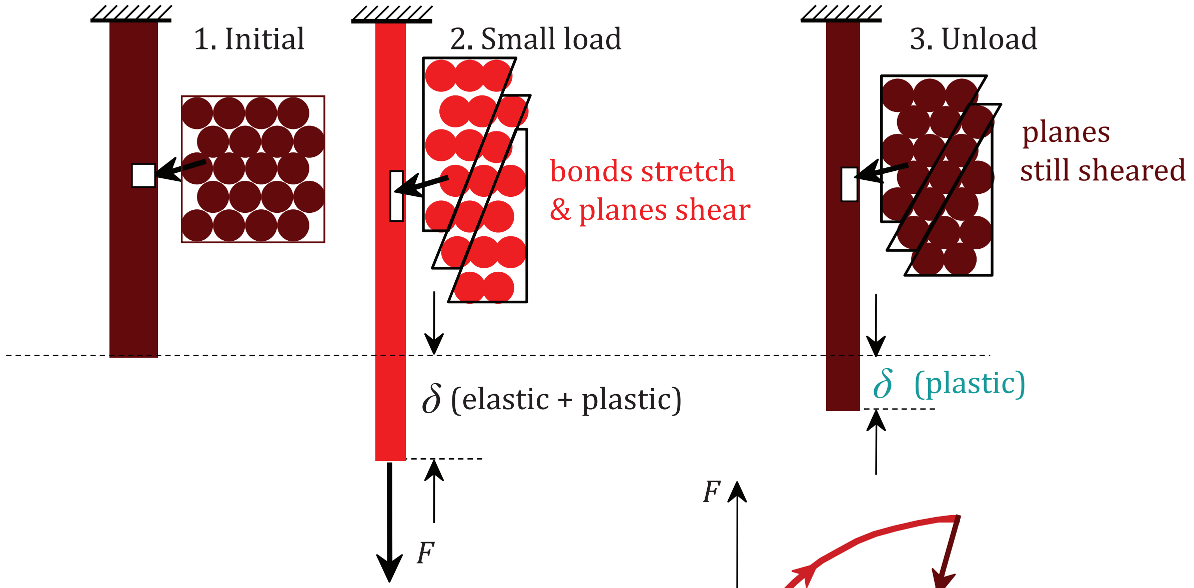
Elastic Deformation



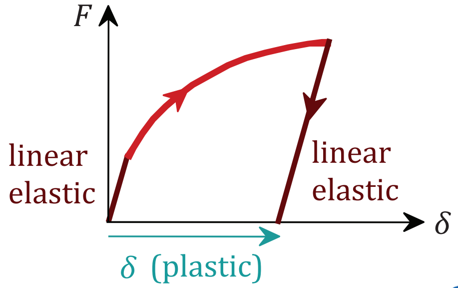
Elastic means reversible!



Plastic Deformation (Metals)

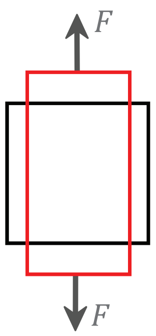


Plastic means permanent!

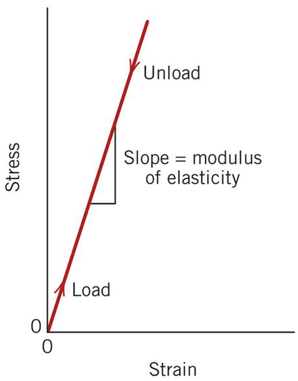


8.3 Elastic Deformation

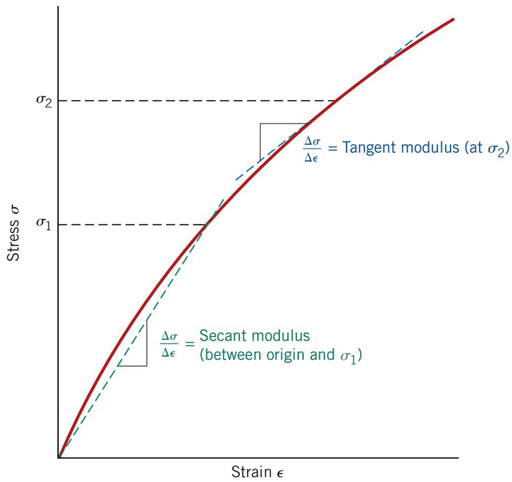
- **Elastic deformation (nonpermanent): When the applied load is released, the piece returns to its original shape.**
- **Linear elastic materials: $\sigma = E\varepsilon$ (Hooke's Law)**
  - Modulus of Elasticity, E (also known as Young's modulus)



simple tension test



Linear elastic material



Nonlinear elastic material

Mechanical Properties

- The elastic modulus is proportional to the slope of the interatomic force-separation curve at equilibrium spacing:

$$E \propto \left(\frac{dF}{dr}\right)_{r=r_0}$$

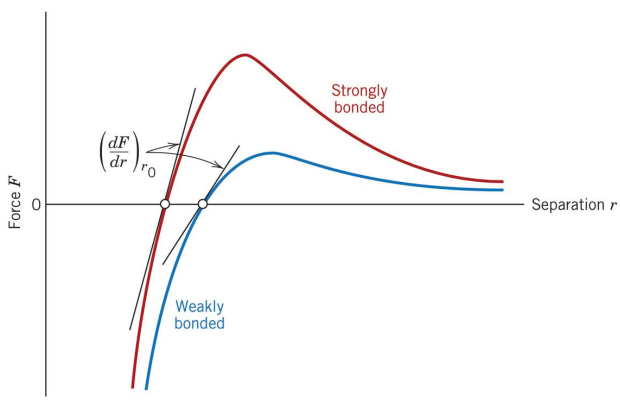


Fig. 8.7, *Callister & Rethwisch 9e.*

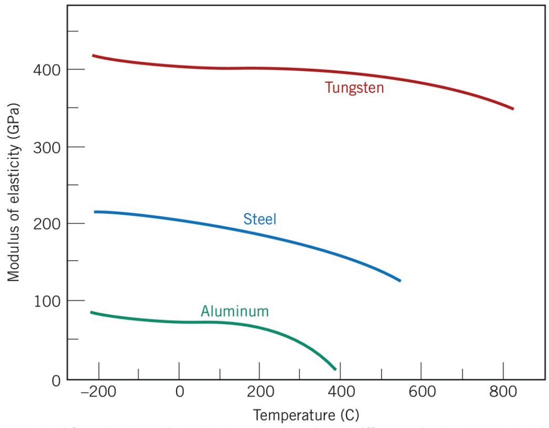


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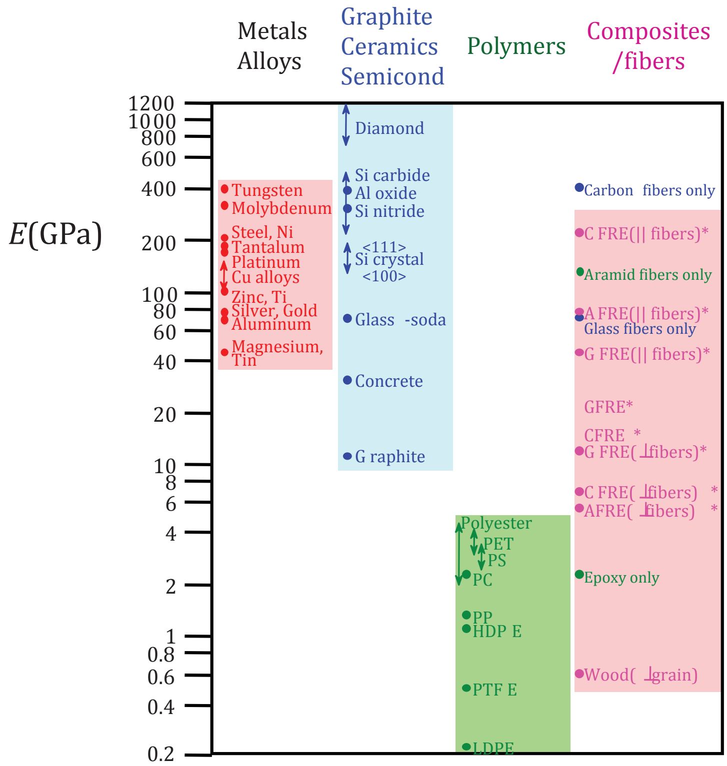
Fig. 8.8, *Callister & Rethwisch 9e.*

Young's Moduli: Comparison



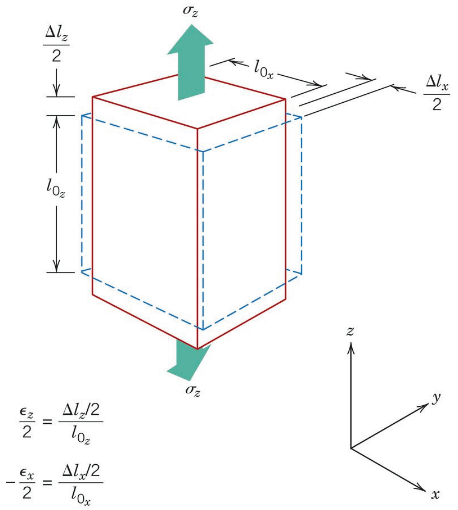
Based on data in Table B.2, *Callister & Rethwisch 9e.*
Composite data based on reinforced epoxy with 60 vol% of aligned carbon (CFRE), aramid (AFRE), or glass (GFRE) fibers.

Poisson's ratio, ν

- **The axial elongation is accompanied by lateral contraction.**
- **Lateral strain is proportional to the axial strain.**
- **Poisson's ratio: the ratio of the lateral strain to the axial strain**

$$\nu = -\frac{\text{lateral strain}}{\text{axial strain}} = -\frac{\varepsilon_x}{\varepsilon_z} = -\frac{\varepsilon_y}{\varepsilon_z}$$

- **Most of materials: ν = 0.25 ~0.35**
- **Cork: ν = 0 (e.g. wine cap)**
- **Rubber: ν = 0.5 (incompressible material)**
- **Limitation on Poisson's ratio**
  - Homogeneous and isotropic materials
- **Units:**
  - E: [GPa] or [psi]
  - ν: dimensionless
- **Typical values of Poisson's ratio**
  - metals: $\nu \sim 0.33$
  - ceramics: $\nu \sim 0.25$
  - polymers: $\nu \sim 0.40$



$$\frac{\epsilon_z}{2} = \frac{\Delta l_z/2}{l_{0_z}}$$

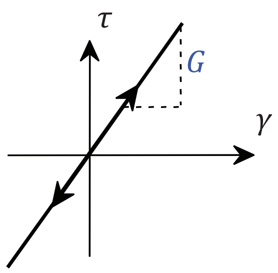
$$-\frac{\epsilon_x}{2} = \frac{\Delta l_x/2}{l_{0_x}}$$

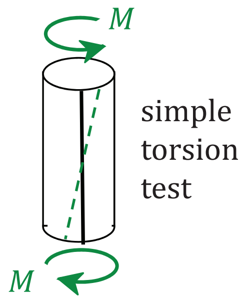
Fig. 8.9 Axial (z) elongation (positive strain) and lateral strain (x and y) contractions (negative strains) in response to an imposed tensile stress. *Callister & Rethwisch 9e.*

Other Elastic Properties

- **Elastic shear modulus, *G*:**

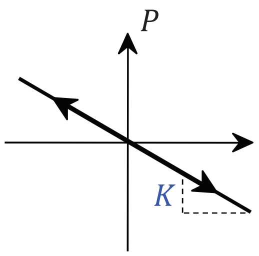
$$\tau = G\gamma$$



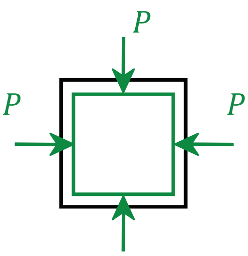


- **Elastic bulk modulus, K:**

$$P = -K\frac{\Delta V}{V_0}$$



$$\frac{\Delta V}{V_0}$$



Pressure test:
Initial volume = V_0
Volume change = ΔV

- **Special relations for isotropic materials:**

$$G = \frac{E}{2(1+\nu)} \qquad K = \frac{E}{3(1-2\nu)}$$

Basic Concepts in Mechanics of Materials

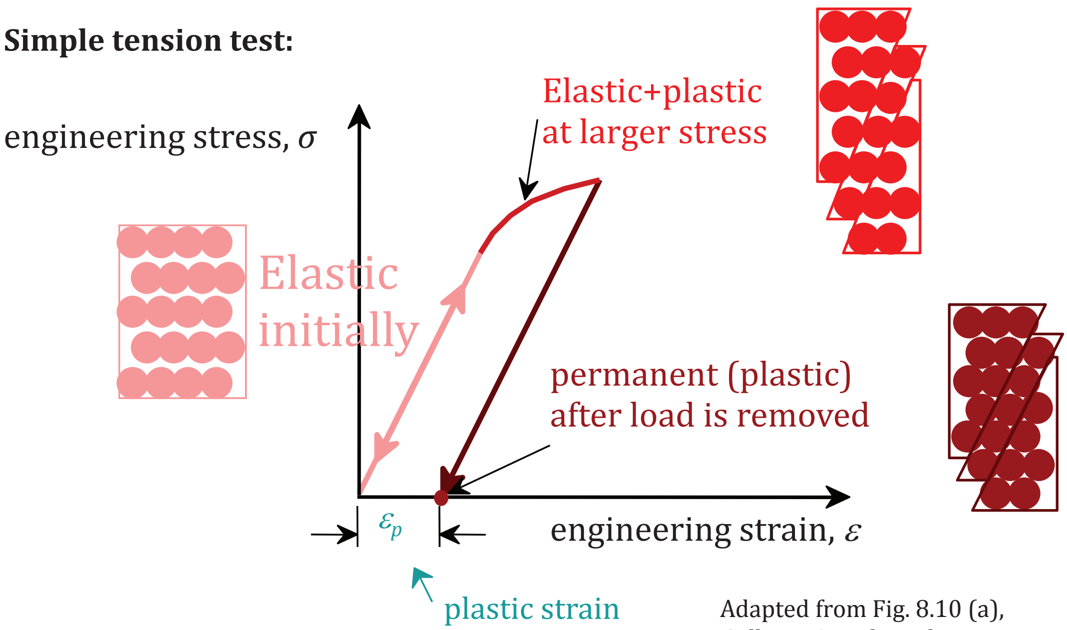
- **Three basic equations of linear elasticity**
  - Equations of equilibrium (평형 방정식)
  - Strain-displacement relations (변형률-변위 관계식)
  - Stress-strain relations (응력-변형률 관계식): Generalized Hooke's law

- **Terminologies**
  - Linear (선형) vs. nonlinear (비선형)
  - Elastic (탄성) vs. inelastic (비탄성)
  - Stiffness (강성) vs. strength (강도)
  - Homogeneous (균질) vs. inhomogeneous (비균질)
  - Nominal stress (공칭응력) vs. true stress (진응력)
  - Nominal strain (공칭변형률) vs. true strain (진변형률)
  - Ductile materials (연성재료) vs. brittle materials (취성재료)

8.4 Plastic Deformation

- **Plastic deformation: permanent or nonrecoverable deformation**

- **Simple tension test:**



Adapted from Fig. 8.10 (a), *Callister & Rethwisch 9e.*

(at lower temperatures, i.e. $T < T_{melt}/3$)

Tensile Test

- Tensile test to understand the mechanical behavior of materials
- Standard: ASTM (American Society for Testing and Materials)

• **Typical tensile specimen**

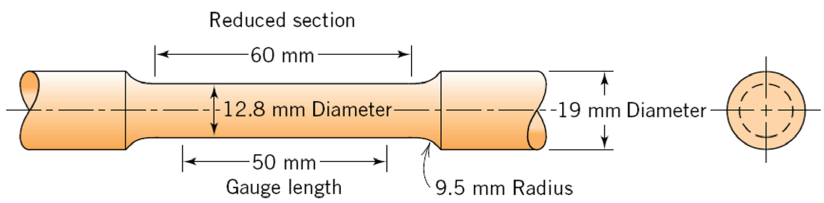
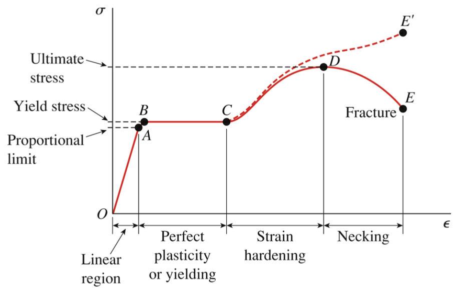
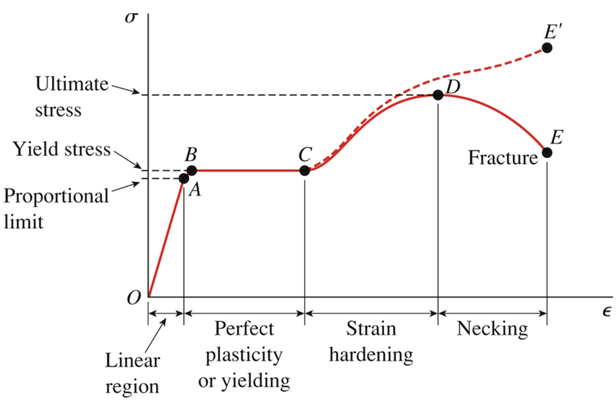


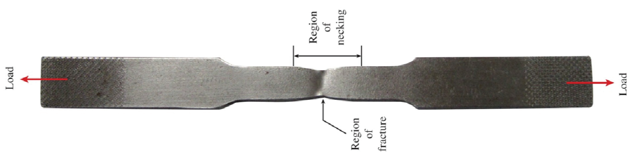
Fig. 8.2, *Callister & Rethwisch 9e*



Stress-Strain Curve

- **Typical stress-strain curve of mild steel**





- Region OB: linear elastic region
- Region BC: yielding (항복), the material deforms without an increase in the applied load

➔ The material becomes perfectly plastic (The elongation is typically 10 to 15 times larger than that of region OA)

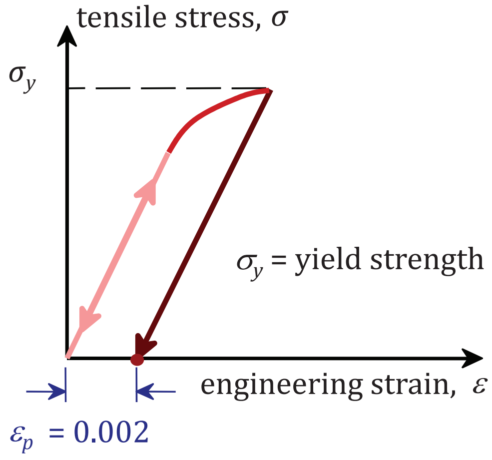
- Region CD: strain hardening (변형경화) or work hardening (가공경화)

➔ The resistance of the material to further deformation increases due to the change of its crystal structures

- Stress at the point D: ultimate stress (극한응력) or ultimate strength (극한강도)
- Region DE: Necking; further stretching is accompanied by a reduction in the load, and the reduction of area becomes clearly visible
- Point E: fracture
- Region CE': True stress-true strain curve ➔ True stress keeps increasing
- Region CDE: Nominal stress starts to decrease from the point D

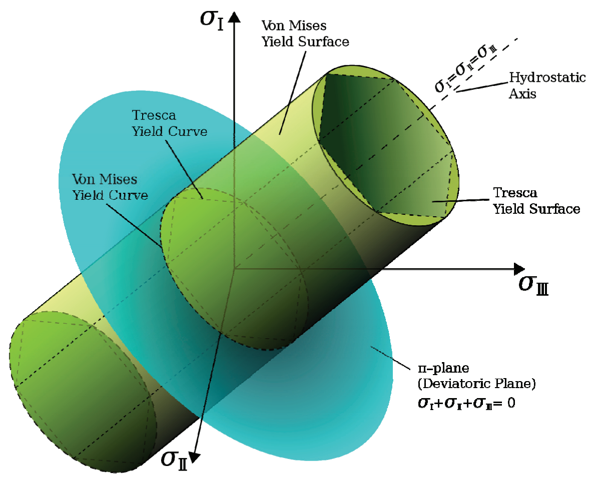
Yield Strength and Yield Criteria

- **Yield strength: stress at which noticeable plastic deformation has occurred.**



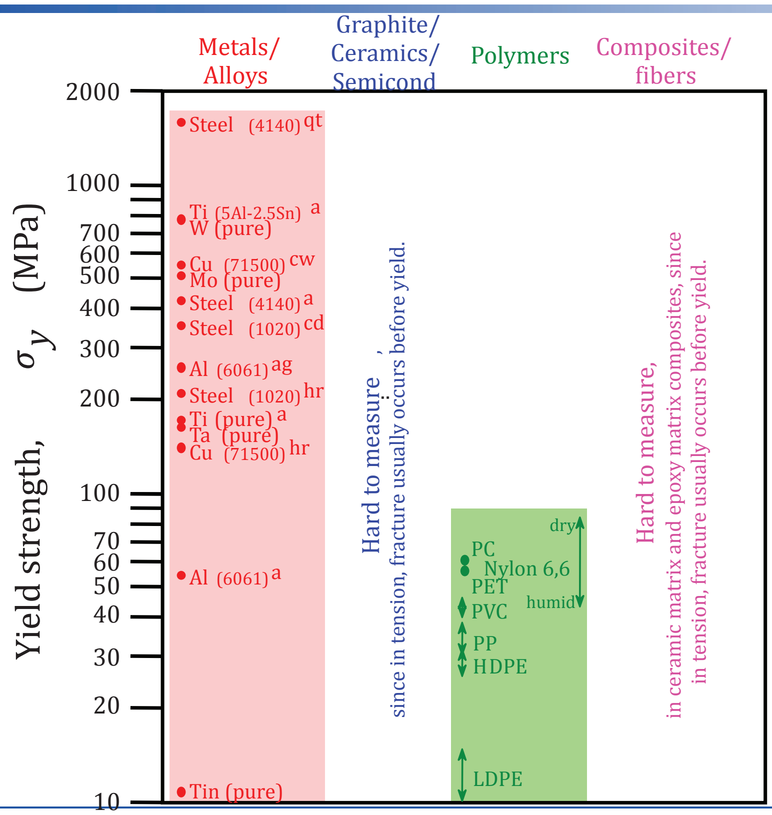
Adapted from Fig. 8.10 (a), *Callister & Rethwisch 9e.*

- **von Mises yield criterion: the yielding of materials begins when the second deviatoric stress invariant J_2 reaches a critical value.**



$$\sigma_v = \sqrt{\frac{3}{2}\sum_{i=}^{3}\sum_{j=}^{3}\sigma'_{ij}\sigma'_{ij}} = \sqrt{\frac{1}{2}\left[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2\right]}$$

Yield Strength: Comparison



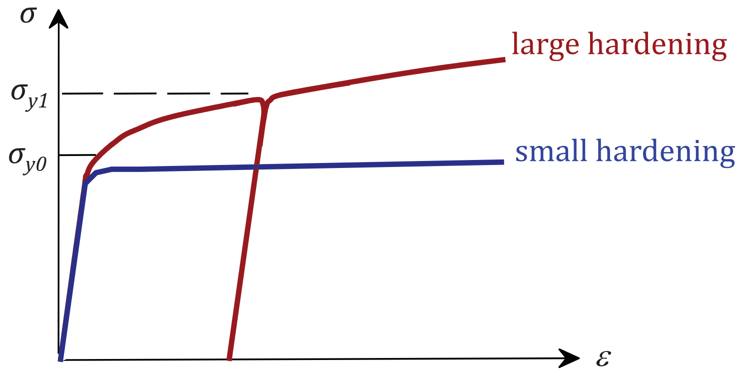
Room temperature values

Based on data in Table B.4, *Callister & Rethwisch 9e.*

a = annealed
hr = hot rolled
ag = aged
cd = cold drawn
cw = cold worked
qt = quenched & tempered

Work Hardening or Strain Hardening

- An increase in σ_y due to plastic deformation.



- Curve fit to the stress-strain response:

$$\sigma_T = K(\varepsilon_T)^n$$

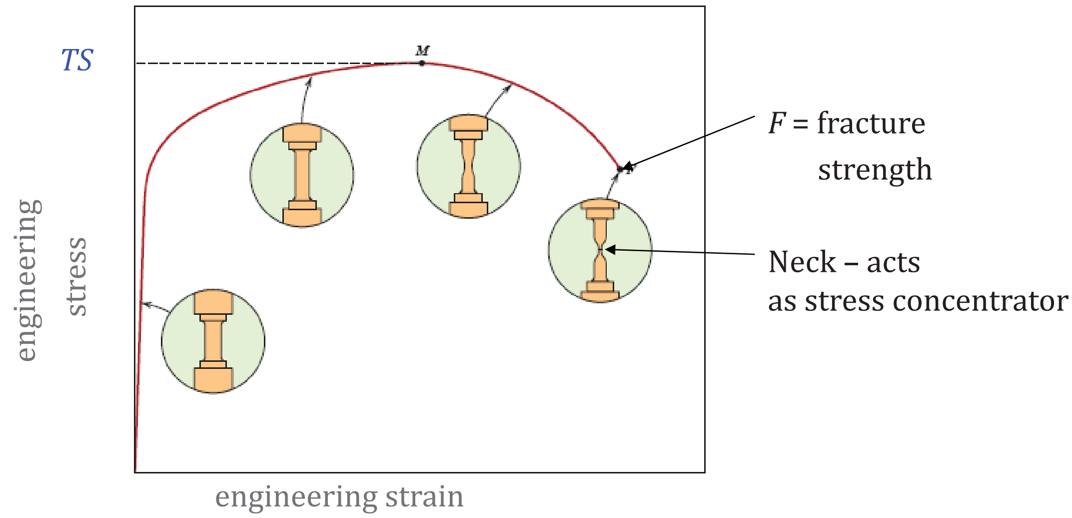
"true" stress (F/A)

"true" strain: $\ln(l/l_o)$

hardening exponent:
$n =$ 0.15 (some steels)
to $n =$ 0.5 (some coppers)

Tensile Strength (Ultimate Strength)

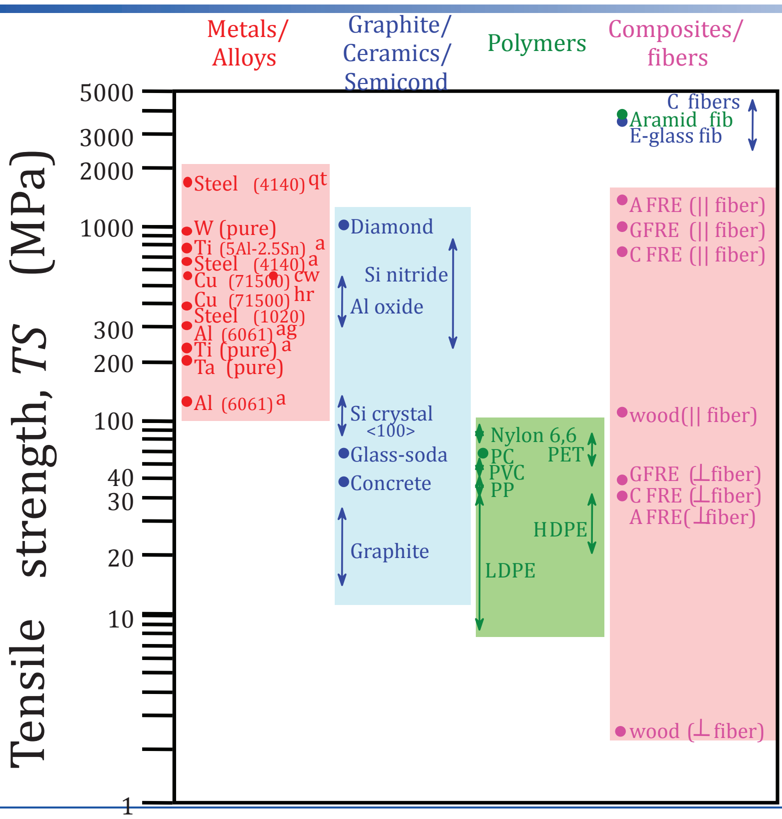
- Maximum stress on engineering stress-strain curve.



Adapted from Fig. 8.11, *Callister & Rethwisch 9e.*

- Metals: occurs when noticeable necking starts.
- Polymers: occurs when polymer backbone chains are aligned and about to break.

Tensile Strength: Comparison



Room temperature values

Based on data in Table B4, *Callister & Rethwisch 9e.*

a = annealed
hr = hot rolled
ag = aged
cd = cold drawn
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qt = quenched & tempered

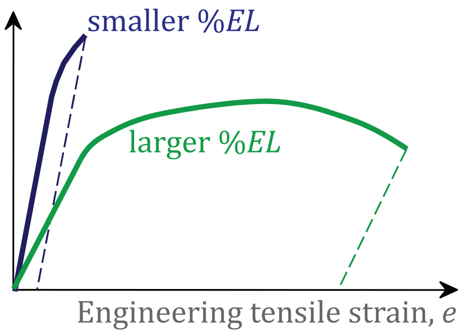
AFRE, GFRE, & CFRE = aramid, glass, & carbon fiber-reinforced epoxy composites, with 60 vol% fibers.

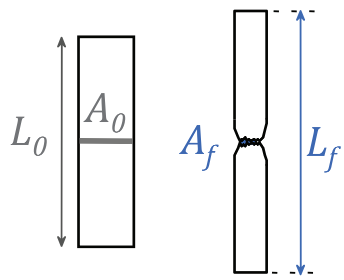
Ductility

- Percent elongation: Plastic tensile strain at failure:

$$\%EL = \frac{L_f - L_0}{L_0} \times 100$$

Engineering tensile stress, σ





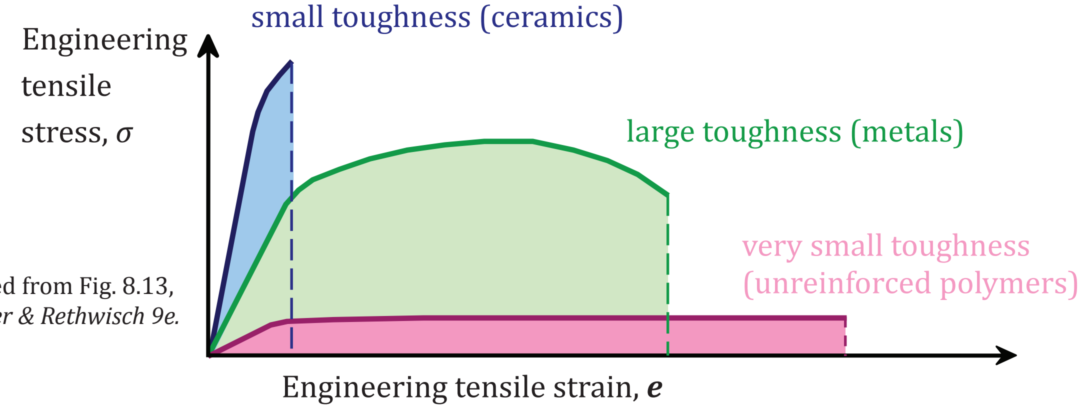
Adapted from Fig. 8.13, *Callister & Rethwisch 9e.*

- Percent reduction in area: Another ductility measure:

$$\%RA = \frac{A_0 - A_f}{A_0} \times 100$$

Toughness

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



Adapted from Fig. 8.13, *Callister & Rethwisch 9e.*

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

Elastic Energy Density & True Stress & Strain

- **Elastic Energy Density (Resilience)**
  - Ability of a material to store energy
  - Energy stored best in elastic region

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

  - If we assume a linear stress-strain curve this simplifies to

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

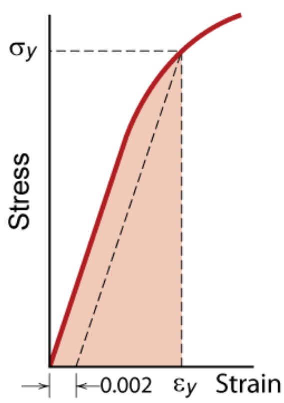
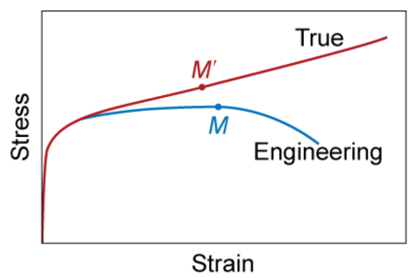


Fig. 8.15, *Callister & Rethwisch 9e.*

- **True Stress & Strain**
  - Sample area changes when sample stretched.
  - True stress: $\sigma_T = F/A_i$
  - True strain: $\varepsilon_T = \ln(\ell_i/\ell_o)$

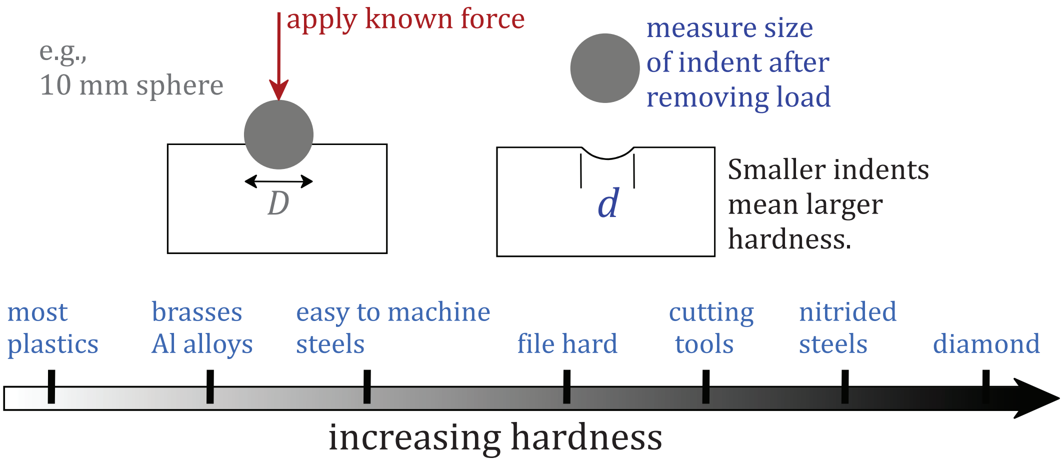
$$\sigma_T = \sigma(1+\varepsilon)$$
$$\varepsilon_T = \ln(1+\varepsilon)$$



Adapted from Fig. 8.16, *Callister & Rethwisch 9e.*

Hardness

- Resistance to permanently indenting the surface.
- Hardness measurement: simple, inexpensive, nondestructive
- Large hardness means:
  - resistance to plastic deformation or cracking in compression.
  - better wear properties.



Hardness Measurement

Table 8.5 Hardness-Testing Techniques

Test	*Indenter*	*Shape of Indentation* — *Side View*	*Shape of Indentation* — *Top View*	*Load*	*Formula for Hardness Number*[a]
Brinell	10-mm sphere of steel or tungsten carbide	D, d	d	P	$HB = \frac{2P}{\pi D[D - \sqrt{D^2 - d^2}]}$
Vickers microhardness	Diamond pyramid	136°	d_1, d_1	P	$HV = 1.854P/d_1^2$
Knoop microhardness	Diamond pyramid	t; $l/b = 7.11$, $b/t = 4.00$	b, l	P	$HK = 14.2P/l^2$
Rockwell and superficial Rockwell	Diamond cone: 1.588, 3.175, 6.350, and 12.70 mm diameter steel spheres	120°		60 kg, 100 kg, 150 kg } Rockwell; 15 kg, 30 kg, 45 kg } Superficial Rockwell	

[a]For the hardness formulas given, P (the applied load) is in kg, and D, d, d_1, and l are all in millimeters.

Source: Adapted from H. W. Hayden, W. G. Moffatt, and J. Wulff, *The Structure and Properties of Materials*, Vol. III, *Mechanical Behavior*. Copyright © 1965 by John Wiley & Sons, New York.

Design or Safety Factors

- Design uncertainties mean we do not push the limit.
- Factor of safety, N

$$\sigma_w = \frac{\sigma_y}{N}$$

Often N is between 1.2 and 4

- Example: Calculate a diameter, d, to ensure that yield does not occur in the 1045 carbon steel rod below. Use a factor of safety of 5.

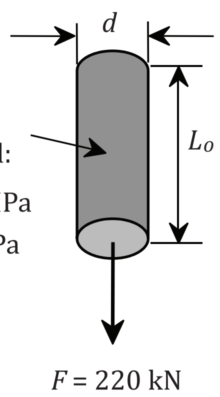
$$\sigma_{working} = \frac{\sigma_y}{N}$$

$\sigma_{working} = \frac{220 \text{ kN}}{\pi(d^2/4)}$, $N = 5$

1045 plain carbon steel:

σ_y = 310 MPa

TS = 565 MPa



$$\therefore d = 0.067 \text{ m} = 6.7 \text{ cm}$$