CHAPTER 8 MECHANICAL PROPERTIES OF METALS

LEARNING OBJECTIVE:

Students should be able:

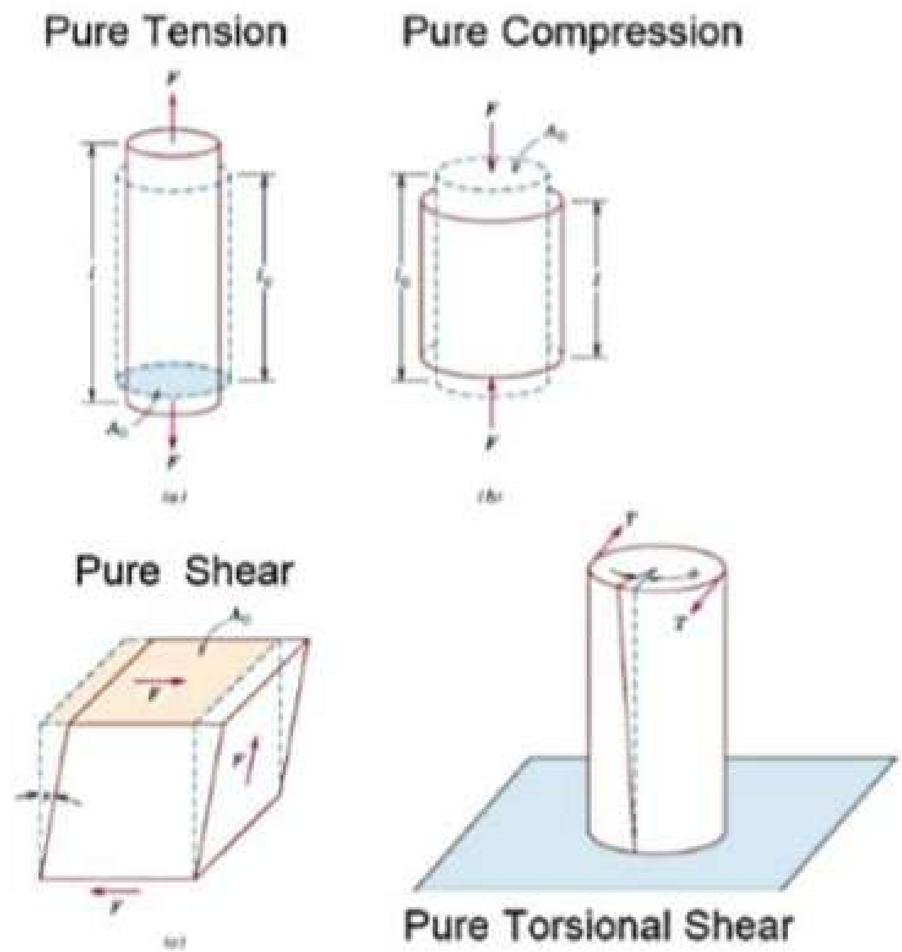
- Describe the stress and strain diagram.
- Differentiate between elastic and plastic deformation.
- Define the tensile strength, modulus of elasticity, ductility.
- Describe the hardness and toughness properties

MECHANICAL PROPERTIES

Properties obtain from a response or deformation due to an applied load or force.

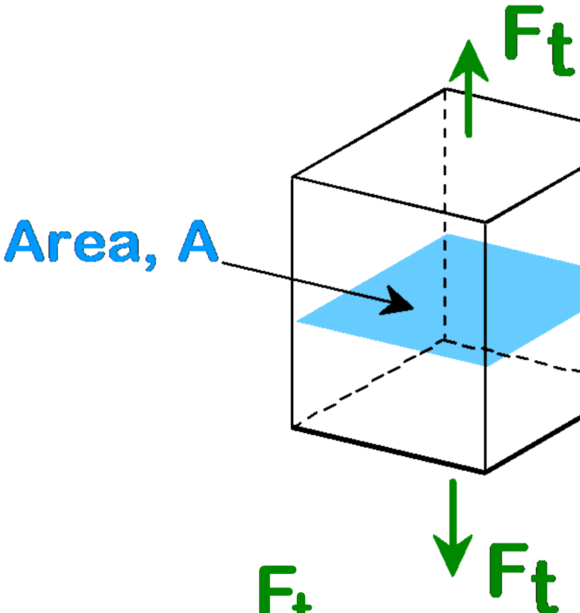
Example: Strength, hardness, toughness, elasticity, plasticity, brittleness, and ductility and malleability

TYPES OF LOADING



ENGINEERING STRESS

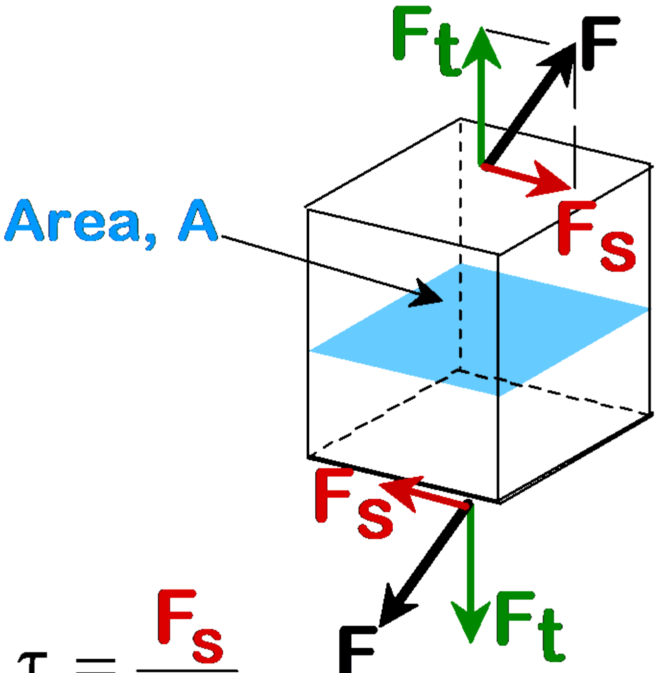
- **Tensile** stress, σ:



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

original area before loading

- **Shear** stress, τ:



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

Stress has units:
N/m^2 or MPa (1 MPa=10^6 N/m^2)

COMMON STATE OF STRESS

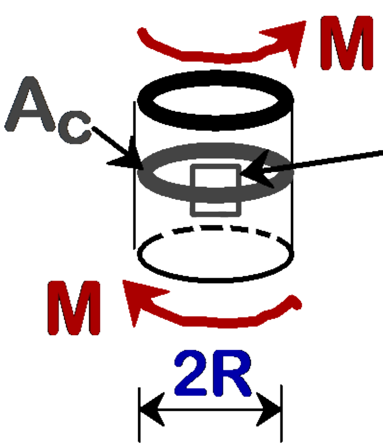
- Simple tension: cable

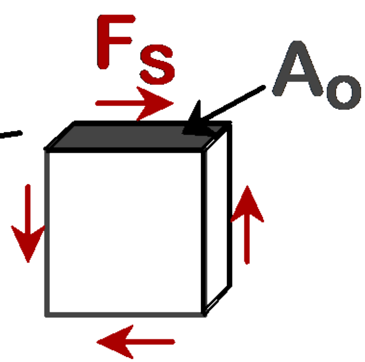
A_o = cross sectional Area (when unloaded)

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

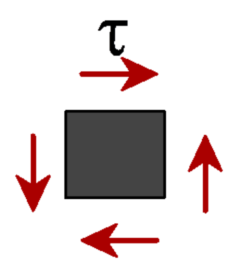
Ski lift (photo courtesy P.M. Anderson)

- Simple shear: drive shaft





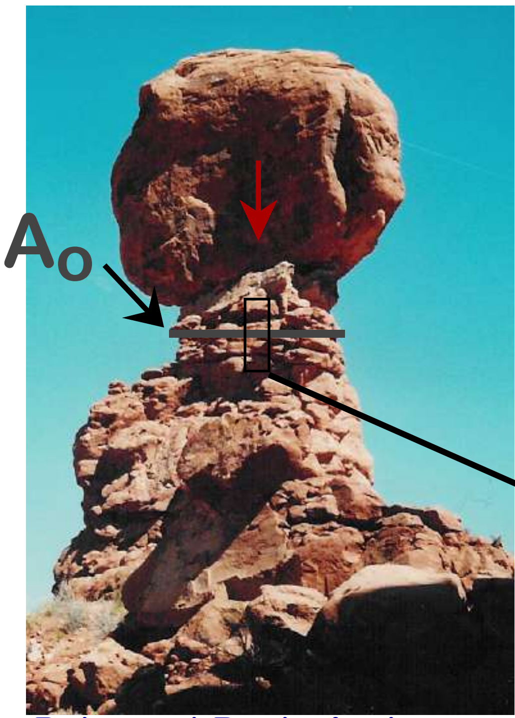
$$\tau = \frac{F_s}{A_o}$$



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

OTHER COMMON STRESS

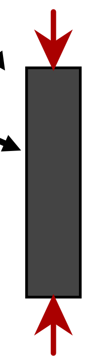
- Simple compression:



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

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

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

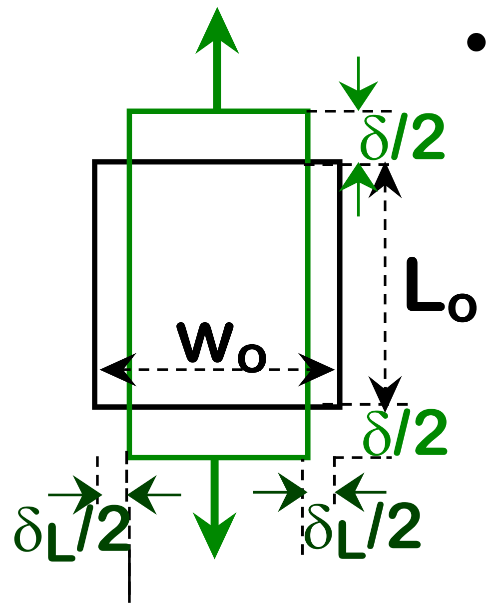


Note: compressive structure member ($\sigma < 0$ here).

ENGINEERING STRAIN

- **Tensile strain:**

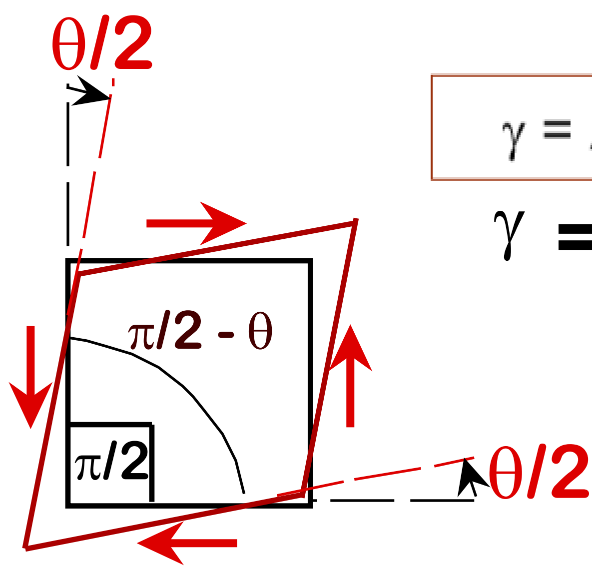
$$\varepsilon = \frac{\delta}{L_o}$$



- **Lateral strain:**

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

- **Shear strain:**



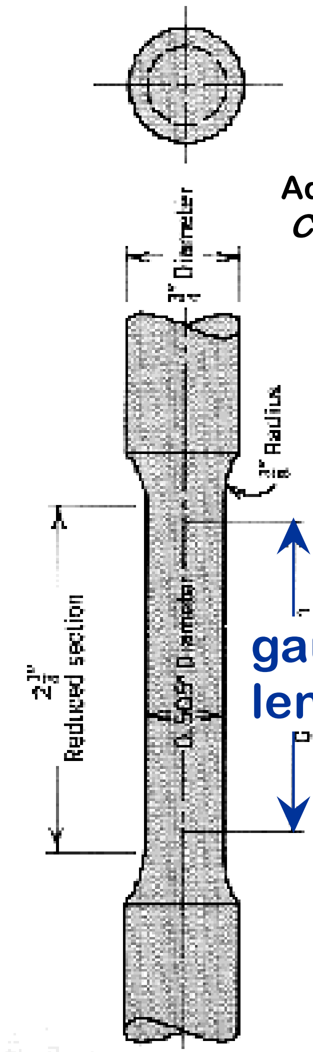
$$\gamma = \Delta x / y = \tan \theta$$

$$\gamma = \tan \theta$$

Strain is always dimensionless.

STRESS AND STRAIN TESTING

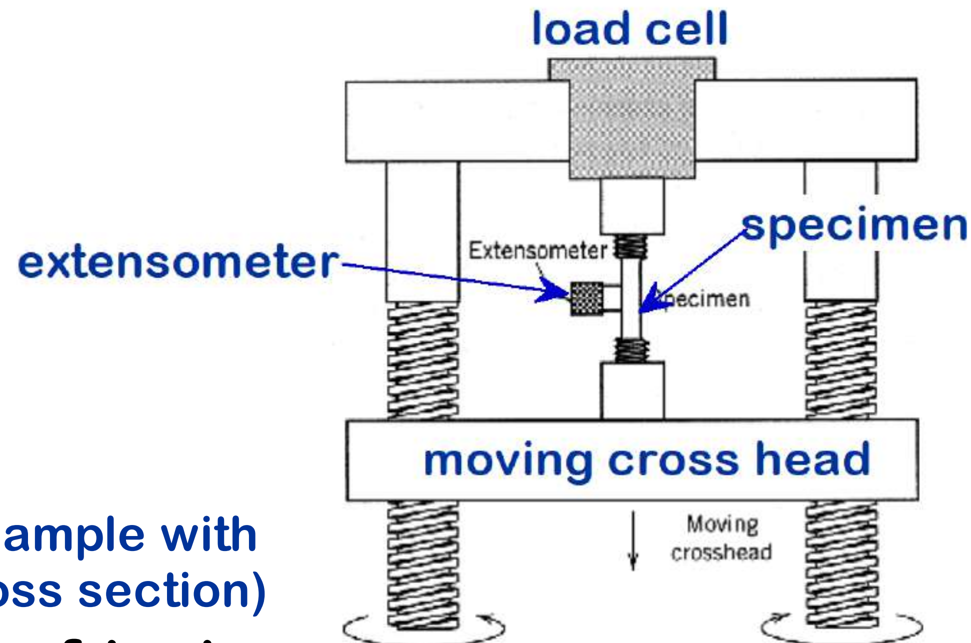
- Typical tensile specimen



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

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

- Typical tensile test machine

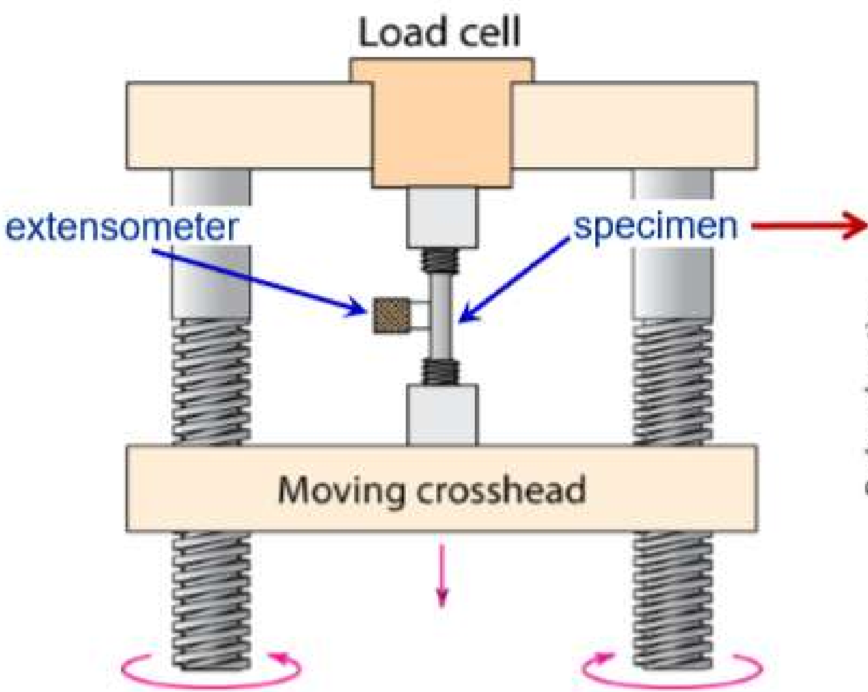


- Other types of tests:
  - --compression: brittle materials (e.g., concrete)
  - --torsion: cylindrical tubes, shafts.

STRESS AND STRAIN TESTING

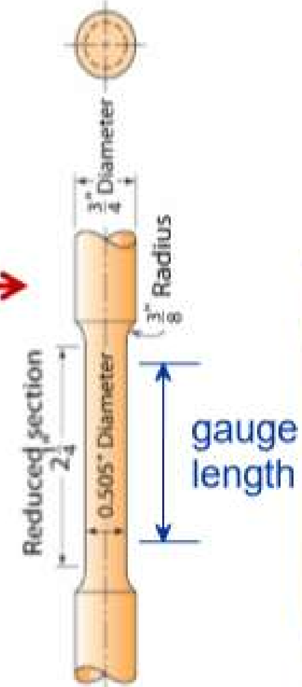
Stress-Strain Testing

- **Typical tensile test machine**



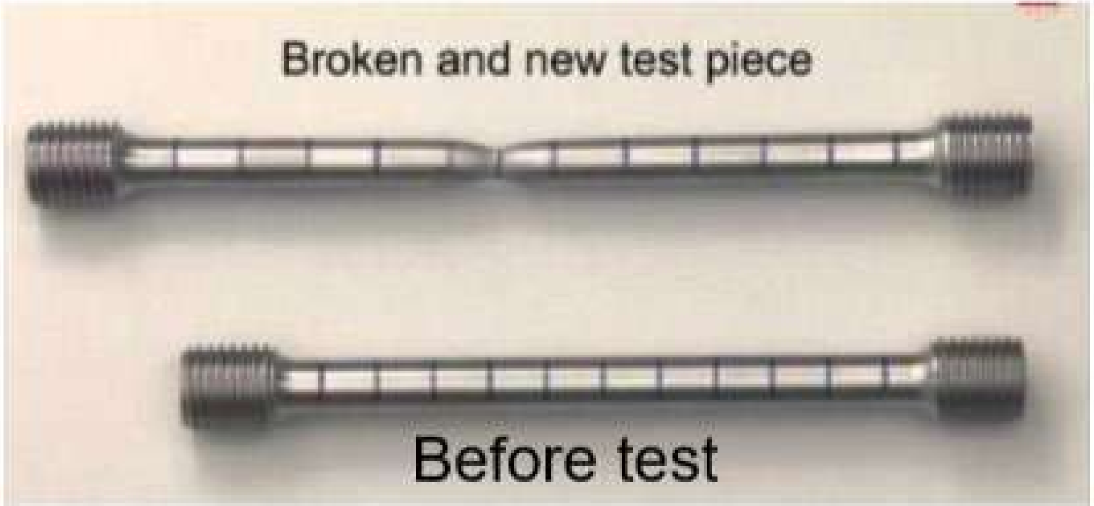
Adapted from Fig. 6.3, *Callister & Rethwisch 8e.* (Fig. 6.3 is taken from H.W. Hayden, W.G. Moffatt, and J. Wulff, *The Structure and Properties of Materials*, Vol. III, *Mechanical Behavior*, p. 2, John Wiley and Sons, New York, 1965.)

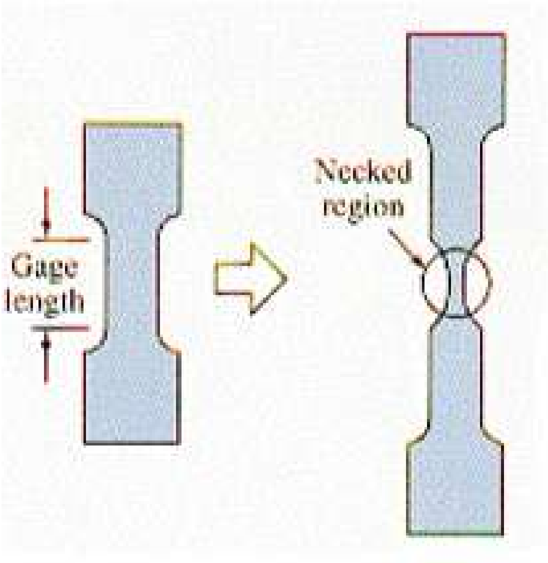
- **Typical tensile specimen**



Adapted from Fig. 6.2, *Callister & Rethwisch 8e.*

After the test


Broken and new test piece
Before test

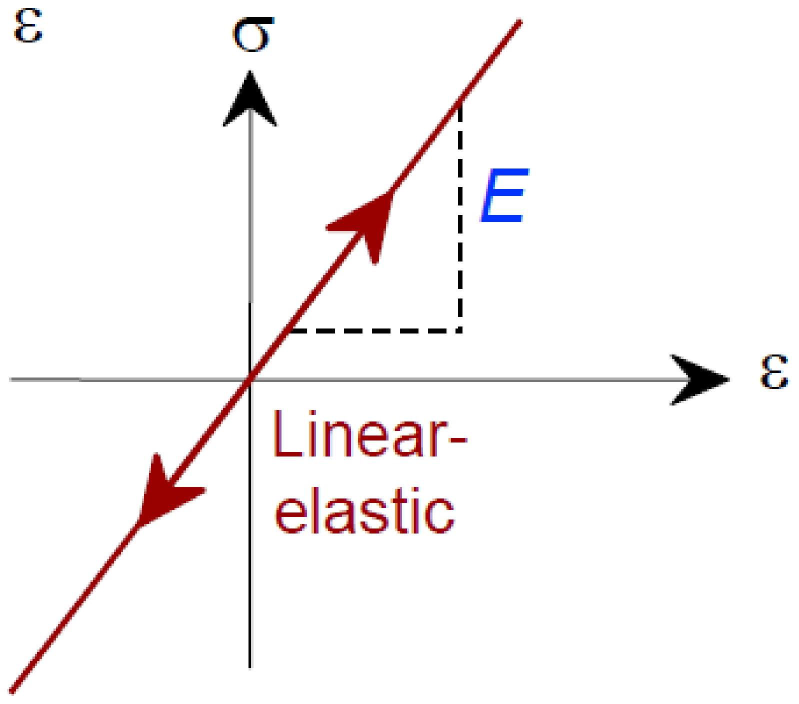

Gage length
Necked region

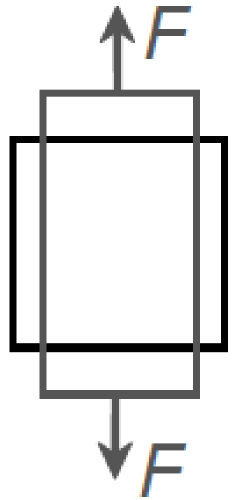
Stress Strain Behaviour
Linear Elastic Properties

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

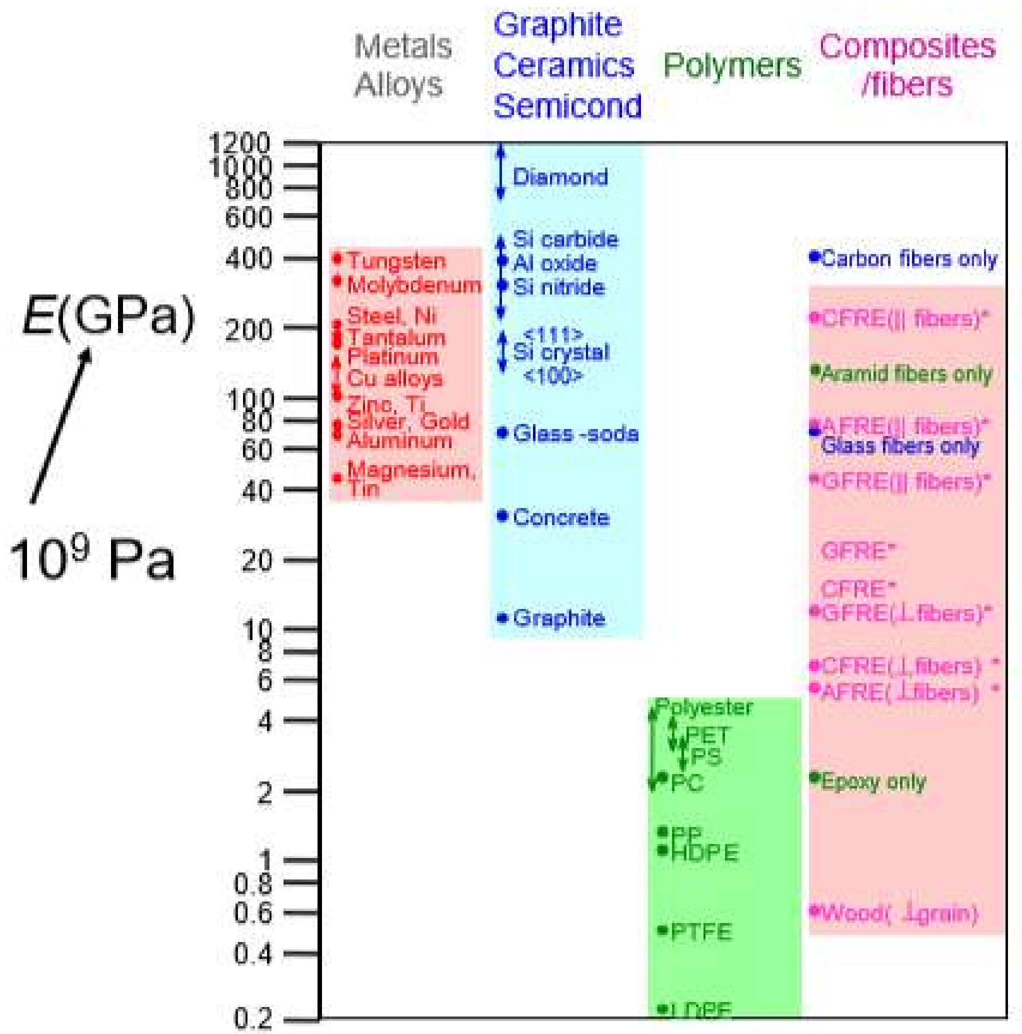
- **Hooke's Law:**

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





Young's Moduli: Comparison



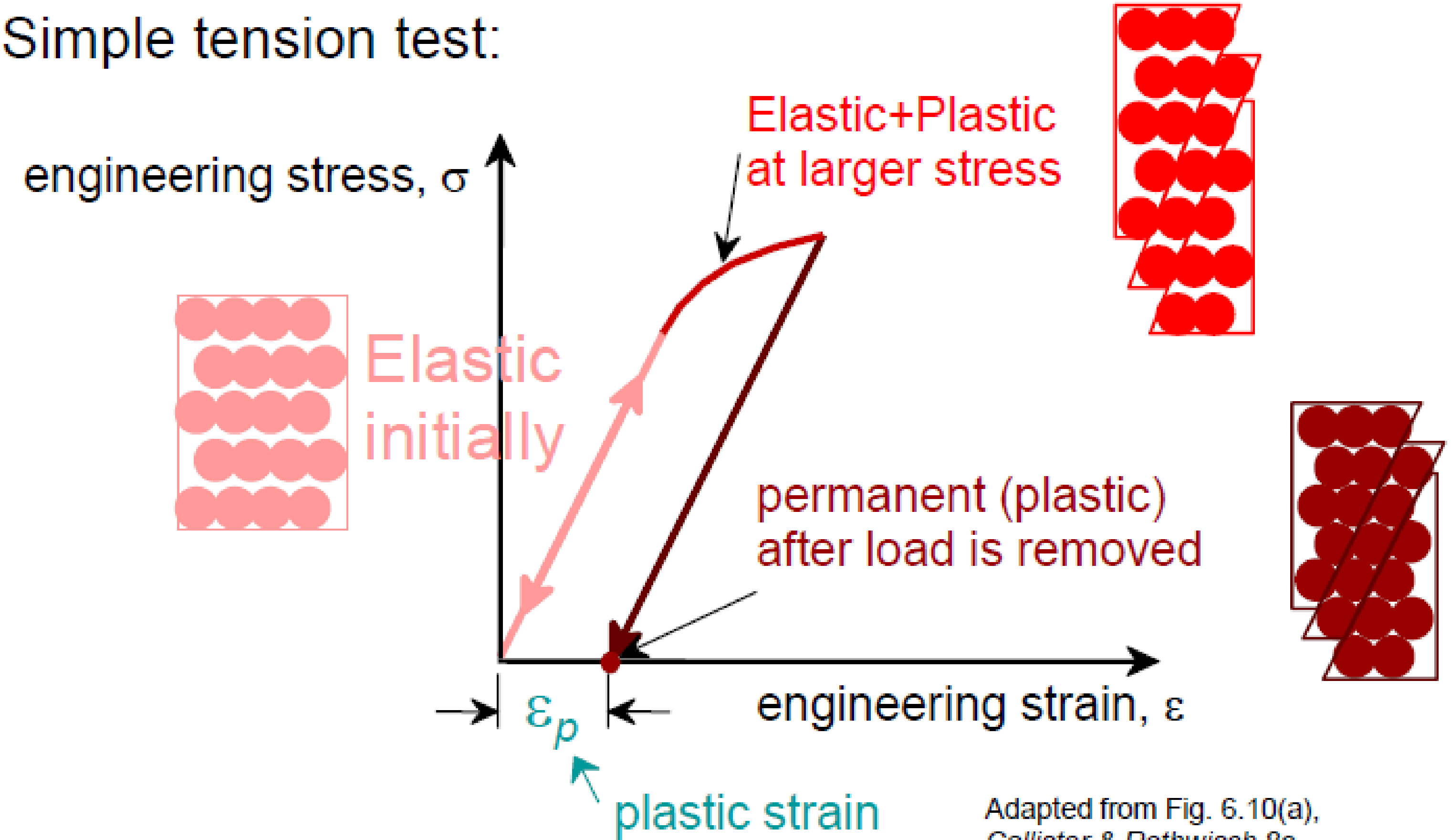
Based on data in Table B.2, *Callister & Rethwisch 8e.*
Composite data based on reinforced epoxy with 60 vol% of aligned carbon (CFRE), aramid (AFRE), or glass (GFRE) fibers.

High modulus of elasticity – relatively stiff, do not deflect easily.

Plastic (Permanent) Deformation

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

- Simple tension test:

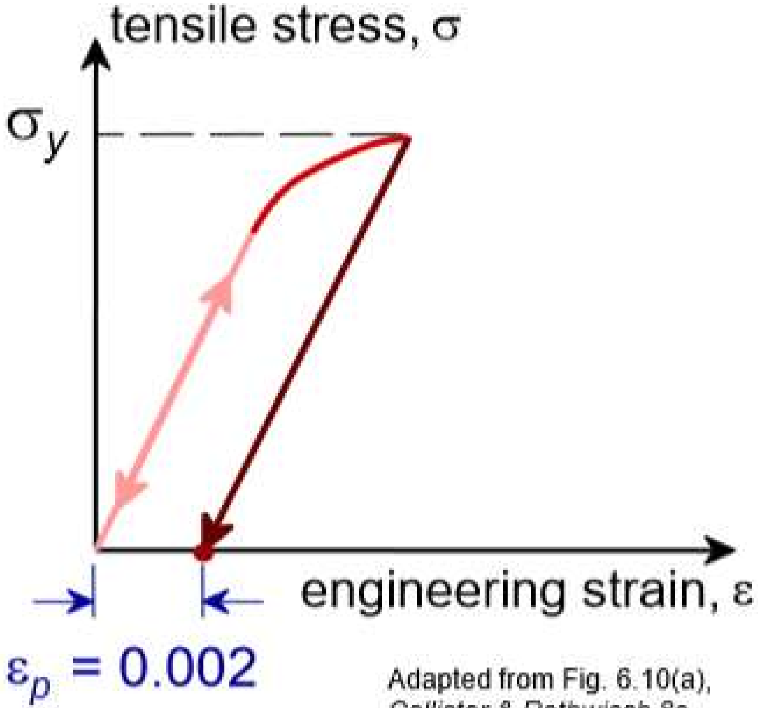


Adapted from Fig. 6.10(a), *Callister & Rethwisch 8e.*

Tensile properties - Yield Strength, σ_y

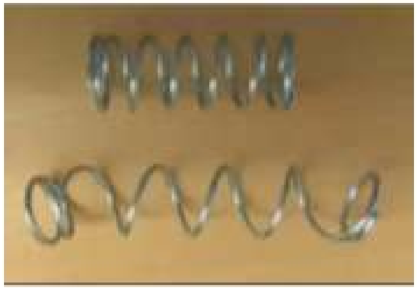
- Stress at which ***noticeable*** plastic deformation has occurred.

when $\varepsilon_p = 0.002$

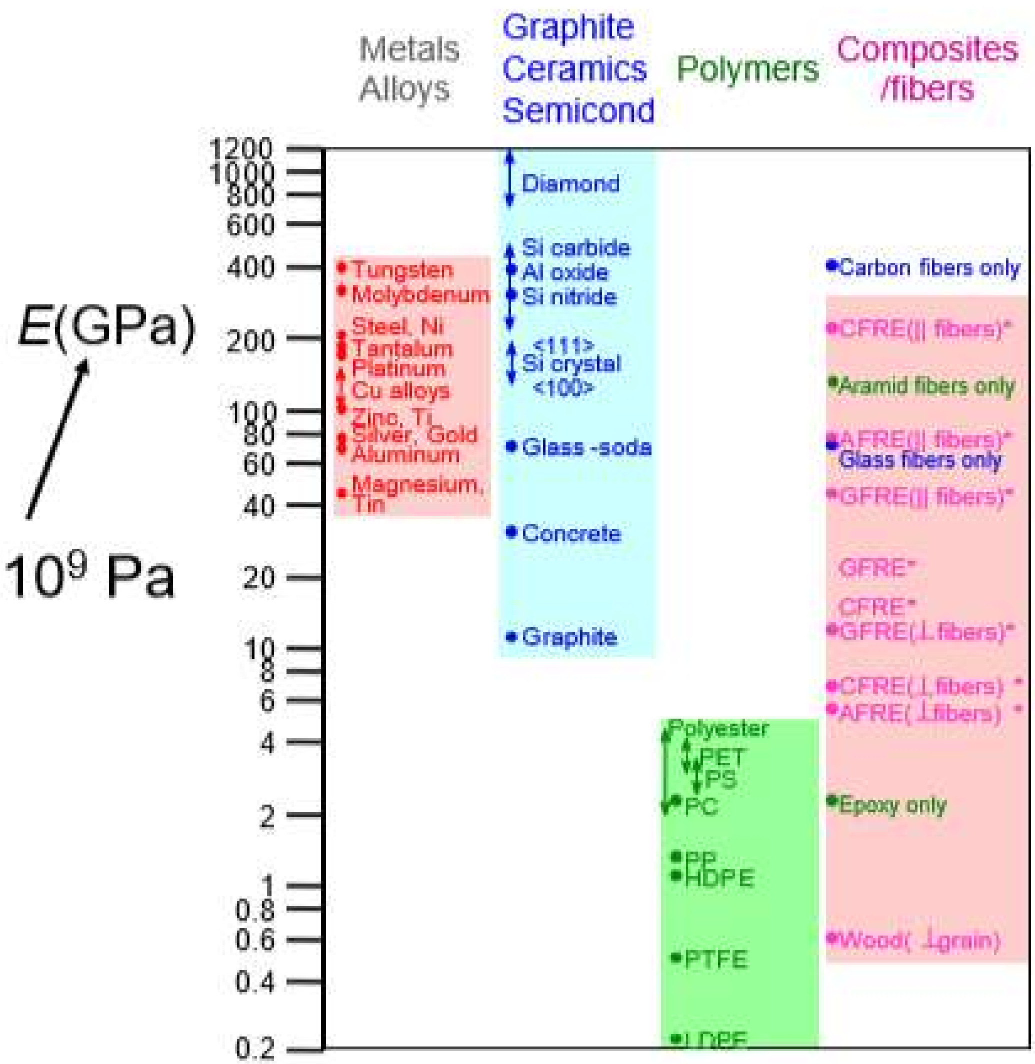


Adapted from Fig. 6.10(a), *Callister & Rethwisch 8e.*

σ_y = yield strength



Young's Moduli: Comparison



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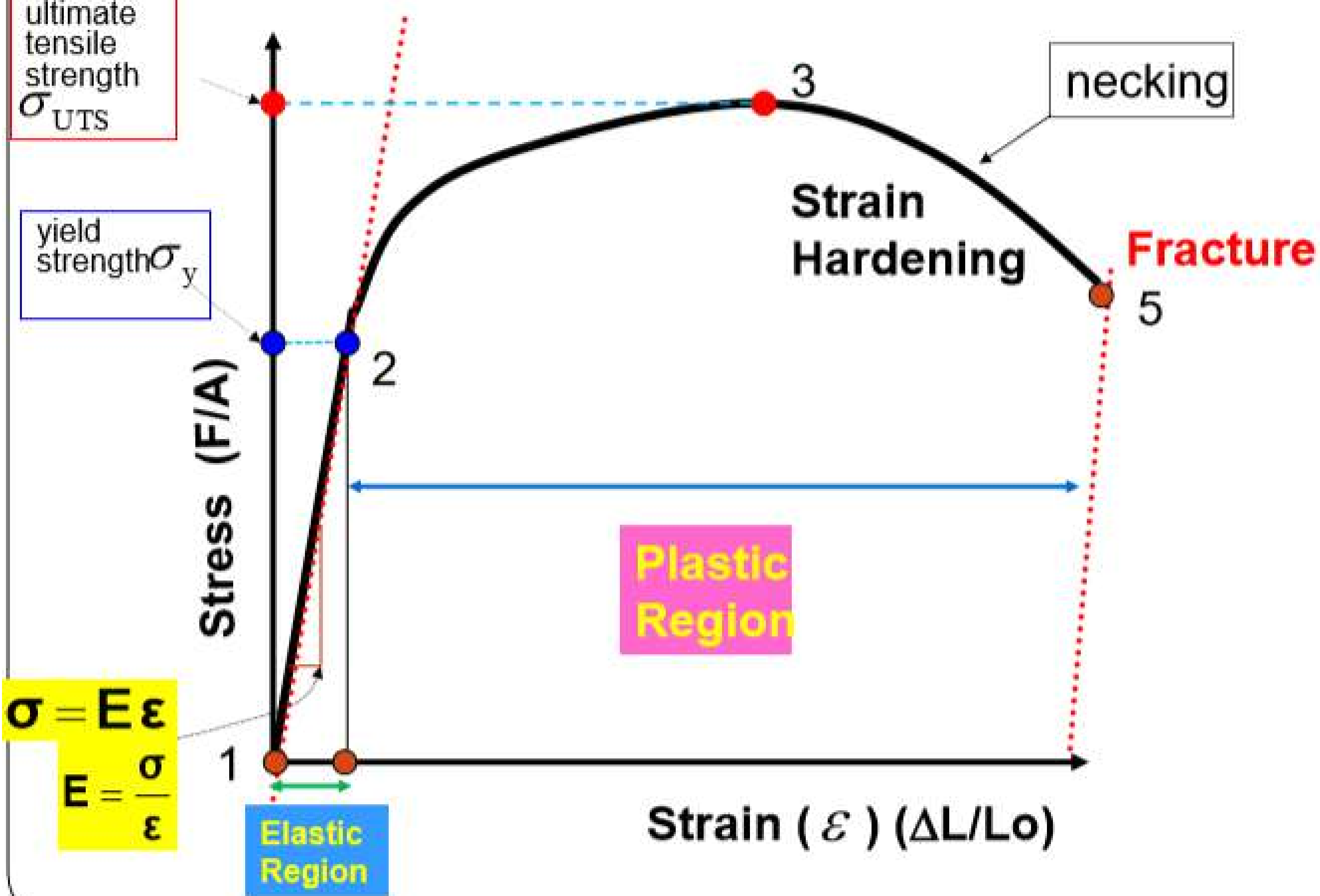
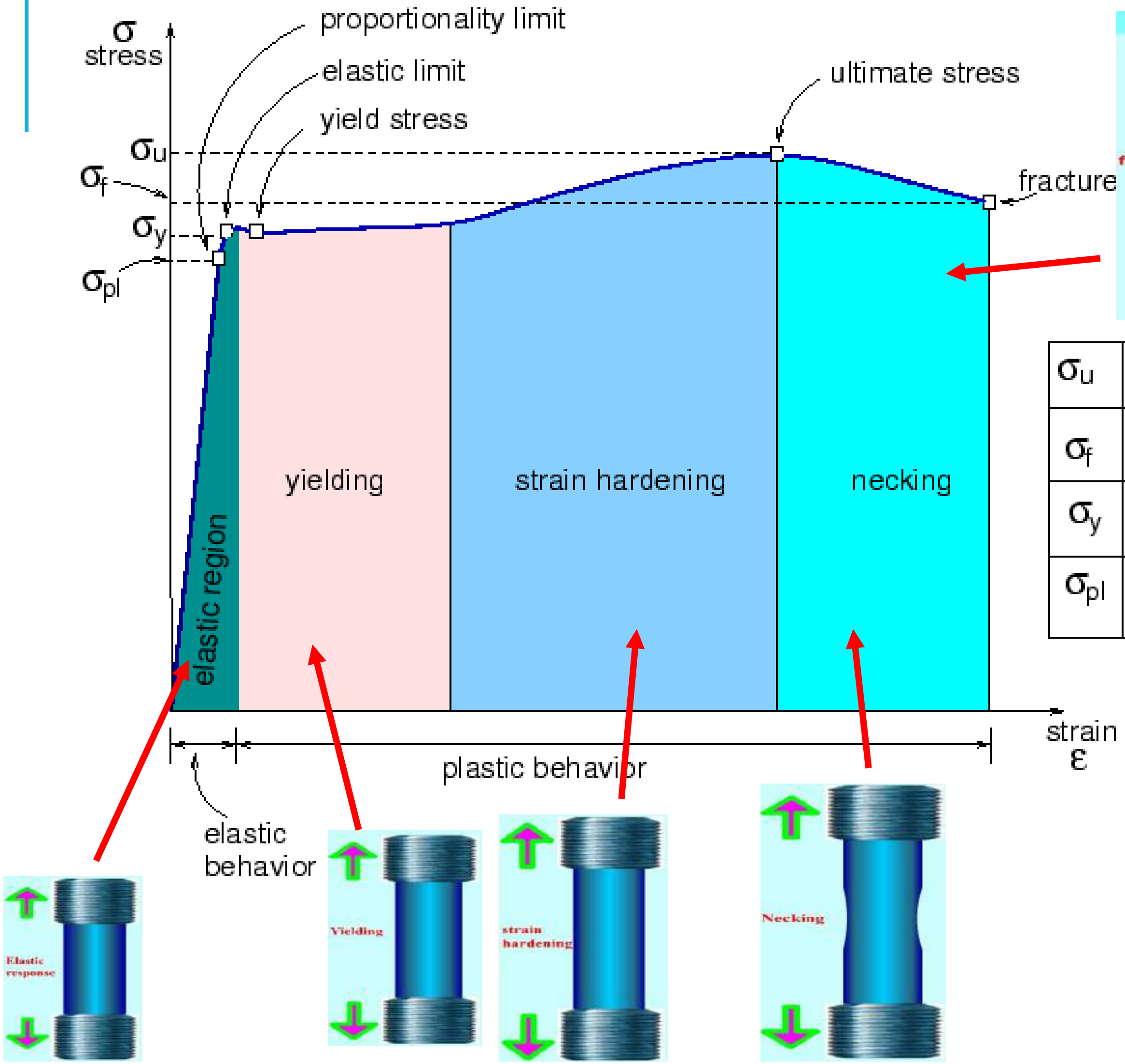
High modulus of elasticity – relatively stiff, do not deflect easily.

Stress-Strain Diagram



- This diagram is used to determine how material will react under a certain load.



σ_u	Ultimate stress
σ_f	Fracture stress
σ_y	Yield stress
σ_{pl}	Proportionality limit

Figure : Stress strain diagram

Typical regions that can be observed in a stress-strain curve are:

- Elastic region
- Yielding
- Strain Hardening
- Necking and Failure

STRESS AND STRAIN DIAGRAM

Elastic Range: material will resume its original dimension after load is removed

Linear elastic: straight line section from which E is defined *(Stiffness)*

Nonlinear elastic: material behaviors nonlinearly and ends at a point called elastic limit

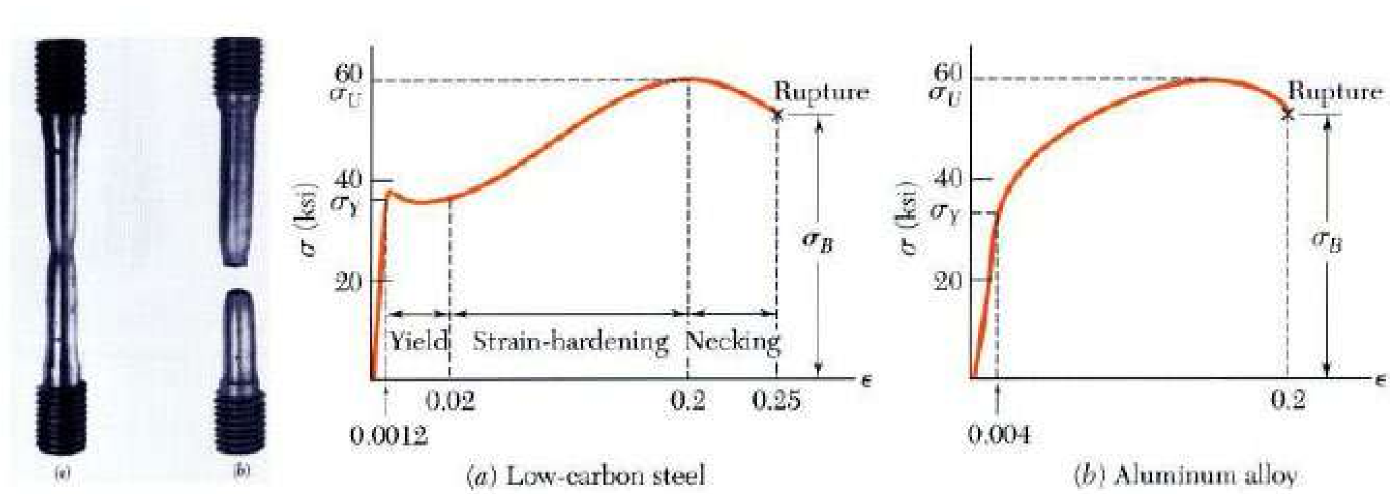
Plastic Range: Permanent deformation after load is removed

Yield point : Starting point of this range and it also defines the material's yield strength

Yield strength : Failure criterion

Ultimate strength: largest stress the material can bear Strain at fracture gives ductility.

STRESS AND STRAIN : DUCTILE MATERIAL



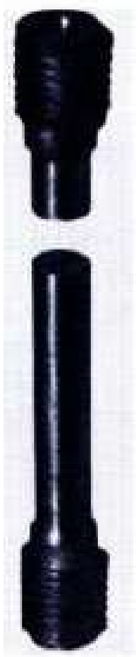
•Materials that undergo large strains before failure are classified as ductile.

• Ductile materials include mild steel, aluminum and some of its alloys, copper, magnesium, lead, molybdenum, nickel, brass, bronze, nylon, teflon and many others

STRESS & STRAIN DIAGRAM: BRITTLE MATERIAL

•Materials that fail in tension at relatively low values of strain are classified as brittle materials.

• Examples are concrete, stone, cast iron, glass, ceramic materials, and many common metallic alloys.



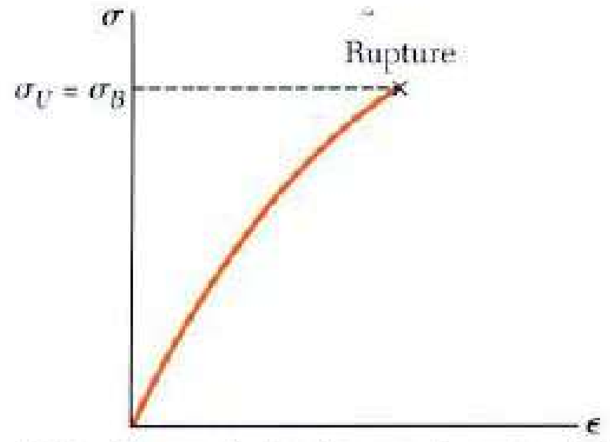
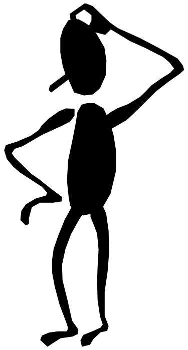


Fig. 2.11 Stress-strain diagram for a typical brittle material.



What are the differences between ductile fracture & brittle fracture?

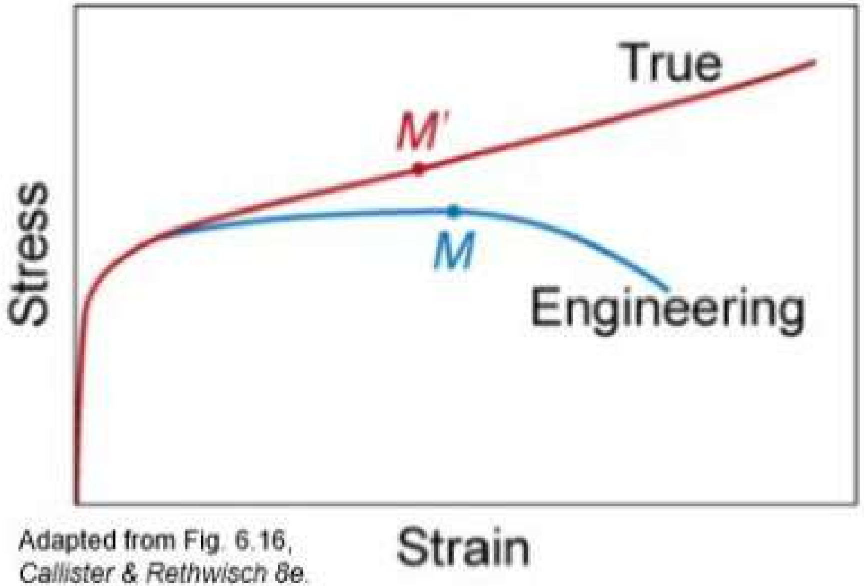
Ductile fracture	Brittle fracture
•Plastic deformation	•Small/ no plastic deformation
•High energy absorption before fracture	•Low energy absorption before fracture
•Characterized by slow crack propagation	•Characterized by rapid crack propagation
•Detectable failure	•Unexpected failure
•Eg: Metals, polymers	•Eg: Ceramics, polymers

True Stress & Strain

Note: Surface area changes when sample stretched

- True stress $\sigma_T = F / A_i$
- True strain $\varepsilon_T = \ln(l_i / l_0)$

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



Adapted from Fig. 6.16, *Callister & Rethwisch 8e.*

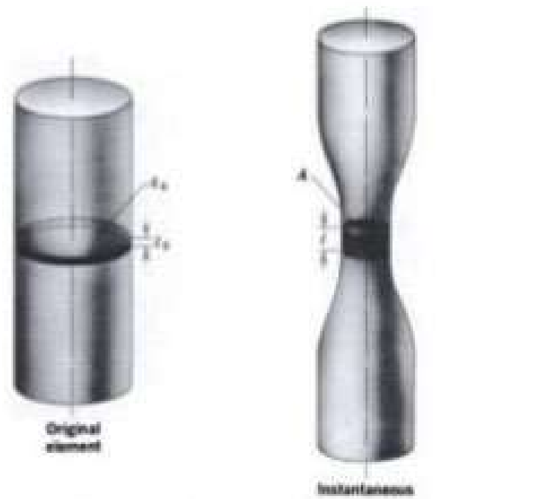


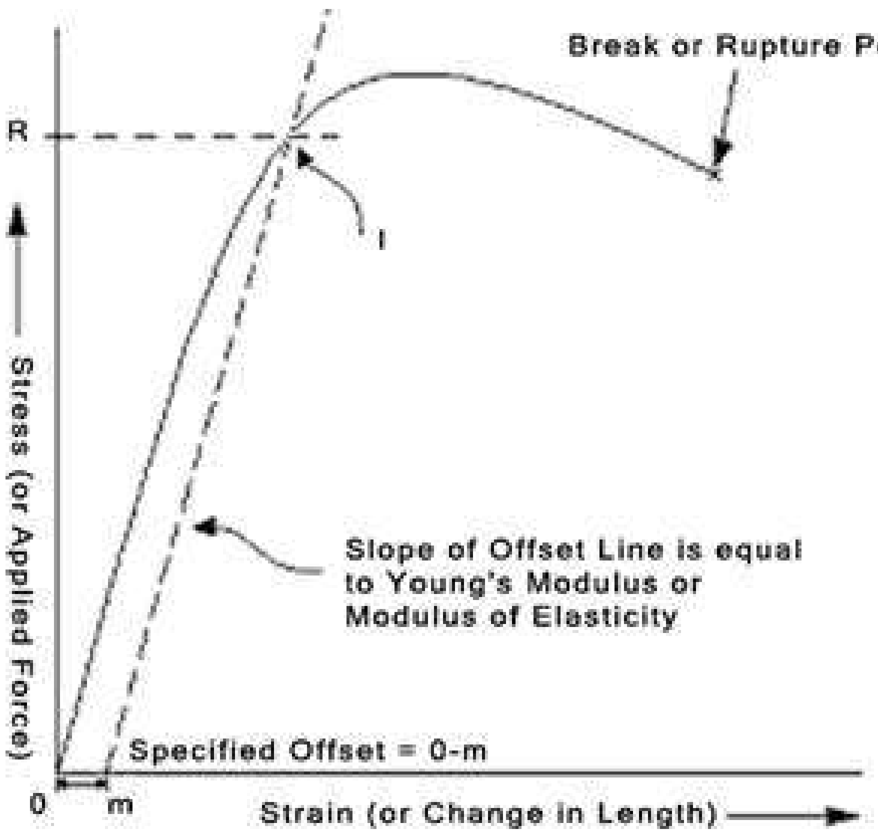
Figure 2.7 Localized plastic flow causes "necking" to occur in a tensile specimen.

THE MECHANICAL PROPERTIES DATA OBTAINED FROM THE TENSILE TEST (STRESS STRAIN CURVE) :

1. *Modulus of elasticity*
2. *Yield strength (0.2 offset)*
3. *Ultimate tensile strength*
4. *Ductility*
5. *Toughness*

1) Modulus of elasticity (stiffness)

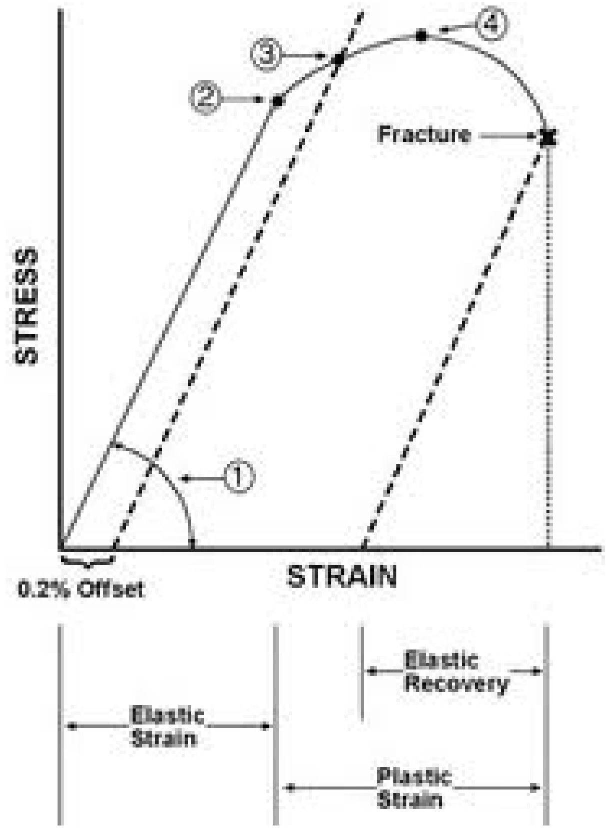
- a.k.a. Young Modulus.
- Related to the bonding strength between the atoms in a metal or alloy.
- High elasticity === very stiff === do not deflect easily === if the load on the specimen is released, the specimen will return to its original length.



$$E = \frac{\sigma}{\varepsilon} = \frac{\frac{F}{A_0}}{\frac{\Delta L}{L_0}}$$

2) Yield strength

- It is a strength which a metal or alloy shows significant plastic deformation.
- If there is no definite point on the stress strain curve, the yield strength is chosen when 0.2% plastic strain has taken place.
- 0.2% yield strength = 0.2% offset yield strength.

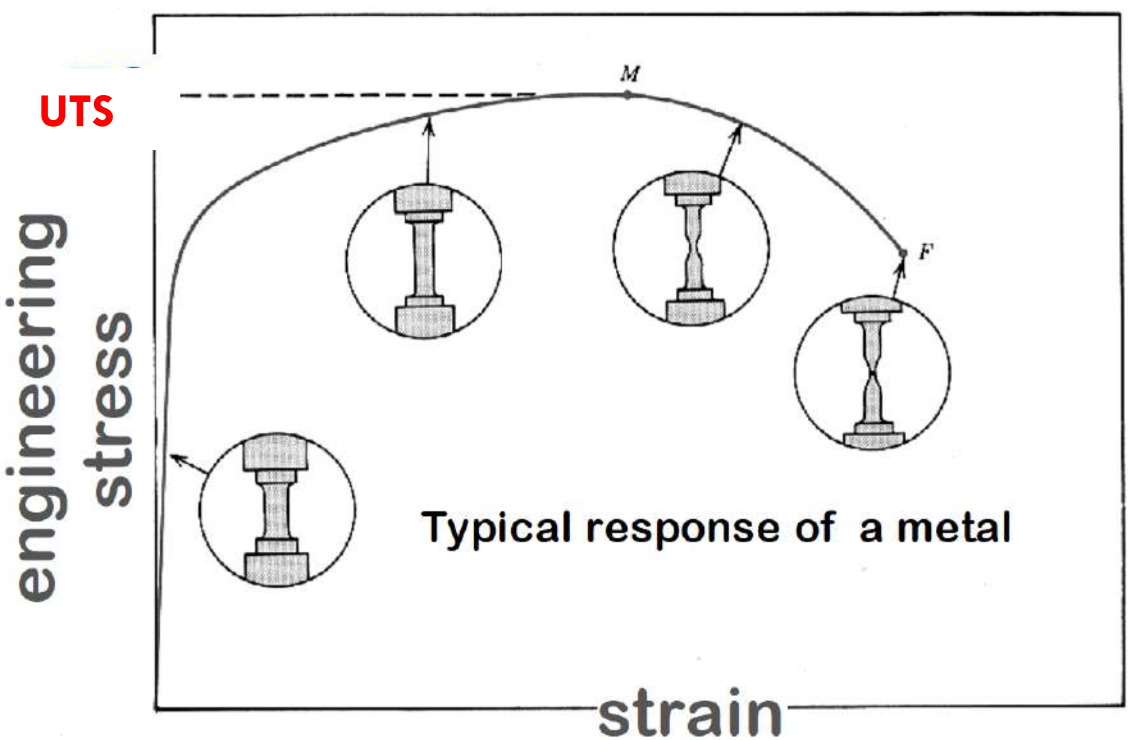


3) Ultimate tensile strength

- Max strength.

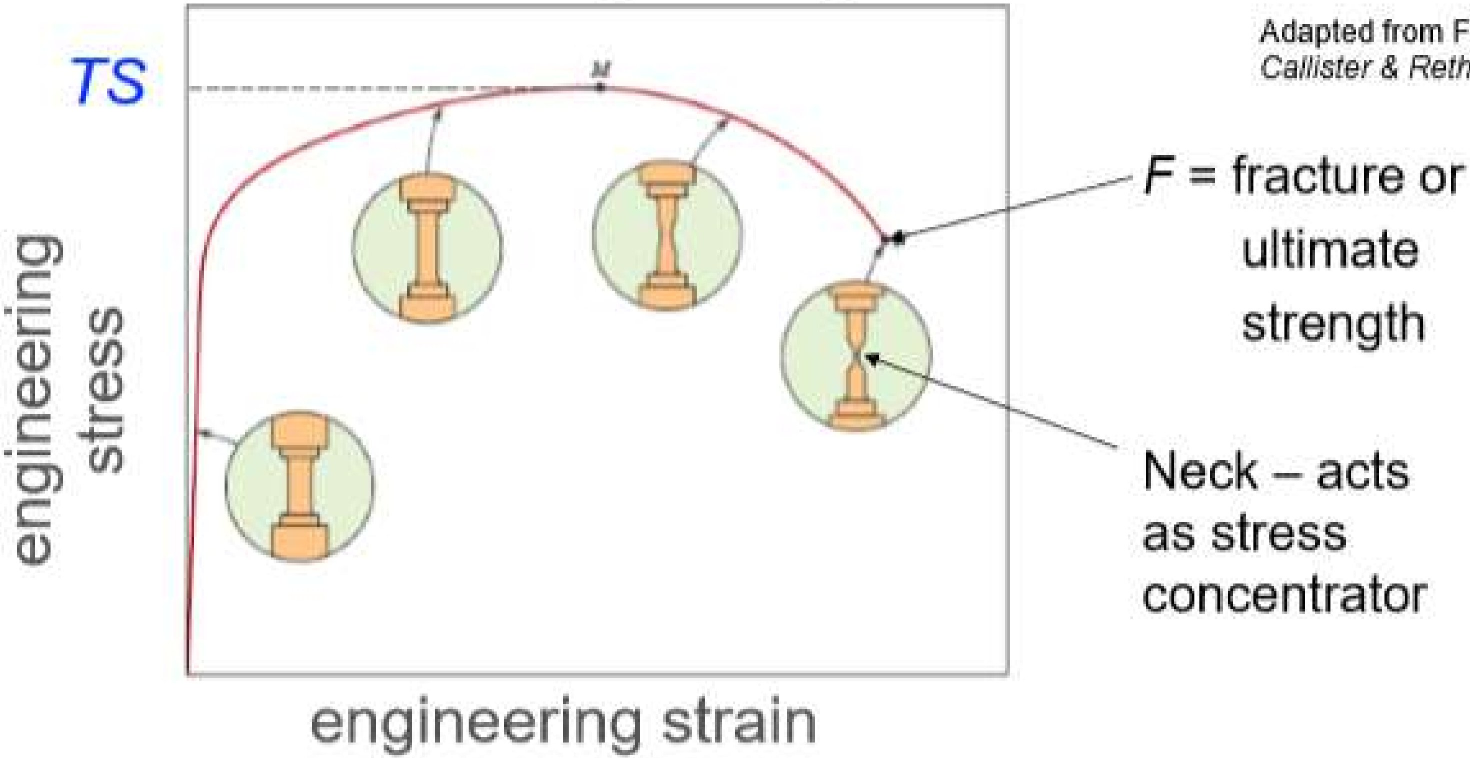
- Ultimate tensile strength can give indication of the presence defects.

defects occur (metal) = UTS lower



Tensile Strength, TS

- Maximum stress on engineering stress-strain curve.



Adapted from Fig. 6.11, *Callister & Rethwisch 8e.*

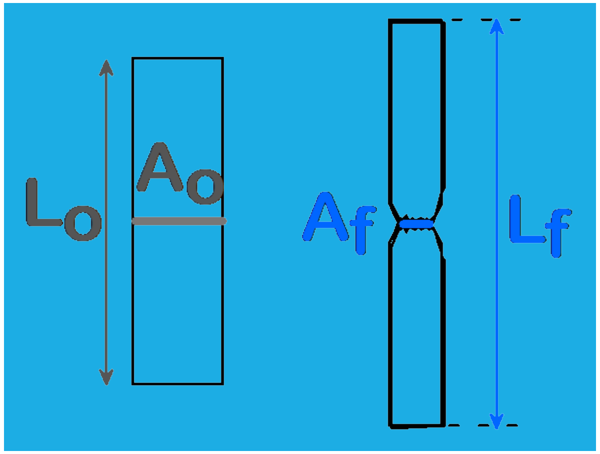
- Metals: occurs when noticeable necking starts.
- Polymers: occurs when polymer backbone chains are aligned and about to break.
- Ceramics: occurs when crack propagation start

4) Ductility

% elongation at fracture

- Ductility of metals is expressed as % elongation.
- Higher ductility = higher the % of elongation.

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



- Besides measuring ductility, the % of elongation at fracture can be used as an index of the metal's quality.

Porosity (metal) = % of elongation decrease

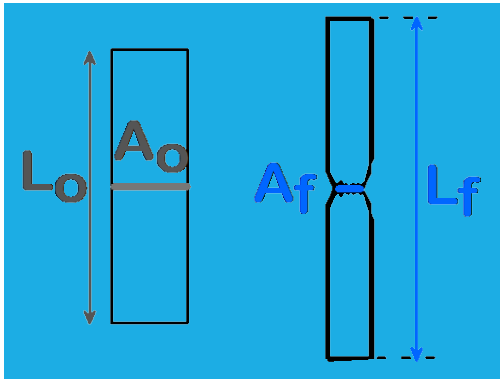
% reduction in area at fracture

- Ductility of metals can also be expressed as % reduction in area.

- Used specimen with 12.7mm diameter.

- After the test, the diameter of the reduced cross section at the fracture is measured (initial and final diameter).

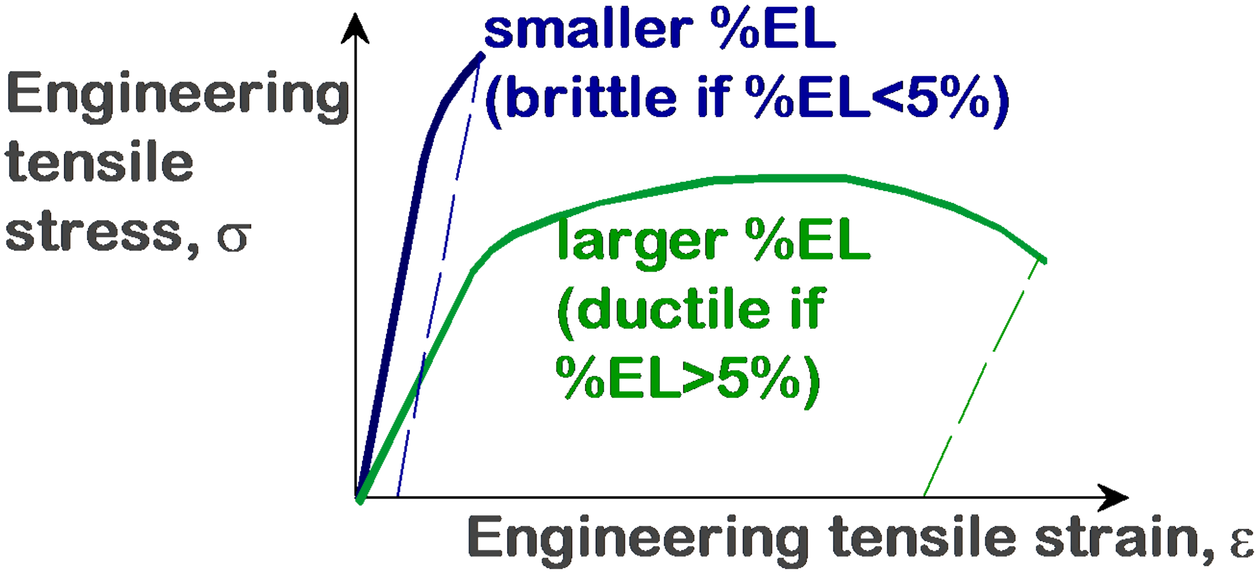
$$\%AR = \frac{A_o - A_f}{A_o} x100$$

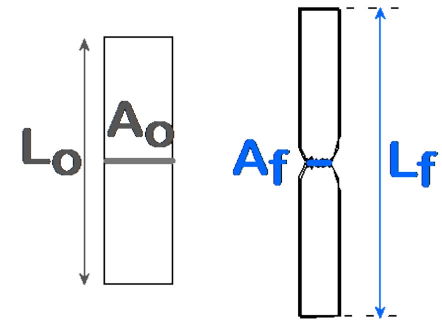


- Besides measuring ductility, the % of reduction in area at fracture can be used as an index of the metal's quality.

Porosity (metal) = % of reduction in area decrease

- Plastic tensile strain at failure:

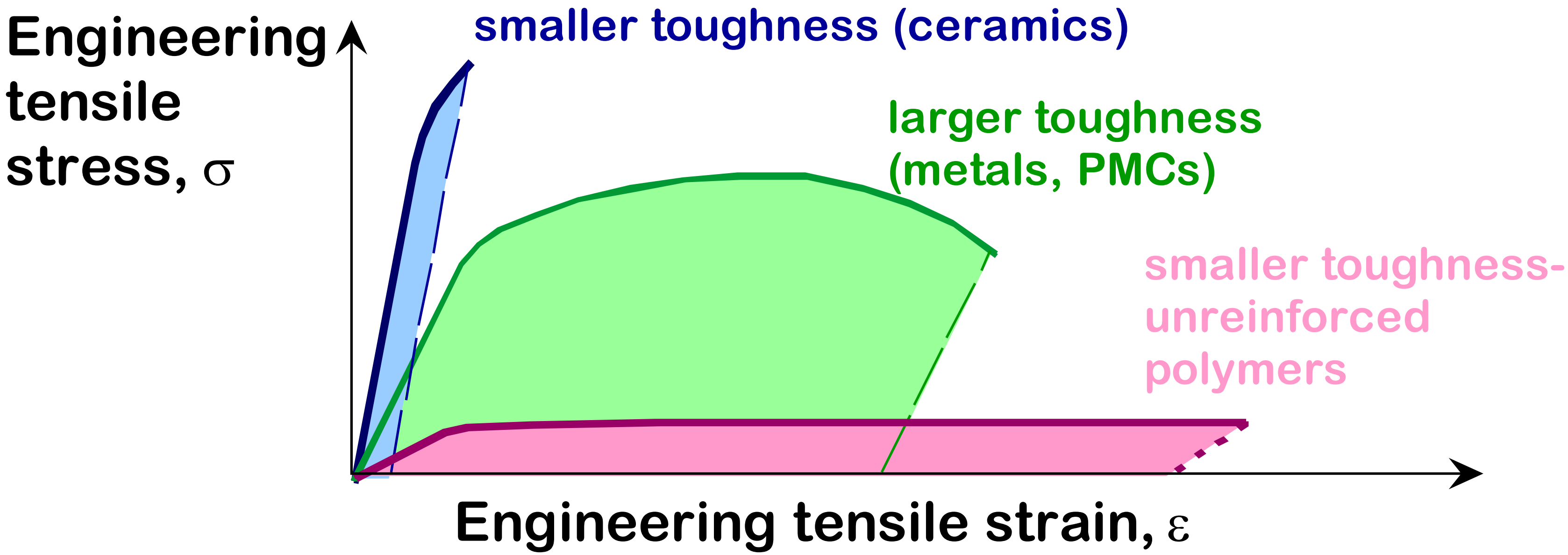


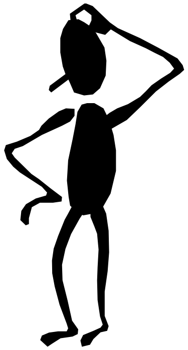


- Note: %AR and %EL are often comparable.
  --Reason: crystal slip does not change material volume.
  --%AR > %EL possible if internal voids form in neck.

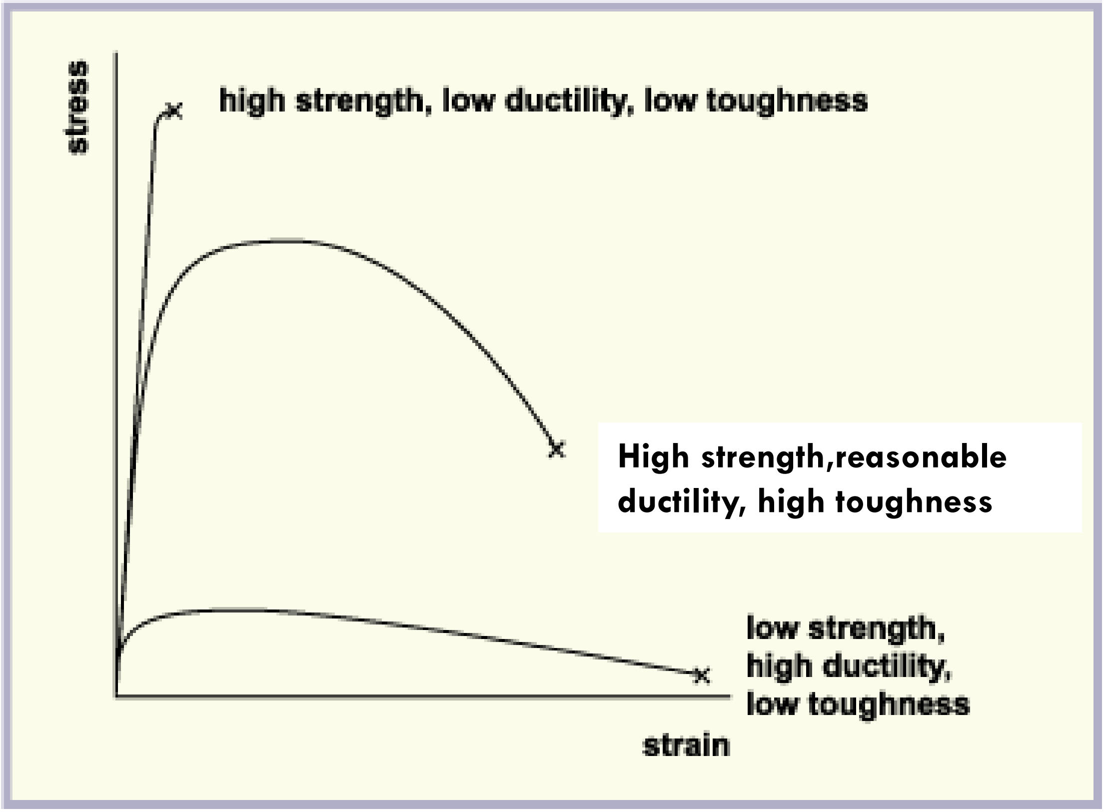
5) TOUGHNESS

- It is the extent to which a material can withstand shocks.
- Approximate by the area under the stress-strain curve.



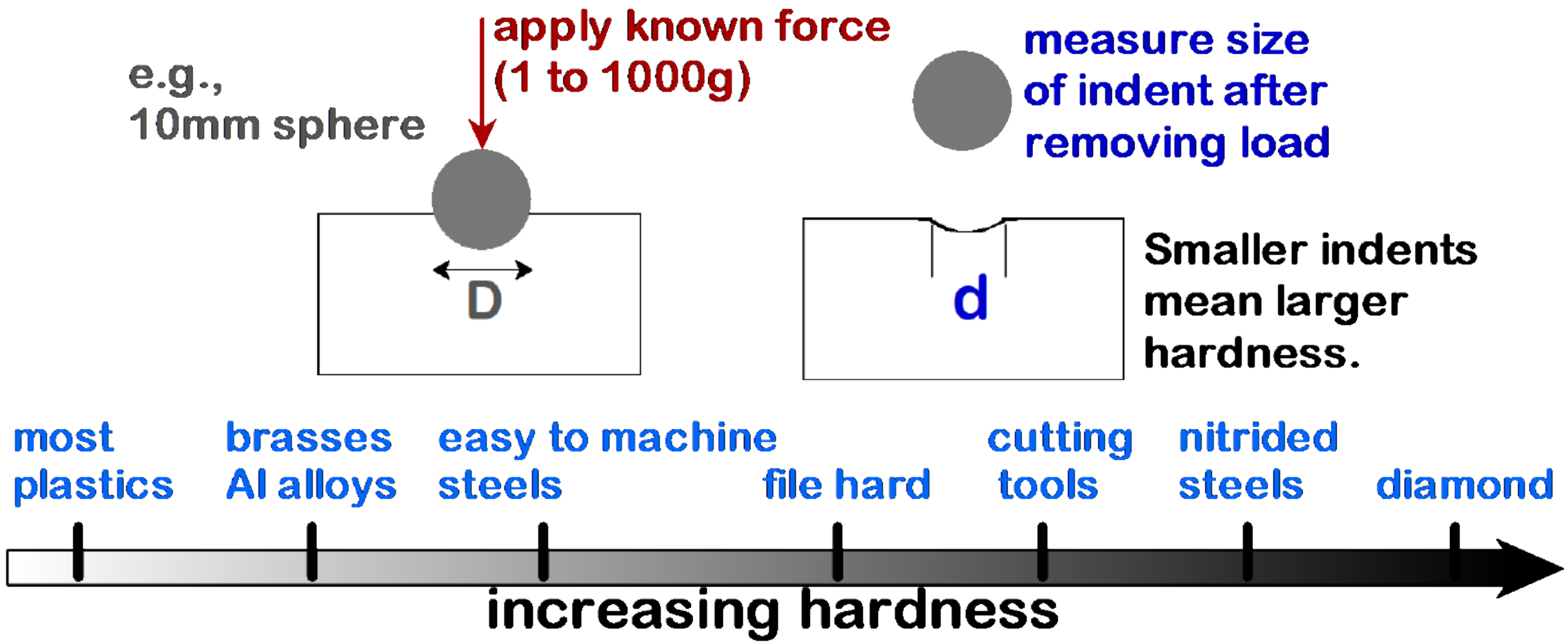


Look at the graph below and discuss.



HARDNESS

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

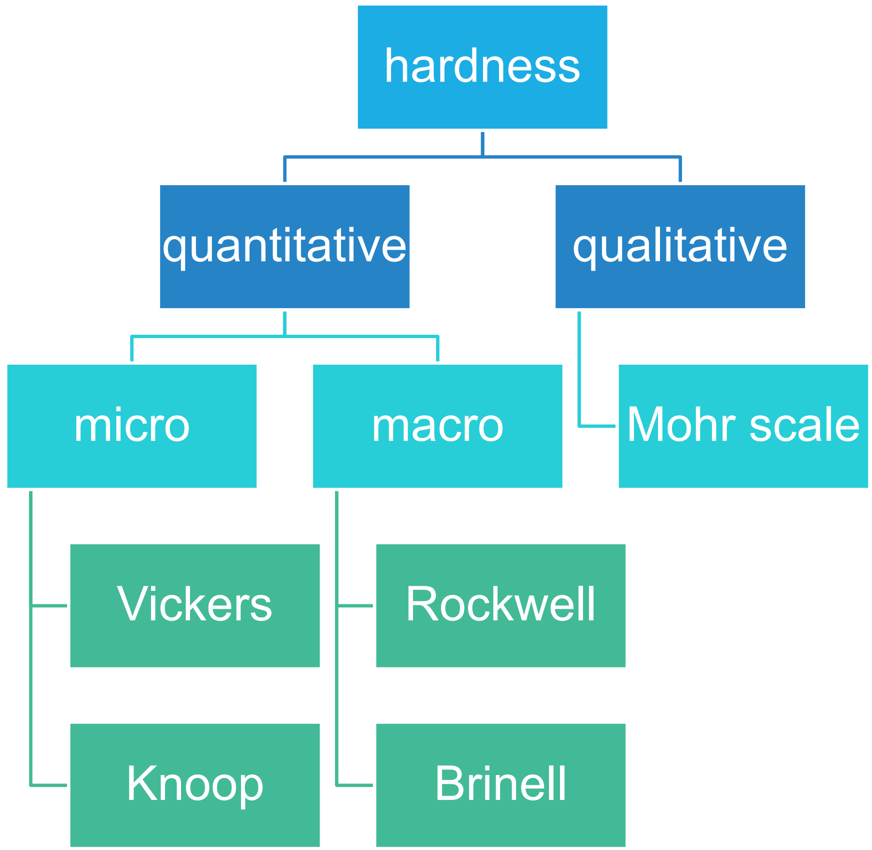


Hardness: Measurement

- 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

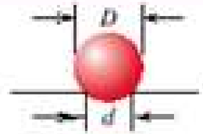
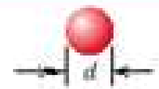
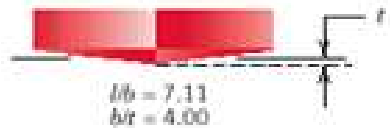
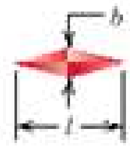
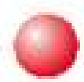
- HB = Brinell Hardness
  - *TS* (psia) = 500 x HB
  - *TS* (MPa) = 3.45 x HB

HARDNESS MEASUREMENT METHODS



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			P	$HB = \dfrac{2P}{\pi D[D - \sqrt{D^2 - d^2}]}$
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.

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 sy.
- Toughness: The energy needed to break a unit volume of material.
- Ductility: The plastic strain at failure.
- Hardness: The ability of material to resist the deformation