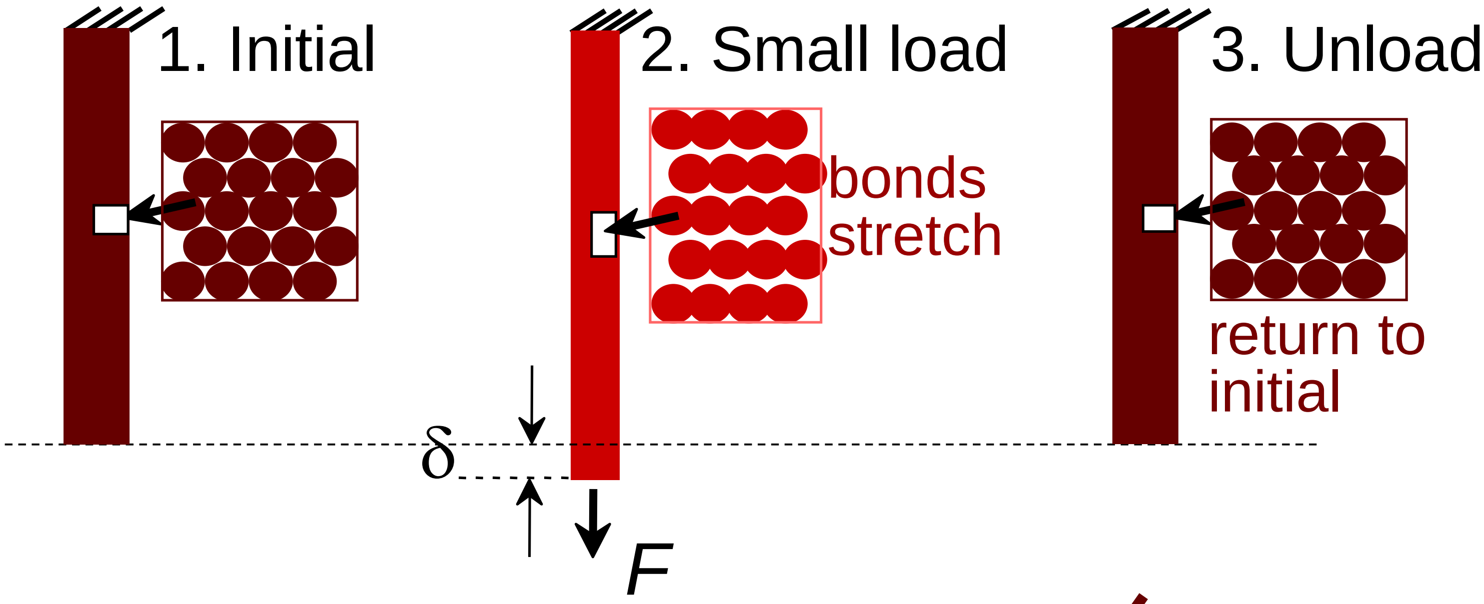
Mechanical Properties

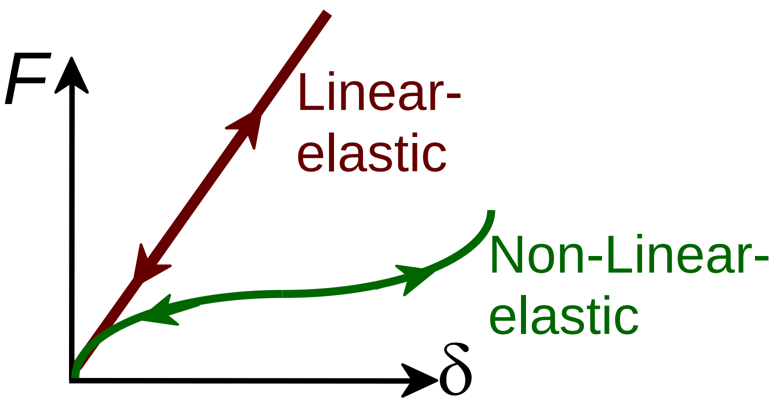
ISSUES TO COVERED

- 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?

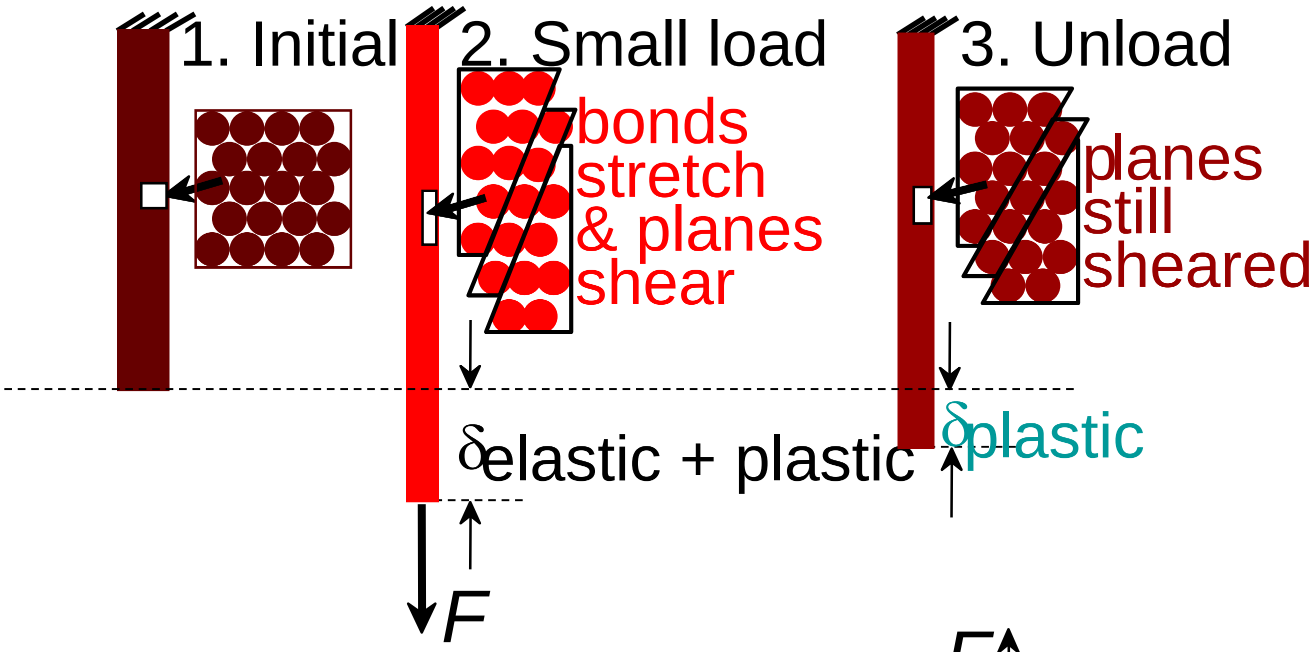
Elastic Deformation



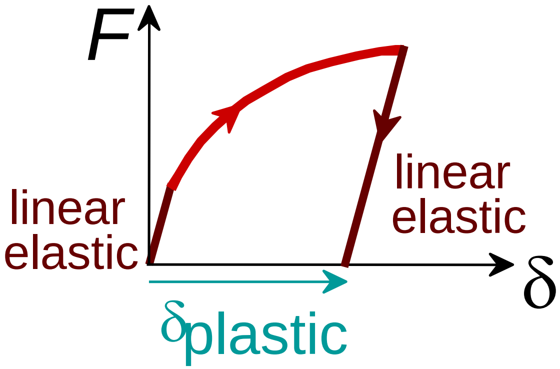
Elastic means reversible!



Plastic Deformation (Metals)

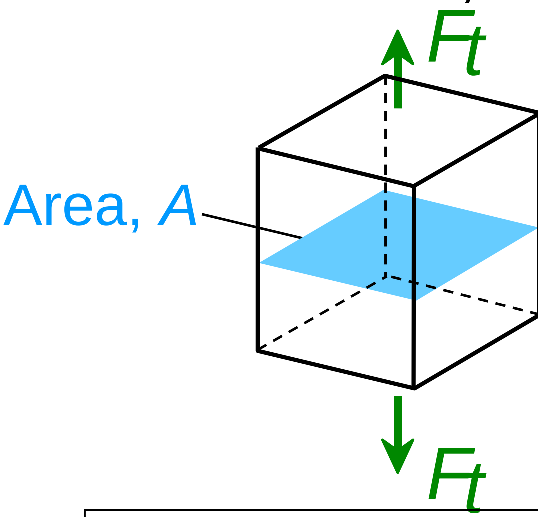


Plastic means permanent!



Engineering Stress

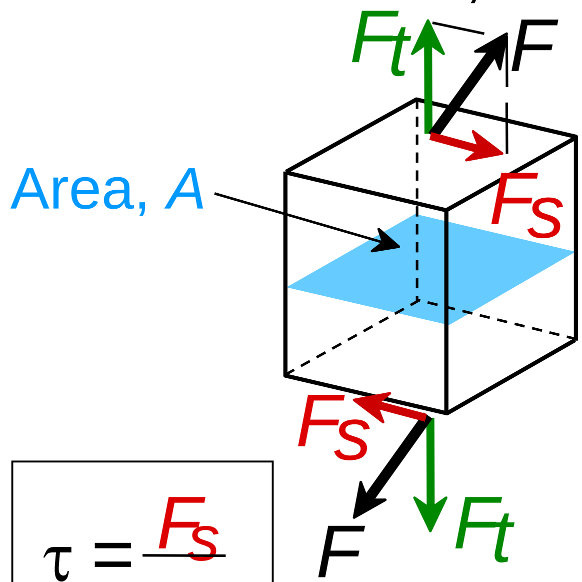
- Tensile stress, σ:



$$\sigma = \frac{F_t}{A_o} = \frac{lb_f}{in^2} \text{ or } \frac{N}{m^2}$$

original area before loading

- Shear stress, τ:

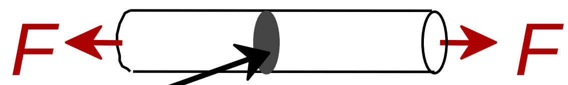


$$\tau = \frac{F_s}{A_o}$$

∴ Stress has units: N/m^2 or $lb_f/in2$

Common States of Stress

- **Simple tension: cable**

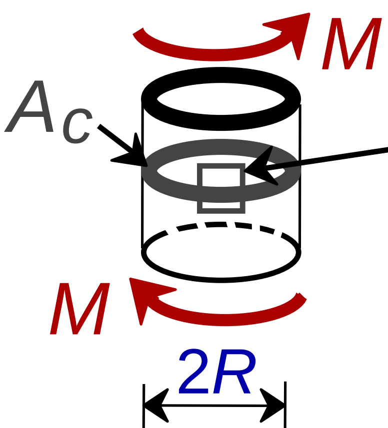


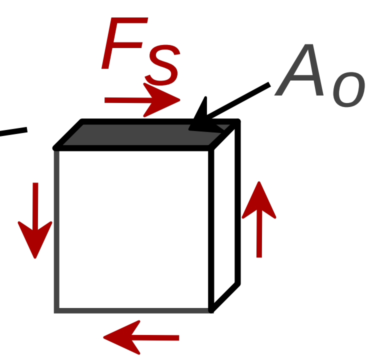
A_o = cross sectional area (when unloaded)

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

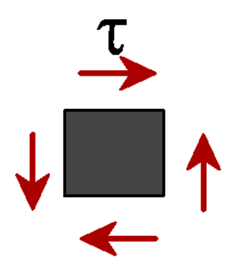
Ski lift (photo courtesy P.M. Anderson)

- **Torsion (a form of shear): drive shaft**





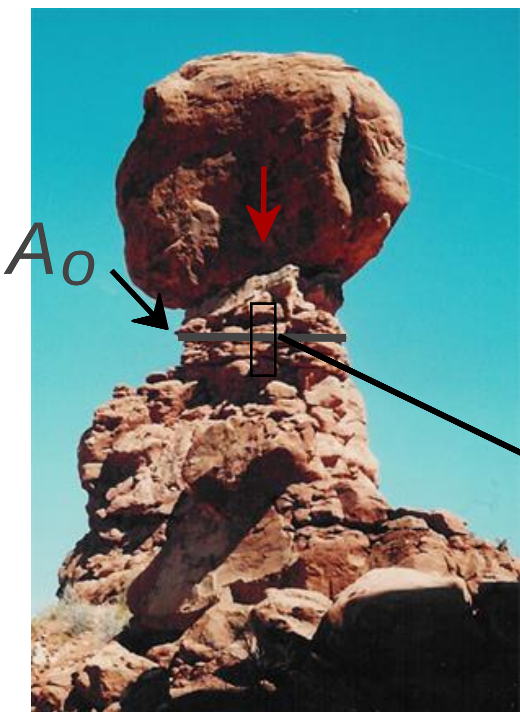
$$\tau = \frac{F_s}{A_o}$$



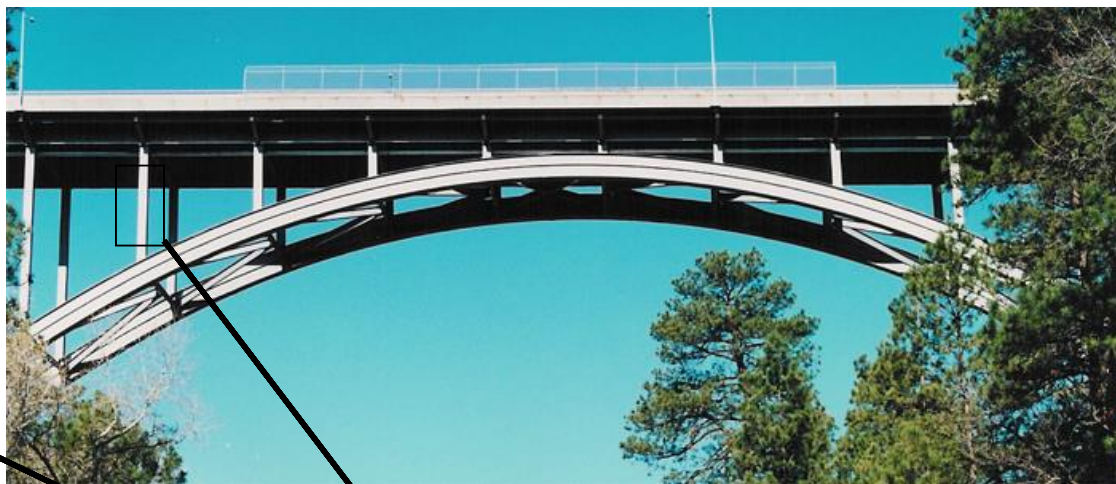
Note: $\tau = M/A_cR$ here.

OTHER COMMON STRESS STATES (1)

Simple compression:

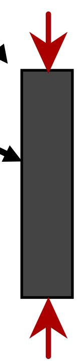


Balanced Rock, Arches National Park
(photo courtesy P.M. Anderson)



Canyon Bridge, Los Alamos, NM
(photo courtesy P.M. Anderson)

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

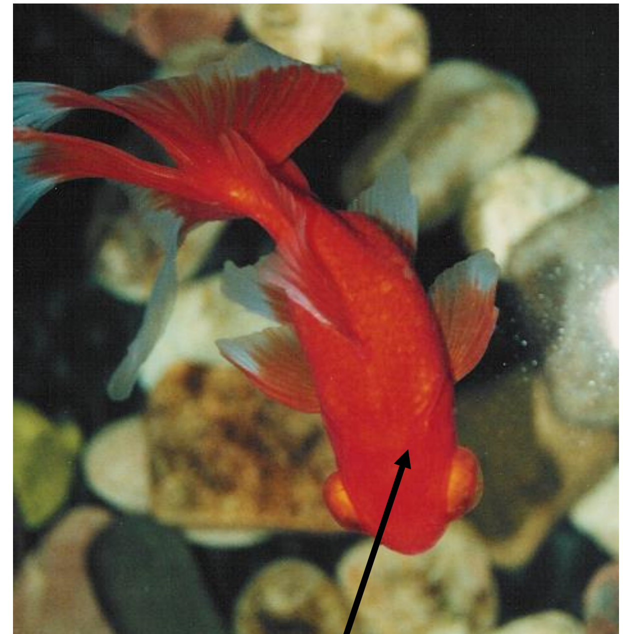


Note: compressive structure member ($\sigma < 0$ here).

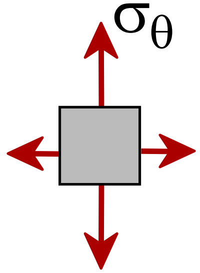
OTHER COMMON STRESS STATES (2)

- **Bi-axial tension:**
- **Hydrostatic compression:**

Pressurized tank
(photo courtesy P.M. Anderson)

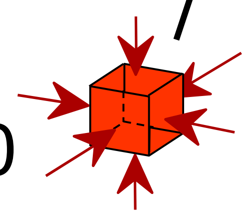


Fish under water
(photo courtesy P.M. Anderson)



$\sigma_\theta > 0$

$\sigma_z > 0$

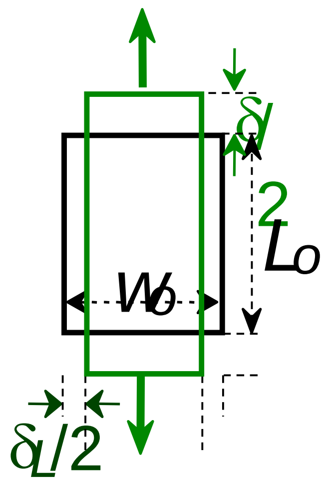


$\sigma_h < 0$

Engineering Strain

- **Tensile strain:**

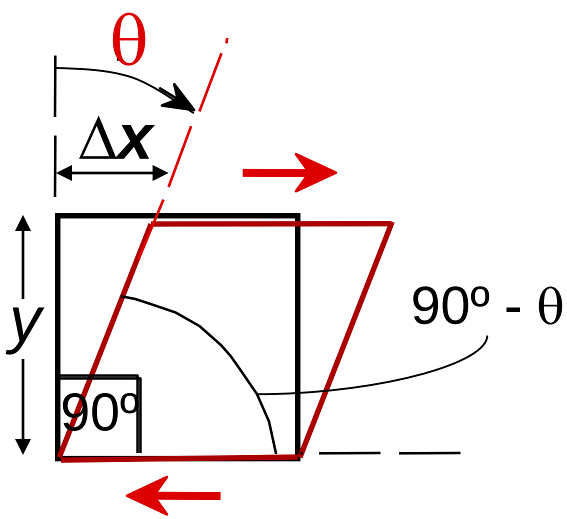
$$\varepsilon = \frac{\delta}{L_o}$$



- **Lateral strain:**

$$\varepsilon_L = -\frac{\delta_L}{w_o}$$

- **Shear strain:**



$$\gamma = \Delta x / y = \tan\ \theta$$

Strain is always dimensionless.

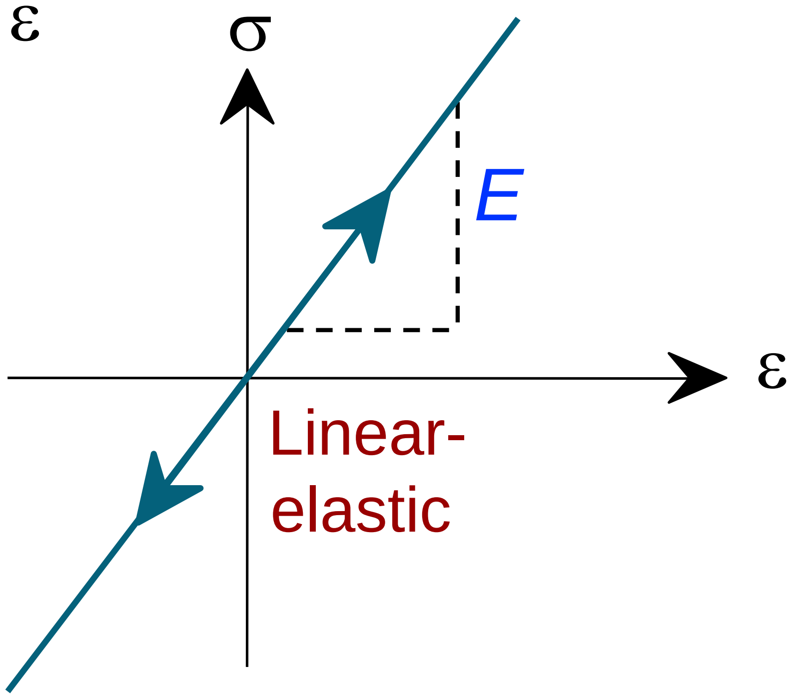
Adapted from Fig. 6.1 (a) and (c), *Callister 7e.*

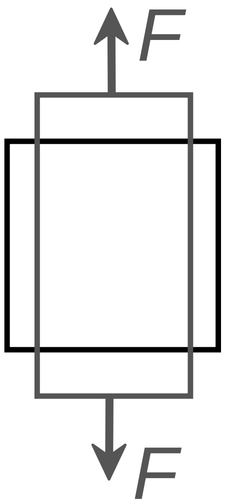
Linear Elastic Properties

- **Modulus of Elasticity, *E*:**
  (also known as Young's modulus)

- **Hooke's Law:**

$$\sigma = E\,\varepsilon$$





EXAMPLE PROBLEM 6.1

- A piece of copper originally **305mm** (12 in.) long is pulled in tension with a stress of **276MPa** (40,000psi). If the deformation is entirely elastic, what will be the resultant elongation?

$$\sigma = \epsilon E = \left(\frac{\Delta l}{l_0}\right) E$$

$$\Delta l = \frac{\sigma l_0}{E}$$

- Magnitude of *E* for copper from Table 6.1 is 110 GPa

$$\Delta l = \frac{(276 \text{ MPa})(305 \text{ mm})}{110 \times 10^3 \text{ MPa}} = 0.77 \text{ mm } (0.03 \text{ in.})$$

EXAMPLE PROBLEM 6.2

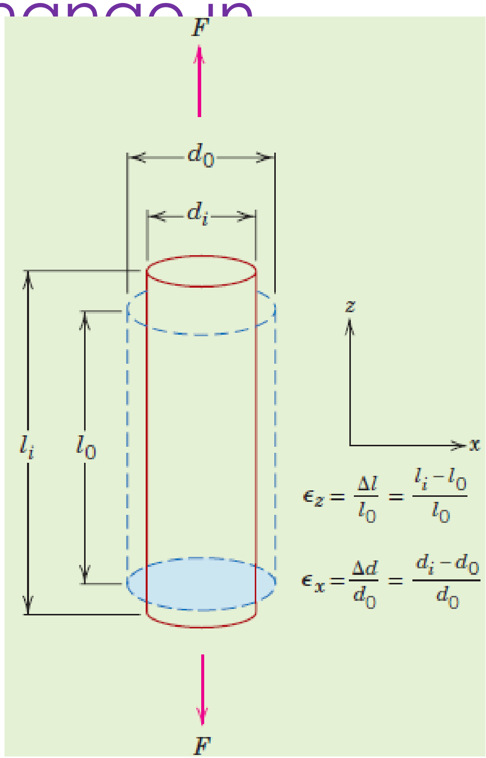
- A tensile stress is to be applied along the long axis of a cylindrical brass rod that has a diameter of **10mm**. Determine the magnitude of the load required to produce a **0.0025mm** change in diameter if the deformation is entire

For the strain in the x direction:

$$\epsilon_x = \frac{\Delta d}{d_0} = \frac{-2.5 \times 10^{-3}\ \text{mm}}{10\ \text{mm}} = -2.5 \times 10^{-4}$$

$$\epsilon_z = -\frac{\epsilon_x}{\nu} = -\frac{(-2.5 \times 10^{-4})}{0.34} = 7.35 \times 10^{-4}$$

$$\sigma = \epsilon_z E = (7.35 \times 10^{-4})(97 \times 10^3\ \text{MPa}) = 71.3\ \text{MPa}$$



EXAMPLE PROBLEM 6.2

$$F = \sigma A_0 = \sigma\left(\frac{d_0}{2}\right)^2 \pi$$

$$= (71.3 \times 10^6\ \text{N/m}^2)\left(\frac{10 \times 10^{-3}\ \text{m}}{2}\right)^2 \pi = 5600\ \text{N}$$

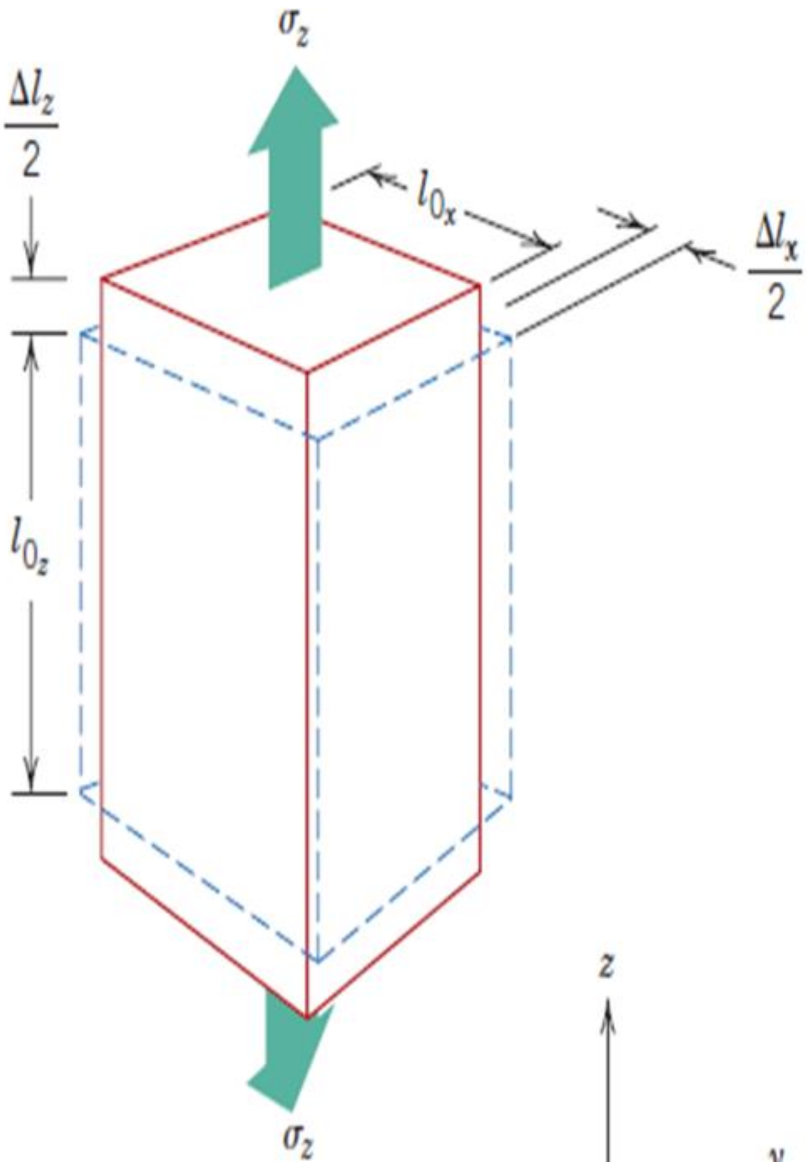
Poisson's ratio, ν

- **Poisson's ratio, ν**:is defined as the ratio of the lateral and axial strains

$$\nu = -\frac{\epsilon_x}{\epsilon_z} = -\frac{\epsilon_y}{\epsilon_z}$$

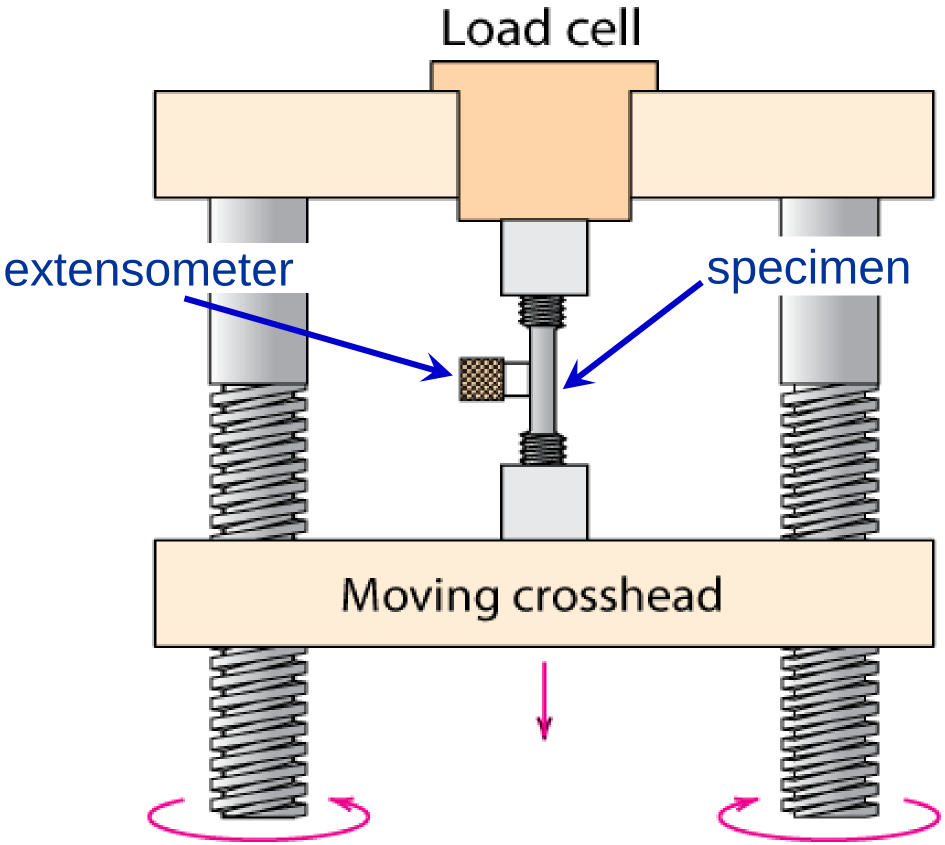
metals: ν ~ 0.33
ceramics: ν ~ 0.25
polymers: ν ~ 0.40

Units:
E: [GPa] or [psi]
ν: dimensionless



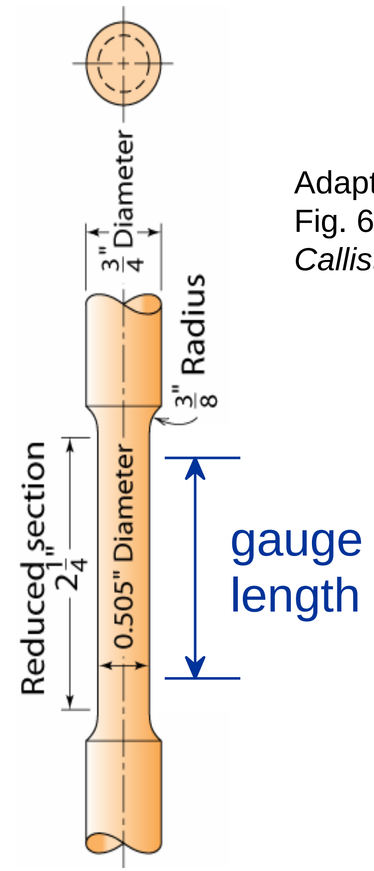
Stress-Strain Testing

- **Typical tensile test machine**



Adapted from Fig. 6.3, *Callister 7e.* (Fig. 6.3 is taken from H.W. Hayden, W.G. Moffatt, and J. Wulff, *The Structure and Properties of Materials*, Vol. III, *Mechanical Behavior*, p. 2, John Wiley and Sons, New York, 1965.)

- **Typical tensile specimen**

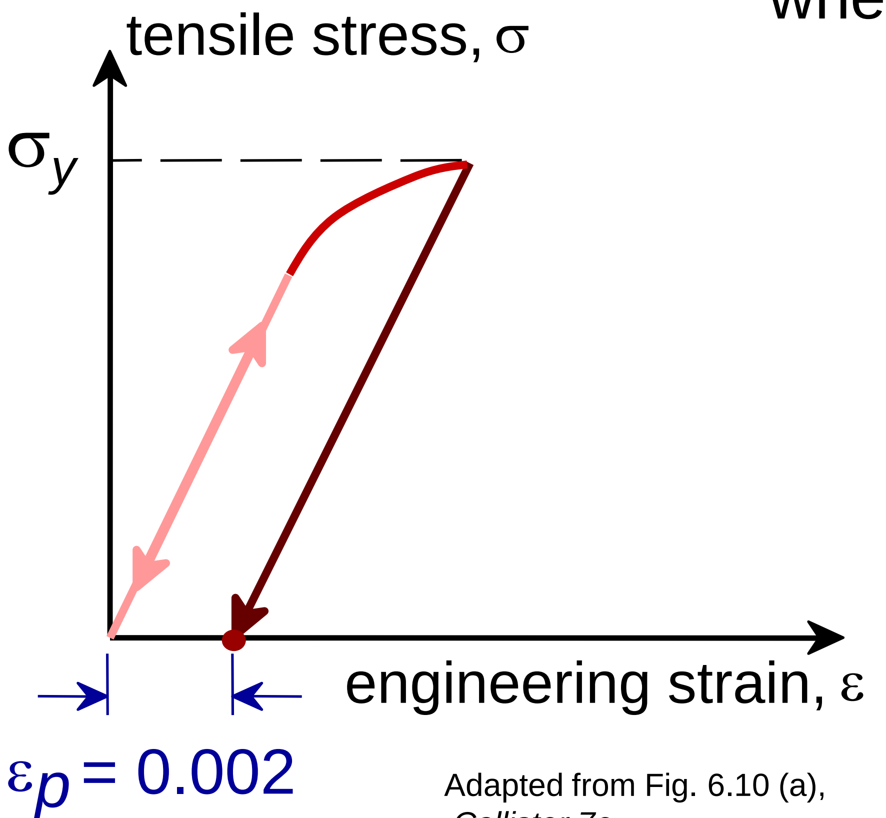


Adapted from Fig. 6.2, *Callister 7e.*

Yield Strength, σ_y

- **Stress at which *noticeable* plastic deformation has occurred.**

when $\varepsilon_p = 0.002$



Adapted from Fig. 6.10 (a), *Callister 7e.*

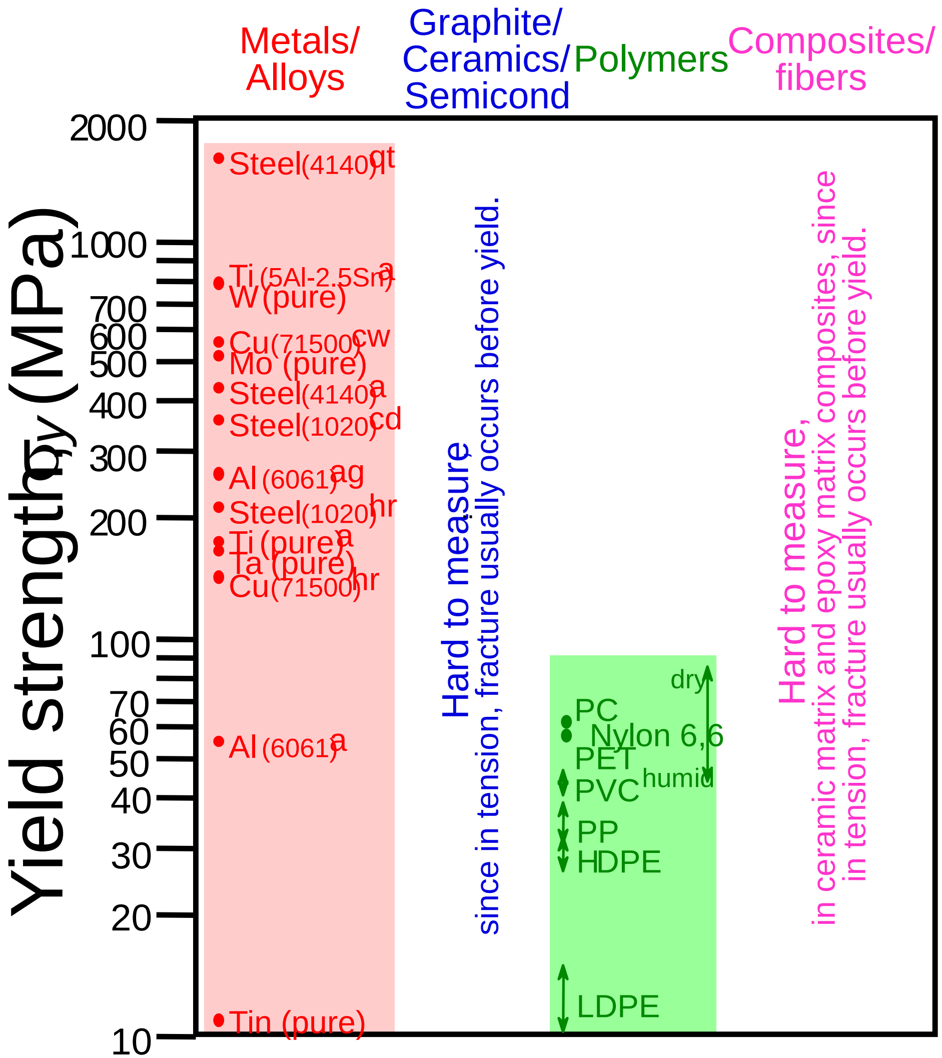
σ_y = yield strength

Note: for 2 inch sample

$\varepsilon = 0.002 = \Delta z/z$

$\therefore\ \Delta z = 0.004$ in

Yield Strength : Comparison



Room T values

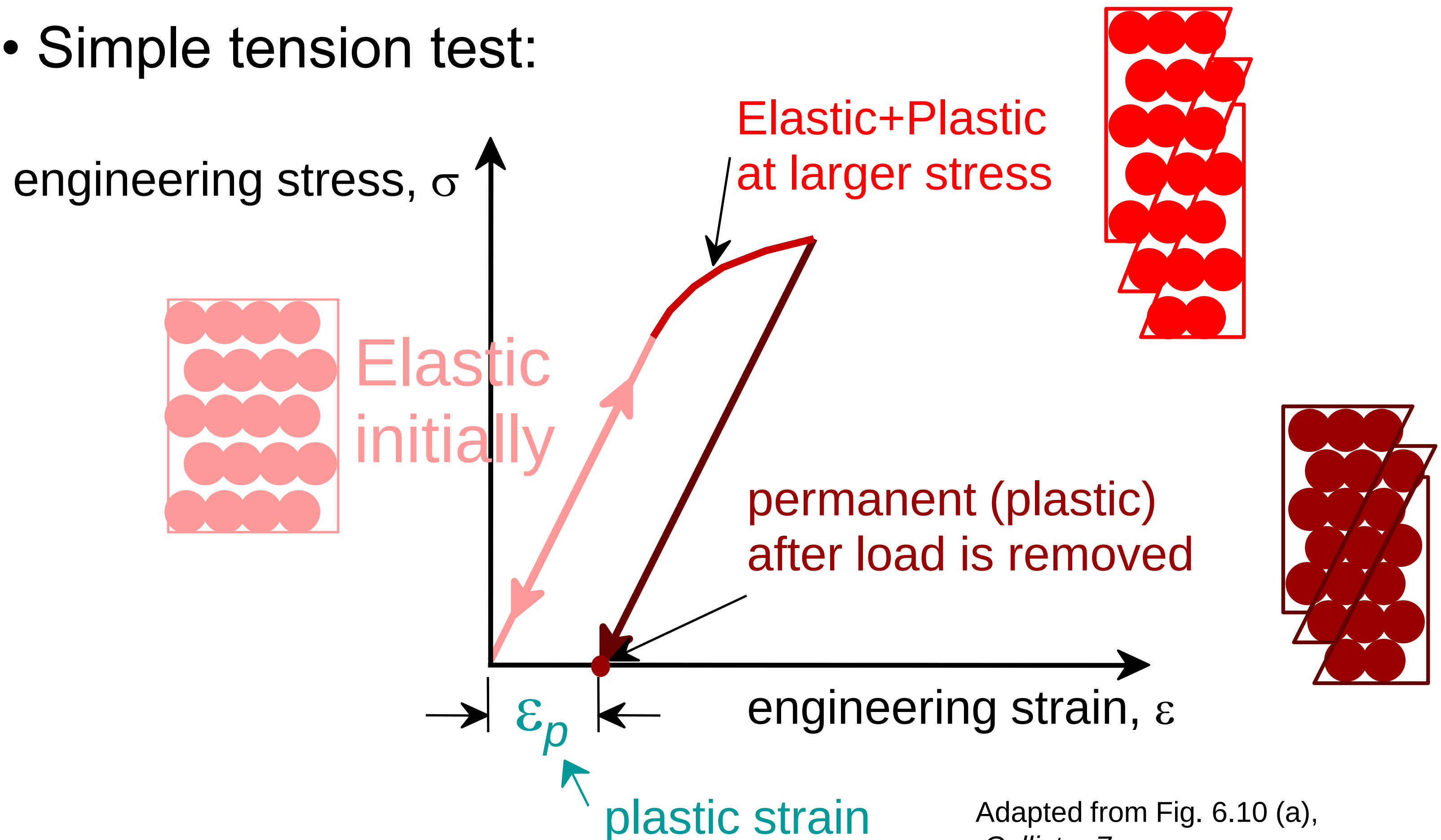
Based on data in Table B4, *Callister 7e*.

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

Plastic (Permanent) Deformation

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

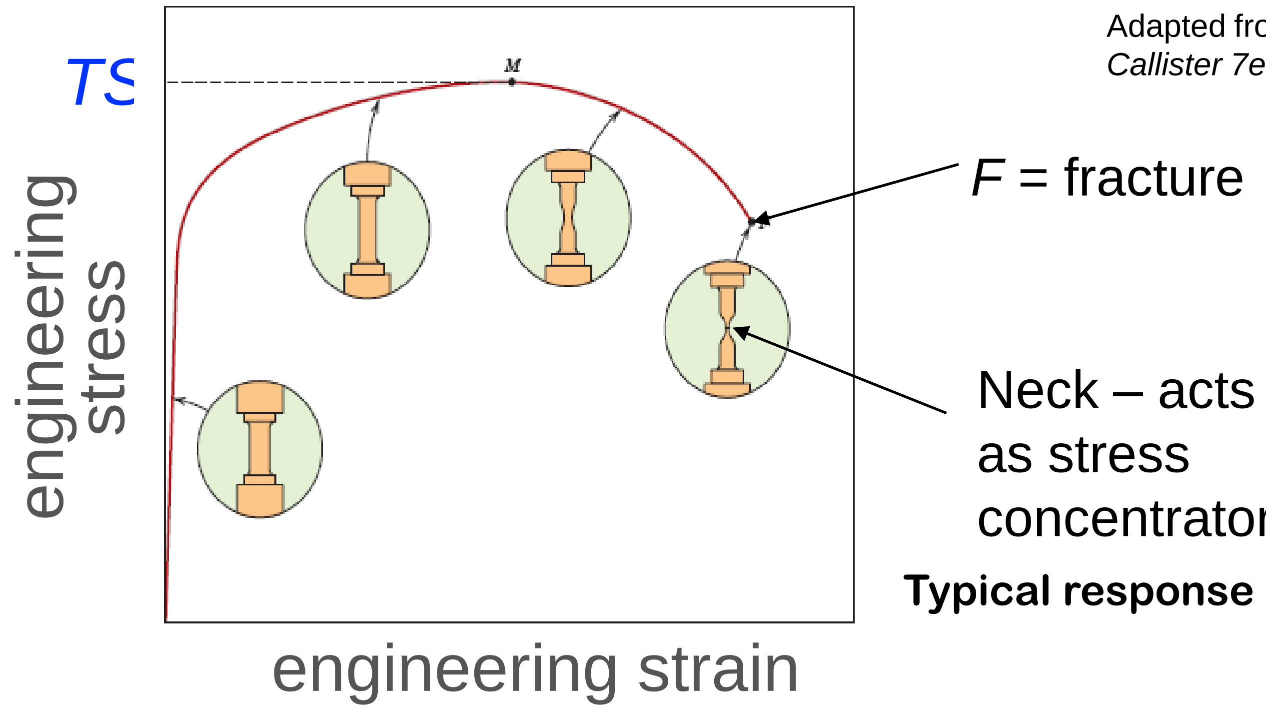
- Simple tension test:



Adapted from Fig. 6.10 (a), *Callister 7e.*

Tensile Strength, TS

- Maximum stress on engineering stress-strain curve.

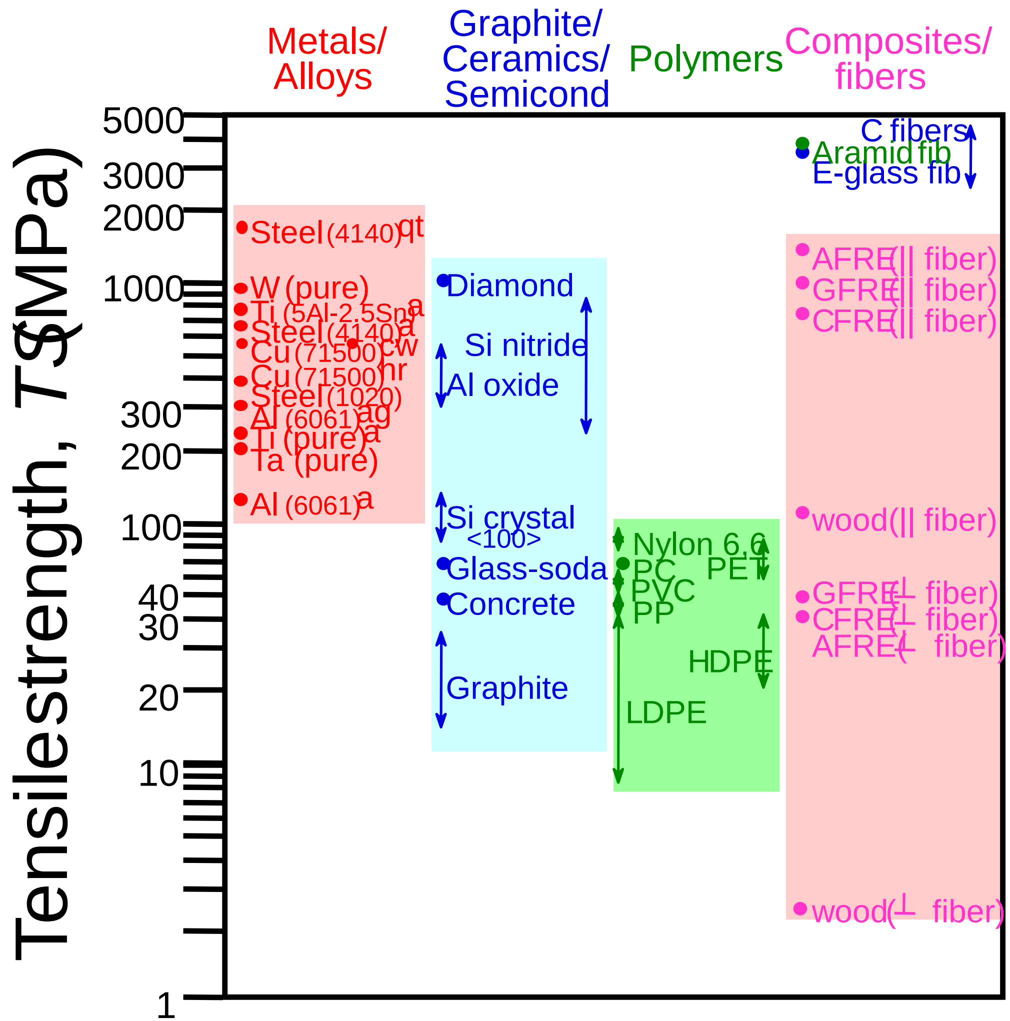


Adapted from Fig. 6.11, *Callister 7e.*

Typical response of a metal

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

Tensile Strength : Comparison



Room Temp. values

Based on data in Table B4, *Callister 7e*.

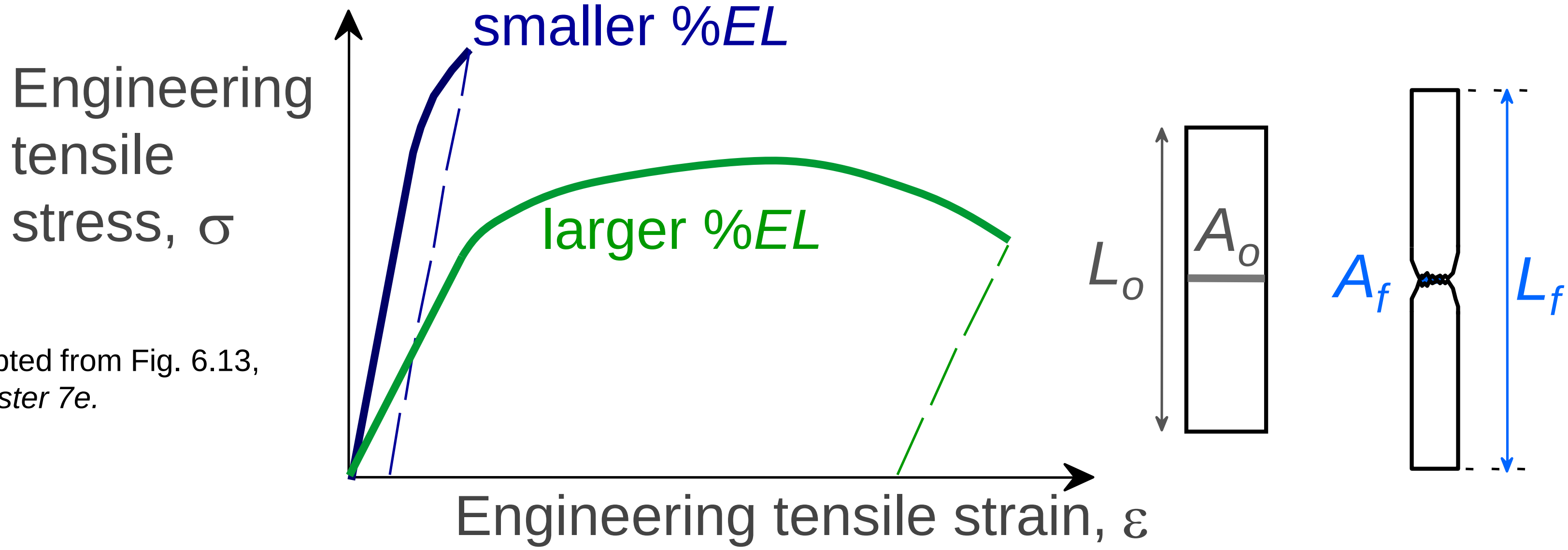
a = annealed
hr = hot rolled
ag = aged
cd = cold drawn
cw = cold worked
qt = quenched & tempered

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

Ductility

- Plastic tensile strain at failure:

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



Adapted from Fig. 6.13, *Callister 7e.*

- Another ductility measure:

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

EXAMPLE PROBLEM 6.3

- A cylindrical specimen of steel having an original diameter of **12.8mm** is tensile tested to fracture and found to have an engineering fracture strength $\boldsymbol{\sigma_f}$ of **460MPa**. If its cross-sectional diameter at fracture is **10.7mm**, determine:

(a) The ductility in terms of percent reduction in area

(b) The true stress at fracture

Ductility is computed as

$$\%\text{RA} = \frac{\left(\frac{12.8\text{ mm}}{2}\right)^2 \pi - \left(\frac{10.7\text{ mm}}{2}\right)^2 \pi}{\left(\frac{12.8\text{ mm}}{2}\right)^2 \pi} \times 100$$

$$= \frac{128.7\text{ mm}^2 - 89.9\text{ mm}^2}{128.7\text{ mm}^2} \times 100 = 30\%$$

EXAMPLE PROBLEM 6.3

True stress is defined by Equation $\sigma_T = \frac{F}{A_i}$

where the area is taken as the fracture area A_f

However, the load at fracture must first be computed from the fracture strength as

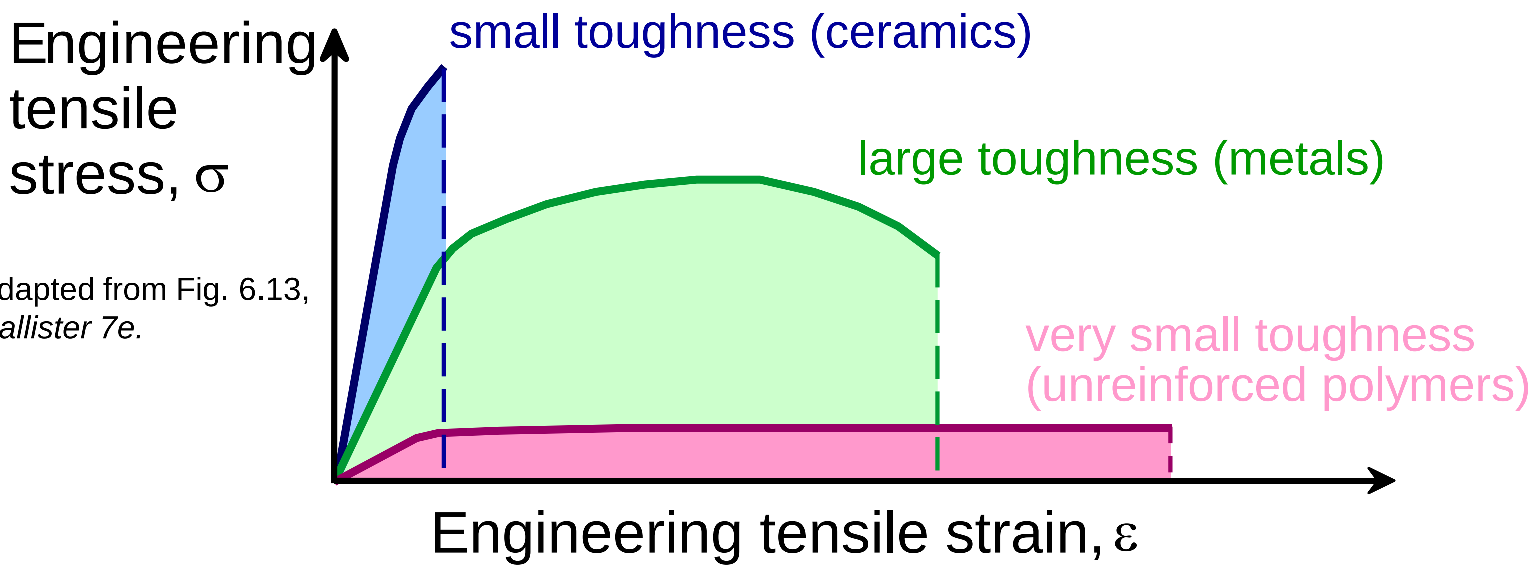
$$F = \sigma_f A_0 = (460 \times 10^6\ \text{N/m}^2)(128.7\ \text{mm}^2)\left(\frac{1\ \text{m}^2}{10^6\ \text{mm}^2}\right) = 59{,}200\ \text{N}$$

And the true stress is calculated as

$$\sigma_T = \frac{F}{A_f} = \frac{59{,}200\ \text{N}}{(89.9\ \text{mm}^2)\left(\frac{1\ \text{m}^2}{10^6\ \text{mm}^2}\right)} = 6.6 \times 10^8\ \text{N/m}^2 = 660\ \text{MPa}$$

Toughness

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



Adapted from Fig. 6.13, *Callister 7e.*

Brittle fracture: elastic energy

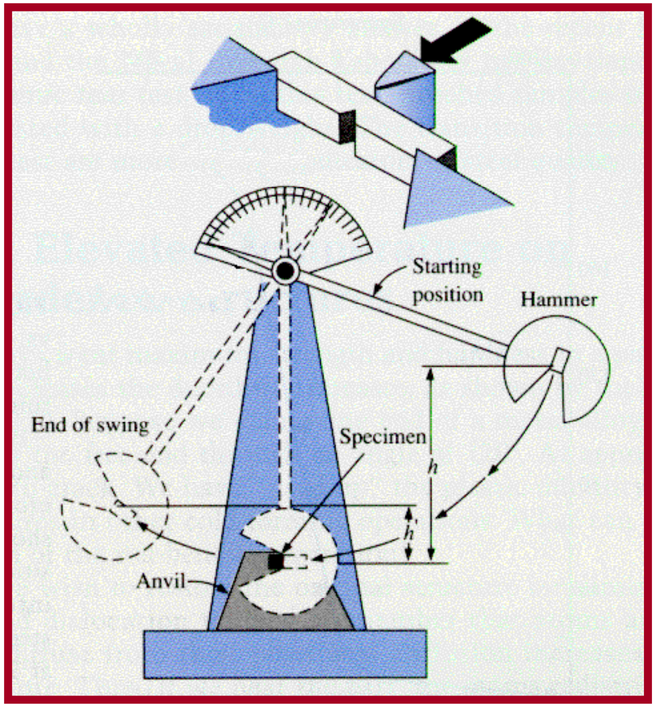
Ductile fracture: elastic + plastic energy

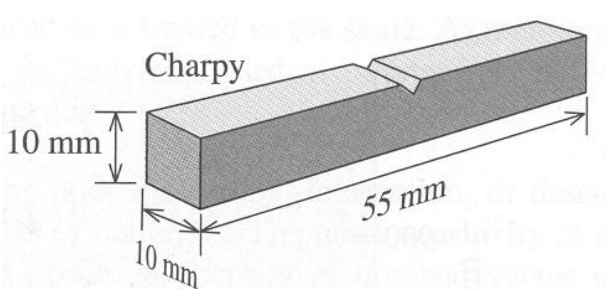
Impact Fracture Testing

In an impact test, a notched specimen is fractured by an impact blow, and the energy absorbed during the fracture is measured.

There are two types of tests – Charpy impact test and Izod impact test.

Impact Test: The Charpy Test

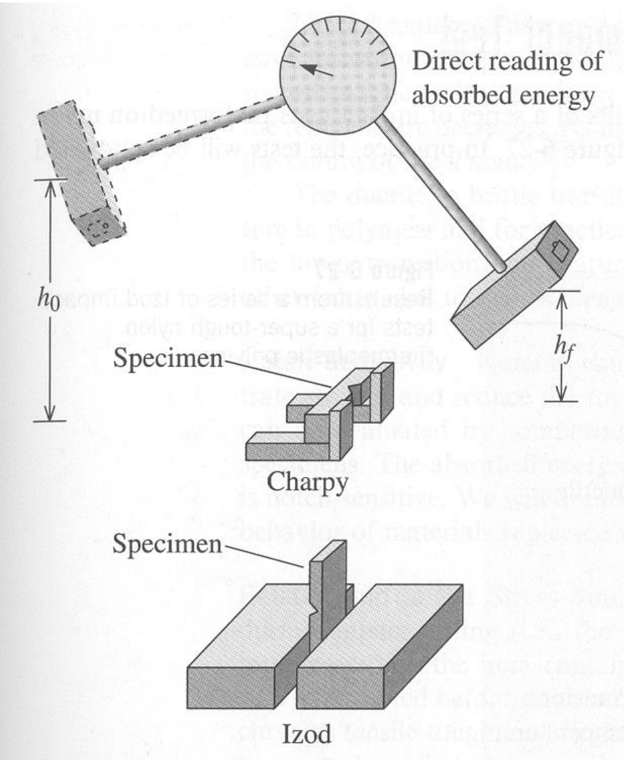


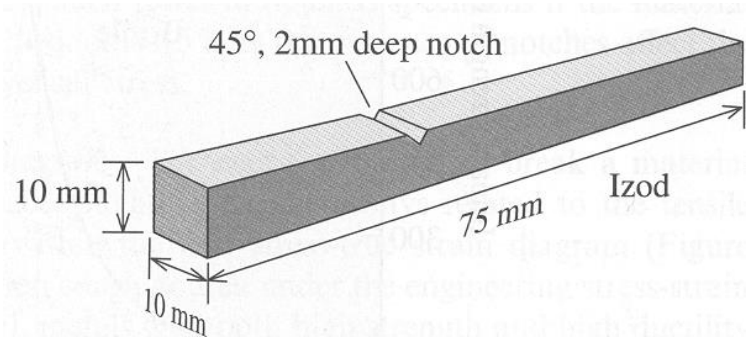


The ability of a material to withstand an impact blow is referred to as notch toughness.

The energy absorbed is the difference in height between initial and final position of the hammer. The material fractures at the notch and the structure of the cracked surface will help indicate whether it was a brittle or ductile fracture.

Impact Test: The Izod Test





Generally used for polymers. Izod test is different from the Charpy test in terms of the configuration of the notched test specimen

Impact Tests: Test conditions

- The FCC alloys→ generally ductile fracture mode

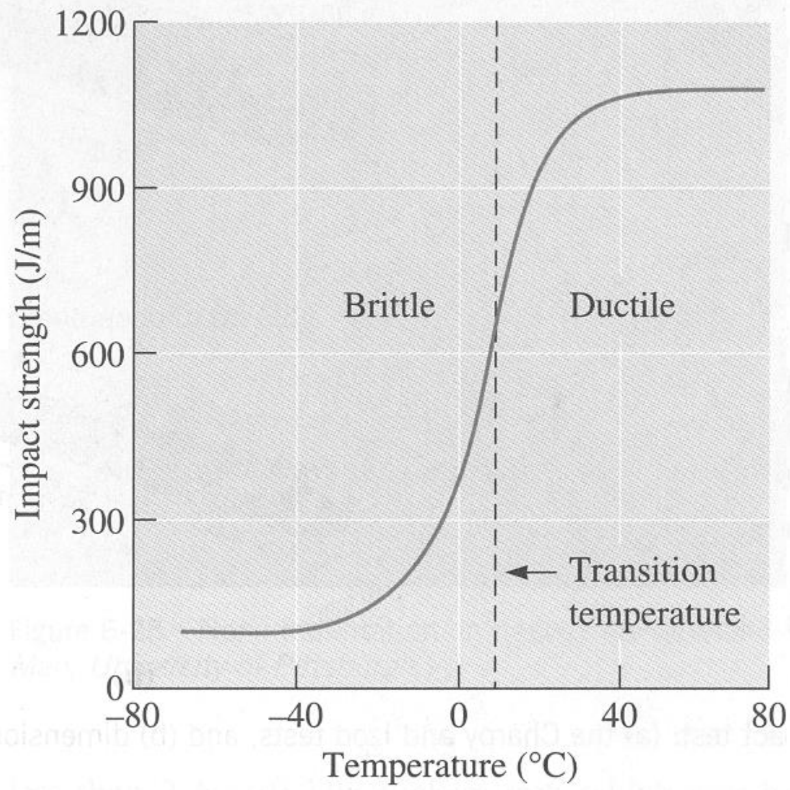
- The HCP alloys→ generally brittle fracture mode

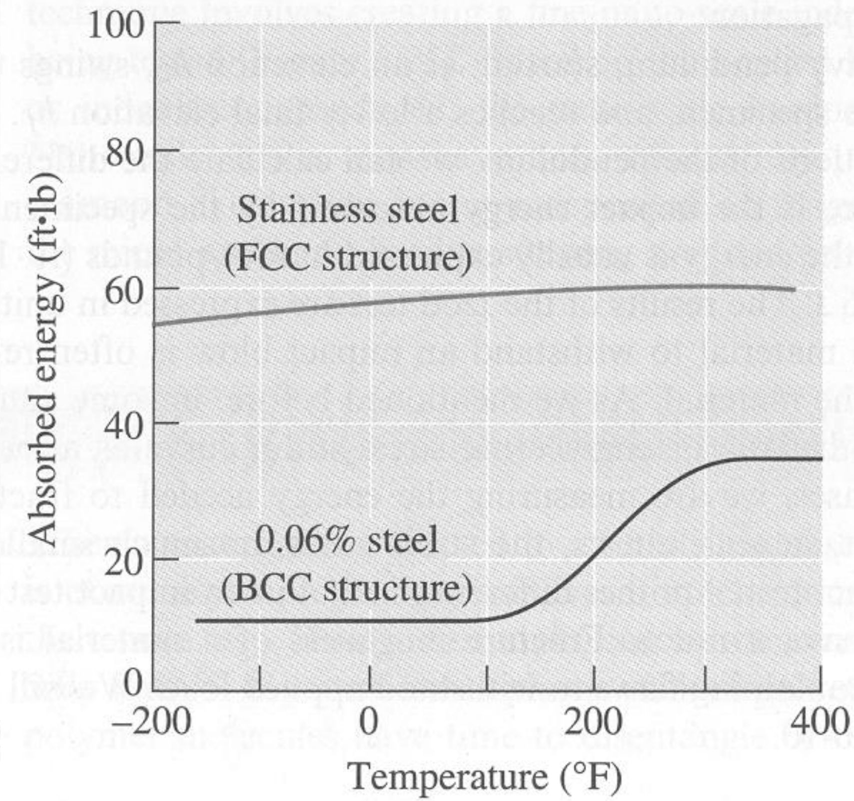
- Temperature is important
- The BCC alloys→ brittle modes at relatively low temperatures and ductile mode at relatively high temperature

Transition Temperatures

- **As temperature decreases a ductile material can become brittle - ductile-to-brittle transition**
  - **The transition temperature is the temp at which a material changes from ductile-to-brittle behavior**

Ductile to Brittle Transition



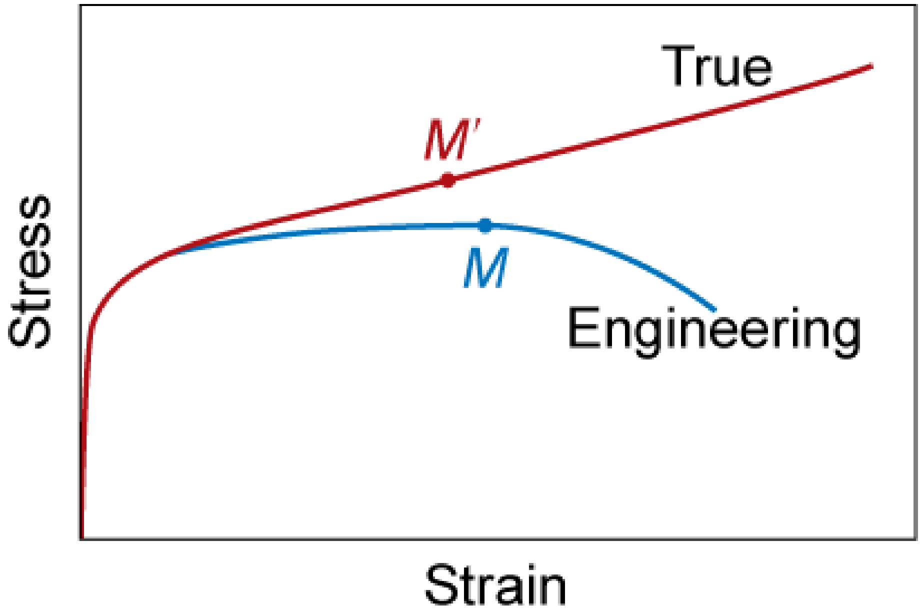


True Stress & Strain

Note: S.A. changes when sample stretched

- True stress $\sigma_T = F/A_i$
- True Strain $\varepsilon_T = \ln(\ell_i/\ell_o)$

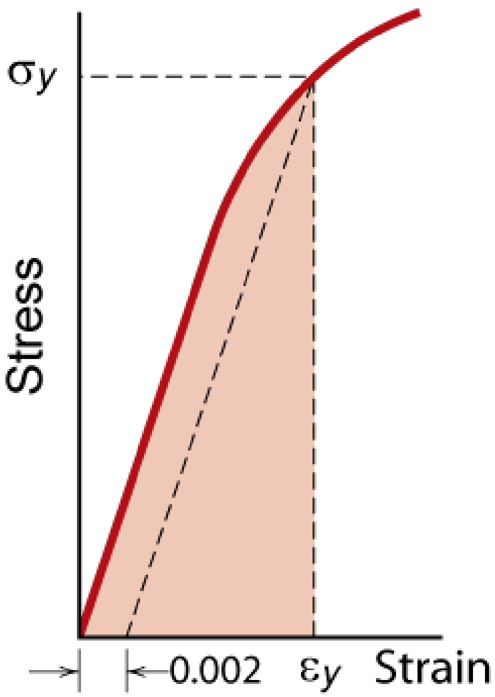
$$\sigma_T = \sigma(1+\varepsilon)$$
$$\varepsilon_T = \ln(1+\varepsilon)$$



Adapted from Fig. 6.16, *Callister 7e.*

Modulus of Resilience, U_R

- Ability of a material to store energy
- Energy stored best in elastic region



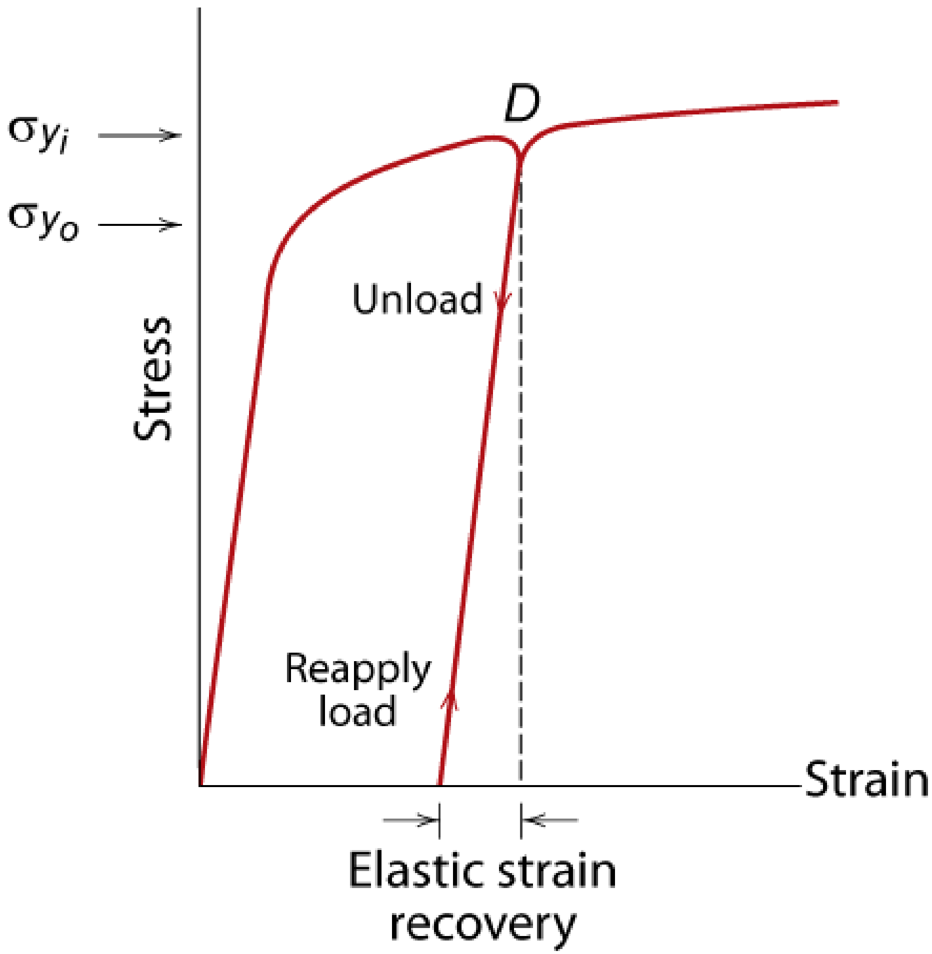
Adapted from Fig. 6.15, *Callister 7e.*

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

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

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

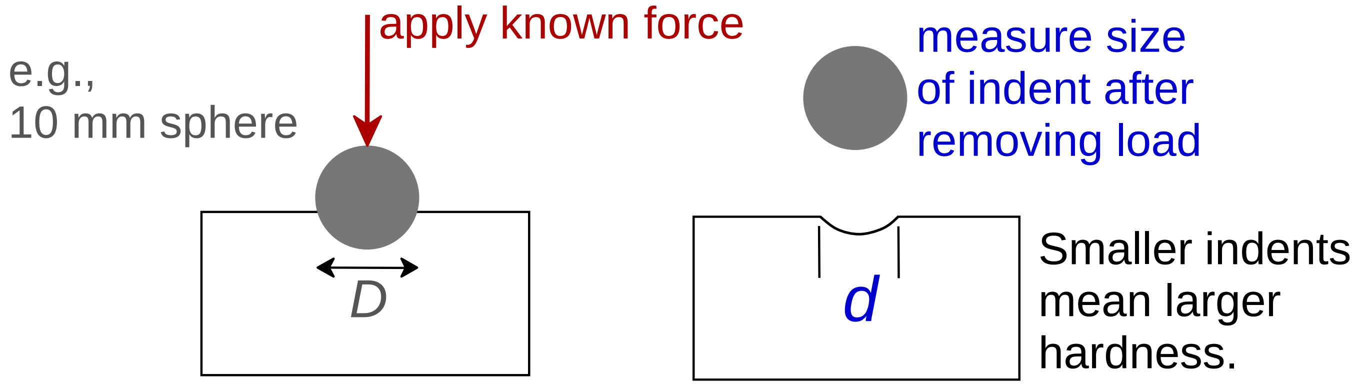
Elastic Strain Recovery

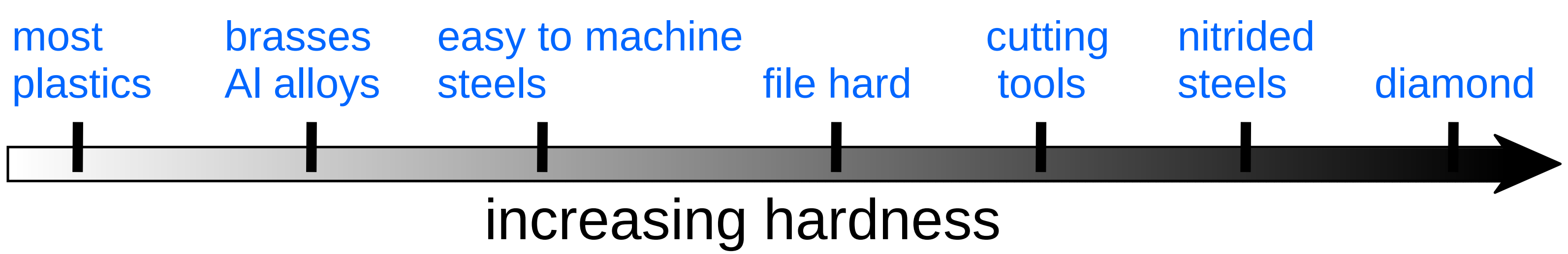


Adapted from Fig. 6.17, *Callister 7e.*

Hardness

- Resistance to permanently indenting the surface.
- Large hardness means:
  --resistance to plastic deformation or cracking in compression.
  --better wear properties.

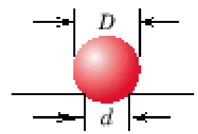
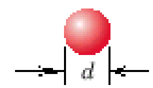
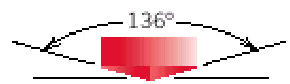
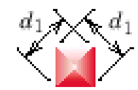
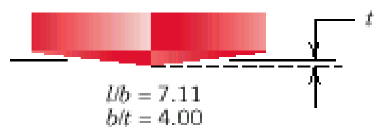
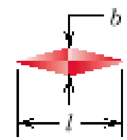
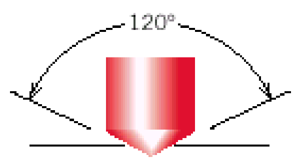
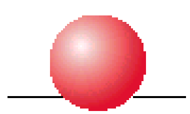
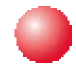
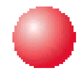




Hardness: Measurement

- Rockwell
  - No major sample damage
  - Each scale runs to 130 but only useful in range 20-100.
  - Minor load 10 kg
  - Major load 60 (A), 100 (B) & 150 (C) kg
    - A = diamond, B = 1/16 in. ball, C = diamond
- HB = Brinell Hardness
  - *TS* (psia) = 500 x HB
  - *TS* (MPa) = 3.45 x HB

Table 6.5 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			P	$HB = \frac{2P}{\pi D[D - \sqrt{D^2 - d^2}]}$
Vickers microhardness	Diamond pyramid			P	$HV = 1.854P/d_1^2$
Knoop microhardness	Diamond pyramid			P	$HK = 14.2P/l^2$
Rockwell and Superficial Rockwell	Diamond cone; $\frac{1}{16}, \frac{1}{8}, \frac{1}{4}, \frac{1}{2}$ in. diameter steel spheres	 	 	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, while D, d, d_1, and l are all in mm.

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. Reprinted by permission of John Wiley & Sons, Inc.

Hardness of Metals and Ceramics

Material	Vickers Hardness, HV	Knoop Hardness, HK
Hardened tool steel[a]	800	850
Cemented carbide (WC - Co)[a]	2000	1400
Alumina, Al_2O_3	2200	1500
Tungsten carbide, WC	2600	1900
Silicon carbide, SiC	2600	1900

Material	Vickers Hardness, HV	Knoop Hardness, HK
Titanium nitride, TiN	3000	2300
Titanium carbide, TiC	3200	2500
Cubic boron nitride, BN	6000	4000
Diamond, sintered polycrystal	7000	5000
Diamond, natural	10,000	8000

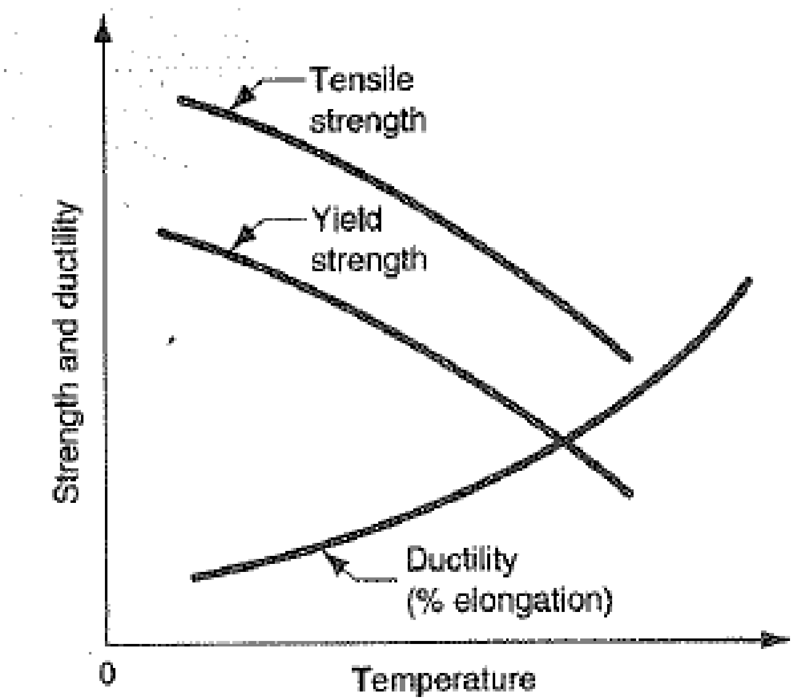
Hardness of Polymers

Polymer	Brinell Hardness, HB
Nylon	12
Phenol formaldehyde	50
Polyethylene, low density	2
Polyethylene, high density	4

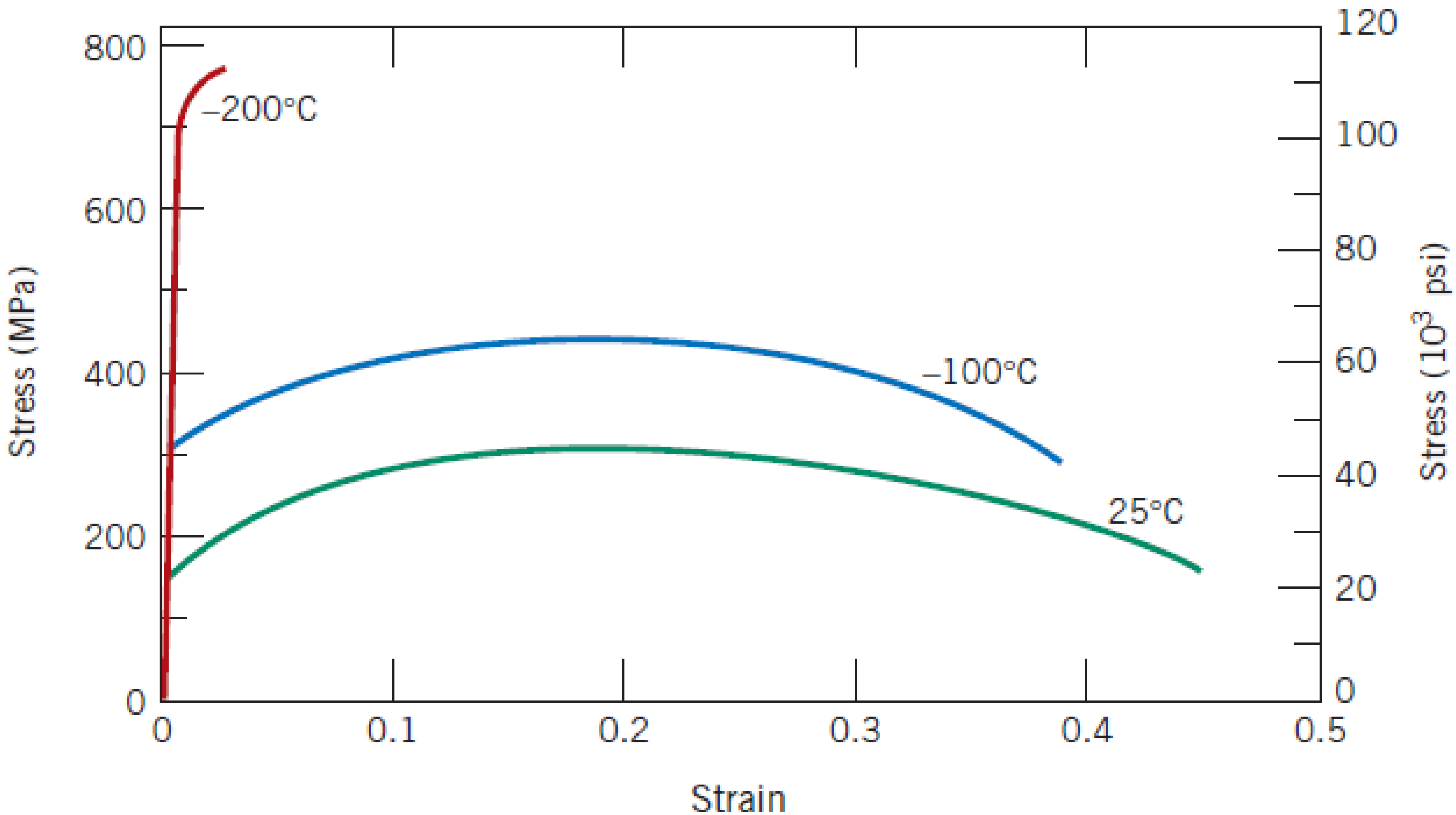
Polymer	Brinell Hardness, HB
Polypropylene	7
Polystyrene	20
Polyvinyl-chloride	10

Effect of Temperature on Mechanical Properties

- Generally speaking, materials are lower in strength and higher in ductility, at elevated temperatures

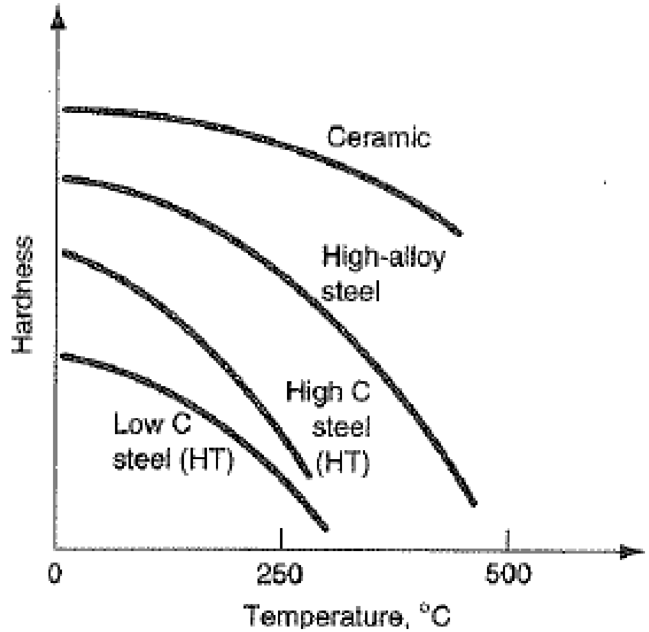


Engineering stress– strain behavior for Iron at three temperatures



Hot Hardness

- A property used to characterize strength and hardness at elevated temperatures is Hot Hardness
- It is the ability of a material to retain its hardness at elevated temperatures



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 σ_y.
- Toughness: The energy needed to break a unit volume of material.
- Ductility: The plastic strain at failure.