MATERIALS SCIENCE

SSP 2412

MECHANICAL PROPERTIES & TESTING

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Introduction

The mechanical properties of a material are used to determine its suitability for a particular application

Deal directly with behavior of materials under applied forces: Basic understanding of Stress, Strain, Strength, Associated problems, etc.

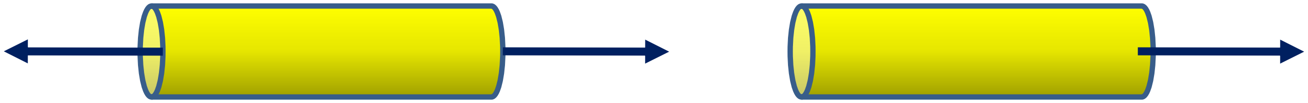
Strength of Material

Stress is defined as the internal resistance set up by a body when it is deformed. It is measured in N/m^2 and this unit is specifically called Pascal (Pa). A bigger unit of stress is the mega Pascal (MPa).

$1\ Pa = 1N/m^2$,
$1MPa = 10^6\ N/m^2 = 1N/mm^2$.

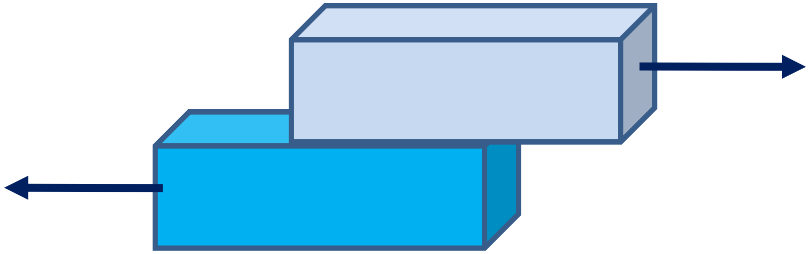
Three Basic Types of Stresses
Basically three different types of stresses can be identified. These are related to the nature of the deforming force applied on the body. That is, whether they are tensile, compressive or shearing.

Tensile Stress is the stress state leading to expansion; that is, the length of a material tends to increase in the tensile direction. The volume of the material stays constant.



Compressive Stress is the stress that, when applied, acts towards the centre of that material. When a material is subjected to compressive stress, then this material is under compression. Usually, compressive stress applied to bars, columns.

Shear stress is defined as a stress which is applied parallel or tangential to a face of a material, as opposed to a normal stress which is applied perpendicularly.



Stress

- Stress: Intensity of the internally distributed forces or component of forces that resist a change in the form of a body. It include stress due to:
  - Tension, Compression, Shear, Torsion, Flexure
- Stress is calculated by force per unit area. Applied force divided by the cross sectional area of the specimen.
- Stress units

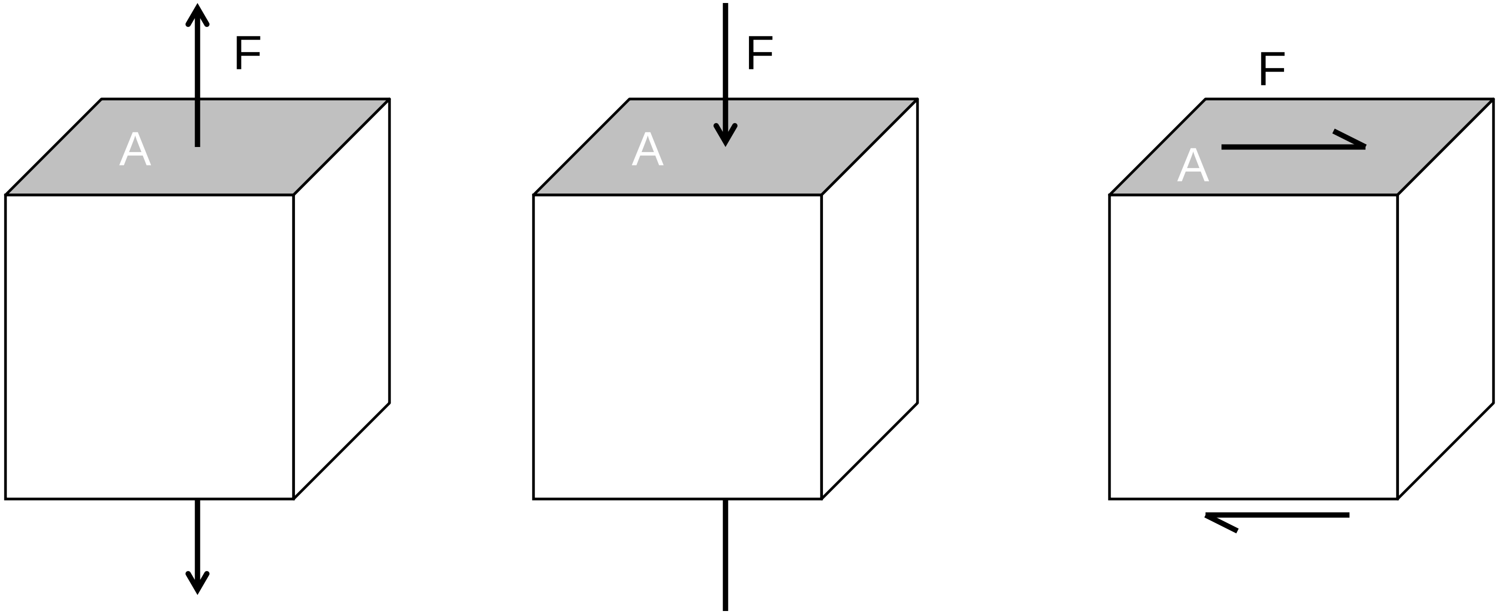
$$\sigma = \frac{F}{A}$$

  - Pascals = Pa = Newtons/m^2
  - Psi Pounds per square inch); 1MPa = 1 x10^6 Pa = 145 psi
- Example 1,
  - Wire 12 cm long is tied vertically. The wire has a diameter of 2 mm in and supports 100 N. What is the stress that is developed?
  - Stress = F/A = F/πr^2 = 100/(3.1415927x(5x10^{-3})^2)= 1.27 MPa

Stress

$$\text{Normal} = \sigma = \frac{F}{A}$$

$$\text{Shear} = \tau = \frac{F}{A}$$

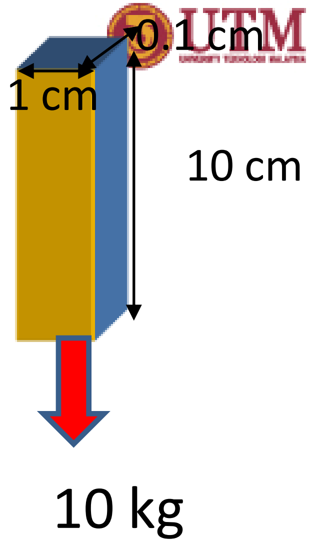


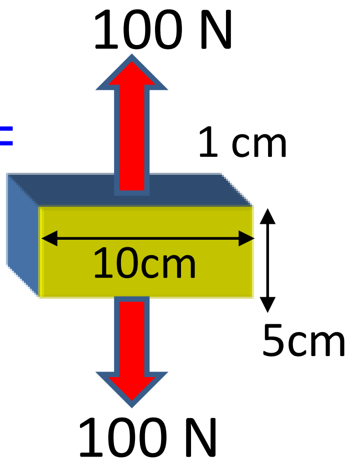
Tension: $\sigma>0$

Compression: $\sigma<0$

Stress

- Example 2,
  - i) Tensile Bar is 10 cm x 1 cm x 0.1 cm is mounted vertically in test machine. The bar supports 10 kg. What is the stress that is developed? What is the Load?
    - Stress = F/A = F/(width*thickness) = 10x9.8 N/(1cm x 0.1cm) = 9.8 MPa
    - Load = 98 N
  - ii) Block is 10 cm x 1 cm x 5 cm is mounted on its side in a test machine. The block is pulled with 100 N on both sides. What is the stress that is developed? What is the Load?
    - Stress = F/A = F/(width*thickness) = 100N/(.01m * 0.10 m)= 100,000 N/m^2 = 100,000 Pa = 0.1 MPa= 0.1 MPa x 145psi/MPa = 14.5 psi
    - Load = 100 N



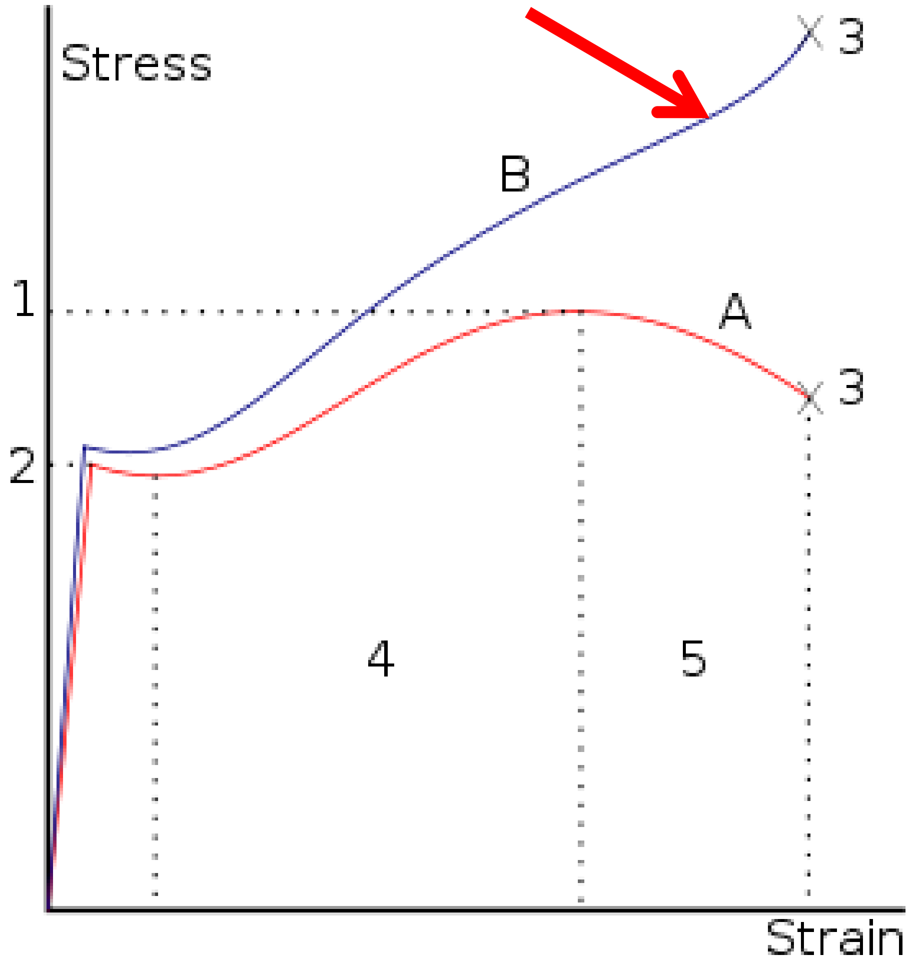


True Stress

True Stress is the applied load divided by actual area of the cross section through which load operates. It takes into account the change in cross section that occurs with changing load.

True stress is larger than the nominal stress(stress which act perpendicular to the cut surface, Tensile/compressive).The engineering stress-strain curve does not give a true indication of the deformation characteristics of a metal because it is based entirely on the original dimensions of the specimen, and these dimensions change continuously during the test. Also, ductile metal which is pulled in tension becomes unstable and necks down during the course of the test. Because the cross-sectional area of the specimen is decreasing rapidly at this stage in the test, the load required continuing deformation falls off. The average stress based on original area like wise decreases, and this produces the fall-off in the stress-strain curve beyond the point of maximum load. **True stress can results in a true stress-strain curve shown by a blue curve (compared to a nominal red curve). See an arrow in next slide.**

True Stress-Strain Curve



Example 3,
What is the true stress of question in example 1 if wire diameter slightly reduced to 1.92 mm?

Stress = F/A' = F/πr' ^{2} =
100/[πx(4.8 x10^{-3})^2] = 1.38 MPa

This result shows that true stress is slightly greater than nominal stress (1.38 Mpa > 1.27 Mpa)

Strain

Strain is the geometrical measure of deformation representing the relative displacement between particles in the material body.

- It measures how much a given displacement differs locally from a rigid-body displacement.
- Strain defines the amount of stretch or compression along a material line elements of materials, the *normal strain*, and the amount of distortion associated with the sliding of plane layers over each other, the *shear strain*, within a deforming body.
- Strain is a dimensionless quantity, which can be expressed as a decimal fraction, a percentage or in parts-per notation. This could be applied by elongation, shortening, or volume changes, or angular distortion.

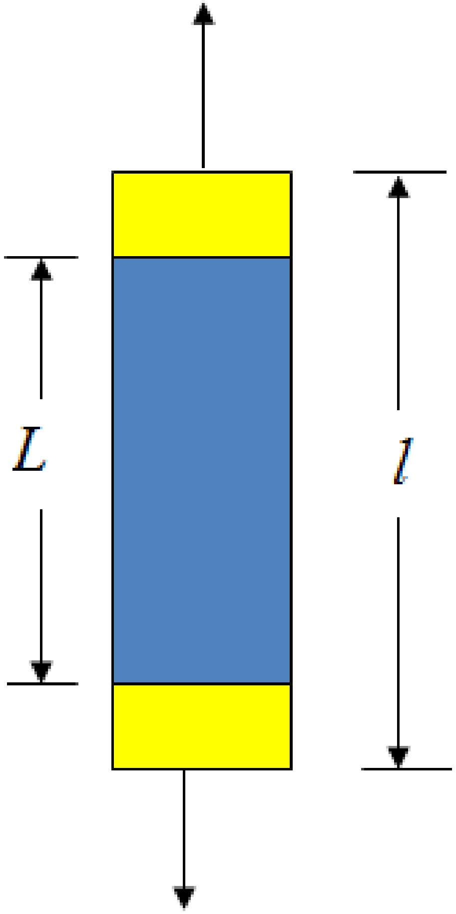
Strain

- Strain is given by a relationship,

$$e = \frac{\Delta l}{L} = \frac{l - L}{L}$$

- Where L is the original length and l is the final length of the bar

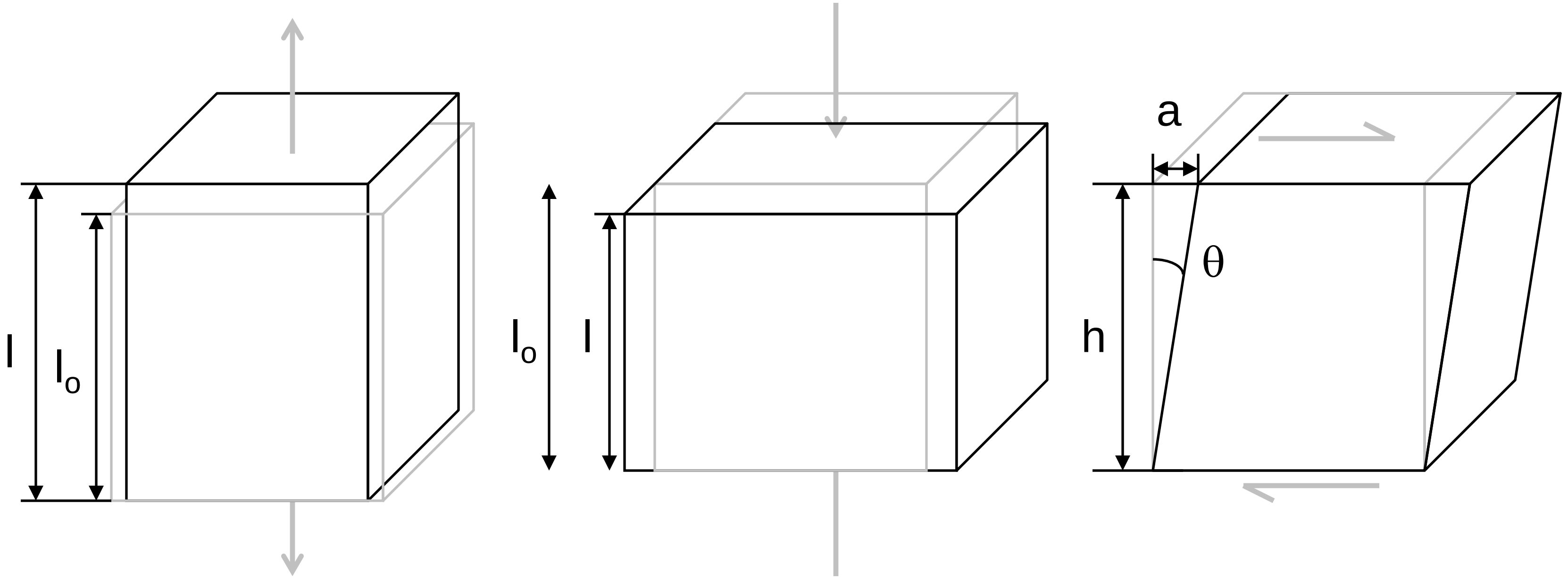
- Example 4: For L=30 cm and l = 31.5 cm, then e = (31.5-30)/30 = 0.5 = 5%



Strain

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

$$\text{Shear strain} = \gamma = \frac{a}{h} = \tan\theta$$



True Strain

True strain is the **logarithmic strain** ε, also called *natural strain*, or *Hencky strain*. This logarithmic strain is obtained by integrating this incremental strain:

$$\int \delta\varepsilon = \int_L^\ell \frac{\delta\ell}{\ell}$$

$$\varepsilon = \ln\left(\frac{\ell}{L}\right) = \ln\lambda$$

$$= \ln(1+e)$$

$$= e - e^2/2 + e^3/3 - \cdots$$

Example 5,
What is the true strain of question in example 3?

ε = ln (31.5/30) = 0.488
= 48.8% (Smaller than *e*)

True strain provides the correct measure of the final strain when deformation takes place in a series of increments

True & Engineering Stress/Strain

	Stress	Strain
Engineering (initial dimensions)	$\sigma_E = \frac{F}{A_o}$	$\varepsilon_E = \frac{l - l_o}{l_o} = \frac{\Delta l}{l_o}$
True (instantaneous dimensions)	$\sigma_T = \frac{F}{A_i}$	$\varepsilon_T = \int_{l_o}^{l_i} \frac{dl}{l} = ln\left(\frac{l_i}{l_o}\right)$
	Using and $A_i \cdot l_i = A_o \cdot l_o$ $\sigma_T = \sigma_E (1 + \varepsilon_E)$	$\varepsilon_T = ln(\varepsilon_E + 1)$

Modulus of elasticity

Elastic modulus, or **modulus of elasticity**, is the mathematical description of an object or substance's tendency to be deformed elastically (i.e., non-permanently) when a force is applied to it. The elastic modulus of an object is defined as the slope of its stress-strain curve in the elastic deformation region.

Three primary types:

- **Young's modulus** (*E*) describes tensile elasticity, or the tendency of an object to deform along an axis when opposing forces are applied along that axis; it is defined as the ratio of tensile stress to tensile strain. It is often referred to simply as the *elastic modulus*.

$$E = \frac{\text{Tensile stress}}{\text{Tensile Strain}} = \frac{\sigma}{\varepsilon}$$

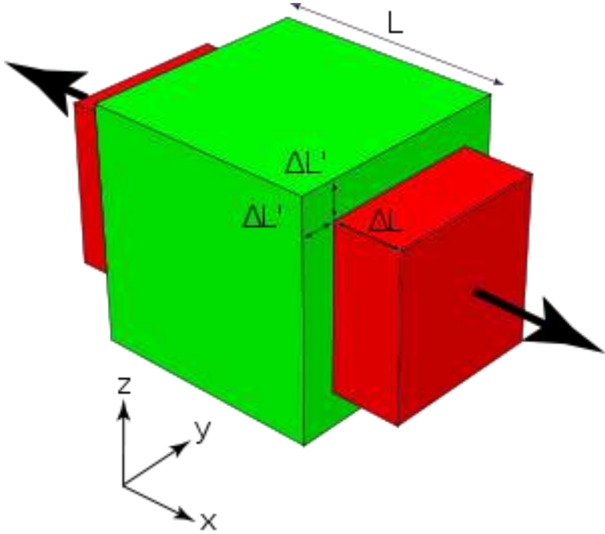
- **Shear modulus** or *modulus of rigidity* (*G*) - Tendency to shear (the deformation of shape at constant volume) when acted upon by opposing forces; it is defined as shear stress over shear strain. Part of the derivation of viscosity.
- **Bulk modulus** (*K*) - Tendency to deform in all directions when uniformly loaded in all directions; it is defined as volumetric stress over volumetric strain, and is the inverse of compressibility The bulk modulus is an extension of Young's modulus to three dimensions.

Typical Modulus of Elasticity Values for Various Materials

Material	**Elastic Modulus**	
	MPa	**psi**
Diamond	1,200,000	170,000,000
Steel	200,000	30,000,000
Aluminium	70,000	10,000,000
Wood	7,000-14,000	1,000,000-2,000,000
Crushed Stone	150-300	20,000-40,000
Silty Soils	35-150	5,000-20,000
Clay Soils	35-100	5,000-15,000
Rubber	7	1,000

Elastic Deformation - Poisson Ratio

Poisson's ratio (ν) is the ratio, when a sample object is stretched, of the contraction or transverse strain (perpendicular to the applied load), to the extension or axial strain (in the direction of the applied load).



When a material is compressed in one direction, it usually tends to expand in the other two directions perpendicular to the direction of compression. This phenomenon is called the **Poisson effect**. Poisson's ratio ν is a measure of the Poisson effect. The Poisson ratio is the ratio of the fraction (or percent) of expansion divided by the fraction (or percent) of compression, for small values of these changes.

Poisson's Ratio, v can be expressed as,

$$v = -\varepsilon_t / \varepsilon_a$$

ε_t = transverse/lateral strain= $\Delta D/D$
ε_a= axial/longitudinal strain= $\Delta L/L$

Which occur within the proportionality limit of the materials.

For most of the materials its value ranges from 0.25 to 0.35. For cork it is nearly zero.

Typical Poisson's Ratios from some Common Materials

Material	Pois. Ratio
Upper limit	0.5
Aluminium	0.334
Stainless steel 18-8	0.305
Zinc	0.331
Lead	0.431
Brass, 70-30	0.331
Brass, cast	0.357
Bronze	0.34
Concrete	0.2
Copper	0.355
Cork	0
Glass	0.24
Glass, Ceramic	0.29
Ice	0.33
Rubber	0.48 - 0.50
Iron, Cast - gray	0.211

Poisson Ratio of Compression Bar

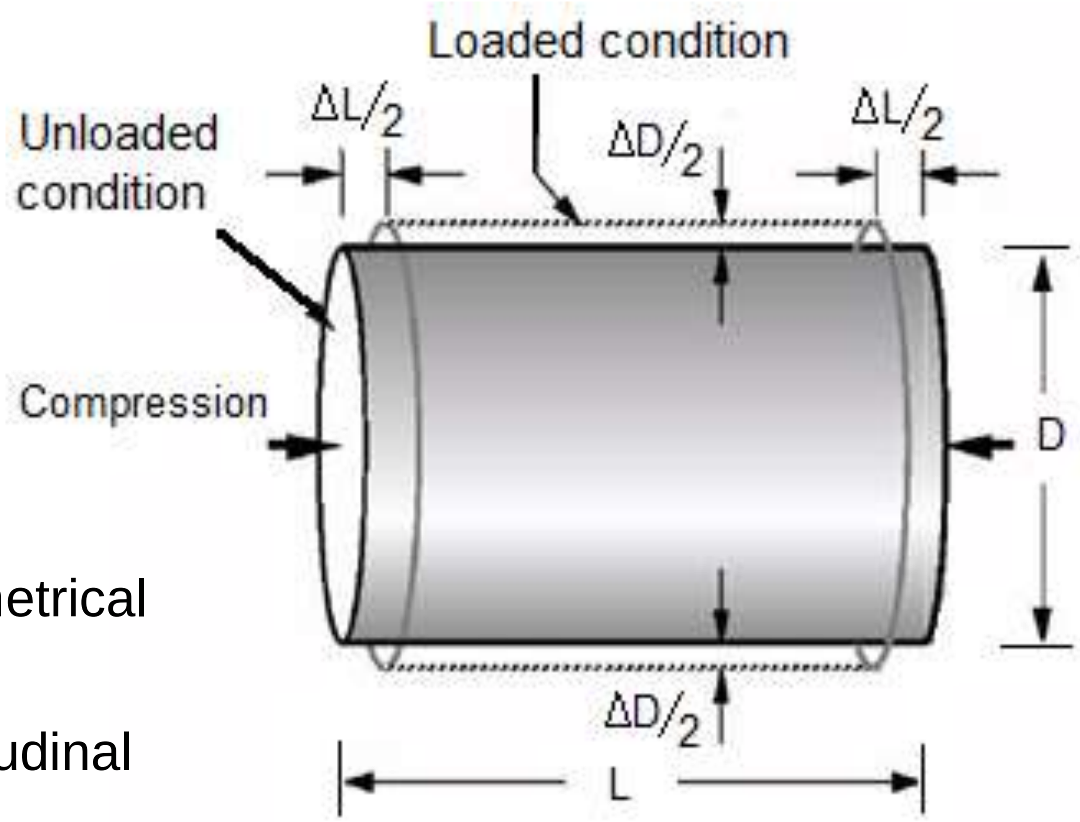
Consider compression of a metallic bar (cylindrical), by the force acting on both ends of the bar - shown in figure

$$\nu = -\varepsilon_D / \varepsilon_L$$

Where,

$\varepsilon_D = \Delta D/D$: Strain along diametrical vertical axis)

$\varepsilon_L = \Delta L/L$: Strain along longitudinal (horizontal axis)

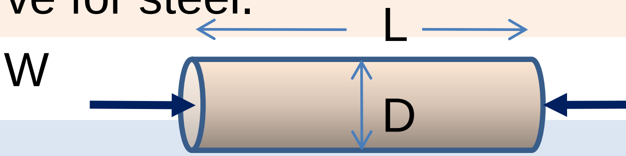


In case of tensile bar, the *D* is contracting (smaller than that of unloaded condition) , while *L* is slightly longer than before (elongated).

Problem Examples

Example 1

A stainless steel rod of length 100 cm and diameter 1.5 mm is taken for compression test under a load of 10^7 N as shown in Fig. 1. If the Young modulus and Poisson ratio are 100 GPa and 0.31, respectively, determine i) ΔL, ii) ΔD, iii) volume of the rod in loaded condition, with $\Delta V = 0.5\ \text{mm}^3$ and iv) stress-strain curve for steel.



Example 2

Based on the following Fig., a steel bar L = 50 cm and D = 5 mm diameter is compressed with a load W =100 kg on both sides, causing an increment of 2.8% in its diameter and reduction of 8.4% in its length. Calculate i) force on bar, ii) length's contraction and diameter's expansion at one end, iii) Young modulus and iv) Poisson ratio.

Example 3

A 2 m long rectangular bar of 7.5 cm × 5 cm is subjected to an axial tensile load of 1000 kN. Bar gets elongated by 2 mm in length and decreases in width by 10×10^{-6} m. determine the modulus of elasticity E and Poisson's ratio v of the material of bar.

Solution 1

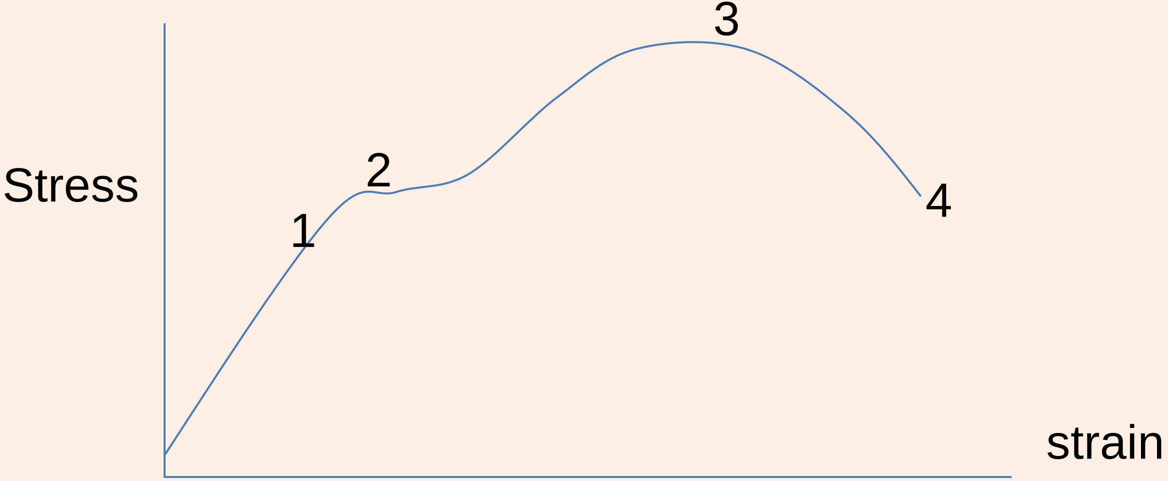
Solution to Example 1:

i) $E = (F/A)/(\Delta L/L)$, $\Delta L = 10^7 \text{ x } 10^3/ 100 \text{ x } 10^9 = 0.1$ mm

ii) Using $v = 0.31 = (\Delta D/D)/(\Delta L/L)$, $\Delta D/D = 0.31 \text{ x } 0.1/1000$,
$\Delta D = 4.65 \text{ x } 10^{-5}$ mm.

iii) $\Delta V = V' - \pi\,(D/2)^2 L$, $V' = \Delta V + \pi(1.5/2)^2 \text{ x} 10^3 = 0.5 + 562.5 = 563$ mm^3

iv) Stress-strain curve:



1: Elastic limit
2: Yield point
3: Ultimate strength
4: Fracture point

Solution 2

Solution to Example 2:

i) Force on bar, $F = mg = 100 \times 9.8 = 980\ \text{N}$

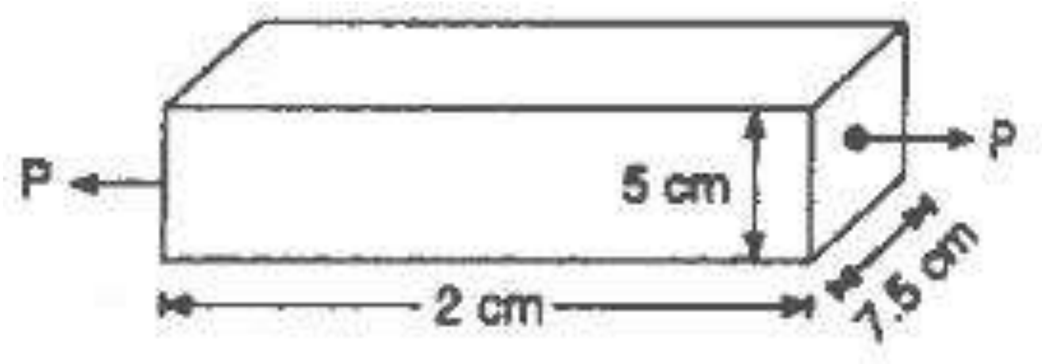
ii) a) Using $\varepsilon_L = \Delta L/L = 8.4/100$, $\Delta L = 50\ \text{cm} \times 8.4/100 = 4.2\ \text{cm}$; thus $\Delta L/2 = 2.1\ \text{cm}$.

b) Using $\varepsilon_D = \Delta D/D = 2.8/100$, $\Delta D = 5\ \text{mm} \times 2.8/100 = 1.4\ \text{mm}$, thus $\Delta D/2 = 0.7\ \text{mm}$.

iii) Using equation, $E = \frac{\text{Tensile stress}}{\text{Tensile Strain}} = \frac{\sigma}{\varepsilon}$, $E = FL/A\Delta L = 980 \times 0.5/[\pi \times (2.5 \times 10^{-3})^2] = 25\ \text{MPa}$

iv) Using equation, $\nu = -\varepsilon_D / \varepsilon_L = 2.8/8.4 = 0.333$

Solution 3



Where $E = 266.67 \times 10^6/0.001 = 2.67 \times 10^{11}$ N/m^2, or = 266.67 GPa

Lateral strain = $\Delta D/D = 10 \times 10^{-6}/7.5 \times 10^{-2} = 1.333 \times 10^{-4}$

Longitudinal strain = $\Delta L/L = 2 \times 10^{-3}/2 = 0.001$

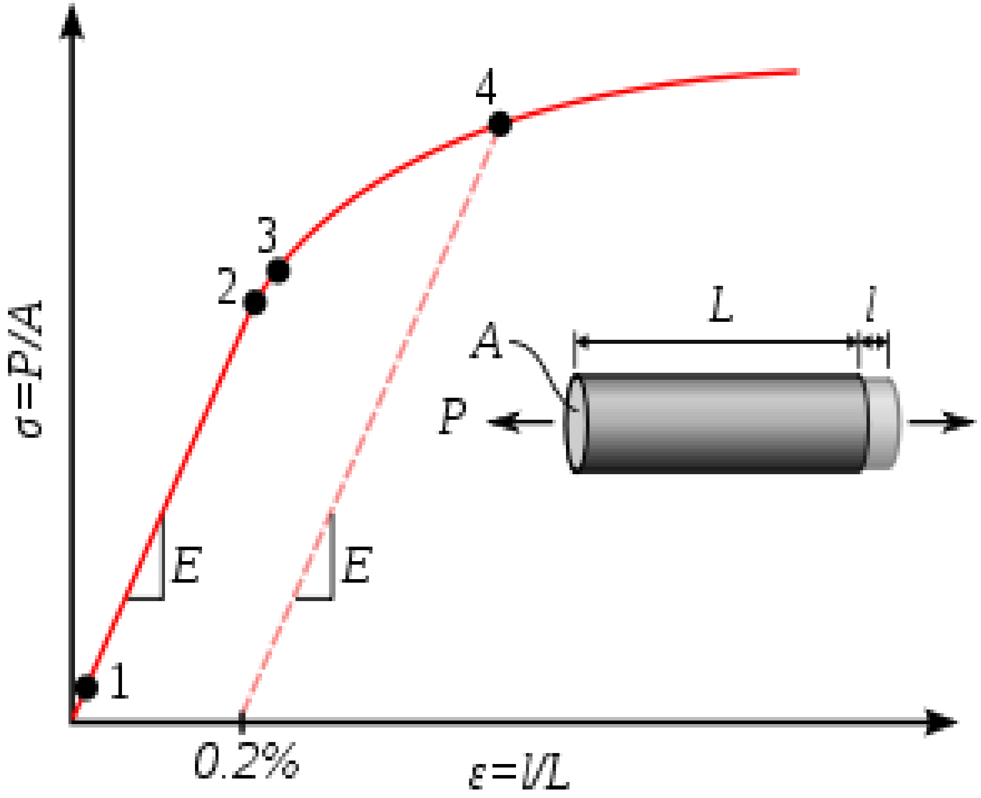
Poisson's ratio, v = lateral strain/Longitudinal strain

Thus, $\underline{v = 1.333 \times 10^{-4} / 0.001 = 0.1333}$

Stress-Strain Curve

Stress–strain curve is a graphical representation of the relationship between stress, derived from measuring the load applied on the sample, and strain, derived from measuring the deformation of the sample, i.e. elongation, compression, or distortion. The nature of the curve varies from material to material. The following diagrams illustrate the stress–strain behaviour of typical materials in terms of the engineering stress and engineering strain where the stress and strain are calculated based on the original dimensions of the sample and not the instantaneous values.

Stress-Strain Curve for Non-ferrous Alloy

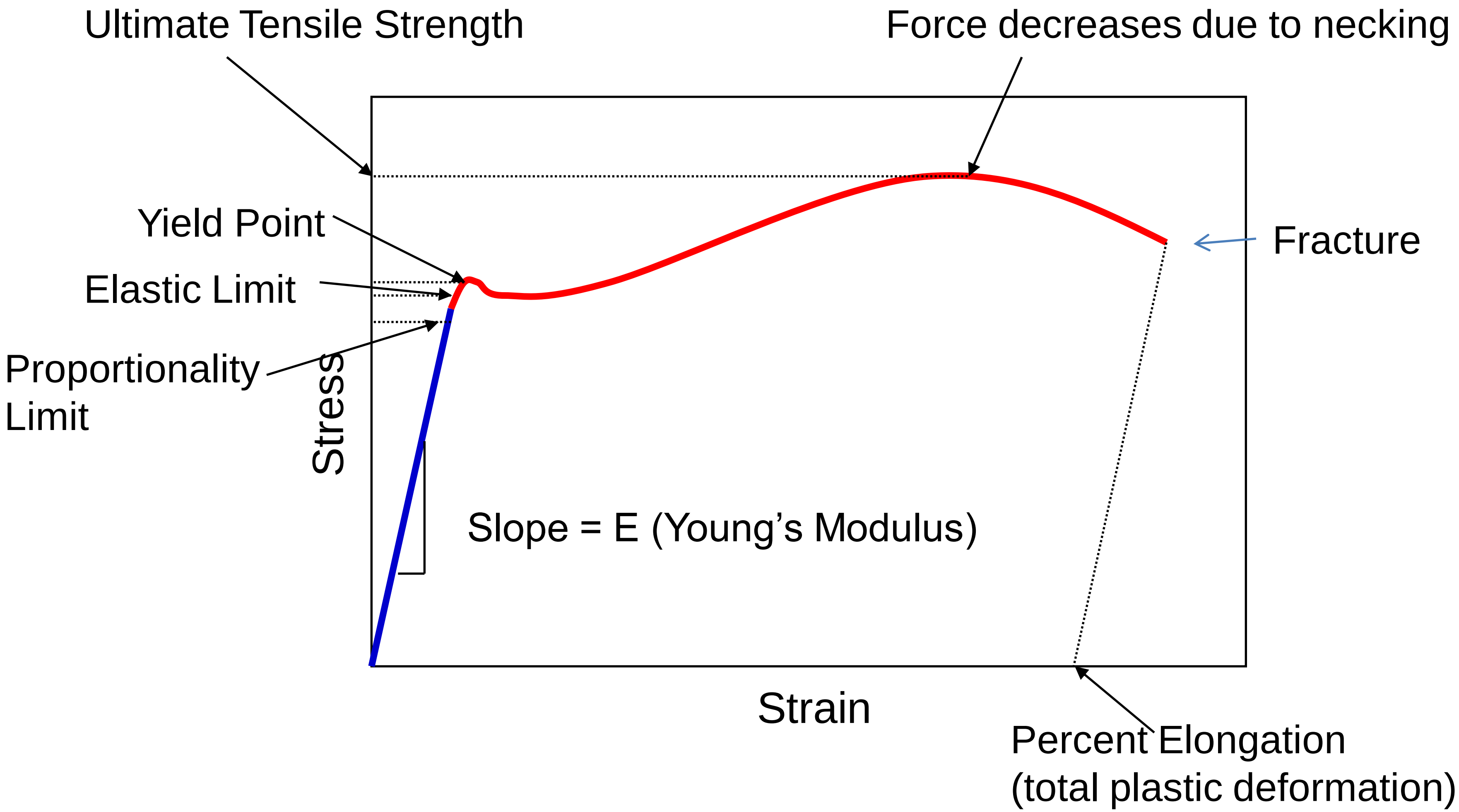


1: True elastic limit
2: Proportionality limit
3: Elastic limit
4: Offset yield strength

Brittle Material

Brittle materials (e.g. concrete, carbon fiber) are those that break easily under applied load. Brittle materials show little or no plastic deformation before fracture and do not have a yield point, and do not strain-harden. Therefore the ultimate strength and breaking strength are the same. A most unusual stress-strain curve is shown in the figure. Typical brittle materials like glass do not show any plastic deformation but fail while the deformation is elastic. One of the characteristics of a brittle failure is that the two broken parts can be reassembled to produce the same shape as the original component as there will not be a neck formation like in the case of ductile materials. A typical stress strain curve for a brittle material will be linear. Testing of several identical specimen, cast iron, or soil, tensile strength is negligible compared to the compressive strength and it is assumed zero for many engineering applications. Glass fibers have a tensile strength stronger than steel, but bulk glass usually does not. This is because of the Stress Intensity Factor associated with defects in the material. As the size of the sample gets larger, the size of defects also grows. In general, the tensile strength of a rope is always less than sum of the tensile strength of its individual fibers.

Stress-Strain Curve



Ductile Material

Materials those can be deformed by application of force without breaking off easily are said to be ductile. Examples are metals (e.g. steel, iron, gold). Ductile materials demonstrate large amounts of plastic deformation before fracture. Ductile materials have a fracture strength lower than the ultimate tensile strength (UTS), whereas in brittle materials the fracture strength is equivalent to the UTS. If a ductile material reaches its ultimate tensile strength in a load-controlled situation, it will continue to deform, with no additional load application, until it ruptures. However, if the loading is displacement-controlled, the deformation of the material may relieve the load, preventing rupture.

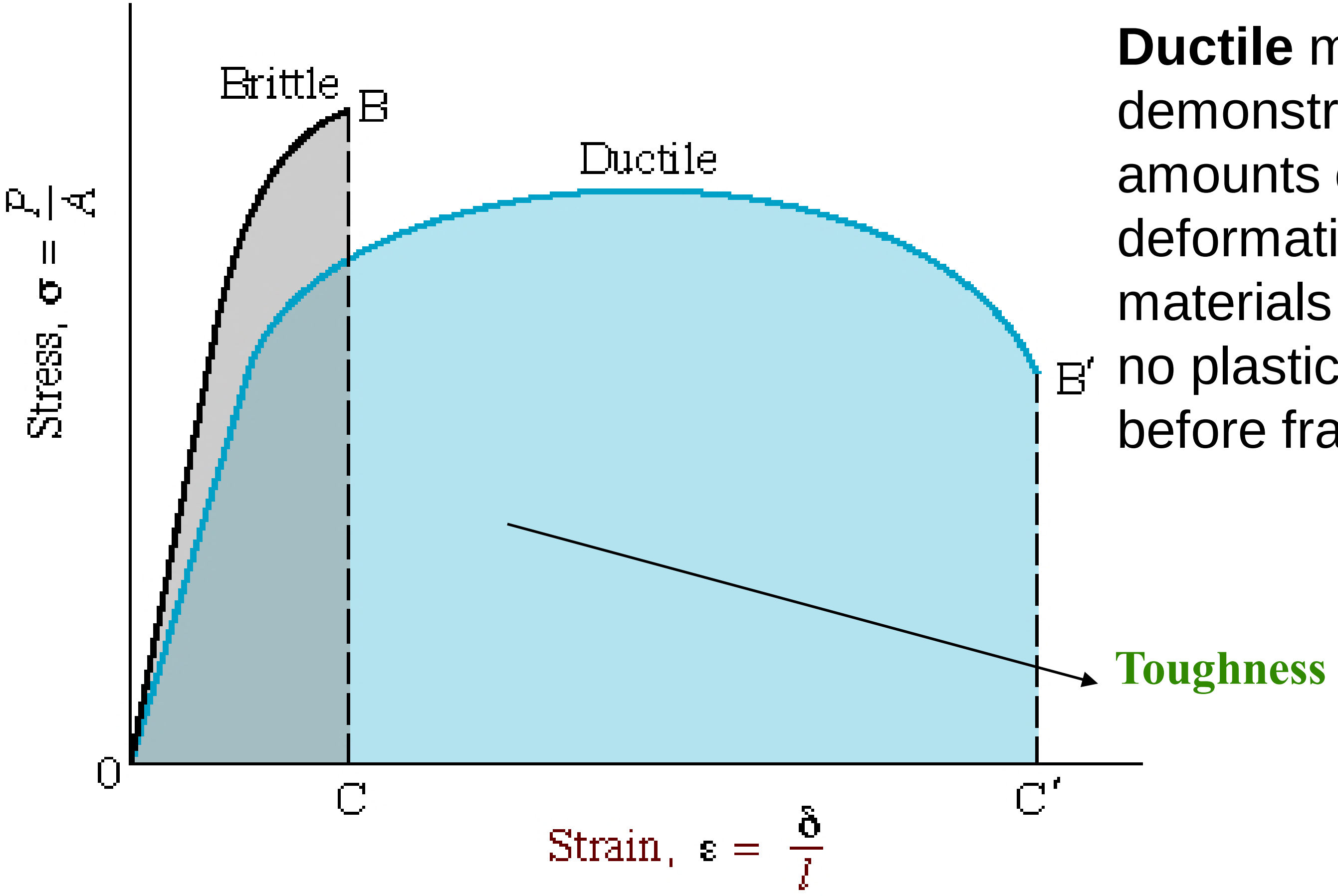
If the stress-strain curve is plotted in terms of *true stress* and *true strain* the curve will always slope upwards and never reverse, as true stress is corrected for the decrease in cross-sectional area. The true stress on the material at the time of rupture is known as the breaking strength.

Ductility vs Brittleness

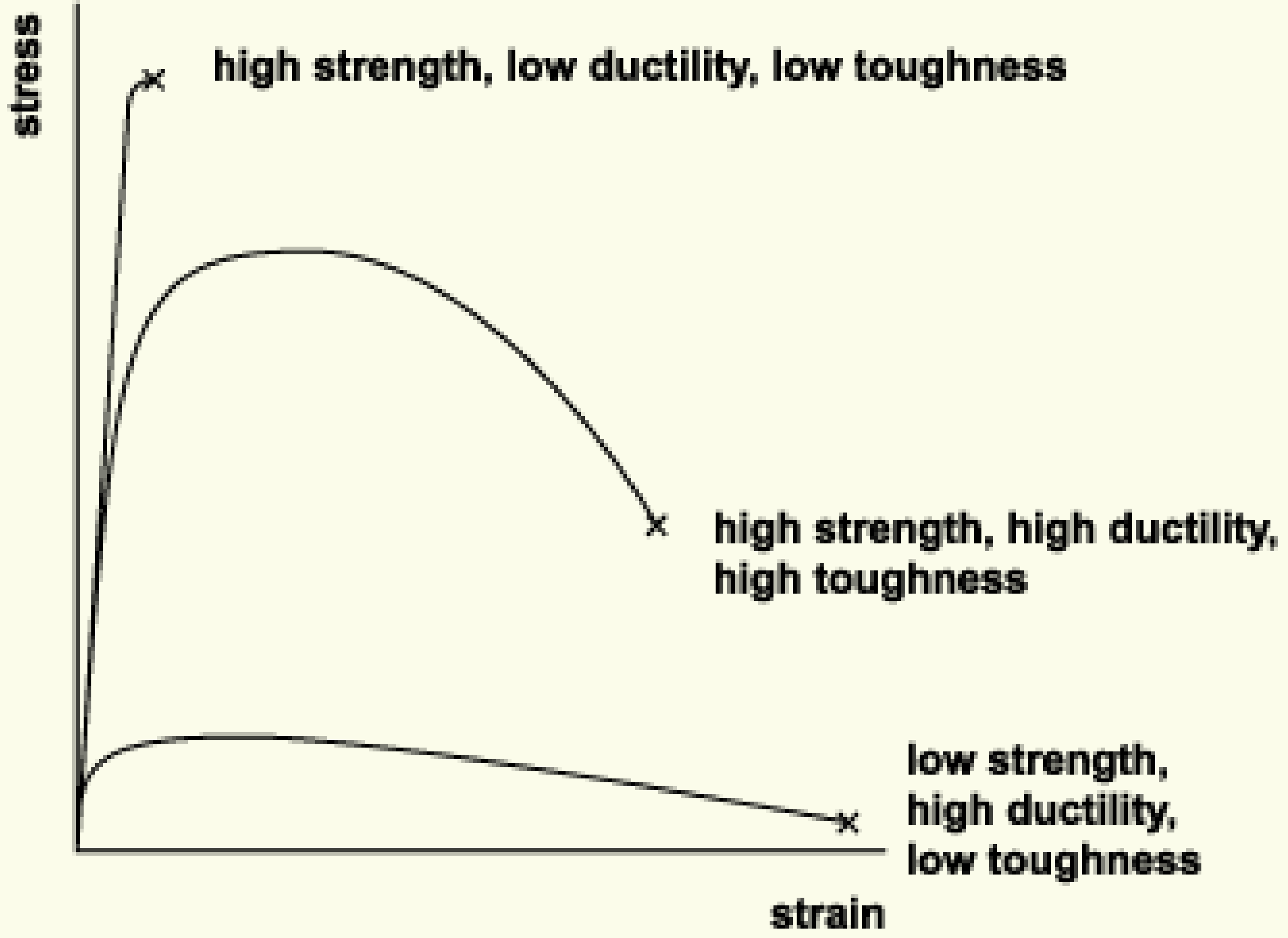
Ductility is more commonly defined as the ability of a material to deform easily upon the application of a tensile force, or as the ability of a material to withstand plastic deformation without rupture. Ductility may also be thought of in terms of bendability and crushability. Ductile materials show large deformation before fracture. The lack of ductility is often termed brittleness. Usually, if two materials have the same strength and hardness, the one that has the higher ductility is more desirable. The ductility of many metals can change if conditions are altered. An increase in temperature will increase ductility. A decrease in temperature will cause a decrease in ductility and a change from ductile to brittle behavior.

Brittleness is tendency of a material to fracture or fail upon the application of a relatively small amount of force, impact or shock. Opposite of toughness.

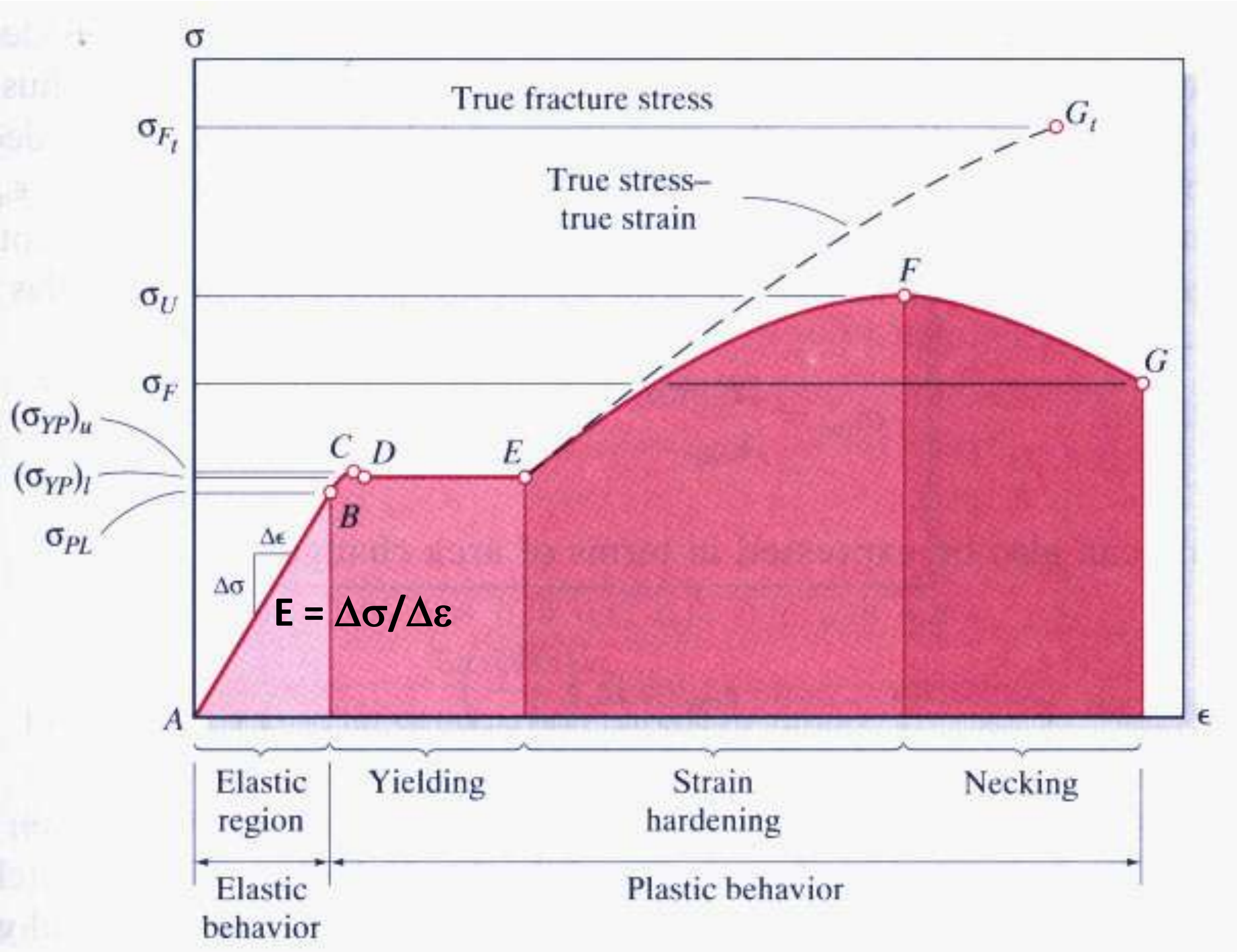
Brittle and Ductile Metal Comparison



Ductile materials demonstrate large amounts of plastic deformation while **brittle** materials show little or no plastic deformation before fracture


stress
high strength, low ductility, low toughness
high strength, high ductility, high toughness
low strength, high ductility, low toughness
strain

Complete Stress-Strain Diagram



$E = \Delta\sigma/\Delta\varepsilon$

- **Modulus of elasticity**: the initial slope of the curve, related directly to the strength of the atomic bonds.
- **Yield strength**: usually defined as the point at which a consistent and measurable amount of permanent strain remains in the specimen
- **Modulus of resilience**: the area under the linear part of the curve, measuring the stored elastic energy.

- Tensile strength: the maximum stress applied to the specimen.
- Failure stress: the stress applied to the specimen at failure (usually less than the maximum tensile strength because necking reduces the cross-sectional area).
- Ductility: the total elongation of the specimen due to plastic deformation, neglecting the elastic stretching (the broken ends snap back and separate after failure).
- Toughness: the total area under the curve, which measures the energy absorbed by the specimen in the process of breaking.

- Students are sometimes confused by the elastic contraction that occurs when the applied stress is released, either by reversing the test machine or when the specimen breaks. The contraction follows the same slope as the linear elastic portion of the stress-strain curve, defined by the modulus of elasticity of the specimen. It is the result of the atoms moving back to their equilibrium separation distance. Hence it is shown on the diagram as a line parallel to the elastic portion of the curve. Any net strain remaining after the stress is released is plastic deformation

Necking

- The Engineering Stress-Strain curve of a ductile material usually drops past the tensile strength point. This is because the cross-sectional area of the material decreases because of slip along atom planes that are oriented at an angle to the applied force (of course, the slip occurs by dislocation motion). This local deformation is called a neck

- Because of the decreased area, a smaller amount of force is required to continue the material's deformation. A plot of the true local stress vs. true strain, based on the changing specimen dimensions rather than the original dimensions, would continue to rise when necking occurs. However, these are rarely used because they are difficult to measure.

Offset Yield Strength

- Defining the yield stress as the point separating elastic from plastic deformation is easier than determining that point. The elastic portion of the curve is not perfectly linear, and microscopic amounts of deformation can occur. As a matter of practical convenience, the yield strength is determined by constructing a line parallel to the initial portion of the stress-strain curve but offset by 0.2% from the origin.

- The intersection of this line and the measured stress-strain line is used as an approximation of the material's yield strength, called the 0.2% offset yield.
- Some materials do show an abrupt yield point. In plain carbon steels, the carbon atoms may diffuse to the dislocations in the material and pin them so that they cannot easily move. When the applied stress causes the dislocations to jump free of these points, they can move more easily. In many polymers, a similar effect is produced when bonds between molecules break and they begin to move.

- There is a direct relationship between the energy absorbed in impact and the toughness measured as the area under the stress strain curve. Materials with a high toughness value absorb more energy in fracture, which may provide a margin of safety in real structures in the event of failure.

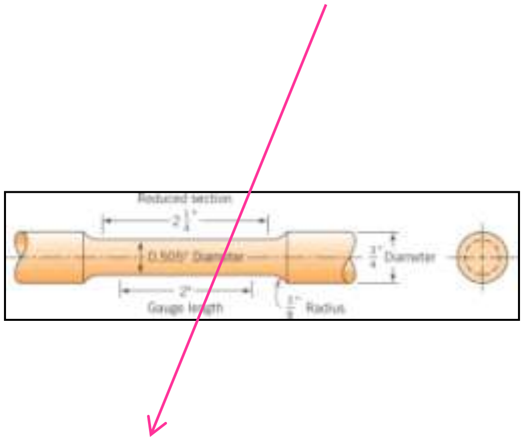
Mechanical Testing

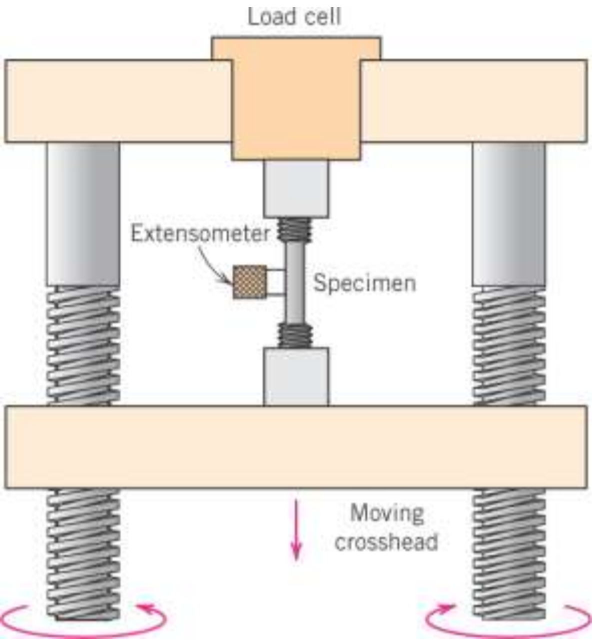
☐ The Tensile Test: Stress-Strain Diagram
☐ Properties Obtained from a Tensile Test
☐ True Stress and True Strain
☐ Hardness of Materials

Stress-Strain Test

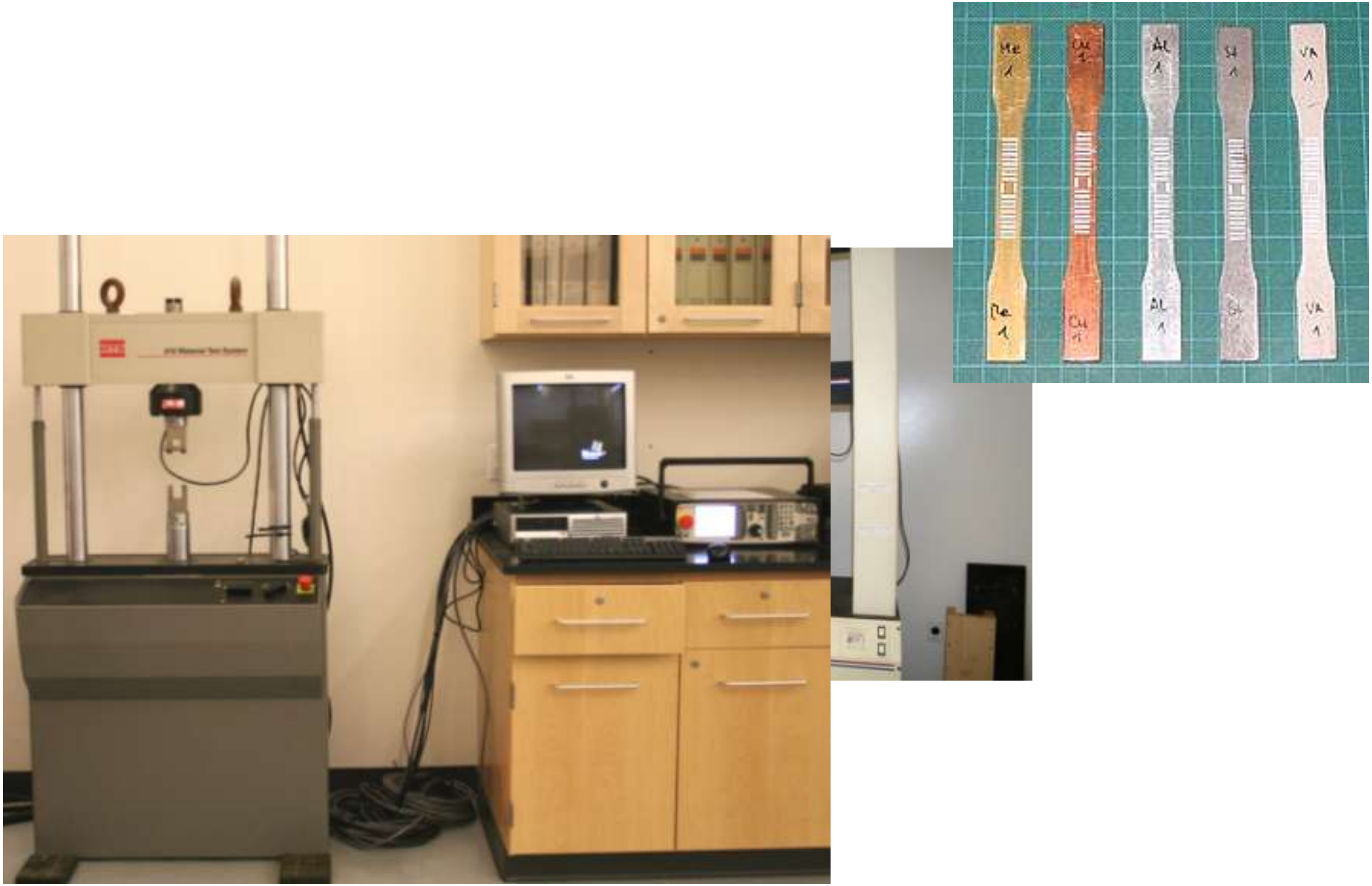
- specimen

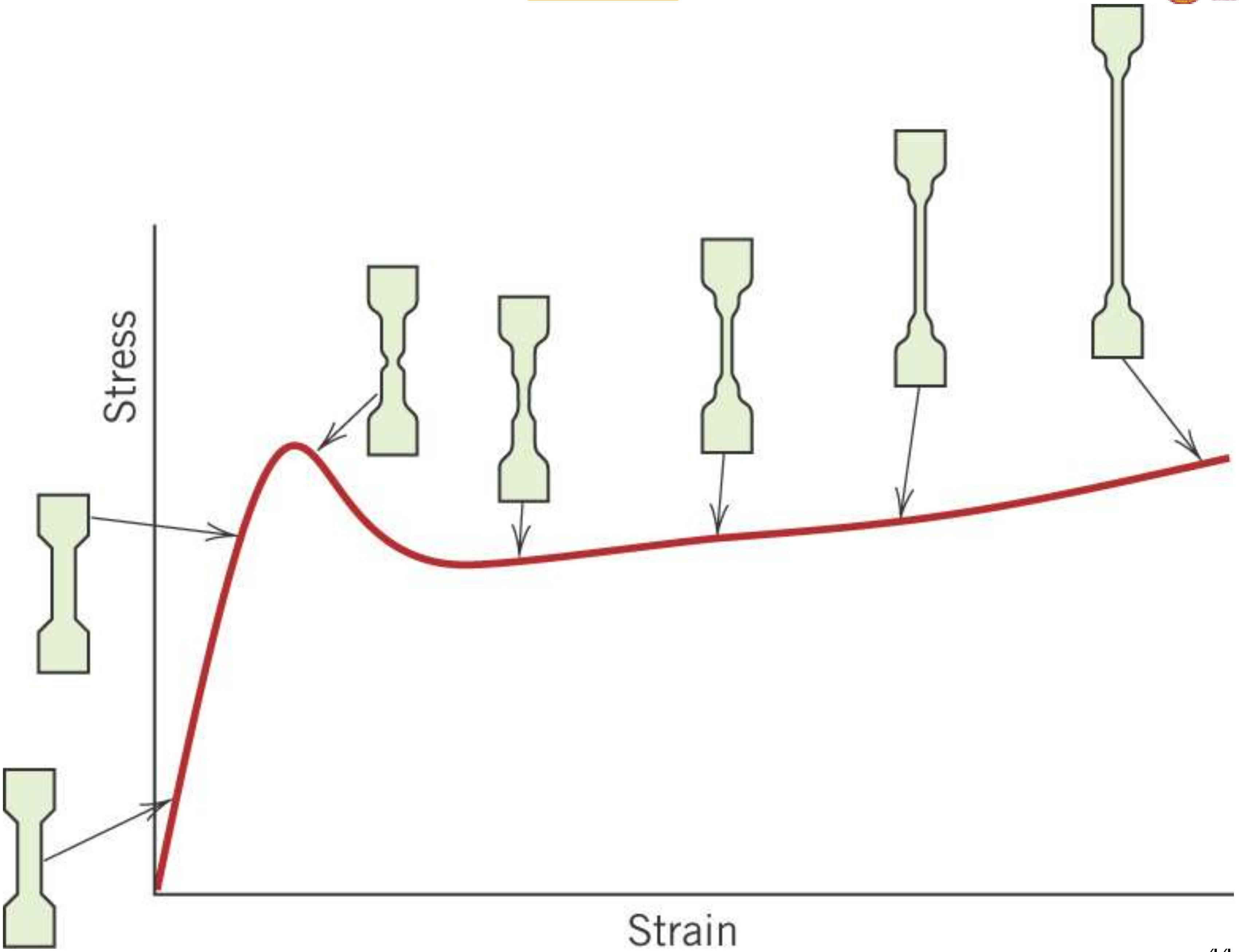
- machine

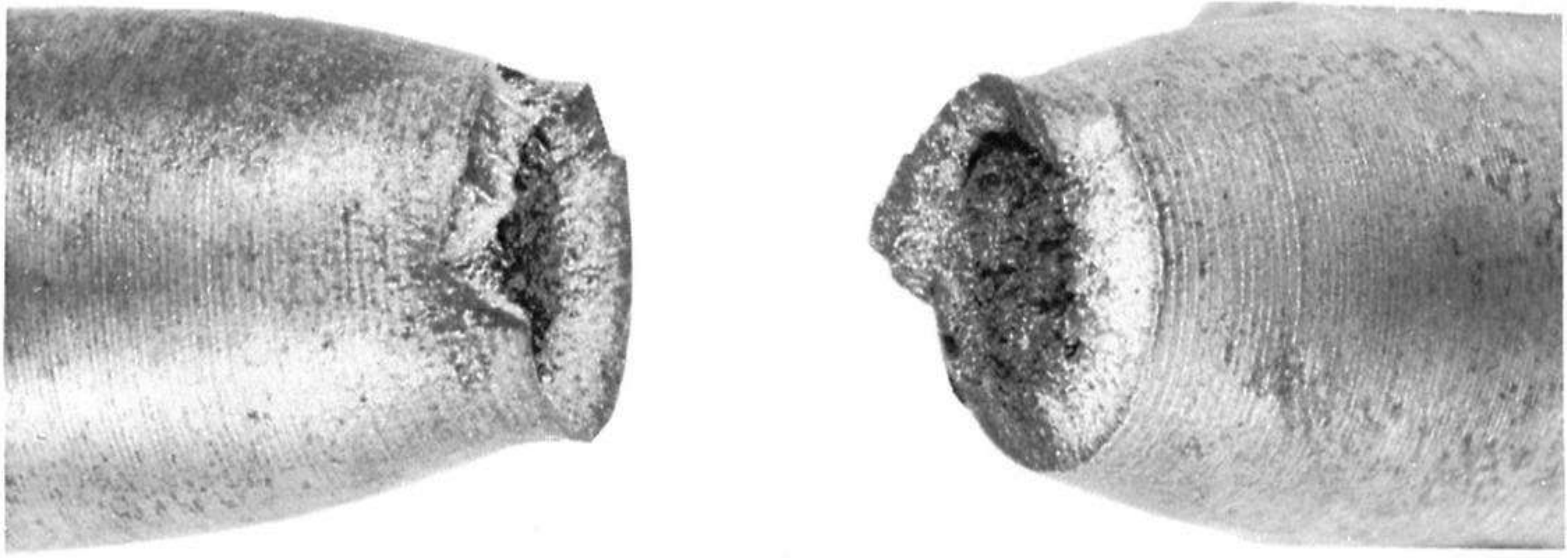




Tensile Test Machine

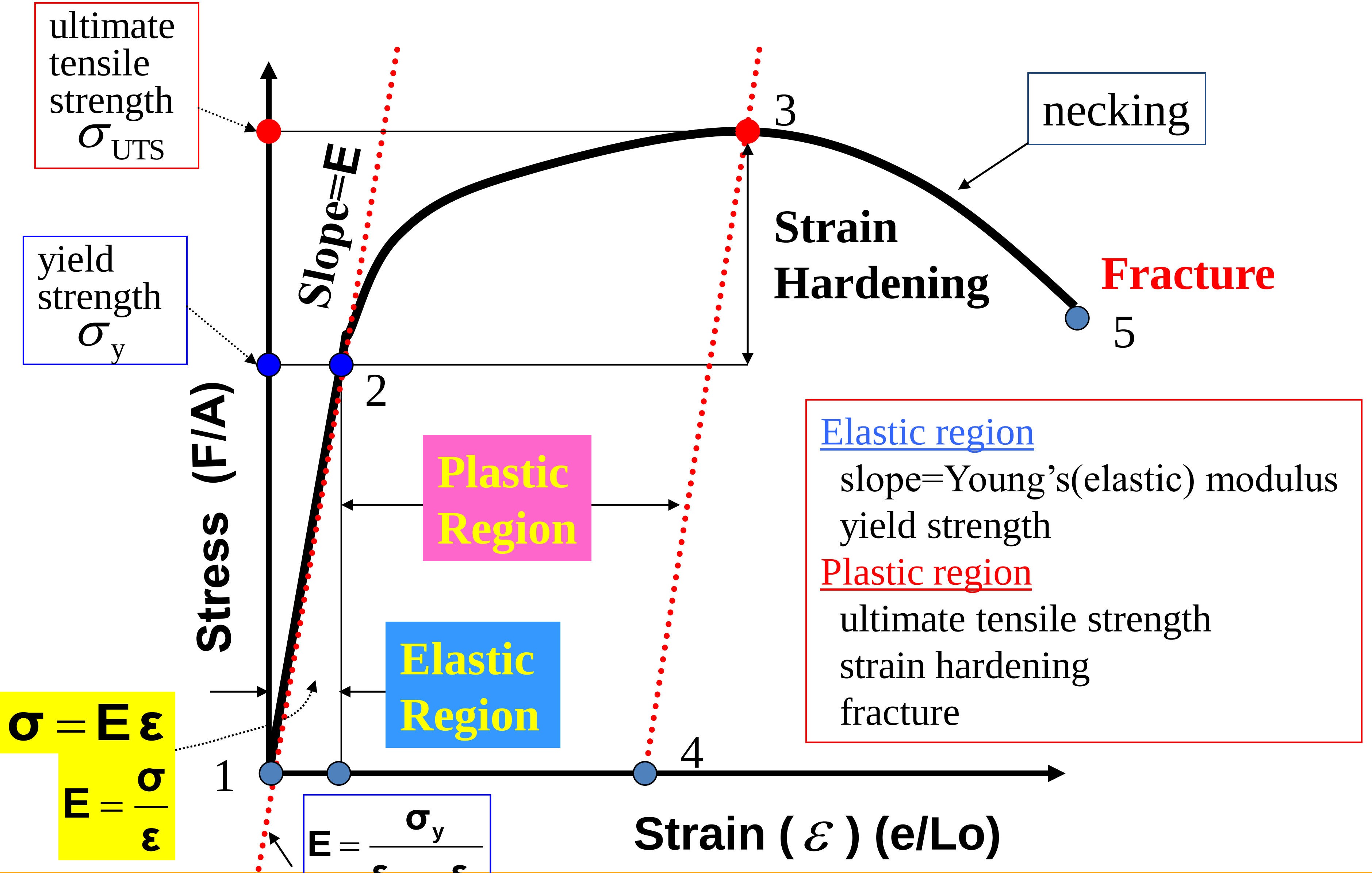



Stress
Strain



- Localized deformation of a ductile material during a tensile test produces a necked region.
- The image shows necked region in a fractured sample

Stress-Strain Diagram



ultimate tensile strength σ_{UTS}

yield strength σ_y

Stress (F/A)

Slope=E

3

necking

Strain Hardening

Fracture

5

2

Plastic Region

Elastic Region

1

4

$\sigma = E\varepsilon$

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

$E = \frac{\sigma_y}{\varepsilon_2 - \varepsilon_1}$

Strain (ε) (e/Lo)

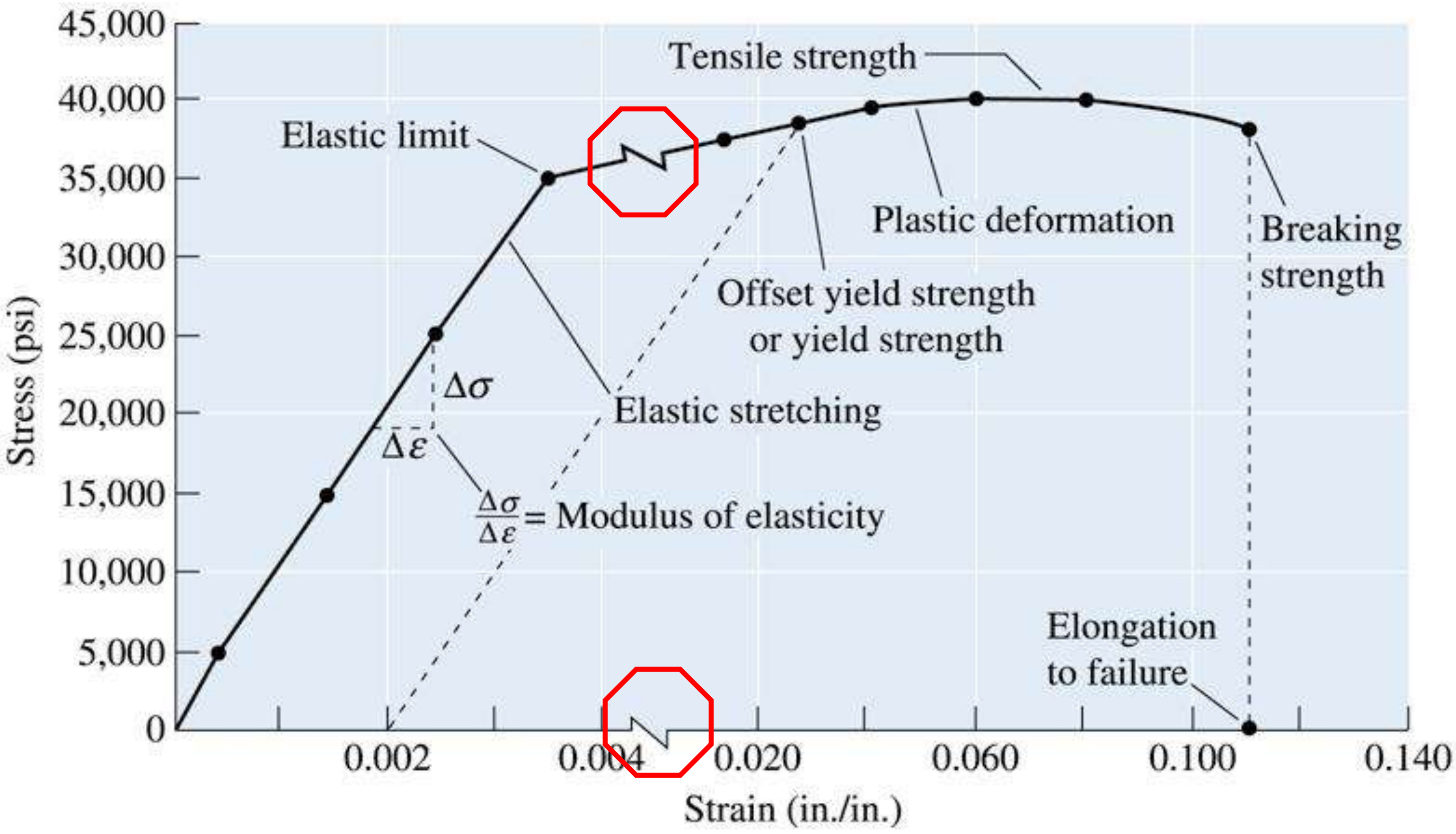
Elastic region

- slope=Young's(elastic) modulus
- yield strength

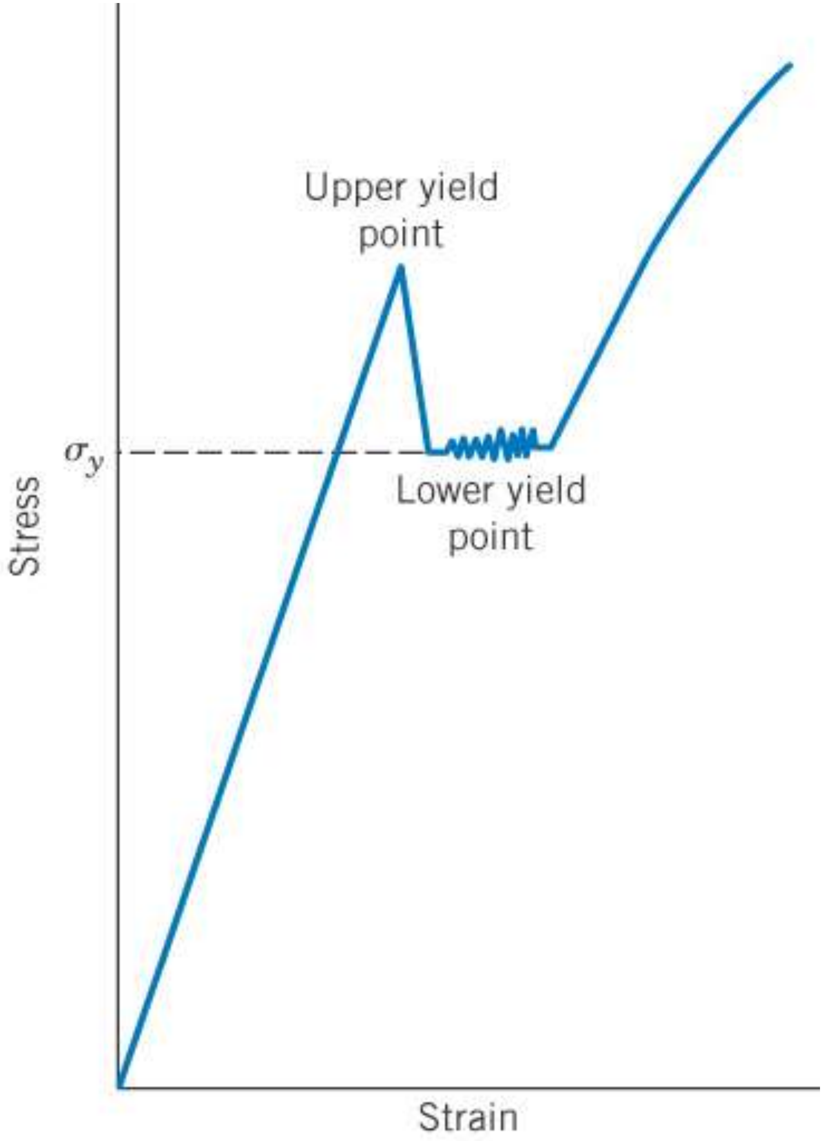
Plastic region

- ultimate tensile strength
- strain hardening
- fracture

The stress-strain curve for an aluminum alloy.

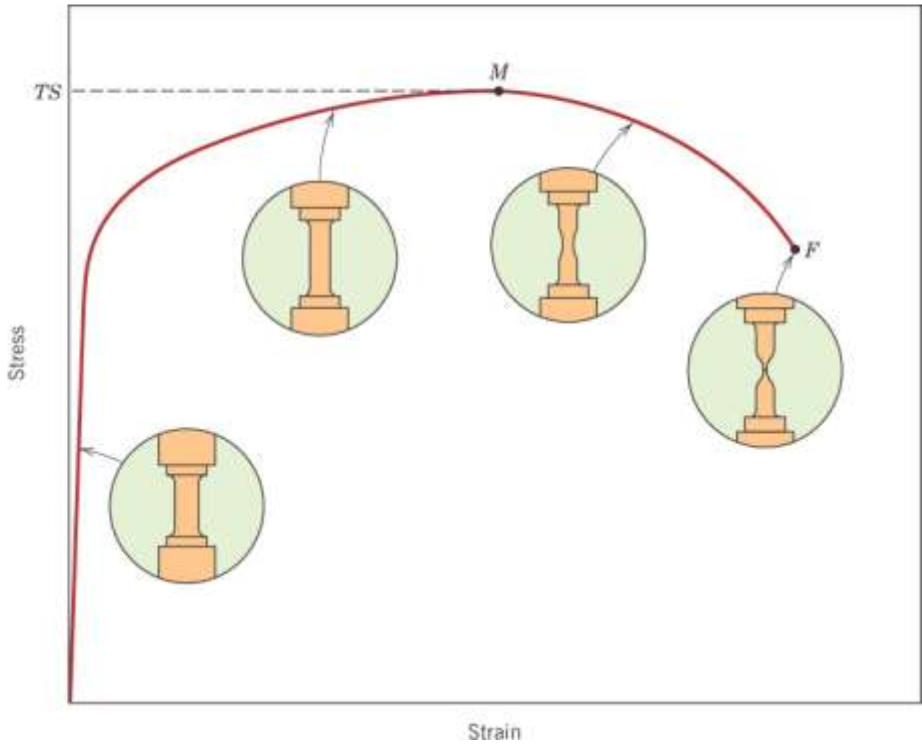


- Stress-strain behavior found for some steels with yield point phenomenon.



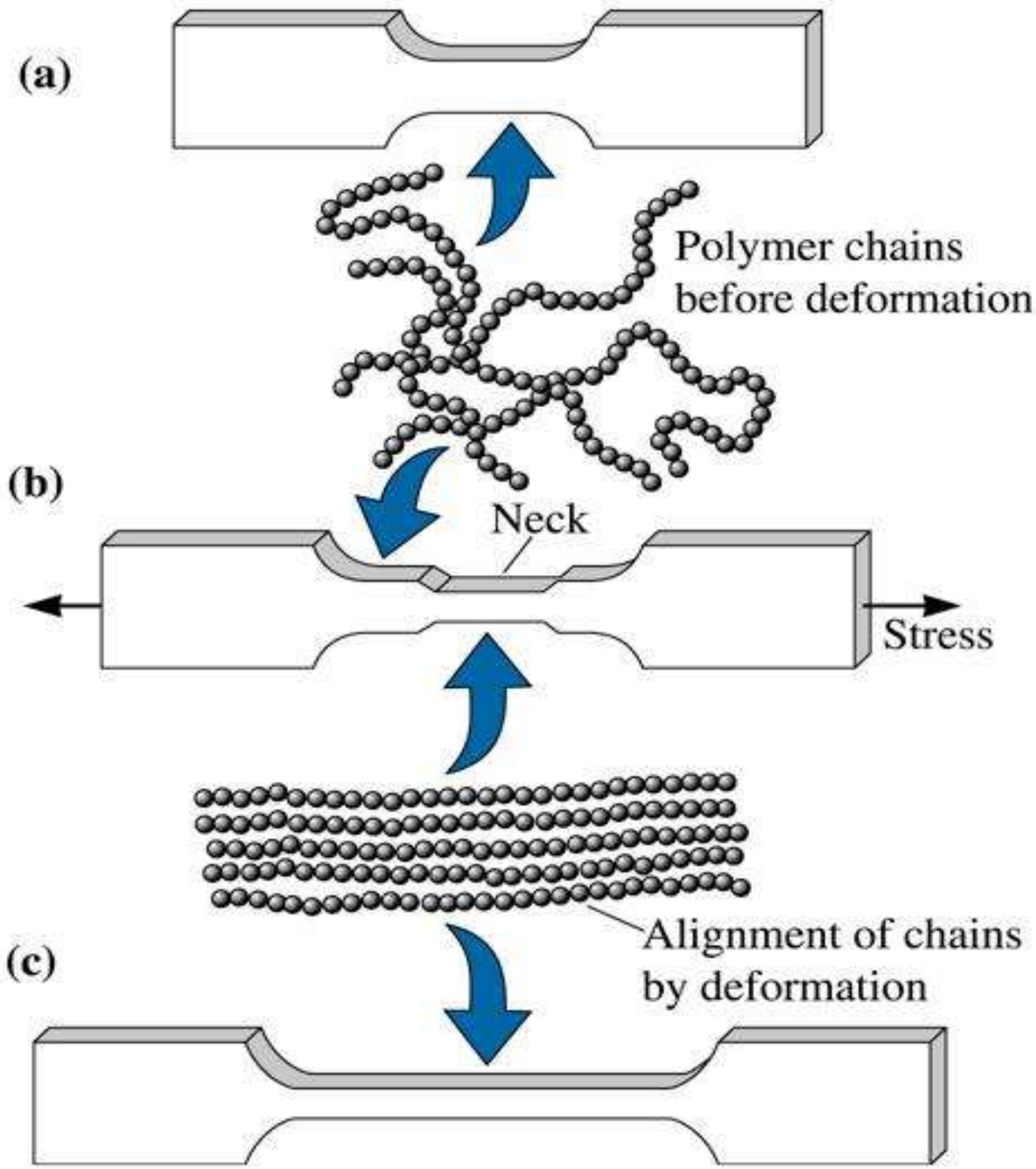
Tensile Strength, TS

- After yielding, the stress necessary to continue plastic deformation in metals increases to a maximum point (M) and then decreases to the eventual fracture point (F).
- All deformation up to the maximum stress is uniform throughout the tensile sample.
- However, at max stress, a small constriction or neck begins to form.
- Subsequent deformation will be confined to this neck area.
- Fracture strength corresponds to the stress at fracture.



Region between M and F:

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



In an undeformed thermoplastic polymer tensile sample,

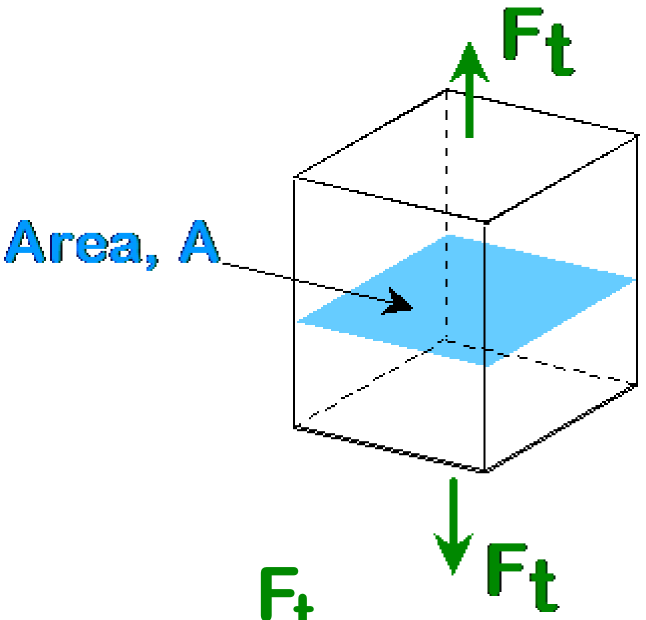
(a) the polymer chains are randomly oriented.

(b) When a stress is applied, a neck develops as chains become aligned locally. The neck continues to grow until the chains in the entire gage length have aligned.

(c) The strength of the polymer is increased

Engineering Stress

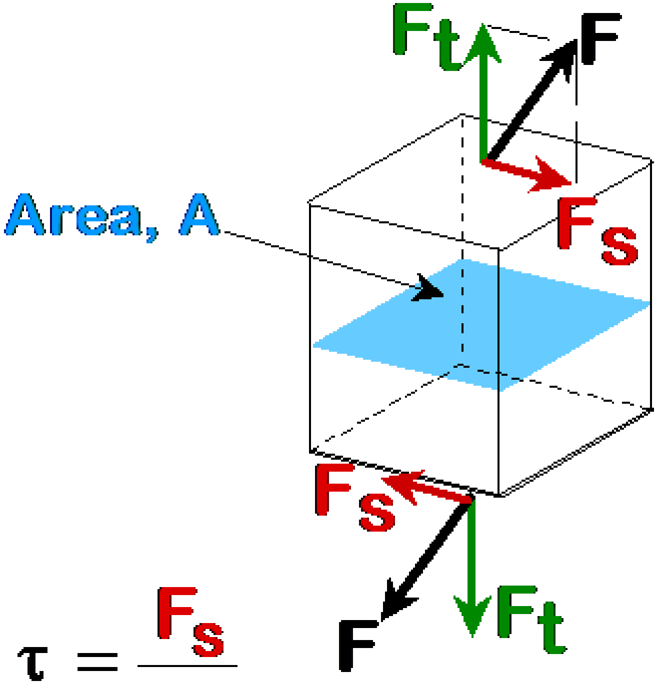
- **Tensile stress, σ:**



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

original area before loading

- **Shear stress, τ:**



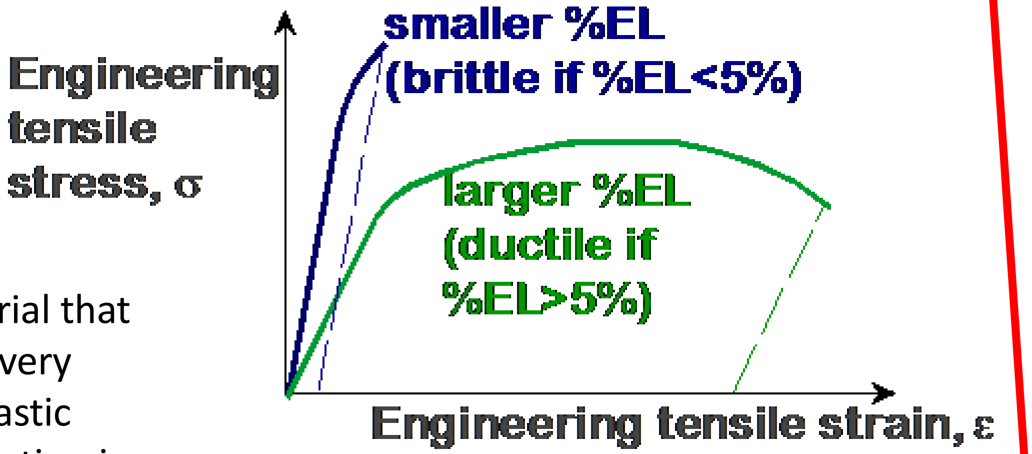
$$\tau = \frac{F_s}{A_o}$$

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

Ductility, %EL

Ductility is a measure of the plastic deformation that has been sustained at fracture:

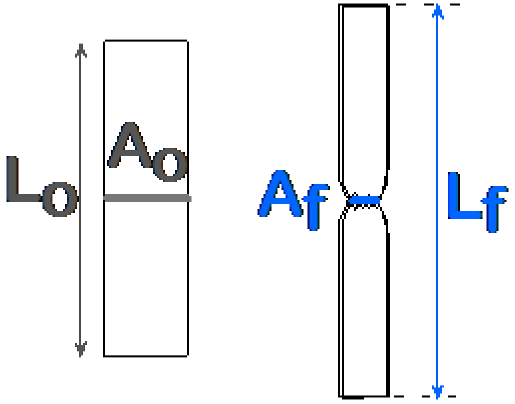
$$\% EL = \frac{l_f - l_o}{l_o} x100$$



A material that suffers very little plastic deformation is brittle.

- Another ductility measure:

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



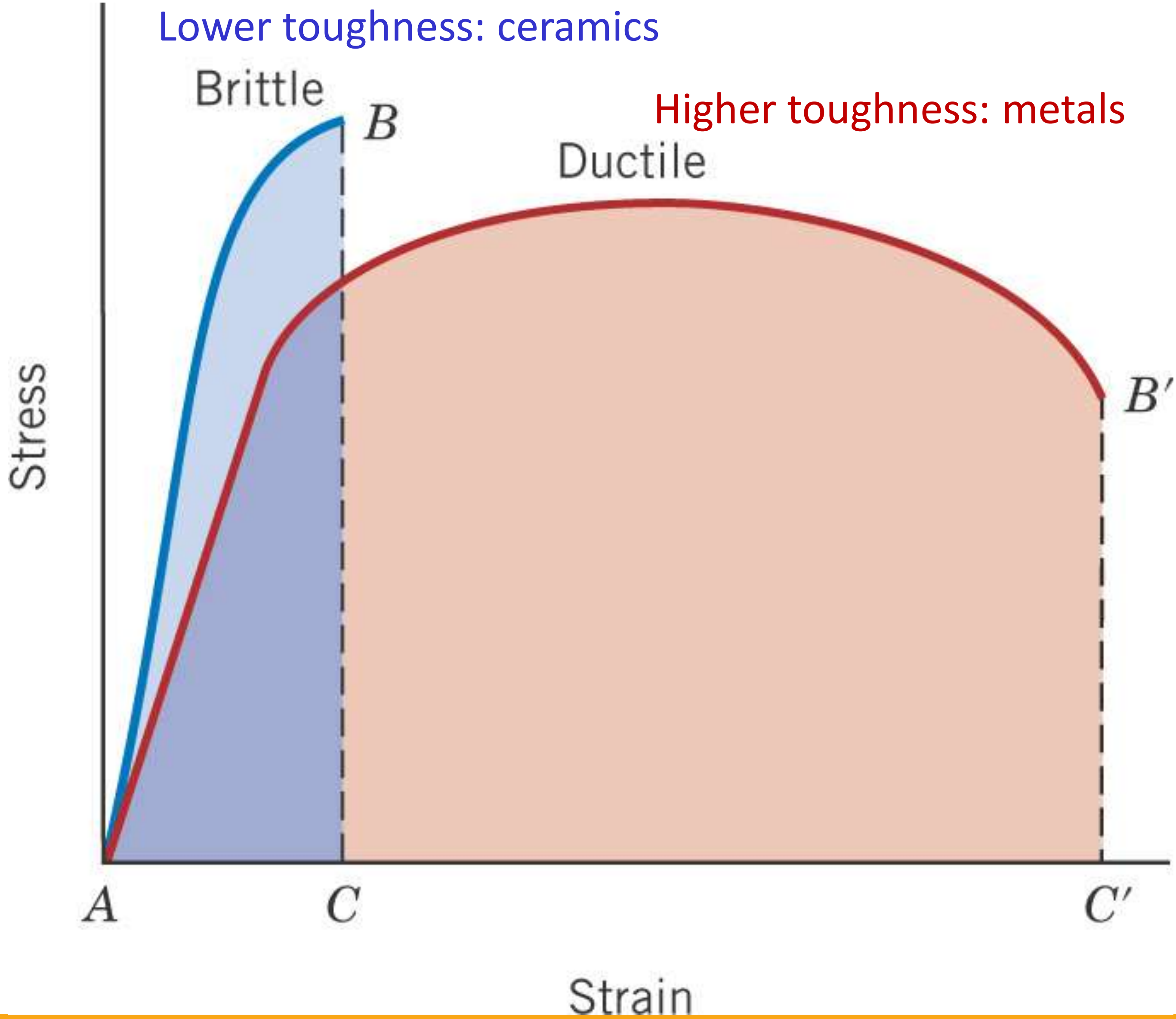
- Ductility may be expressed as either **percent elongation** (% plastic strain at fracture) or **percent reduction in area**.
- %AR > %EL is possible if internal voids formed in neck.

Toughness

Toughness is the ability to absorb energy up to fracture (energy per unit volume of material).

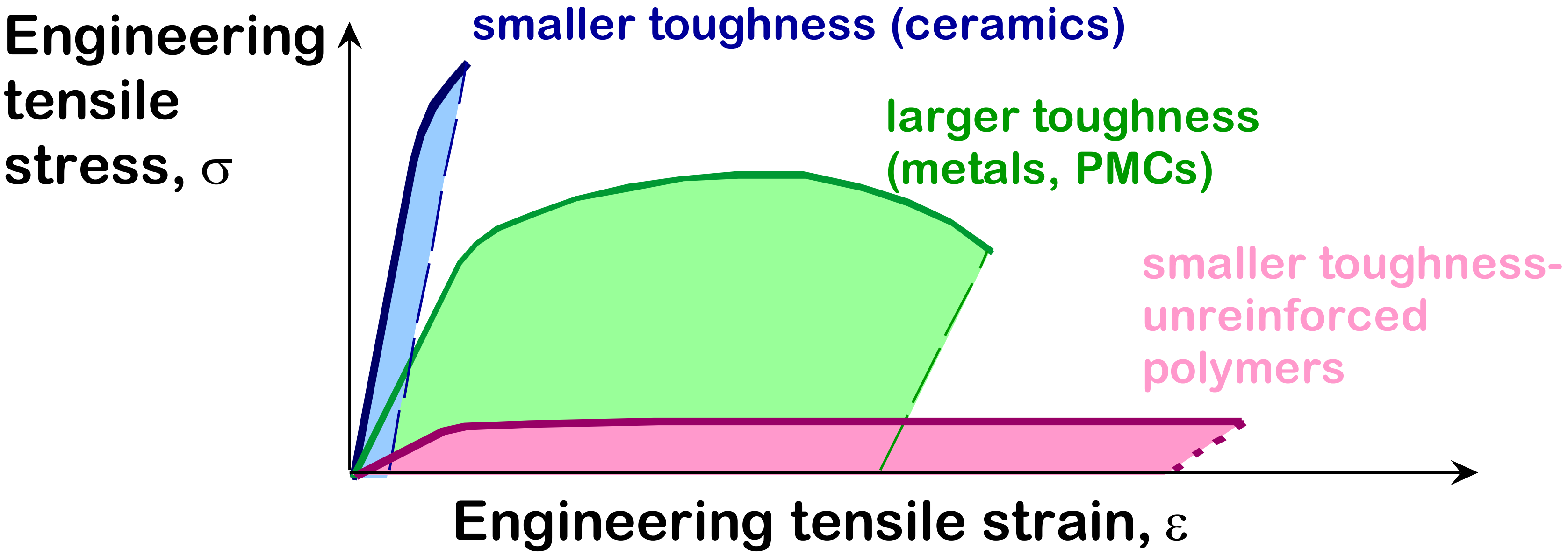
A “tough” material has strength and ductility.

Approximated by the area under the stress-strain curve.



Toughness

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

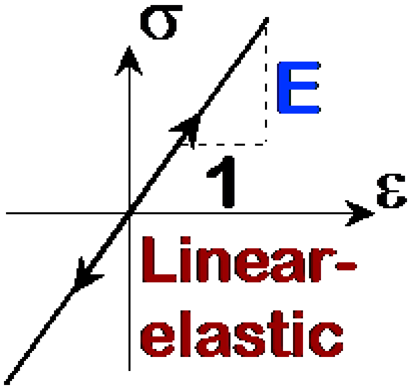


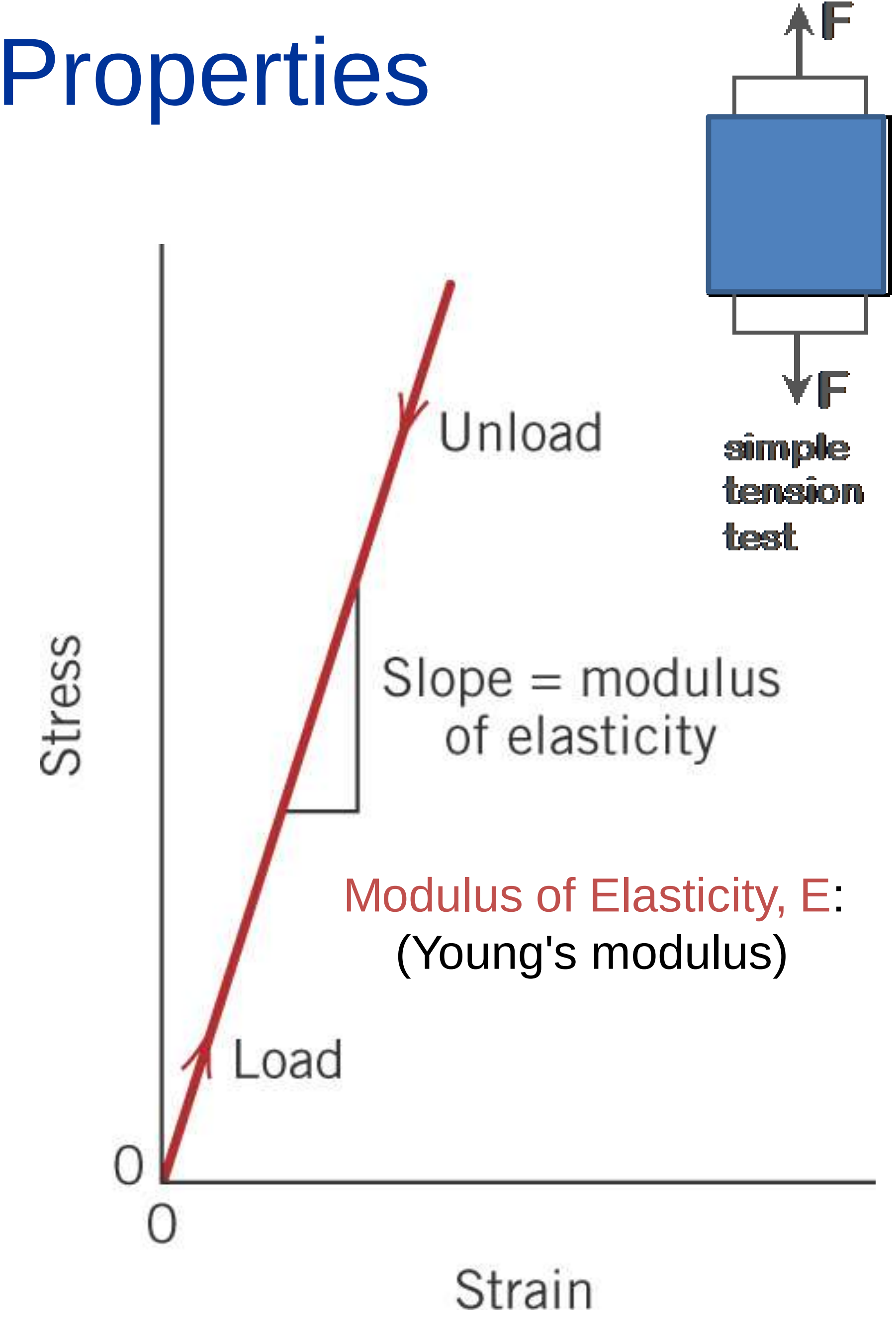
Linear Elastic Properties

- **Hooke's Law**: $\sigma = E\,\varepsilon$

- **Poisson's ratio**: $\nu = \varepsilon_x/\varepsilon_y$

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

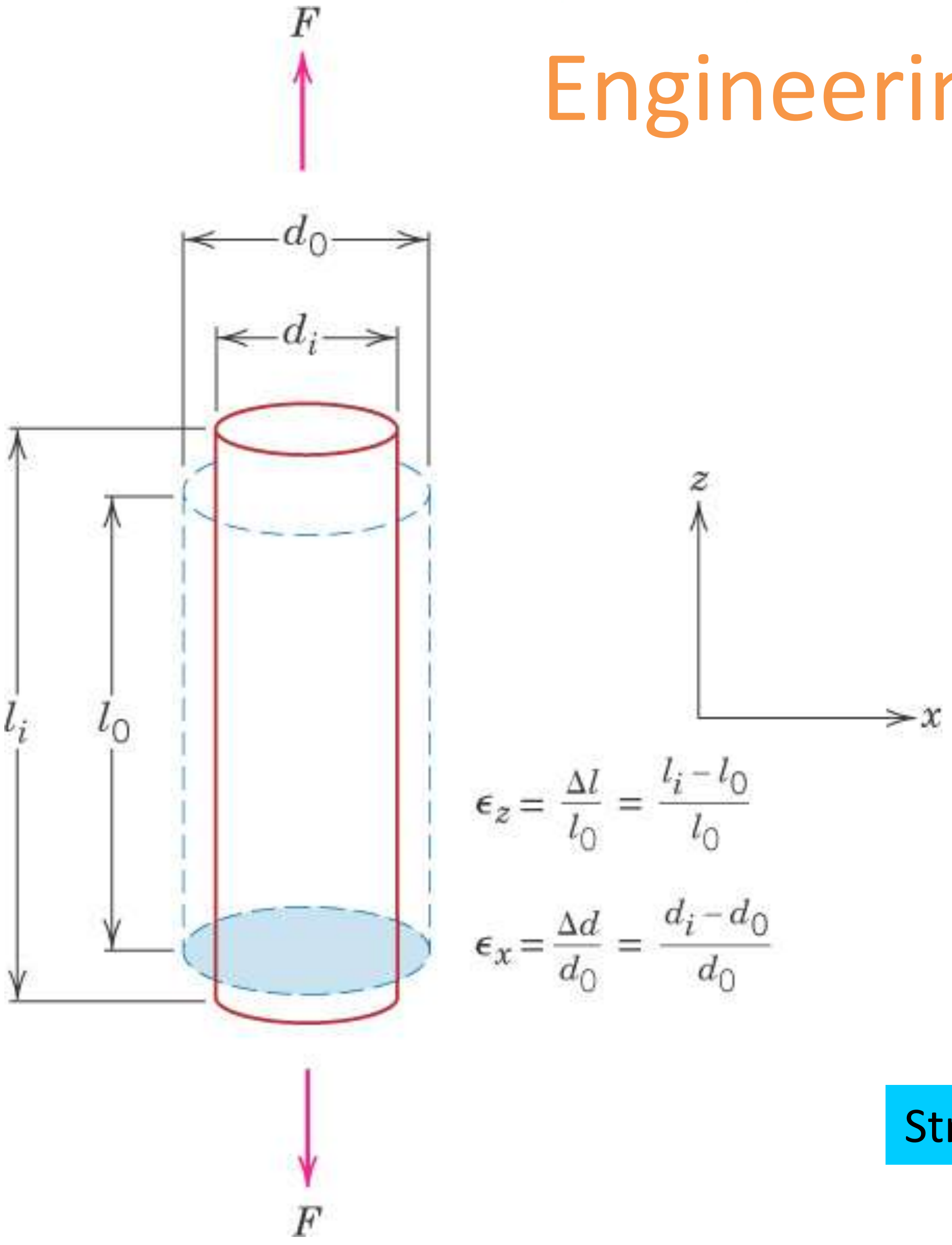




Modulus of Elasticity, E:
(Young's modulus)

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

Engineering Strain

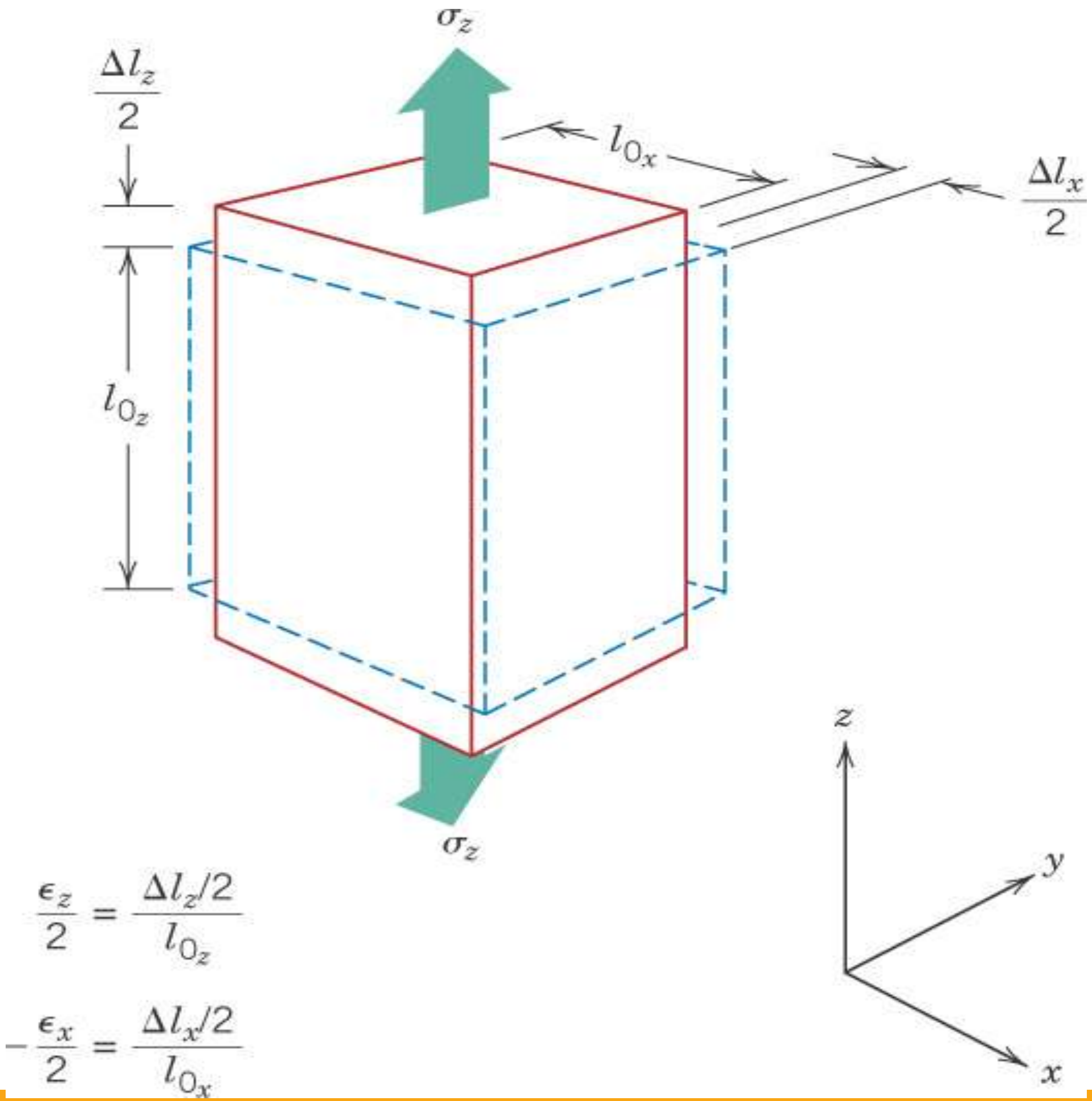


$$\epsilon_z = \frac{\Delta l}{l_0} = \frac{l_i - l_0}{l_0}$$

$$\epsilon_x = \frac{\Delta d}{d_0} = \frac{d_i - d_0}{d_0}$$

Strain is dimensionless.

Axial (z) elongation (positive strain) and lateral (x and y) contractions (negative strains) in response to an imposed tensile stress.

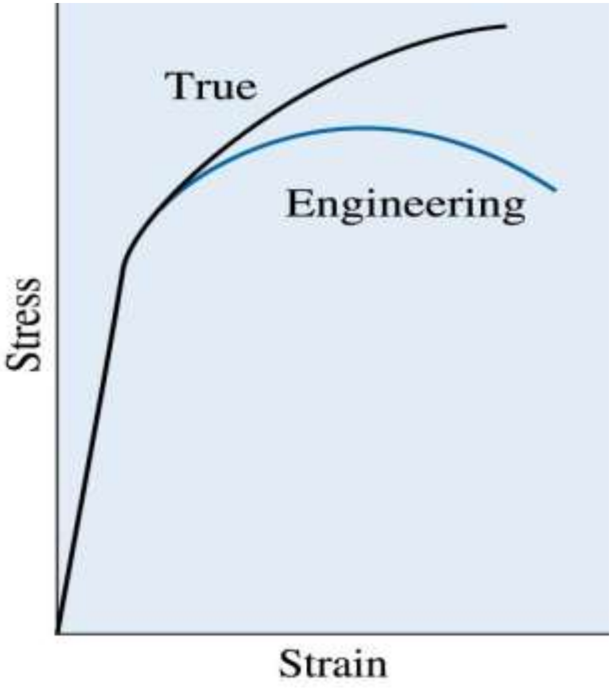


$$\frac{\epsilon_z}{2} = \frac{\Delta l_z/2}{l_{0_z}}$$

$$-\frac{\epsilon_x}{2} = \frac{\Delta l_x/2}{l_{0_x}}$$

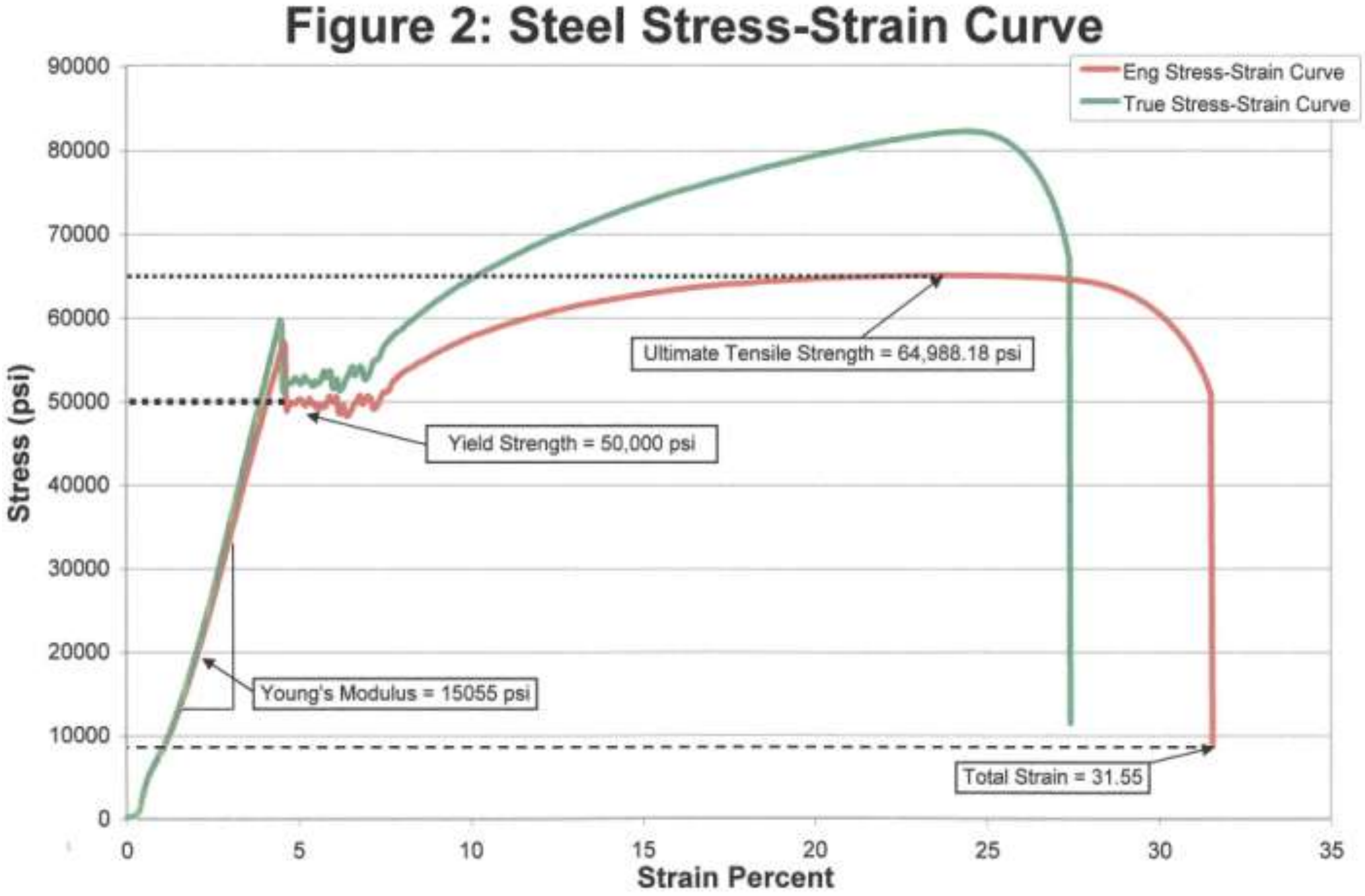
True Stress and True Strain

- True stress The load divided by the actual cross-sectional area of the specimen at that load.
- True strain The strain calculated using actual and not original dimensions, given by $\varepsilon_t \ln(l/l_0)$.



- The relation between the true stress-true strain diagram and engineering stress-engineering strain diagram.
- The curves are identical to the yield point.

Stress-Strain Results for Steel Sample

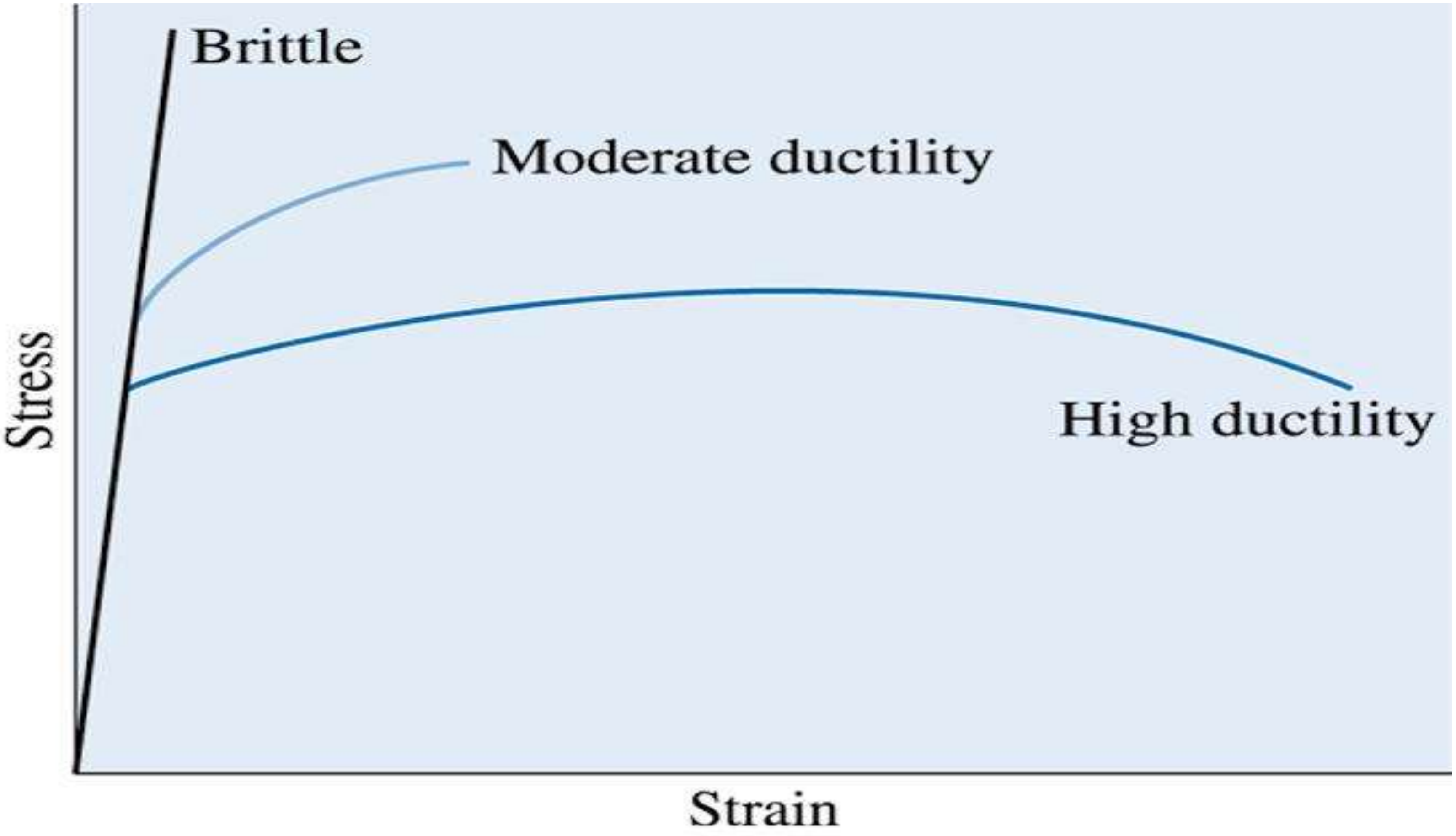


Mechanical Behavior - Ceramics

- The stress-strain behavior of brittle ceramics is not usually obtained by a tensile test.
  1. It is difficult to prepare and test specimens with specific geometry.
  2. It is difficult to grip brittle materials without fracturing them.
  3. Ceramics fail after roughly 0.1% strain; specimen have to be perfectly aligned.

The Bend Test for Brittle Materials

- Bend test - Application of a force to the center of a bar that is supported on each end to determine the resistance of the material to a static or slowly applied load.
- Flexural strength or modulus of rupture -The stress required to fracture a specimen in a bend test.
- Flexural modulus - The modulus of elasticity calculated from the results of a bend test, giving the slope of the stress-deflection curve.



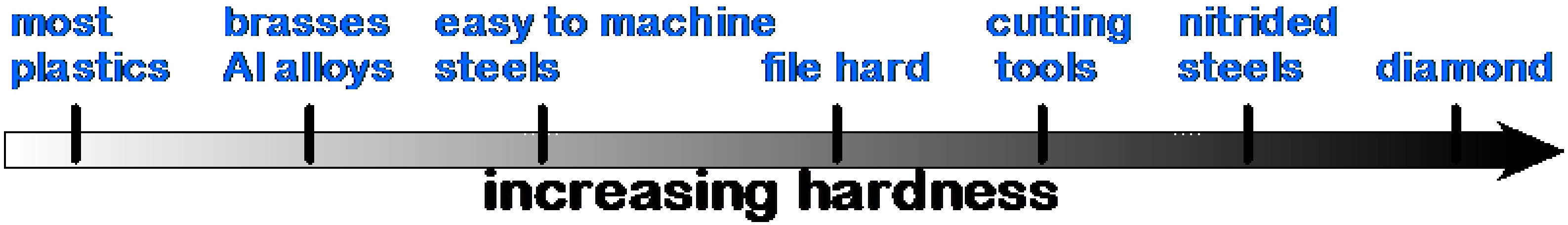
The stress-strain behavior of brittle materials compared with that of more ductile materials

Hardness of Materials

- Hardness test - Measures the resistance of a material to penetration by a sharp object.
- Macrohardness - Overall bulk hardness of materials measured using loads >2 N.
- Microhardness - Hardness of materials typically measured using loads less than 2 N using such test as Knoop (HK).
- Nano-hardness - Hardness of materials measured at 1–10 nm length scale using extremely small (~100 μN) forces.

Hardness

- **Hardness** is a measure of a material's resistance to localized plastic deformation OR resistance of metal to plastic deformation, usually by indentation.
- Quantitative hardness techniques have been developed where a small indenter is forced into the surface of a material.
- The depth or size of the indentation is measured, and corresponds to a hardness number.
- The softer the material, the larger and deeper the indentation (and lower hardness number).



Vickers Hardness Test

In this test a Diamond Indenter is pressed into the surface of the material being tested. Standard loads used include 5, 10, 20, 30, 50, and 100 kgf.
(49,05, 98,1 196,2 490,5 and 981 N).
The load is stated in specifying the hardness number i.e HD(10) = 100. the indenter is a square based pyramid (136° included angle) to suit the material being tested

The Hardness Number HD = 1.844 x Load/ Average diagonal length of indentation, The resulting formulae for the Vickers hardness is calculated as

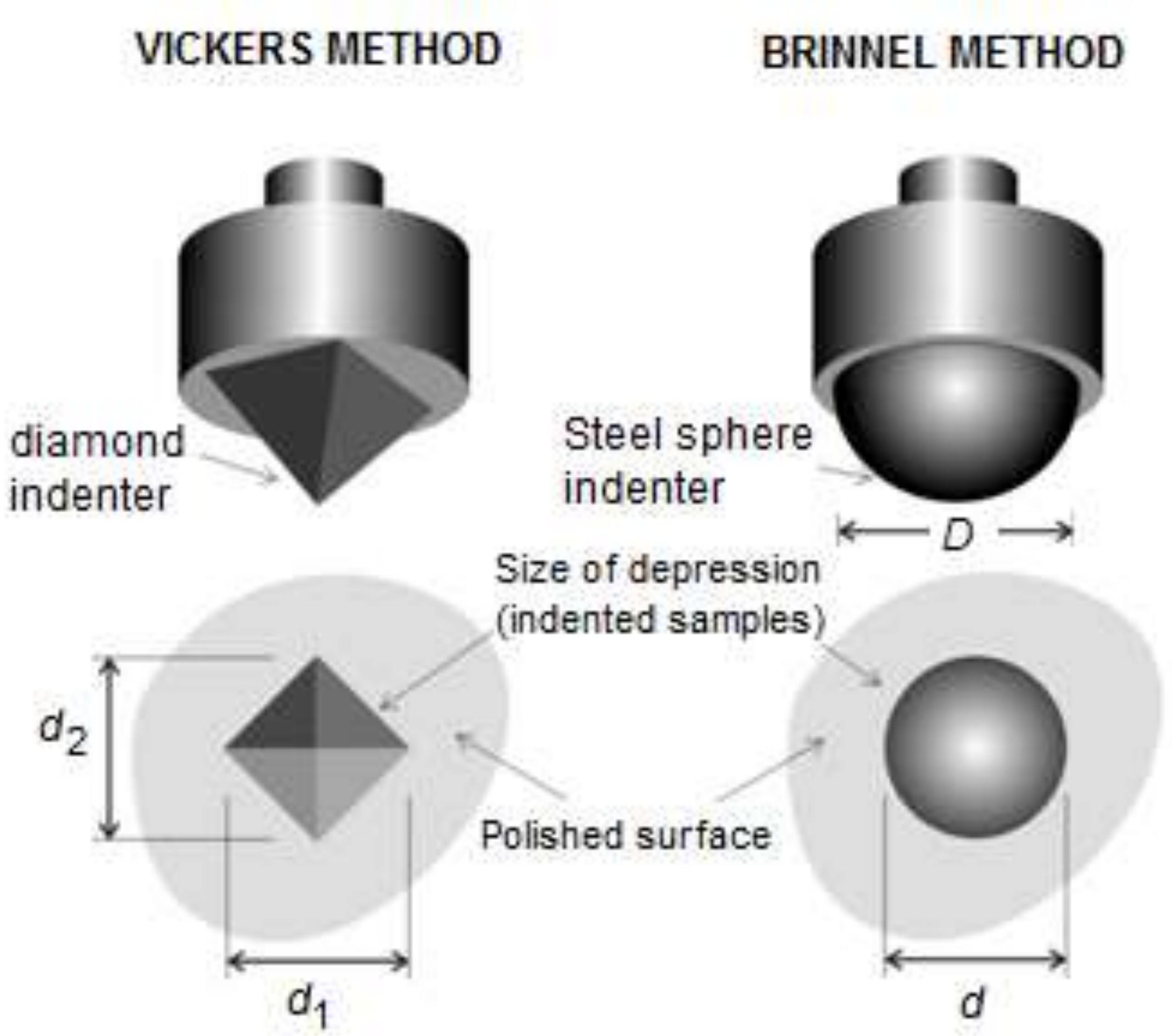
$$\mathrm{HVN} = 2F\,\frac{\sin\left(\frac{\alpha}{2}\right)}{d^2} = 1.854.4\left(\frac{F}{d^2}\right)$$

Where, HVN = Vickers hardness number, *F* = Test load (in kg), *d* = Average diagonal length of an imprint (mμ), *α* = 136° Face angle of the Vickers indenter.

Example 4: Calculate HVN if a load of 2000 kg is set for indenter to produce the indented sample with diameter of 3 mm.

Solution: HVN = 1.854 x 2000 x 9.8 / $(3)^2$ = <u>4038</u>

Vickers and Brinell Methods



Brinell Hardness Test

♦In this test a hardened steel ball is pressed into the surface of the test material using a prescribed ball. The ball and load have to be selected to suit the material being tested.

♦ The Brinell hardness test consists of indenting the test material with a 10 mm diameter hardened steel or carbide ball subjected to a load of 3000 kgf (29,430 N). For softer materials the load can be reduced to 1500 kgf (14,715 N) or 500 kgf (4,905 N) to avoid excessive indentation. The full load is normally applied for 10 to 15 seconds for harder ferrous metals and for 30 seconds or more for other metals softer metals. The diameter of the indentation left in the test material is measured with a microscope.

♦ The Brinell hardness number is calculated by dividing the load applied by the surface area of the indentation.

Brinell hardness number is given by,

$$HBN = \frac{2F}{\pi D\left(D - \sqrt{D^2 - d^2}\right)}$$

Where,
F= Load in kgf (N)
D = Diameter of indenter ball in mm
d = Average diameter of indented sample in mm

Example 5: Calculate BHN if D = 10 mm and d = 2.8 mm under the load of 1200 N.

Solution: HBN = $2 \times 1200/[\pi \times 10 (10 - \sqrt{(10^2 - 2.8^2)})] = \underline{306}$

Hardness Testers

VICKERS Test Machine

BRINELL Test Machine

Rockwell Hardness Test

In this test a Hard Steel Ball or a Diamond Cone Indenter is pressed into the surface of the material being tested/ The result of the test is read directly from machine. The indenter is forced into the test material under a preliminary minor load (98N)and after equilibrium are achieved an indicating device, which follows the movements of the indenter, is set to the datum position. An additional major load is then applied with resulting increase in penetration. The conditions are then allowed to stabilise and then the additional major load is removed,leaving the minor load in place. The resulting permanent penetration esulting from the application and removal of the additional major load is used to calculate the Rockwell hardness number.

HR = E - e

F1 = additional major
e = permanent increase in depth of penetration due to major load , measured in units of 0.001 mm
E = a constant of 100 units for diamond and ball indenters
HR = Rockwell hardness number
D = diameter of steel ball

OTHER HARDNESS TESTS

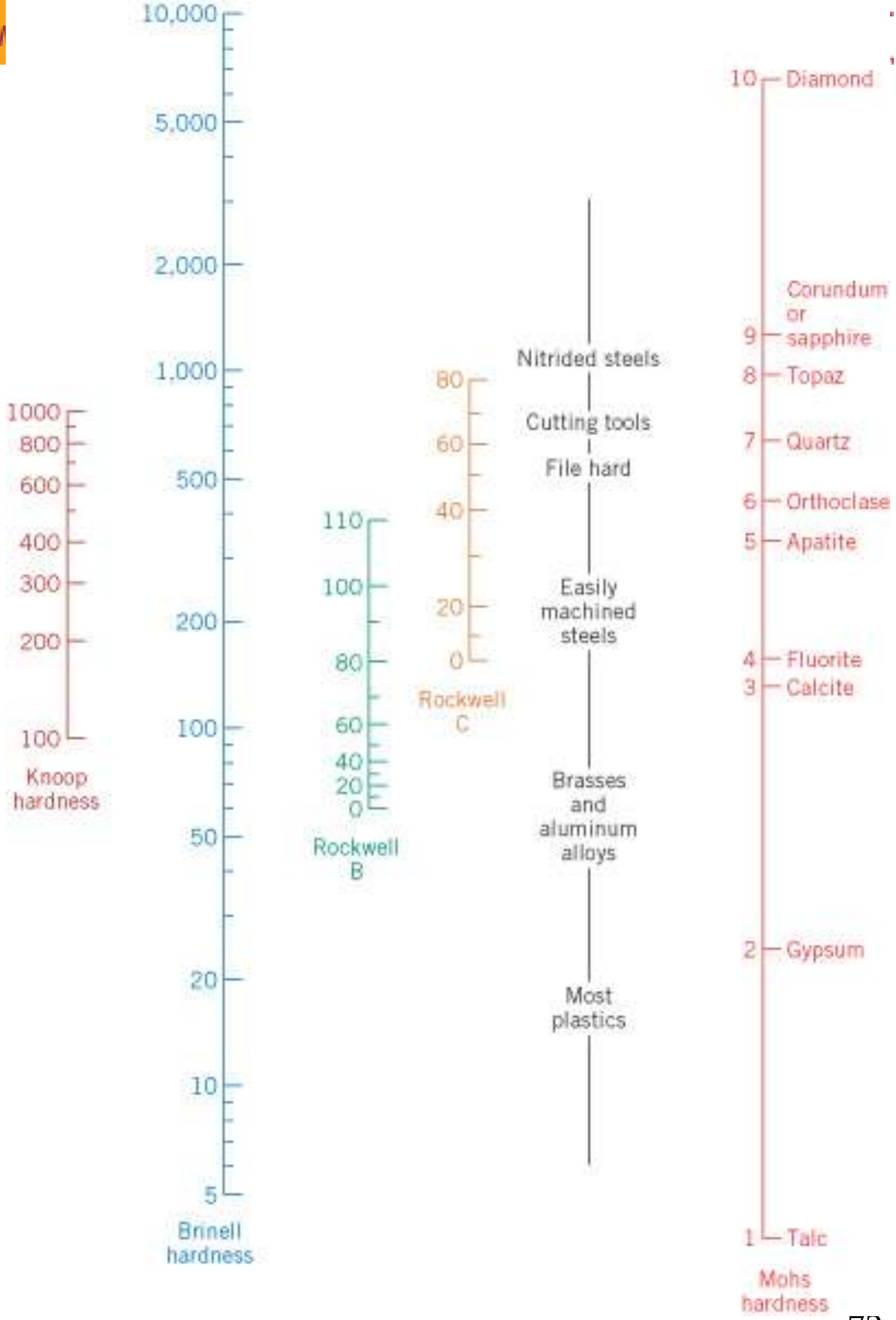
Moh's Hardness Scale

The Moh's hardness scale consists of 10 minerals arranged in order from 1 to 10. Diamond is rated as the hardest and is indexed as 10; talc as the softest with index number 1. Each mineral in the scale will scratch all those below it.

Knoop Test

The Knoop indenter has a polished rhombohedral shape with an included longitudinal angle of 172° 30’ and an included transverse angle of 130° 0’. The narrowness of the indenter makes it ideal for testing specimens with steep hardness gradients and coatings. Knoop is a better choice for hardness testing of hard brittle materials.

Conversion of Hardness Scales

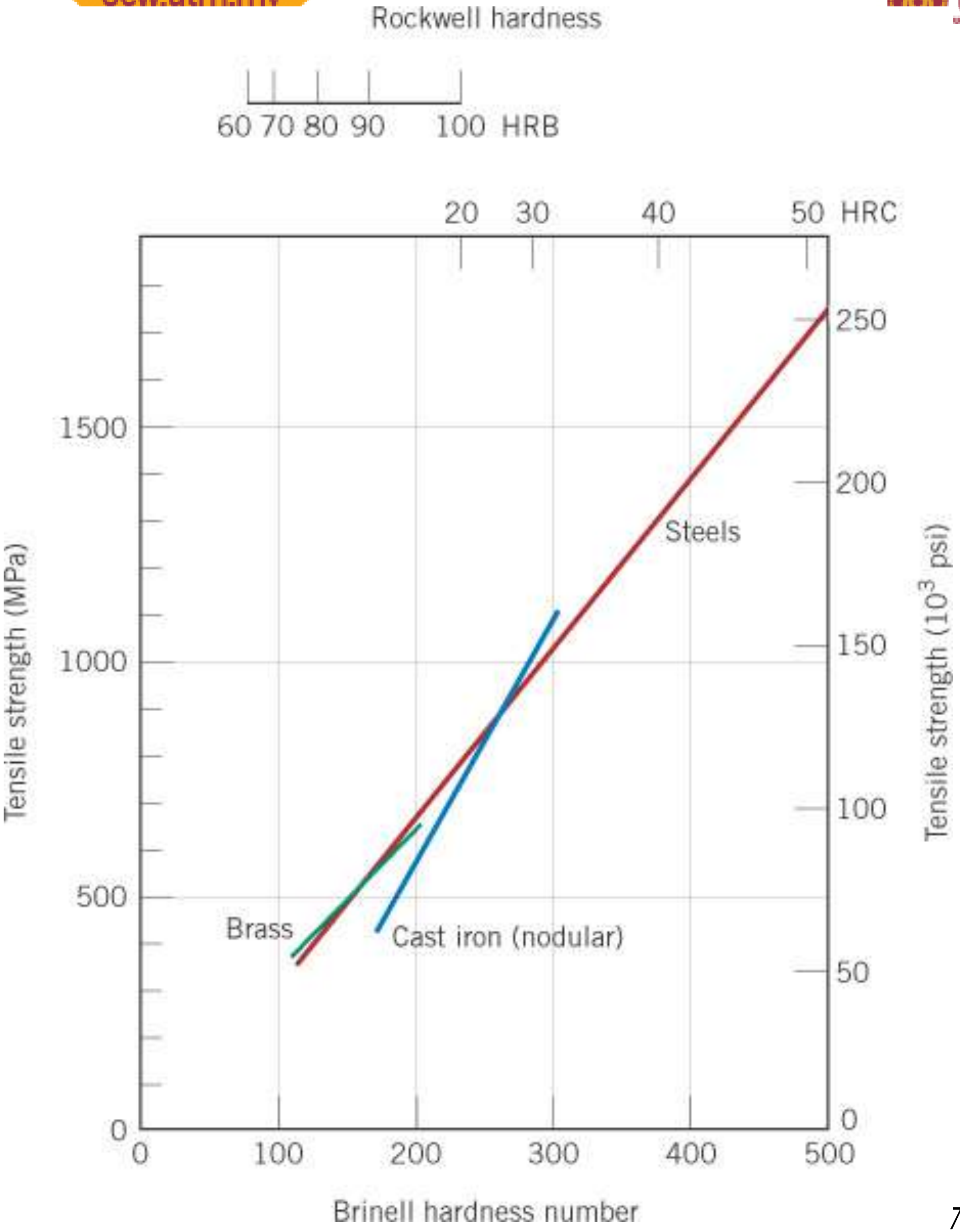


Also see: ASTM E140 - 07

Volume 03.01

Standard Hardness Conversion Tables for Metals Relationship Among Brinell Hardness, Vickers Hardness, Rockwell Hardness, Superficial Hardness, Knoop Hardness, and Scleroscope Hardness

Correlation between Hardness and Tensile Strength



- Both hardness and tensile strength are indicators of a metal’s resistance to plastic deformation.
- For cast iron, steel and brass, the two are roughly proportional.

- Tensile strength (psi) = 500*BHR

Table 7.6a Rockwell Hardness Scales

Scale Symbol	*Indenter*	*Major Load (kg)*
A	Diamond	60
B	$\frac{1}{16}$-in. ball	100
C	Diamond	150
D	Diamond	100
E	$\frac{1}{8}$-in. ball	100
F	$\frac{1}{16}$-in. ball	60
G	$\frac{1}{16}$-in. ball	150
H	$\frac{1}{8}$-in. ball	60
K	$\frac{1}{8}$-in. ball	150

TABLE 6-5 ■ *Comparison of typical hardness tests*

Test	Indentor	Load	Application
Brinell	10-mm ball	3000 kg	Cast iron and steel
Brinell	10-mm ball	500 kg	Nonferrous alloys
Rockwell *A*	Brale	60 kg	Very hard materials
Rockwell *B*	1/16-in. ball	100 kg	Brass, low-strength steel
Rockwell *C*	Brale	150 kg	High-strength steel
Rockwell *D*	Brale	100 kg	High-strength steel
Rockwell *E*	1/8-in. ball	100 kg	Very soft materials
Rockwell *F*	1/16-in. ball	60 kg	Aluminum, soft materials
Vickers	Diamond pyramid	10 kg	All materials
Knoop	Diamond pyramid	500 g	All materials

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.