

# Chapter 6: Mechanical Properties of Metals

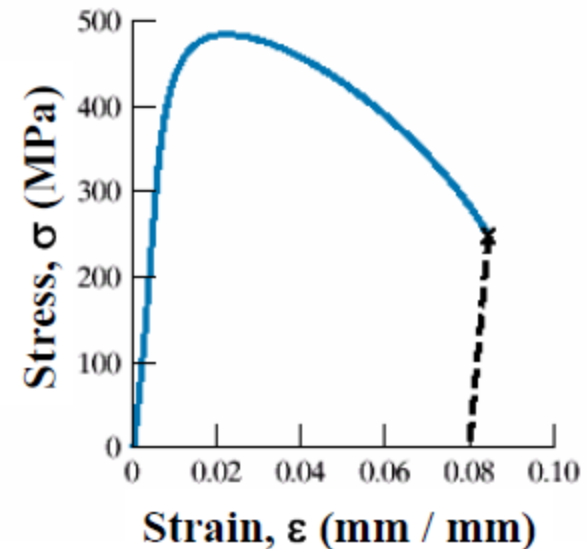
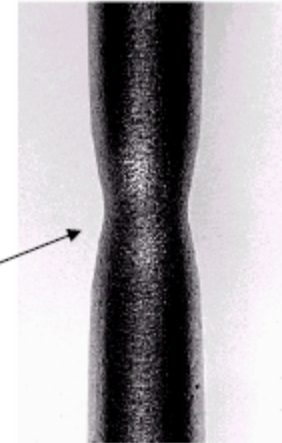
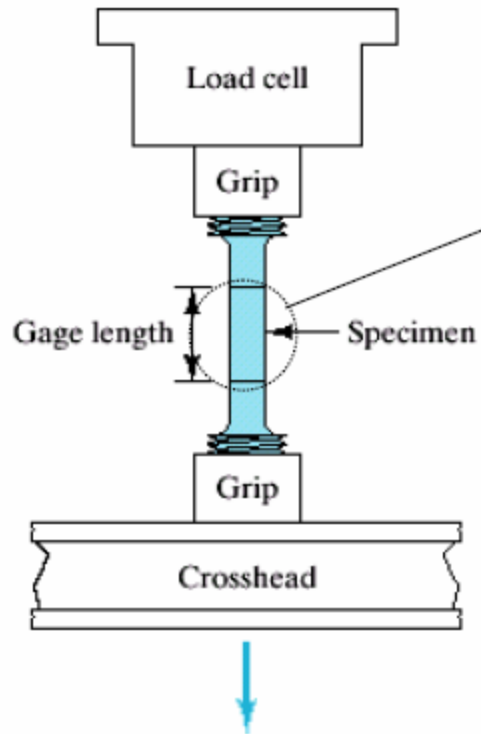
Dr. Feras Fraige

# Outline

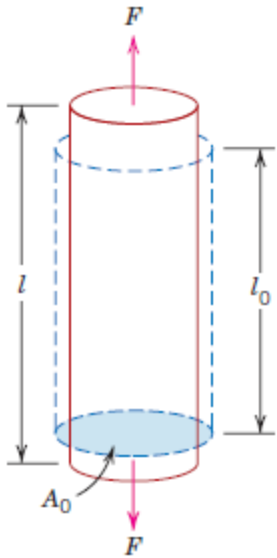
- **Stress and Strain**
  - ✓ Tension
  - ✓ Compression
  - ✓ Shear
  - ✓ Torsion
- **Elastic deformation**
- **Plastic Deformation**
  - ✓ Yield Strength
  - ✓ Tensile Strength
  - ✓ Ductility
  - ✓ Toughness
  - ✓ Hardness

# Introduction

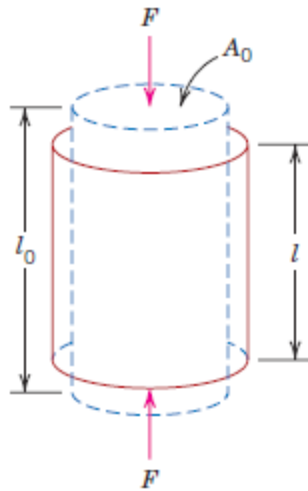
To understand and describe how materials deform (elongate, compress, twist) or break as a function of applied load, time, temperature, and other conditions we need first to discuss standard test methods and standard language for mechanical properties of materials.



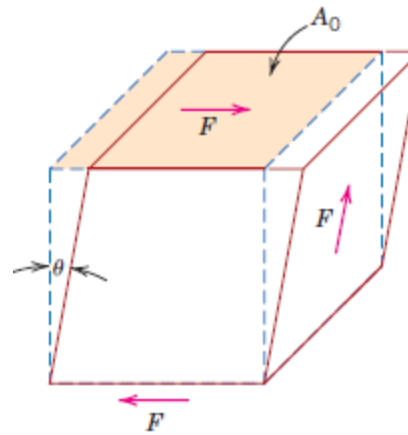
# Types of Loading



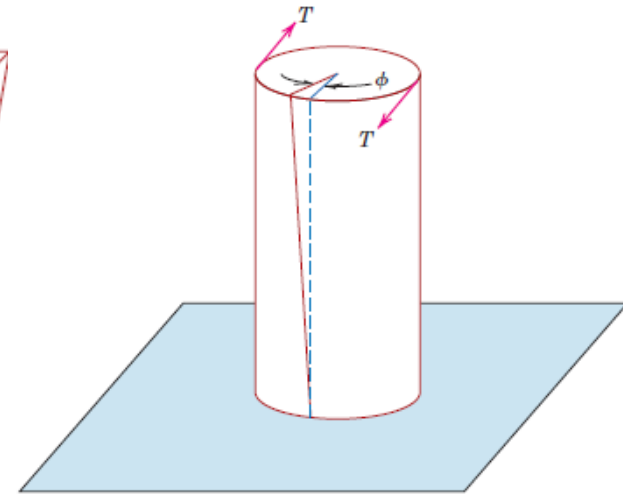
**Tensile**



**Compressive**



**Shear**



**Torsion**

# Concepts of Stress and Strain (tension and compression)

- To compare specimens of different sizes, the load is calculated per unit area.

**Engineering stress:**  $\sigma = F / A_0$

- F is load applied perpendicular to specimen cross-section;  $A_0$  is cross-sectional area (perpendicular to the force) **before application of the load**. Units of  $\sigma$  is  $\text{N/m}^2$  or Pa.

**Engineering strain:**  $\varepsilon = \Delta l / l_0 \quad (\times 100 \%)$

- $\Delta l$  is change in length,  $l_0$  is the original length. Dimensionless (No unit).

- These definitions of stress and strain allow one to compare test results for specimens of different cross-sectional area  $A_0$  and of different length  $l_0$ .
- **Stress and strain are positive for tensile loads, negative for compressive loads**

# Concepts of Stress and Strain (shear)

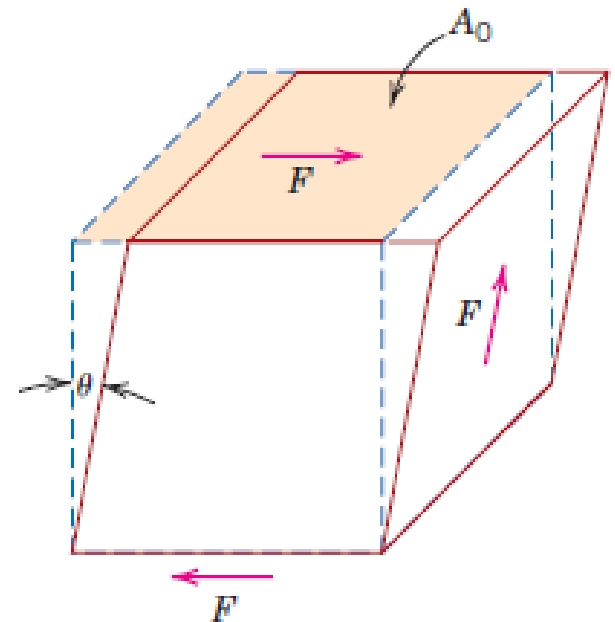
Shear stress:  $\tau = F / A_0$

- $F$  is load applied parallel to the upper and lower faces each of which has an area  $A_0$ .

Shear strain:  $\gamma = \tan \theta$  (x 100%)

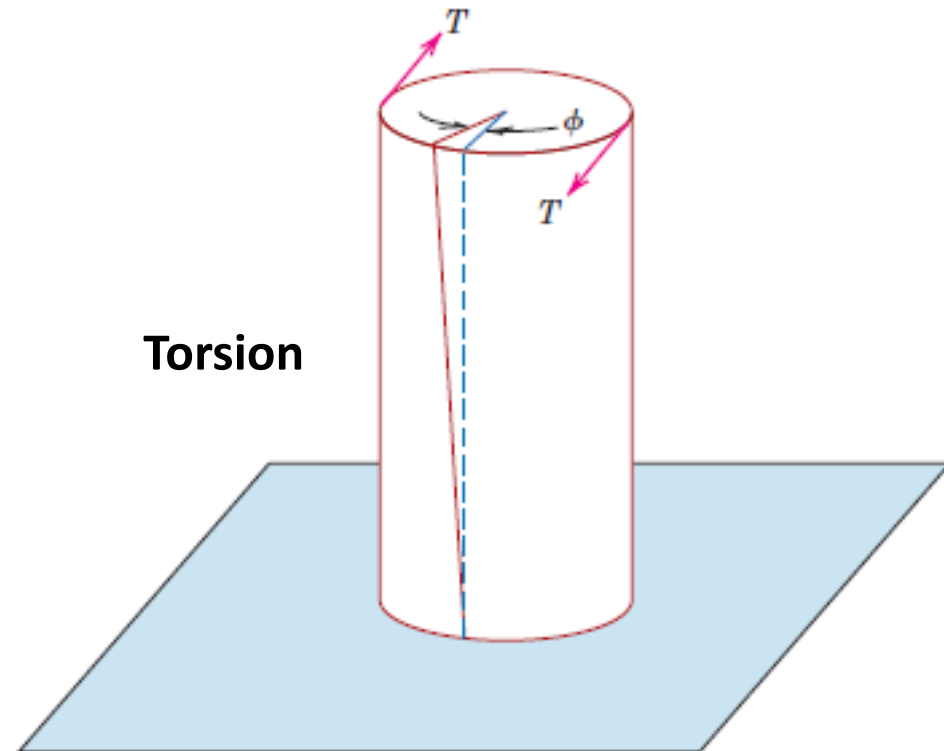
- $\theta$  is the strain angle.

Shear



# Concepts of Stress and Strain (torsion)

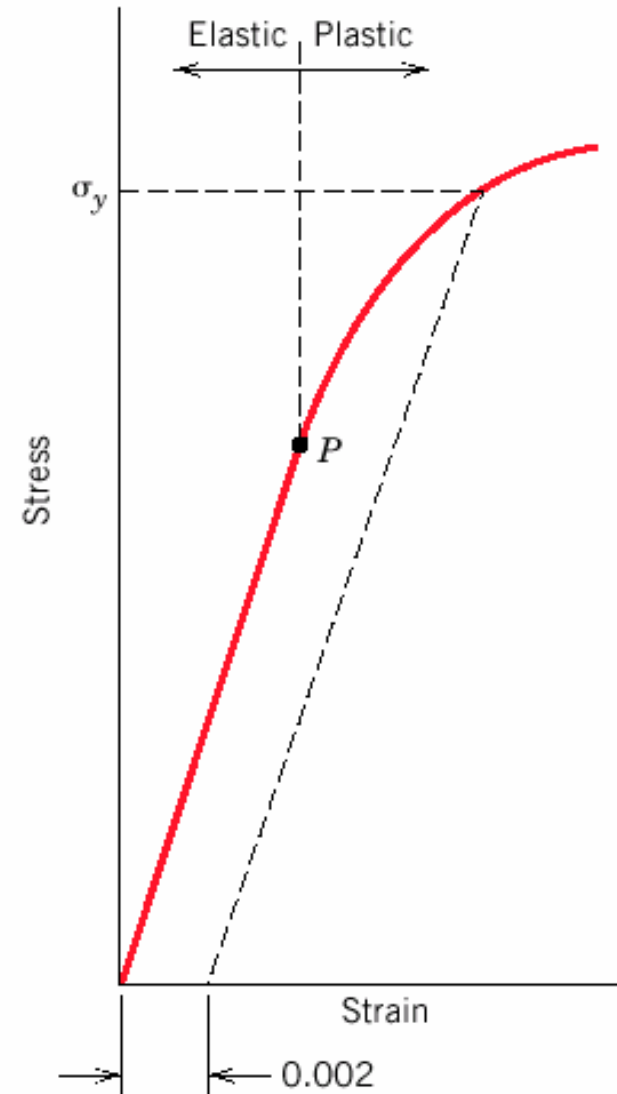
- Torsion is variation of pure shear. The shear stress in this case is a function of applied torque  $T$ , shear strain is related to the angle of twist,  $\phi$ .





# Stress-Strain Behavior

- **Elastic deformation**
  - ✓ **Reversible:** when the stress is removed, the material returns to the dimensions it had before the loading.
  - ✓ Usually strains are small (except for the case of some plastics, e.g. rubber).
- **Plastic deformation**
  - ✓ **Irreversible:** when the stress is removed, the material does not return to its original dimensions.



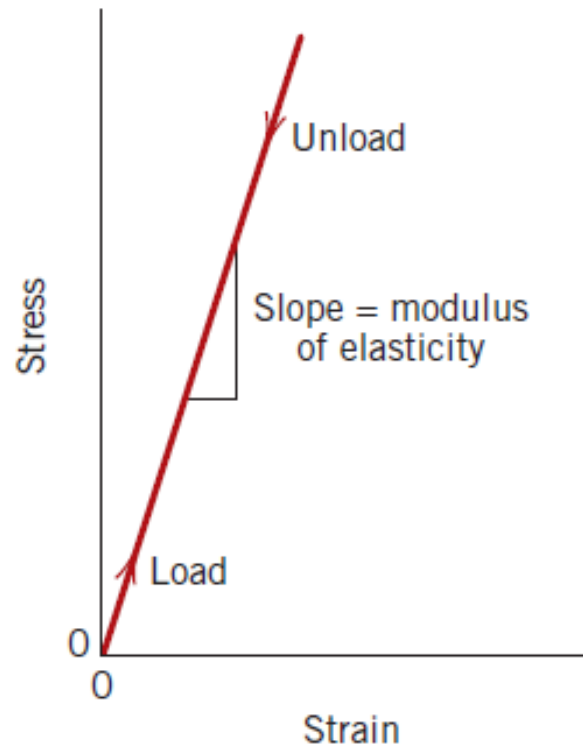
# Stress-Strain Behavior: Elastic Deformation

- In tensile tests, if the deformation is elastic, the stress-strain relationship is called Hooke's law:

$$\sigma = E \varepsilon$$

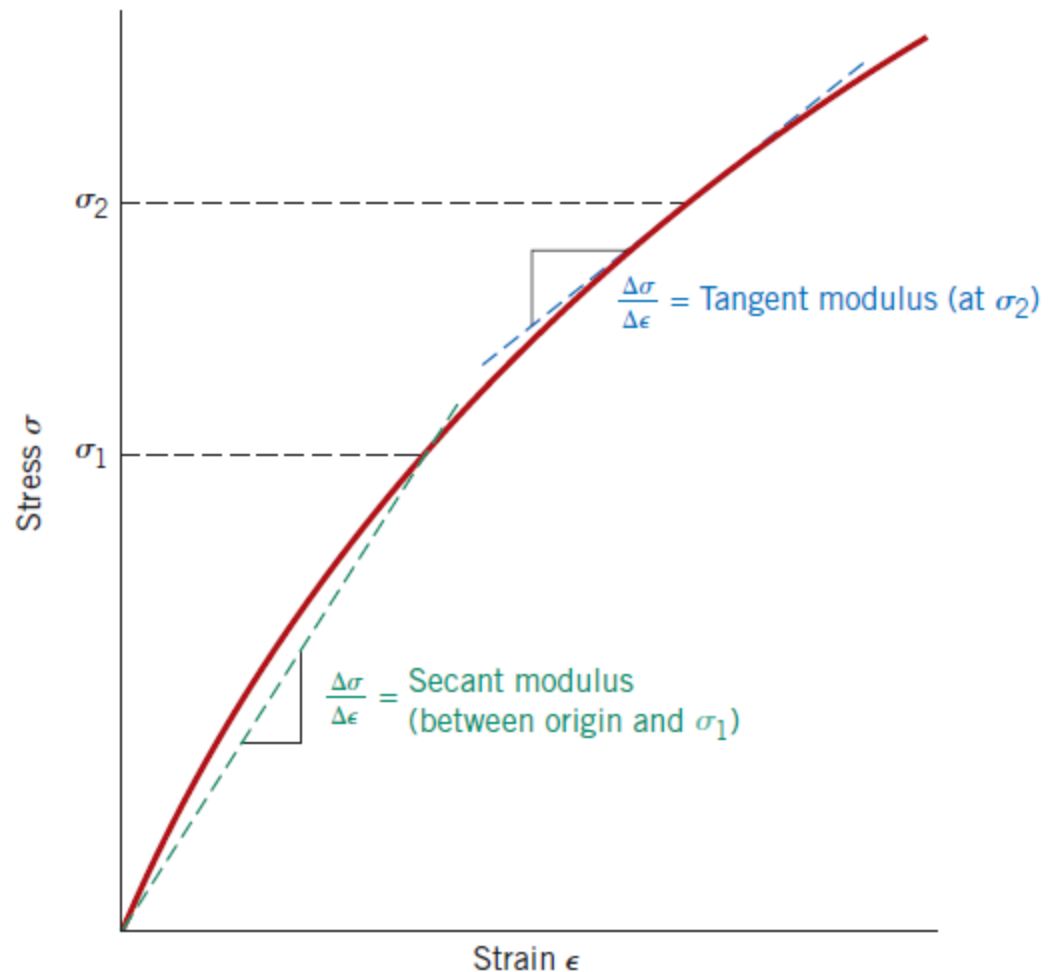
- E is **Young's modulus or modulus of elasticity**, has the same units as  $\sigma$ , N/m<sup>2</sup> or Pa

Higher E → higher “stiffness”



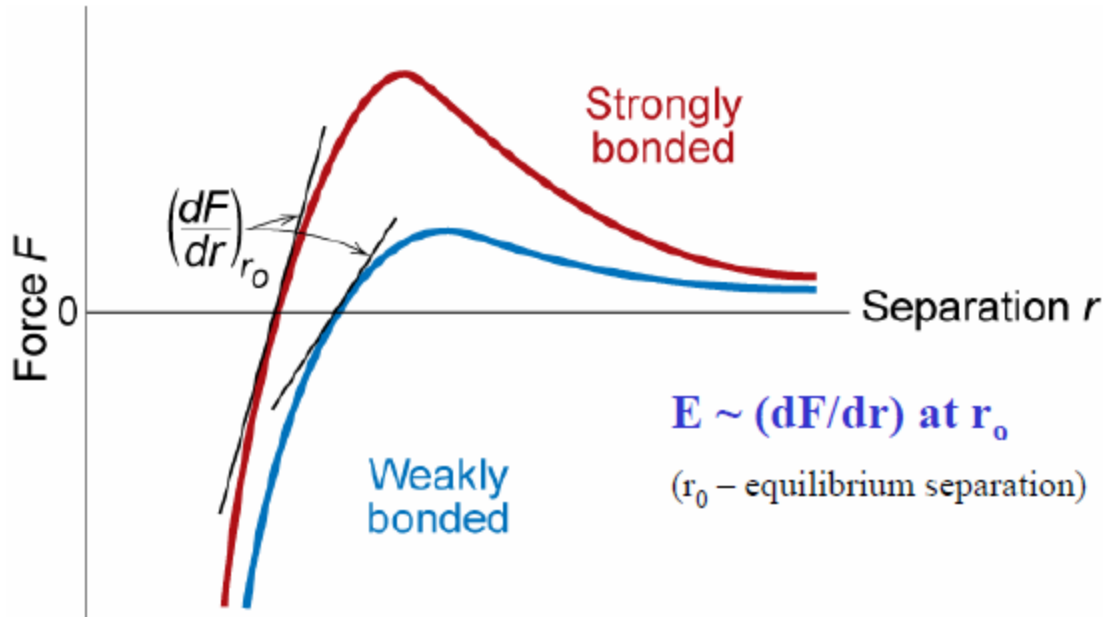
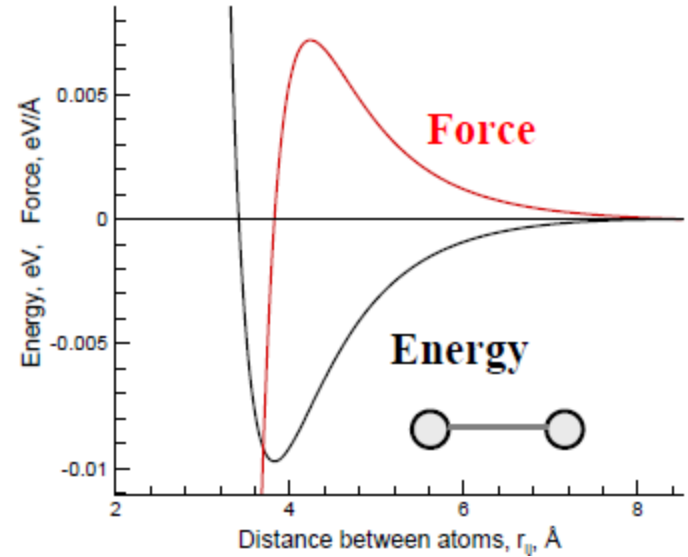
# Elastic Deformation: Nonlinear Elastic Behavior

- In some materials (many polymers, concrete...), elastic deformation is not linear, but it is still reversible.



# Elastic Deformation: Atomic scale picture

Chapter 2:  
force-separation  
curve for  
interacting atoms



# Elastic Deformation: Anelasticity

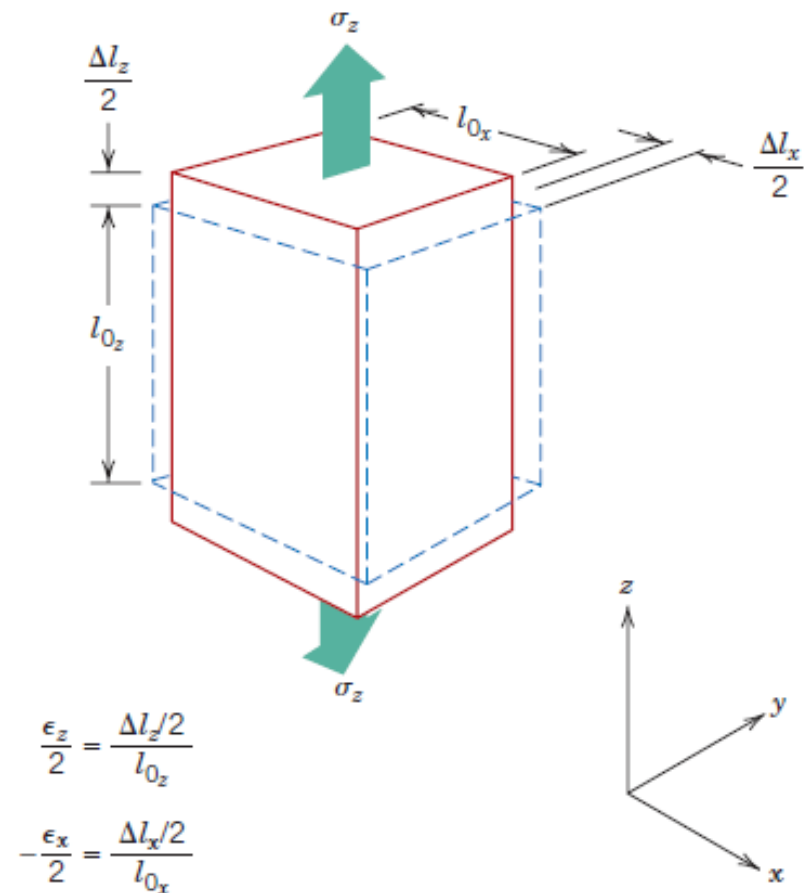
## (time dependence of elastic deformation)

- So far we have assumed that elastic deformation is time independent (i.e. applied stress produces instantaneous elastic strain)
- However, in reality elastic deformation takes time (finite rate of atomic/molecular deformation processes) - continues after initial loading, and after load release. This time dependent elastic behavior is known as **anelasticity**.
- The effect is normally small for metals but can be significant for polymers (“visco-elastic behavior”).

# Elastic Deformation: Poisson's ratio

$$\nu = -\frac{\epsilon_x}{\epsilon_z} = -\frac{\epsilon_y}{\epsilon_z}$$

- Materials subject to tension shrink laterally. Those subject to compression, bulge. The ratio of lateral and axial strains is called the **Poisson's ratio  $\nu$** . Sign in the above equations shows that lateral strain is in opposite sense to longitudinal strain
- $\nu$  is dimensionless
- Theoretical value for : isotropic material: 0.25
- Maximum value: 0.50,
- Typical value: 0.24 - 0.30



# Elastic Deformation: Shear Modulus

- Relationship of shear stress to shear strain:

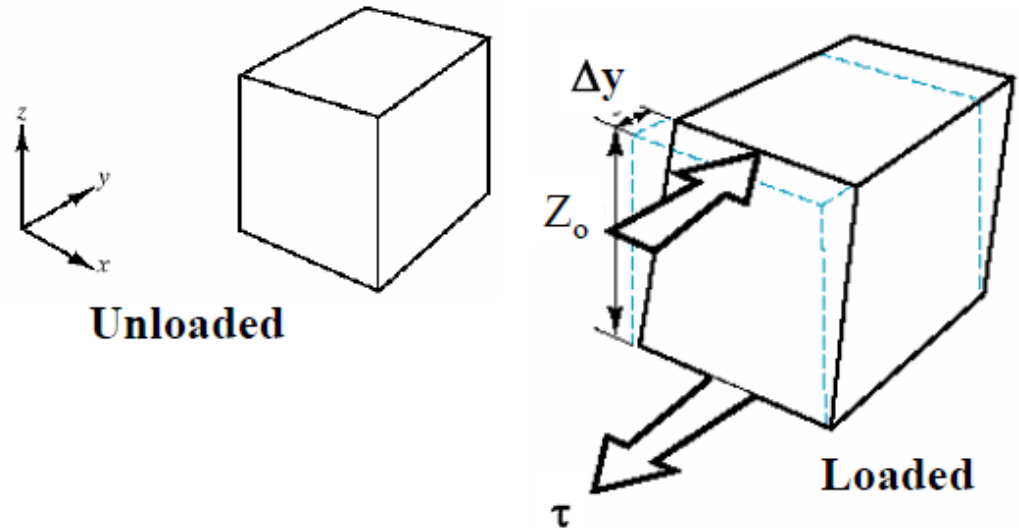
$$\tau = G \gamma; \quad \text{Where } \gamma = \tan \theta = \Delta y / Z_0$$

- **G is Shear Modulus (Units: N/m<sup>2</sup> or Pa)**

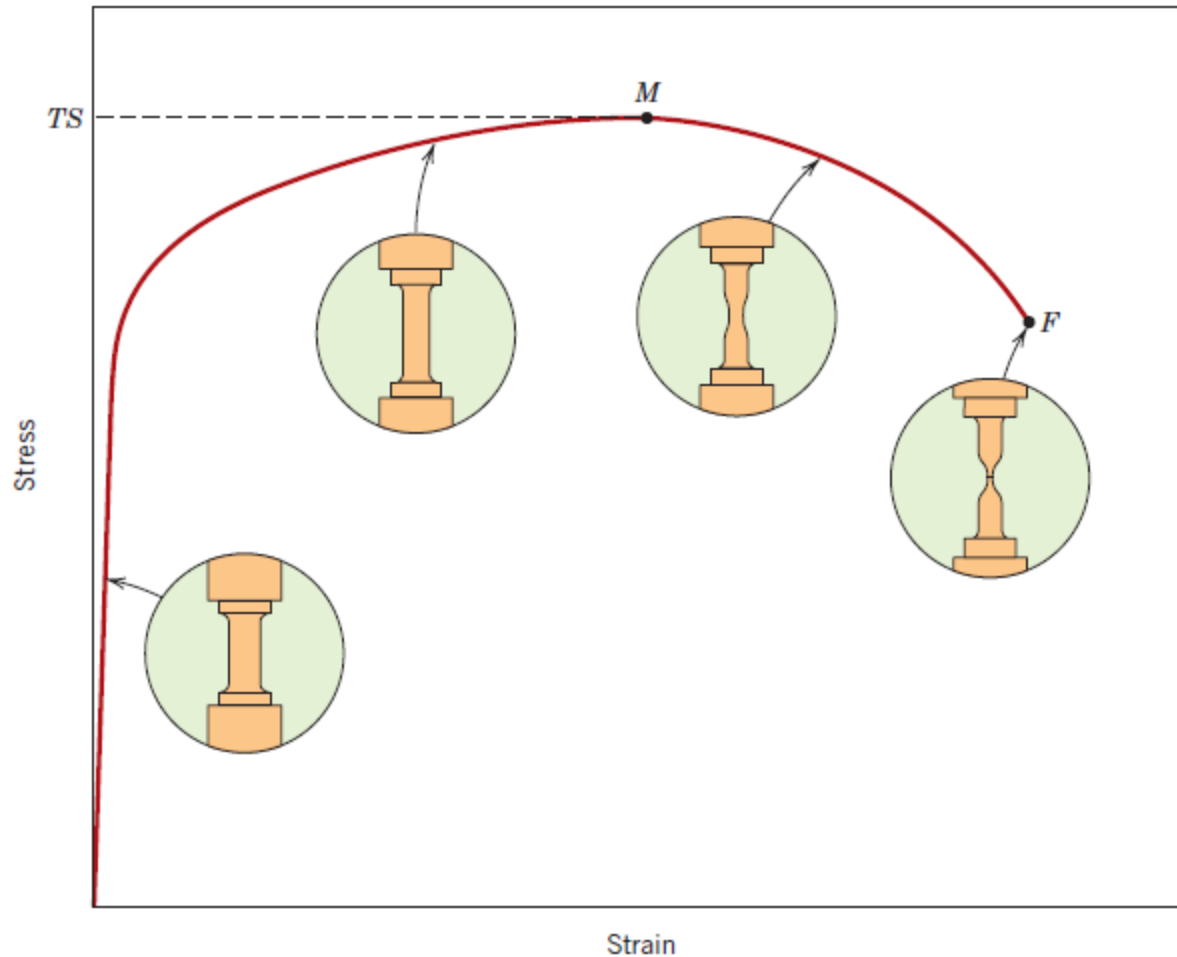
- For isotropic material:

$$E = 2G(1+\nu) \rightarrow G \sim 0.4E$$

- (Note: single crystals are usually elastically anisotropic: the elastic behavior varies with crystallographic direction, see Chapter 3)



# Stress-Strain Behavior: Plastic deformation



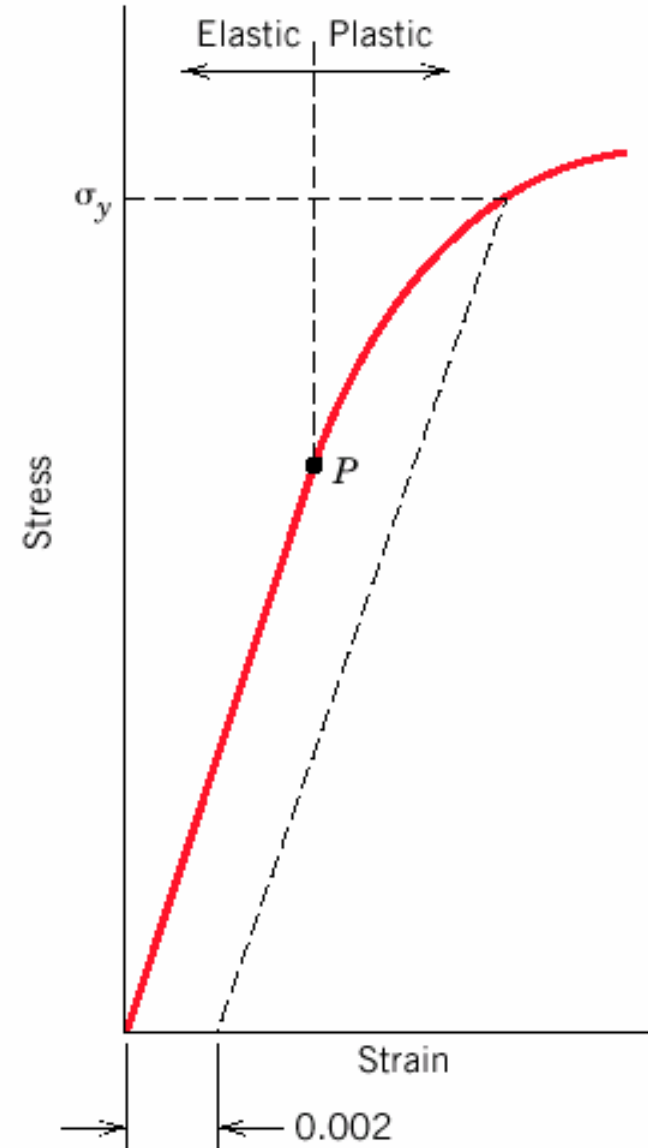


# Plastic deformation

- stress and strain are not proportional to each other.
- the deformation is not reversible.
- deformation occurs by breaking and re-arrangement of atomic bonds (in crystalline materials primarily by motion of dislocations, Chapter 7)

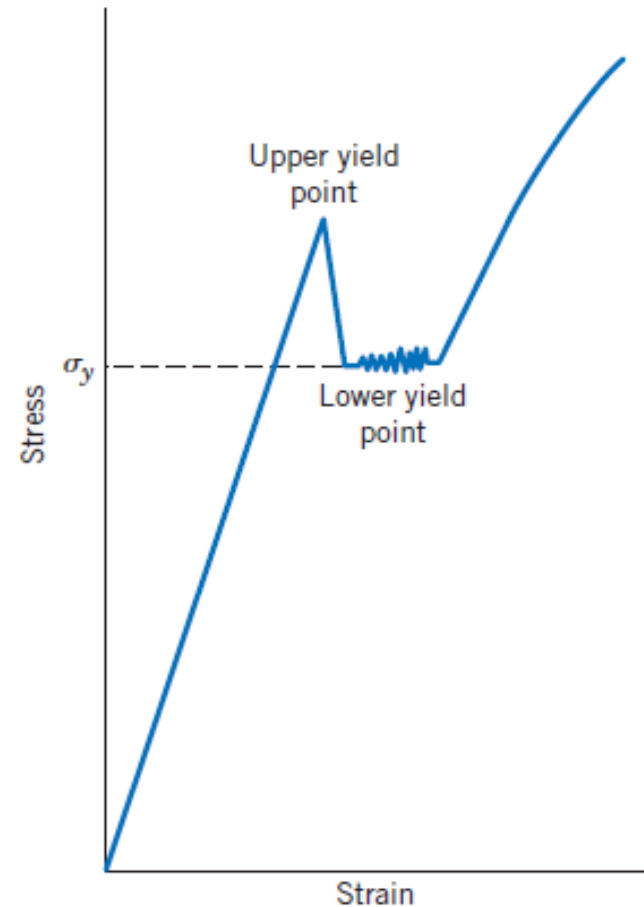
# Tensile Properties: Yielding

- Yield strength  $\sigma_y$  - is chosen as that causing a permanent strain of 0.002
- Yield point P - the strain deviates from being proportional to the stress (the proportional limit)
- The yield stress is a measure of resistance to plastic deformation



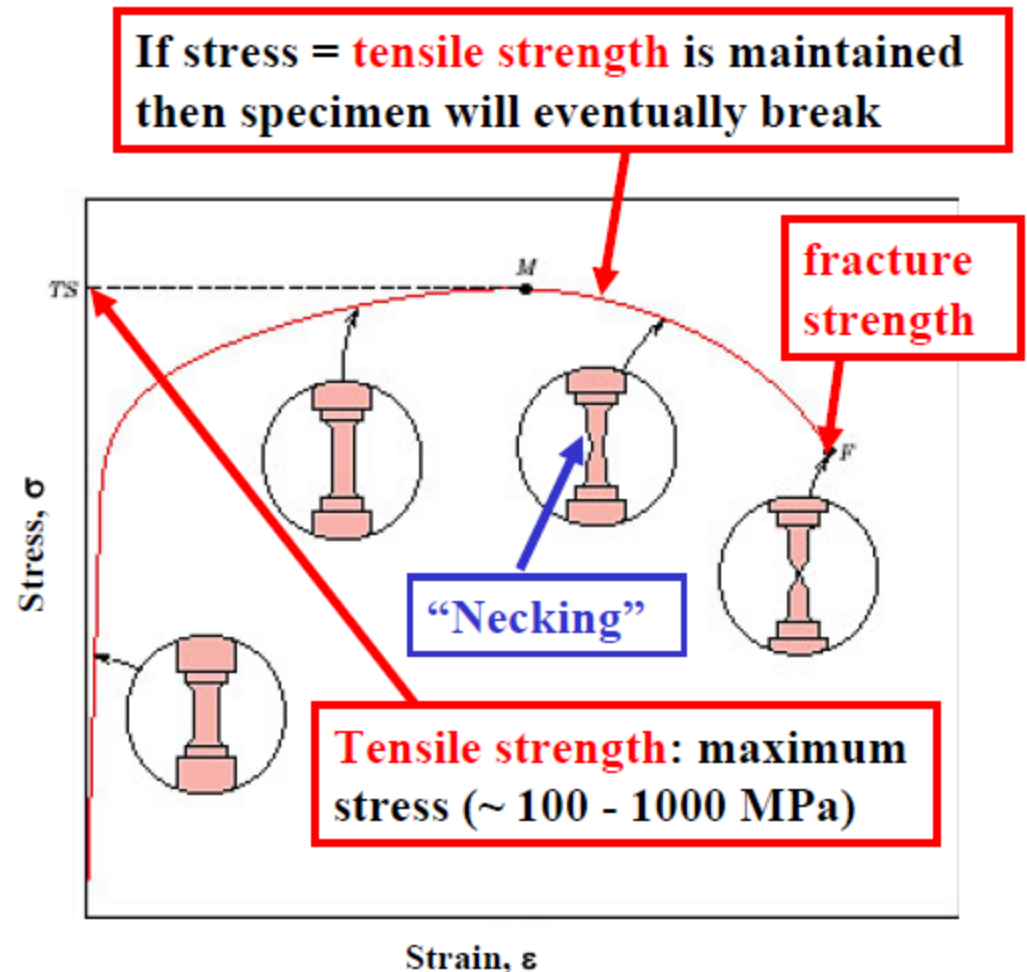
# Tensile Properties: Yielding

- In some materials (e.g. low-carbon steel), the stress vs. strain curve includes two yield points (upper and lower). **The yield strength is defined in this case as the average stress at the lower yield point.**



# Tensile Strength

- For structural applications, the yield stress is usually a more important property than the tensile strength, since once the yield stress has passed, the structure has deformed beyond acceptable limits.

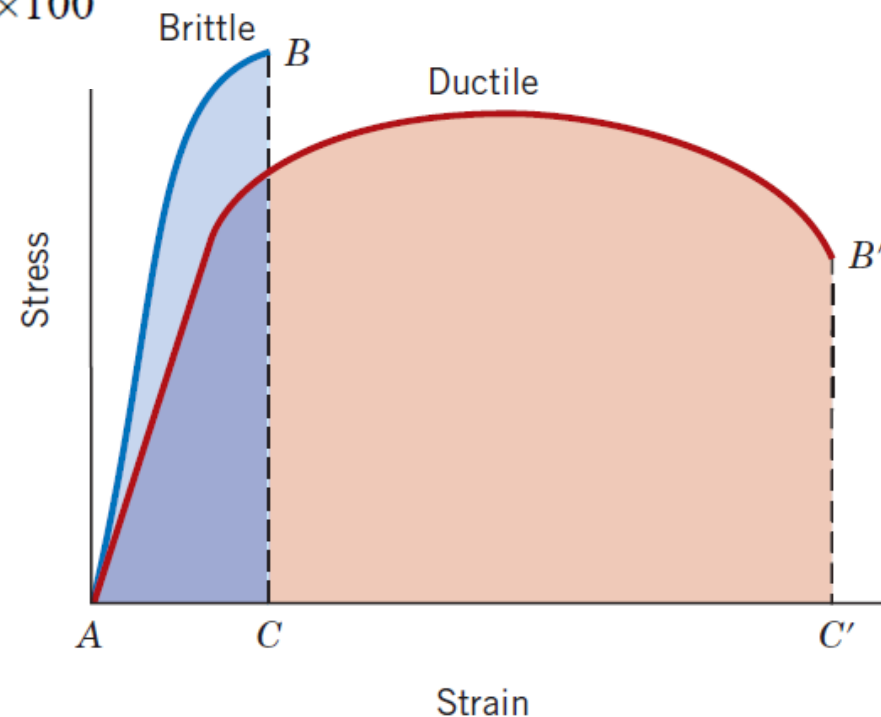
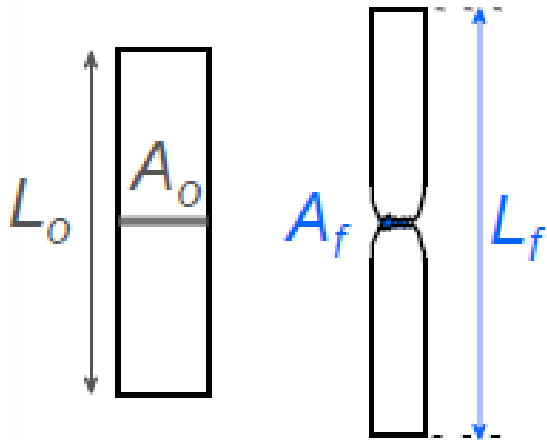


# Tensile properties: Ductility

- **Ductility** is a measure of the deformation at fracture.

Defined by **percent elongation**  $\%EL = \left( \frac{l_f - l_0}{l_0} \right) \times 100$   
(plastic tensile strain at failure)

or **percent reduction in area**  $\%RA = \left( \frac{A_0 - A_f}{A_0} \right) \times 100$



# Typical mechanical properties of metals

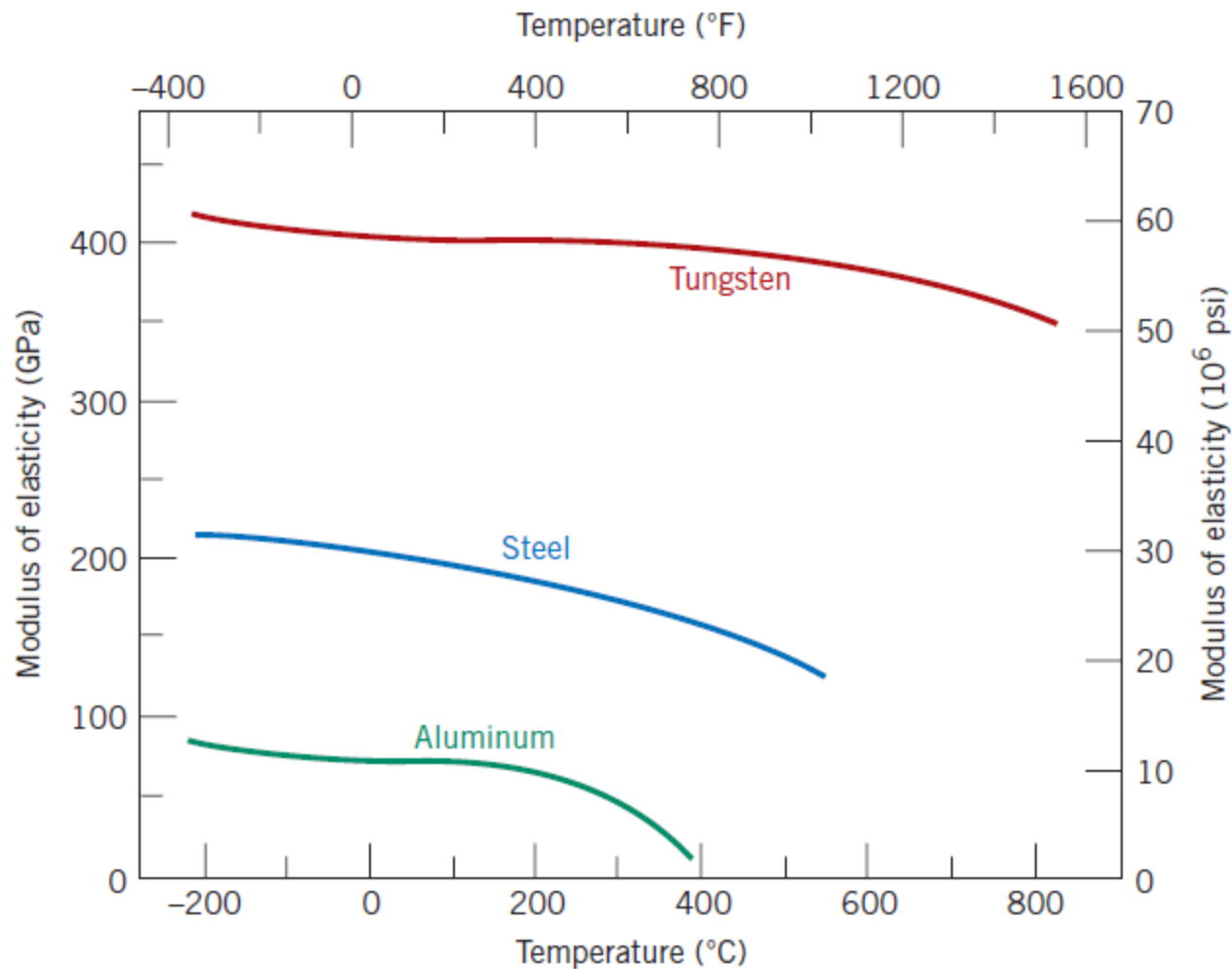
**Table 6.2** Typical Mechanical Properties of Several Metals and Alloys in an Annealed State

<i>Metal Alloy</i>	<i>Yield Strength MPa (ksi)</i>	<i>Tensile Strength MPa (ksi)</i>	<i>Ductility, %EL [in 50 mm (2 in.)]</i>
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

# Typical mechanical properties of metals

- The yield strength and tensile strength vary with prior thermal and mechanical treatment, impurity levels, etc. This variability is related to the behavior of dislocations in the material, Chapter 7. But elastic moduli are relatively insensitive to these effects.
- The yield and tensile strengths and modulus of elasticity decrease with increasing temperature, ductility increases with temperature.

# Typical mechanical properties of metals

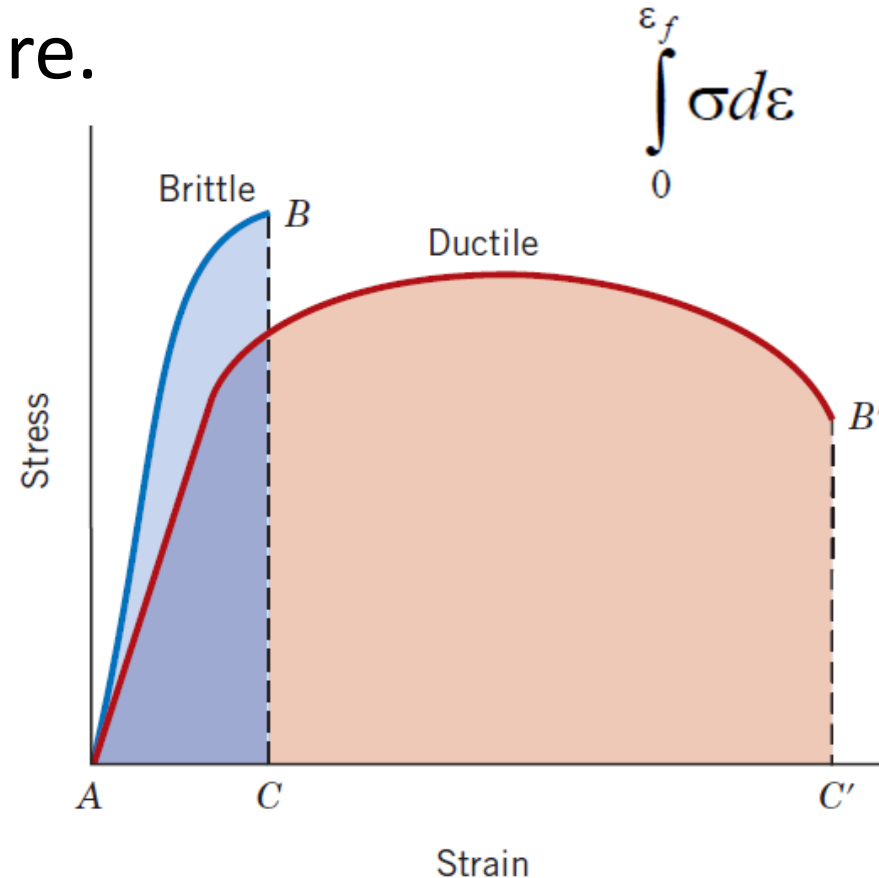




# Toughness

- **Toughness = the ability to absorb energy up to fracture = the total area under the strain-stress curve up to fracture.**

Units: the energy per unit volume, e.g. J/m<sup>3</sup>  
Can be measured by an impact test (Chapter 8).



# True Stress and Strain

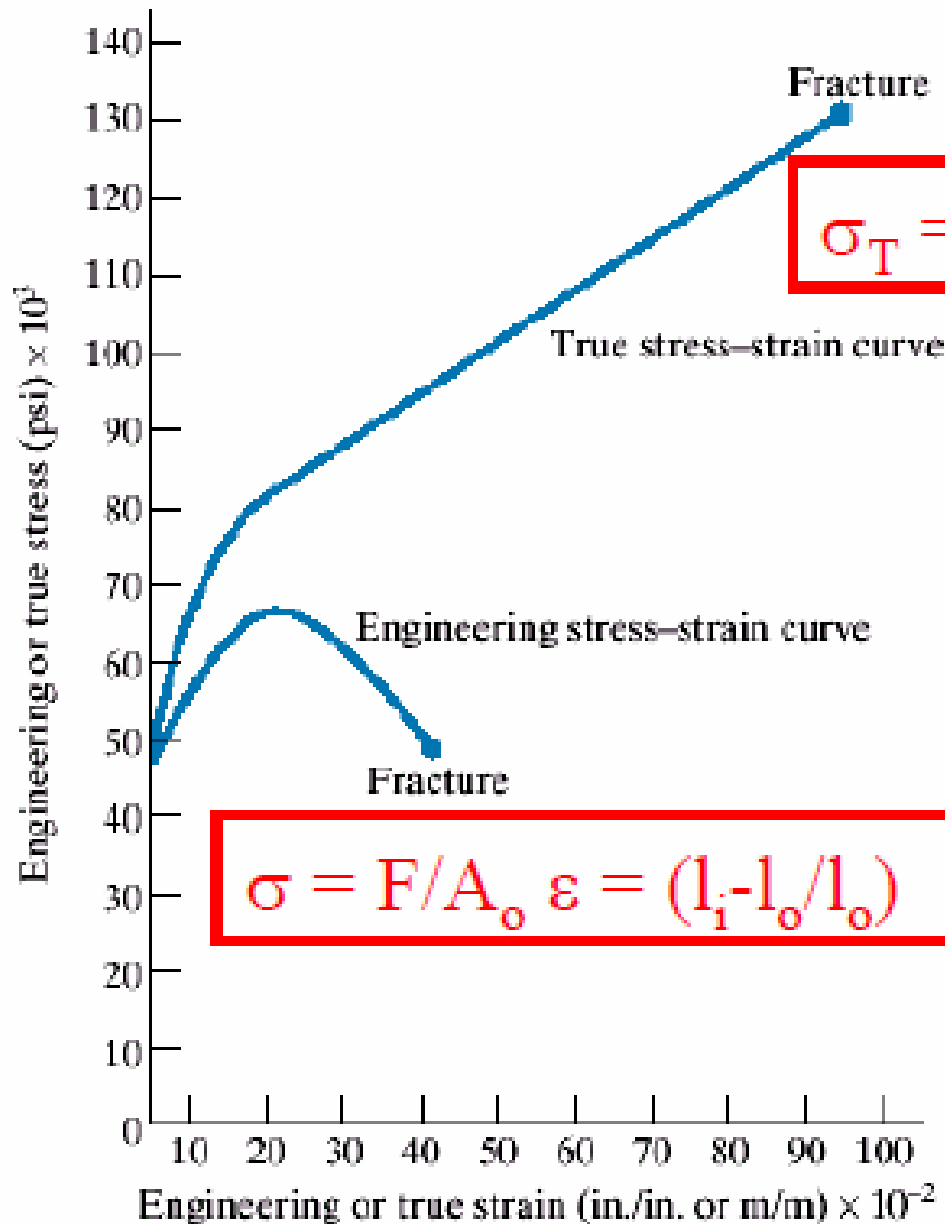
- **True stress = load divided by actual area in the necked-down region ( $A_i$ ):**

$$\sigma_T = F/A_i$$

- Sometimes it is convenient to use **true strain defined as**

$$\varepsilon_T = \ln(l_i/l_o)$$

- **True stress continues to rise to the point of fracture, in contrast to the engineering stress.**



$$\sigma_T = F/A_i \quad \varepsilon_T = \ln(l_i/l_o)$$

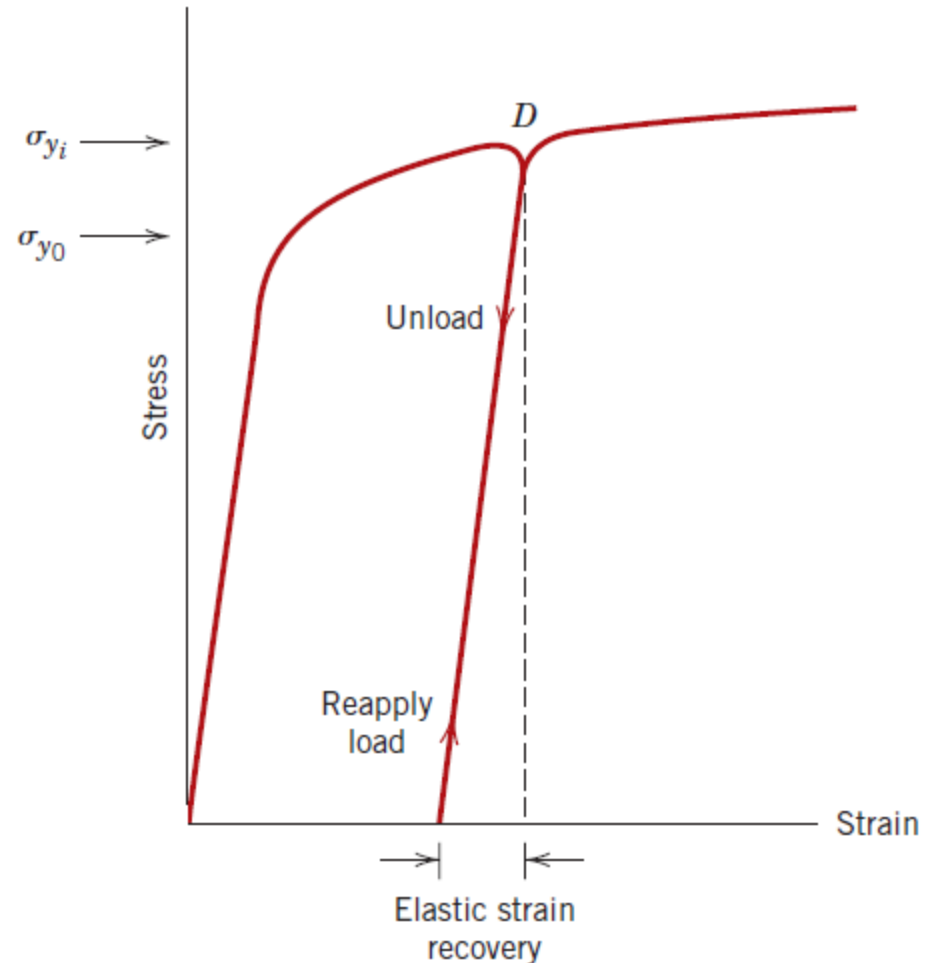
If no volume change occurs during deformation,  $A_i l_i = A_o l_o$  and the true and engineering stress and strain are related as

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

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

# Elastic Recovery During Plastic Deformation

- If a material is deformed plastically and the stress is then released, the material ends up with a permanent strain.
- If the stress is reapplied, the material again responds elastically at the beginning up to a new yield point that is higher than the original yield point.
- The amount of elastic strain that it will take before reaching the yield point is called **elastic strain recovery**.



# Hardness

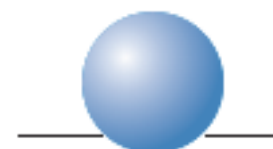
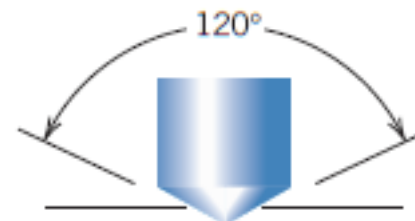
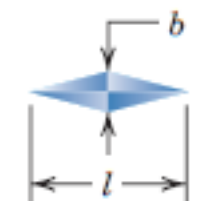
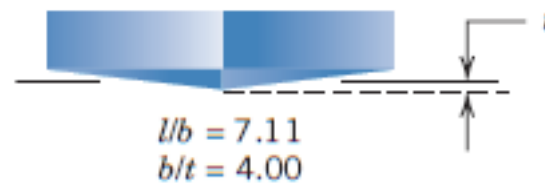
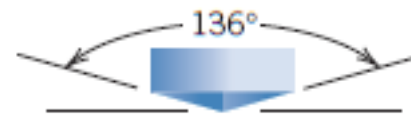
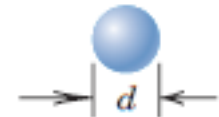
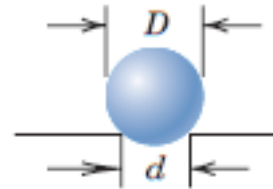
- **Hardness is a measure of the material's resistance to localized plastic deformation (e.g. dent or scratch).**
- A qualitative Moh's scale, determined by the ability of a material to scratch another material: from 1 (softest = talc) to 10 (hardest = diamond).

- Different types of quantitative hardness test has been designed (Rockwell, Brinell, Vickers, etc.).
- Usually a small indenter (sphere, cone, or pyramid) is forced into the surface of a material under conditions of controlled magnitude and rate of loading. The depth or size of indentation is measured.
- The tests somewhat approximate, but popular because they are easy and non-destructive (except for the small dent).

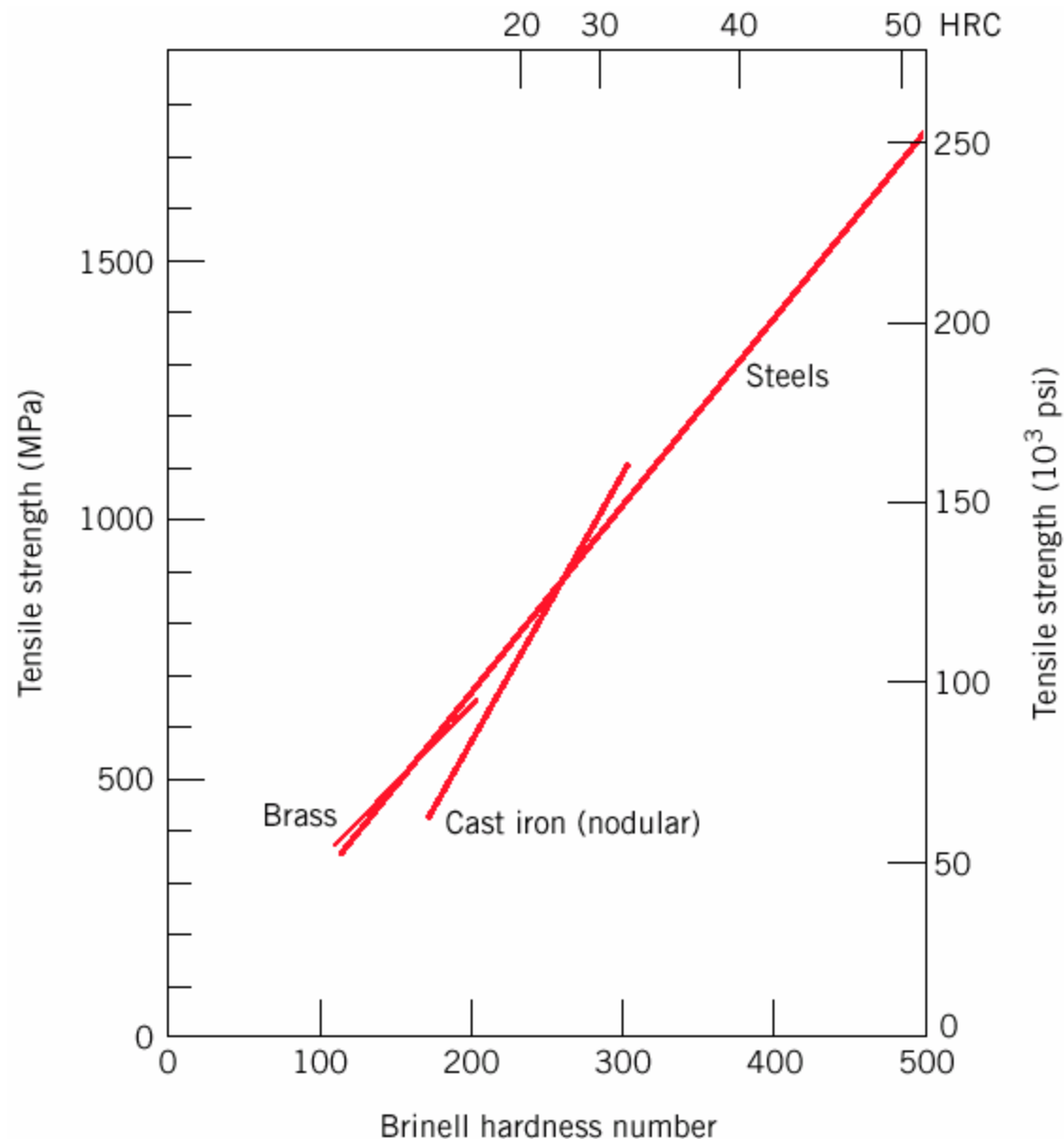
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*Shape of Indentation*

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*Side View**Top View*

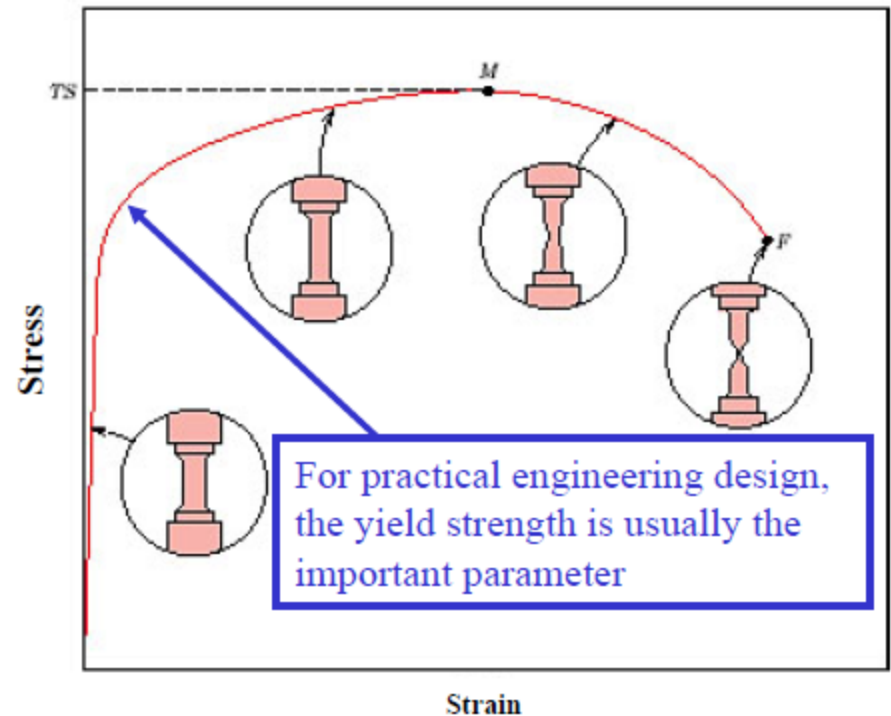
- Both tensile strength and hardness may be regarded as degree of resistance to plastic deformation.
- **Hardness is proportional to the tensile strength – but** note that the proportionality constant is different for different materials.





# What are the limits of “safe” deformation?

- **Design stress:**  $\sigma_d = N' \sigma_c$  where  $\sigma_c =$  maximum anticipated stress,  $N'$  is the “design factor”  $> 1$ . Want to make sure that  $\sigma_d < \sigma_y$
- **Safe or working stress:**  
 $\sigma_w = \sigma_y / N$  where  $N$  is “factor of safety”  $> 1$ .



# Summary

- **Stress and strain: Size-independent measures of load** and displacement, respectively.
- **Elastic behavior: Reversible mechanical deformation**, often shows a linear relation between stress and strain.
- Elastic deformation is characterized by **elastic moduli** ( $E$  or  $G$ ).  
*To minimize deformation, select a material with a large elastic moduli ( $E$  or  $G$ ).*
- **Plastic behavior: Permanent deformation, occurs** when the tensile (or compressive) uniaxial stress reaches the **yield strength**  $\sigma_y$ .
- **Tensile strength: maximum stress supported by the** material.
- **Toughness: The energy needed to break a unit** volume of material.
- **Ductility: The plastic strain at failure.**

## Summary

Make sure you understand language and concepts:

- Anelasticity
- Ductility
- Elastic deformation
- Elastic recovery
- Engineering strain and stress
- Engineering stress
- Hardness
- Modulus of elasticity
- Plastic deformation
- Poisson's ratio
- Shear
- Tensile strength
- True strain and stress
- Toughness
- Yielding
- Yield strength