BFF1113
Engineering Materials

DR. NOOR MAZNI ISMAIL
FACULTY OF MANUFACTURING ENGINEERING

Course Guidelines:

1. Introduction to Engineering Materials
2. Bonding and Properties
3. Crystal Structures & Properties
4. Imperfection in Solids
5. <u>Mechanical Properties of Materials</u>
6. Physical Properties of Materials
7. Failure & Fundamental of Fracture
8. Metal Alloys
9. Phase Diagram
10. Phase Transformation – Heat Treatment
11. Processing and Application of Metals
12. Ceramic Materials
13. Polymer Materials
14. Composite Materials
15. Corrosion & Degradation of Materials
16. Environment and Sustainability

Mechanical Behavior, Testing, and Manufacturing Properties of Materials

1. **STRESS & STRAIN**
2. **MECHANICAL BEHAVIOUR**
   i. **Tension**
   ii. Compression
   iii. Shear & Torsion
   iv. Bending
   v. Hardness
   vi. Fatigue
   vii. Creep
   viii. Impact
   ix. Residual Stresses

Why STUDY the mechanical properties?

- **Things break.**
- **Study mechanical properties to better understand why and how things break.**
- **Measuring mechanical properties assists in the evaluation and design of materials and products that are more efficient and less costly because they last longer.**
- **For example, vehicles such as bicycles, automobiles, or airplanes, the goal is lighter weight and stronger materials.**

ISSUES TO ADDRESS...

- **Stress and strain**: What are they ?
- **Elastic behavior:** When loads are small, how much deformation occurs?
- **Plastic behavior:** At what point does permanent deformation occur?
- **Toughness and ductility**: What are they and how do we measure them?

CONCEPTS OF STRESS AND STRAIN

STRESS ?

$$\sigma = F / A$$

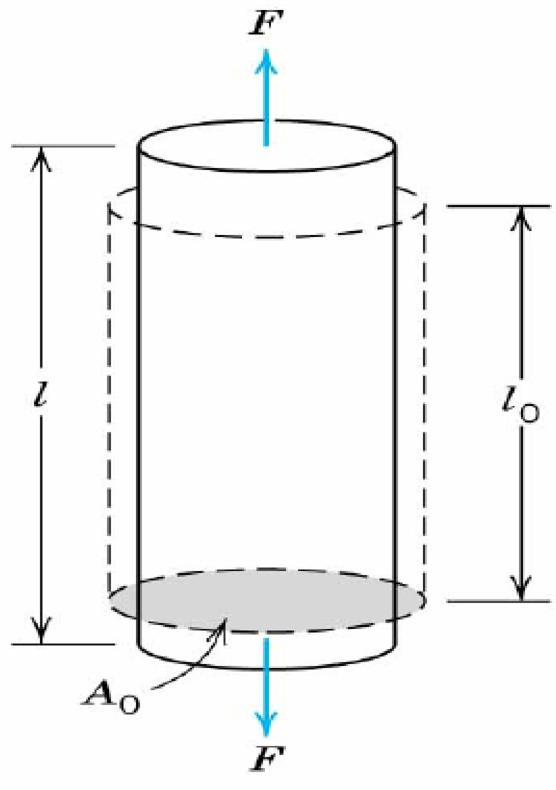
The ***intensity*** of internal force at a point, *also known as* ***force per unit area.***

STRAIN ?

$$\varepsilon = (L - L_0) / L_0$$

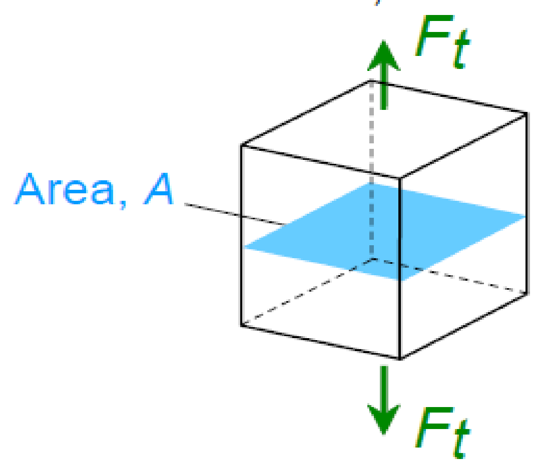
- **Measurement of body deformation**
- **Extension per unit length**
- When a force is applied to a body, it will change the body’s shape and size. These changes are ***deformation***

STRESS



(a)

- Tensile stress, σ:



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

original area before loading

F – load applied perpendicular to the specimen cross section (N)

A_o – original cross section area (m^2)

The unit of σ = MPa (where 1 MPa= 10^6 N/m^2)

Example: Tensile Stress acting on a Rod

A force of *10 kN* is acting on a circular rod with diameter *10 mm*. The stress in the rod can be calculated as:

$\sigma = (10 \times 10^{3}\ N) / (\pi\ ((10 \times 10^{-3}\ m) / 2)^{2})$

$= \underline{127388535}\ (N/m^{2})$

$= \underline{127}\ (MPa)$

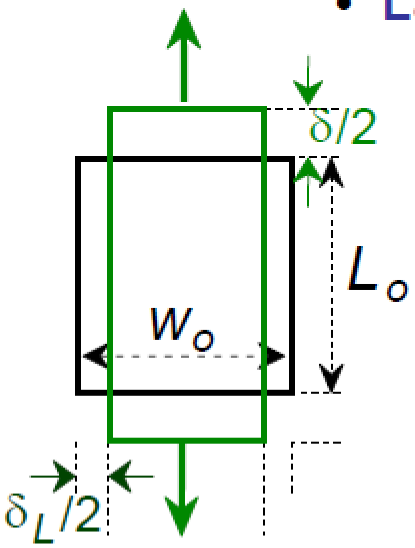
STRAIN

- **Tensile strain:**

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

- **Lateral strain:**

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



Where;
δ = change in length
Lo = original length before load is applied

Strain is always dimensionless.

Example: Strain

What is the strain of a 1.5 m wire that stretches by 2 mm if a load is applied?

Strain = $2 \times 10^{-3} \div 1.5 = 0.0013 = 0.13\ \%$

Poisson's ratio, ν

- Poisson's ratio (ν) is defined as the ratio of lateral and axial strain

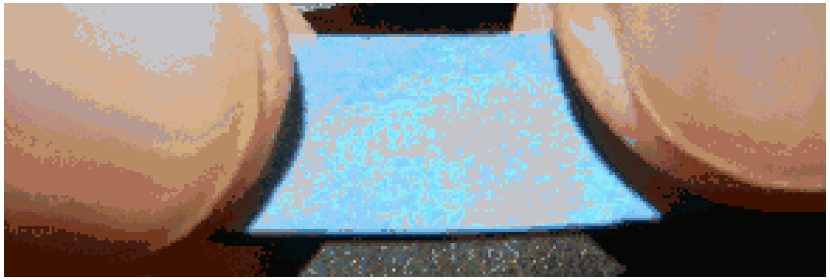
$$\nu = -\frac{\varepsilon_x}{\varepsilon_z} = -\frac{\varepsilon_y}{\varepsilon_z}$$

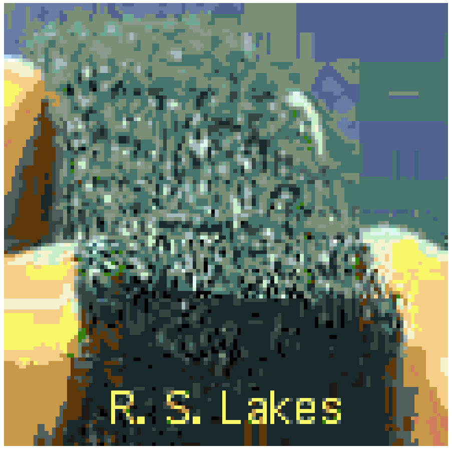
Ratio of lateral strain (transverse) to axial (logitudinal) strain is known as **Poisson's ratio, v**

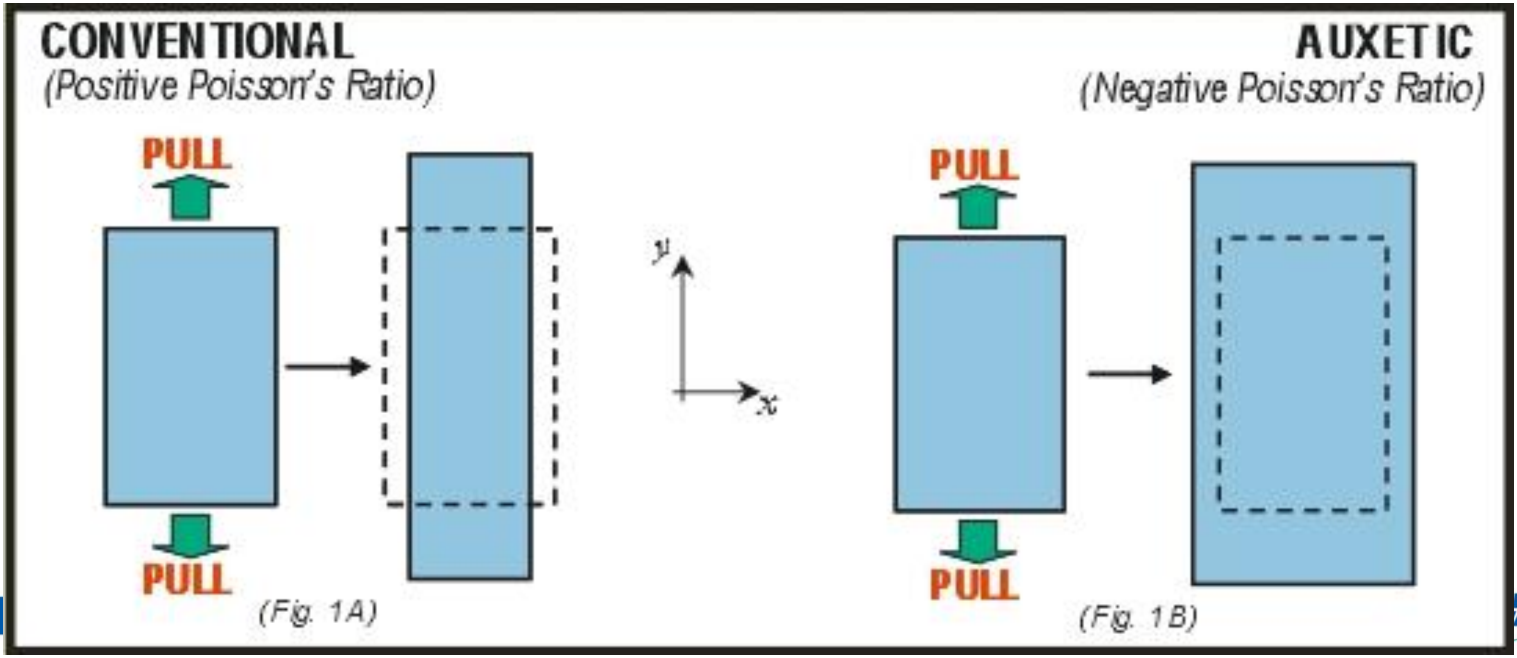
- The maximum value of ν is 0.5
- For many metal and alloys, values of ν range between 0.2 to 0.35

Polymer foam

Rubber band



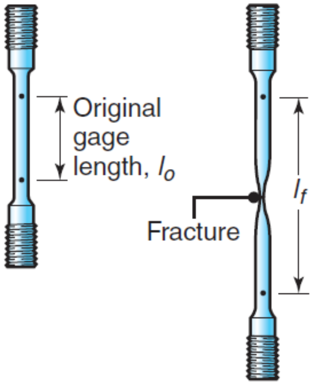




TENSION

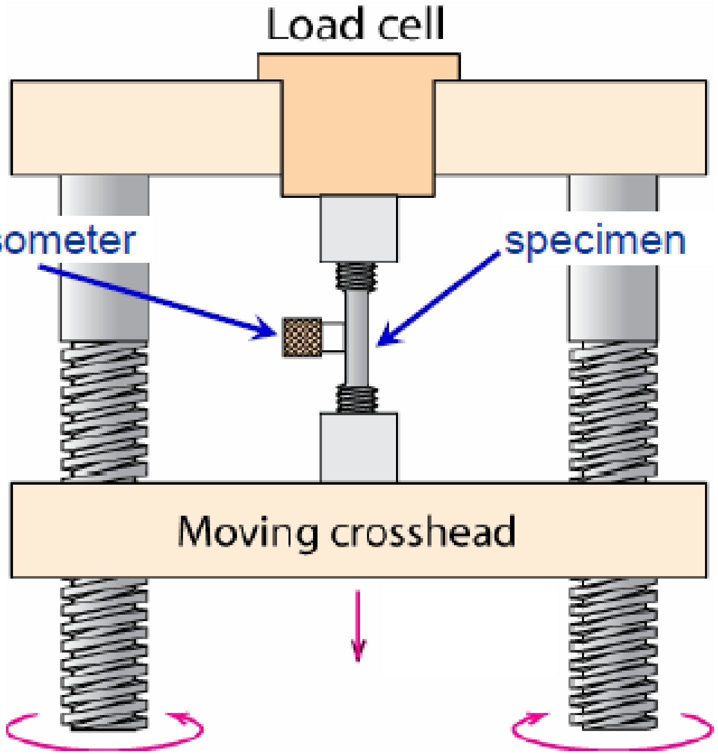
Tension test

- **Tension test** is a method for determining the *mechanical properties* of materials. It is one of the common mechanical stress-strain test.
- Specimen has an **original gage length**, l_o, and a cross-sectional area, A_o.
- Specimen can be tested at different temperatures and rates of deformation.



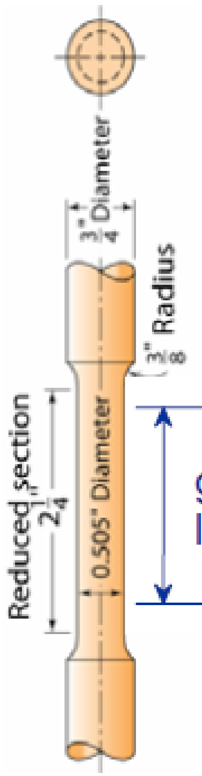
Tensile Stress-Strain Testing

- **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.)

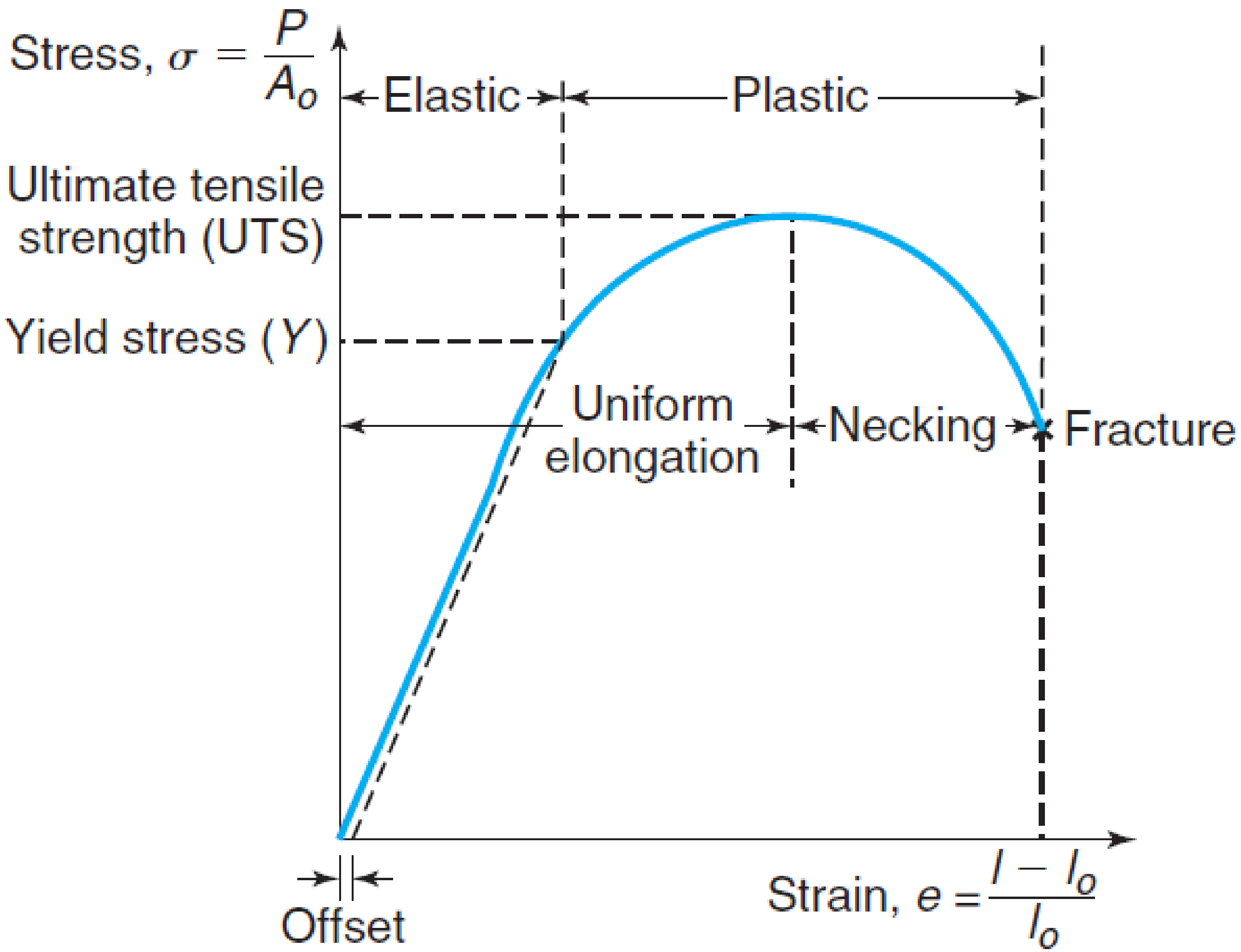
- **Typical tensile specimen**



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

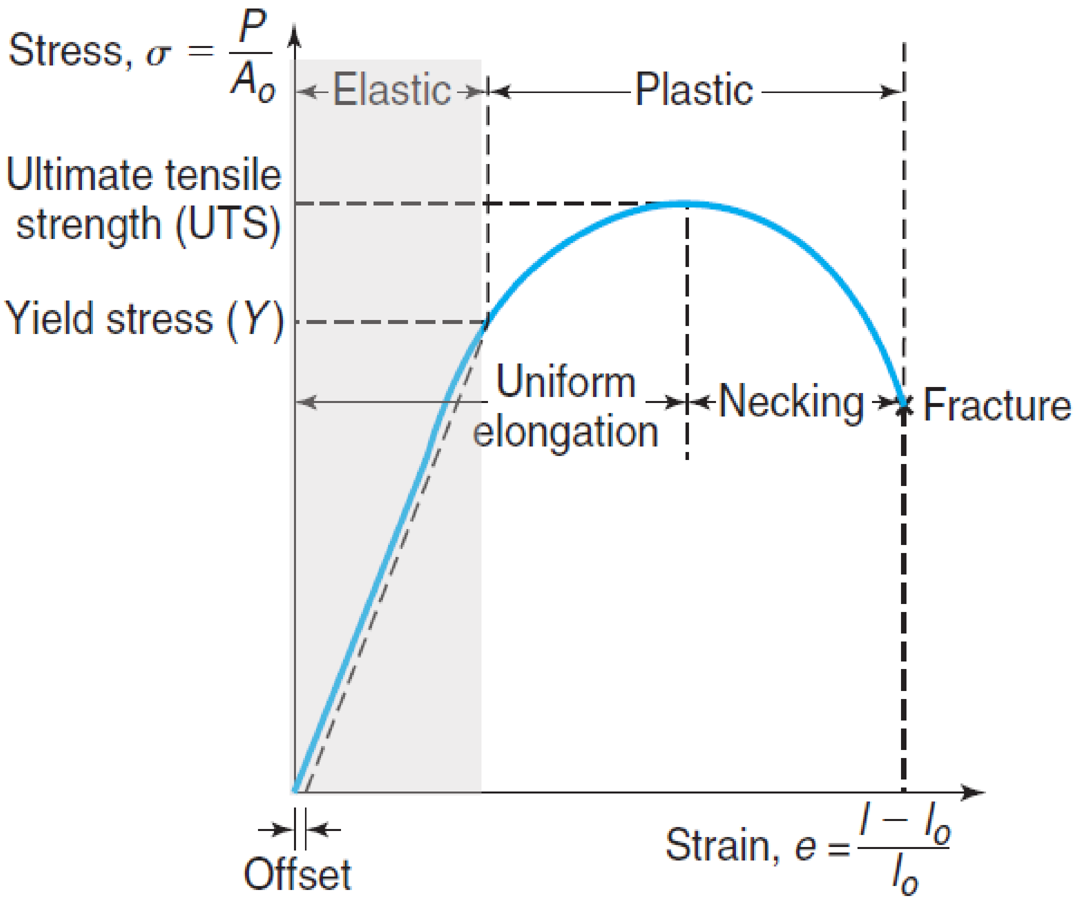
STRESS-STRAIN GRAPH

Tension: Stress–Strain Curves

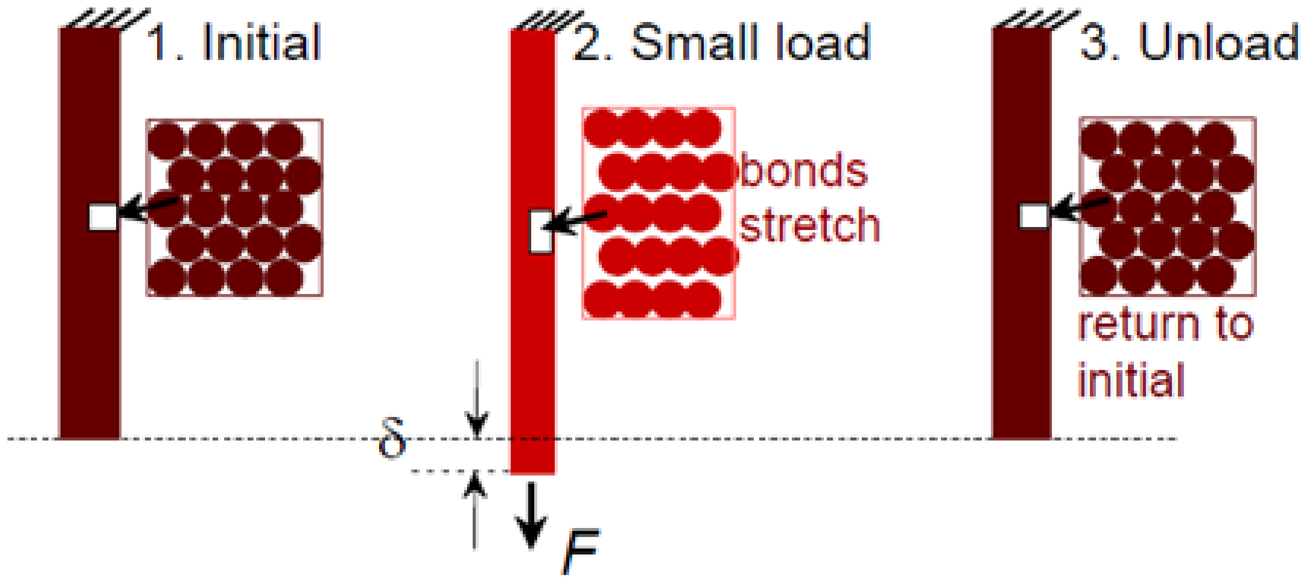


ELASTIC REGION

- Elastic region: initial linear elastic behavior, whereby stress is proportional to strain.
- Elastic limit, if the load remove, specimen will still return to original shape.



Elastic Deformation



Elastic means reversible!

ELASTIC REGION

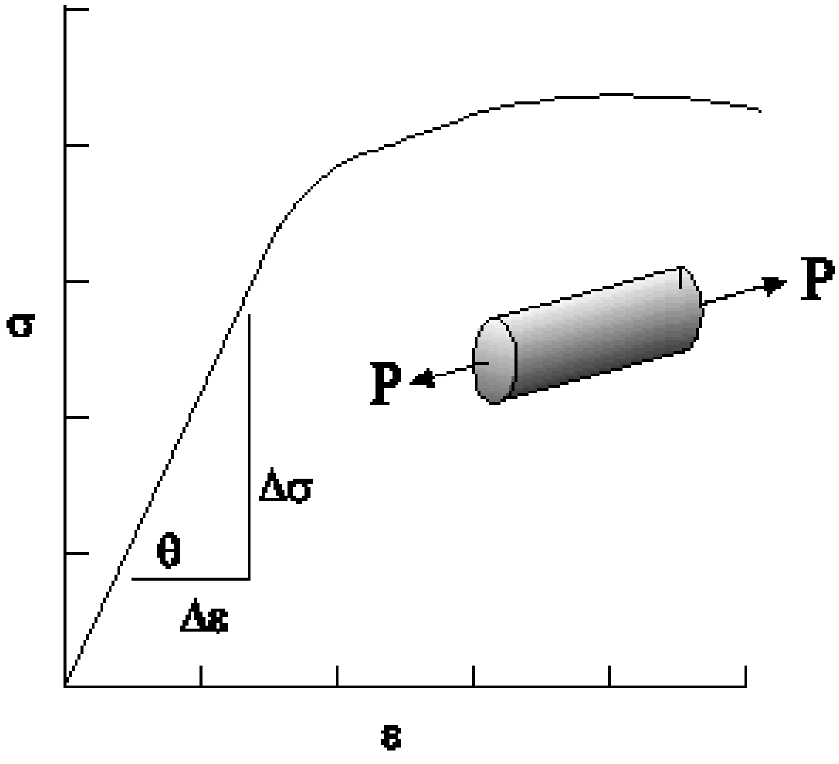
1. Modulus of Elasticity or Young Modulus

2. Yield Strength

MODULUS OF ELASTICITY, E

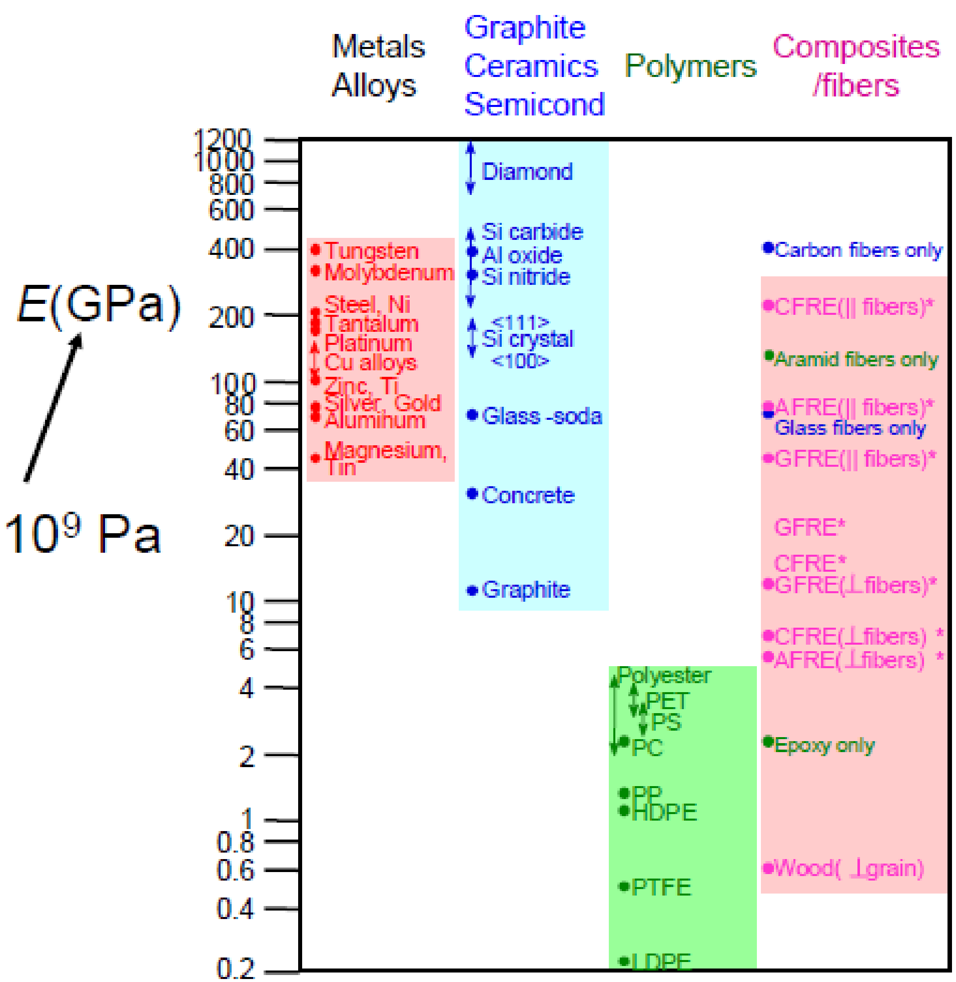
- E, called the Modulus of Elasticity, is the slope of this straight line on the stress-strain diagram. This linear relationship is known as Hooke's law. Defined as:

$$E = \frac{\sigma}{e}$$



- Higher the *E* value, higher the **stiffness** of the material

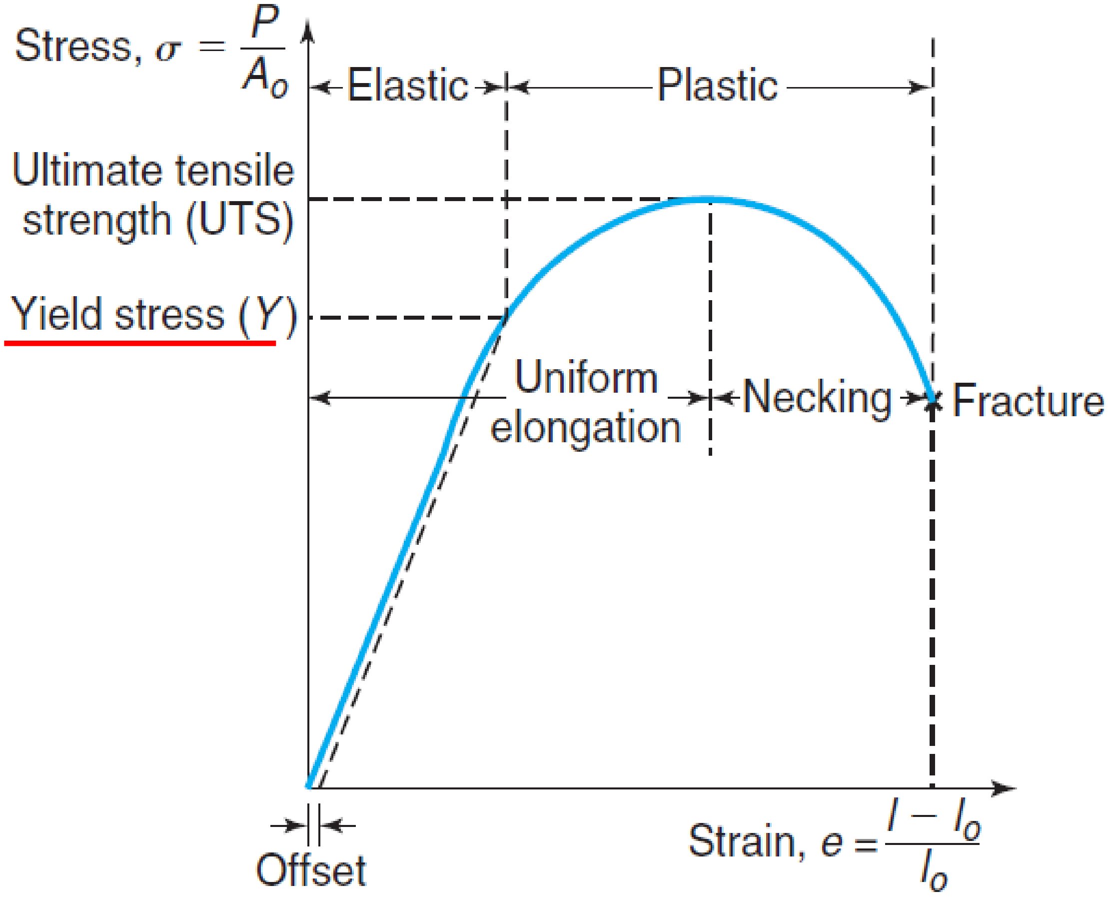
Young's Moduli: Comparison



Based on data in Table B2, *Callister 7e*.
Composite data based on reinforced epoxy with 60 vol% of aligned carbon (CFRE), aramid (AFRE), or glass (GFRE) fibers.

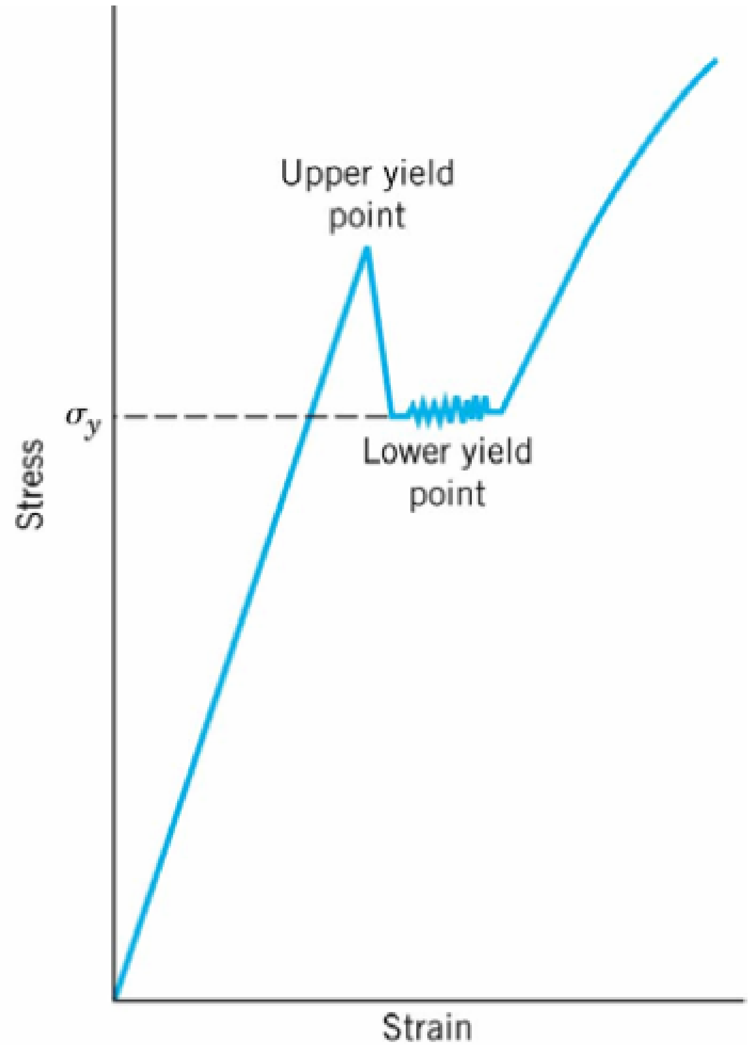
As load increased, specimen begins *nonlinear* elastic deformation at a stress called the *proportional limit*

Permanent (**plastic**) **deformation** occurs when the **yield stress**, ***Y***, is reached



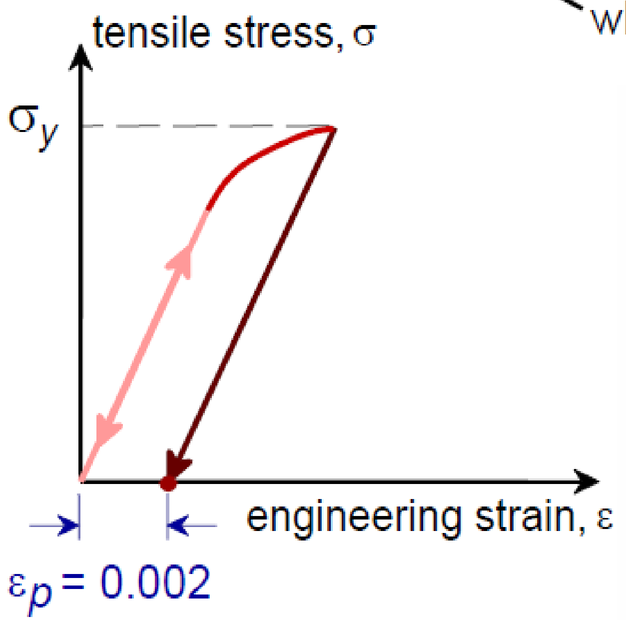
YIELD STRENGTH, σ_y

- Some steel and other materials exhibit stress-strain behavior which demonstrating the yield point phenomenon
- Thus it not necessary to employ the strain offset method to determine the yield strength
- Yield strength = average stress that is associated with the lower yield point

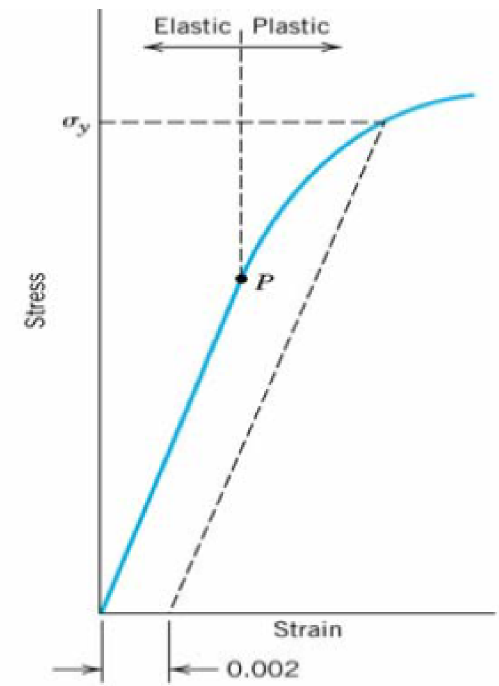


Yield Strength, σ_y

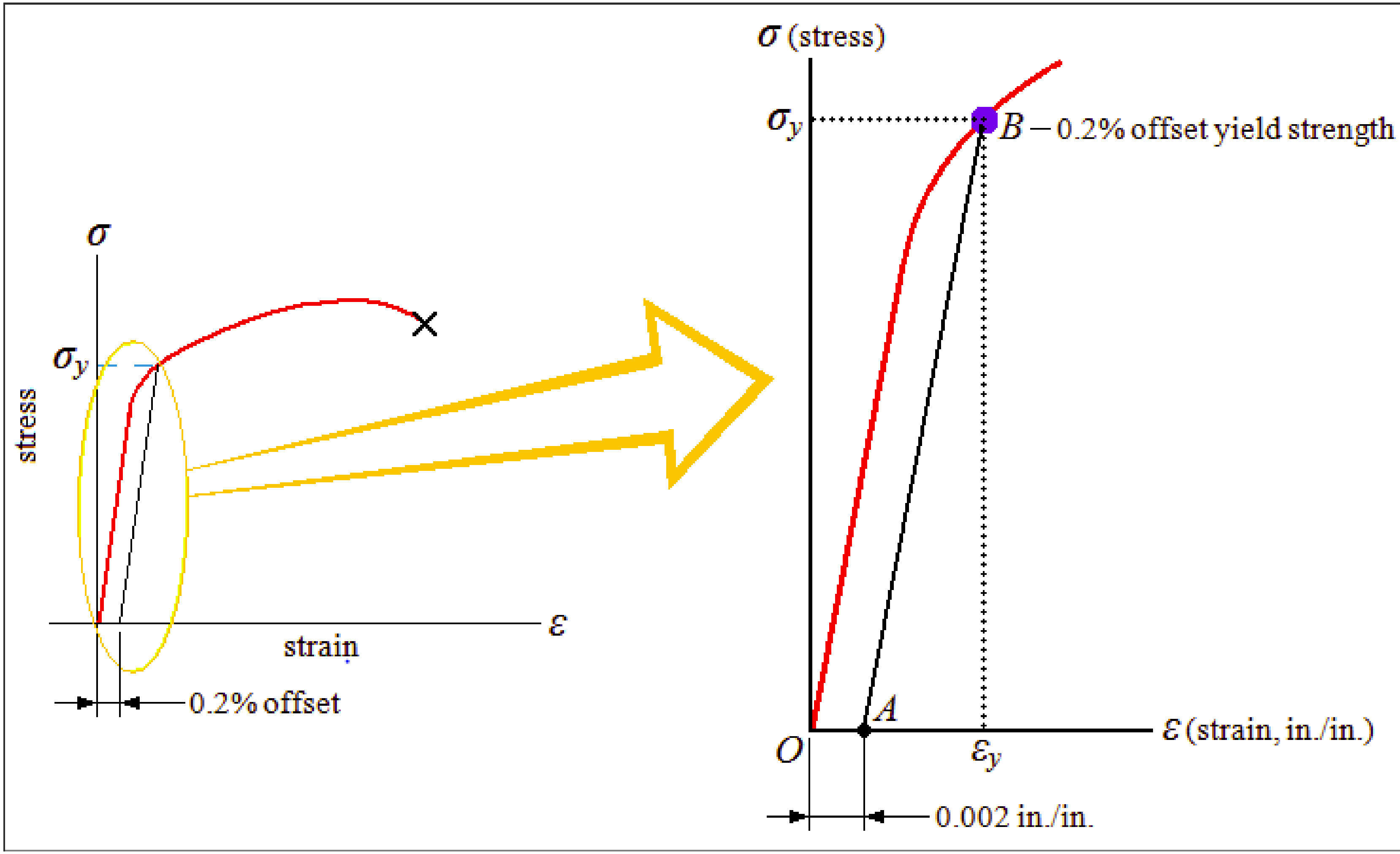
- **Stress at which *noticeable* plastic deformation has occurred.** when $\varepsilon_p = 0.002$



Adapted from Fig. 6.10 (a
Callister 7e.

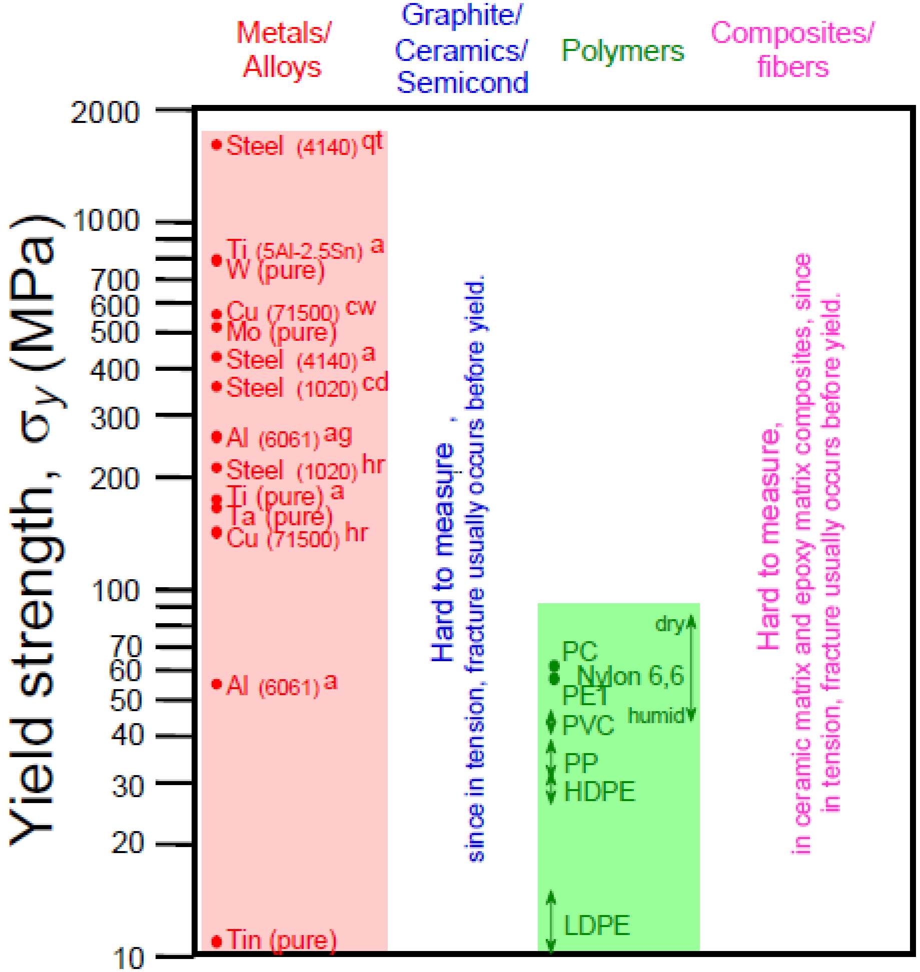


- *Y* is defined by drawing a line with the same slope as the linear elastic curve
- Yield stress is the stress where 0.2% or 0.002 offset line intersects the stress–strain curve



Determination of the yield strength using the offset method

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

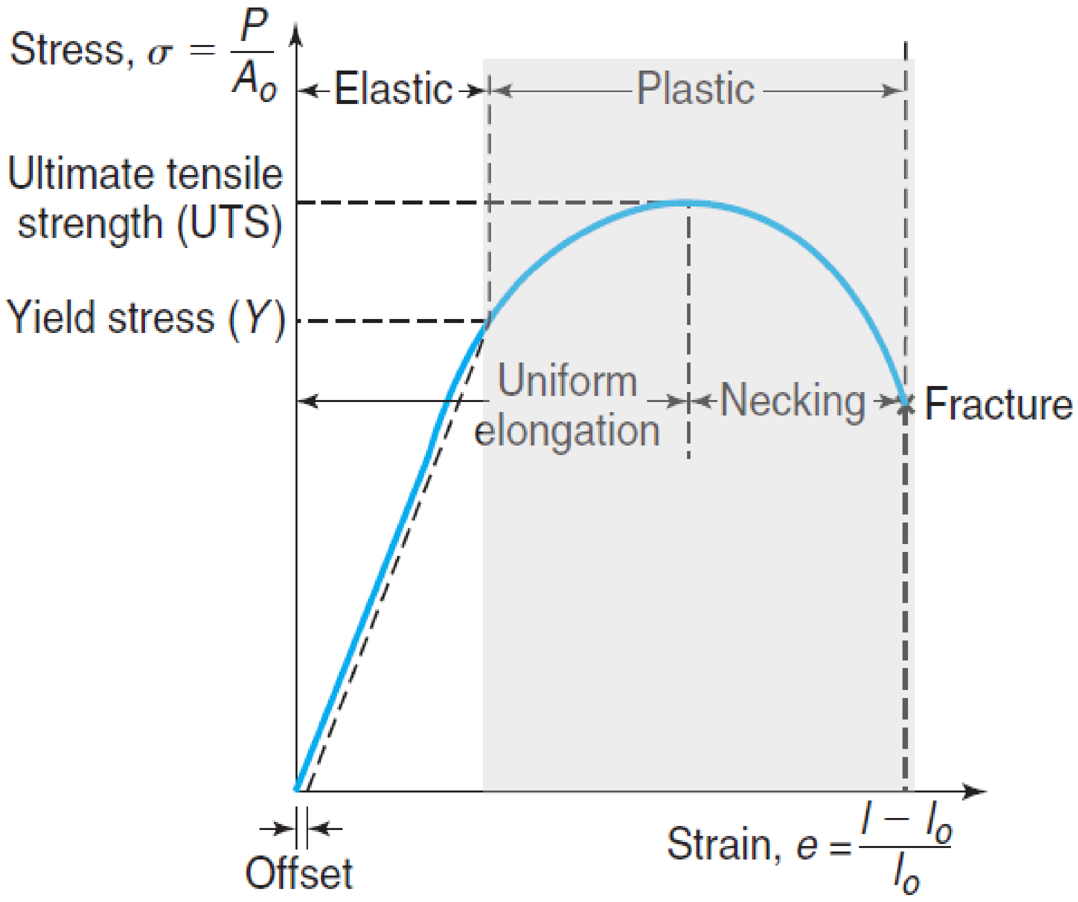
PLASTIC REGION

- When the material is stressed beyond the yield point, permanent deformation will occur.

When specimen is loaded beyond its ultimate tensile strength, it begins to **neck**

Maximum engineering stress is called the **tensile strength** or **ultimate tensile strength (UTS)**

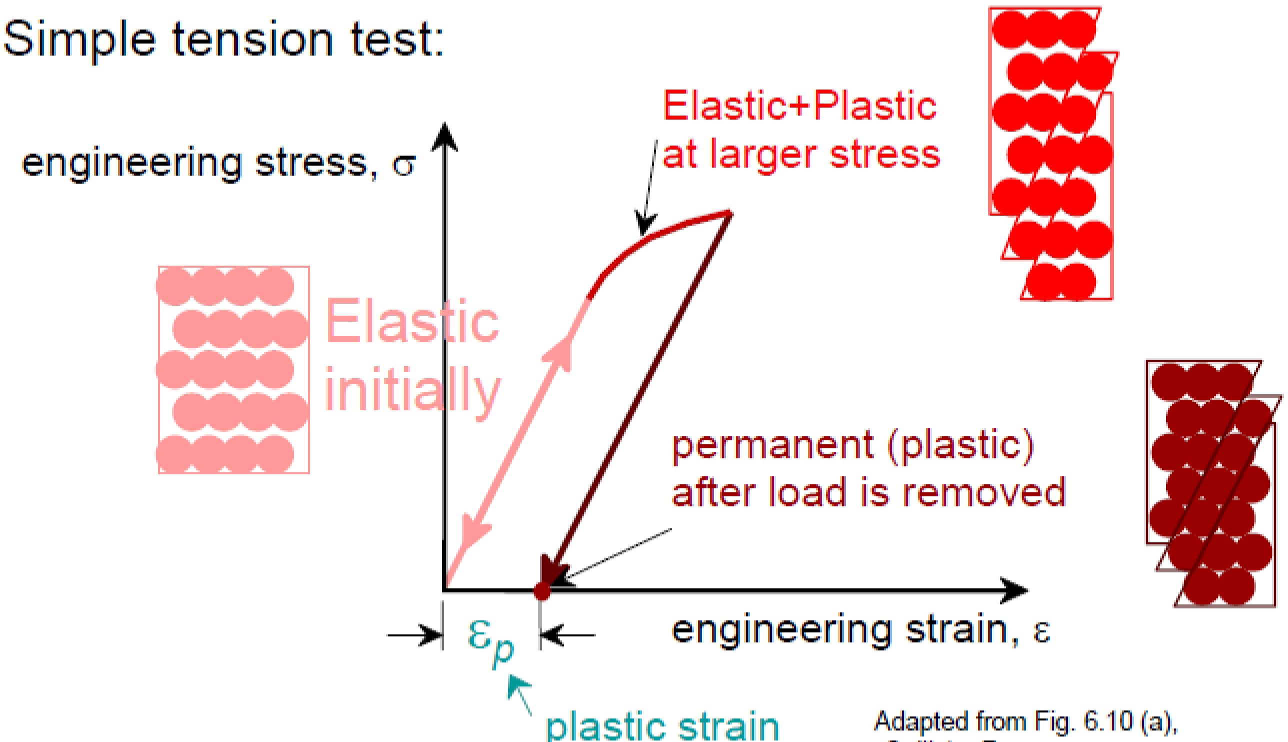
Engineering stress at fracture is called **breaking** or **fracture stress**



Plastic (Permanent) Deformation

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

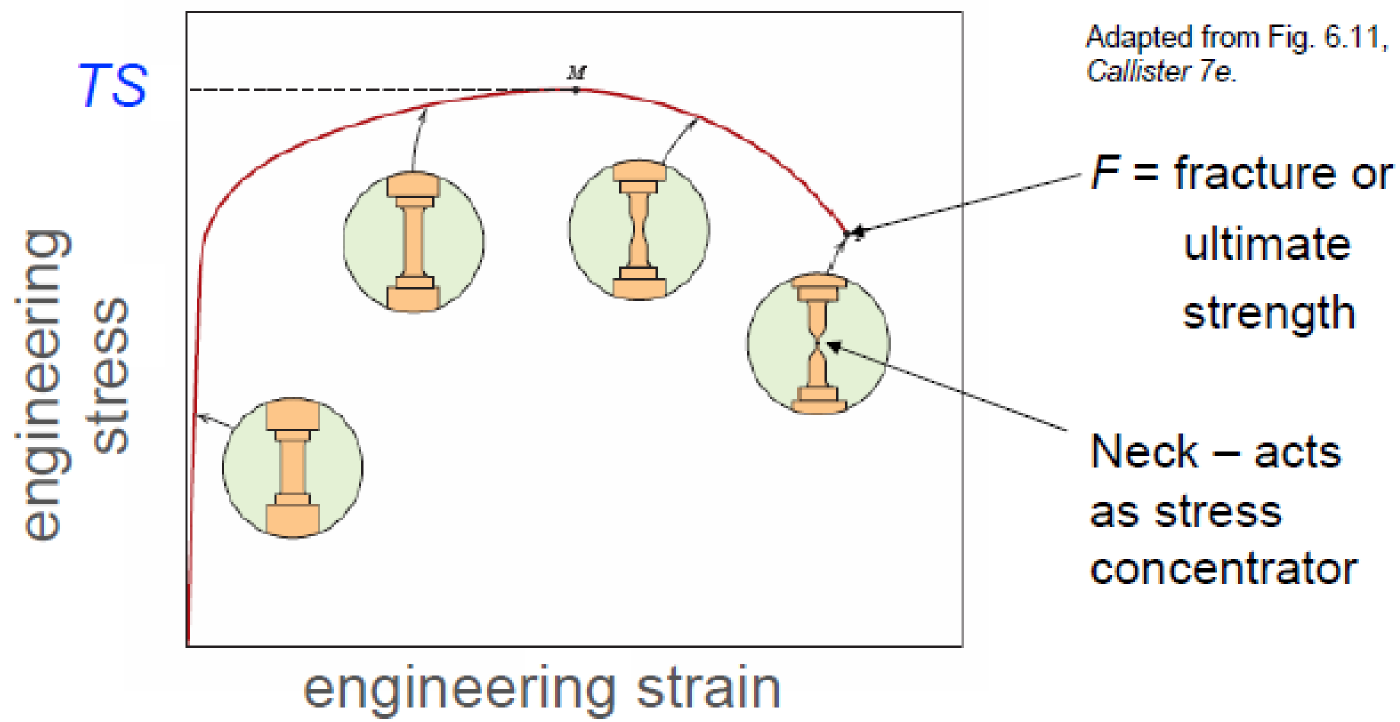
- Simple tension test:



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

Tensile Strength, TS

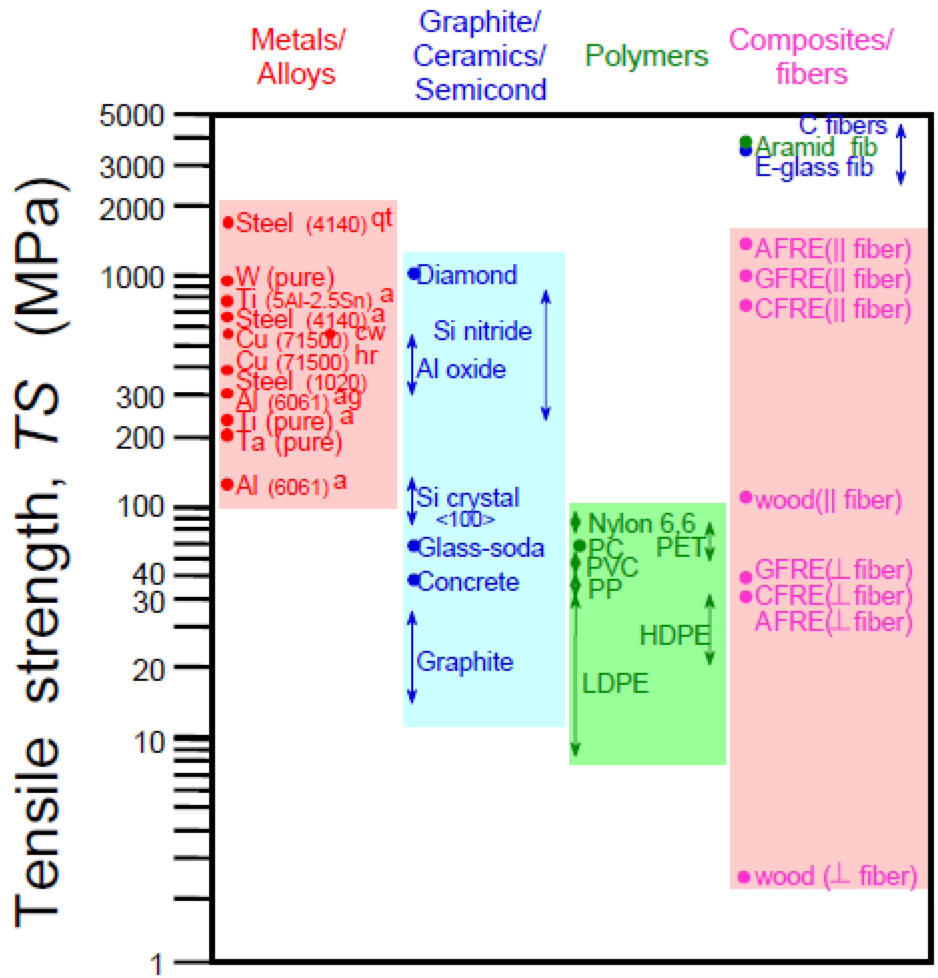
- Maximum stress on engineering stress-strain curve.



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

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

Tensile Strength : Comparison



Room Temp. values

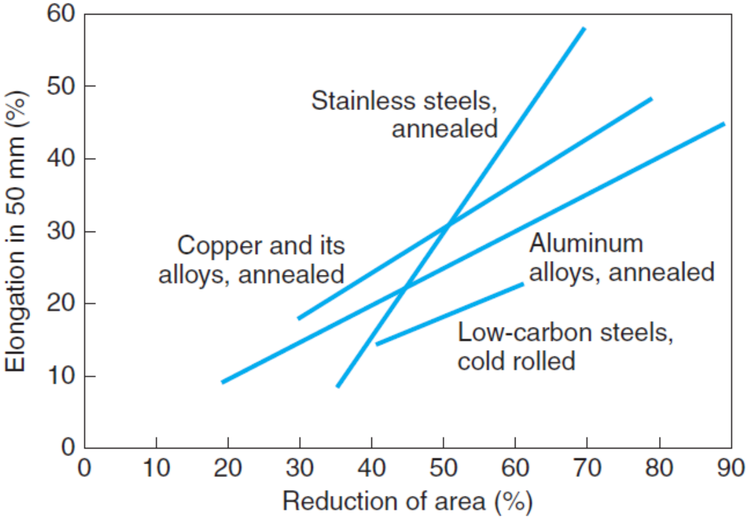
Based on data in Table B4, *Callister 7e.*

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

- **Ductility** is the extent of plastic deformation that the material undergoes before fracture.
- Ability of a material to undergo permanent deformation through elongation or bending without fracturing.
- Materials with no plastic deformation is termed brittle.

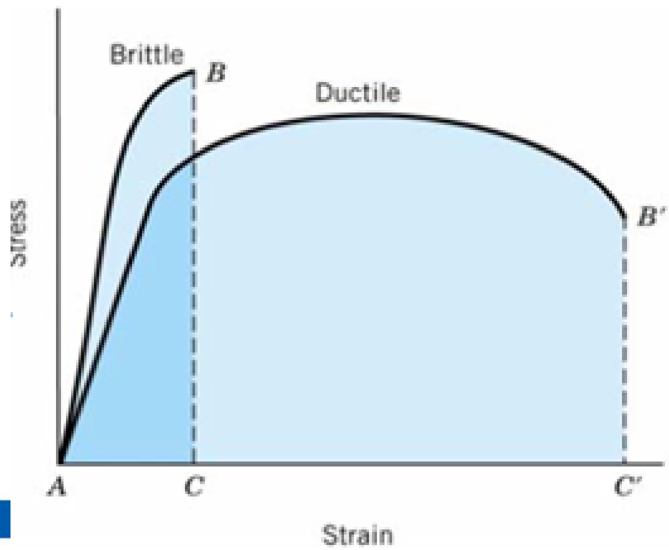


- **Measure ductility:**
  - **Total elongation** of the specimen is:

$$\text{Elongation} = \frac{(l_f - l_0)}{l_0} \times 100$$

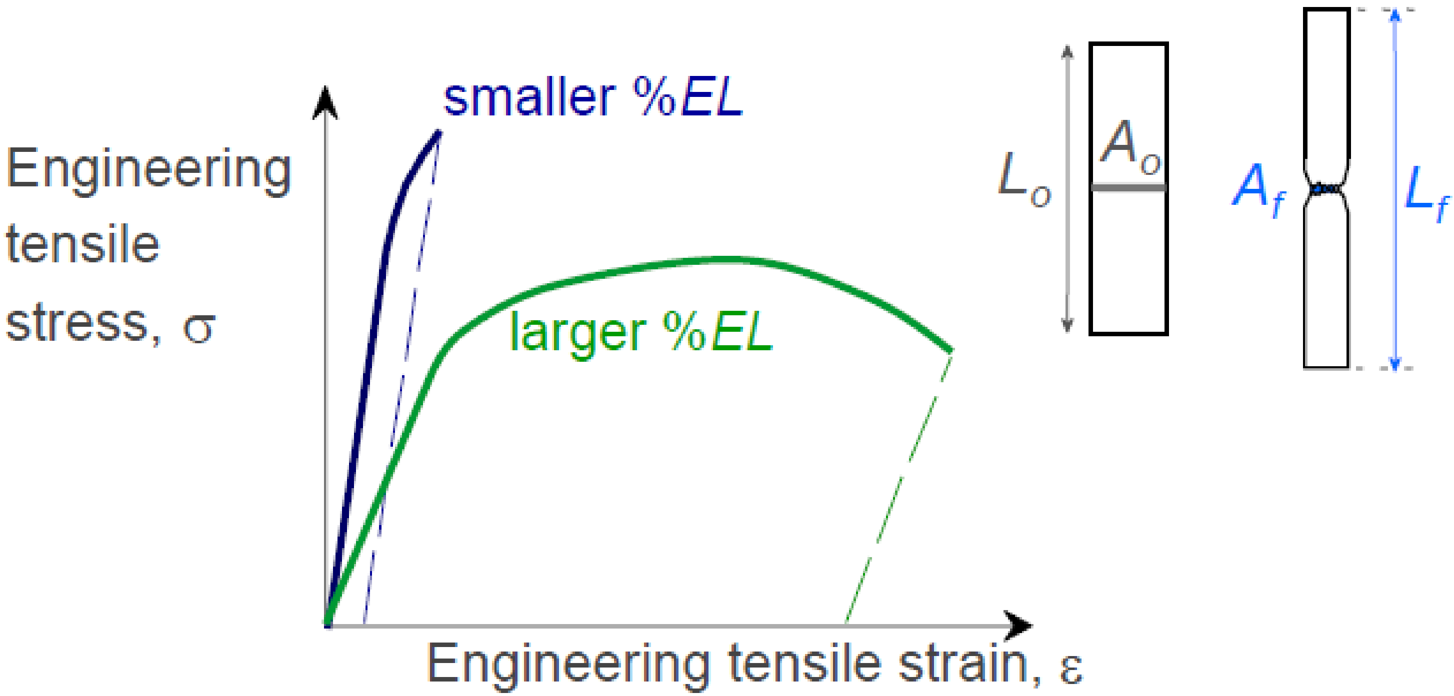
- Second measure of ductility is the reduction of area:

$$\text{Reduction area} = \frac{(A_0 - A_f)}{A_0} \times 100$$



Percent elongation (%EL)

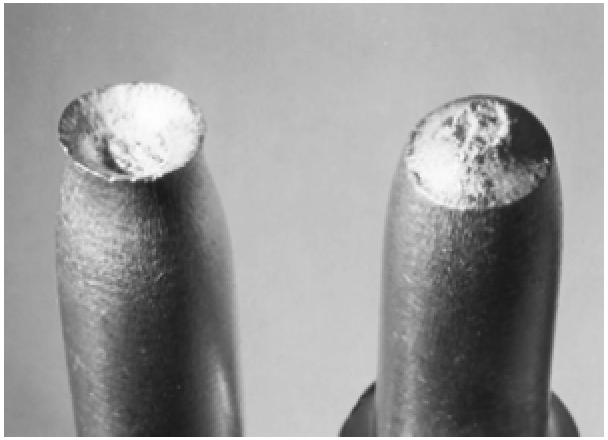
$$\%EL = \frac{L_f - L_o}{L_o} x100$$



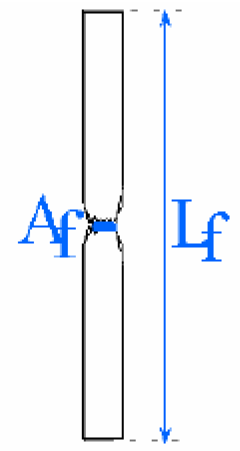
% Reduction in Area, %AR

- Another ductility measure:

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

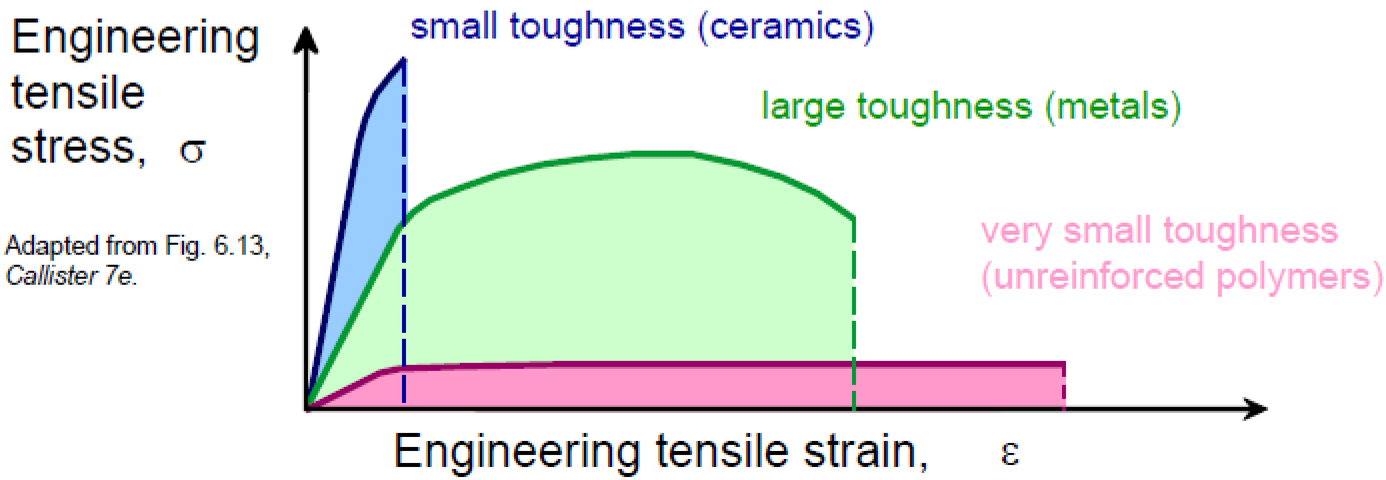


Cup-and-cone fracture



Toughness

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

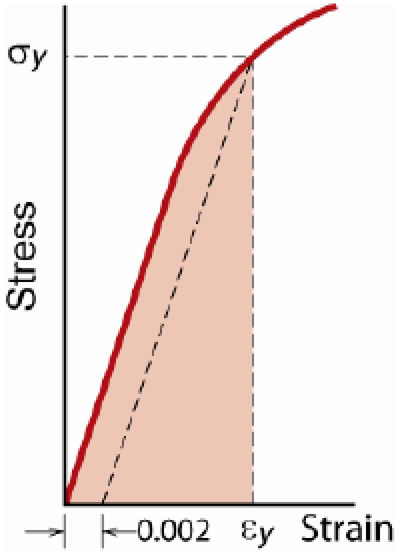


Adapted from Fig. 6.13, *Callister 7e.*

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

Resilience, U_r

- **Adsorb energy without any permanant damage to the material**



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

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

CLASS ACTIVITY

Universiti Malaysia PAHANG
Engineering • Technology • Creativity

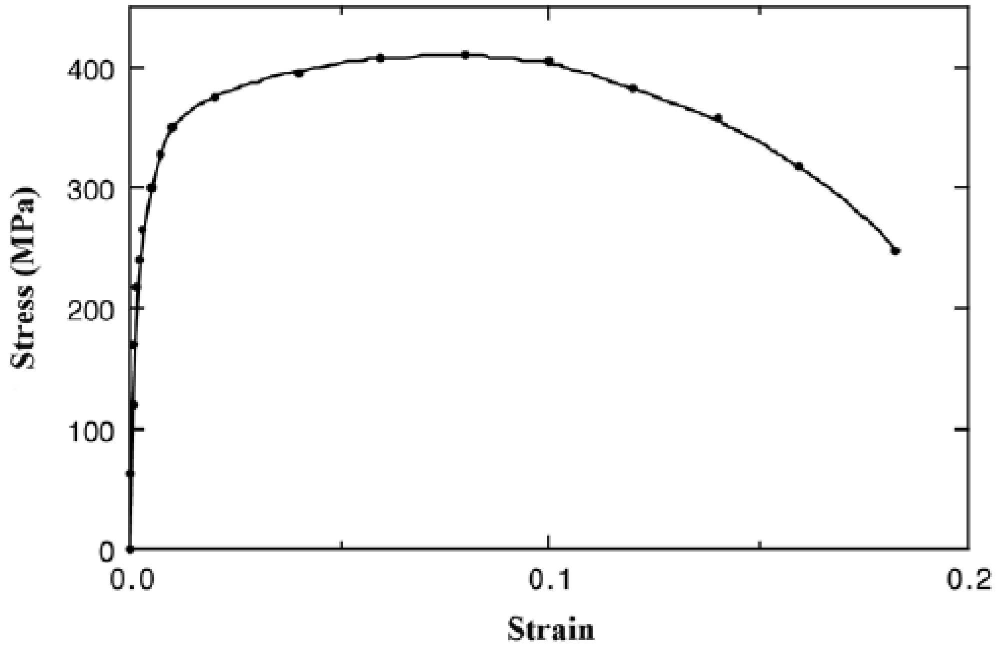
A specimen of ductile cast iron having a rectangular cross section of dimensions 4.8 mm × 15.9 mm is deformed in tension. Using the load–elongation data tabulated below, complete problems (a) and (b).

Load (N)	Length (mm)
0	75.000
9,140	75.050
16,540	75.113
20,170	75.225
25,070	75.525
28,640	76.500
31,100	79.500
30,820	82.500
27,190	85.500
18,970	88.725

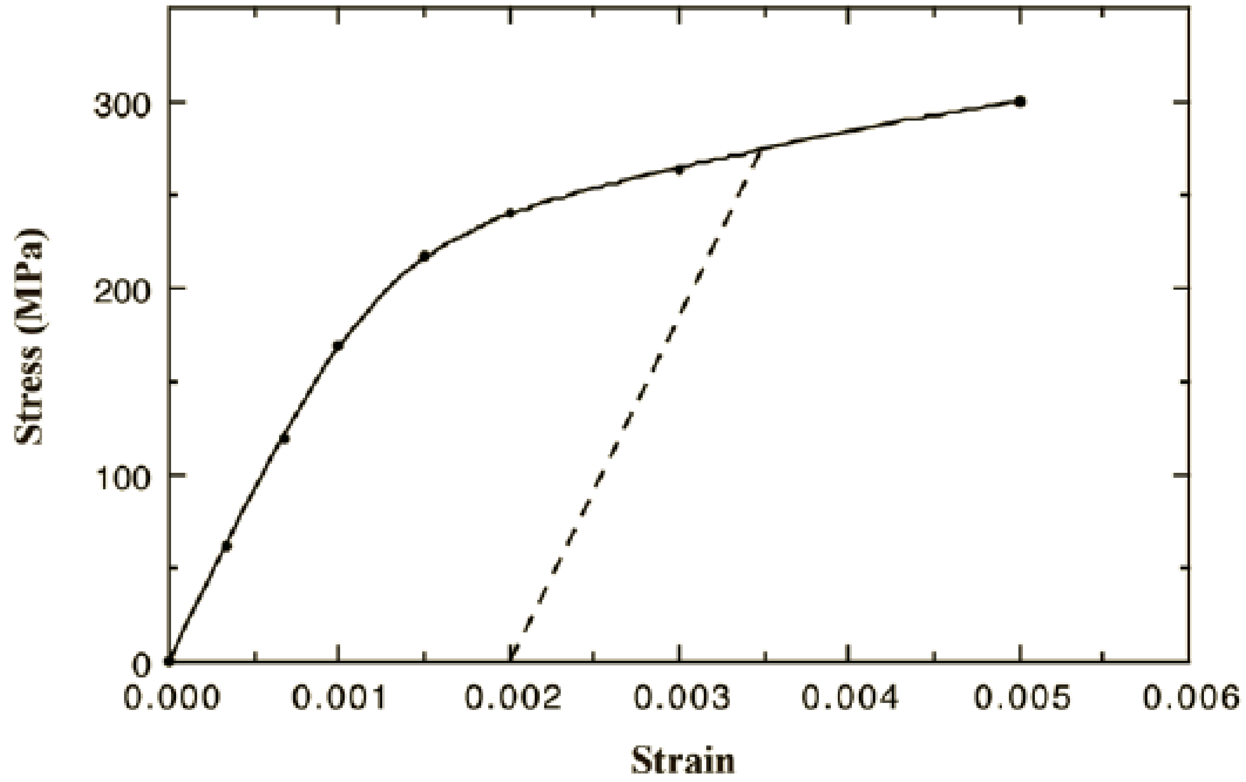
(a) Plot the data as engineering **stress (MPa)** versus engineering **strain (mm/mm)**.
(b) Determine the tensile strength of this alloy.
(c) Determine the Young Modulus of the alloy.
(d) Determine the Yield Strength of the alloy, use 0.2% offset.

ANSWER

(a) The data are plotted below: the entire stress–strain curve,



(b) The tensile strength is approximately 410 MPa, corresponding to the maximum stress on the complete stress–strain plot.



c) The elastic modulus is the slope in the linear elastic region (Equation 6.10) as

$$E = \frac{\Delta \sigma}{\Delta \epsilon} = \frac{100 \text{ MPa} - 0 \text{ MPa}}{0.0005 - 0} = 200 \times 10^3 \text{ MPa} = 200 \text{ GPa}$$

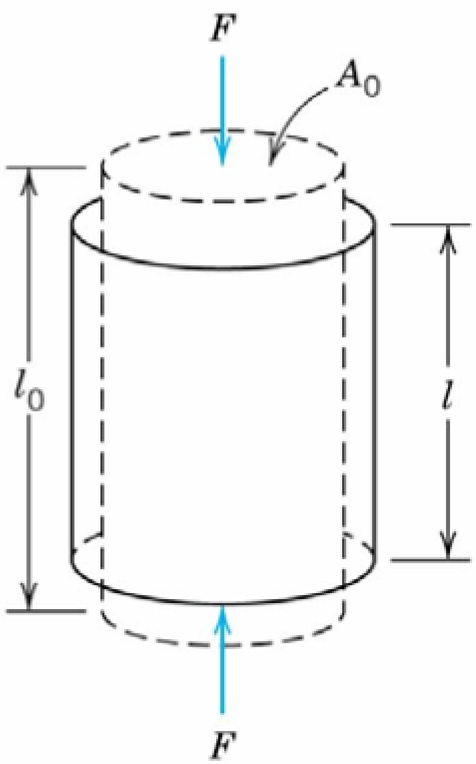
d) For the yield strength, the 0.002 strain offset line is drawn dashed. It intersects the stress–strain curve at approximately 280 MPa.

Mechanical Properties of Materials

1. INTRODUCTION
2. TENSION
3. **COMPRESSION √**
4. **SHEAR & TORSION √**
5. **BENDING √**
6. **HARDNESS √**
7. **FATIGUE √**
8. **CREEP √**
9. **IMPACT √**
10. **RESIDUAL STRESSES √**

3. COMPRESSION

ii. Compression

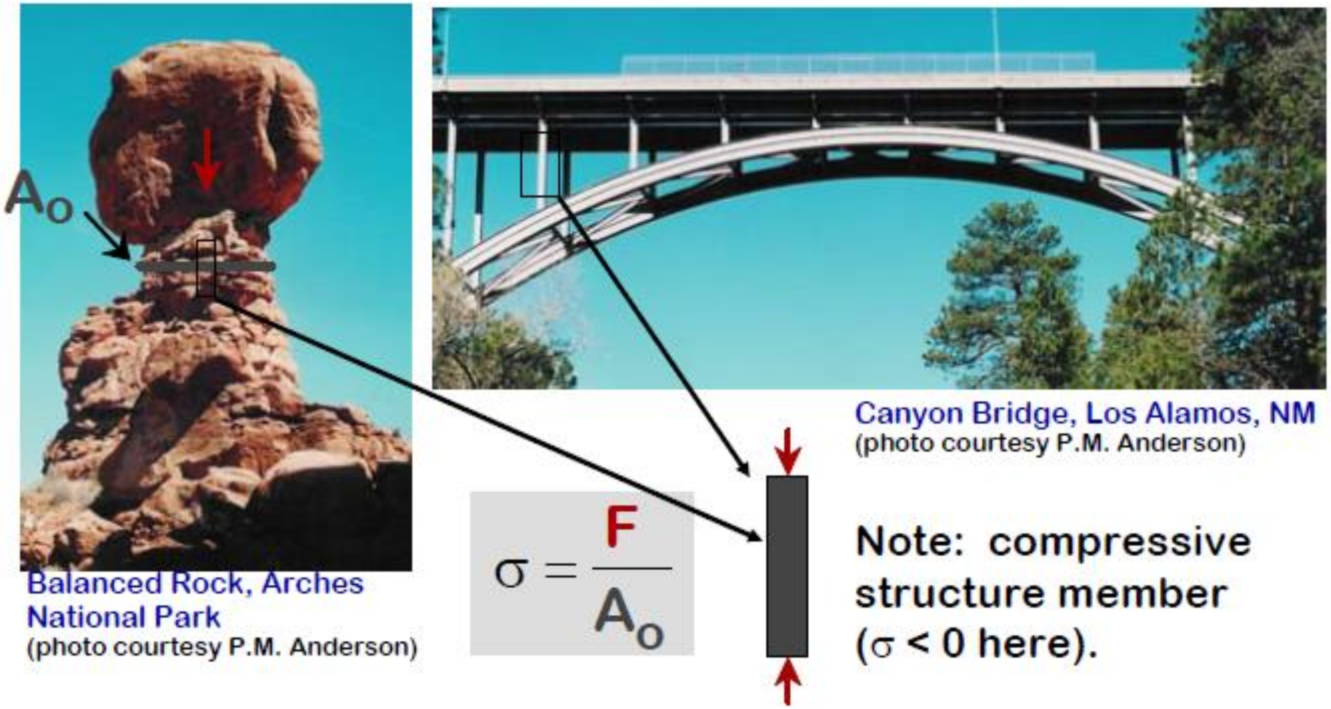


-The force is in compressive form
-The specimen contracts along the direction of the stress
-Compressive force is taken to be -ve, thus yields -ve stress
-Since lo is greater than l, the compressive strains are also -ve

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

$$\varepsilon = \frac{-\Delta l}{l_o}$$

Simple compression



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

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

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

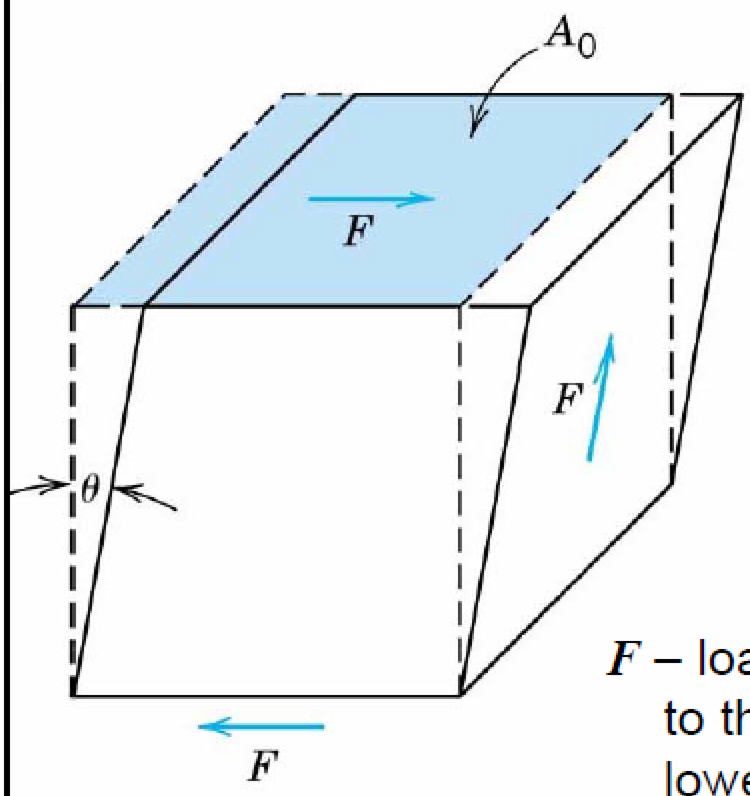
Note: compressive structure member ($\sigma < 0$ here).

Compression test: http://www.youtube.com/watch?v=eAUfJ90QtDY

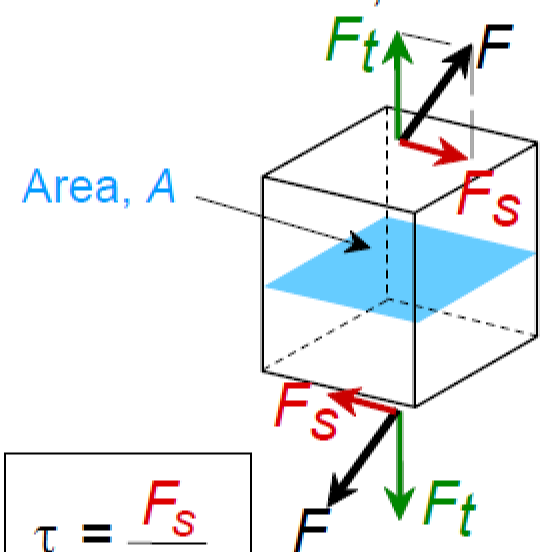
Strength of concrete core sample

4. SHEAR / TORSION

iii. Shear



- Shear stress, τ:

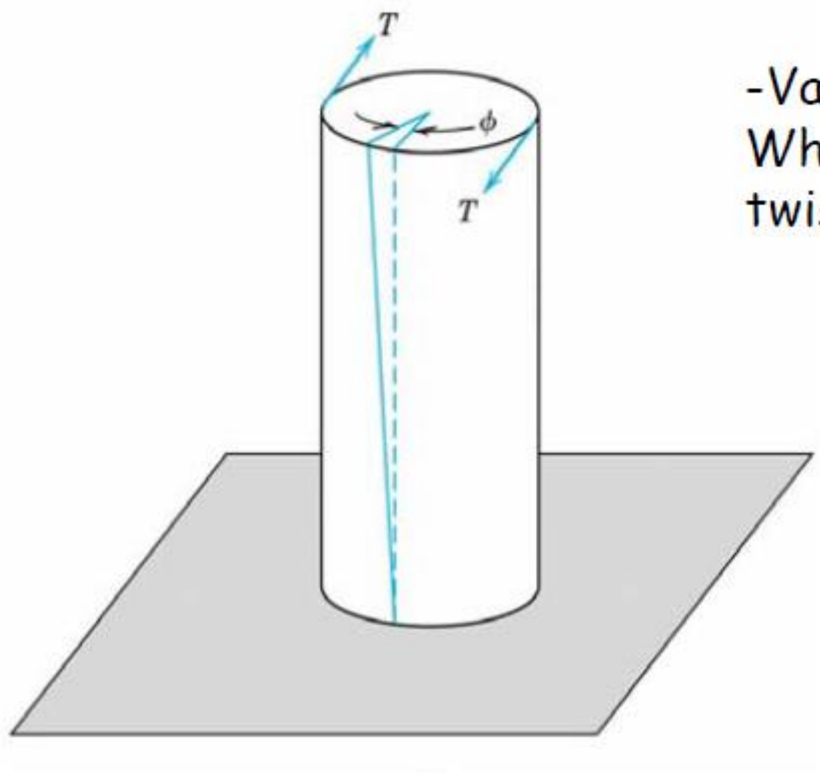


$$\tau = \frac{F_s}{A_o}$$

F – load/force parallel to the upper and lower faces (N)

A_o – area (m^2)

iv. **Torsion**



-Variation of pure shear, Where the structure is twisted

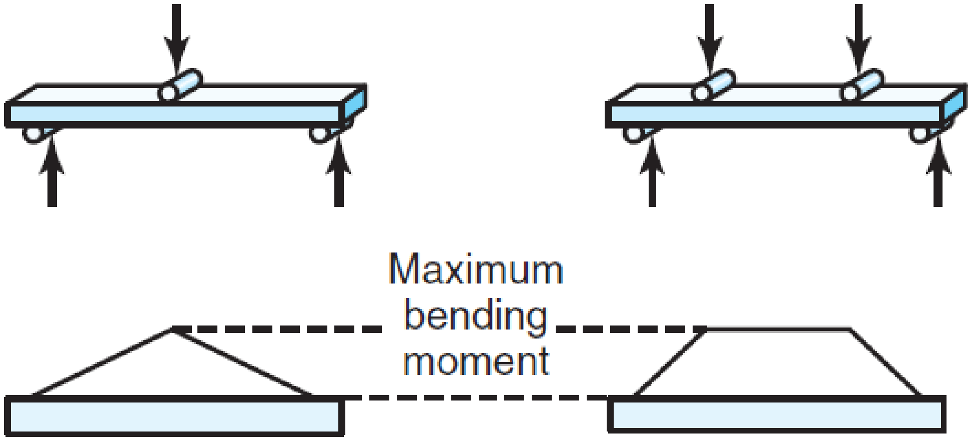
Shear & Torsion: http://www.youtube.com/watch?v=5UPJ3waHtp4

5. BENDING

Bending (Flexure)

- Test method for brittle materials is the **bend** or **flexure test**
- Involves a specimen that has a rectangular cross section and is supported
- The stress at fracture in bending is known as the **modulus of rupture**, or **transverse rupture strength**

Three point bending test video



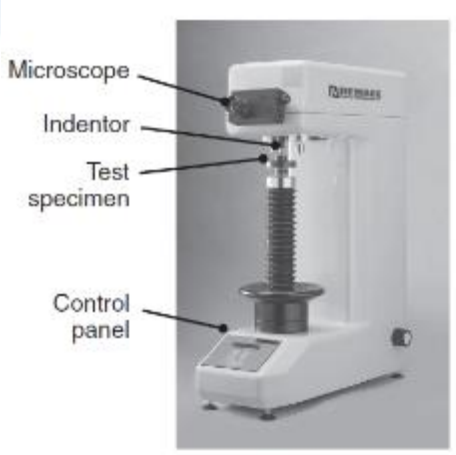
6. HARDNESS

Hardness

- Hardness is an indication of the strength of the material and of its resistance to scratching and to wear. Defined as *resistance to permanent indentation*
- A measure of a materials resistance to localized plastic deformation.
- Large hardness means:
  - Resistance to plastic deformation or cracking in compression
  - Better wear properties.
- Resistance to indentation depends on the shape of the indenter and on the load applied – hardness test.

Hardness Tests

- Several test methods use different *indenter* materials and shapes



(a)

A Micro Vickers hardness tester

(b)

Rockwell hardness tester

(c)

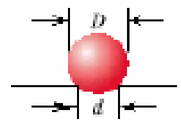
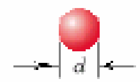
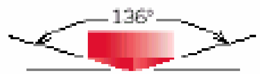
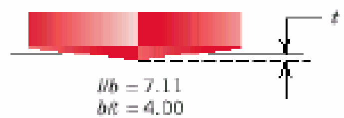
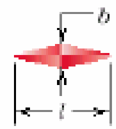
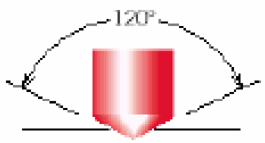
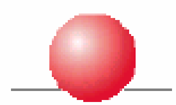
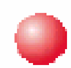
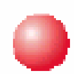
Durometer

(d)

Leeb tester

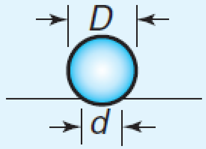
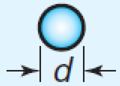
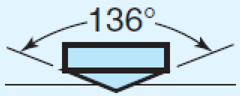
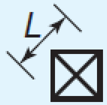
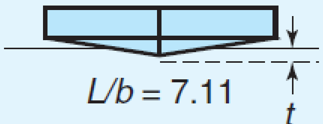
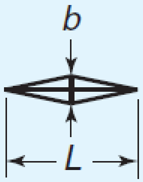
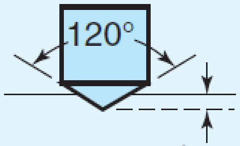
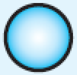
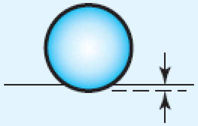
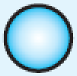
Hardness: Measurement

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)	

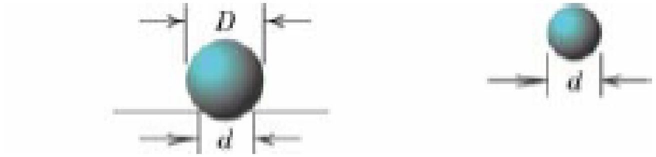
[a] For the hardness formulas given, P (the applied load) is in kg, while D, d, d_1, and l are all in mm.

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.

Test	Indenter	Shape of indentation: Side view	Shape of indentation: Top view	Load, *P*	Hardness number
Brinell	10-mm steel or tungsten-carbide ball			500 kg 1500 kg 3000 kg	$HB = \frac{2P}{(\pi D)\left(D - \sqrt{D^2 - d^2}\right)}$
Vickers	Diamond pyramid			1–120 kg	$HV = \frac{1.854P}{L^2}$
Knoop	Diamond pyramid	 $L/b = 7.11$ $b/t = 4.00$		25 g–5 kg	$HK = \frac{14.2P}{L^2}$
Rockwell					
A C D	Diamond cone	 $t =$ mm		60 kg 150 kg 100 kg	HRA HRC HRD $= 100 - 500t$
B F G	1.6-mm diameter steel ball	 $t =$ mm		100 kg 60 kg 150 kg	HRB HRF HRG $= 130 - 500t$
E	3.2-mm diameter steel ball			100 kg	HRE $= 130 - 500t$

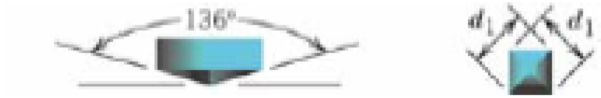
TYPES OF HARDNESS TEST

1. Brinell

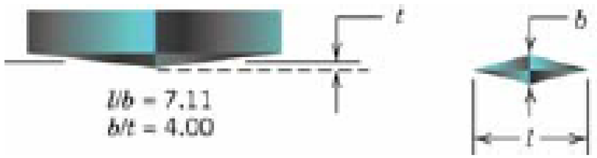


2. Vickers & Knoop Microhardness

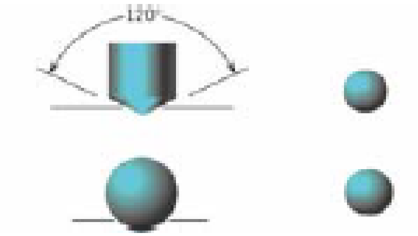
Vickers



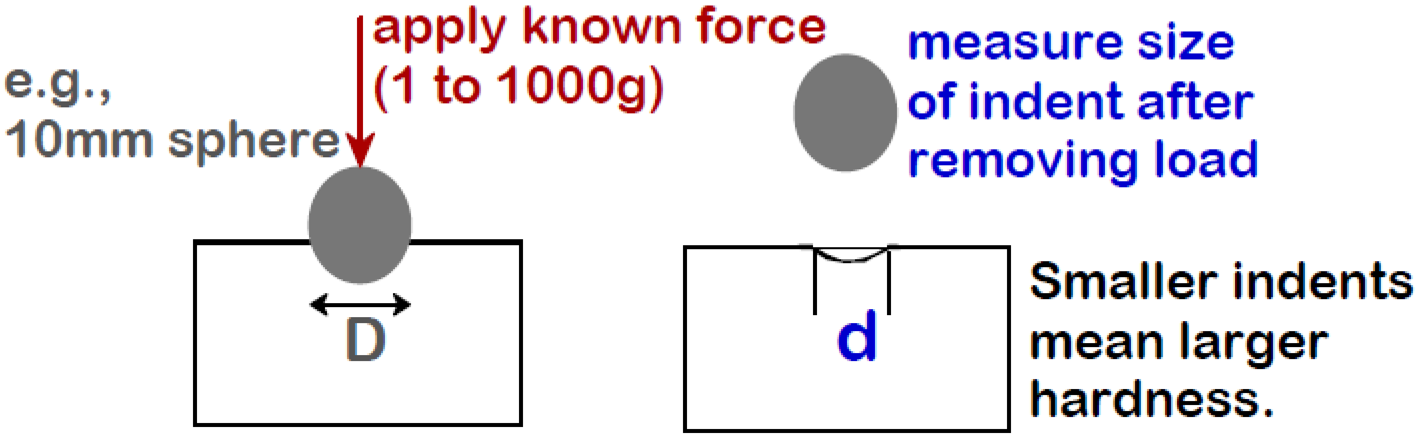
Knoop

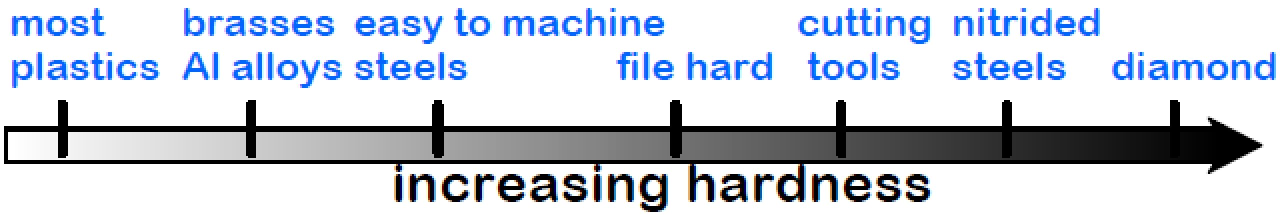


3. Rockwell

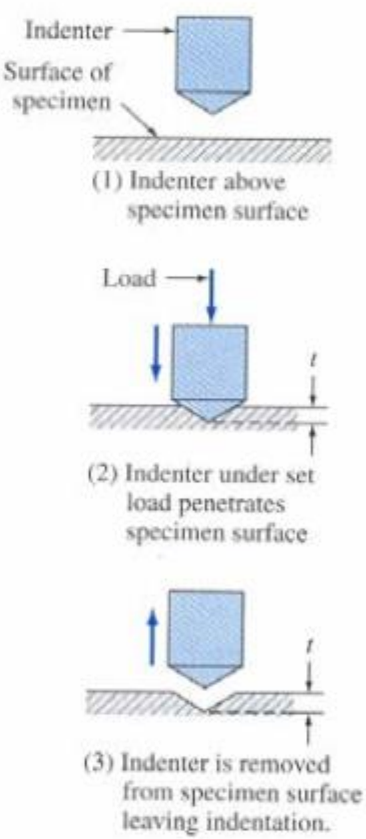


HARDNESS TEST





INSTRUMENT & HARDNESS TEST

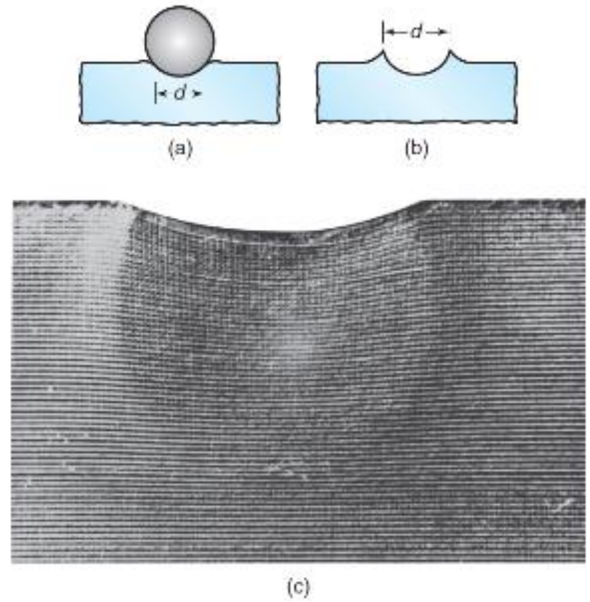


(b)

Hardness Tests

Brinell Test

- Brinell hardness number (HB) is the ratio *P* to the curved surface area of the indentation
- Harder the material to be tested, the smaller the impression



Rockwell Test

- Measures the *depth* of penetration
- Indenter is pressed onto the surface
- Difference in the depths of penetration is a measure of the hardness of the material

Vickers Test

- Uses a pyramid-shaped diamond indenter
- Vickers hardness number is indicated by HV

Hardness Tests

Knoop Test

- Uses a diamond indenter in the shape of an elongated pyramid
- Hardness number is indicated by HK
- It is a **microhardness** test, suitable for very thin specimens and brittle materials

Scleroscope and Leeb Test

- Uses a diamond-tipped indenter dropping onto the specimen from a certain height
- Hardness is related to the *rebound* of the indenter

Hardness test: http://www.youtube.com/watch?v=M7dY3l-zG1M

Hardness:

EXAMPLE 2.2

Calculation of Modulus of Resilience from Hardness

A piece of steel is highly deformed at room temperature. Its hardness is found to be 300 HB. Estimate the area under the stress–strain curve up to the yield point (that is, the *resilience*) for this material if the yield strength is one-third the Brinell hardness.

Given, E = 210 GPa

Hardness:
Hardness-testing Procedures

Solution

Since the yield strength is one-third the Brinell hardness,

$$Y = \frac{300}{3} = 100 \text{ kg/mm}^2$$

The area under the stress–strain curve is

$$\text{Modulus of Resilience} = \frac{Y^2}{2E}$$

From Table 2.2, *E* 210 GPa for steel, thus

$$\text{Modulus of Resilience} = \frac{Y^2}{2E} = \frac{(100)^2}{2(210{,}000)} \times 9.81 = 0.2336 \text{ mm-kg/mm}^3$$

7. FATIGUE

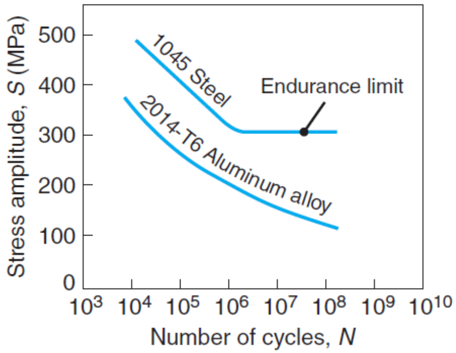
What is Fatigue?

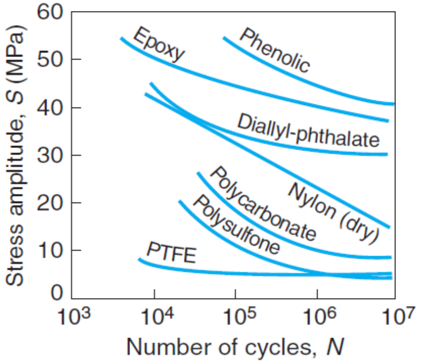
http://www.youtube.com/watch?v=fWGxwJgiqS8&list=PL9181F19B552A38AB&index=5

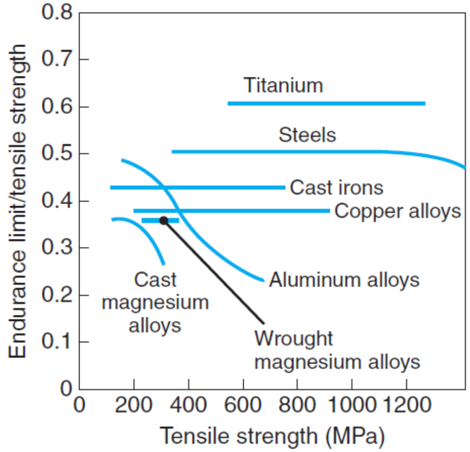
- **Cyclic stresses** may be caused by fluctuating mechanical loads, e.g. gear and rotating machine elements
- Failure is due to cracks that grow with every stress cycle and propagate until a critical crack length is reached
- Known as **fatigue failure**
- Fatigue *test methods* involve testing specimens under a combination of tension and bending

Fatigue

- Stress amplitude is defined as the maximum stress
- Typical plots are called ***S–N* curves**
- Maximum stress without fatigue failure, regardless of the number of cycles, is known as the **endurance limit** or **fatigue limit**
- Endurance limit for metals can be related to their ultimate tensile strength







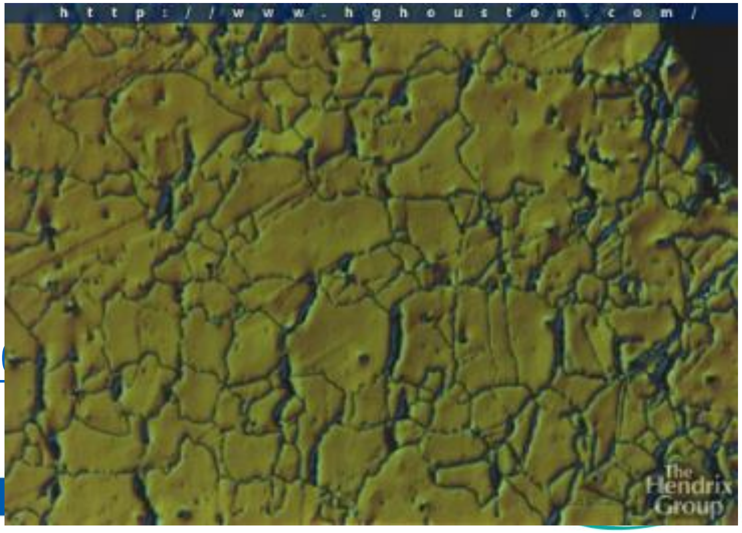
8. CREEP

Creep

- **Creep** is the permanent elongation of a component under a static load / constant stress maintained for a period of time
- Occurs in metals and certain nonmetallic materials (thermoplastics and rubber)
- Mechanism of creep at elevated temperature in metals is due to **grain-boundary sliding**
- *Creep test* consists of subjecting a specimen to a constant tensile load at elevated temperature

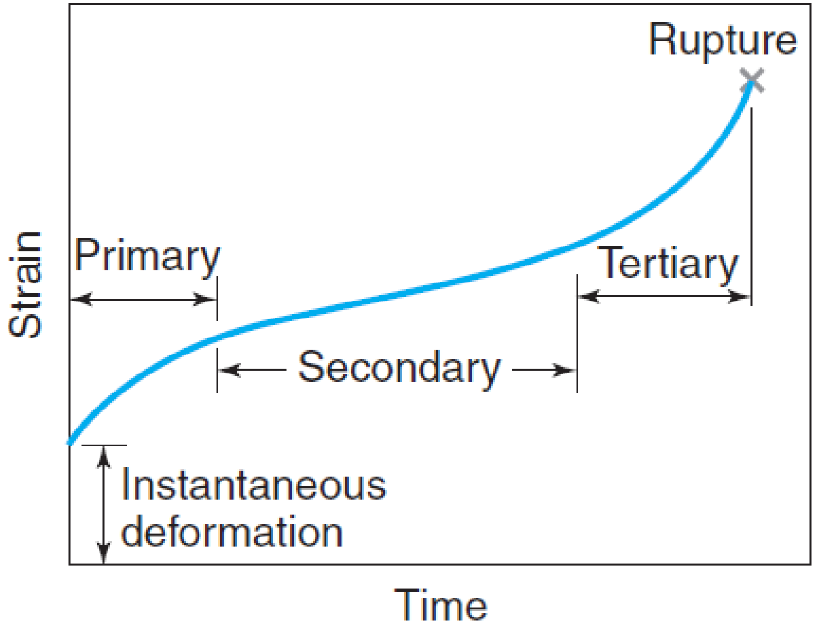
What is Creep ?
http://www.youtube.com/watch?v=hUk2_Y34WRI

Creep failure in steel :
http://www.youtube.com/watch?v=
-qB8EJa3ss



Creep

- Creep curve consists of *primary*, *secondary*, and *tertiary* stages
- Specimen eventually fails by necking and fracture, called **rupture** or **creep rupture**
- *video*

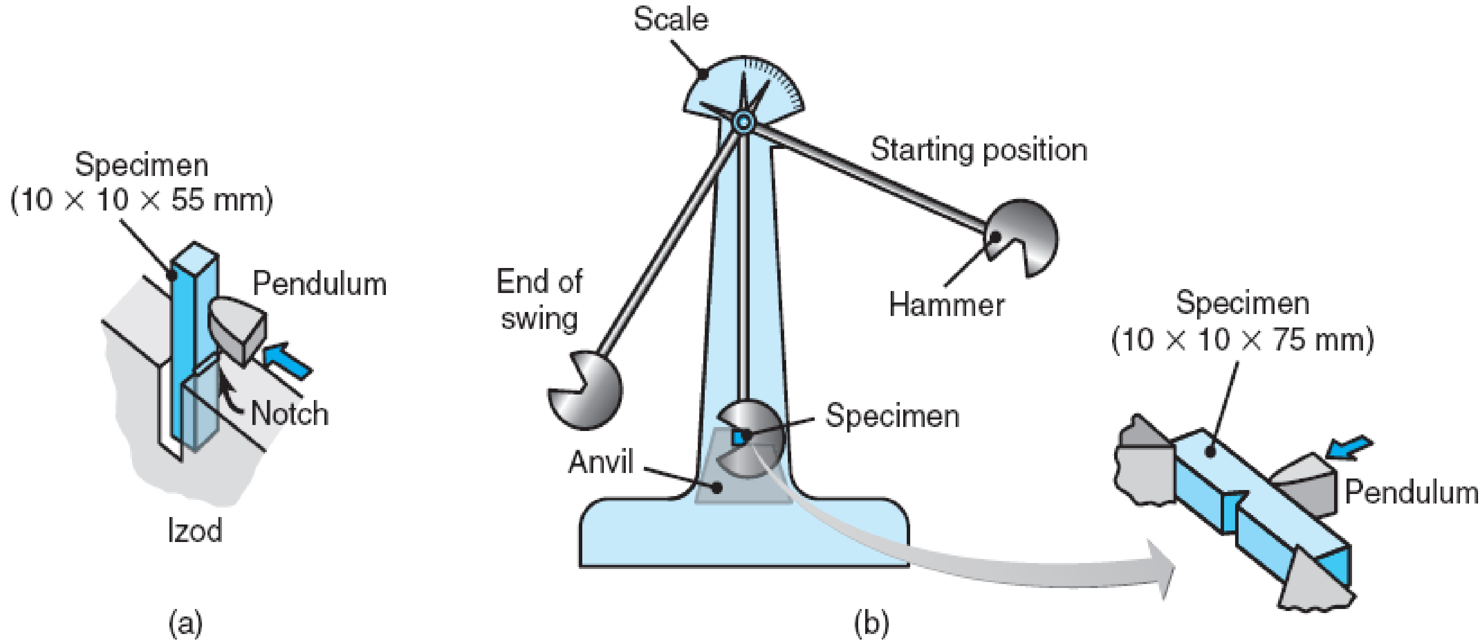


Measure the changes in length at various time increments

9. IMPACT

Impact

- Materials are subjected to **impact**, or **dynamic loading** during manufacturing.
- *Impact test* consists of placing a notched specimen in an impact tester and breaking the specimen with a swinging pendulum.
- Specimen is supported at both ends for **Charpy** test.
- Specimen is supported at one end like a cantilever beam in **Izod** test.



Charpy impact test – Example
http://www.youtube.com/watch?v=X61eRGH8Ww

10. RESIDUAL STRESS

Residual Stresses

- Stresses that remain within a part after it has been formed and all the external forces are removed
- When workpieces are subjected to plastic deformation, they develop **residual stresses**
- Residual stress is often a cause of premature failure of critical components.

Residual stresses can also be caused by temperature gradients within a body, such as occur during cooling of a casting or a forging. The local expansions and con-tractions caused by temperature gradients within the material produce a nonuniform deformation, such as is seen in the permanent bending of a beam.

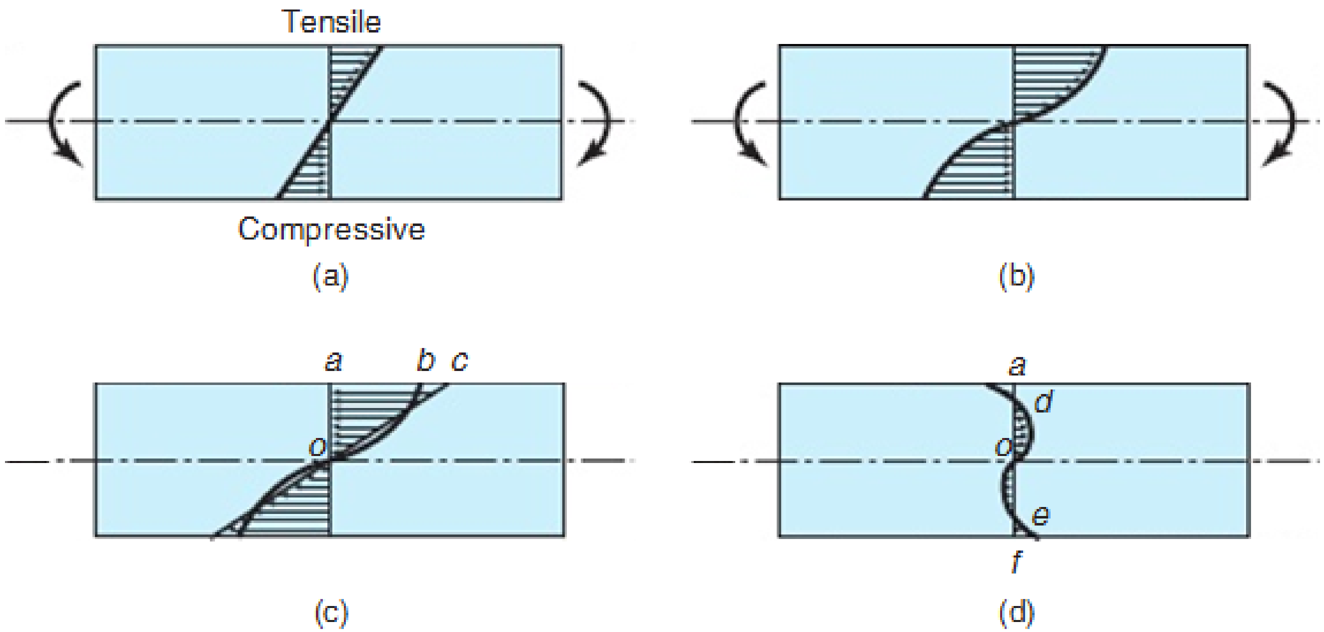


FIGURE 2.30 Residual stresses developed in bending a beam having a rectangular cross section. Note that the horizontal forces and moments caused by residual stresses in the beam must be balanced internally. Because of nonuniform deformation, especially during cold-metalworking operations, most parts develop residual stresses.

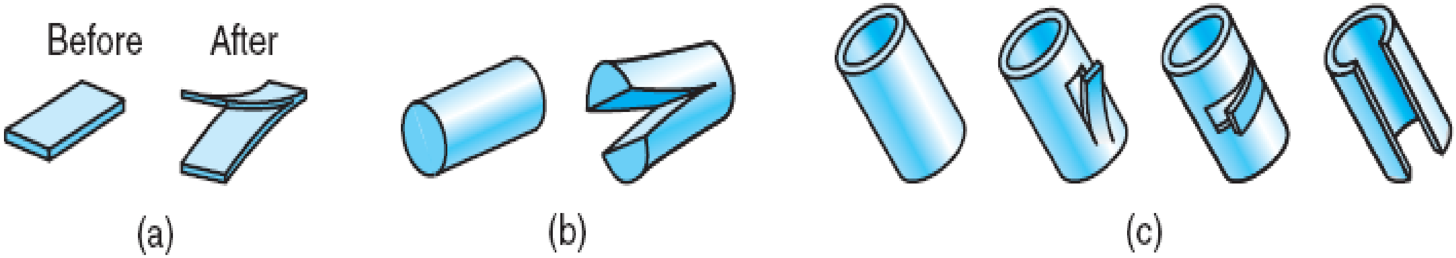
Case study:

- the collapse of the suspension bridge at Silver Bridge in West Virginia, United States in December 1967.
- The eyebar links were castings which showed high levels of residual stress, which in one I bar, encouraged crack growth. When the crack reached a critical size, it grew catastrophically, and from that moment, the whole structure started to fail in a chain reaction.
- Because the structure failed in less than a minute, 46 drivers and passengers in cars on the bridge at the time were killed as the suspended roadway fell into the river below.

The collapsed Silver Bridge, as seen from the Ohio side

Residual Stresses

- The equilibrium of residual stresses in may be disturbed by the re-moval of a layer of material from the part, such as by machining or grinding.
- The bar will then acquire a new radius of curvature in order to balance the internal forces.
- Such disturbances of residual stresses lead to warping of parts .The equilibrium of residual stresses may also be disturbed by relaxation of the stresses over a period of time (see below).



Residual Stresses

Universiti Malaysia PAHANG
Engineering • Technology • Creativity

Reduction and Elimination of Residual Stresses

- Residual stresses can be reducedor eliminated either by stress-relief annealing or by a further deformation of the part, such as stretching it. Given sufficient time, residual stresses may also diminishat room temperature (by relaxation of residual stresses). The time required for relax-ation can be greatly reduced by raising the temperature of the workpiece.

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.