Materials Engineering 272-C
Fall 2001, Lectures 9 & 10

Introduction to Mechanical Properties of Metals

From an applications standpoint, one of the most important topics within Materials Science & Engineering is the study of how materials respond to external loading or deformation. The broader classification of this discipline is referred to as ‘mechanical properties of materials.’

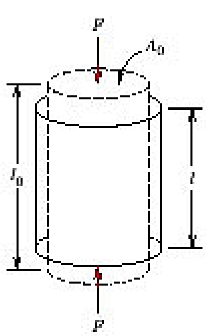
An understanding of the fundamental mechanisms governing mechanical behavior is essential for the judicious selection of materials intended for structural or load-bearing applications. Our discussion will focus primarily on metals; the mechanical behavior of ceramics and polymers will be discussed separately, since the underlying mechanisms are fundamentally different in these systems. Later in the semester, we will discuss failure modes such as fatigue, fracture, ductile-to-brittle transition, and creep, all of which require a fundamental understanding of the mechanical properties of materials.

We begin with a brief review of some of the basic concepts:

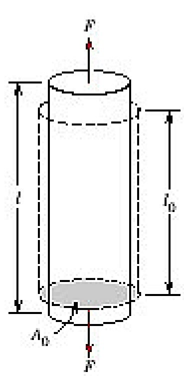
Loading can assume any of the following forms:

(Loading, in this context, is synonymous with force)

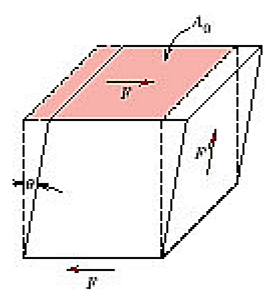
compression



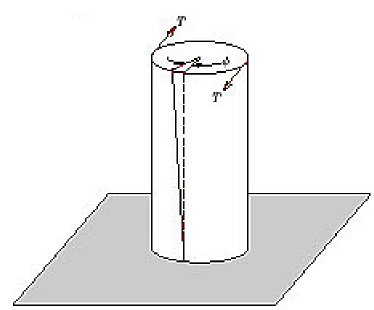
tension



shear

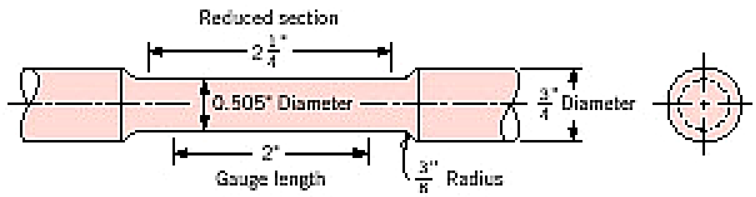


torsion

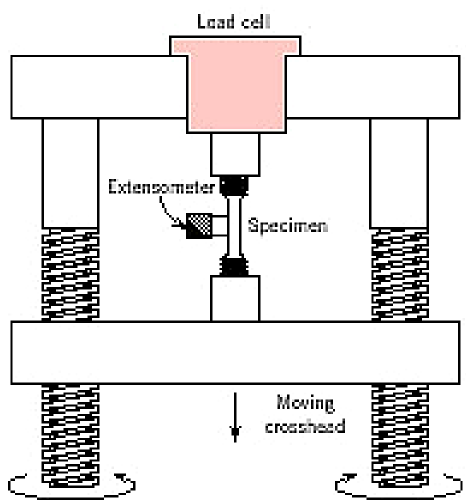


When we conduct mechanical testing on a material, we apply a load and pull (in the case of tensile tests), push (in the case of compression tests), or shear the material at a constant rate.

A typical standard tensile test specimen:



A typical tensile test machine:



The material's response to the applied tensile or compressive load is a change in length. We can monitor the change in length very precisely with an instrument called an *extensometer*.

We define the quantity $\frac{\Delta l}{l_o} = \frac{l - l_o}{l_o}$ as the **strain**,

strain can also be reported as a percentage

where l = instantaneous length
l_o = initial length

Strain is a dimensionless quantity (or, can be reported as m/m or in./in.)

Example problem:

The original gauge length (l_o) marked on an aluminum test piece is 40 mm. The test piece is strained in tension so that the gauge length becomes 42.3 mm. What is the strain, ε?

Solution:

$$\varepsilon = \frac{\Delta l}{l_o} = \frac{l - l_o}{l_o} = \frac{42.3 - 40.0}{40.0} = 0.0575$$

or, expressed as a percentage, ε = 5.75%

Typically, loading is normalized to cross sectional area:

$$\frac{F}{A_o}$$

We refer to this ratio as the applied **stress**

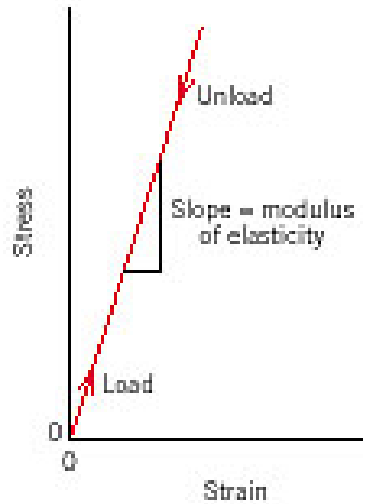
when normalized to initial area, this is **engineering stress**.

when normalized to actual area, this is **true stress**.

In tensile testing, we measure how much force is required to maintain a constant strain rate. As the material's strength changes, we see the results directly as a change in stress.

Elastic response:

Initially, stress and strain are directly proportional to each other:



also called Young's modulus

Rationale: atoms can be thought of as masses connected to each other through a network of springs. According to Hooke's law, the extension of a spring, x, and the applied force, F, are related by the spring contant, k:

$F = -kx$, where the – sign indicates a restoring force.

The constant of proportionality, *Young's modulus or modulus of elasticity*, is a measure of the material's stiffness.

Materials possessing high stiffness: W, Ta, Mo

Materials possessing low stiffness: Al, Cu, Ag

large slope (large change in restoring force with a change in elongation)

small slope (small change in restoring force with a change in elongation)

In the elastic regime, the deformation is completely reversible, and we can write

$$\frac{F}{A_o} = E\frac{\Delta l}{l_o}$$

-or-

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

where the engineering stress, $\sigma = F/A_o$

and the engineering strain, $\varepsilon = \Delta l/l_o$

Example problem:

A steel wire with a cross sectional area of 0.55 mm^2 and length of 10 m is extended elastically 1.68 mm by a force of 17.24 N. What is the modulus of elasticity for this steel specimen?

Solution:

Stress: $\sigma = F/A_o = (17.24\ N)/(0.55\ mm^2) = 31.34\ N/mm^2 = 31.34 \times 10^6\ N/m^2$

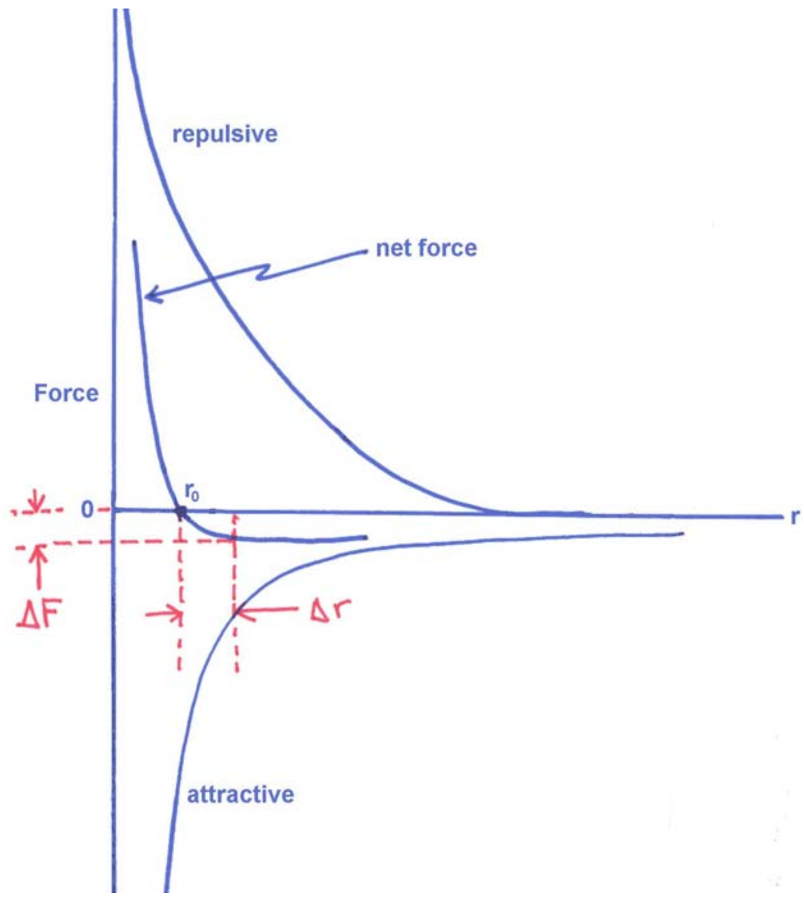
Strain: $\varepsilon = \Delta l/l_o = (1.68 \times 10^{-3}\ m)/(10m) = 0.000168$

Then, $E = \sigma/\varepsilon = (31.34 \times 10^6\ N/m^2)/(0.000168) = 1.87 \times 10^{11}\ N/m^2$

Since $10^9 \Rightarrow$ “Giga” we write this as 1.87×10^2 GPa, or 187 GPa.

Atomic mechanism for mechanical behavior:

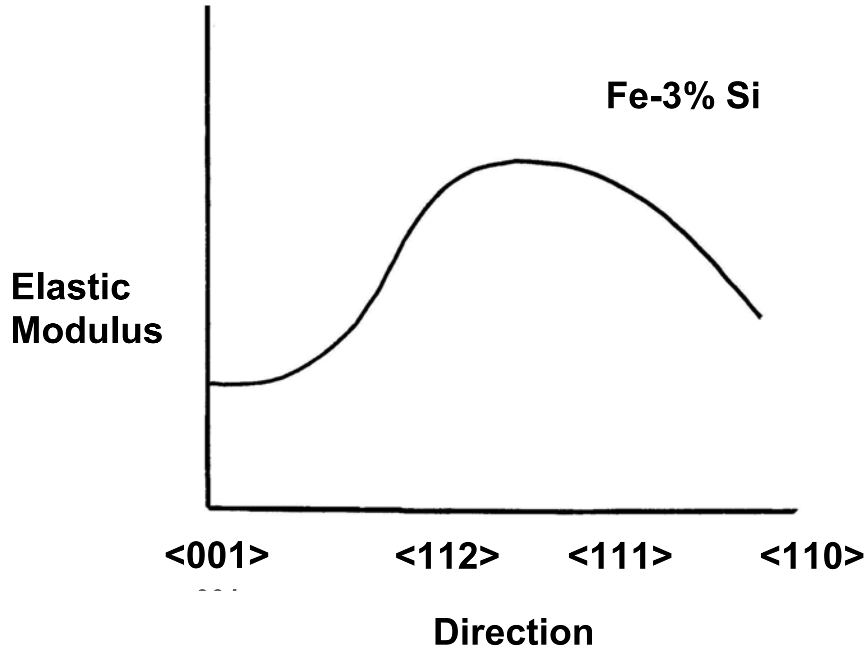
Upon application of a tensile force, atoms are pulled away from their equilibrium position by an amount Δr until the applied force is balanced by the resulting increase in attractive force, ΔF, as shown in the following diagram:



If the local value of the applied force exceeds the bonding strength, atoms can assume new positions relative to each other, giving rise to plastic (or permanent) deformation.

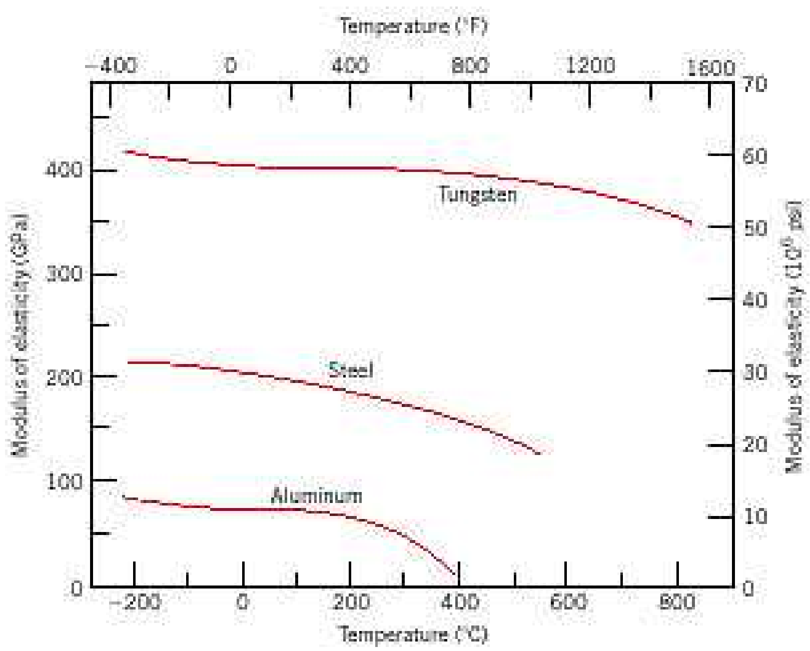
Elastic Modulus:

Moduli can be "anisotropic" in single crystal materials. (Anisotropic means having different values in different directions or orientations.)



Moduli are almost always isotropic in polycrystalline materials (E from each grain is averaged out). This is not true, however, in materials possessing *texture* as a result of rolling, drawing, or swaging.

Temperature dependence of elastic moduli:



In general, the a material's modulus (or stiffness) decreases with increasing temperature. (Can you think of why this happens?)

Example problem:

A piece of Cu originally 305 mm (12 in.) long is pulled in tension with a stress of 276 MPa (40,000 psi). If the deformation is entirely elastic, what will be the resultant elongation?

Solution:

The problem asks us to determine the elongation, which is Δl in equation 6.2. Since the deformation is elastic, strain is linearly proportional to stress according to equation 6.5. The elongation, l, is related to the initial length, l_o, through equation 6.2. Combining these two equations allows us to write an expression for Δl:

$$\sigma = E\varepsilon = E\left(\frac{\Delta l}{l_o}\right)$$

so

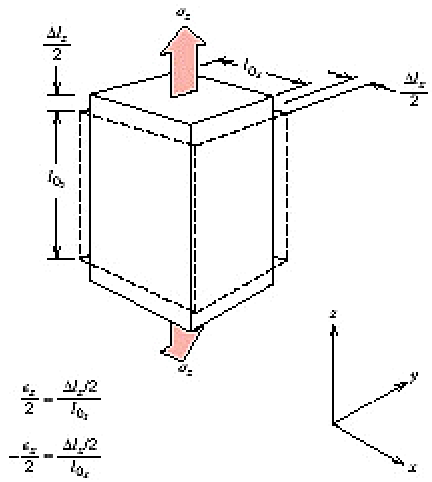
$$\Delta l = \frac{\sigma l_o}{E}$$

The values of σ and l_o are given as 276 MPa and 305 mm, respectively. The value of the elastic modulus, E, can be found in Table 6.1 (p. 118); the value of E for Cu is 110 GPa (16 x 10^6 psi). Therefore, the elongation is found by direct substitution of the known quantities:

$$\Delta l = \frac{(276MPa)(305mm)}{110x10^3 MPa} = 0.77mm$$ (= 0.03 in.)

Poisson's ratio:

When deformed in tension or compression, most materials deform in the opposite sense in either or both transverse directions. For example, If a material in the shape of a rectangular parallelepiped is subjected to tensile loading along the axial direction, z, a contraction is observed along either lateral axis (x or y) or both.



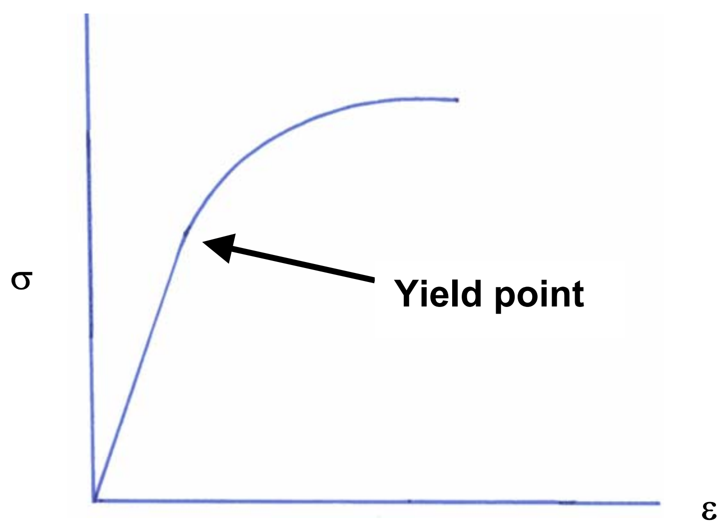
The ratio of lateral (ε_x, ε_y) to axial (ε_z) strain is known as Poisson's ratio:

$\nu = -\frac{\varepsilon_x}{\varepsilon_z} = -\frac{\varepsilon_y}{\varepsilon_z}$ (the "-" sign makes ν a positive quantity since ε_x and ε_y are themselves negative quantities (contraction).

The largest value of ν if there is no net volume change in the material is 0.5.

Now, **plastic deformation**:

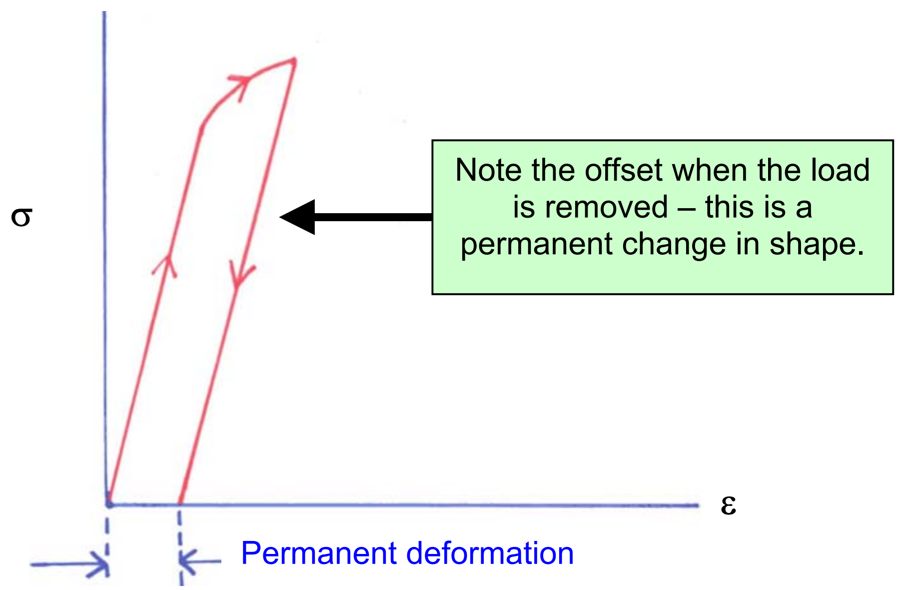
What happens if we continue to apply tensile loading beyond the elastic limit? (i.e., stretching atomic bonds to the point of breaking them and forming a new set of bonds with other atoms.)



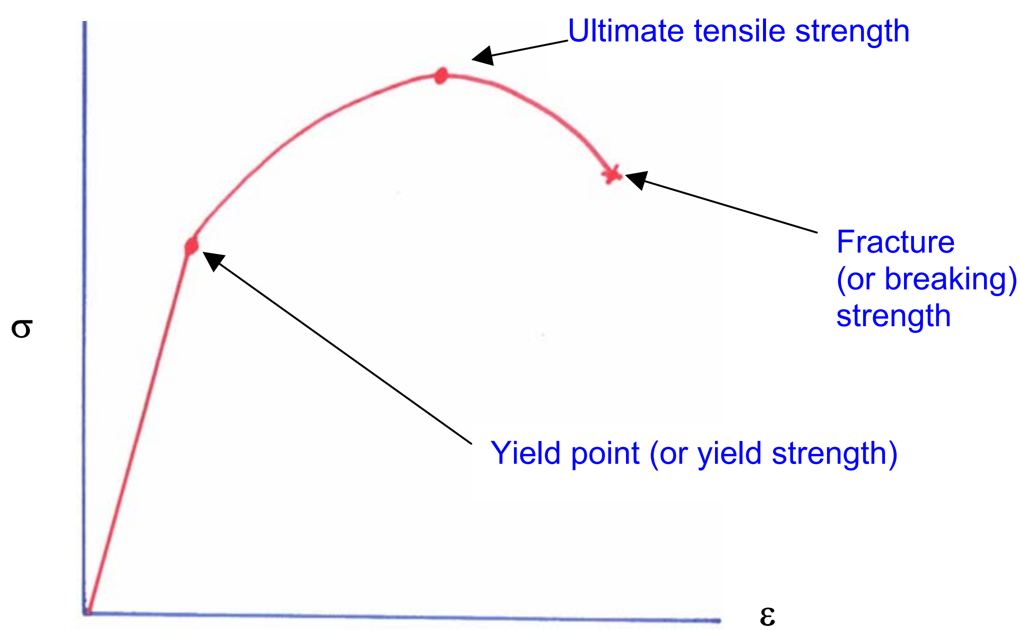
Note: most ceramic materials do NOT exhibit plastic deformation. This is a phenomenon mostly associated with metals (although not all metals exhibit plastic behavior either, cast irons for example). The reason for this is the extent of dislocations in metals (or, if you prefer, their relative absence in ceramics) and their mobility.

Plastic ⇒ permanent (or non-recoverable) deformation

Suppose a tensile load is applied to a specimen and then released after the yield point was reached (i.e., beyond the elastic limit):

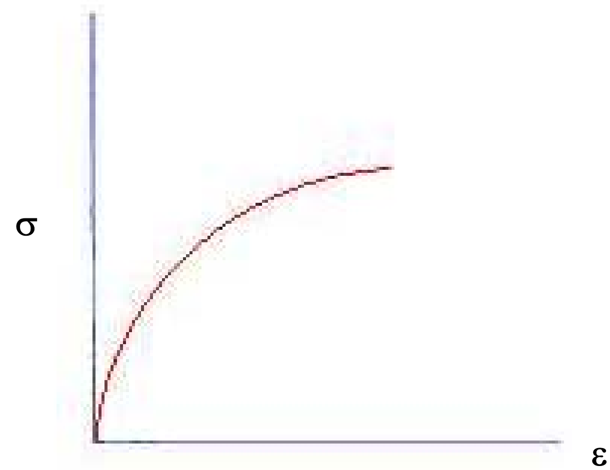


Consider the following important points on the σ - ε diagram:



Most engineering applications are concerned with yield strength. This would correspond to the maximum stress the material could withstand during normal service without experiencing permanent change in shape.

Question: what if the material does not exhibit a well-defined yield point?
e.g.,

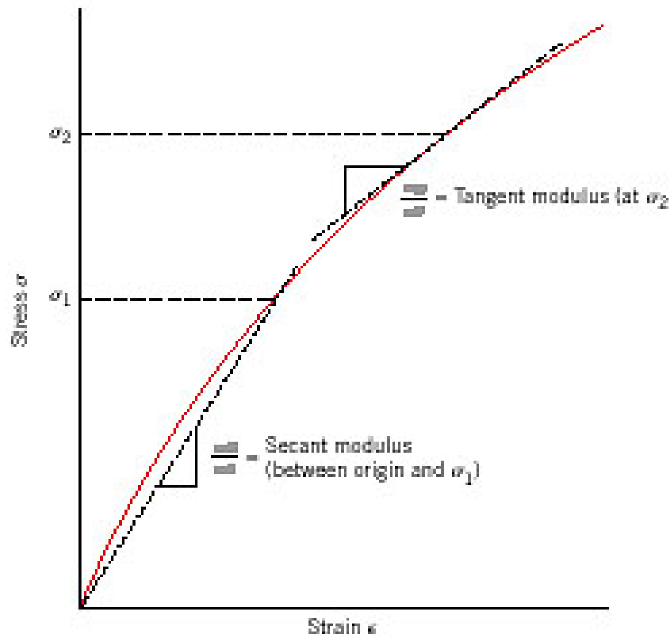


In this case, there is no clear-cut yield point. Many ductile metals and alloys exhibit this type of behavior.

In such situations, we define either a secant modulus or a tangent modulus. The tangent modulus is the slope of the σ-ε curve at some arbitrary point, generally taken at either the 0.002 or 0.005 strain offset point.

The secant modulus is the slope of the secant constructed between the origin and an arbitrary point on the curve, again usually taken as the 0.2% offset point.

An example of these constructions is shown in the following figure:



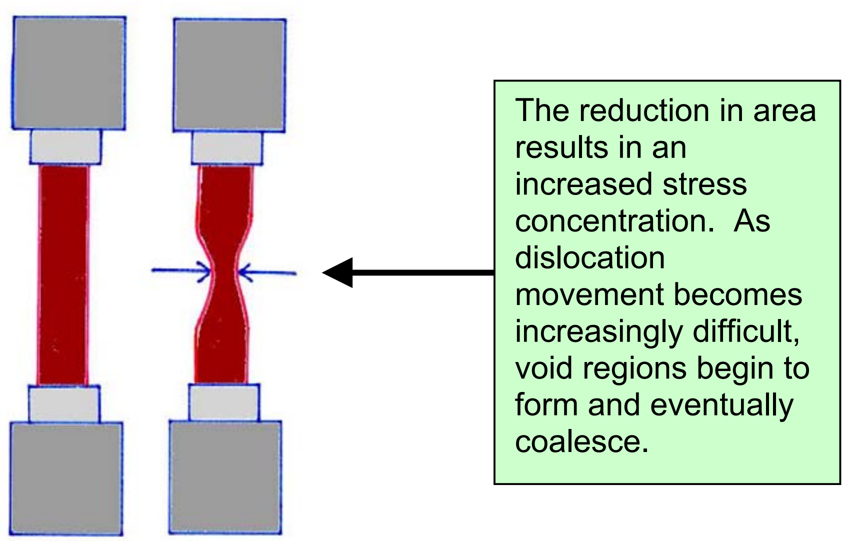
Question: In ductile metals, the σ-ε curve eventually turns down after reaching the ultimate tensile strength (UTS). Does this mean the specimen is becoming "weaker?"

Recall the definition of stress:

"engineering" stress $\equiv F/A_o$

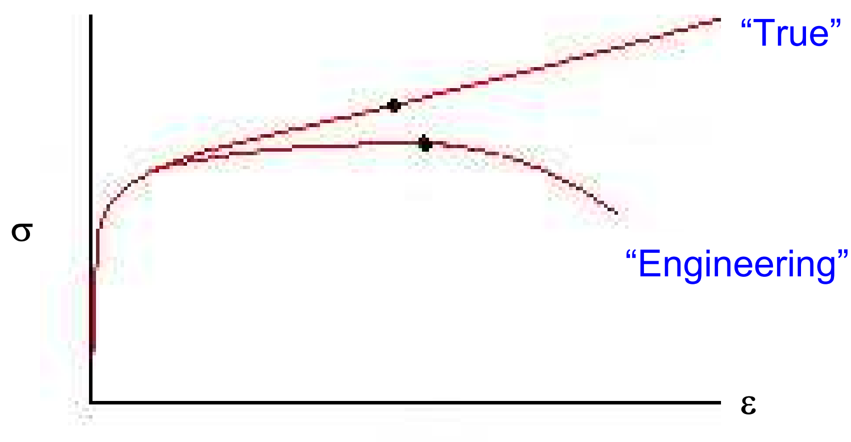
where A_o is the initial cross-sectional area

we know that the gauge area decreases during plastic deformation due to necking as shown below:



Since the actual cross-sectional area is reduced, use of the initial area gives a value for stress that is too high by the ratio (A_o/A)

If we calculate stress based on the instantaneous area, the resulting quantity is called the true stress (as opposed to engineering stress).



Usually, when you see "stress" values reported, it is the engineering stress that is used.

(Even through the true stress-strain curve gives a more accurate picture of the breaking strength of a material, it is difficult to obtain measurements of the actual area in real-time.)

True (breaking or fracture) strength > tensile strength (but the engineering σ-ε diagram does not show this.

As plastic deformation proceeds, the force necessary to maintain increasing strain increases due to work-hardening. As more of the stress becomes concentrated in the neck, a degree of plastic instability develops with the formation of voids. These voids result in even higher stress concentrations and eventual fracture.

Even though the σ-ε curve appears smooth, if we magnified it by a factor of 10^8 – 10^9, we would see the curve as a series of discontinuous steps. This is because dislocations propagate by step-wise or incremental slippage of atoms along close-packed planes.

There are a number of other important mechanical properties:

- Ductility
- Toughness
- Hardness

Ductility:

Ductility is a measure of how much strain a given stress produces. Highly ductile metals can exhibit significant strain before fracturing, whereas brittle ceramics frequently display very little strain. An overly simplistic way of viewing ductility is the degree to which a material is "forgiving" of local deformation without the occurrence of fracture.

An obvious measure of ductility is how much strain (in terms of a percentage) occurs at fracture. Another measure is how much reduction in area takes place. Both are commonly used:

Percent elongation:

$$\%EL = \left(\frac{l_f - l_o}{l_o}\right)x100$$

where l_o is the initial gauge length
l_f is the final gauge length at fracture

Since the magnitude of %EL depends on gauge length, you should specify l_o as well.

Percent reduction in area:

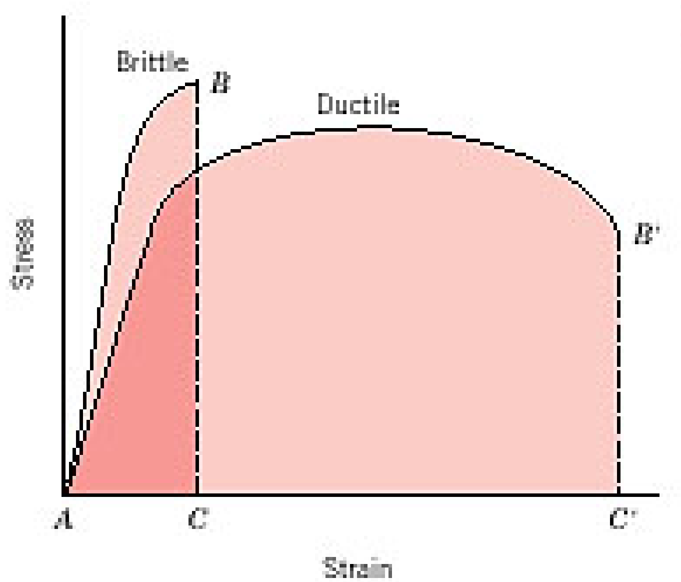
$$\%RA = \left(\frac{A_o - A_f}{A_o}\right)x100$$

where A_o is the initial cross sectional area (in the gauge section)
A_f is the final cross sectional area at fracture

Brittle materials: %EL $\leq$ 5% at fracture

Ductile materials: %EL and %RA both $\geq$ 25%

Consider the following σ-ε diagram for two materials. Ductility is proportional to the area under the curve between the origin and the point of fracture:



Note that the area under the curve labeled "ductile" is much larger than the corresponding area under the curve labeled "brittle."

The following table lists important mechanical properties (all obtained from the σ-ε curve) of various metals:

Table 6.2 Typical Mechanical Properties of Several Metals and Alloys in an Annealed State

Metal Alloy	*Yield Strength MPa (ksi)*	*Tensile Strength MPa (ksi)*	*Ductility, %EL [in 50 mm (2 in.)]*
Aluminum	35 (5)	90 (13)	40
Copper	69 (10)	200 (29)	45
Brass (70Cu–30Zn)	75 (11)	300 (44)	68
Iron	130 (19)	262 (38)	45
Nickel	138 (20)	480 (70)	40
Steel (1020)	180 (26)	380 (55)	25
Titanium	450 (65)	520 (75)	25
Molybdenum	565 (82)	655 (95)	35

Note that the ductility of metals varies greatly; some, such as 1020 steel and Ti are relatively low compared with brass.

Toughness:

Do not confuse toughness with strength. In popular culture these terms are used interchangeably. In engineering, however, they have very distinct meanings.

Toughness refers to the amount of energy a material can absorb energy up to fracture.

There are two conditions under which toughness is determined: high strain rate and low strain rate.

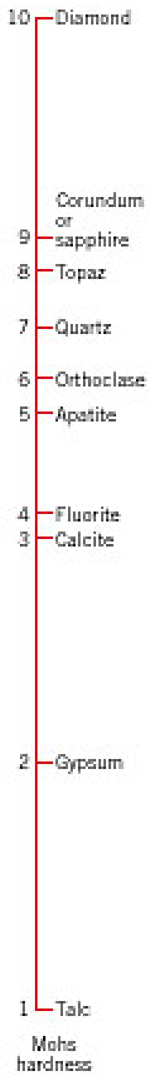
(Strain rate simply refers to how rapidly the deformation is applied. A bullet, for example, gives rise to a very high strain rate situation.)

> *High strain rate toughness tests: impact*
> *A mass on a pivot is allowed to strike the material and introduce fracture. By knowing the mass and starting angle of the pendulum, the initial kinetic energy can be calculated.*
>
> *Low strain rate toughness tests: area under the σ-ε curve*

The units for toughness are energy per unit volume of material: J/m^3

Toughness requires both strength and ductility.

Hardness:



Hardness is one of the oldest indications of mechanical behavior in materials. Specifically, it is the resistance to a localized applied plastic deformation.

The earliest form of hardness characterization assumed the form of a scratch test, where materials were ranked in order of whether they scratched (or were themselves scratched) by other materials. The first attempt to quantify this was the Mohs scale:

The Mohs scale is non-linear, that is, a material with a Mohs hardness of 8 is not twice as hard as a material with a rating of 4.

This test is not quantitative and other methods have long since replaced it for scientific and engineering studies.

Hardness is a consequence of the strength of atomic bonding and the rigidity of the lattice framework. (Intrinsic hardness)

Recently, research results indicate significant increases in hardness can also be produced by microstructural refinement (extrinsic hardness)

Measurement of hardness:

Most techniques today involve indentation methods:

Brinell: hardened steel ball (10, 7.5, or 5 mm in dia.)
Load ~ 3000 Kg_f
Dwell time ~ 15 – 30 s.

Retract indentor – a dimple or crater remains on the surface of the material under test

Diameter of the indentation is then measured

Then, $HB = \dfrac{load\_(Kg)}{area\_of\_contact}$

(don't report units for Brinell – only a number between 0 and ~625)

Best to report HB(load, diameter, time)

problems: HB is a weak function of the load
some uncertainty in measurement of d (ridging or sinking)

Vicker's best for research work
Developed in Britain shortly after WWI
Indentor: diamond
Load: 1 – 10 Kg_f
measure diagonals
two kinds: square-based or elongated (Knoop)

Vicker's **D**iamond **P**yramid **H**ardness:

$$\text{VDPH} = \frac{2P\sin\left(\frac{\theta}{2}\right)}{D^2} \cong \frac{1.8544P(Kg)}{D^2(mm)}$$

Where θ = angle of the indentor (134°)

Units of Vicker's hardness: Kg/mm^2 (numerically "close" to 100*GPa)

Hardest steels:	~ 1100
Al_2O_3:	~ 1500 – 2200
c-BN:	~ 4500
diamond:	~ 7000

Rockwell: Developed in the USA in the 1920's
Uses a combination of loads & indentors

Hardness determination requires difference in penetration depth between initial minor load and larger major load.

Two tests: Rockwell and superficial Rockwell

Rockwell	superficial Rockwell
10 Kg minor load 60, 100, and 150 Kg major load	3 Kg minor load 15, 30, and 45 Kg major load

(superficial tests are usually applied to thin specimens)

Rockwell and superficial Rockwell hardness scales:

Table 6.5a **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 6.5b **Superficial Rockwell Hardness Scales**

Scale Symbol	*Indenter*	*Major Load (kg)*
15N	Diamond	15
30N	Diamond	30
45N	Diamond	45
15T	$\frac{1}{16}$ in. ball	15
30T	$\frac{1}{16}$ in. ball	30
45T	$\frac{1}{16}$ in. ball	45
15W	$\frac{1}{8}$ in. ball	15
30W	$\frac{1}{8}$ in. ball	30
45W	$\frac{1}{8}$ in. ball	45

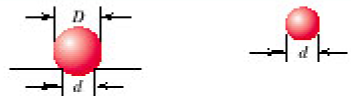
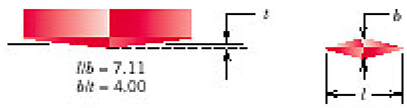
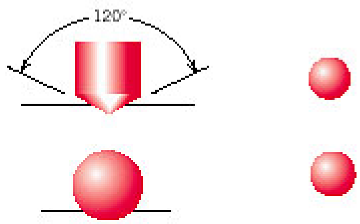
specification: hardness # + scale symbol

examples: 80 HRB = Rockwell hardness of 80 on the B scale

60 HR30W = Superficial hardness of 60 on the 30W scale.

A summary of indentation hardness techniques (reprinted from Callister):

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	$\mathrm{HB} = \dfrac{2P}{\pi D[D - \sqrt{D^2 - d^2}]}$
Vickers microhardness	Diamond pyramid			P	$\mathrm{HV} = 1.854P/d_1^2$
Knoop microhardness	Diamond pyramid			P	$\mathrm{HK} = 14.2P/l^2$
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)	

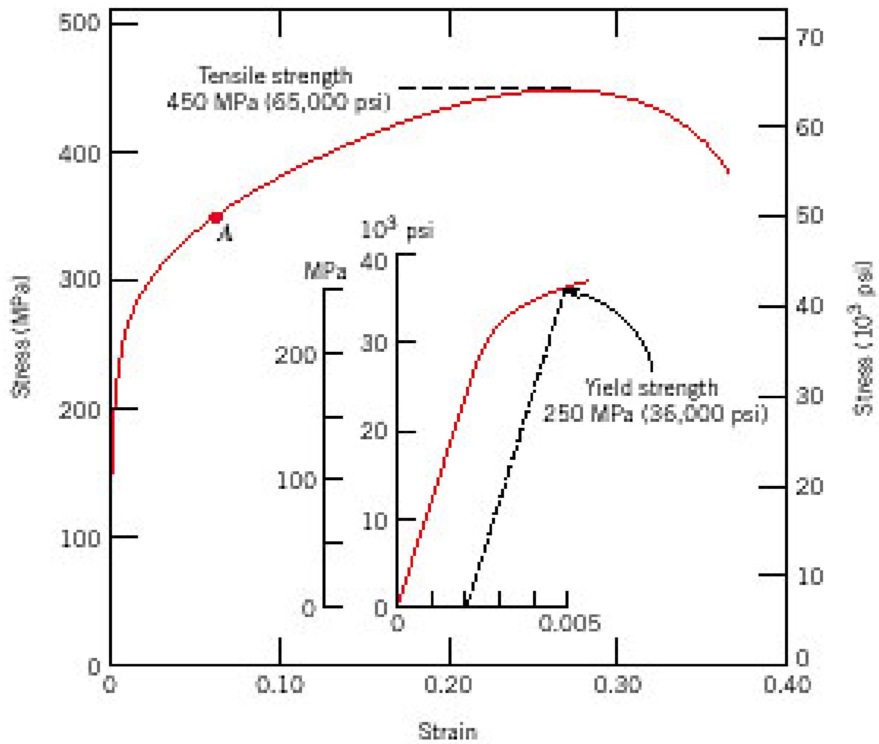
[a] For the hardness formulas given, P (the applied load) is in kg, while D, d, d_1, and l are all in mm.

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.

Example problem 6.3: (worked out in class)

From the tensile stress-strain behavior for a specimen of brass shown in the following figure, determine the following mechanical property values:

a) modulus of elasticity
b) yield strength at a strain offset of 0.002 (0.2%)
c) maximum load that can be sustained by a cylindrical specimen having an original diameter of 12.8 mm (0.505 in.)
d) change in length of a specimen originally 250 mm (10 in.) long that is subjected to a tensile stress of 345 MPa (50,000 psi)



Solution:

a) E is just the slope of the σ-ε curve in the linear (or elastic) portion. The expanded insert is helpful for obtaining values from which to calculate this quantity: $E = slope = \frac{\Delta\sigma}{\Delta\varepsilon} = \frac{\sigma_2 - \sigma_1}{\varepsilon_2 - \varepsilon_1} = \frac{(150-0)}{(0.0016-0)} =$ 93.8 GPa (or 13.6 x 10^6 psi). The accepted value is 97 GPa.

b) The 0.002 strain offset line is constructed as shown above; its intersection with the σ-ε curve occurs at approximately 250 MPa, which corresponds to the yield stress of the brass.

c) The maximum load that can be sustained by the specimen is calculated by using Equation 6.1, in which σ is taken to be the tensile strength (from the figure) of 450 MPa (65,000 psi). Solving for F, the maximum load, yields

$$F = \sigma A_o = \sigma\left(\frac{d_o}{2}\right)^2 \pi = 450x10^6\left(\frac{12.8x10^{-3}}{2}\right)^2 \pi = 57{,}000 \text{ N } (13{,}000 \text{ lb}_f)$$

d) To determine the change in length, Δl, in Equation 6.2, it is necessary to determine the strain that is produced by a stress of 345 MPa. This is accomplished by locating the stress point on the σ-ε curve, point A, and reading the corresponding strain from the strain axis, which is approximately 0.06. Since l_o = 250 mm, we have

$$\Delta l = \varepsilon l_o = (0.06)(250 \text{ mm}) = 15 \text{ mm } (0.6 \text{ in.})$$