Chapter Outline

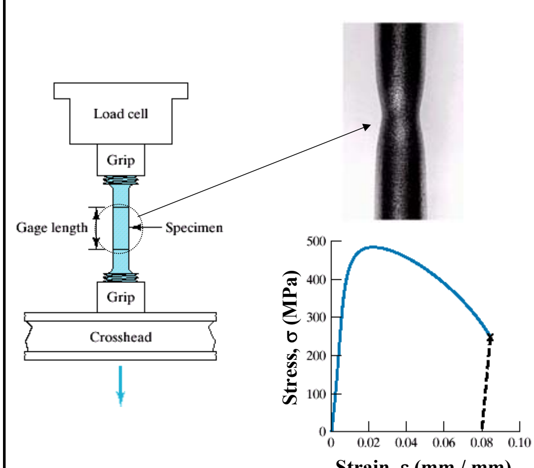
Mechanical Properties of Metals

How do metals respond to external loads?

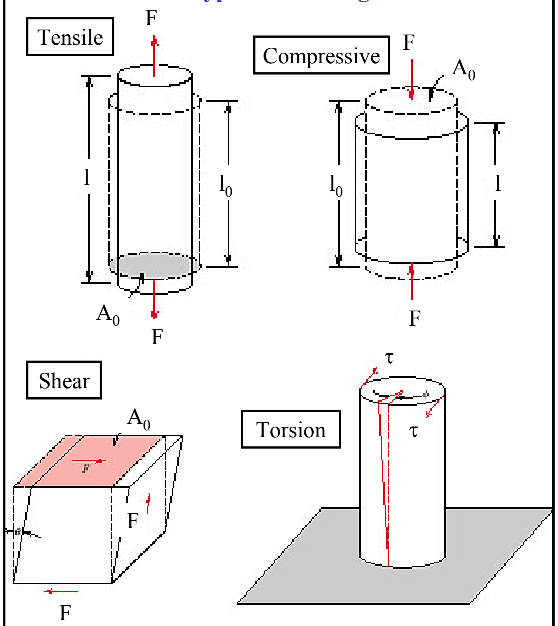
- **Stress and Strain**
  - Tension
  - Compression
  - Shear
  - Torsion
- **Elastic deformation**
- **Plastic Deformation**
  - Yield Strength
  - Tensile Strength
  - Ductility
  - Toughness
  - Hardness

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



Concepts of Stress and Strain (tension and compression)

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

Engineering stress: $\sigma = F / A_o$

F is load applied perpendicular to specimen cross-section; A_0 is cross-sectional area (perpendicular to the force) **before** application of the load.

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

Δl is change in length, l_o is the original length.

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 and torsion)

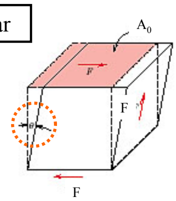
Shear stress: $\tau = F / A_o$

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

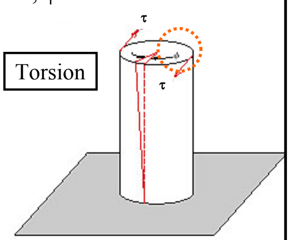
Shear strain: $\gamma = \tan\theta$ (× 100 %) θ is the strain angle

Torsion is variation of pure shear. A shear stress in this case is a function of applied torque T, shear strain is related to the angle of twist, ϕ.

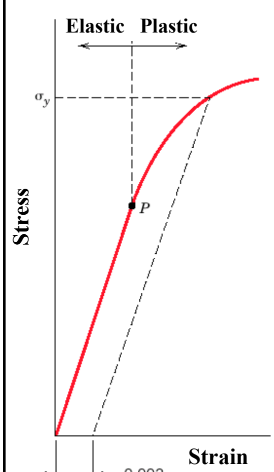
Shear



Torsion



Stress-Strain Behavior



Elastic deformation

Reversible: when the stress is removed, the material returns to the dimension it had before the loading.

Usually strains are small (except for the case of plastics).

Plastic deformation

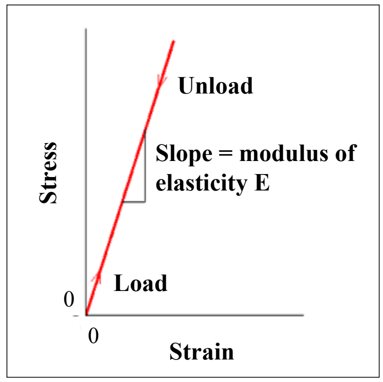
Irreversible: when the stress is removed, the material does not return to its previous dimension.

Stress-Strain Behavior: Elastic deformation

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

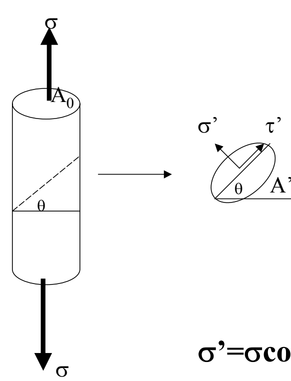
$$\sigma = E\,\varepsilon$$

E is **Young's modulus** or **modulus of elasticity**, has the same units as σ, N/m^2 or Pa



Higher E → higher "stiffness"

Geometric Considerations of the Stress State

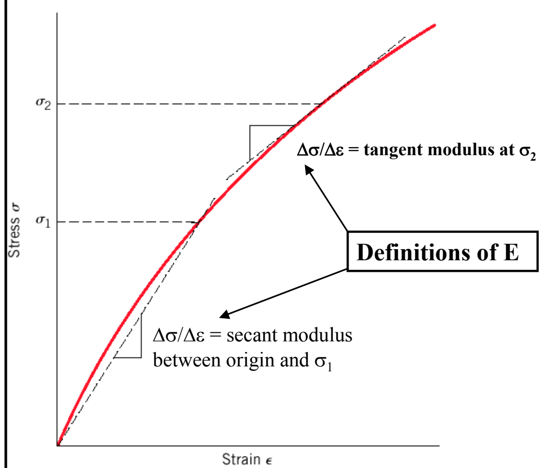


$$\sigma' = \sigma\cos^2\theta$$

$$\tau' = \sigma\sin\theta\cos\theta$$

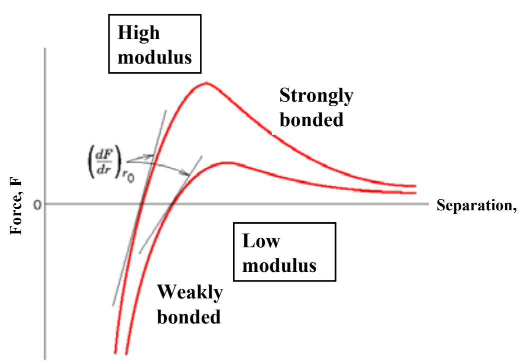
Elastic Deformation: Nonlinear elastic behavior

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



Elastic Deformation: Atomic scale picture

Chapter 2: the force-separation curve for interacting atoms



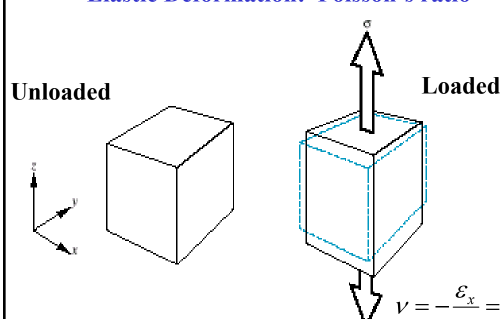
E ~ (dF/dr) at r_o

(r_0 – equilibrium separation)

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



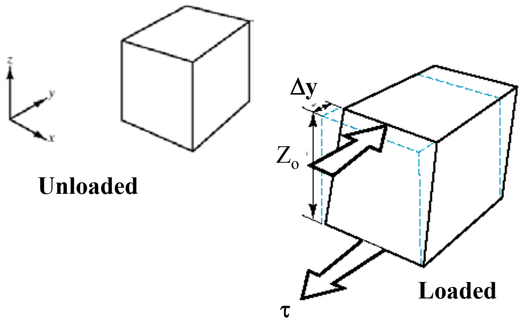
$$\nu = -\frac{\varepsilon_x}{\varepsilon_z} = -\frac{\varepsilon_y}{\varepsilon_z}$$

Materials subject to tension shrink laterally. Those subject to compression, bulge. The ratio of lateral and axial strains is called the Poisson's ratio υ.

υ is dimensionless, sign shows that lateral strain is in opposite sense to longitudinal strain

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:

$\tau = G\gamma$, where: $\gamma = \tan\theta = \Delta y / z_o$

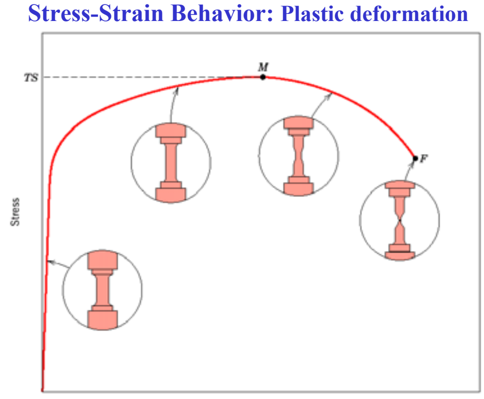
G is Shear Modulus (Units: N/m^2)

For isotropic material:

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

(Note: most materials are elastically anisotropic: the elastic behavior varies with crystallographic direction, see Chapter 3)

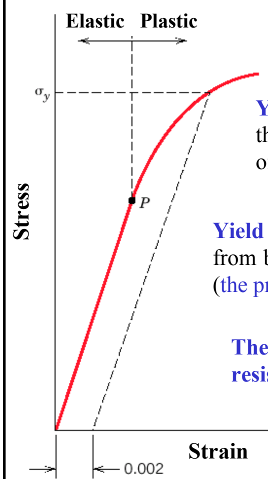
Stress-Strain Behavior: Plastic deformation



Plastic deformation:

- stress and strain are not proportional
- 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

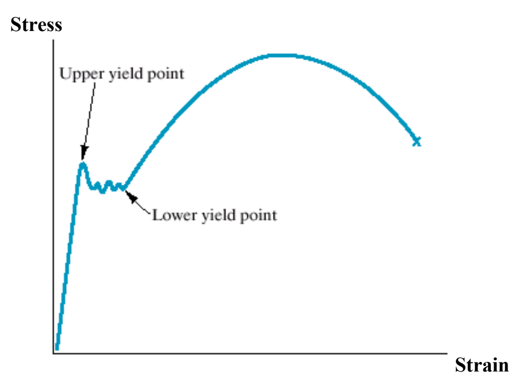


Yield strength σ_y - is chosen as that causing a permanent strain of 0.002

Yield point P - the strain deviates from being proportional to the stress (the proportional limit)

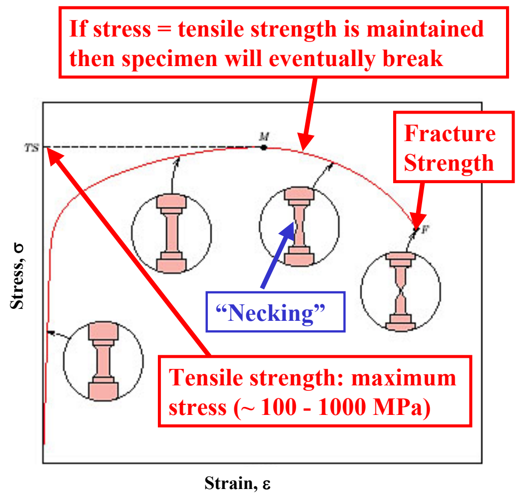
The yield stress is a measure of resistance to plastic deformation

Tensile properties: Yielding



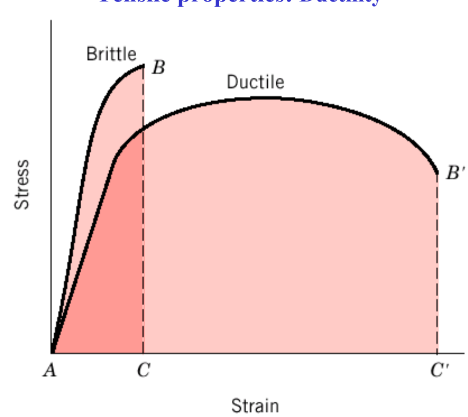
For a low-carbon steel, the stress vs. strain curve includes both an upper and lower yield point. The yield strength is defined in this case as the average stress at the lower yield point.

Tensile Strength



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

Tensile properties: Ductility



Ductility is a measure of the deformation at fracture

Defined by percent elongation → $$\%EL = \left(\frac{l_f - l_0}{l_0}\right) \times 100$$

or

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

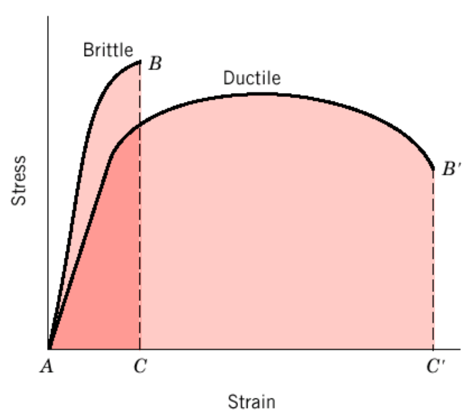
Typical mechanical properties of metals

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

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.

Toughness

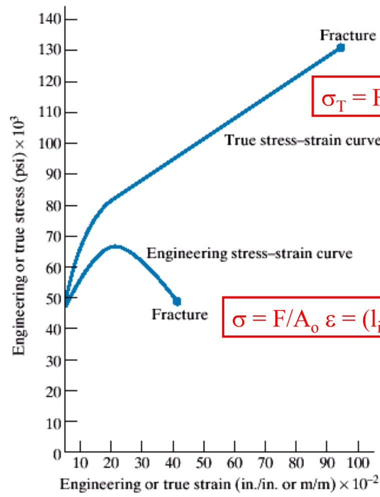


Toughness = the ability to absorb energy up to fracture = the total area under the strain-stress curve up to fracture

Units: the energy per unit volume, e.g. J/m^3

Can be measured by an impact test (Chapter 8).

True Stress and Strain

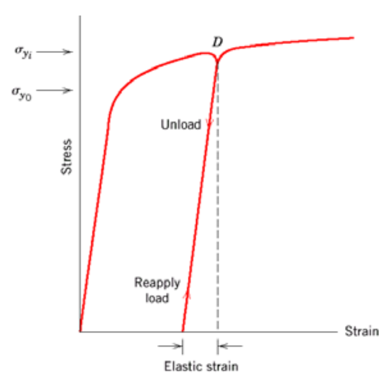


$\sigma_T = F/A_i \quad \varepsilon = \ln(l_i/l_o)$

$\sigma = F/A_o \quad \varepsilon = (l_i - l_o/l_o)$

True stress = load divided by **actual area** in the necked-down region, continues to rise to the point of fracture, in contrast to the engineering stress.

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.

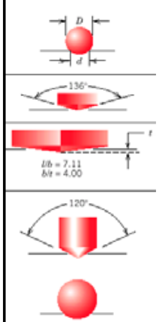
If the stress is reapplied, the material again responds elastically at the beginning up to a new yield point that is higher than the original yield point.

The amount of elastic strain that it will take before reaching the yield point is called **elastic strain recovery**.

Hardness (I)

Hardness is a measure of the material's resistance to localized plastic deformation (e.g. dent or scratch)

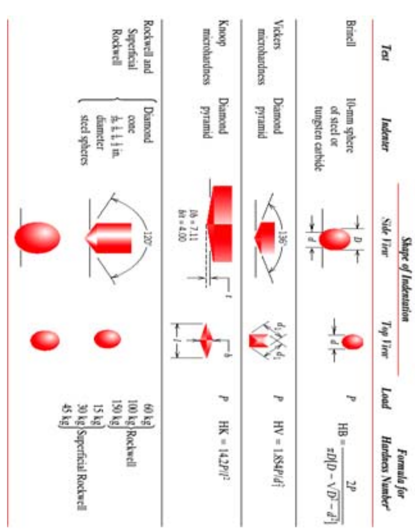
A qualitative Moh's scale, determined by the ability of a material to scratch another material: from 1 (softest = talc) to 10 (hardest = diamond).



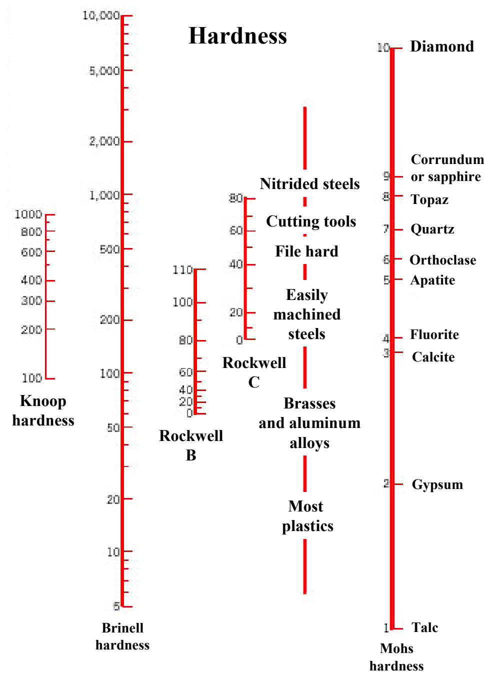
Different types of quantitative hardness test has been designed (Rockwell, Brinell, Vickers, etc.). Usually a small indenter (sphere, cone, or pyramid) is forced into the surface of a material under conditions of controlled magnitude and rate of loading. The depth or size of indentation is measured.

The tests somewhat approximate, but popular because they are easy and non-destructive (except for the small dent).

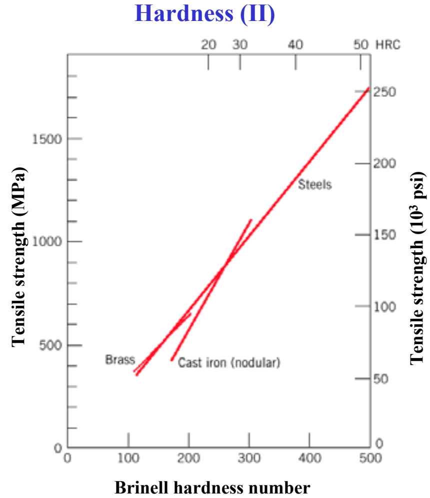
Hardness



Test	Indenter	Load	Formula for Hardness Number
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)	



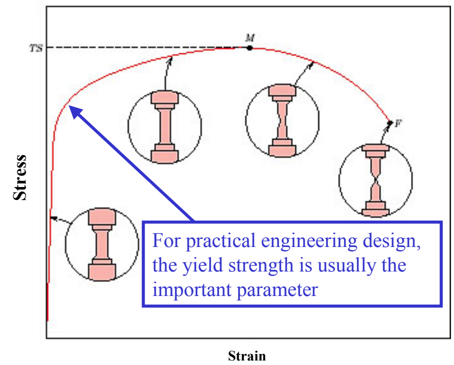
Hardness (II)



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 σ_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.

Take Home Messages

- Make sure you understand
  - Language: (Elastic, plastic, stress, strain, modulus, tension, compression, shear, torsion, anelasticity, yield strength, tensile strength, fracture strength, ductility, resilience, toughness, hardness)
  - Stress-strain relationships
  - Elastic constants: Young's modulus, shear modulus, Poisson ratio
  - Geometries: tension, compression, shear, torsion
  - Elastic vs. plastic deformation
  - Measures of deformation: yield strength, tensile strength, fracture strength, ductility, toughness, hardness