Chapter 5

Mechanical Properties

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Chemical Engineering Department
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Outline

- **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?

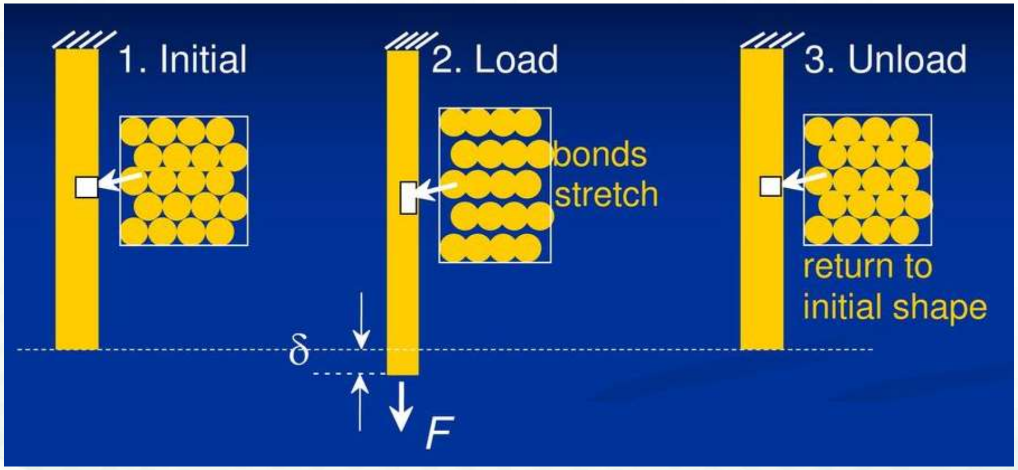
Introduction

- Engineers are primarily concerned with the development and design of machines, structures etc.
- These products are often subjected to forces/deformations, resulting in stresses/strains, the properties of materials under the action of forces and deformations becomes an important engineering consideration.
- The properties of materials when subjected to stresses and strains are called "mechanical properties". In other words the properties that determine the behavior of engineering mats under applied forces are called "mechanical properties".

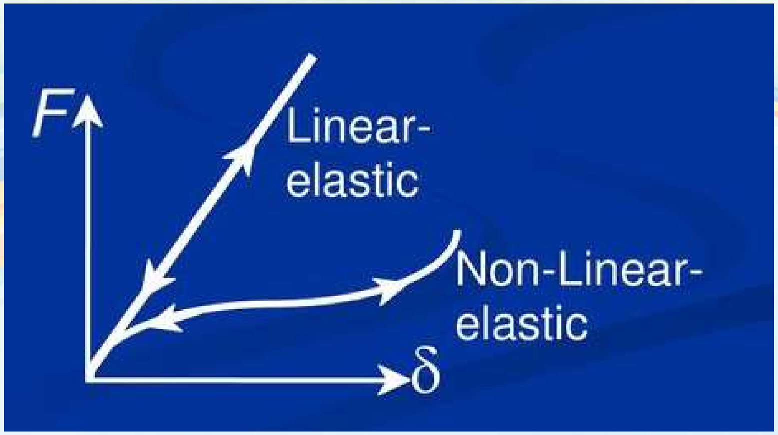
Deformation

- The response of a material to applied forces depends on the type and nature of the bond and the structural arrangement of atoms, molecules or ions.
- Basic deformation types for load carrying materials are:
  1. Elastic deformation (deformations are instantaneously recoverable)
  2. Plastic deformation (non-recoverable)
  3. Viscous deformation (time dependent deformation)
- There are four principal ways in which a load may be applied: namely, tension, compression, shear, and tension

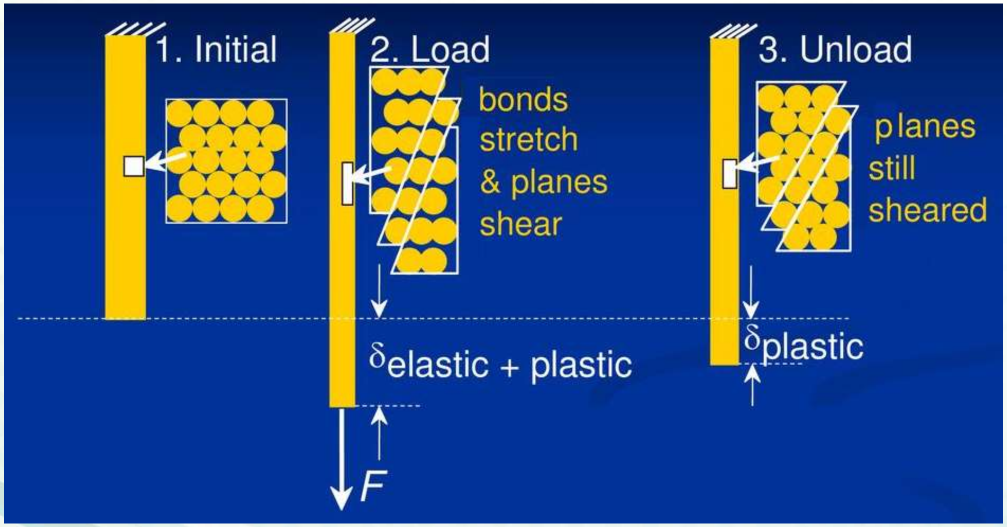
Elastic Deformation



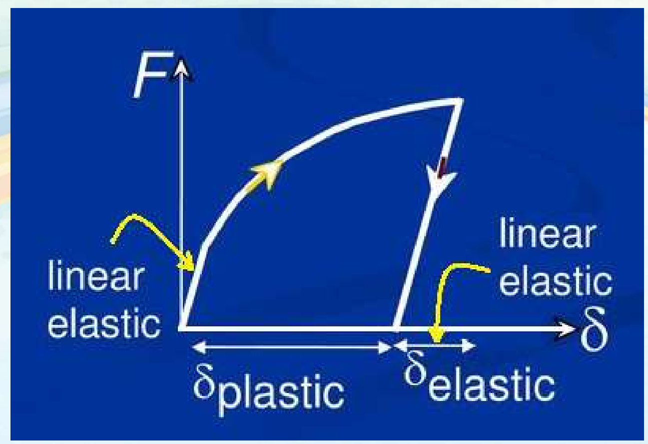
- *Return to the original shape when the applied load is removed.*
- *Elastic means reversible!*



Plastic Deformation

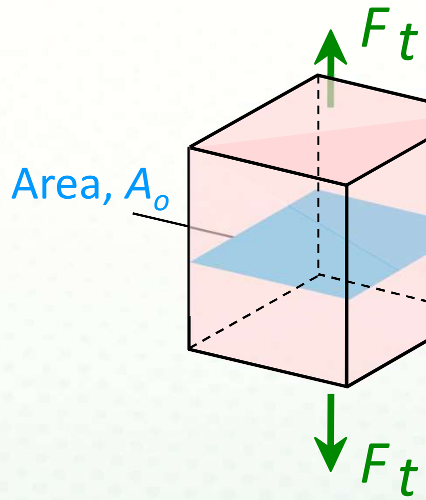


- Could not return to the original shape when the applied load is removed.
- Plastic means permanent!



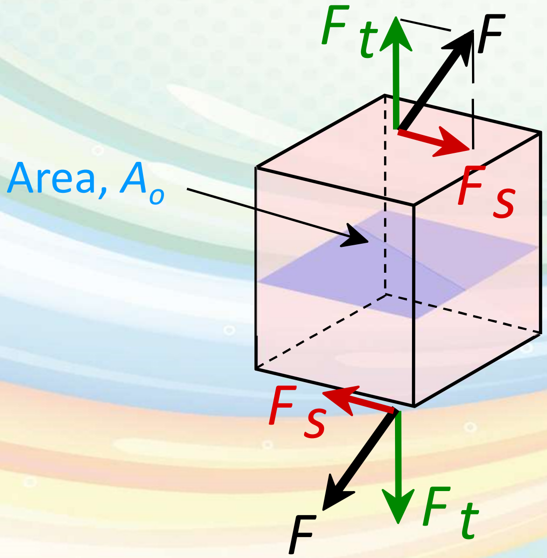
Engineering Stress

- *Tensile stress is the elongation of the material when a stretching force is applied along with the axis of applied force.*



$$\sigma = \frac{F_t}{A_0} = \frac{lb_f}{in^2} \text{ or } \frac{N}{m^2}$$

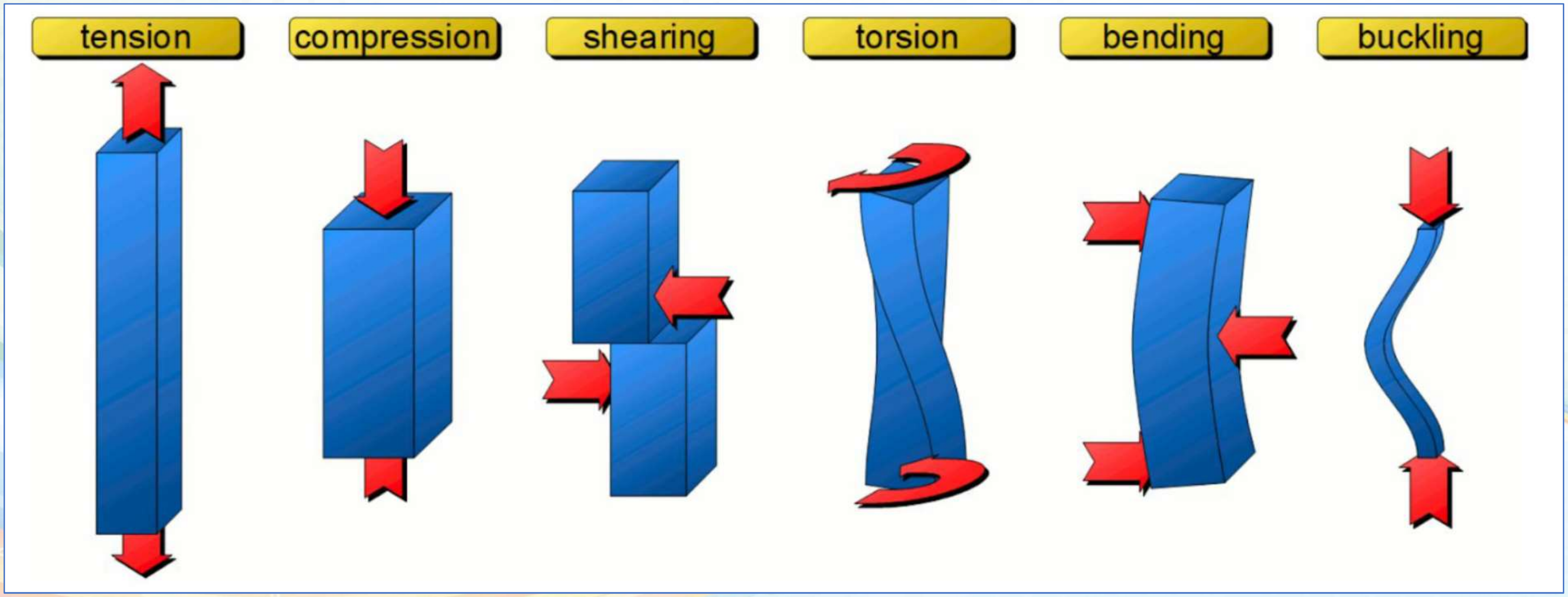
A_o is the original area before loading



- *Shear stress, is the component of stress coplanar with a material cross section. It arises from the shear force, the component of force vector parallel to the material cross section.*

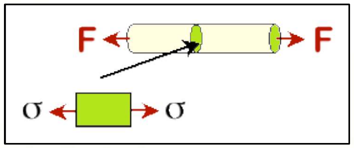
$$\tau = \frac{F_s}{A_0}$$

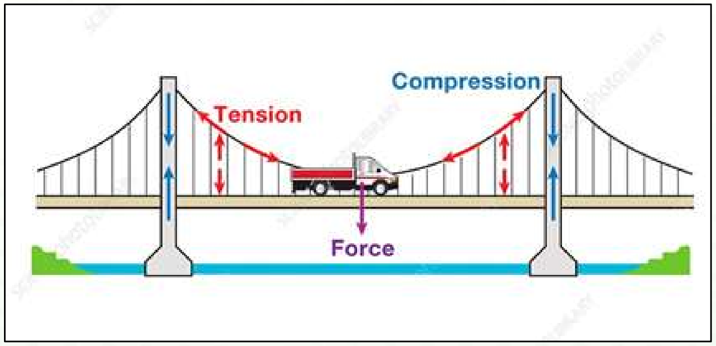
Patterns of Deformation

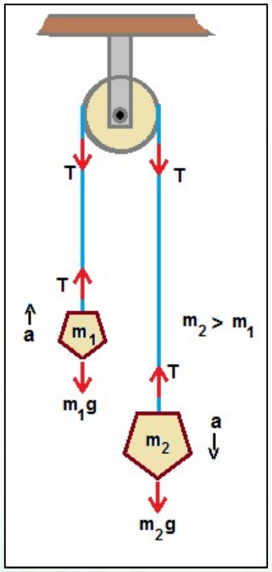


Common States of Stress

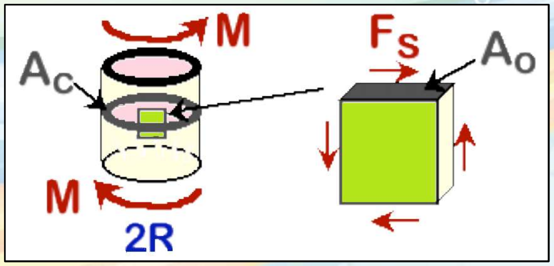
- *Simple tension:* $\sigma = \frac{F_t}{A_0}$

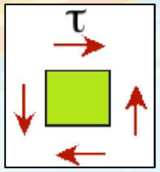






- *Simple shear:* $\tau = \frac{F_s}{A_0}$

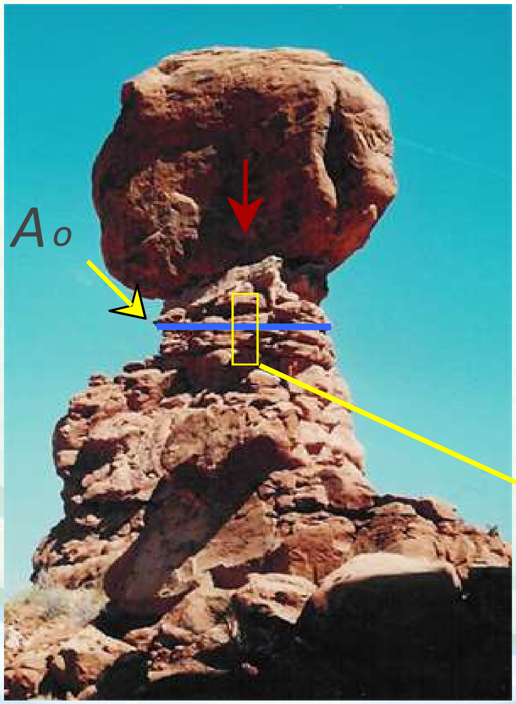


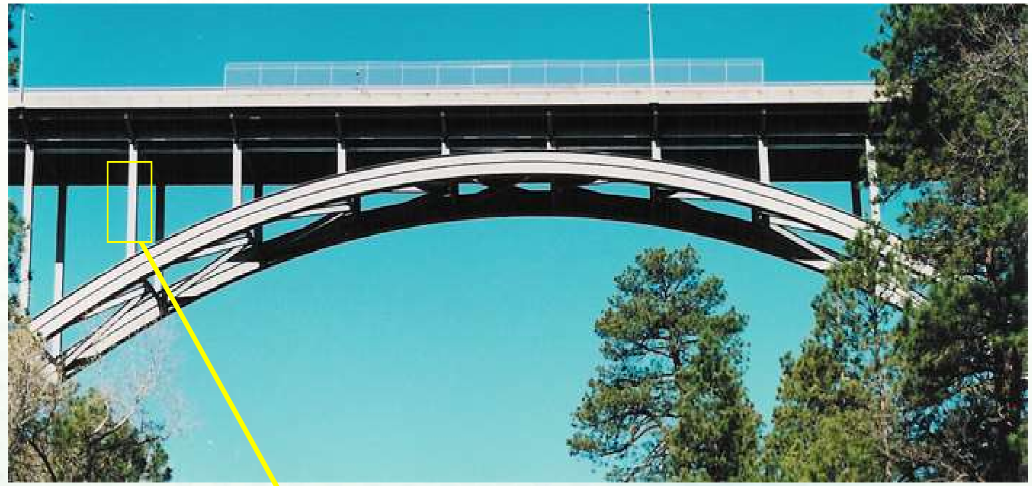


In this case, shear stress

$$\tau = \frac{M}{RA_c}$$

Simple compression:



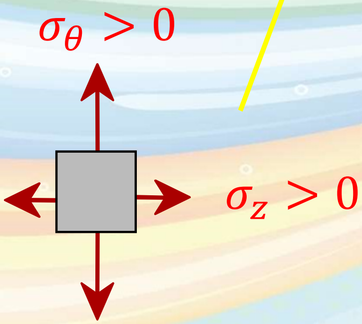


$$\sigma = \frac{F}{A_o}$$

Note: compressive structure member (σ < 0 here).

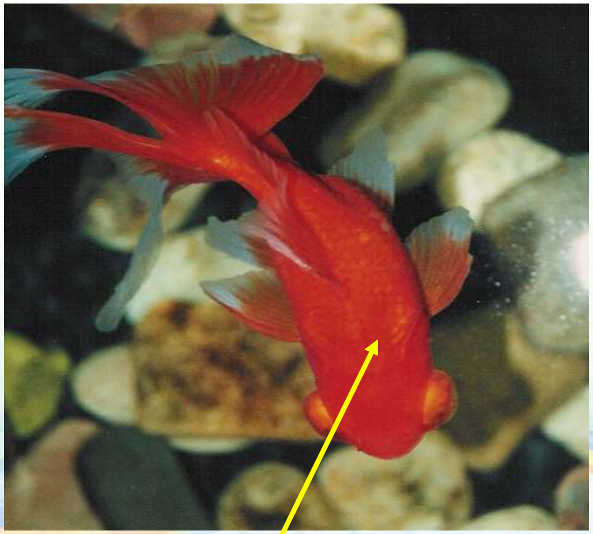
Bi-axial tension

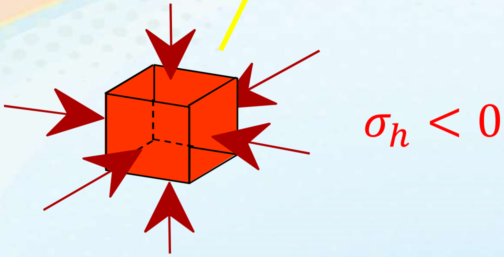
Pressurized tank



Hydrostatic compression

Fish under water



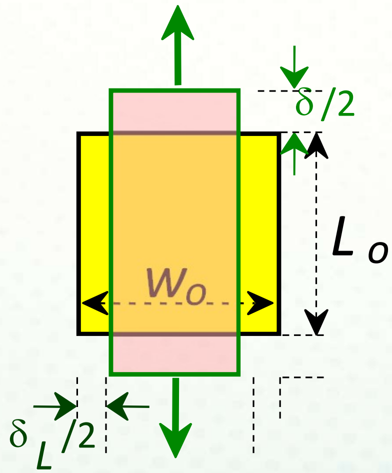


Engineering Strain

Tensile strain

- strain is defined as the change in the shape of an object when stress is applied.
- Strain is always dimensionless.

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



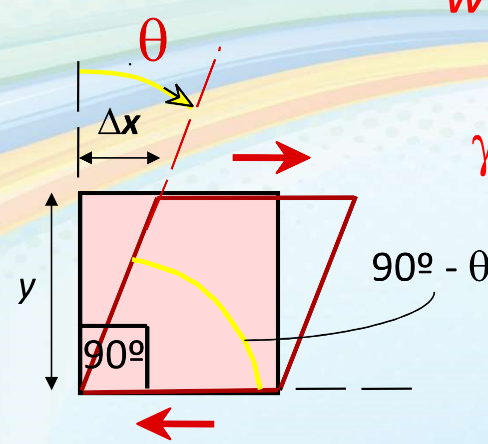
Lateral strain

- Also known as transverse strain, is defined as the ratio of the change in diameter of a circular bar of a material to its diameter due to deformation in the longitudinal direction

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

Shear strain

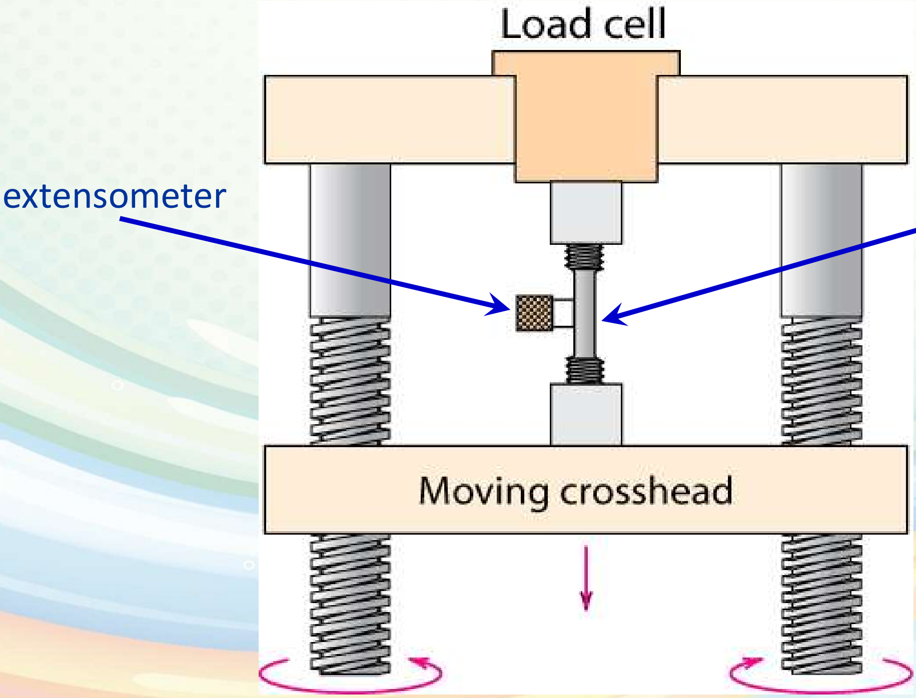
- is the ratio of the change in deformation to its original length perpendicular to the axes of the member due to shear stress. Shear stress is stress in parallel to the cross section of the structural member



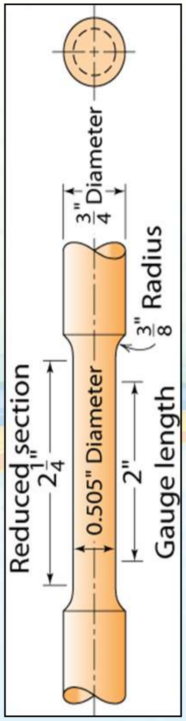
$$\gamma = \Delta x/y = \tan\theta$$

Stress-Strain Testing

Typical tensile test machine



Typical tensile specimen



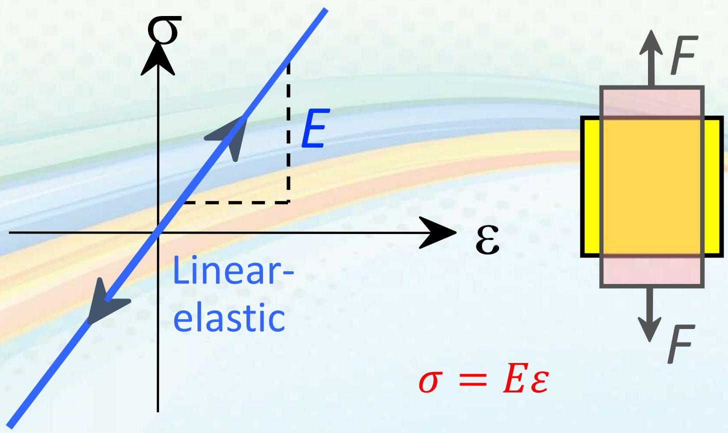
Linear Elastic Properties

Modulus of Elasticity, E:

- Modulus of Elasticity, also known as Elastic Modulus or simply Modulus or Young's modulus, is the measurement of a material's elasticity. Elastic modulus quantifies a material's resistance to non-permanent, or elastic, deformation.

Hooke's Law:

- Law of elasticity discovered by the English scientist Robert Hooke in 1660, which states that, for relatively small deformations of an object, the displacement or size of the deformation is directly proportional to the deforming force or load.

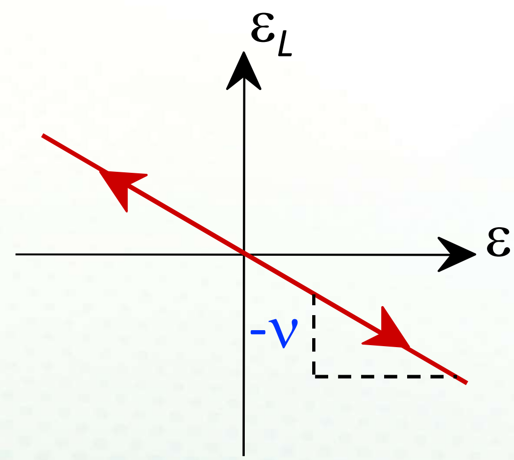


$$\sigma = E\varepsilon$$

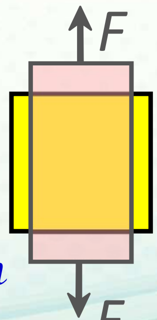
Units of E: [GPa] or [psi]

Poisson's ratio, n

➢ *Poisson's ratio is defined as the ratio of the change in the width per unit width of a material, to the change in its length per unit length, as a result of strain*



$$\nu = -\frac{\varepsilon_{Later}}{\varepsilon_{Longitudinal}}$$



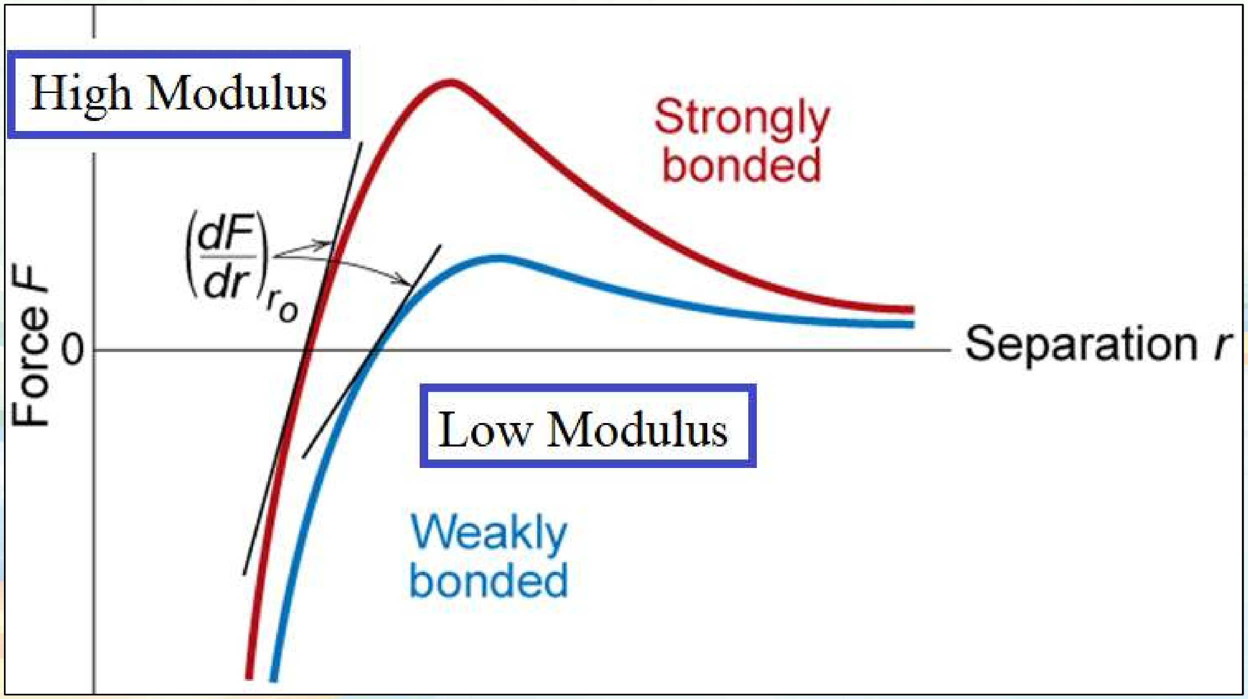
- *Longitudinal strain: in the direction of the applied force*
- *Lateral strain: in the transverse direction*

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

- *Units of ν: dimensionless*

Mechanical Properties

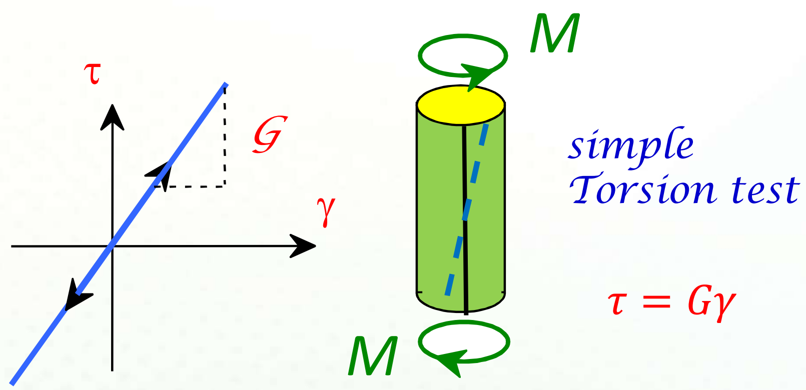
- *Slope of stress strain plot (which is proportional to the elastic modulus) depends on bond strength of metal.*



Other Elastic Properties

Elastic Shear modulus, G:

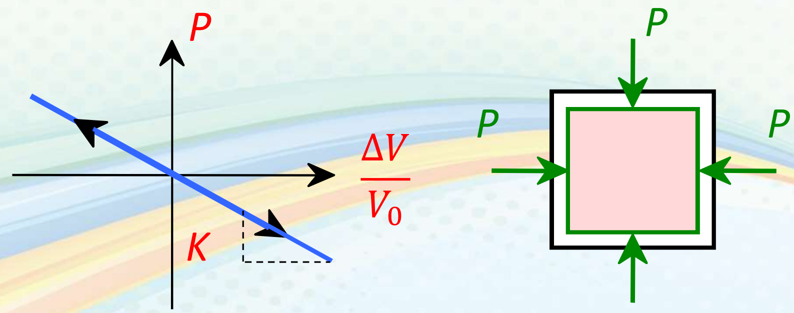
- Or the modulus of rigidity, is derived from the torsion of a cylindrical test piece. It describes the material's response to shear stress.



$$\tau = G\gamma$$

Elastic Bulk modulus, K:

- Bulk modulus, numerical constant that describes the elastic properties of a solid or fluid when it is under pressure on all surfaces.



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

V_o =Initial volume

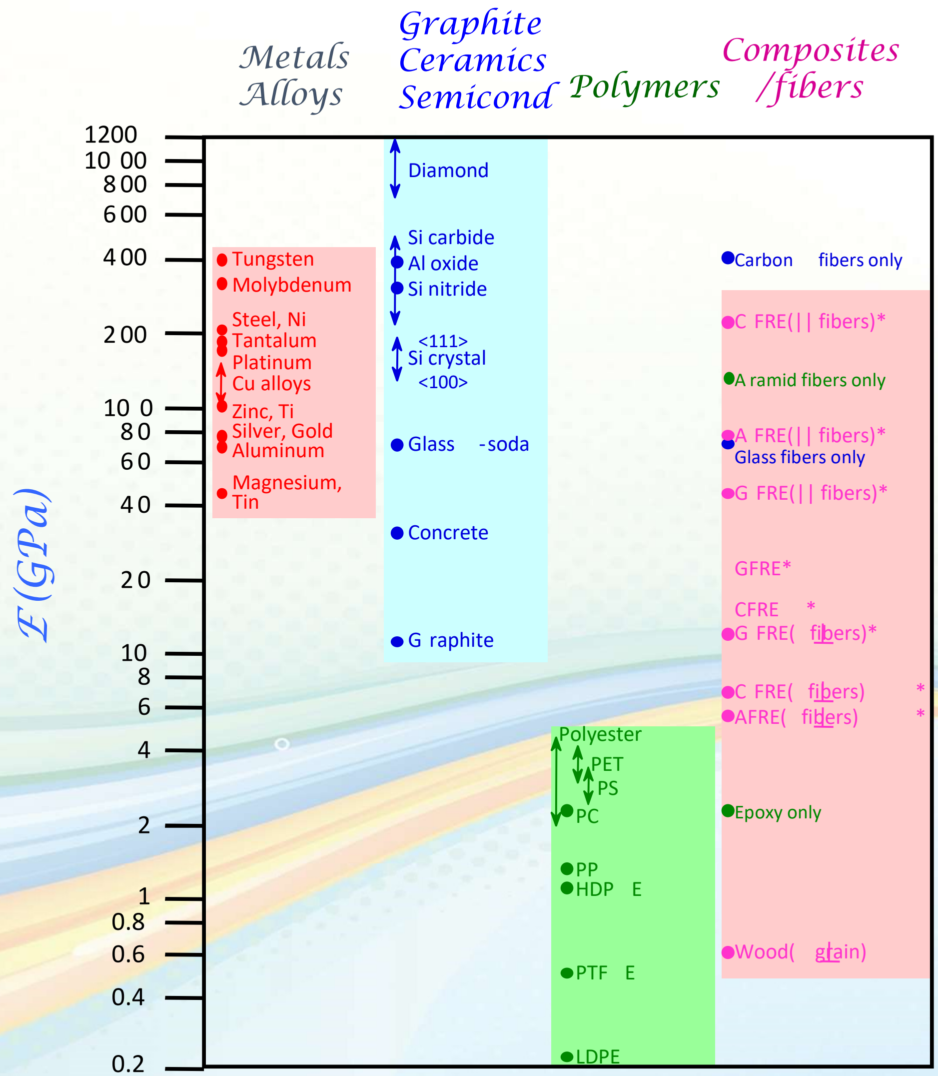
DV = change in volume

- Special relations for isotropic materials:

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

Young's Moduli: Comparison

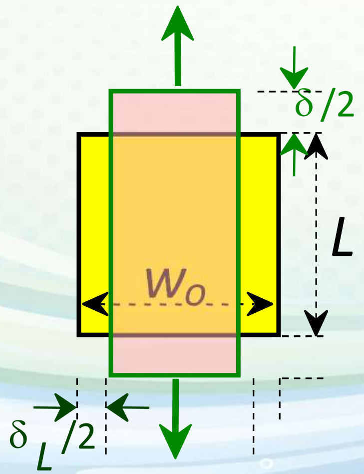
$Gpa = 10^9 Pa$



Useful Linear Elastic Relationships

Simple tension

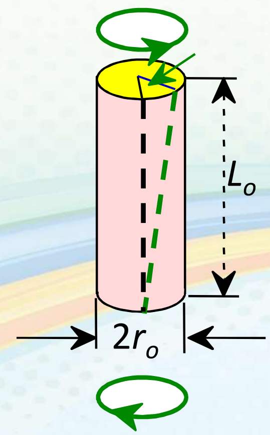
$$\delta = \frac{FL_0}{EA_0} \qquad \delta_L = -\nu\frac{Fw_0}{EA_0}$$



Simple torsion

$$\alpha = \frac{2ML_0}{\pi r_0^4 G}$$

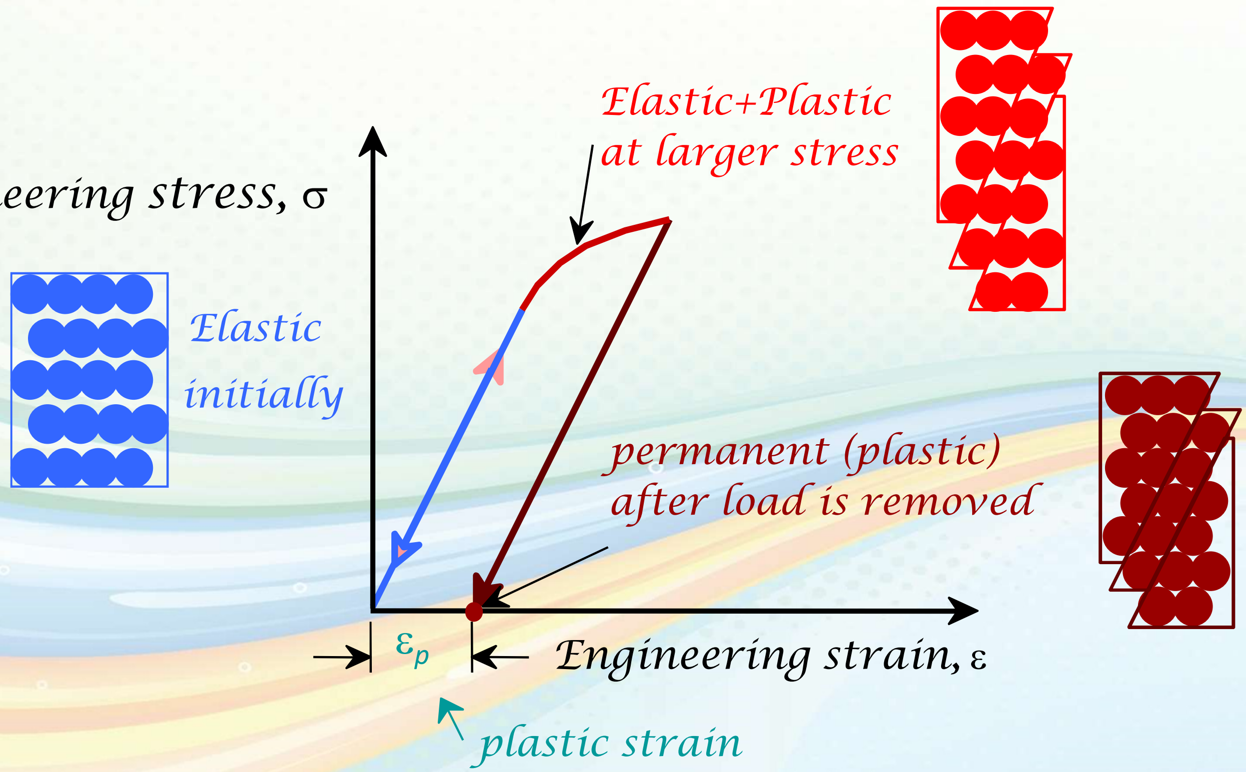
$\mathcal{M}$ = moment
α = angle of twist



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

Plastic (Permanent) Deformation

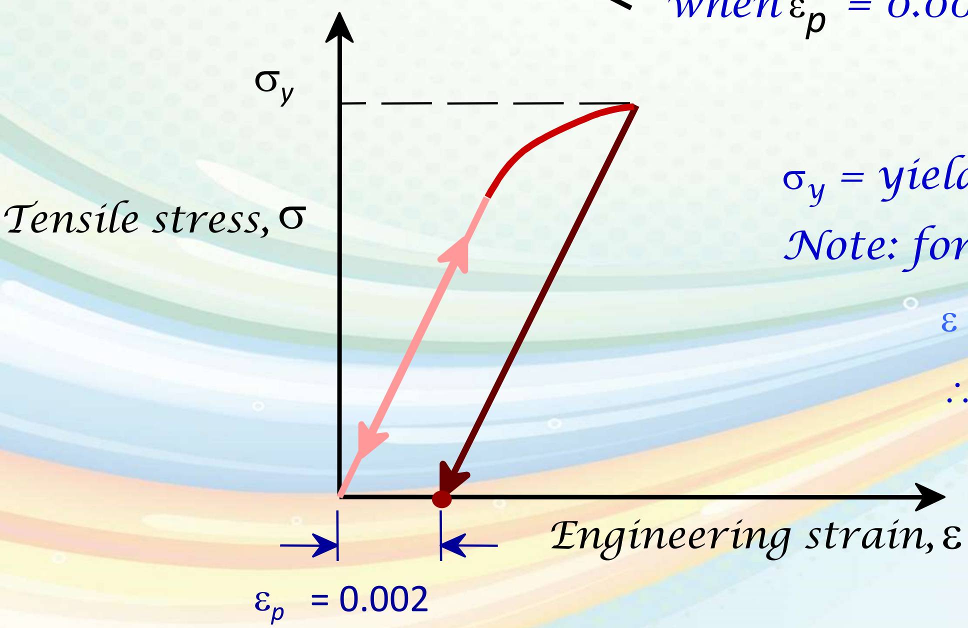
- Simple tension test (at lower temperatures, i.e. $T < T_{melt/3}$)



Yield Strength, σ_y

- *The yield strength is defined as the stress at which a predetermined amount of permanent deformation occurs. The graphical portion of the early stages of a tension test is used to evaluate yield strength.*
- *Stress at which **noticeable** plastic deformation has occurred.*

when $\varepsilon_p = 0.002$



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 temperature values

Based on data in Table B.4, Callister & Rethwisch 8e.

a = annealed

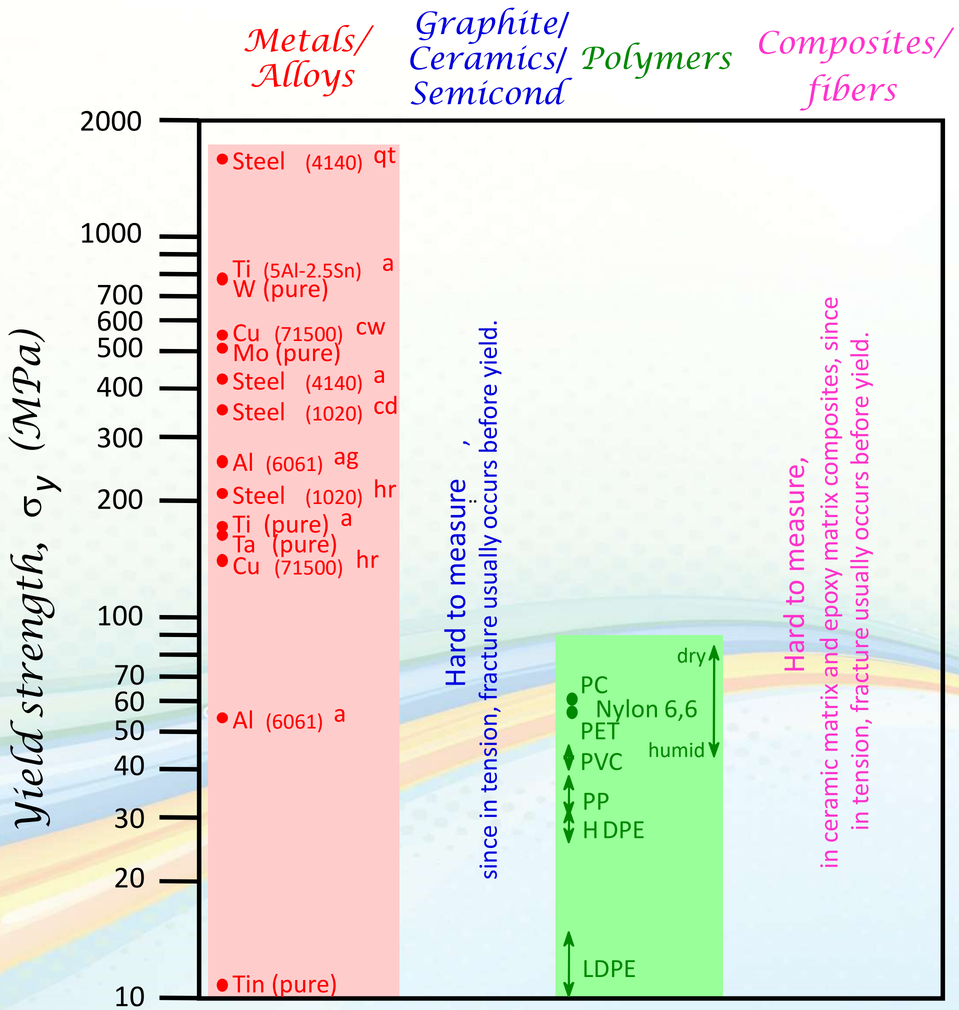
hr = hot rolled

ag = aged

cd = cold drawn

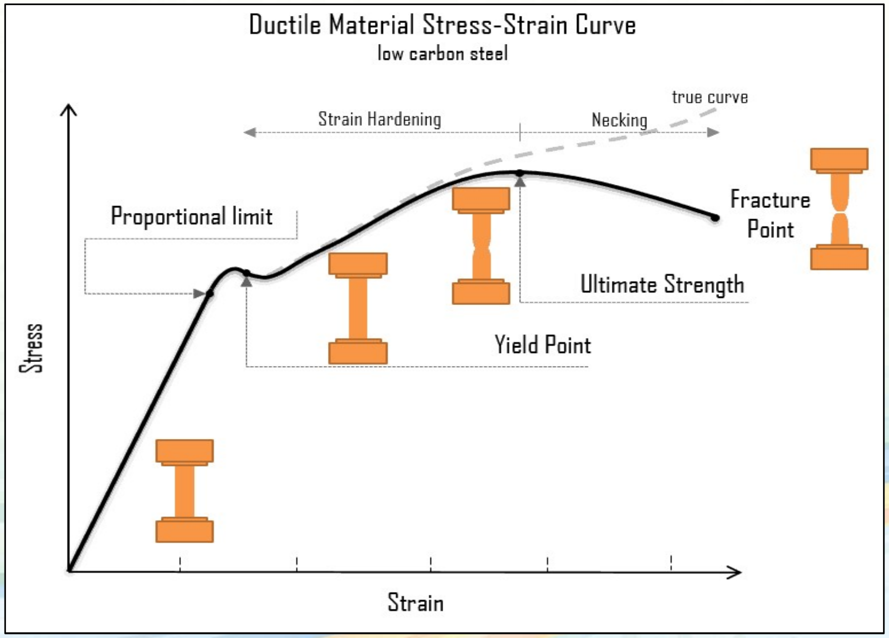
cw = cold worked

qt = quenched & tempered



Tensile Strength, TS

- *Maximum stress on engineering stress-strain curve.*



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

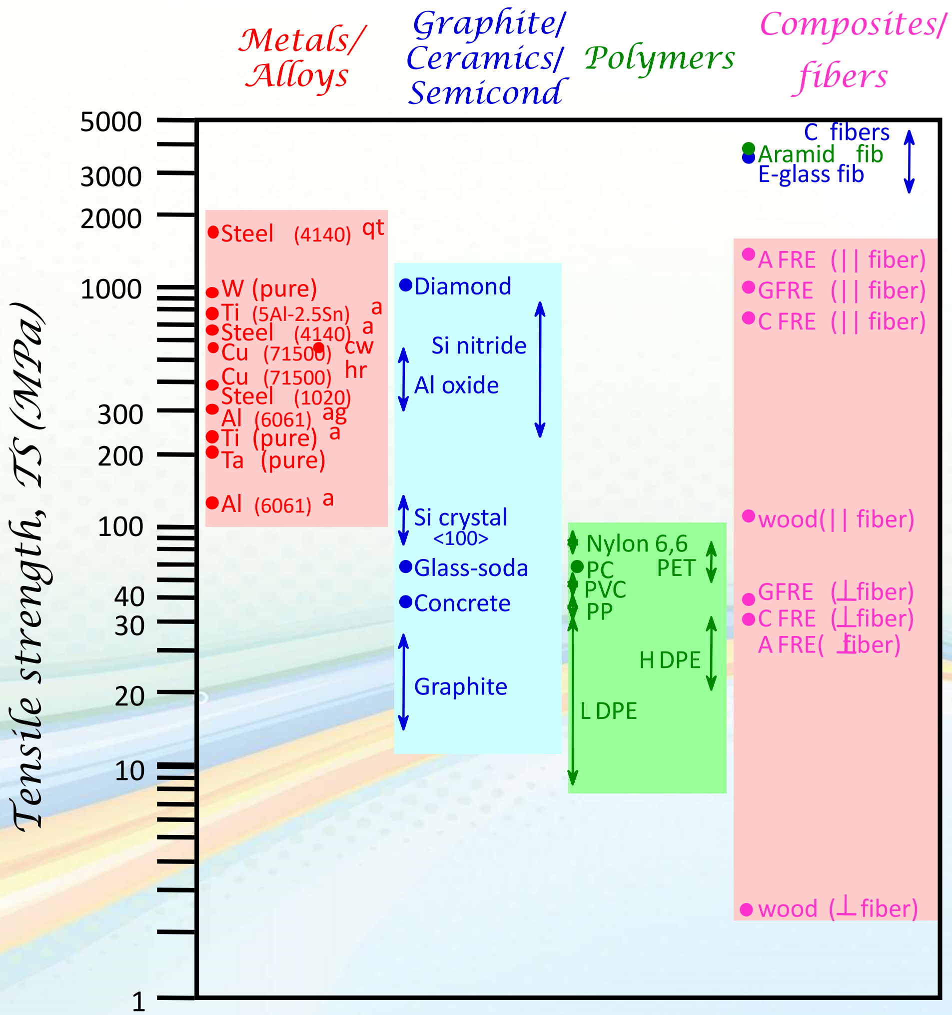
Tensile Strength: Comparison

Room temperature values

Based on data in Table B.4, Callister & Rethwisch 8e.

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

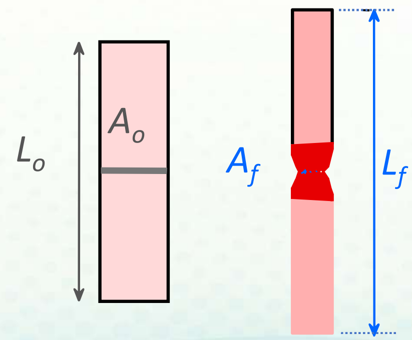
- Ductility is the physical property of a material associated with the ability to be hammered thin or stretched into wire without breaking. A ductile substance can be drawn into a wire.

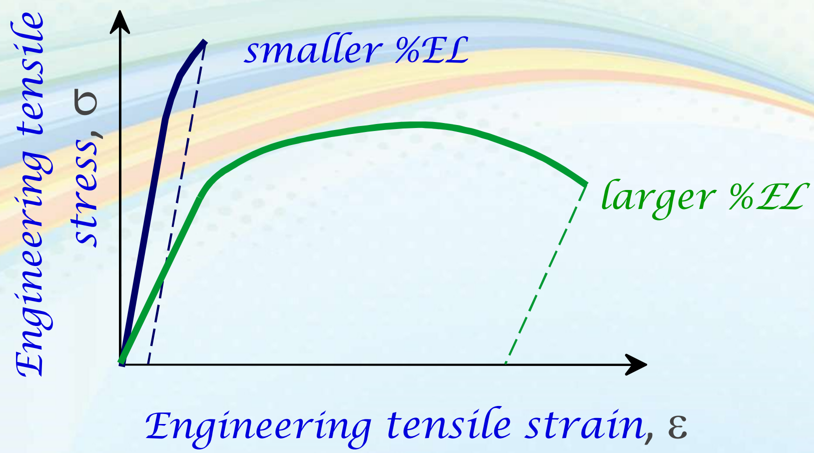
- Plastic tensile strain at failure:

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

- Another ductility measure:

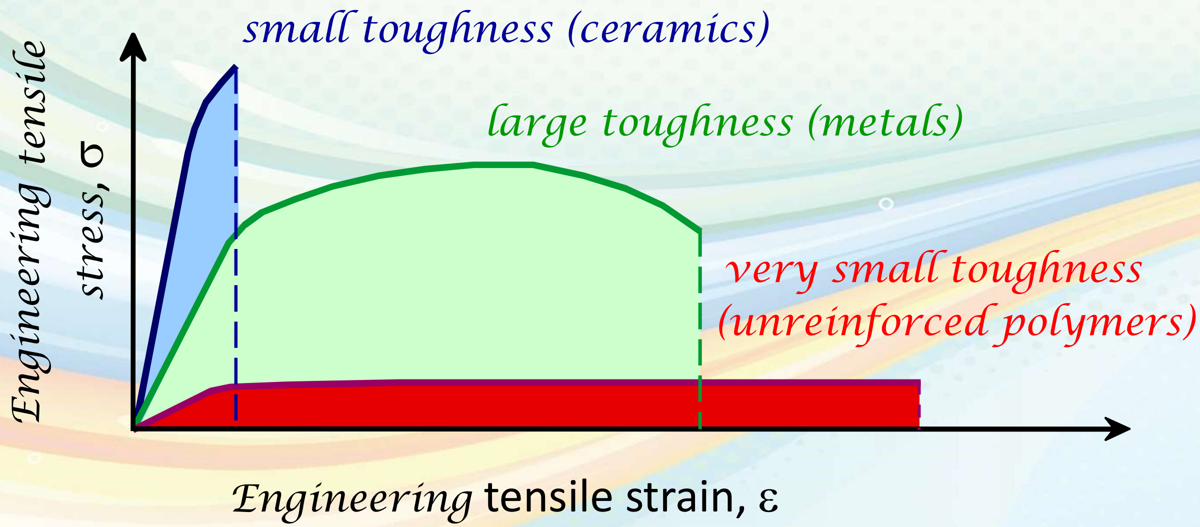
$$\%RA = \frac{A_o - A_f}{A_o} \times 100$$





Toughness

- Toughness is a fundamental material property measuring the ability of a material to absorb energy and withstand shock up to fracture; that is, the ability to absorb energy in the plastic range.
- Energy to break a unit volume of material
- Approximate by the area under the stress-strain curve.



Brittle fracture:

elastic energy

Ductile fracture:

elastic + plastic energy

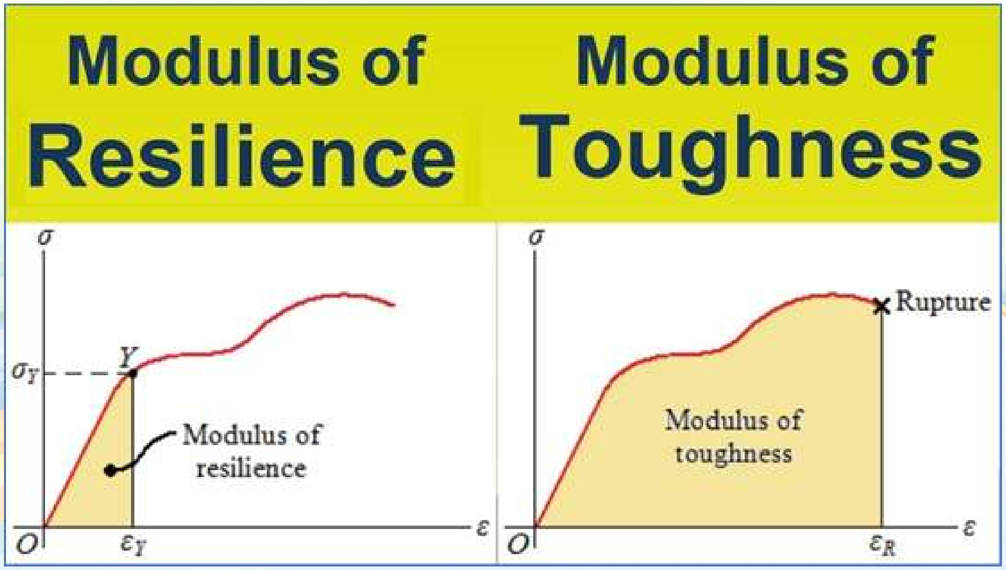
Resilience, Ur

- The ability of a material to absorb energy when deformed elastically and to return it when unloaded is called resilience.
- Ability of a material to store energy .
- Energy stored best in elastic region

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

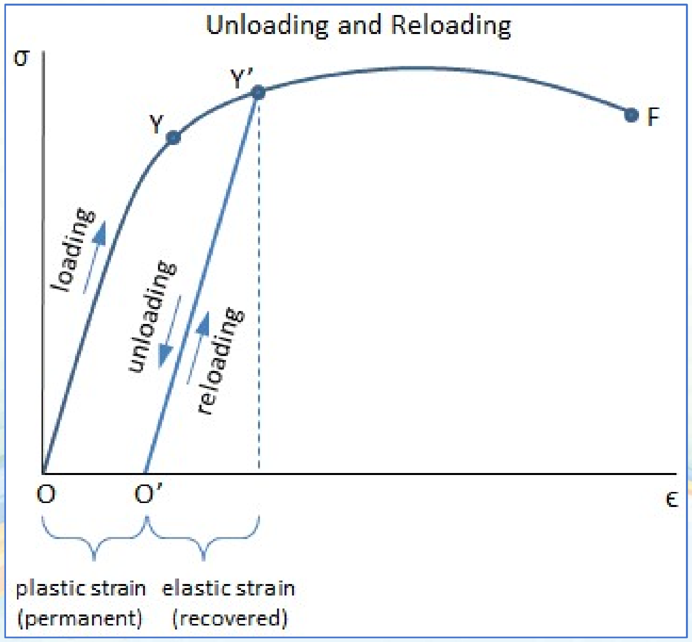
- If we assume a linear stress-strain curve this simplifies to:

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



Elastic Strain Recovery

- If a material is loaded beyond the elastic limit, it will undergo permanent deformation. After unloading the material, the elastic strain will be recovered (return to zero) but the plastic strain will remain.
- The figure shows the stress-strain curve of a material that was loaded beyond the yield point, Y.
- The first time the material was loaded, the stress and strain followed the curve O-Y-Y', and then the load was removed once the stress reached the point Y'.

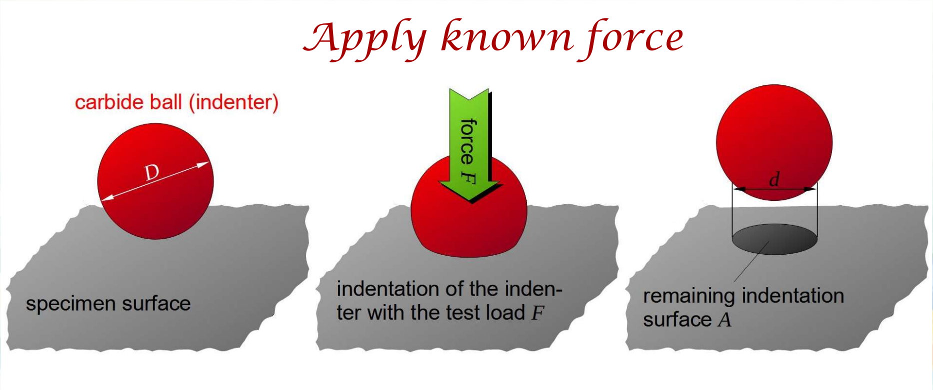


Elastic Strain Recovery

- Since the material was loaded beyond the elastic limit, only the elastic portion of the strain is recovered, there is some permanent strain now in the material.
- If the material were to be loaded again, it would follow line O'-Y'-F, where O'-Y' is the previous unloading line.
- The point Y' is the new yield point. Note that the line O'-Y' is linear with a slope equal to the elastic modulus, and the point Y' has a higher stress value than point Y.
- Therefore, the material now has a higher yield point than it had previously, which is a result of strain hardening that occurred by loading the material beyond the elastic limit.

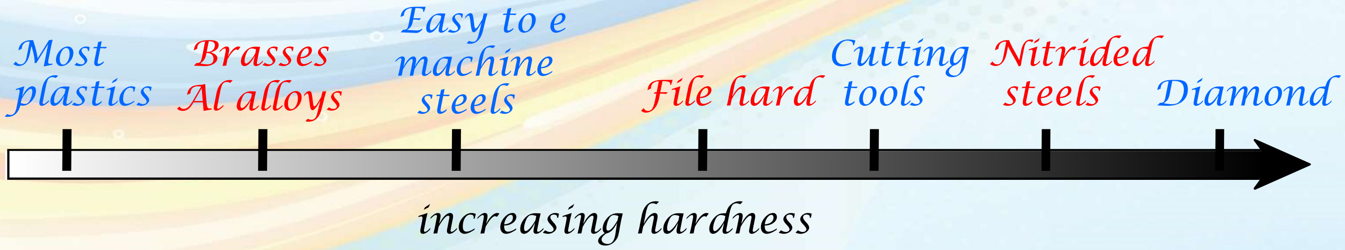
Hardness

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



Measure size of indent after removing load

Smaller indents mean larger hardness.



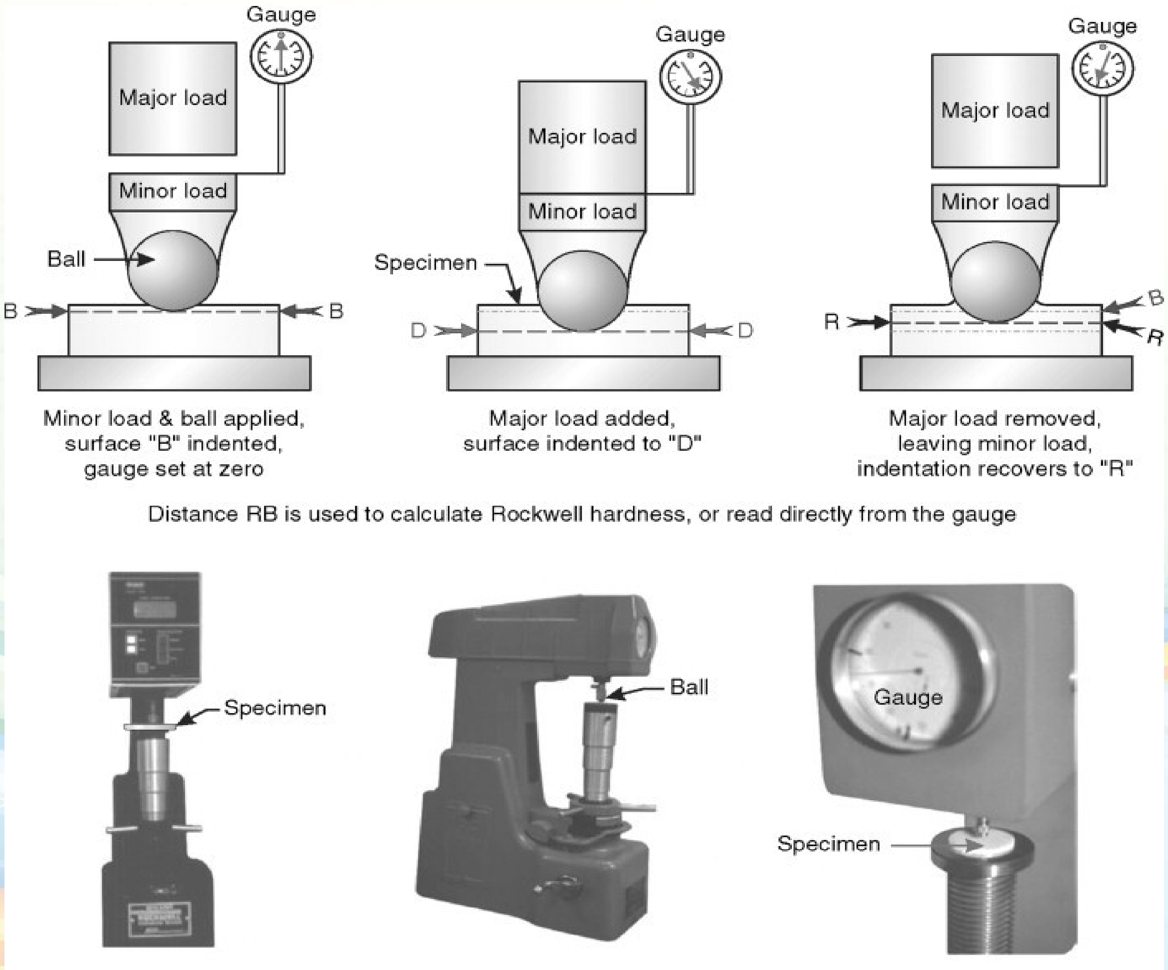
Hardness: Measurement

Rockwell

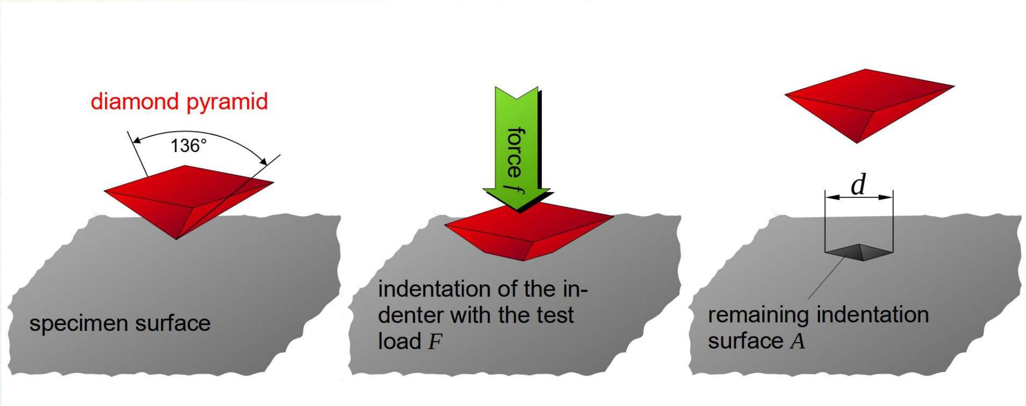
The Rockwell method measures the permanent depth of indentation produced by a force/load on an indenter.

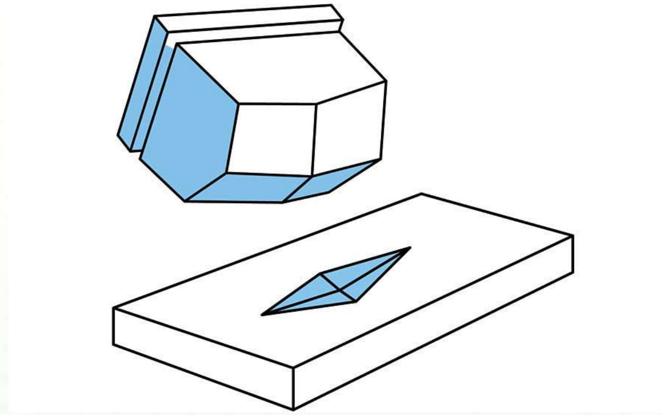
- No major sample damage
- Each scale runs to 130 but only useful in range 20-100.
- Minor load   10 kg
- Major load   60 (A), 100 (B) & 150 (C) kg
  - A = diamond, B = 1/16 in. ball, C = diamond

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



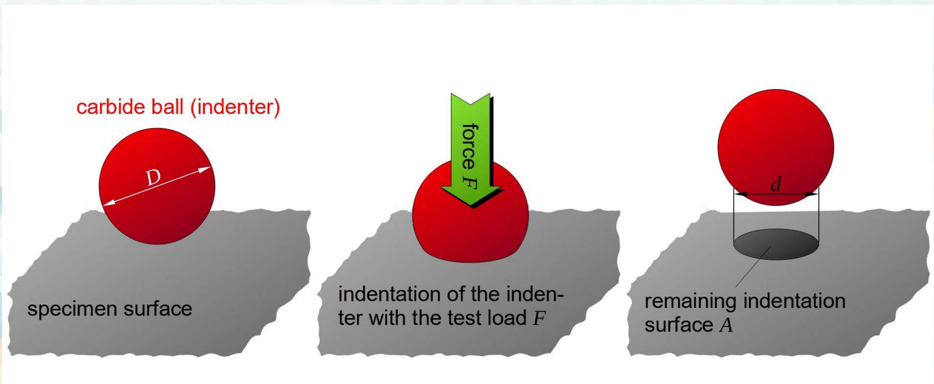
Rockwell Hardness Apparatus





Vickers

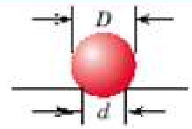
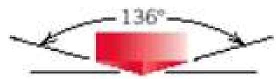
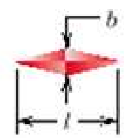
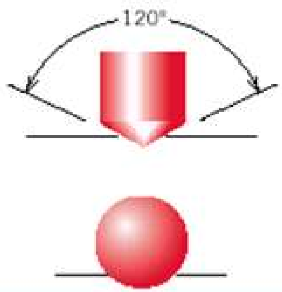
Knoop



Brinell

Hardness: Measurement

Table 6.4 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	

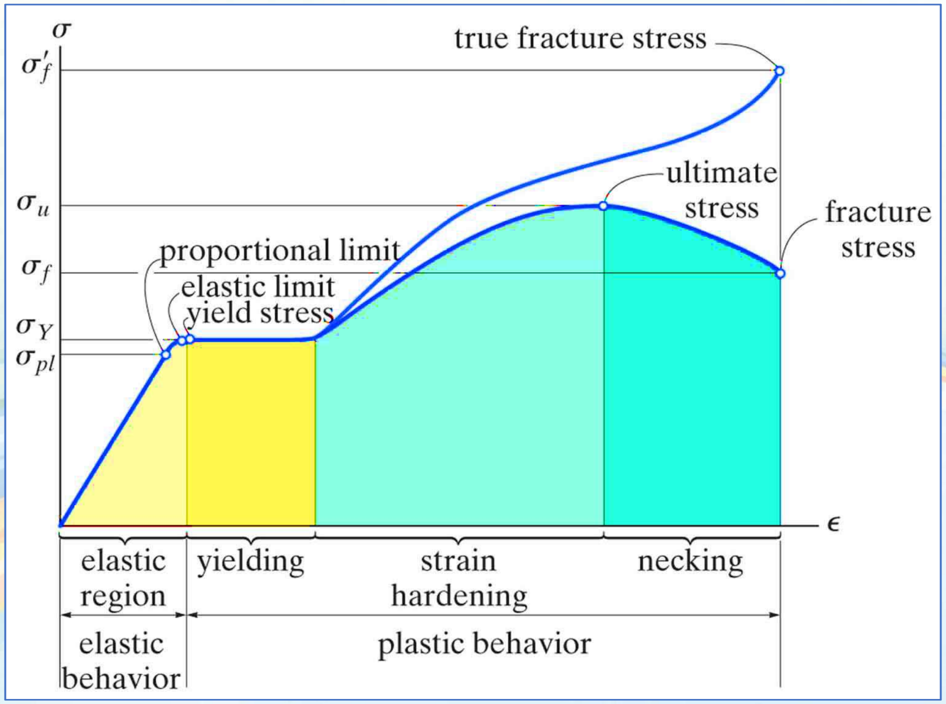
[a] For the hardness formulas given, P (the applied load) is in kg, while D, d, d_1, and l are all in mm.

True Stress & Strain

- True stress is the stress determined by the instantaneous load acting on the. instantaneous cross-sectional area.
- True stress is related to engineering stress: Assuming material volume remains constant

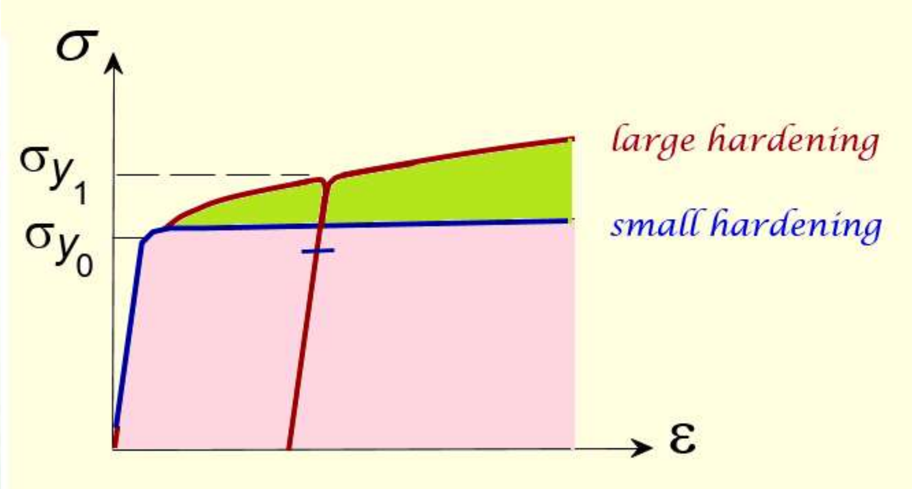
  - ✓ True stress, $\sigma_T = \frac{F}{A_i}$
  - ✓ True strain, $\varepsilon_T = ln\left(\frac{L_i}{L_o}\right)$

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



Hardening

- Metal is known for being a tough substance that can stand up to a lot of wear and tear, but it might not have started out that way.
- Many types of metals have gone through the process of metal hardening in order to make them better suited for the job they need to do.
- Each metal hardening process includes three main steps: heating, soaking and cooling the metal.



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

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

"true" stress (F/A)

"true" strain: ln(L/Lo)

Variability in Material Properties

- Elastic modulus is material property
- Critical properties depend largely on sample flaws (defects, etc.). Large sample to sample variability.
- Statistics
  - Mean:

$$\bar{X} = \frac{\sum_1^n X_n}{n}$$

  - Standard deviation:

$$S = \left[\frac{\sum (X_i - \bar{X})^2}{n-1}\right]^{\frac{1}{2}}$$

where n is the number of data points

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

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.

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

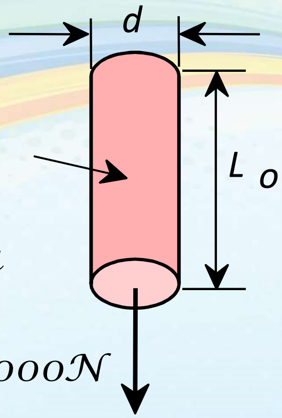
$$\frac{220{,}000\ N}{\pi(d^2/4)}$$

5

1045 plain carbon steel

σ_y = 310 MPa

TS = 565 MPa



F = 220,000N

d = 0.067 m = 6.7 cm

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.
- Hardness: Rockwell, Brinell, Vickers, and Knoop