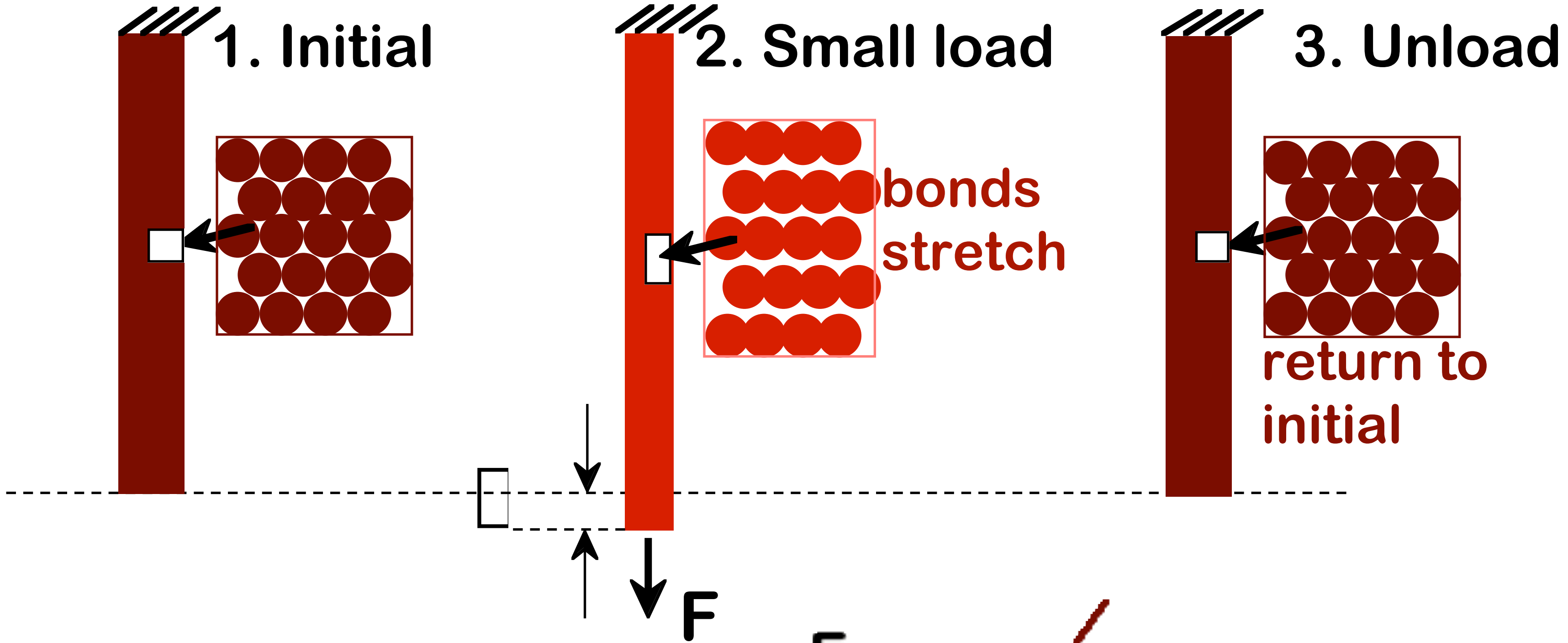
CHAPTER 6: MECHANICAL PROPERTIES

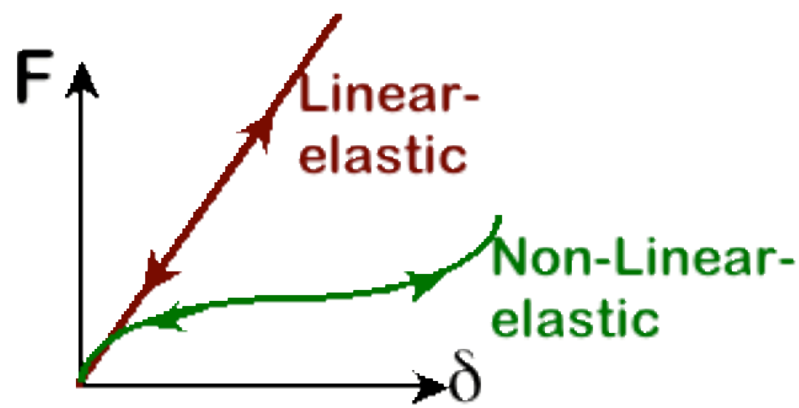
ISSUES TO ADDRESS...

- 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 do dislocations cause permanent deformation? What materials are most resistant to permanent deformation?
- Toughness and ductility: What are they and how do we measure them?

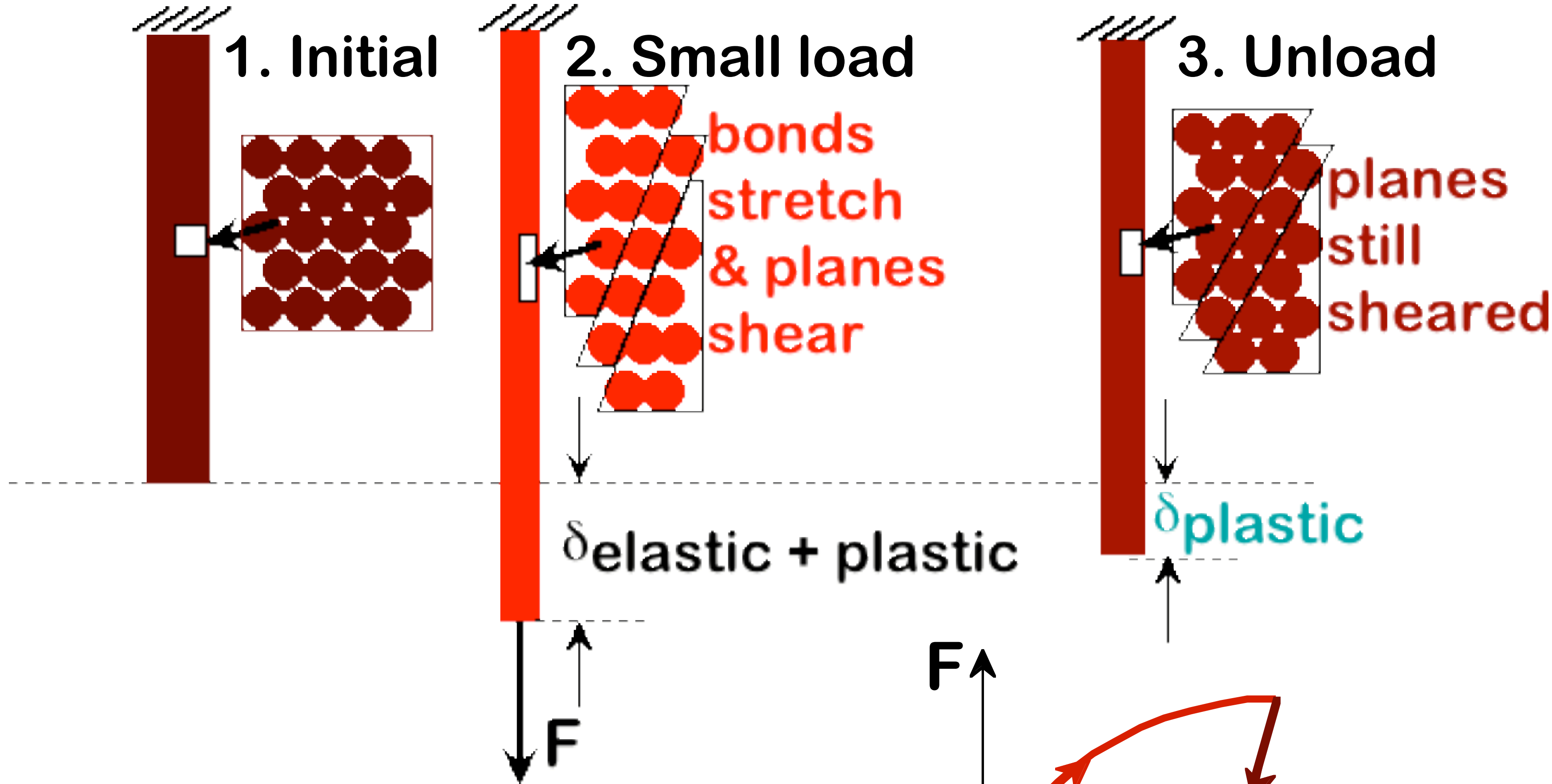
ELASTIC DEFORMATION



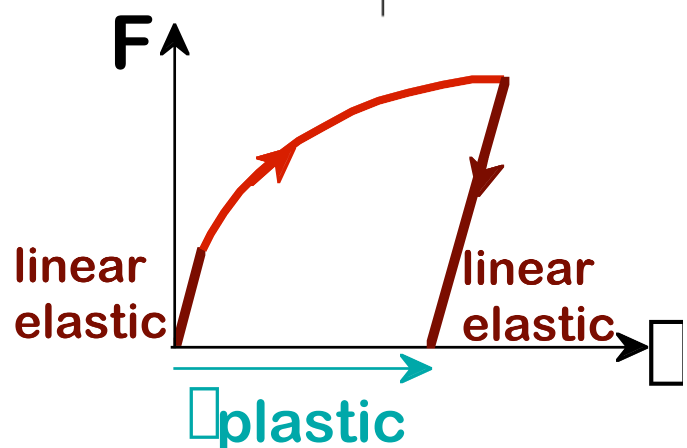
Elastic means reversible!



PLASTIC DEFORMATION (METALS)

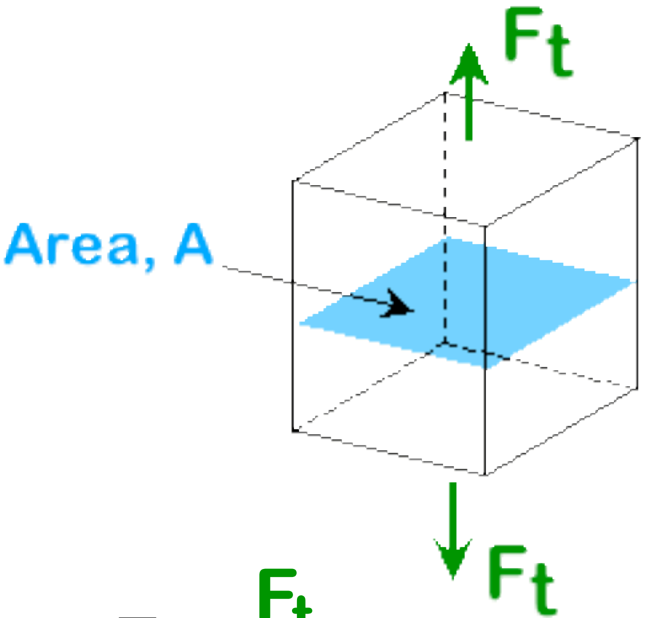


Plastic means permanent!



ENGINEERING STRESS

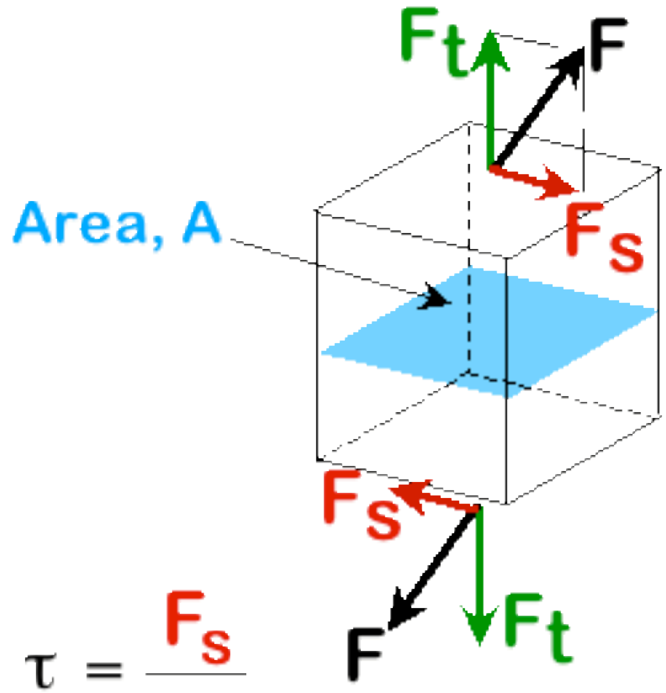
- **Tensile** stress, σ:



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

original area before loading

- **Shear** stress, τ:



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

Stress has units:
N/m^2 or lb/in^2

COMMON STATES OF STRESS

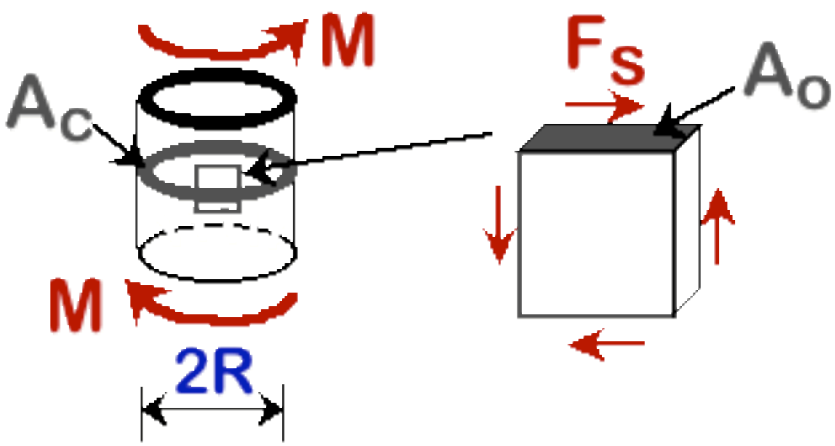
- Simple tension: cable

A_o = cross sectional Area (when unloaded)

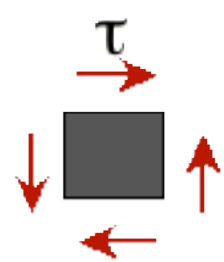
$$\sigma = \frac{F}{A_o}$$

Ski lift (photo courtesy P.M. Anderson)

- Simple shear: drive shaft



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



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

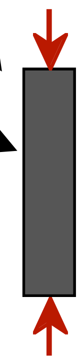
OTHER COMMON STRESS STATES (1)

- Simple **compression:**

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

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

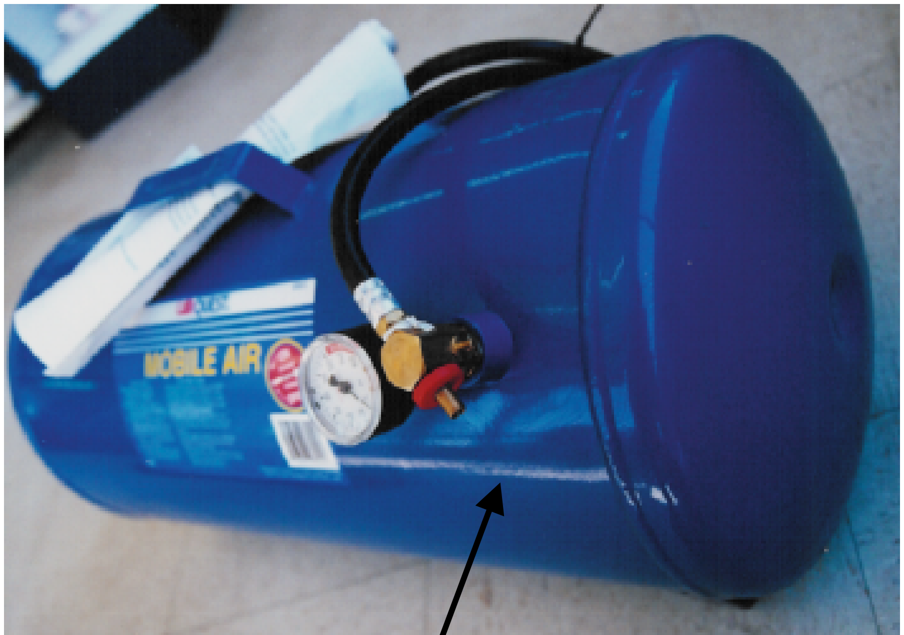
$$\sigma = \frac{F}{A_o}$$



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

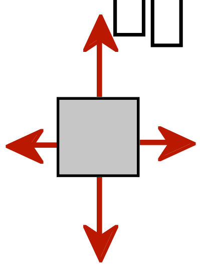
OTHER COMMON STRESS STATES (2)

- **Bi-axial tension:**



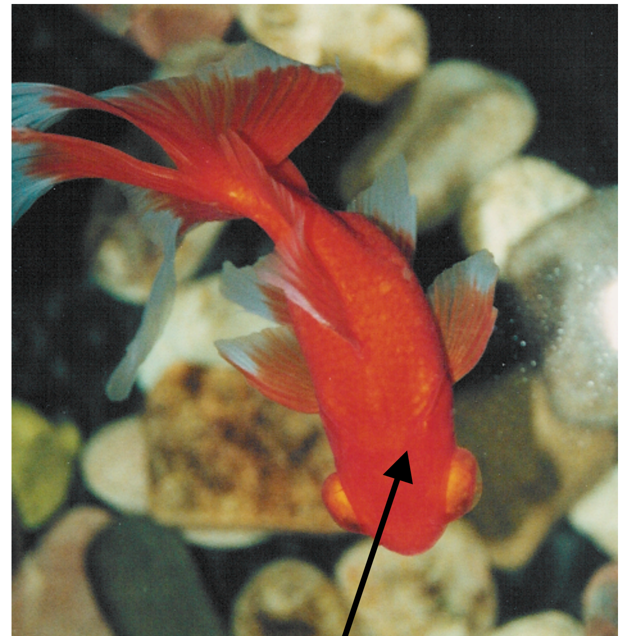
Pressurized tank
(photo courtesy P.M. Anderson)

$\sigma_\theta > 0$

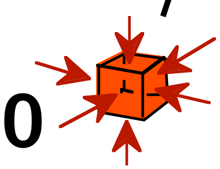


$\sigma_z > 0$

- **Hydrostatic compression:**



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



$\sigma_h < 0$

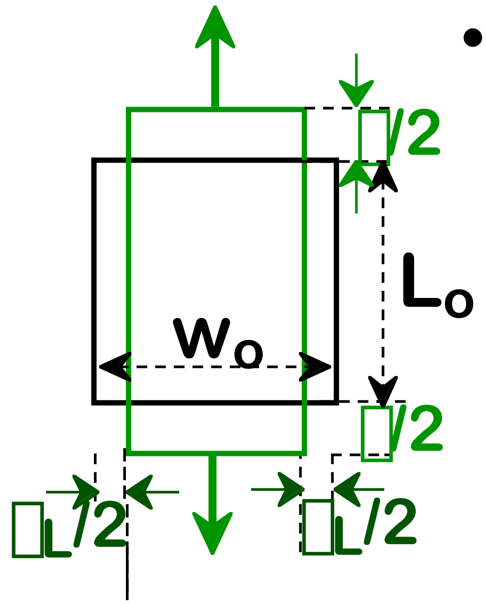
ENGINEERING STRAIN

- **Tensile strain:**

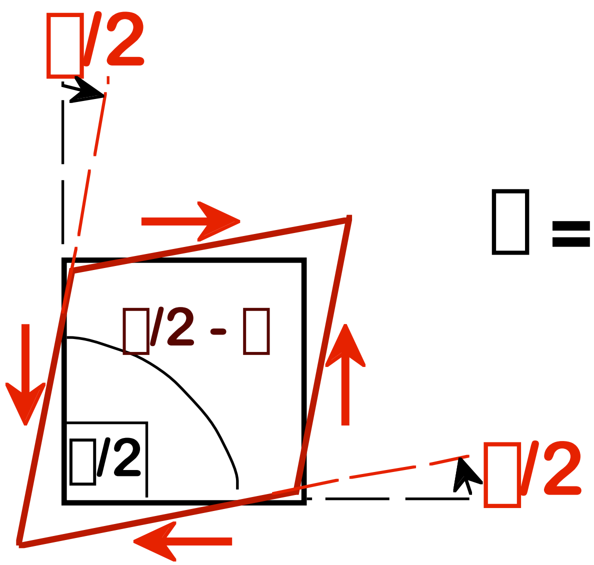
$$\varepsilon = \frac{\delta}{L_o}$$

- **Lateral strain:**

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



- **Shear strain:**

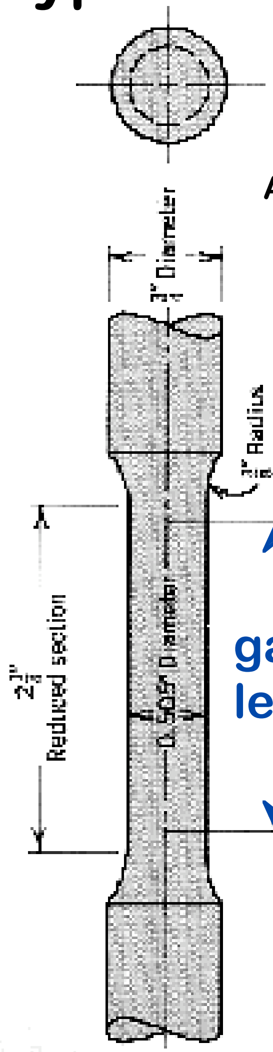


□ = tan □

Strain is always dimensionless.

STRESS-STRAIN TESTING

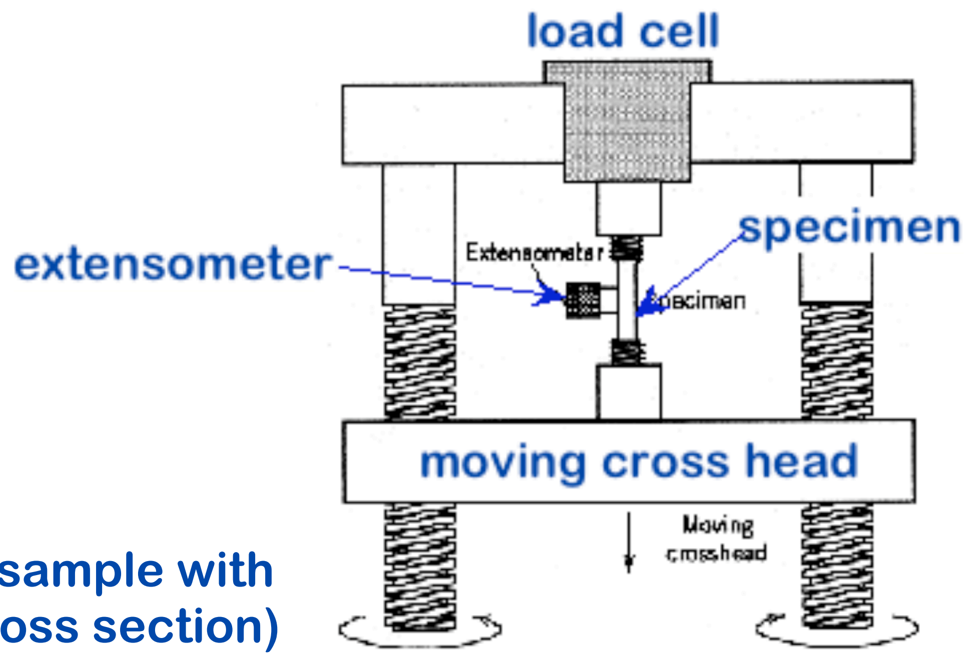
• Typical tensile specimen



Adapted from Fig. 6.2, *Callister 6e.*

gauge length = (portion of sample with reduced cross section)

• Typical tensile test machine



Adapted from Fig. 6.3, *Callister 6e.* (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.)

• Other types of tests:

--compression: brittle materials (e.g., concrete)

--torsion: cylindrical tubes, shafts.

LINEAR ELASTIC PROPERTIES

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

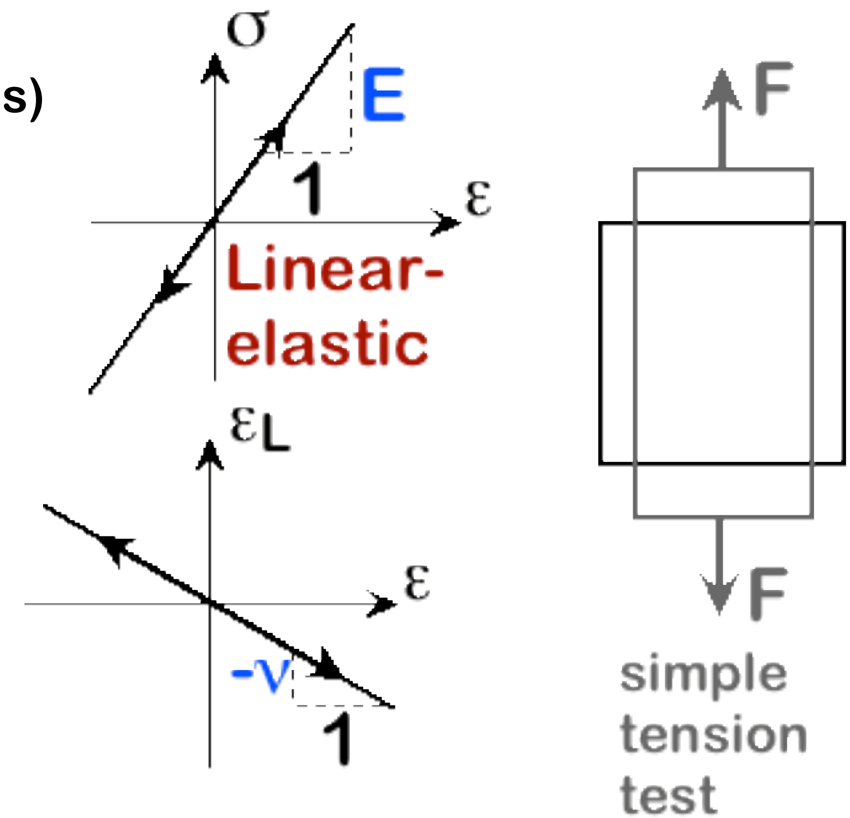
- **Hooke's Law:**

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

- **Poisson's ratio, ν:**

$$\nu = -\frac{\varepsilon_L}{\varepsilon}$$

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

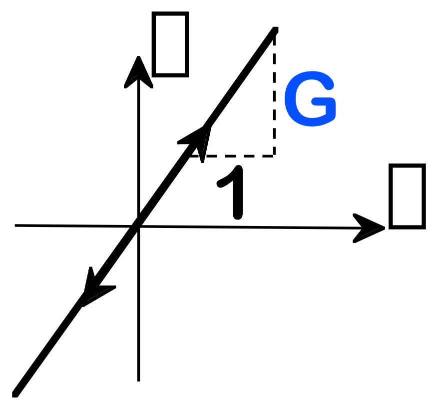


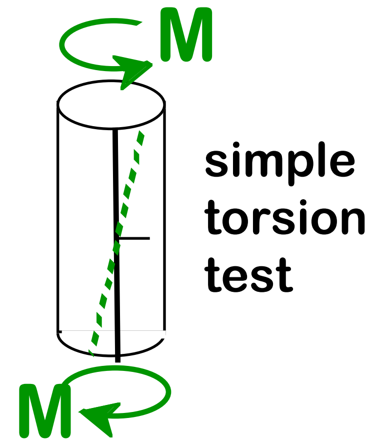
Units:
E: [GPa] or [psi]
ν: dimensionless

OTHER ELASTIC PROPERTIES

- Elastic **Shear modulus, G:**

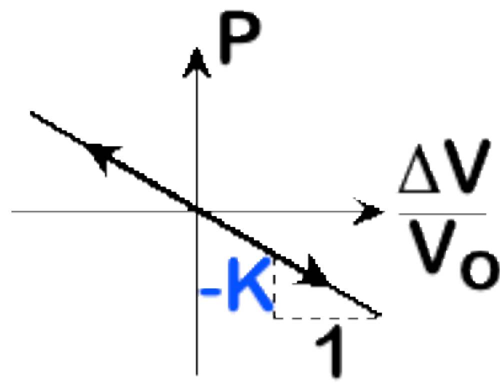
  $\tau = G\gamma$

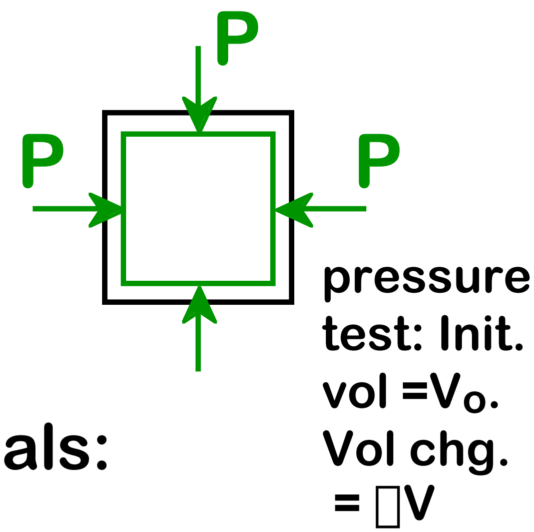




- Elastic **Bulk modulus, K:**

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

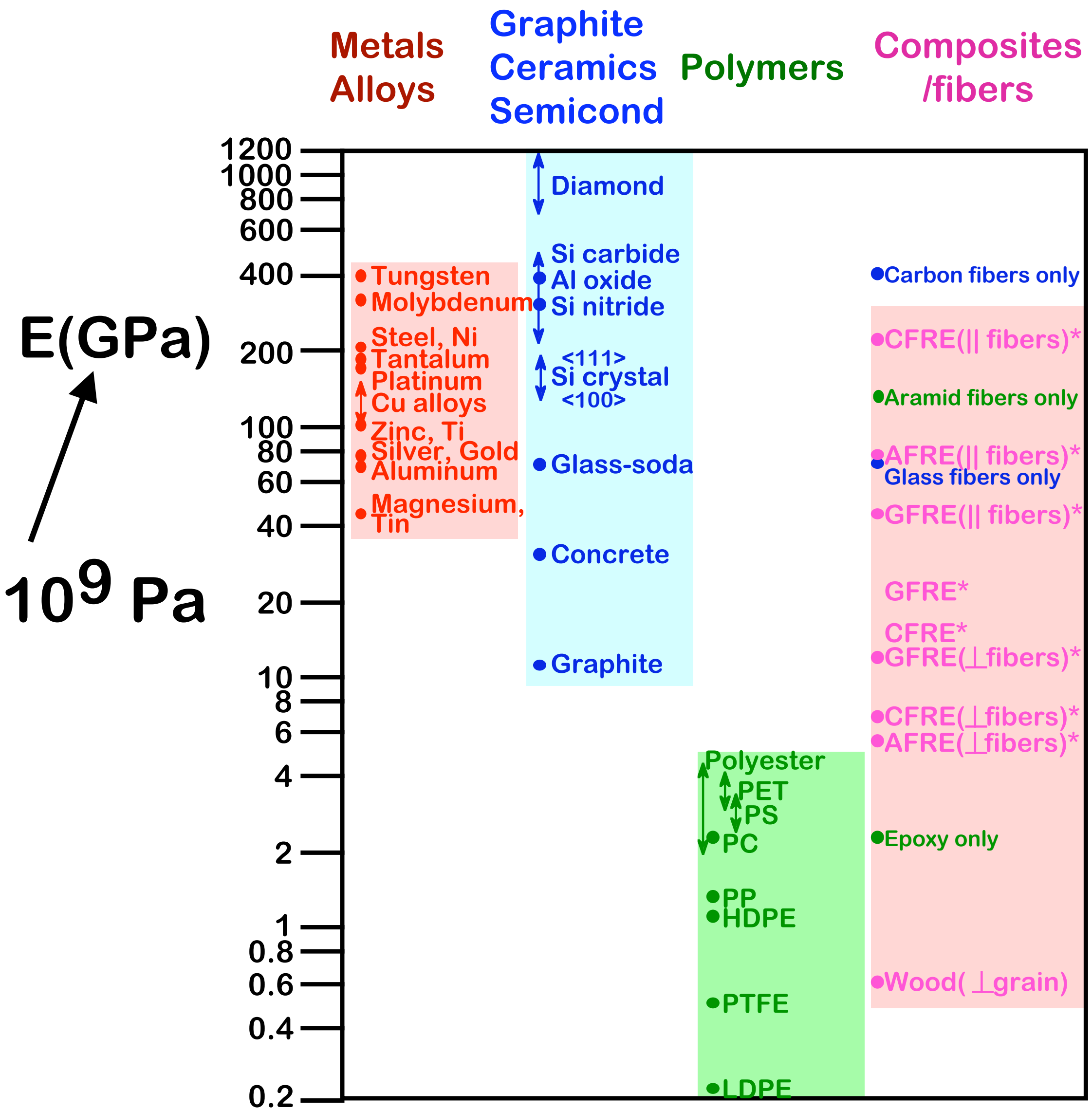




- Special relations for isotropic materials:

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

YOUNG'S MODULI: COMPARISON



$E_{ceramics}$
$> E_{metals}$
$>> E_{polymers}$

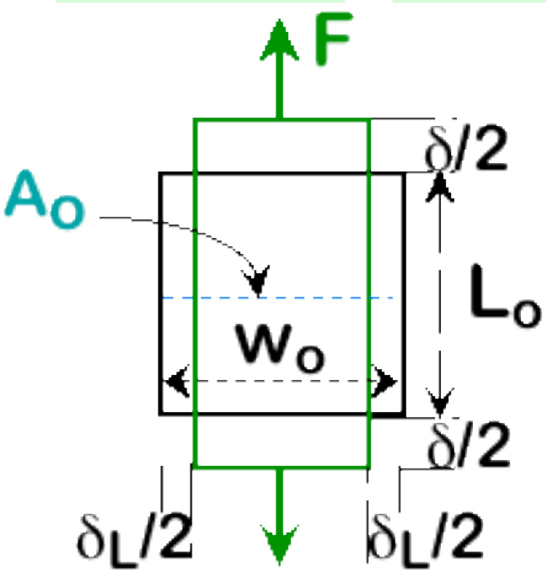
Based on data in Table B2, *Callister 6e*.
Composite data based on reinforced epoxy with 60 vol% of aligned
carbon (CFRE),
aramid (AFRE), or
glass (GFRE)
fibers.

USEFUL LINEAR ELASTIC RELATIONS

- Simple tension:

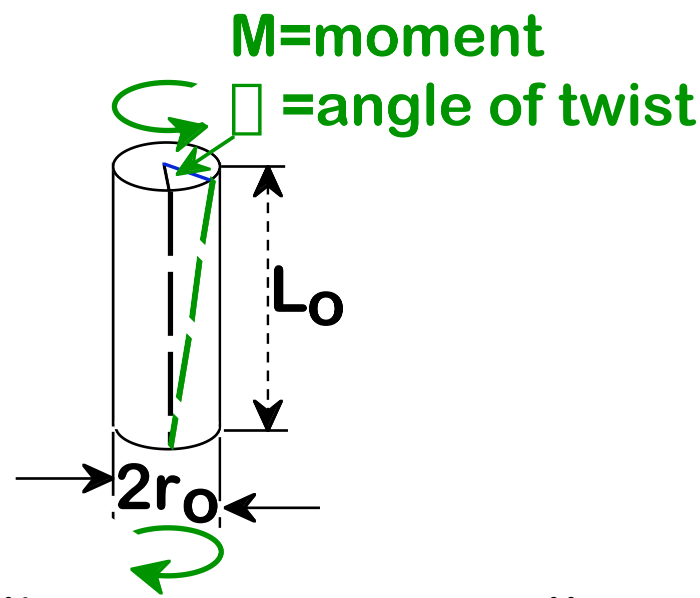
$$\delta = \frac{FL_o}{EA_o}$$

$$\delta_L = -\nu \frac{Fw_o}{EA_o}$$



- Simple torsion:

$$\alpha = \frac{2ML_o}{\pi r_o^4 G}$$

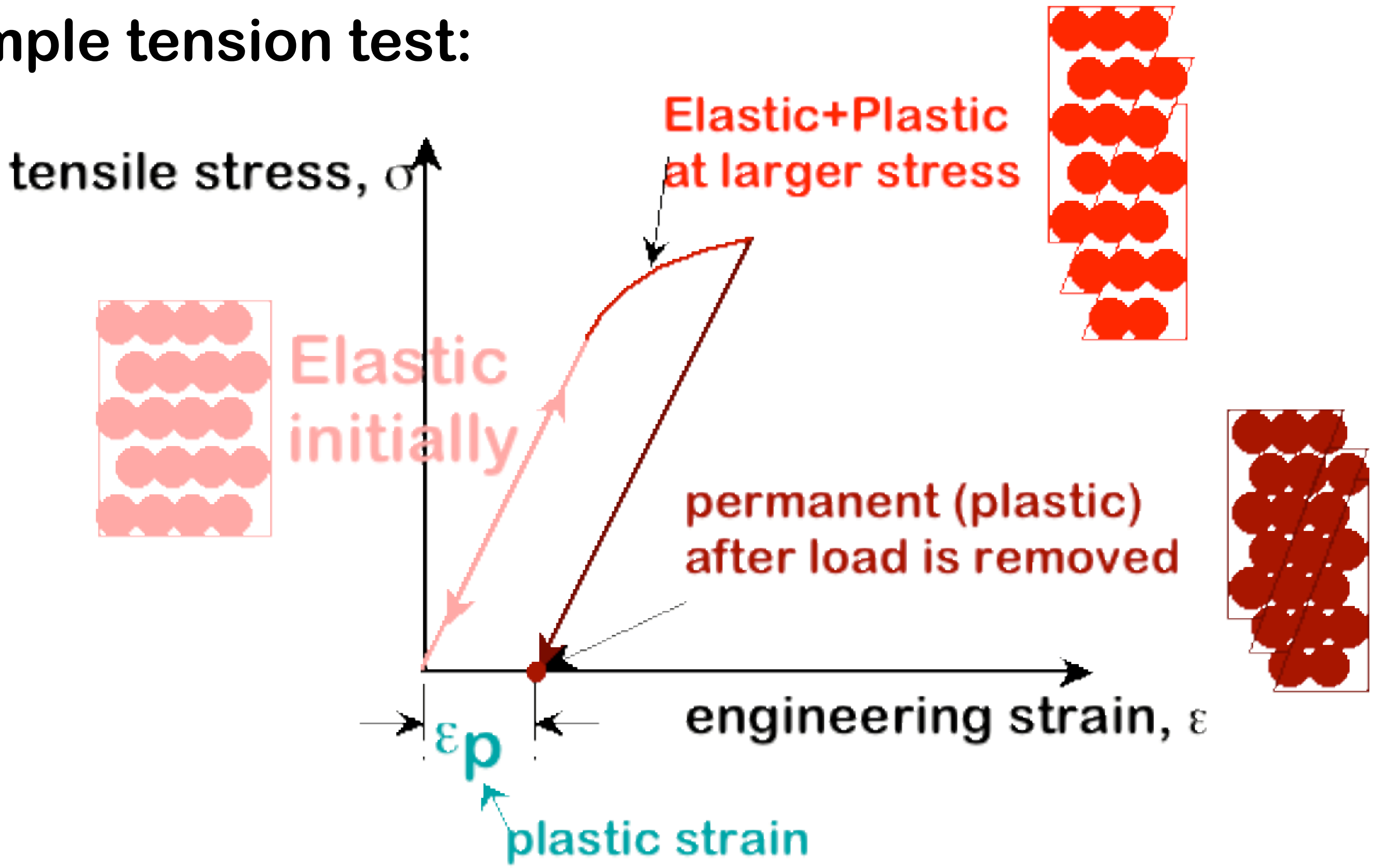


- Material, geometric, and loading parameters all contribute to deflection.
- Larger elastic moduli minimize elastic deflection.

PLASTIC (PERMANENT) DEFORMATION

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

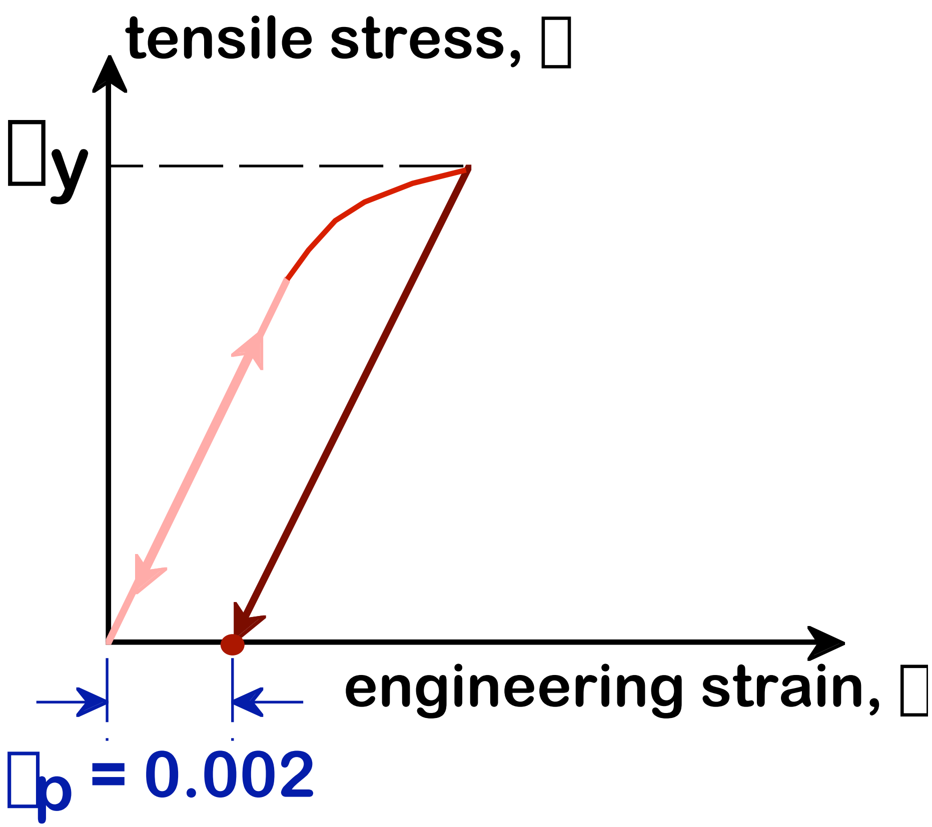
- Simple tension test:



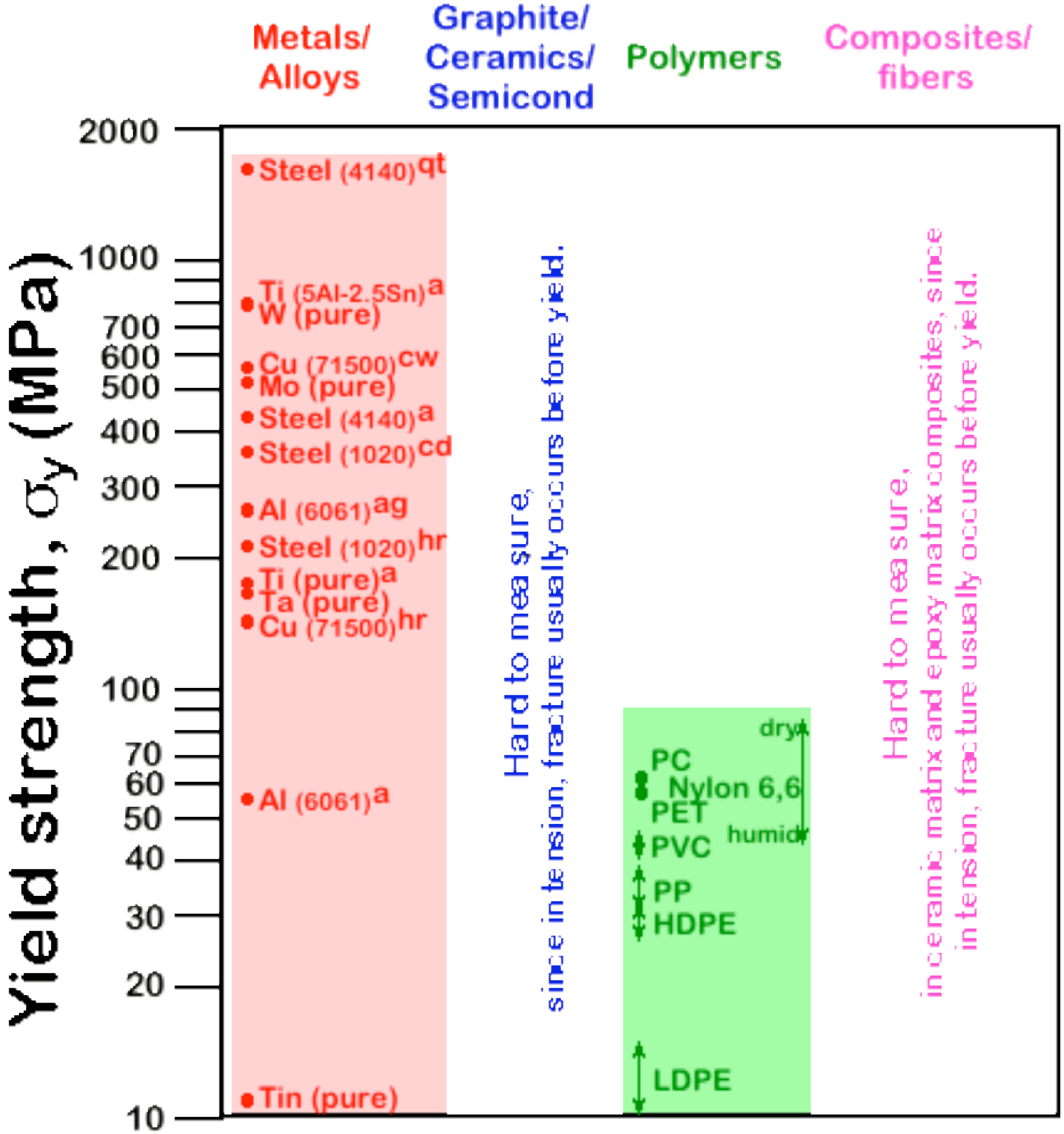
YIELD STRENGTH, σ_y

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

when $\varepsilon_p = 0.002$



YIELD STRENGTH: COMPARISON



σ_y(ceramics)
>> σ_y(metals)
>> σ_y(polymers)

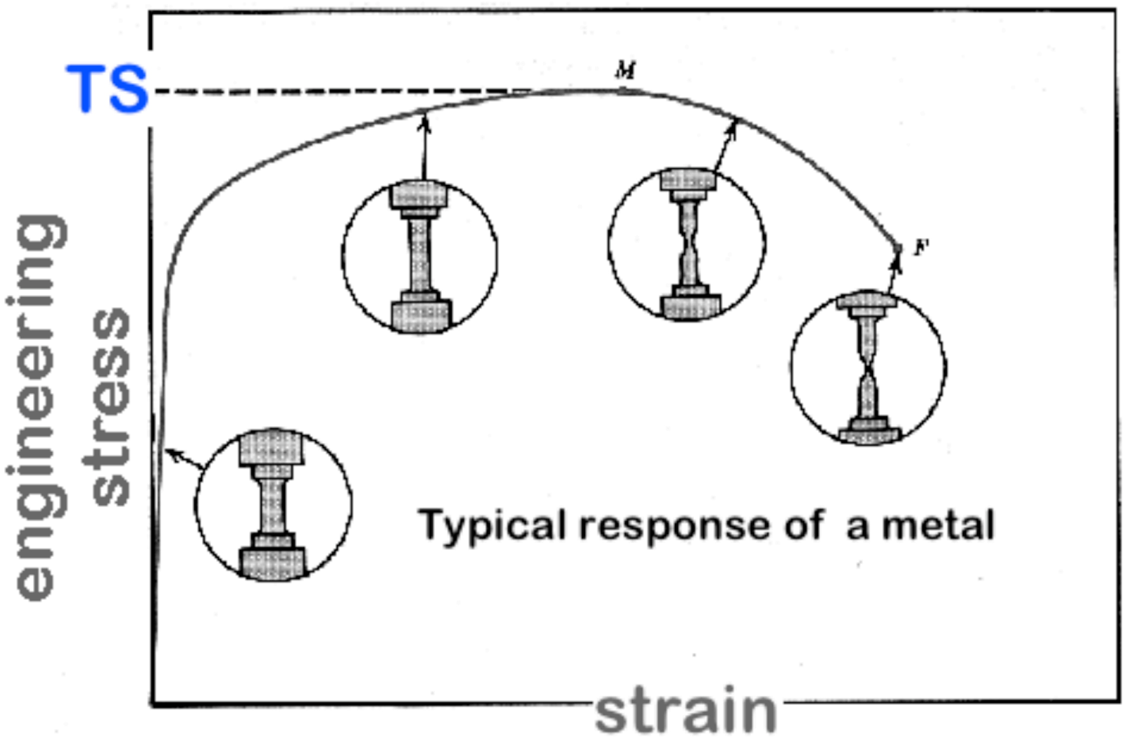
Room T values

Based on data in Table B4, *Callister 6e*.

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

TENSILE STRENGTH, TS

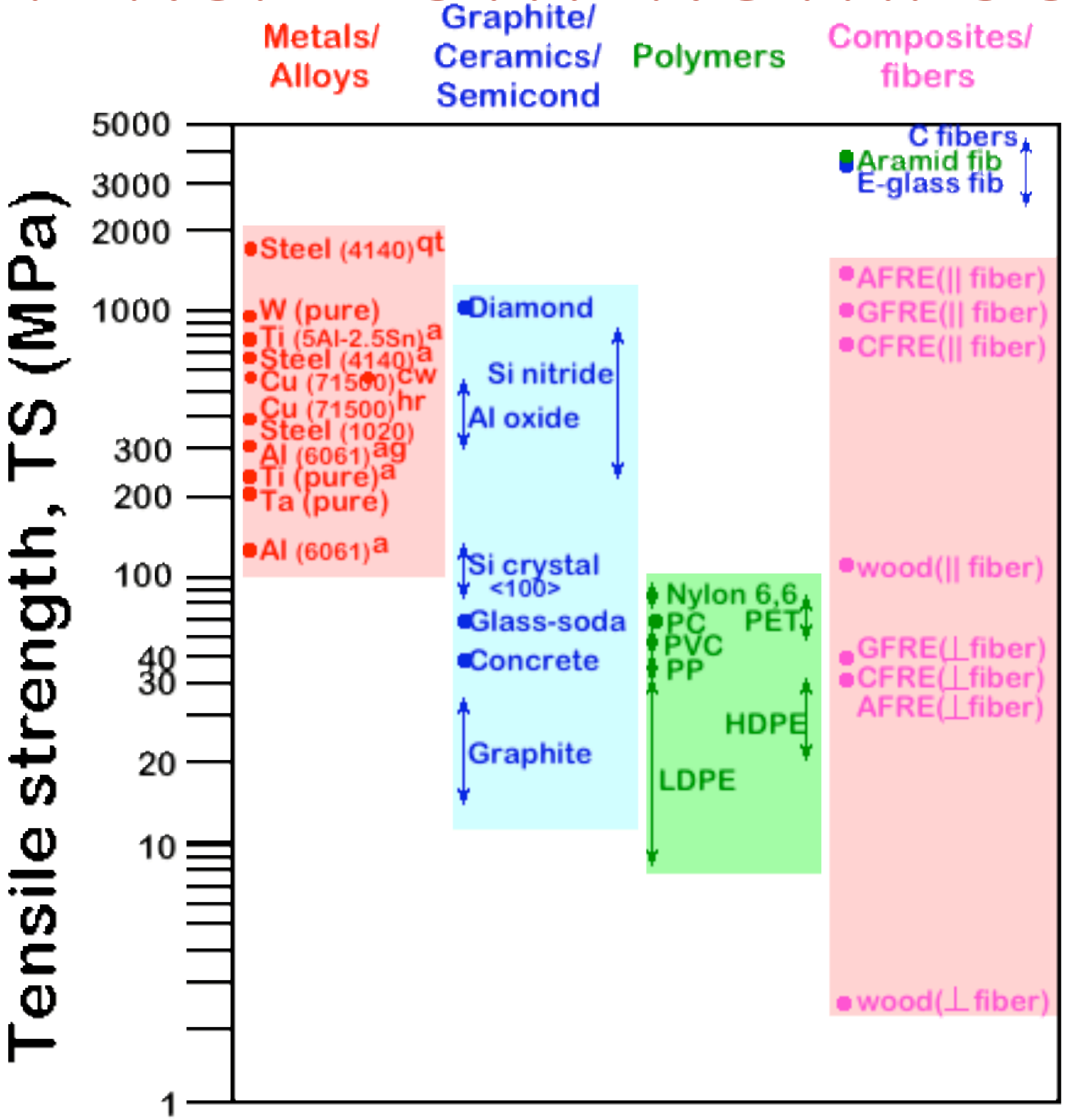
- Maximum possible engineering stress in tension.



Adapted from Fig. 6.11, *Callister 6e.*

- Metals: occurs when noticeable necking starts.
- Ceramics: occurs when crack propagation starts.
- Polymers: occurs when polymer backbones are aligned and about to break.

TENSILE STRENGTH: COMPARISON



$TS_{(ceram)}$
$\sim TS_{(met)}$
$\sim TS_{(comp)}$
$\gg TS_{(poly)}$

Room T values

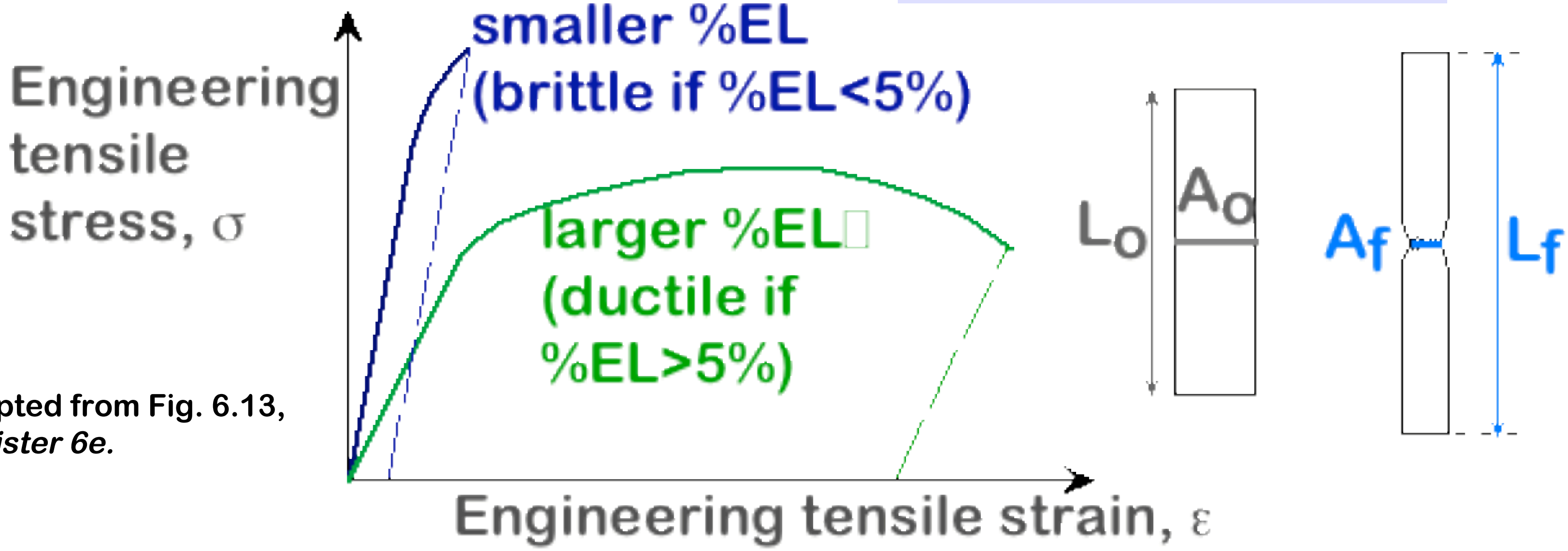
Based on data in Table B4, *Callister 6e*.

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, %EL

- **Plastic tensile strain at failure:** $\%EL = \frac{L_f - L_o}{L_o} x100$



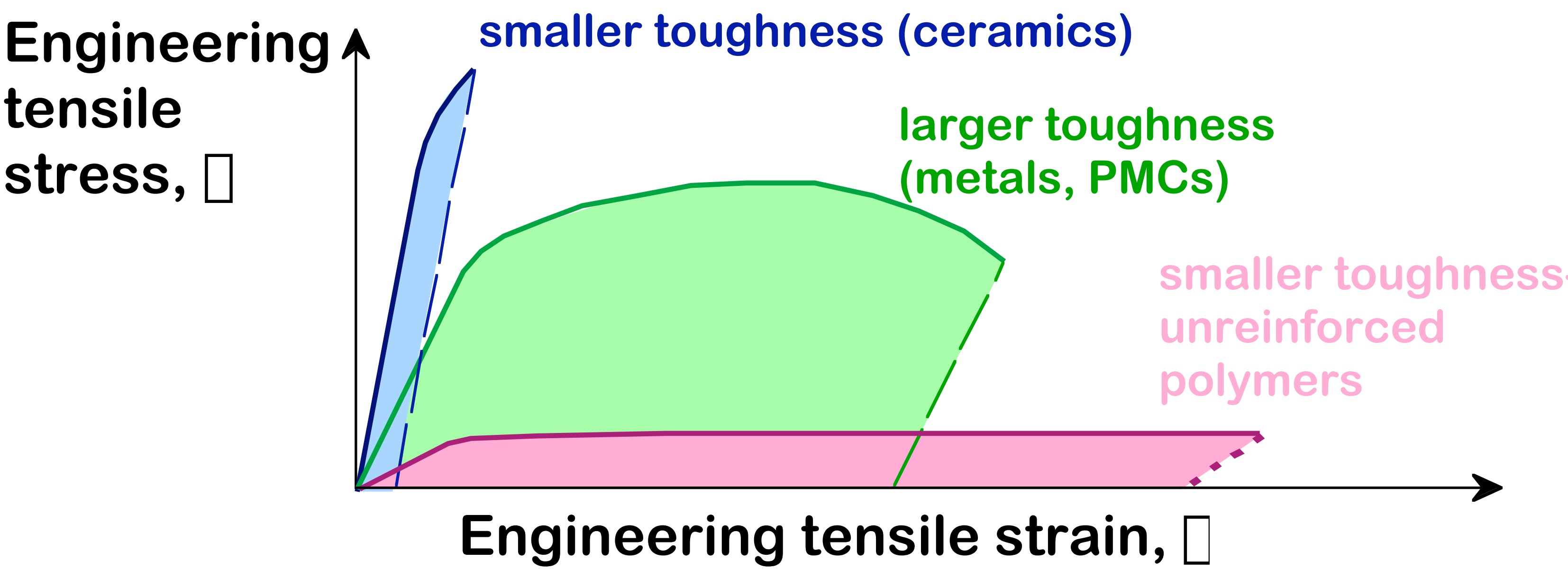
Adapted from Fig. 6.13, *Callister 6e.*

- **Another ductility measure:** $\%AR = \frac{A_o - A_f}{A_o} x100$

- **Note: %AR and %EL are often comparable.**
  --Reason: crystal slip does not change material volume.
  --%AR > %EL possible if internal voids form in neck.

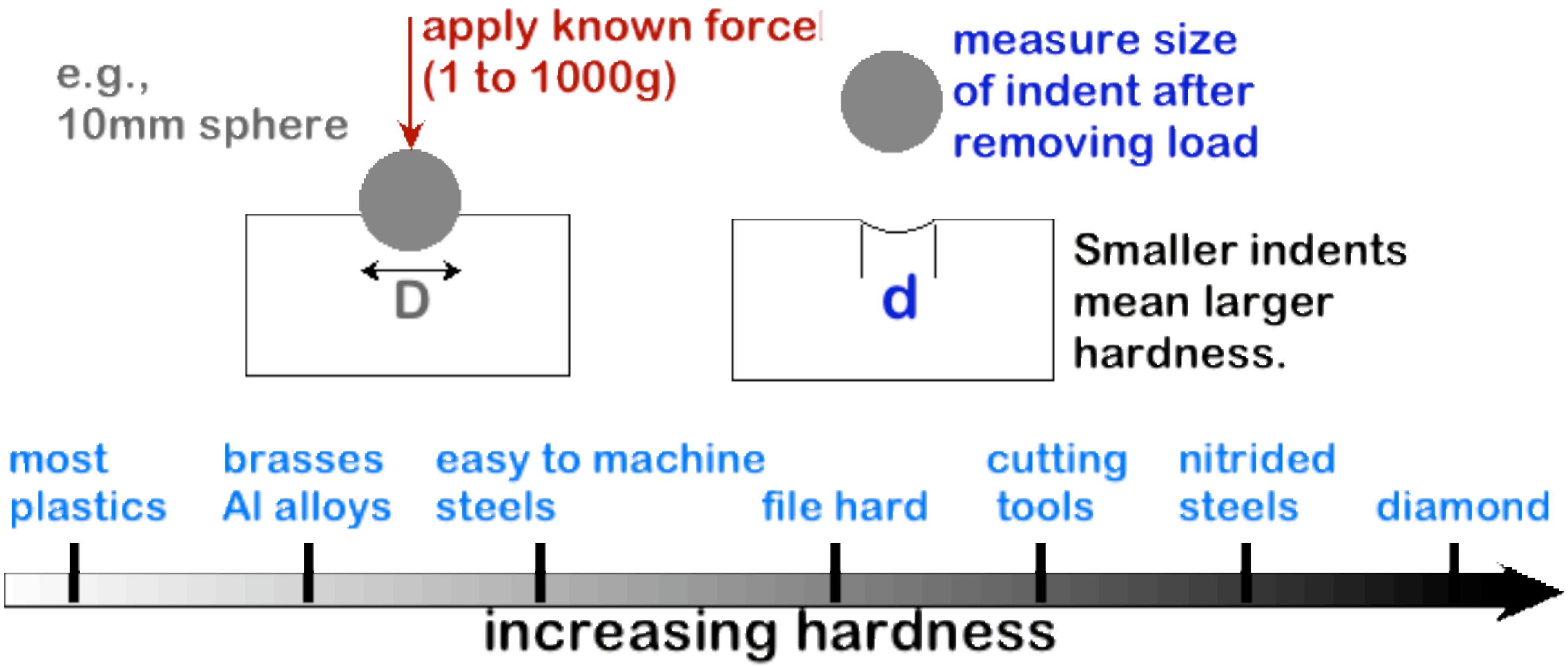
TOUGHNESS

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



HARDNESS

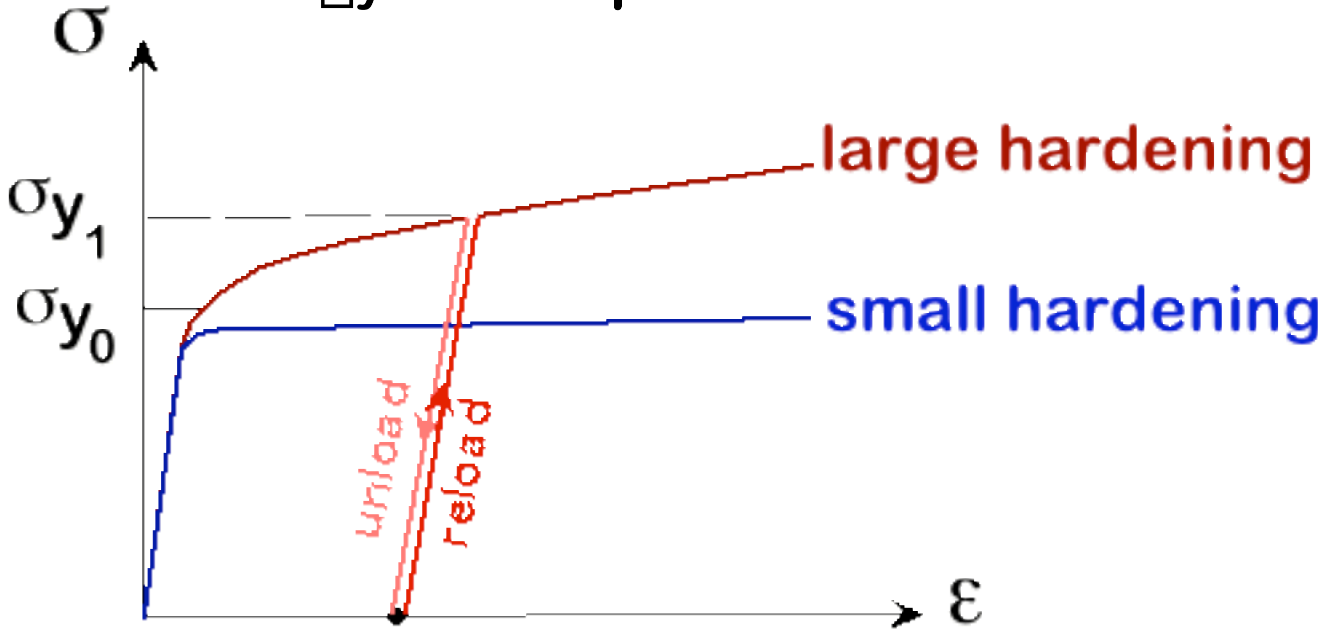
- Resistance to permanently indenting the surface.
- Large hardness means:
  --resistance to plastic deformation or cracking in compression.
  --better wear properties.



Adapted from Fig. 6.18, *Callister 6e.* (Fig. 6.18 is adapted from G.F. Kinney, *Engineering Properties and Applications of Plastics*, p. 202, John Wiley and Sons, 1957.)

HARDENING

- An increase in y due to plastic deformation.



- Curve fit to the stress-strain response:

$$\sigma_T = C\left(\varepsilon_T\right)^n$$

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

"true" stress (F/A)

"true" strain: $\ln(L/L_o)$

DESIGN OR SAFETY FACTORS

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

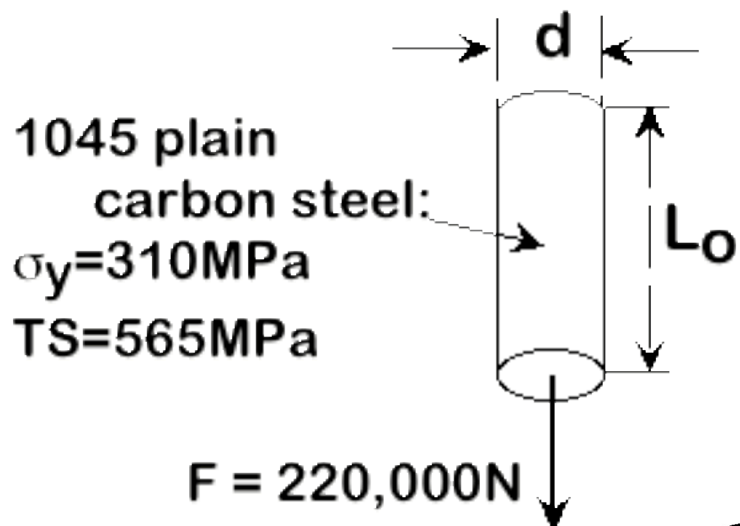
$$\sigma_{working} = \frac{\sigma_y}{N}$$

Often N is between 1.2 and 4

- Ex: 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.

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

$$\frac{220{,}000\text{N}}{\pi\left(d^2/4\right)} \qquad N = 5$$



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.

Note: For materials selection cases related to mechanical behavior, see slides 22-4 to 22-10.

ANNOUNCEMENTS

Reading:

Core Problems:

Self-help Problems: