ME 254: Materials Engineering

Chapter 6: Mechanical Properties of Metals

1st Semester 1435-1436 (Fall 2014)

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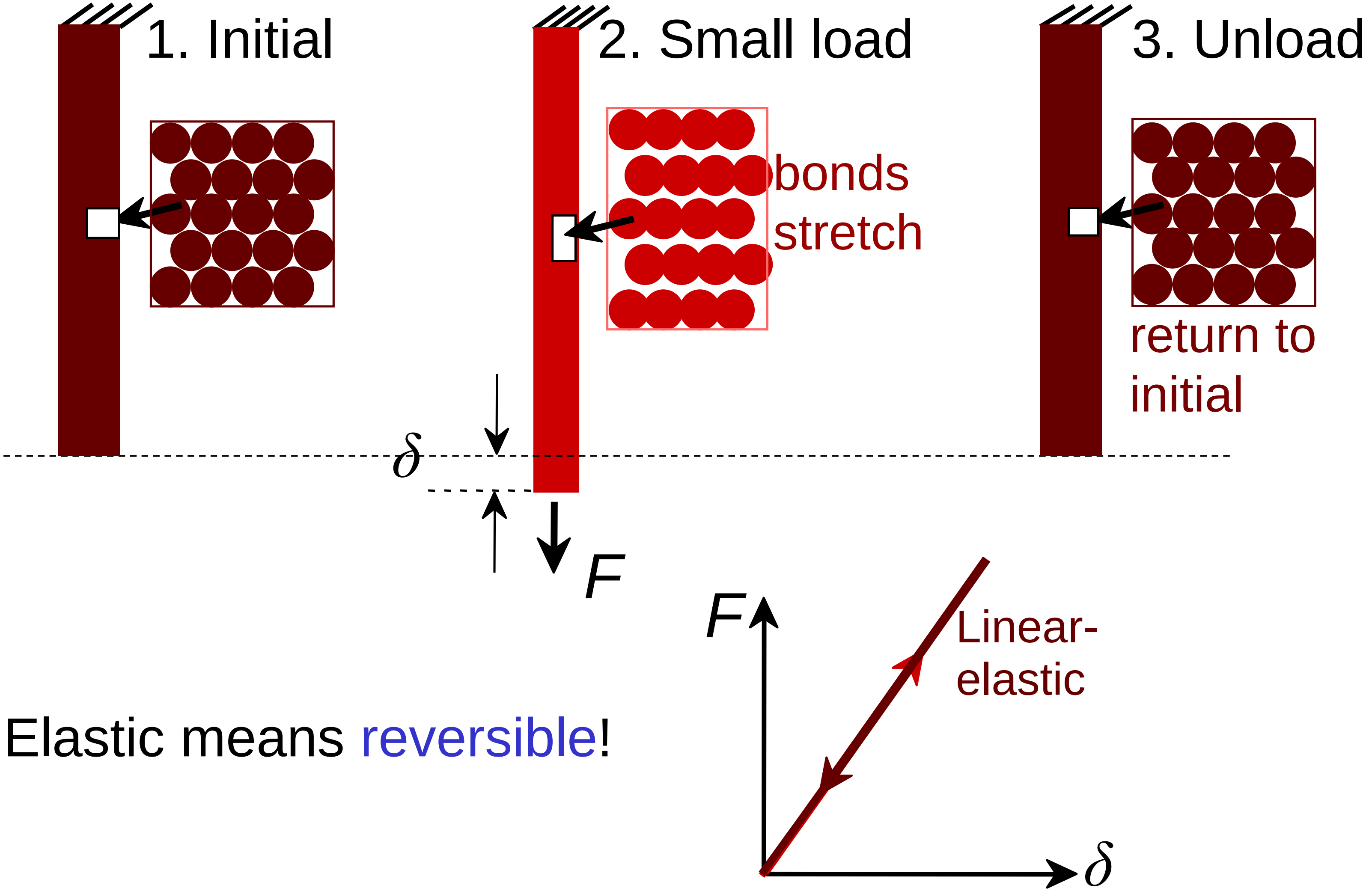
Mechanical Properties of Metals

ISSUES TO ADDRESS...

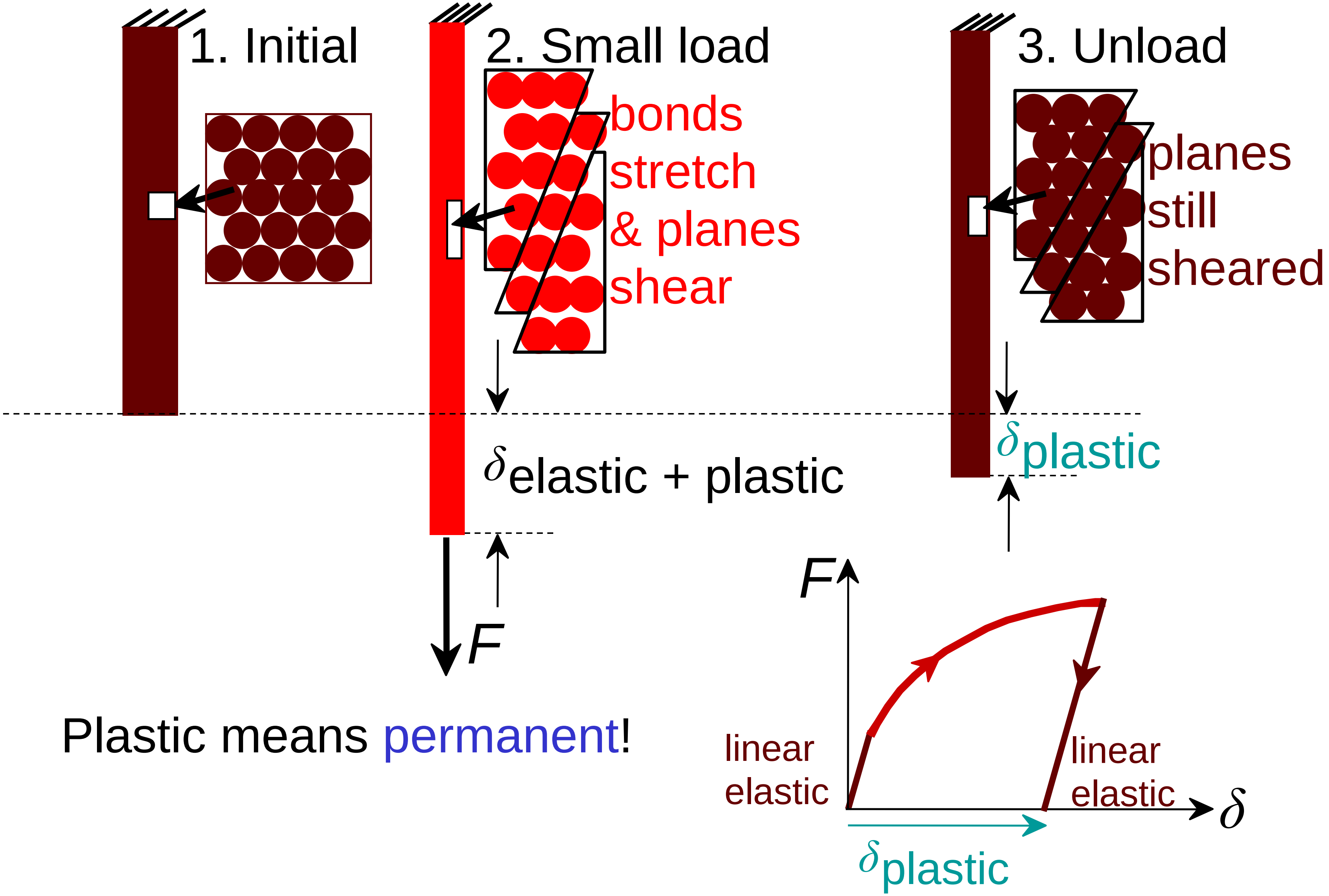
- Stress and strain: What are they and why are they used instead of load and deformation?
- Elastic behavior: When loads are small, how much deformation occurs? What materials deform least?
- Plastic behavior: At what point does permanent deformation occur? What materials are most resistant to permanent deformation?
- Toughness and ductility: What are they and how do we measure them?

Elastic Deformation



Elastic means reversible!

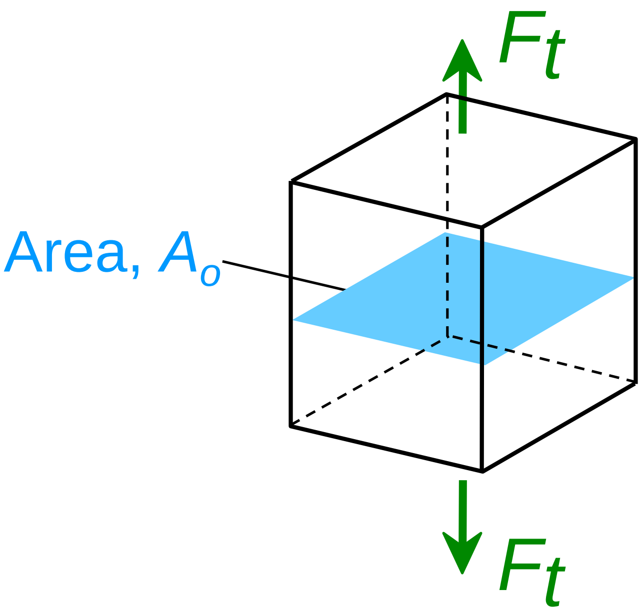
Plastic Deformation (Metals)



Plastic means permanent!

Engineering Stress

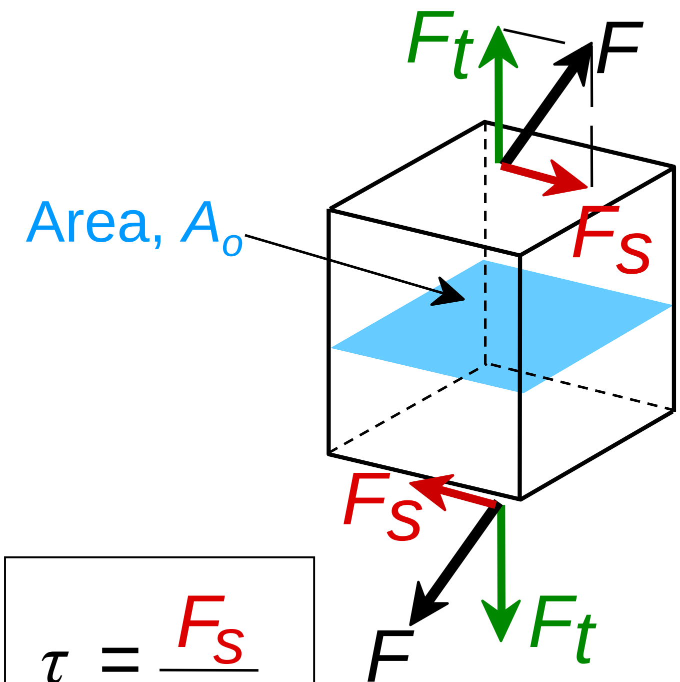
- **Tensile** stress, σ:



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

A_o: original cross-sectional area before loading

- **Shear** stress, τ:

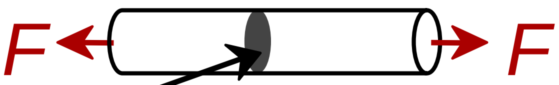


$$\tau = \frac{F_s}{A_o}$$

$\therefore$ Stress has units:
Pa = N/m^2

Common States of Stress

- **Simple tension: cable**

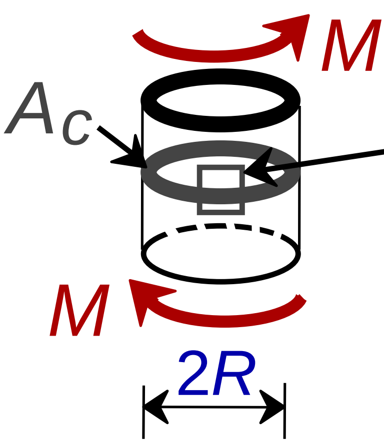


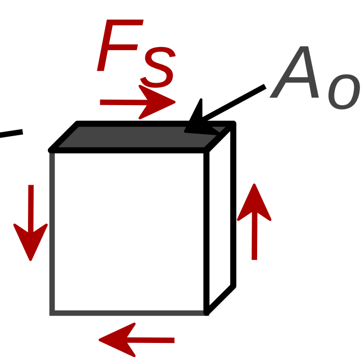
A_o = cross-sectional area (when unloaded)

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

- **Torsion (a form of shear):**

drive shaft

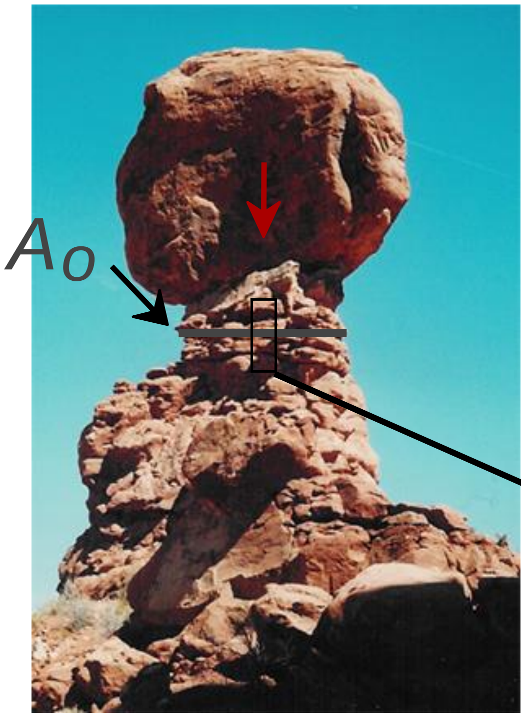




$$\tau = \frac{F_s}{A_o}$$

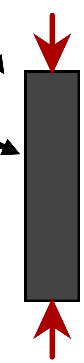
OTHER COMMON STRESS STATE

- **Simple compression:**



Balanced Rock, Arches National Park

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

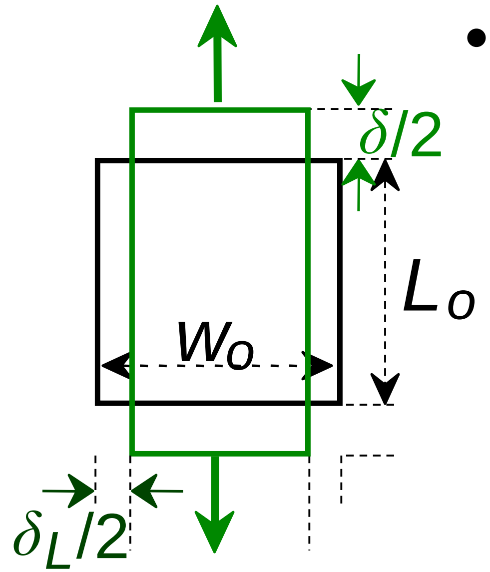


Note: compressive structure member ($\sigma < 0$ here).

Engineering Strain

- **Tensile strain:**

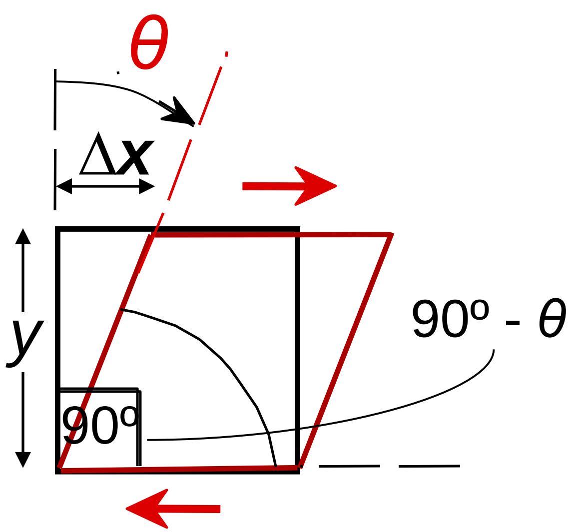
$$e = \frac{\delta}{L_o}$$



- **Lateral strain:**

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

- **Shear strain:**



$$\gamma = \Delta x / y = \tan \theta$$

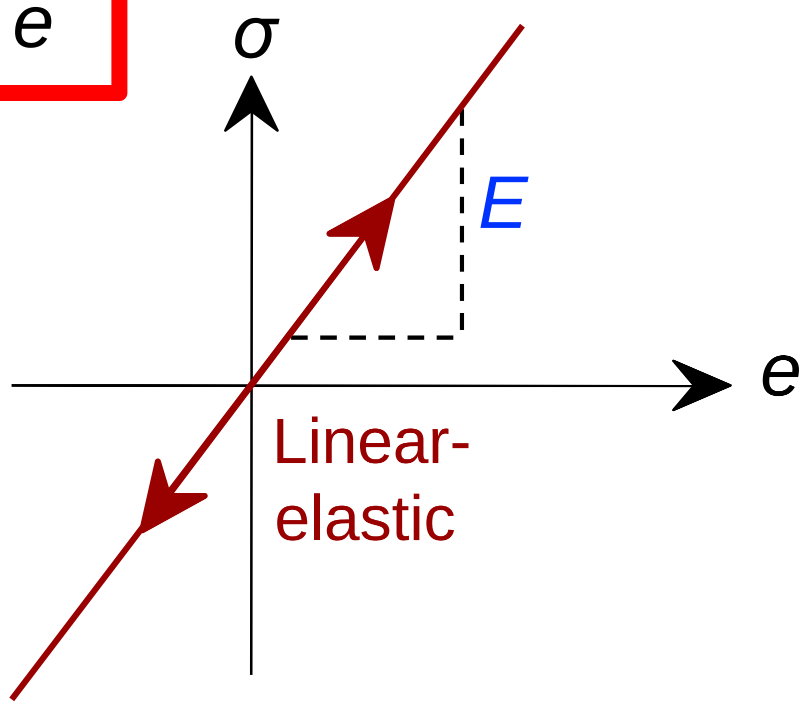
Strain is always dimensionless.

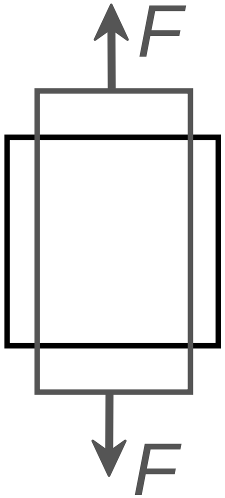
Linear Elastic Properties

- **Modulus of Elasticity, *E*:**
  (also known as Young's modulus)

- **Hooke's Law:**

$$\sigma = E\, e$$

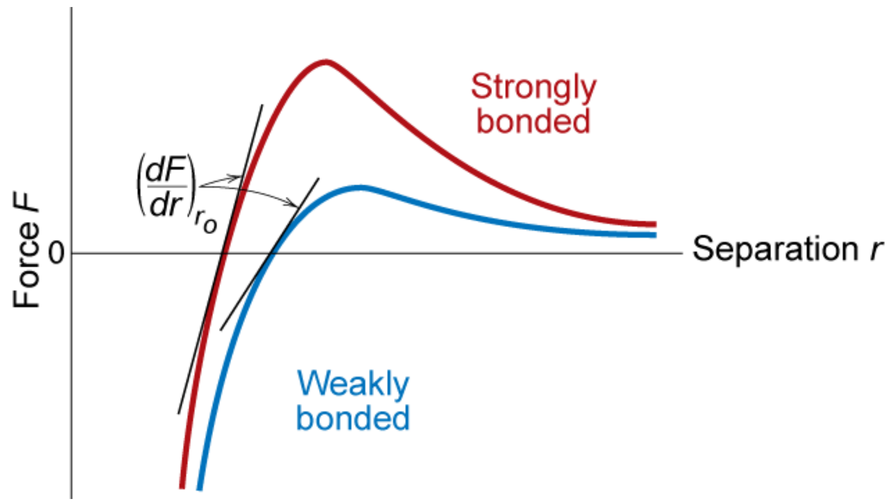




simple
tension
test

Mechanical Properties

Slope of stress strain plot (which is proportional to the elastic modulus) depends on bond strength of metal



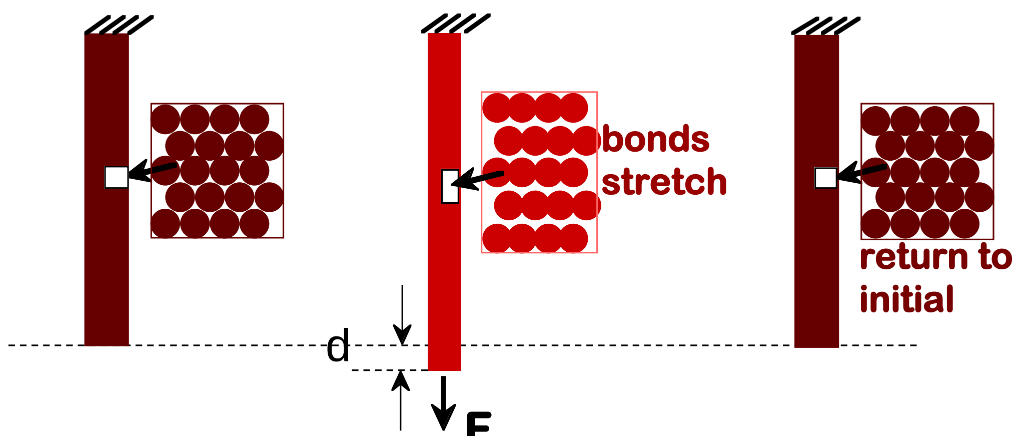
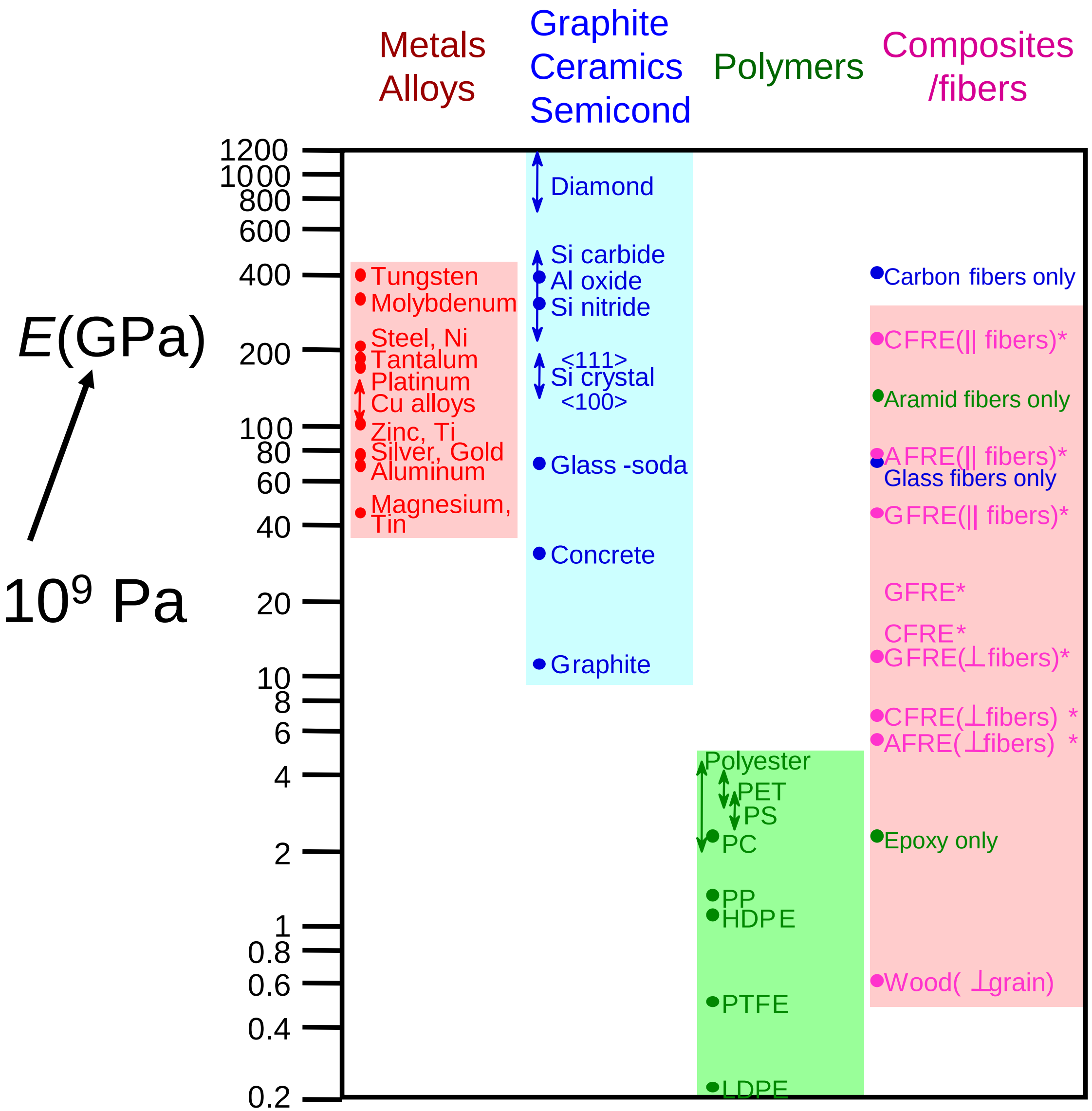
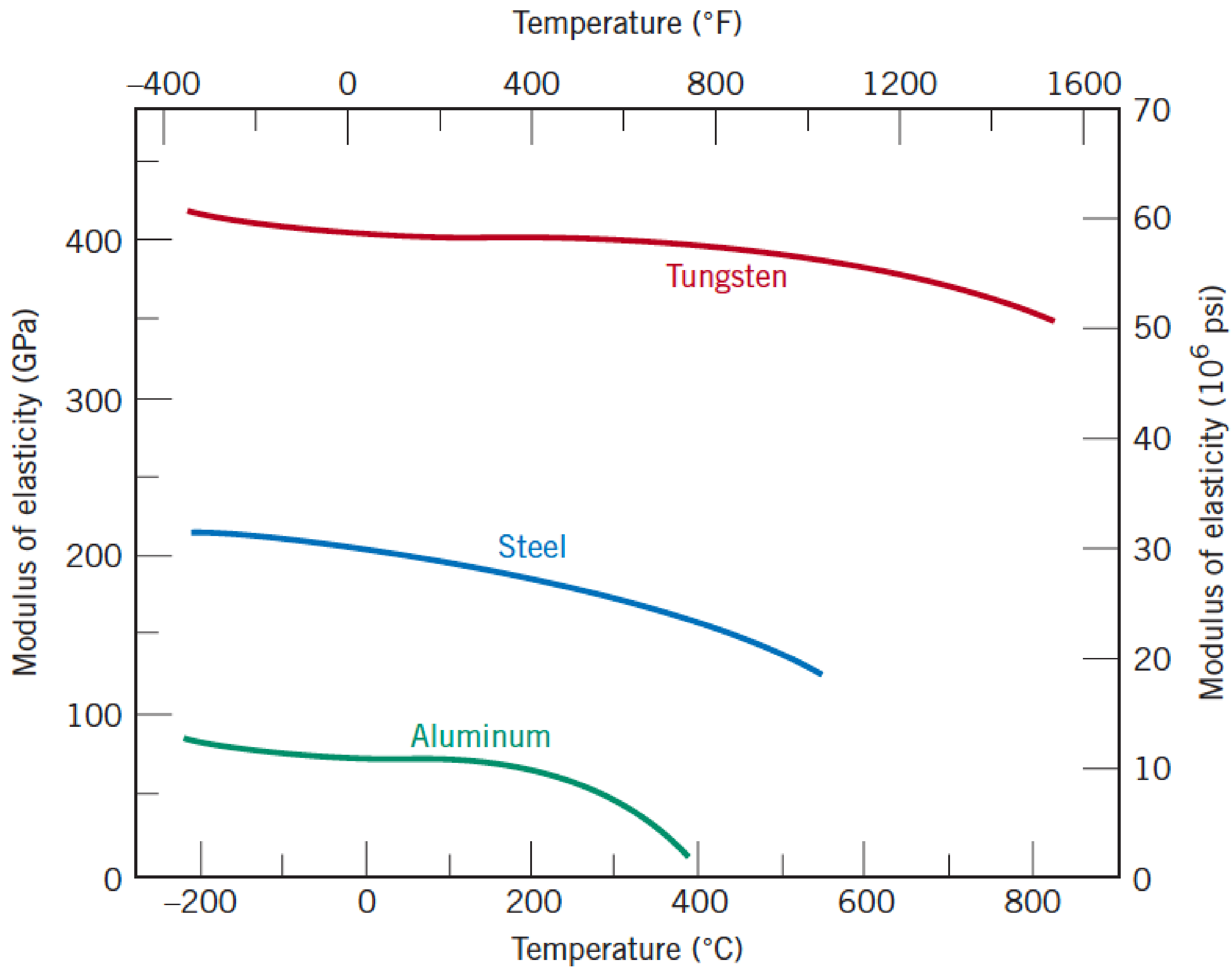


Table 6.1 Room-Temperature Elastic and Shear Moduli, and Poisson's Ratio for Various Metal Alloys

Metal Alloy	*Modulus of Elasticity*		*Shear Modulus*		*Poisson's Ratio*
	GPa	*10^6 psi*	*GPa*	*10^6 psi*	
Aluminum	69	10	25	3.6	0.33
Brass	97	14	37	5.4	0.34
Copper	110	16	46	6.7	0.34
Magnesium	45	6.5	17	2.5	0.29
Nickel	207	30	76	11.0	0.31
Steel	207	30	83	12.0	0.30
Titanium	107	15.5	45	6.5	0.34
Tungsten	407	59	160	23.2	0.28

Young's Moduli: Comparison



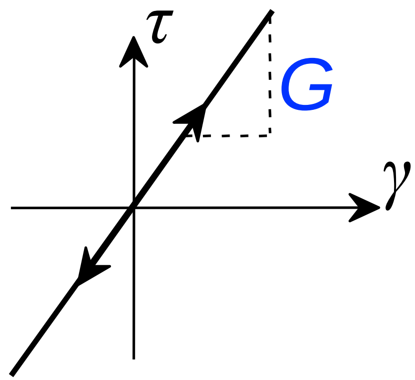

Temperature (°F)
–400
0
400
800
1200
1600
70
60
50
40
30
20
10
0
400
300
200
100
0
Tungsten
Steel
Aluminum
Modulus of elasticity (GPa)
Modulus of elasticity (10^6 psi)
–200
0
200
400
600
800
Temperature (°C)

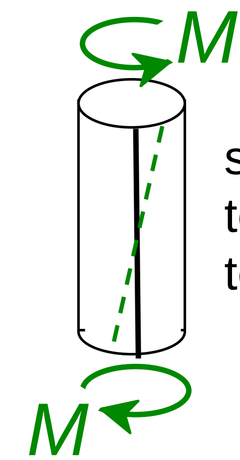
See Example 6.1

Other Elastic Properties

- **Elastic Shear modulus, *G*:**

$$\tau = G\,\gamma$$

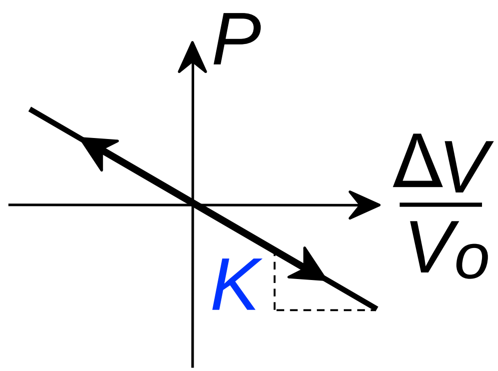


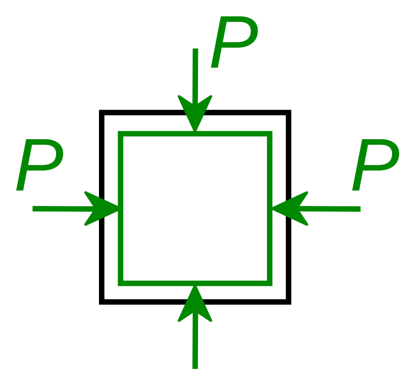


simple torsion test

- **Elastic Bulk modulus, K:**

$$P = -K\frac{\Delta V}{V_o}$$





pressure test: Init. vol $= V_o$. Vol chg. $= \Delta V$

- **Special relations for isotropic materials:**

$$G = \frac{E}{2(1+\nu)} \qquad K = \frac{E}{3(1-2\nu)}$$

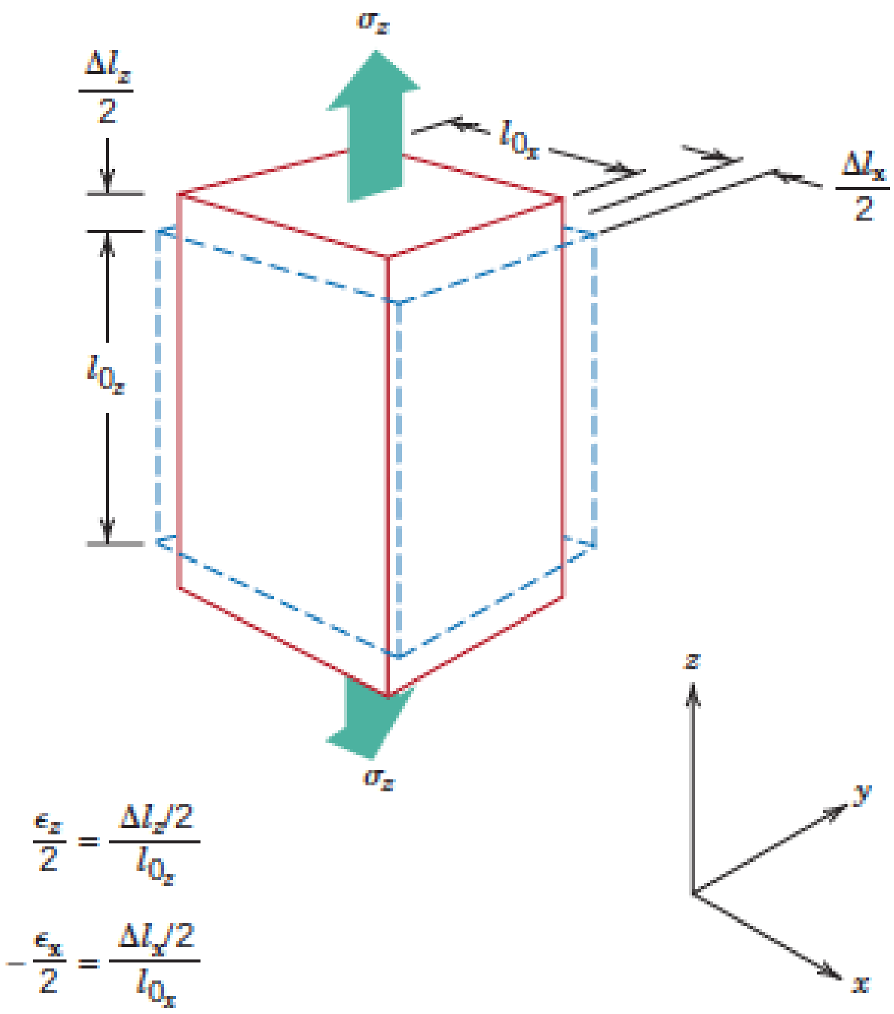
Poisson's ratio, ν

- Poisson's ratio, ν:

$$\nu = - \frac{e_L}{e}$$

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

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



See Example 6.2

Mechanical properties of metals

For Elastic Deformation

$$\sigma = \frac{F}{A_0}$$

$$\sigma = E\epsilon$$

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

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

Mechanical properties of metals

Anelasticity

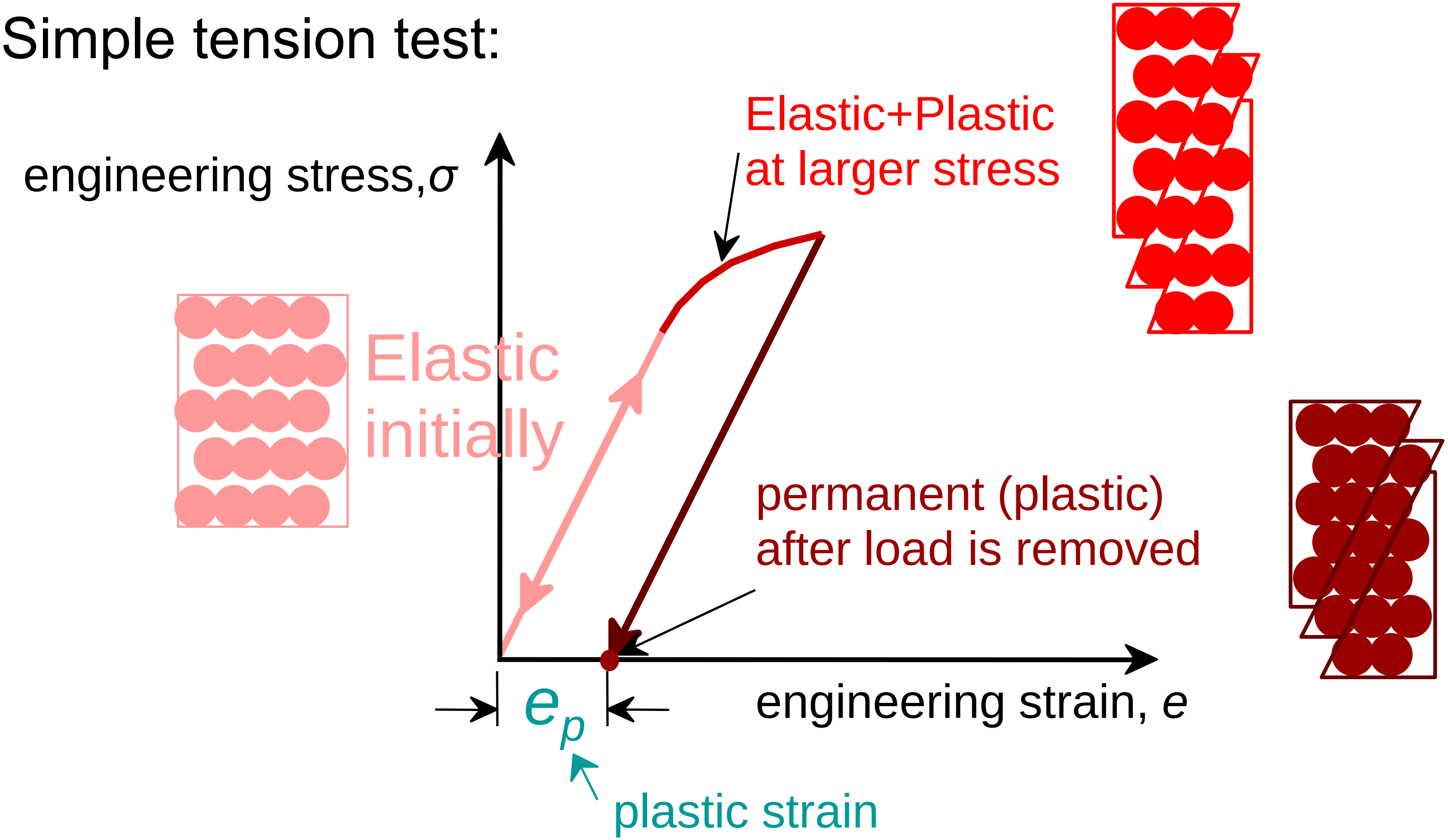
Time-dependent elastic deformation

Viscoelastic deformation

Plastic (Permanent) Deformation

Plastic (Permanent) Deformation

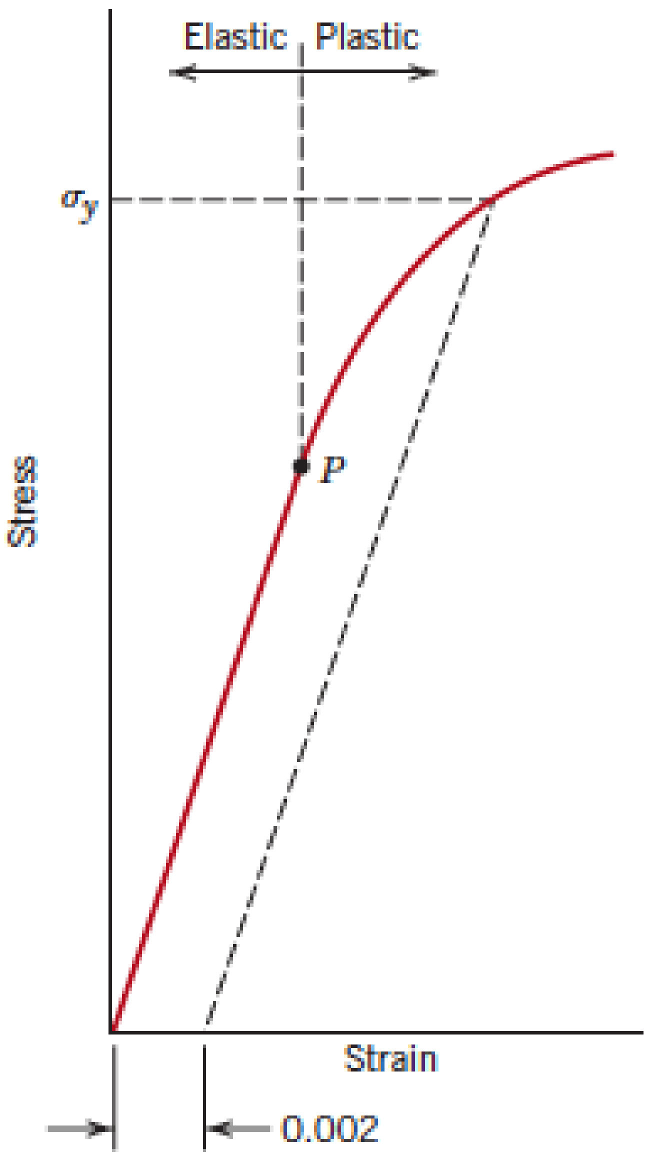
- Simple tension test:



Mechanical properties of metals

Plastic deformation

- ✓ *Permanent deformation*
- ✓ *Breaking bonds, moving atoms, & reforming bonds*
- ✓ *Elastic strain, ε ~ 0.5 % (0.005)*
- ✓ *Mechanism (metals):Slip*



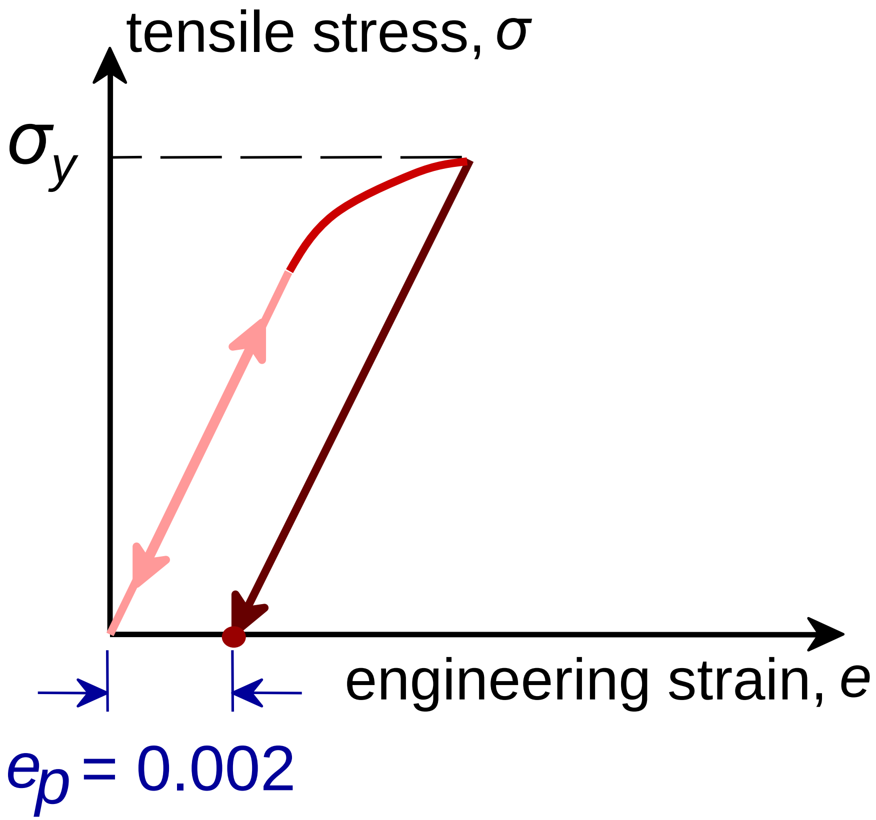
Y

(1) Yield strength σ_y

0.2% strain offset can be used to find σ_y

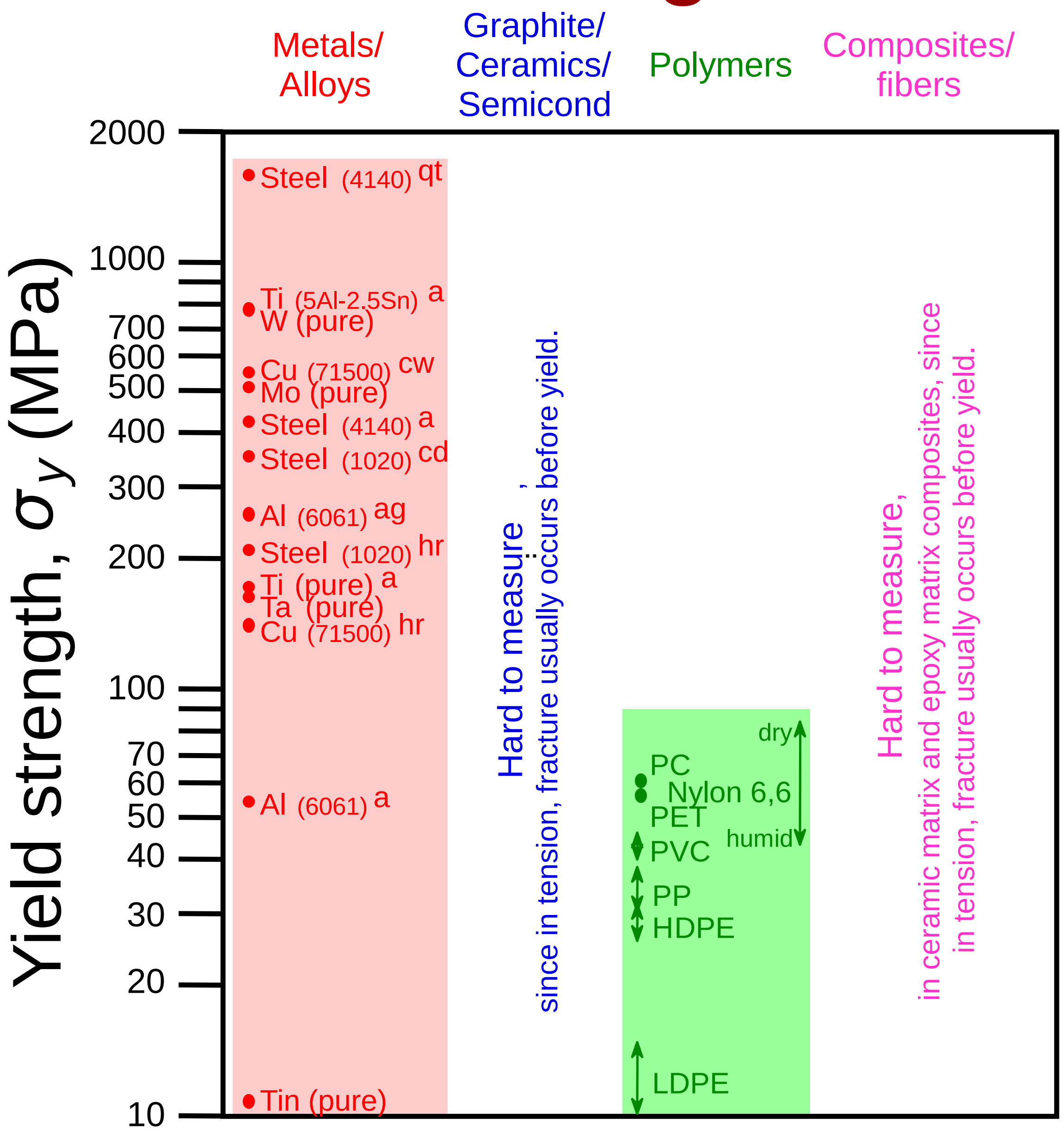
Yield Strength, σ_y

- **Stress at which *noticeable* plastic deformation has occurred.**



σ_y = yield strength

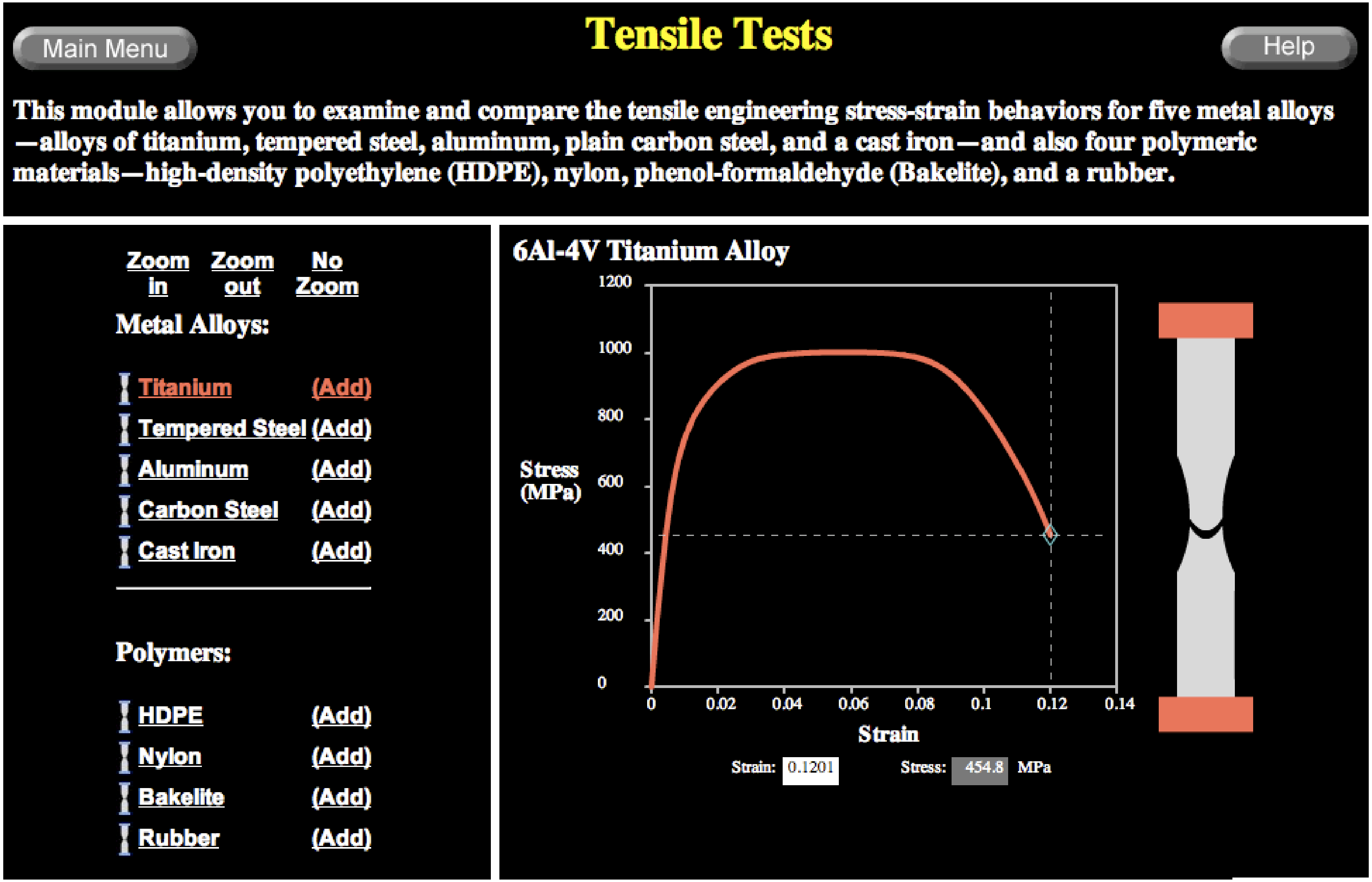
Yield Strength : Comparison



Values at room temperature

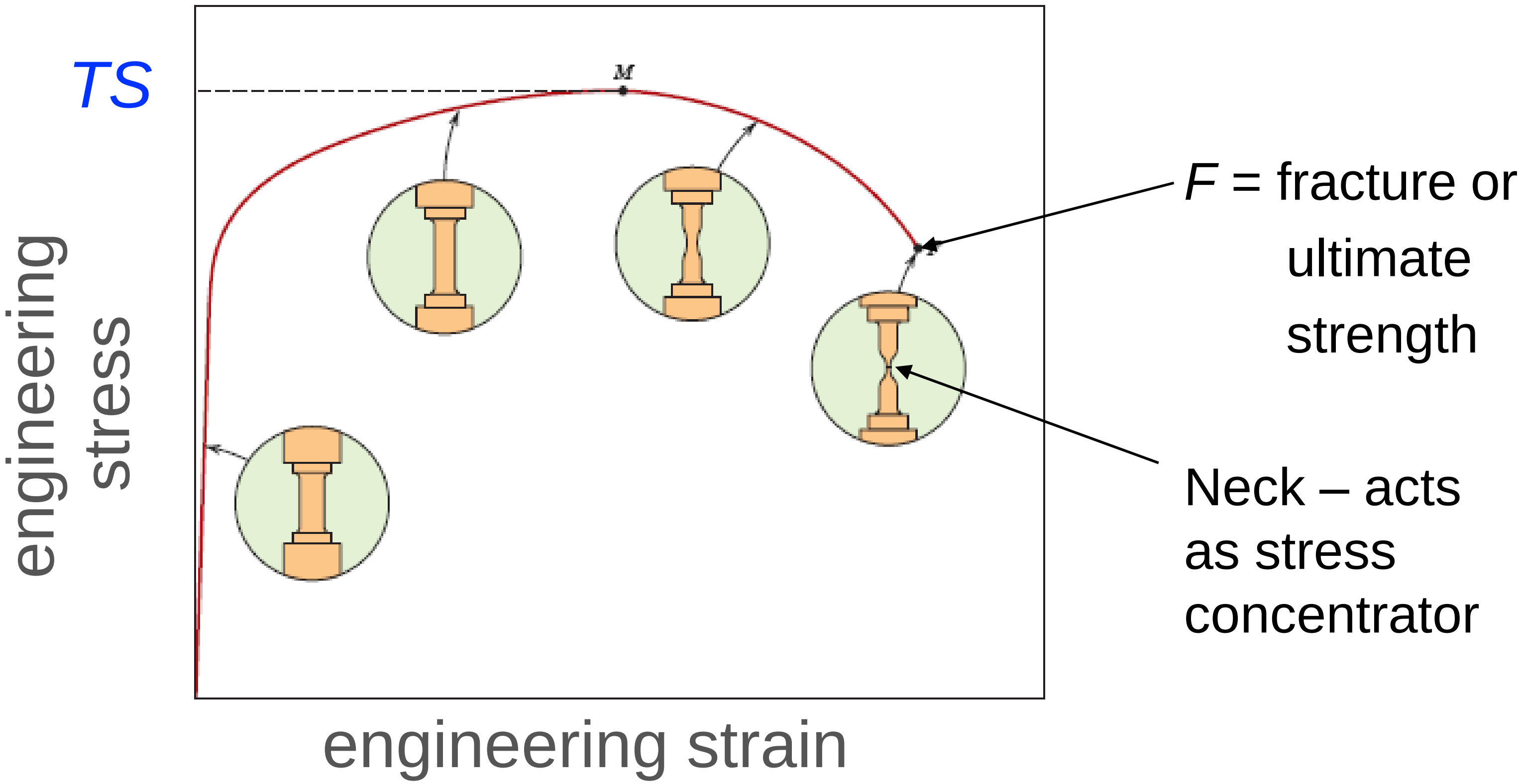
a = annealed
hr = hot rolled
ag = aged
cd = cold drawn
cw = cold worked
qt = quenched & tempered

VMSE: Virtual Tensile Testing



Tensile Strength, TS

- Maximum stress on engineering stress-strain curve.

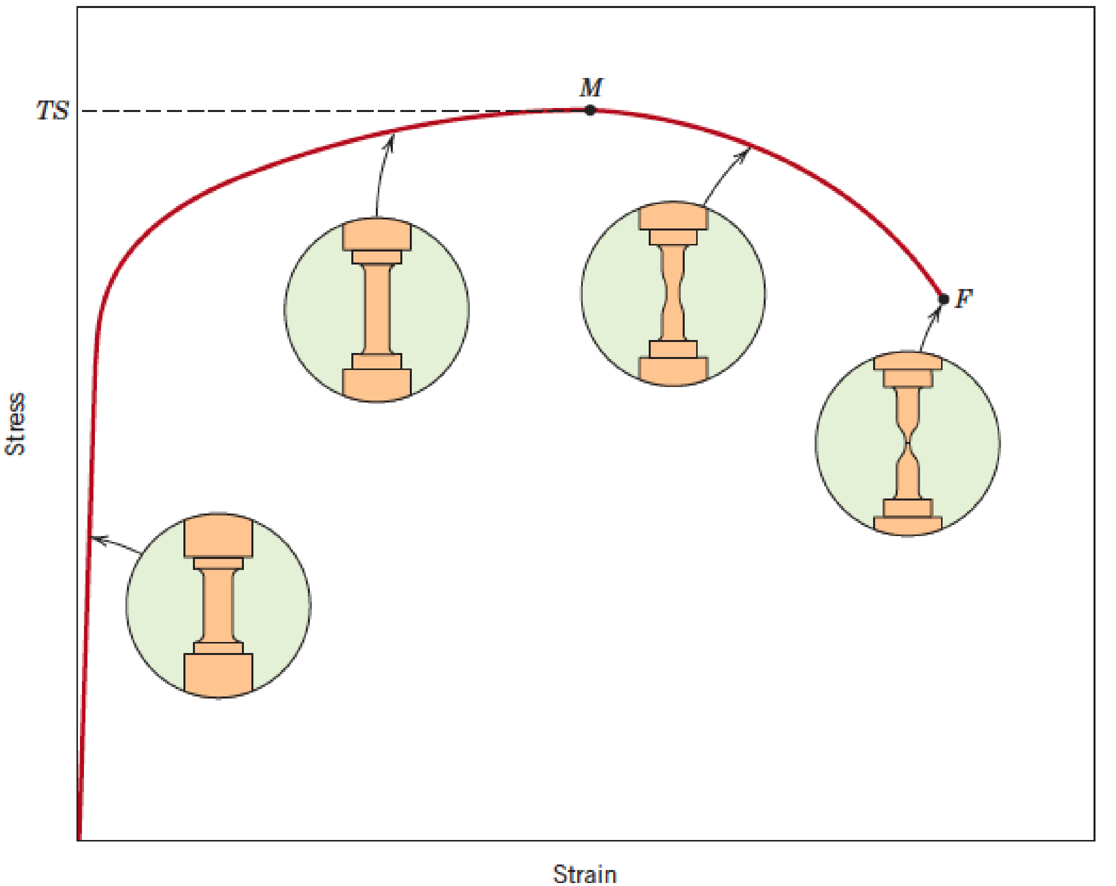


- Metals: occurs when noticeable necking starts.

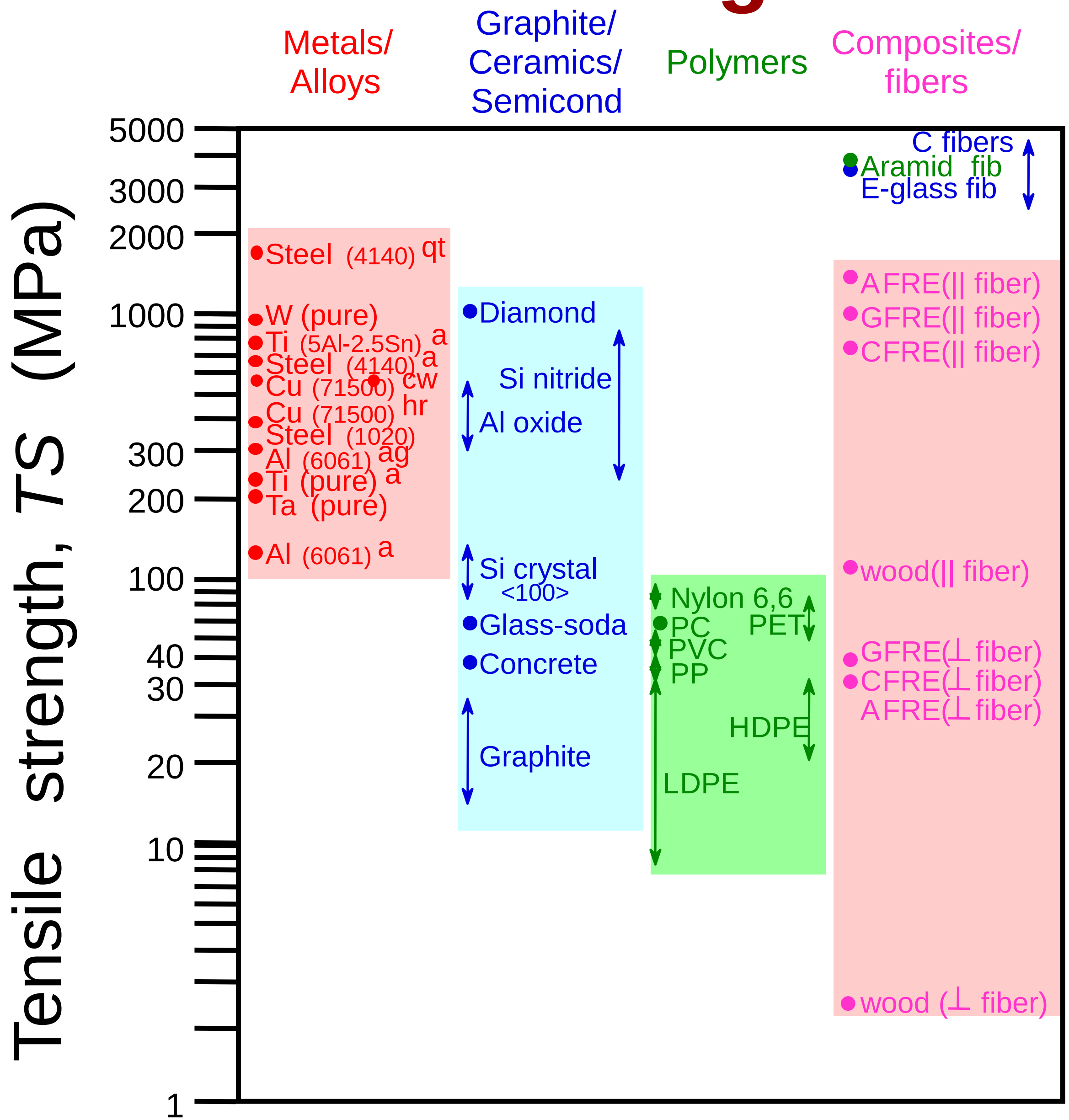
Mechanical properties of metals

(2) Tensile strength, TS

(3) Fracture strength



Tensile Strength: Comparison



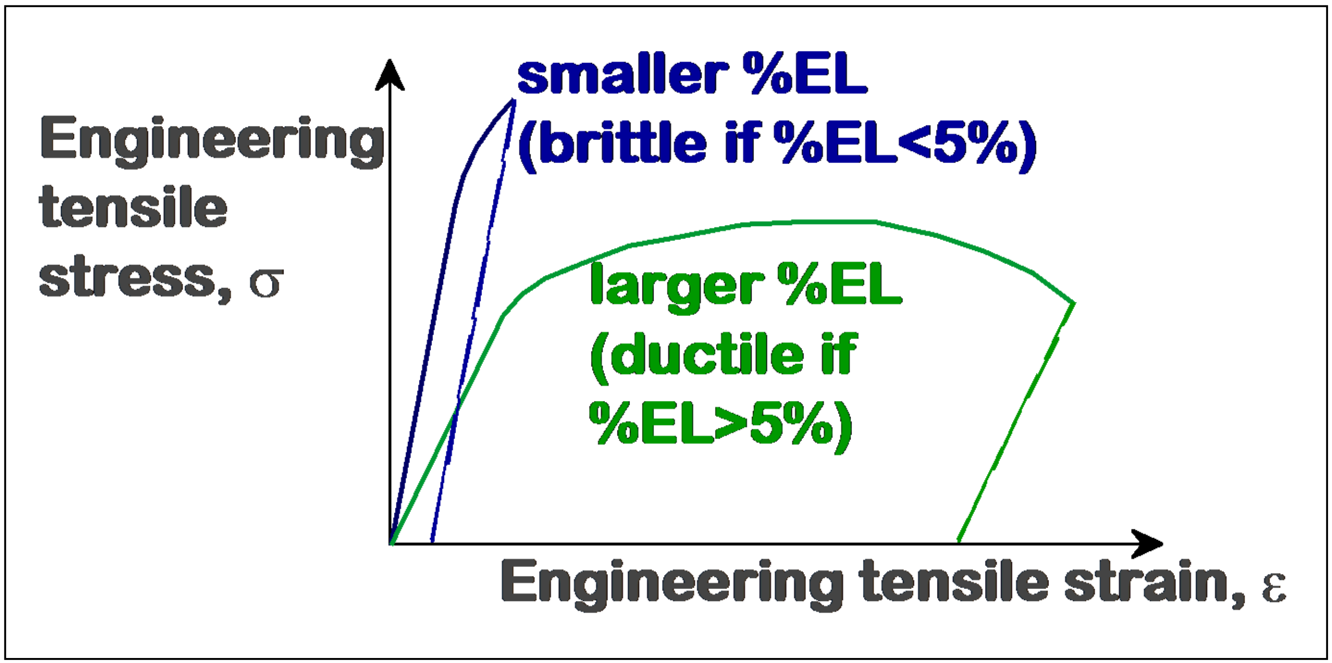
Room temperature values

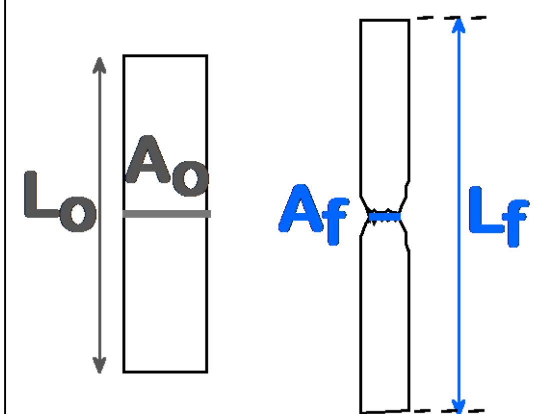
a = annealed
hr = hot rolled
ag = aged
cd = cold drawn
cw = cold worked
qt = quenched & tempered

Mechanical properties of metals

(4) Ductility:

A measure of degree of plastic deformation without fracture





Ductility measure:

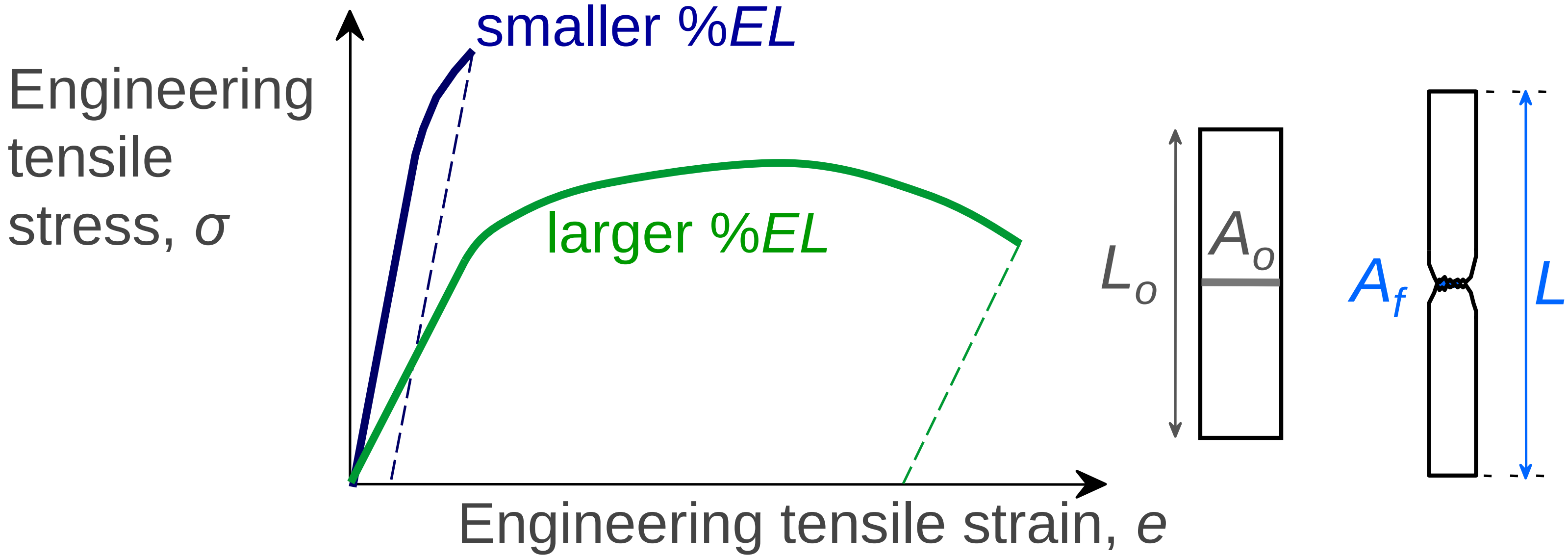
$$\%EL = \left(\frac{l_f - l_0}{l_0}\right) \times 100$$

$$\%RA = \left(\frac{A_0 - A_f}{A_0}\right) \times 100$$

Ductility

- Plastic tensile strain at failure:

$$\%EL = \frac{L_f - L_o}{L_o} \times 100$$



- Another ductility measure:

$$\%RA = \frac{A_o - A_f}{A_o} \times 100$$

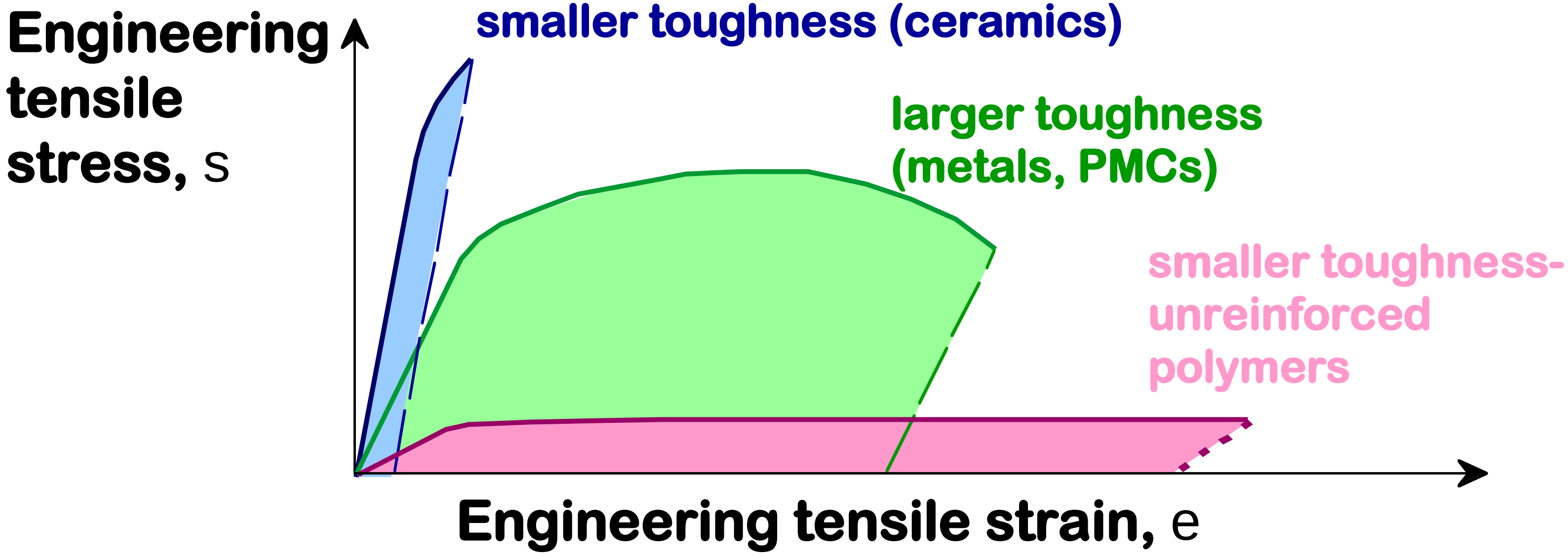
Mechanical properties of metals

(5) Toughness

A measure of the ability of a material to absorb energy up to fracture

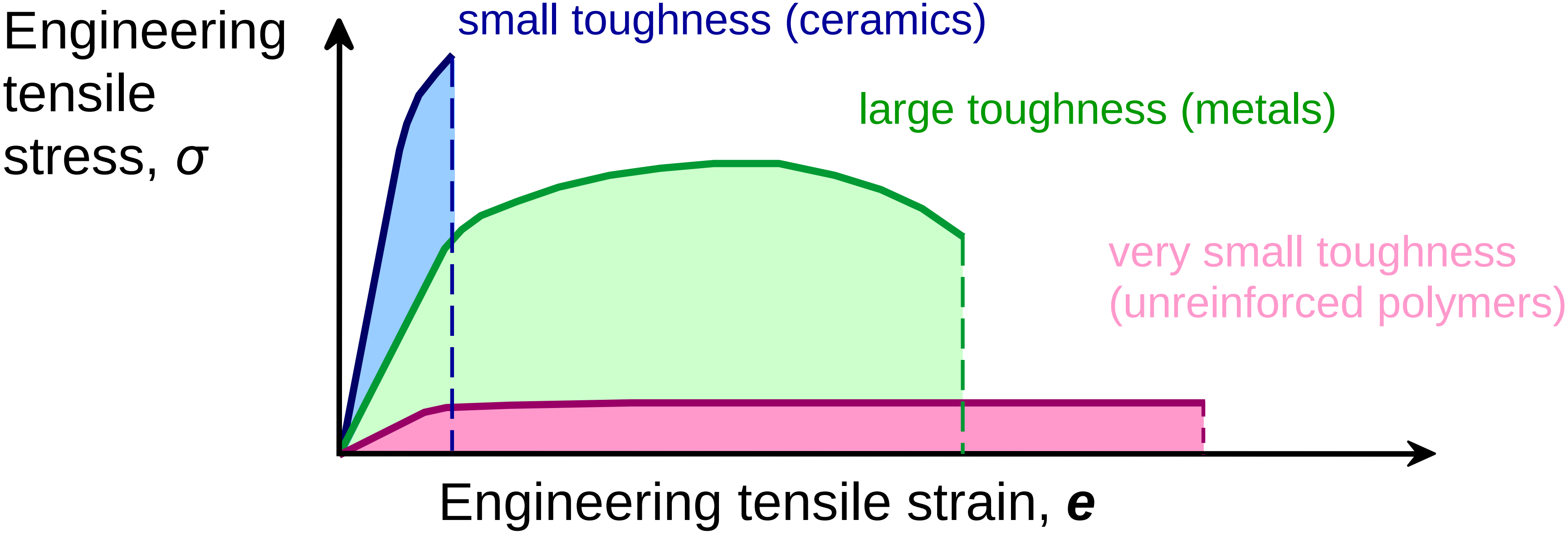
Approximate by the area under the stress-strain curve

Metals: Tough => High strength + Good ductility



Toughness

- Energy to break a unit volume of material



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

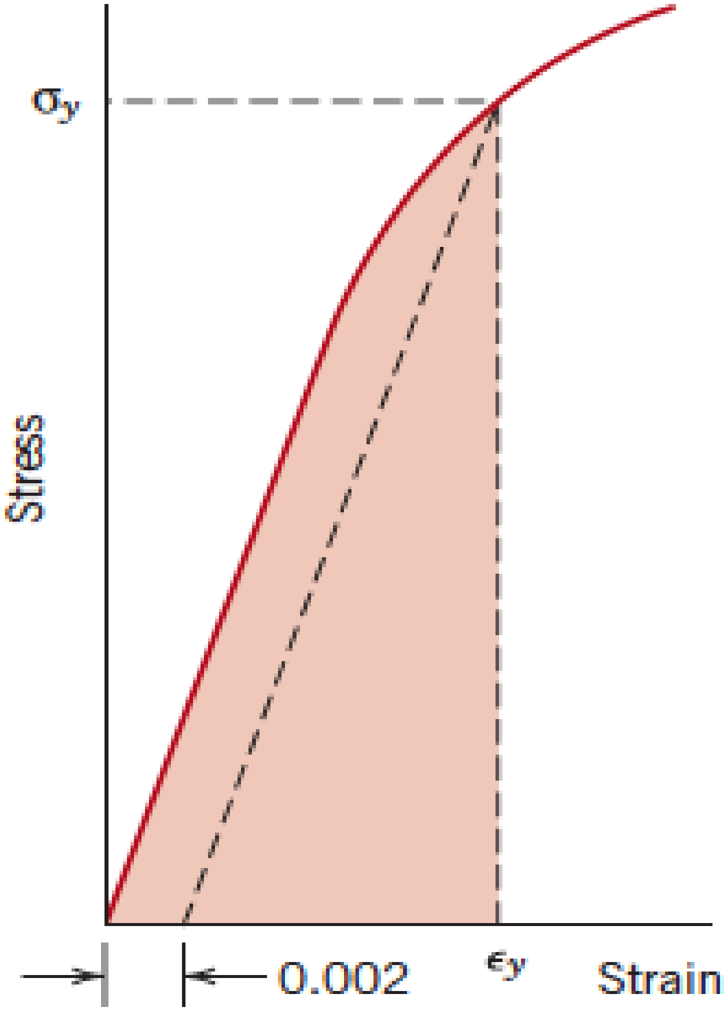
Mechanical properties of metals

(6) Resilience:

It is the capacity of a material to absorb energy when it is deformed elastically

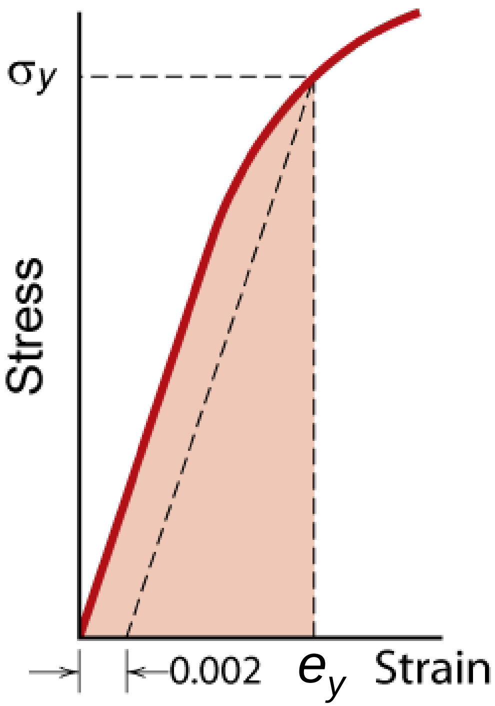
Modulus of resilience, U_r

$$U_r = \int_0^{\epsilon_y} \sigma \, d\epsilon$$



Resilience, U_r

- Ability of a material to store energy
  - Energy stored best in elastic region

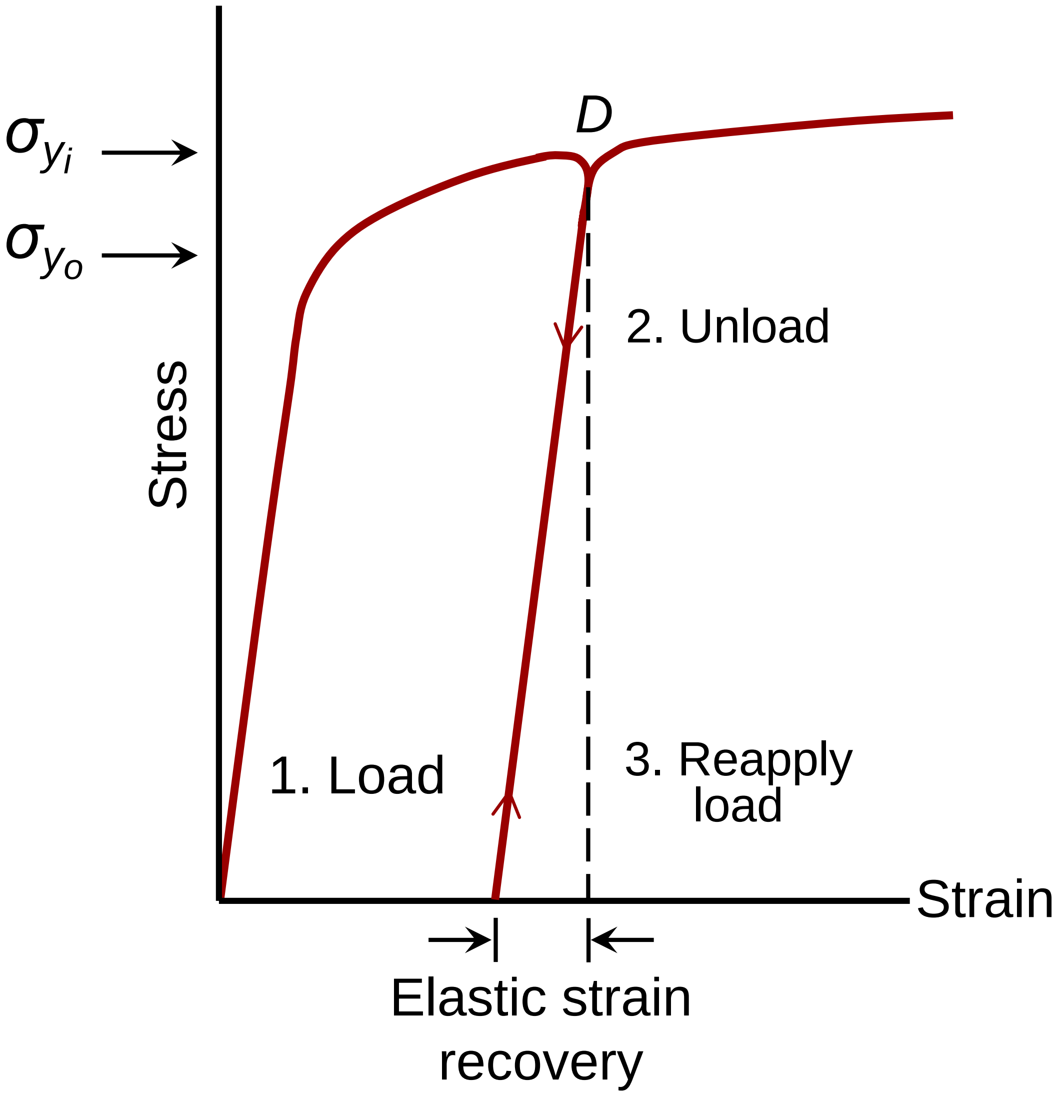


$$U_r = \int_0^{\epsilon_y} \sigma \, d\epsilon$$

If we assume a linear stress-strain curve this simplifies to

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

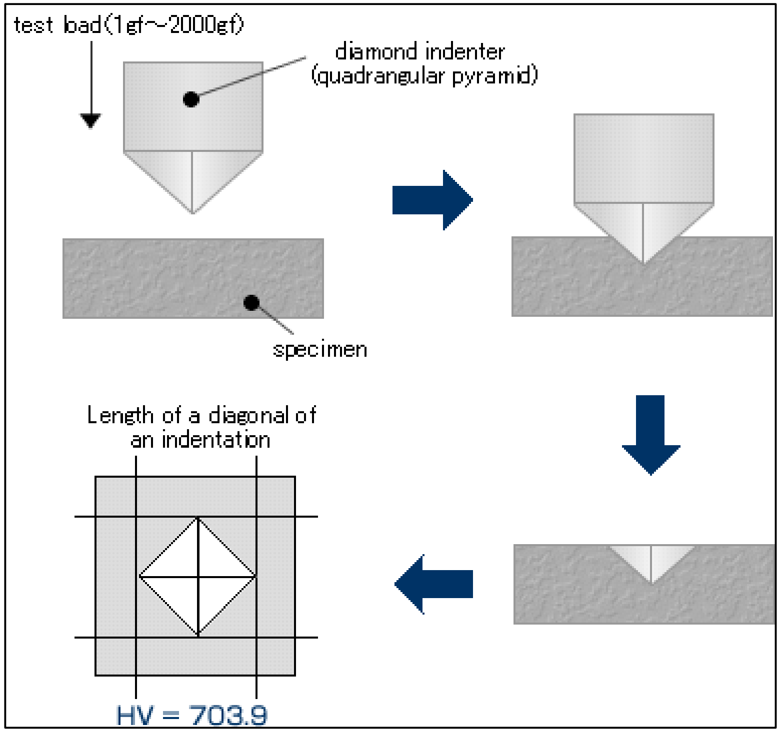
Elastic Strain Recovery



Hardness

A measure of a material's resistance to localized plastic deformation (e.g., a small dent or a scratch)

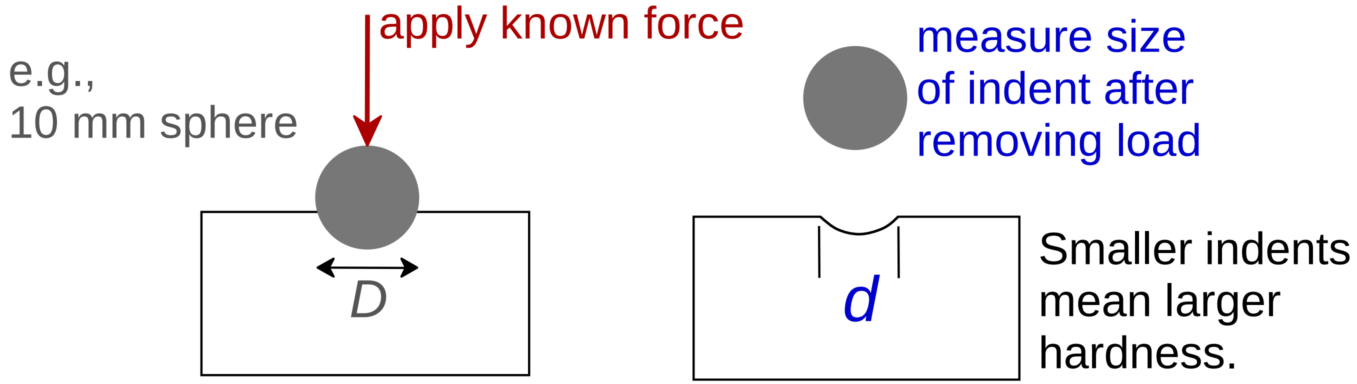
Method:
A small indenter is forced into the surface of a material to be tested, under controlled conditions of load and rate of application. The size of the resulting indentation is measured, which in turn is related to a hardness number.

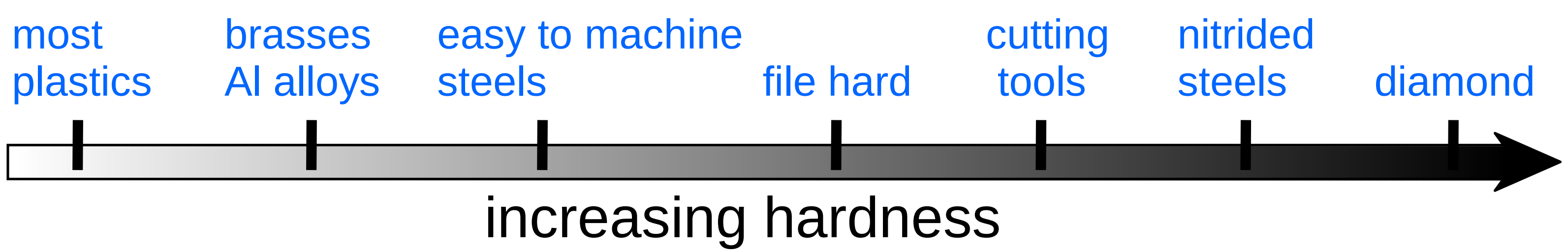


Softer material >> larger indentation > lower hardness index number

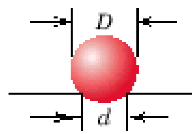
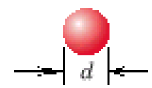
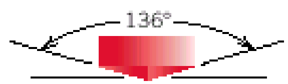
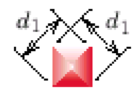
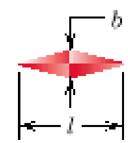
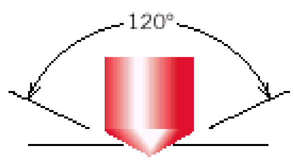
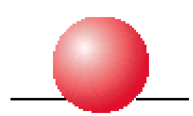
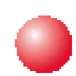
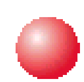
Hardness

- Resistance to permanently indenting the surface.
- Large hardness means:
  - -- resistance to plastic deformation or cracking in compression.
  - -- better wear properties.





Hardness: Measurement

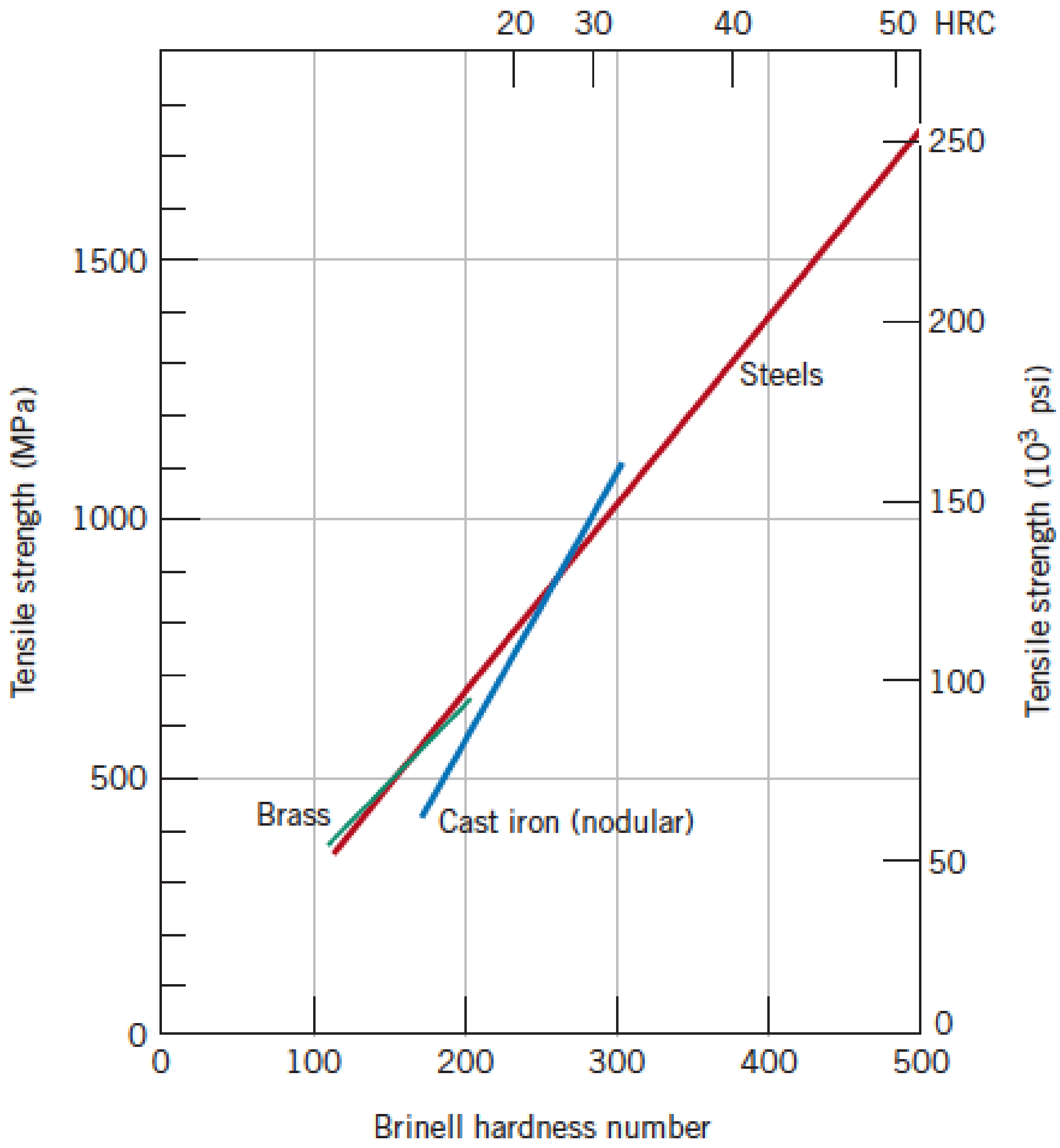
Test	Indenter	Shape of Indentation: Side View	Shape of Indentation: Top View	Load	Formula for Hardness Number[a]
Brinell	10-mm sphere of steel or tungsten carbide			P	$HB = \frac{2P}{\pi D[D - \sqrt{D^2 - d^2}]}$
Vickers microhardness	Diamond pyramid			P	$HV = 1.854P/d_1^2$
Knoop microhardness	Diamond pyramid			P	$HK = 14.2P/l^2$
Rockwell and Superficial Rockwell	Diamond cone; $\frac{1}{16}$, $\frac{1}{8}$, $\frac{1}{4}$, $\frac{1}{2}$ in. diameter steel spheres	 	 	60 kg, 100 kg, 150 kg: Rockwell 15 kg, 30 kg, 45 kg: Superficial Rockwell	

Hardness: Measurement

- Rockwell
  - No major sample damage
  - Each scale runs to 130 but only useful in range 20-100.
  - Minor load   10 kg
  - Major load   60 (A), 100 (B) & 150 (C) kg
    - A = diamond, B = 1/16 in. ball, C = diamond

- HB = Brinell Hardness
  - *TS* (psia) = 500 x HB
  - *TS* (MPa) = 3.45 x HB

Correlation Between Hardness and Tensile Strength (empirical)



True Stress and True Strain

Mechanical properties of metals

True stress: The load F divided by the instantaneous cross-sectional area

$$\sigma_T = \frac{F}{A_i}$$

True strain: The natural logarithm of the ratio of instantaneous gauge length to original gauge length of a specimen

$$\epsilon_T = \ln \frac{l_i}{l_0}$$

It is obtained by integratin the incremental strain

$$\epsilon_T = \int d\epsilon = \int_{l_0}^{l_f} \frac{dl}{l} = \ln \frac{l_f}{l_0}.$$

Constant volume:

Valid only to the onset of necking

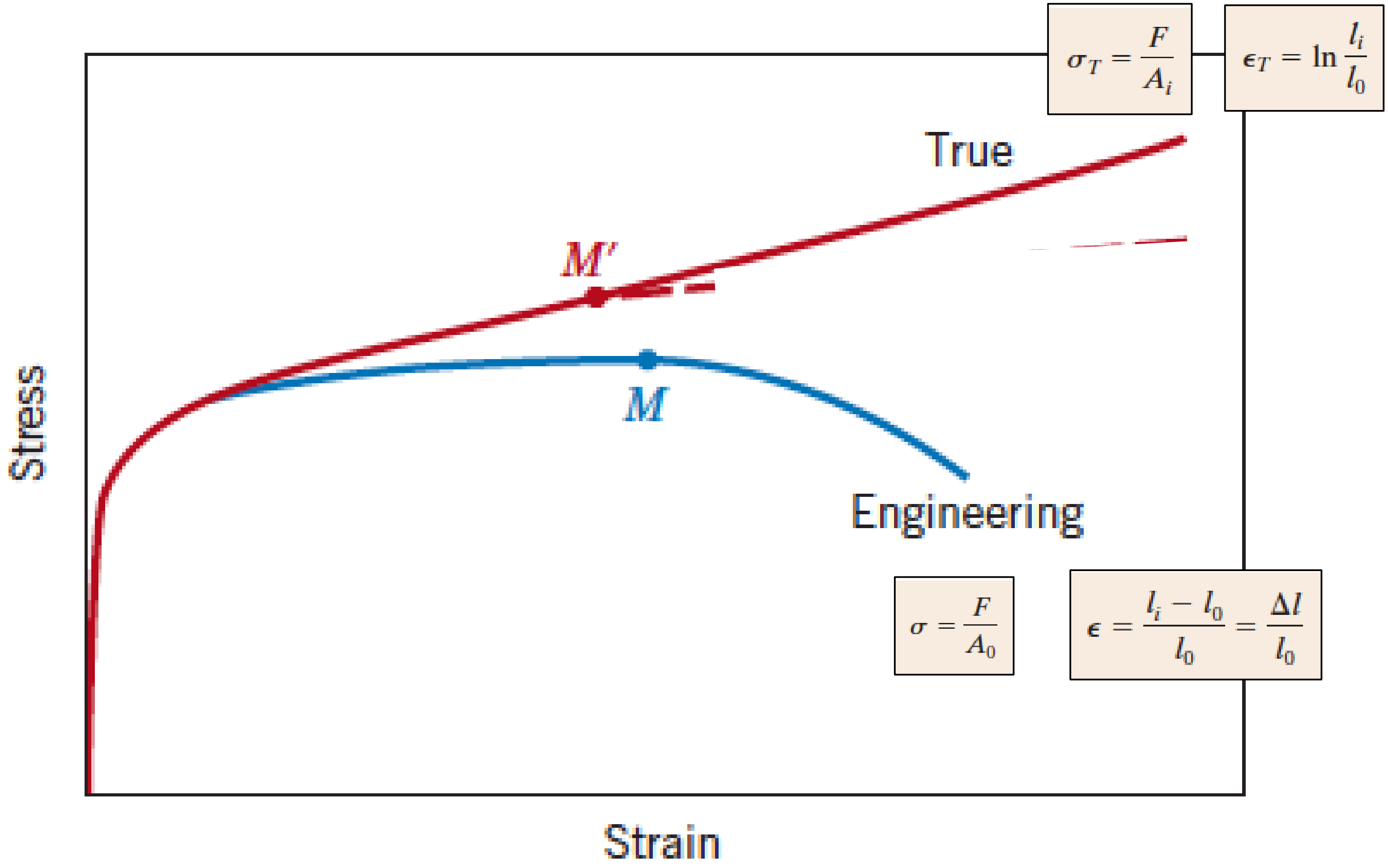
$$A_i l_i = A_0 l_0$$

>>>

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

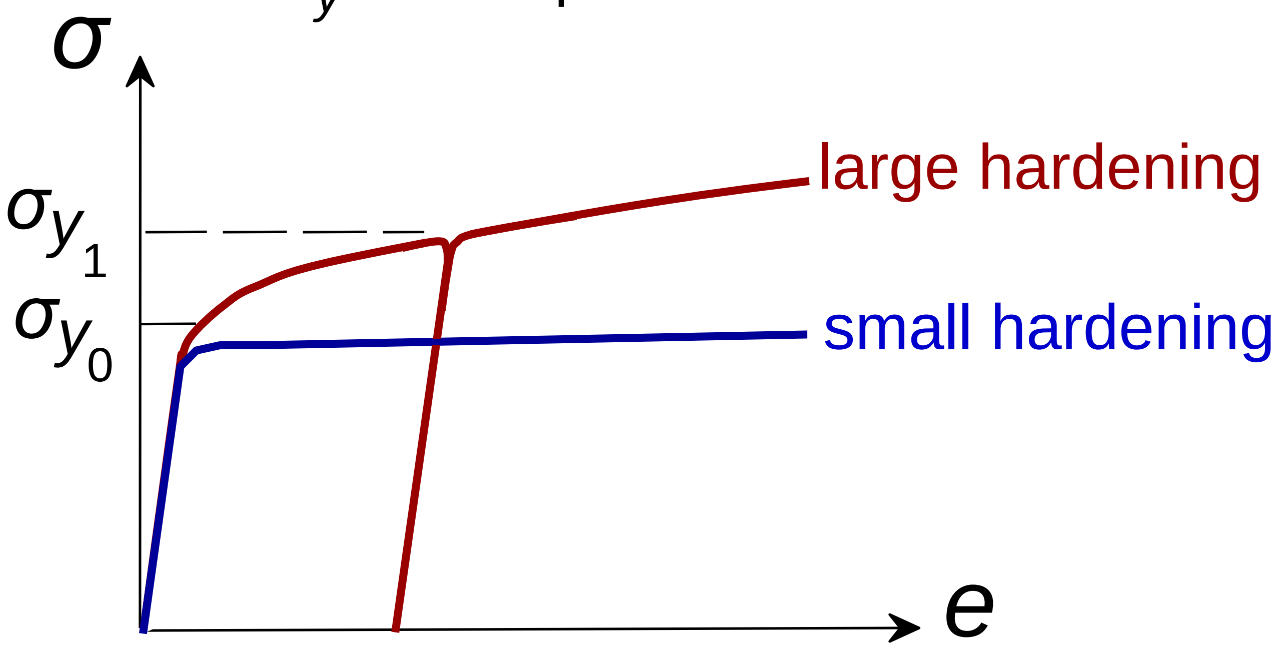
$$\epsilon_T = \ln(1 + \epsilon)$$

Mechanical properties of metals



Hardening

- An increase in σ_y due to plastic deformation.



- Curve fit to the stress-strain response:

$$\sigma_T = K\left(\varepsilon_T\right)^n$$

"true" stress (F/A)

"true" strain: $\ln(\ell/\ell_o)$

hardening exponent:
n = 0.15 (some steels)
to n = 0.5 (some coppers)

Mechanical properties of metals

The region of the true stress–strain curve from the onset of plastic deformation to the point at which necking begins may be approximated by

$$\sigma_T = K\epsilon_T^n$$

K and n are constant.

n: strain hardening exponent

Material	n	K MPa	K psi
Low-carbon steel (annealed)	0.21	600	87,000
4340 steel alloy (tempered @ 315°C)	0.12	2650	385,000
304 stainless steel (annealed)	0.44	1400	205,000
Copper (annealed)	0.44	530	76,500
Naval brass (annealed)	0.21	585	85,000
2024 aluminum alloy (heat treated—T3)	0.17	780	113,000
AZ-31B magnesium alloy (annealed)	0.16	450	66,000

Mechanical properties of metals

See Example 6.5

Problems

6.4, 6.8, 6.9, 6.16, 6.21, 6.24, 6.25, 6.26, 6.27, 6.28, 6.30, 6.37, 6.38, 6.39, 6.40, 6.41, 6.44, 6.45