2019 Fall

Introduction to Materials Science and Engineering

10. 22. 2019

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Office hours: by appointment

Contents for previous class

Chapter 7: Diffusion

I. Introduction of diffusion

: Movement of atoms to reduce its chemical potential μ.

⇨ **driving force: Reduction of G**

Down-hill diffusion movement of atoms from a high C_B region to low C_B region.

Up-hill diffusion movement of atoms from a low C_B region to high C_B region.

II. Diffusion mechanisms

Vacancy diffusion vs. Interstitial diffusion

(a) Self-diffusion

(b) Interdiffusion

III. Steady-state diffusion

Concentration varies with position.

Fick's Frist law: $J = -D\dfrac{dC}{dx}$

Estimation of Diffusion Depth:

$$\frac{C_x - C_0}{C_s - C_0} = 1 - erf\left(\frac{x}{2\sqrt{Dt}}\right)$$

IV. Non-steady-state diffusion

Concentration varies with time and position.

Fick's Second law: $\dfrac{\partial C}{\partial t} = D\dfrac{\partial^2 C}{\partial x^2}$

Diffusion coefficient:

$$D = D_0 exp\left(\frac{Q_d}{RT}\right)$$

V. Factors that influences diffusion

Diffusion **FASTER** for...	Diffusion **SLOWER** for...
open crystal structures	close-packed structures
lower melting T materials	higher melting T materials
materials w/secondary bonding	materials w/covalent bonding
smaller diffusing atoms	larger diffusing atoms
cations	anions
lower density materials	higher density materials

H2 : Chapter 7 example

IH : Chapter 7 연습문제

중간고사

10월 25일 6시 부터 9시 33동 225호, 226호

시험범위 1장부터 – 7장까지
주교재 – 영문기준 207 page까지

Contents for previous class

Chapter 1: Introduction

Chapter 2-6:

Atomic structure and interatomic **bonding**

Fundamentals of **crystallography**

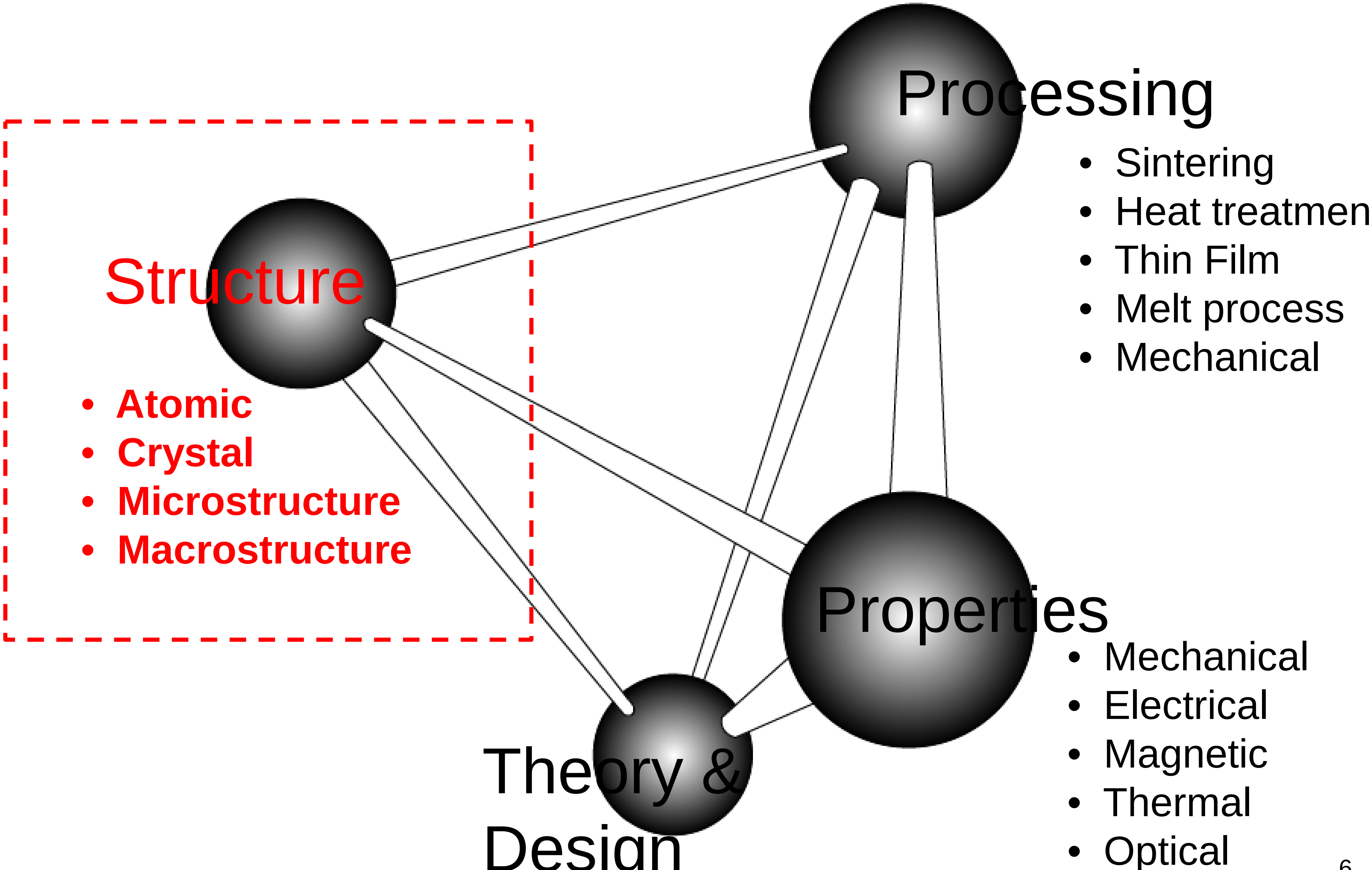
The structure of **crystalline solid**

Structure of Polymers

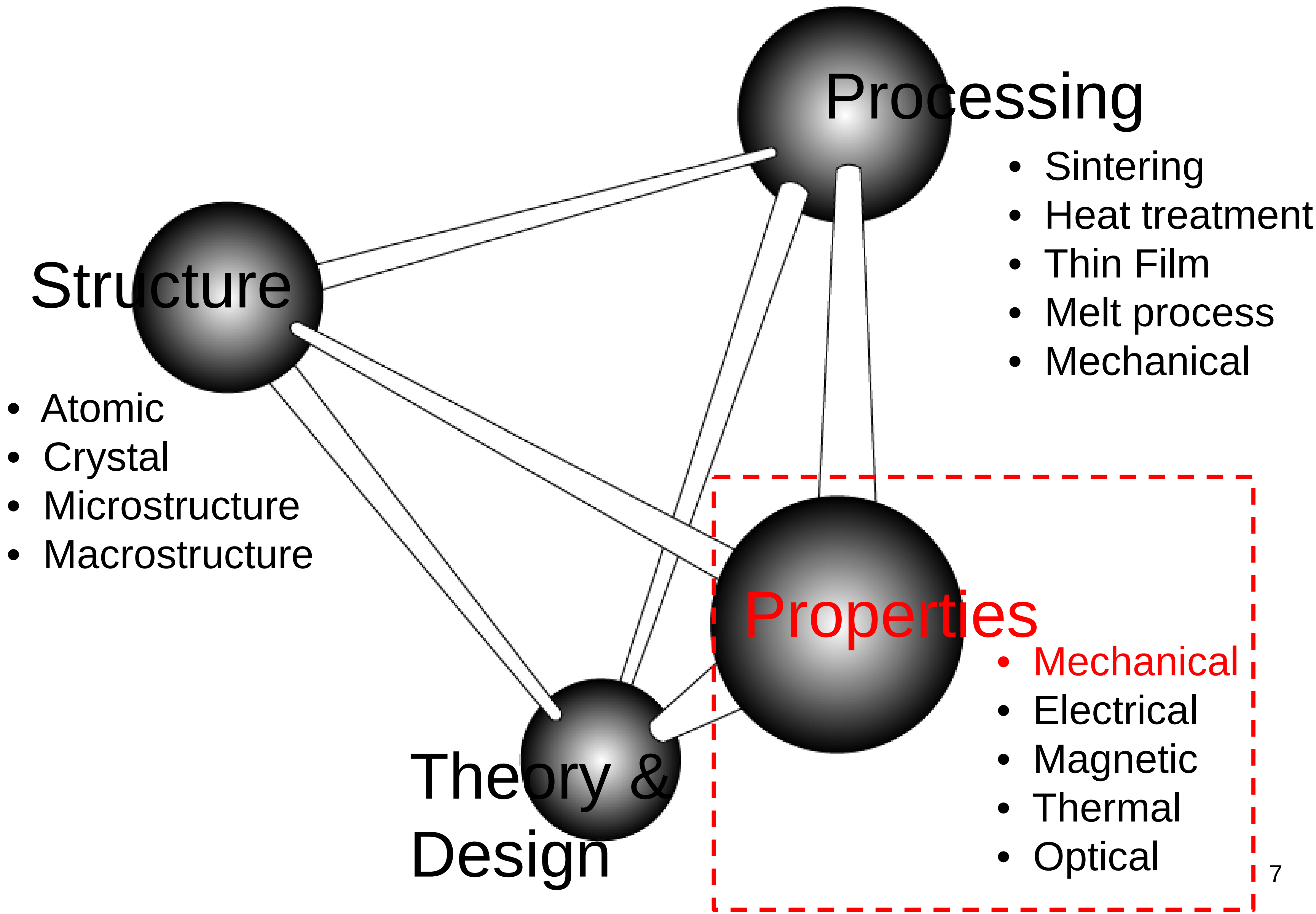
Imperfections in solids

Chapter 7: **Diffusion**

Materials Science and Engineering



Materials Science and Engineering

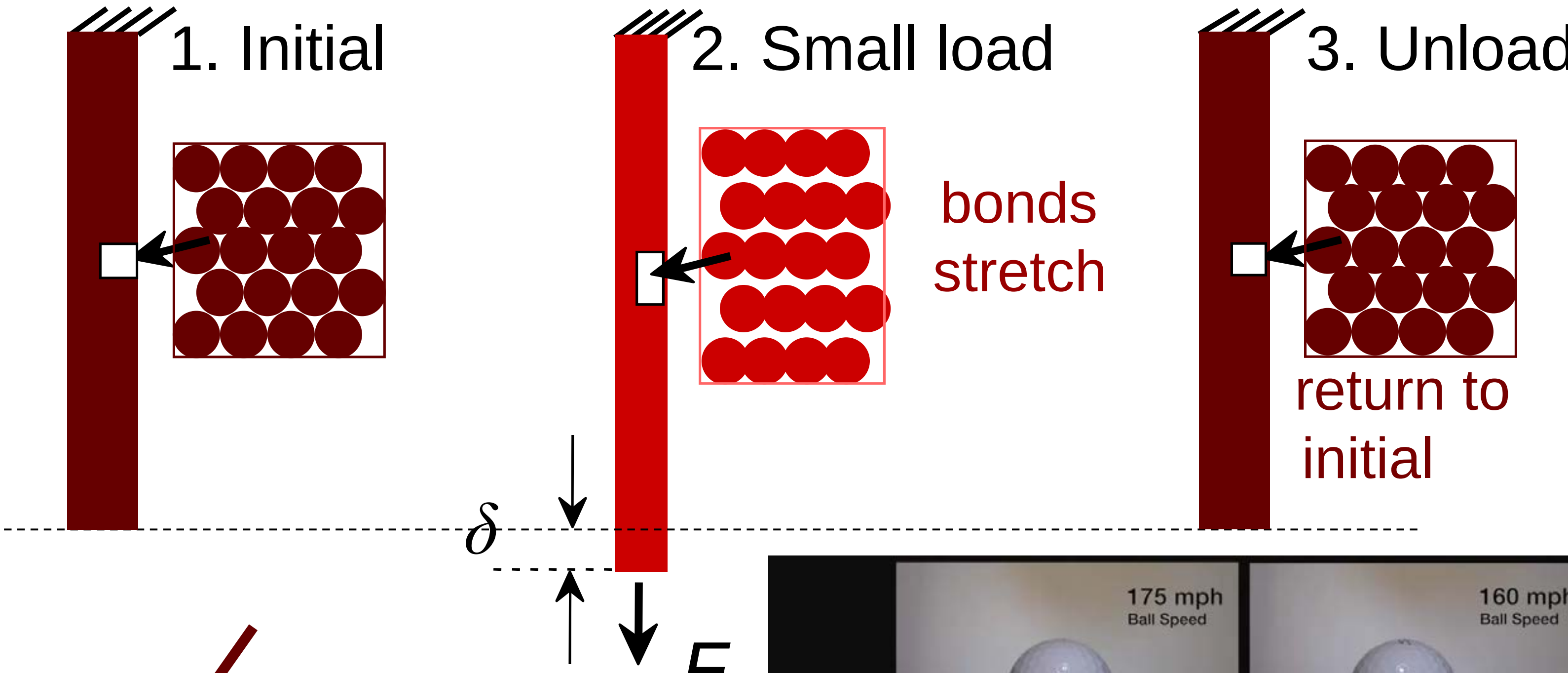


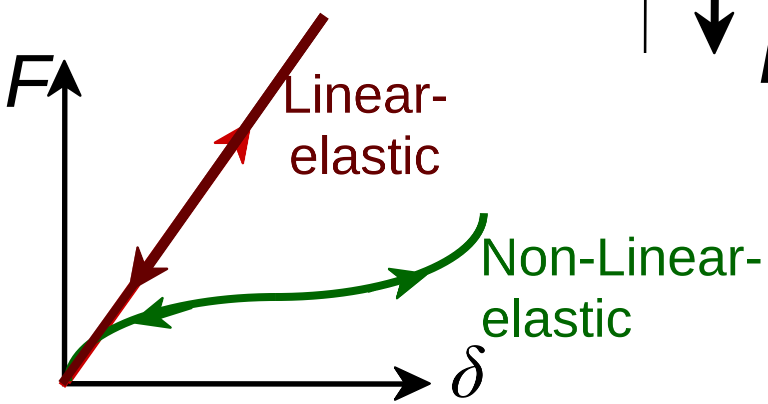
Chapter 8: Mechanical Properties of Metals

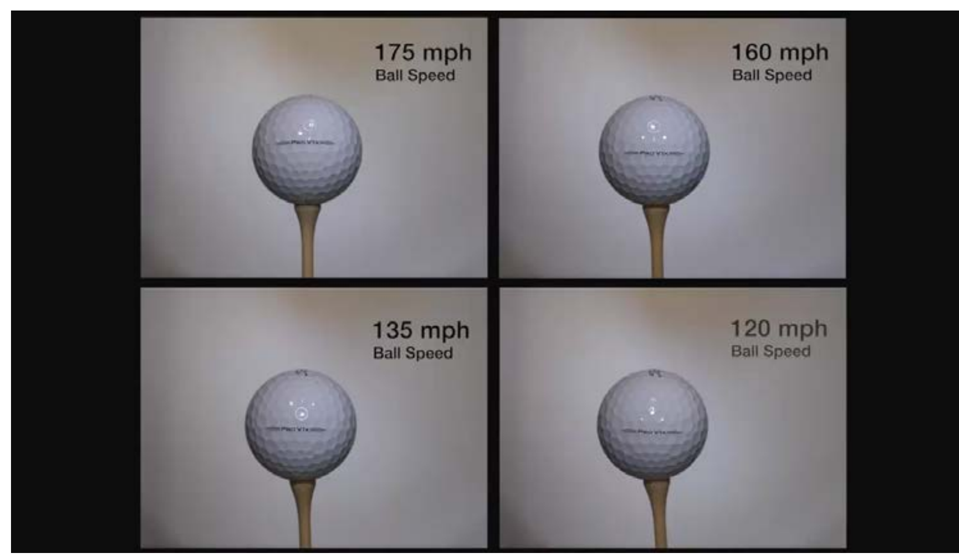
- **Stress and strain**:
  What are they and why are they used instead of load and deformation?
- **Elastic behavior:**
  When loads are small, how much deformation occurs?
  What materials deform least?
- **Plastic behavior:**
  At what point do dislocations cause permanent deformation?
  What materials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

- **Load** - The force applied to a material during testing
- **Stress** - Force or load per unit area of cross-section over which the force or load is acting
- **Strain** - Elongation change in dimension per unit length
- **Engineering stress** - The applied load, or force, divided by the original cross-sectional area of the material
- **Engineering strain** - The amount that a material deforms per unit length in a tensile test
- **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 $\varepsilon_t \ln(l/l_0)$
- **Young's modulus (E)** - The slope of the linear part of the stress-strain curve in the elastic region, same as modulus of elasticity
- **Shear modulus (G)** - The slope of the linear part of the shear stress-shear strain curve

Elastic Deformation



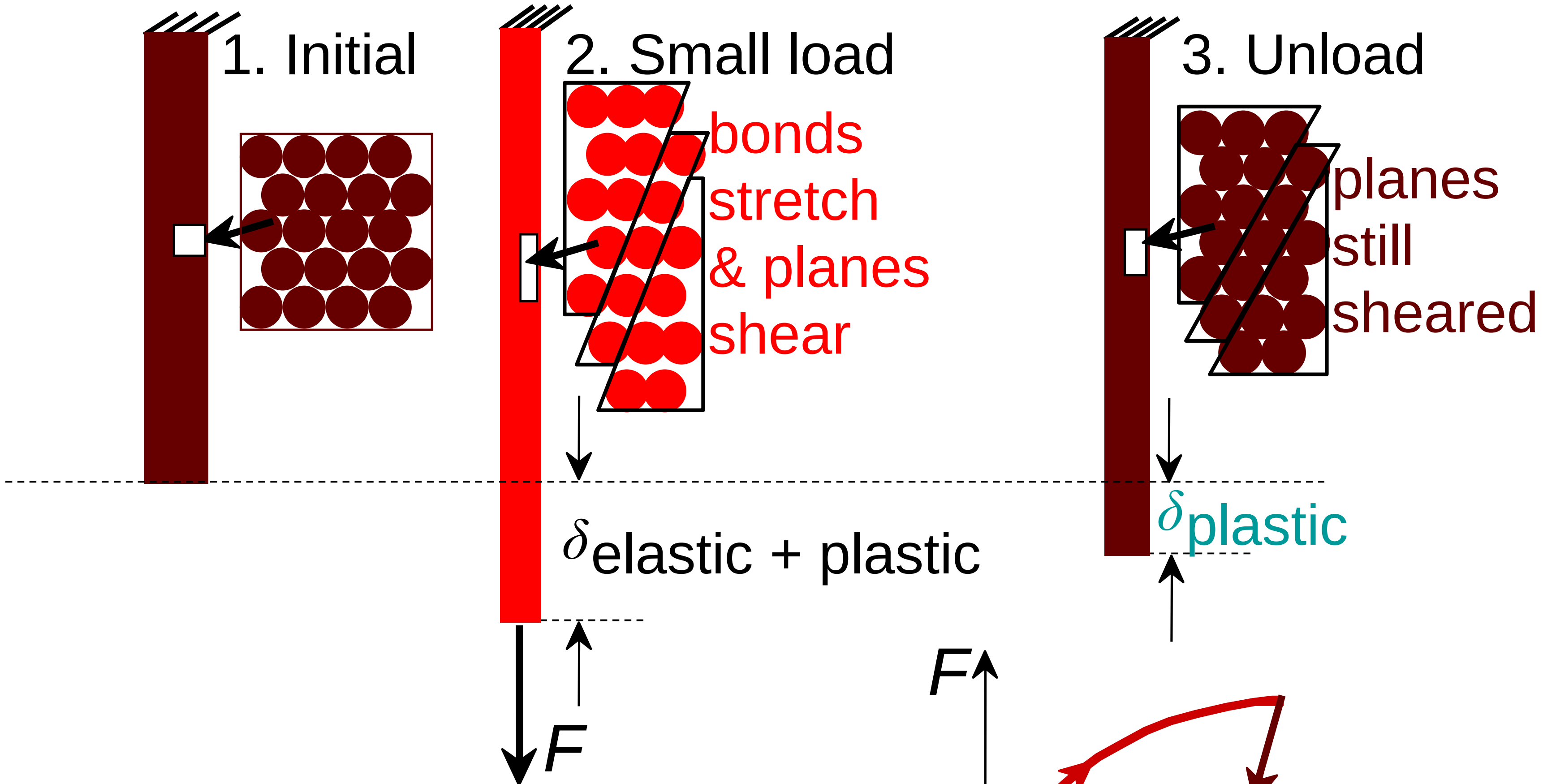




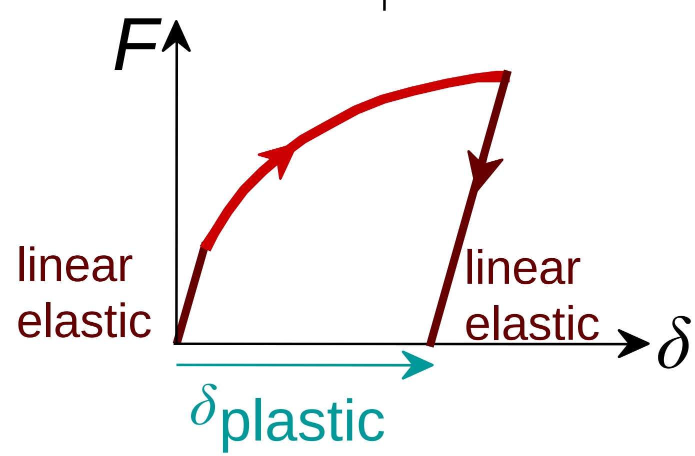
Elastic means reversible!

https://www.youtube.com/watch?v=SIFfY-MS3yA

Plastic Deformation (Metals)

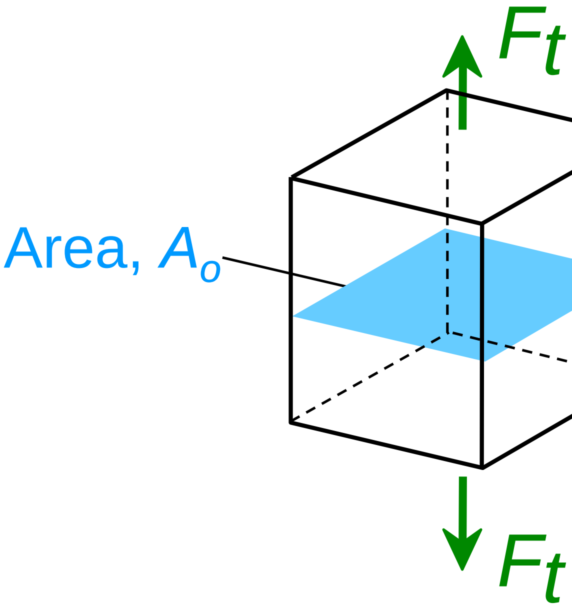


Plastic means permanent!



II. Engineering Stress

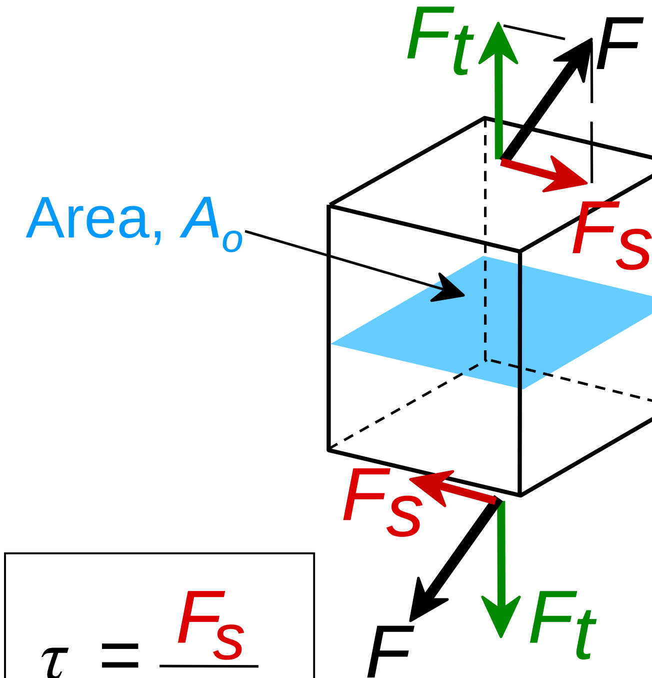
- Tensile stress, σ:



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

original cross-sectional area before loading

- Shear stress, τ:

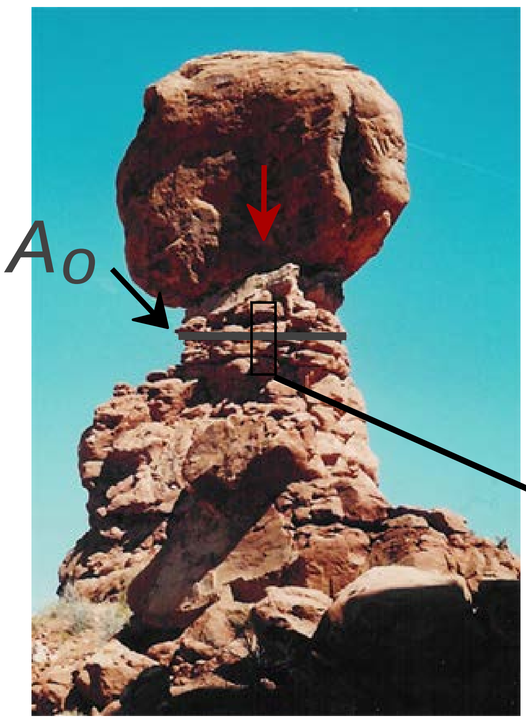


$$\tau = \frac{F_s}{A_o}$$

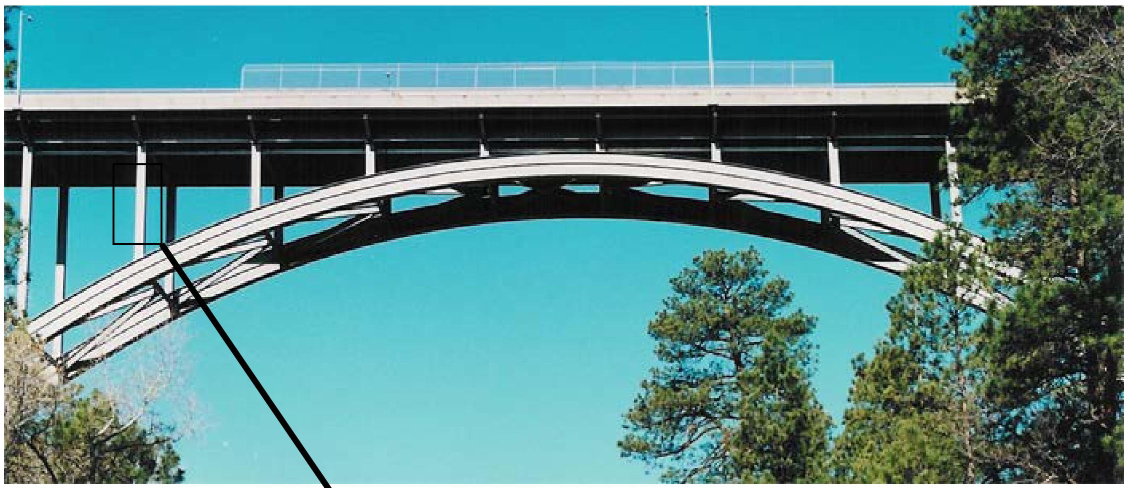
∴ Stress has units: N/m²

II. Common States of **Stress**

a. Simple **compression**:

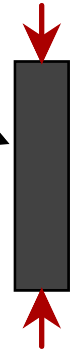


Balanced Rock, Arches National Park
(photo courtesy P.M. Anderson)



Canyon Bridge, Los Alamos, NM
(photo courtesy P.M. Anderson)

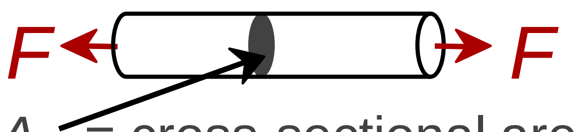
$$\sigma = \frac{F}{A_o}$$



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

II. Common States of **Stress**

b. Simple tension: cable

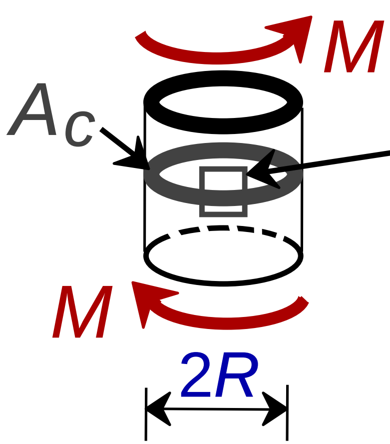


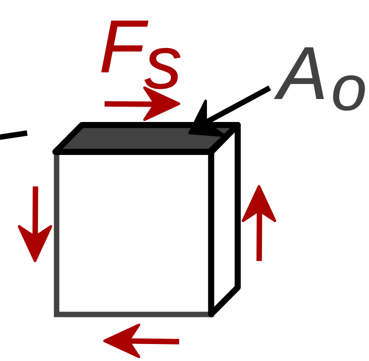
A_o = cross-sectional area (when unloaded)

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

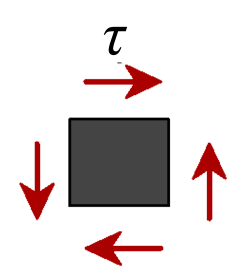
Ski lift (photo courtesy P.M. Anderson)

c. Torsion (a form of shear): drive shaft





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



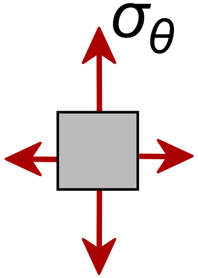
Note: $\tau = M/A_cR$ here.

II. Common States of **Stress**

d. Bi-axial tension:

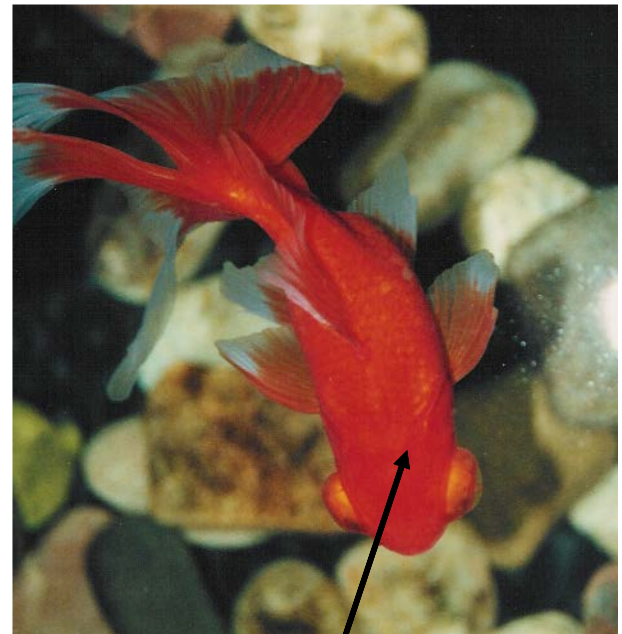
Pressurized tank
(photo courtesy
P.M. Anderson)

$\sigma_\theta > 0$



$\sigma_z > 0$

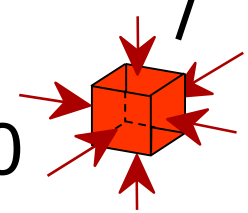
e. Hydrostatic compression:



Fish under water

(photo courtesy
P.M. Anderson)

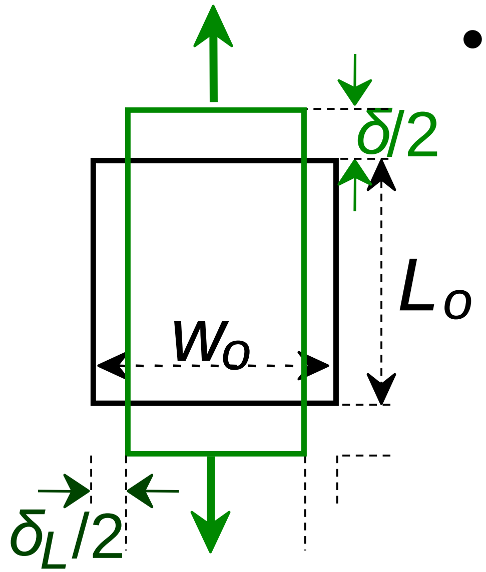
$\sigma_h < 0$



III. Engineering Strain

- **Tensile strain:**

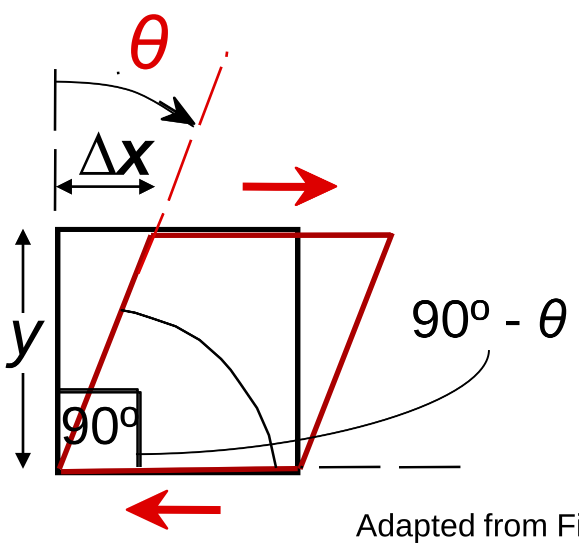
$$\varepsilon = \frac{\delta}{L_o}$$



- **Lateral strain:**

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

- **Shear strain:**



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

Strain is always dimensionless.

Adapted from Fig. 8.1 (a) and (c), *Callister & Rethwisch 9e.*

Stress-Strain Testing

- **Typical tensile test machine**

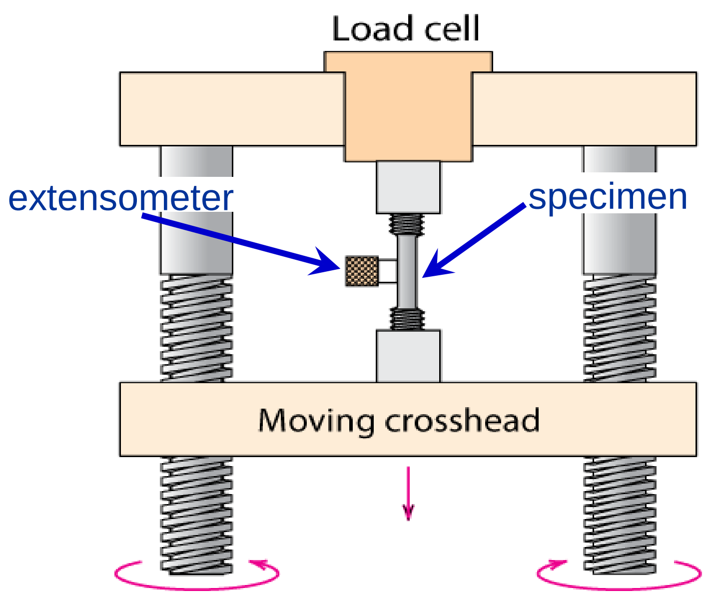
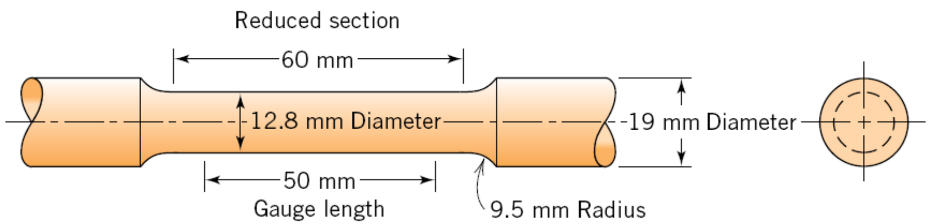


Fig. 8.3, *Callister & Rethwisch 9e.*
(Taken from H.W. Hayden, W.G. Moffatt, and J. Wulff, *The Structure and Properties of Materials*, Vol. III, *Mechanical Behavior*, p. 2, John Wiley and Sons, New York, 1965.)

- **Typical tensile specimen**



➢ **Other types of tests:**

- compression: brittle materials (e.g. concrete)

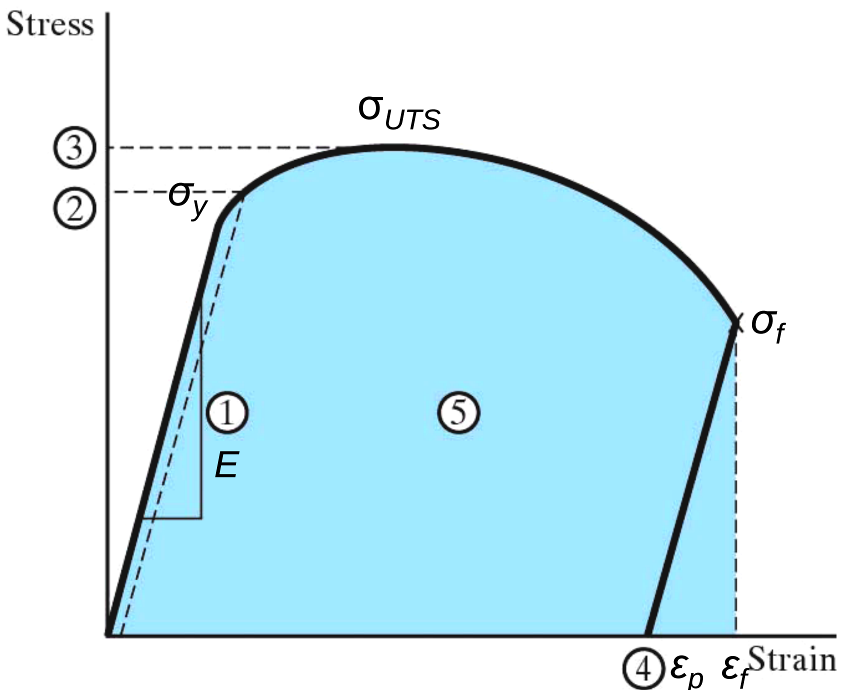
- torsion: cylindrical tubes, shafts

Tensile testing of a steel specimen

IV. Deformation

- Elastic vs. Plastic region
- Key points

1. Elastic modulus (=Young's modulus), *E*
2. 0.2% (0.002 strain) yield stress, σ_y
3. Ultimate yield stress, σ_{UTS}
4. Ductility, ε_p
5. Toughness → $\int \sigma d\varepsilon$
6. Fracture stress, σ_f
7. Fracture strain, ε_f

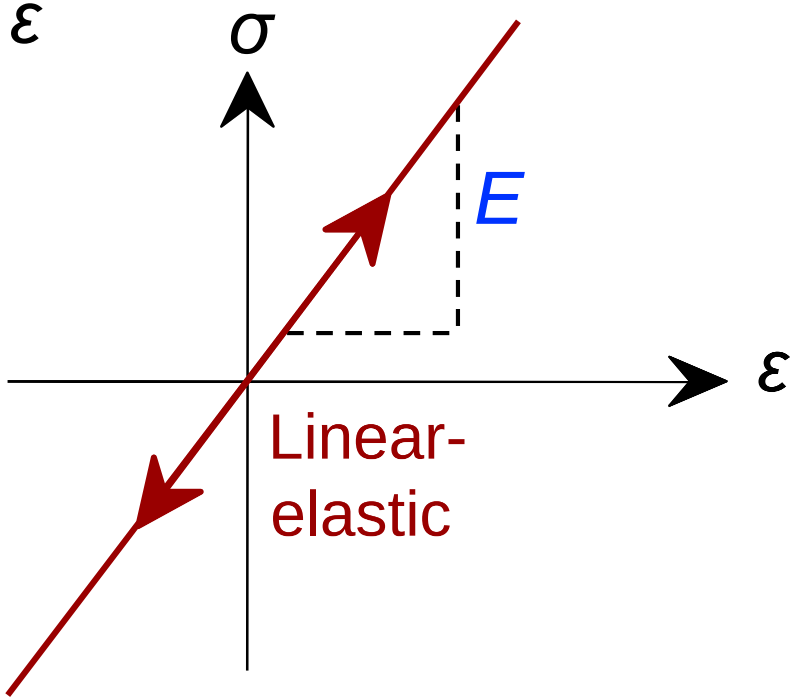


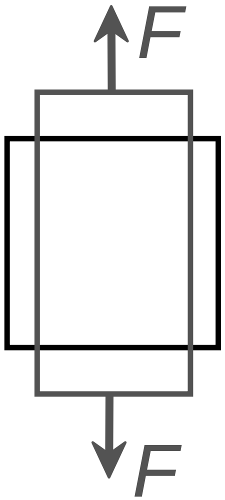
a. Elastic Properties

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

- **Hooke's Law:**

$$\sigma = E\ \varepsilon$$





Properties from Bonding: E

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

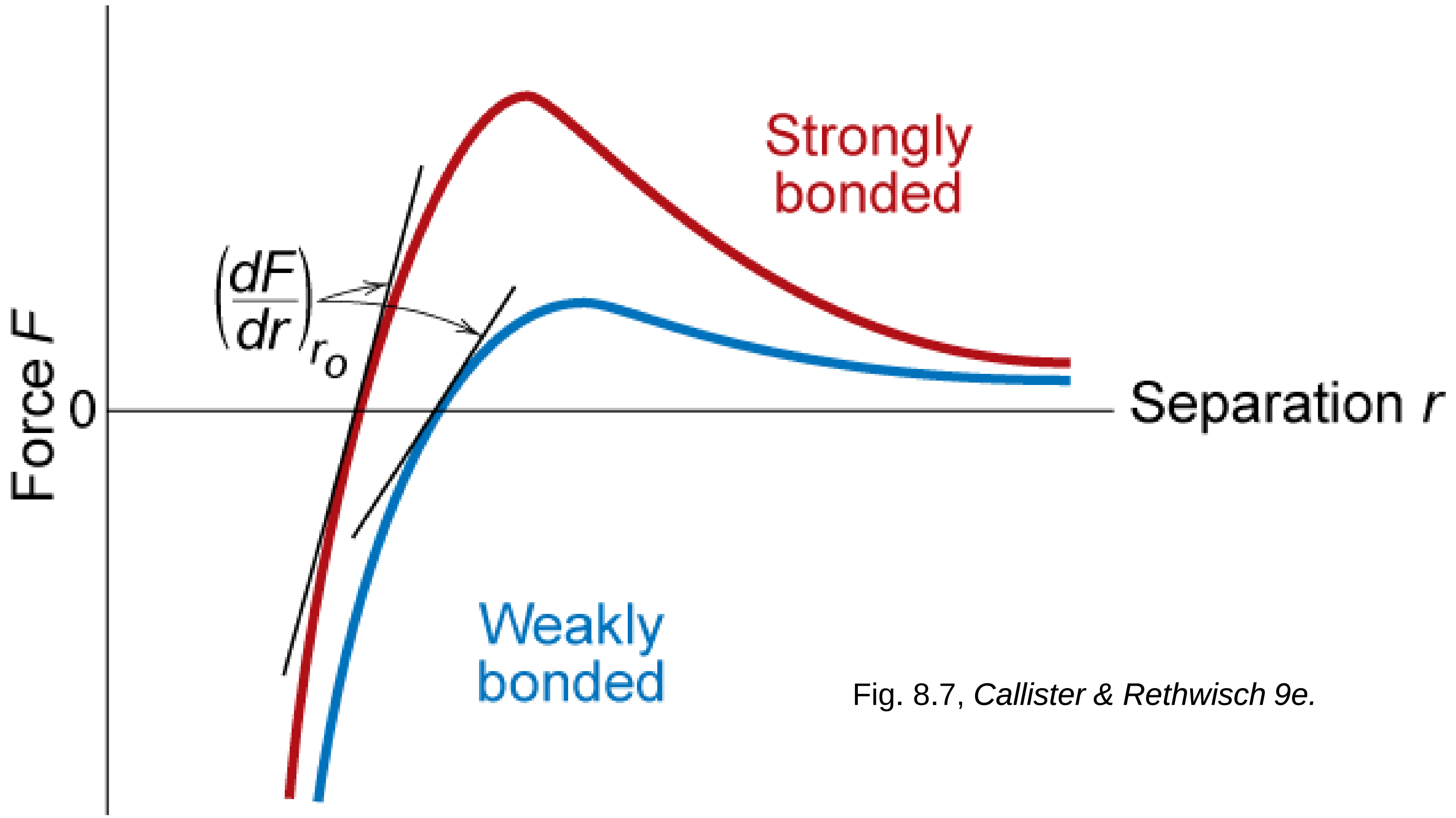


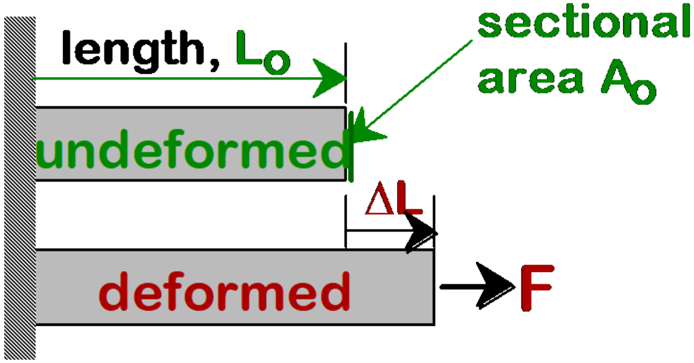
Fig. 8.7, *Callister & Rethwisch 9e.*

Properties from Bonding: E

Elastic modulus

$$\frac{F}{A_o} = E\,\frac{\Delta L}{L_o}$$

- Elastic (Young's) modulus, E (Y)

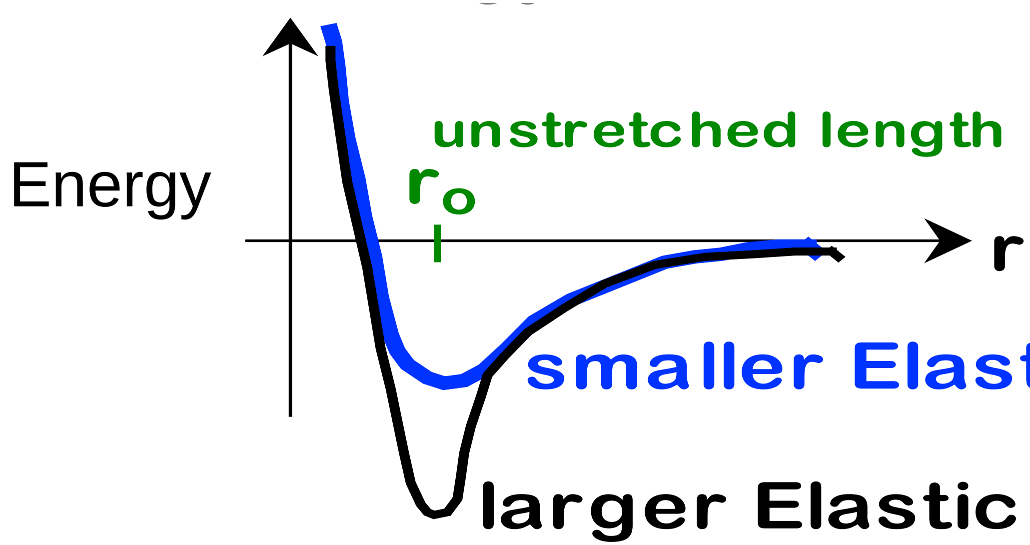


$$\frac{F}{A_o} = E\,\frac{\Delta L}{L_o}$$

$$\sigma = Y\varepsilon$$

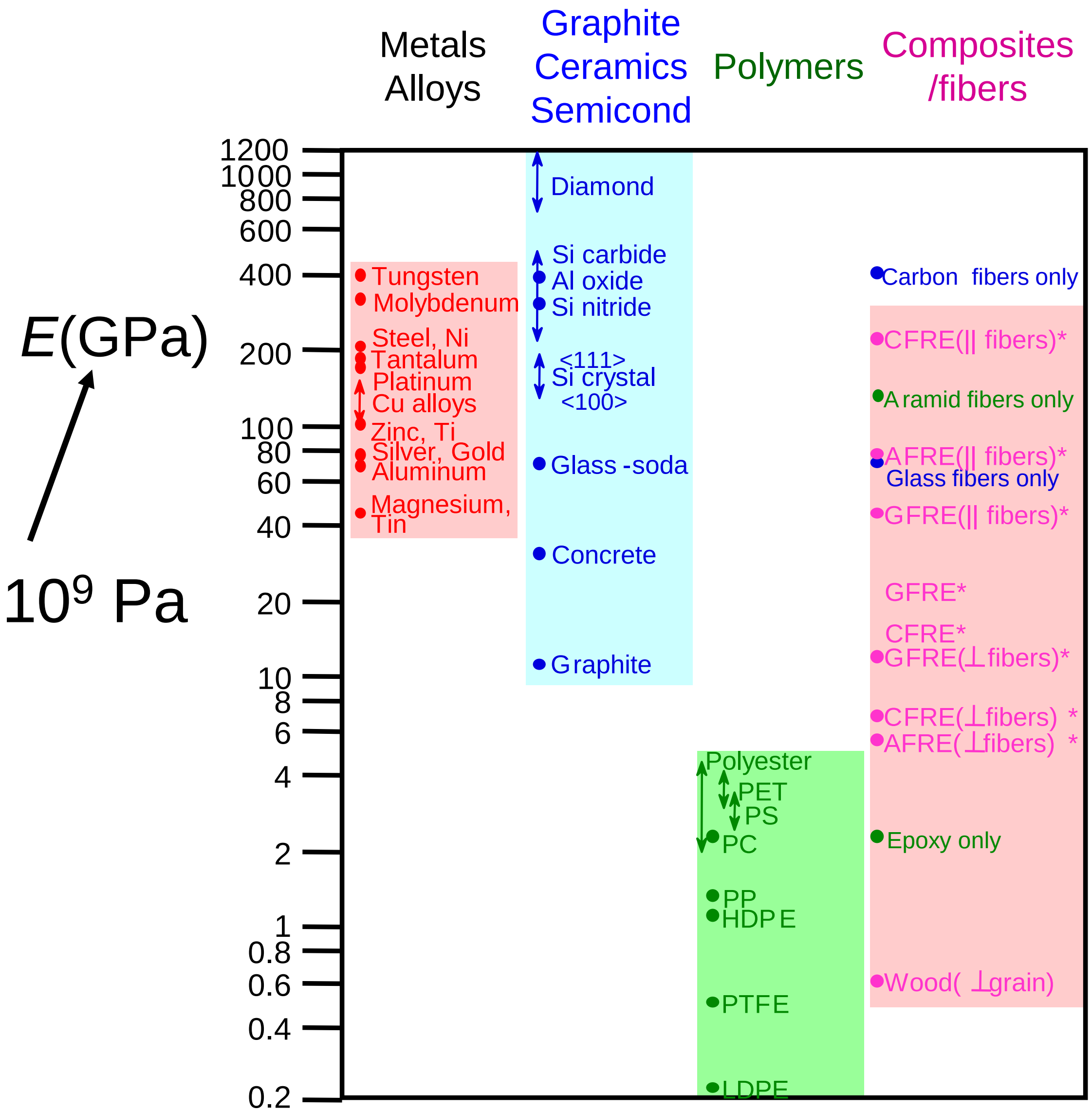
- E ~ curvature at r_o (the bottom of the well)

$$Y \sim \frac{d^2E}{dr^2}\Big)_{r_o}$$



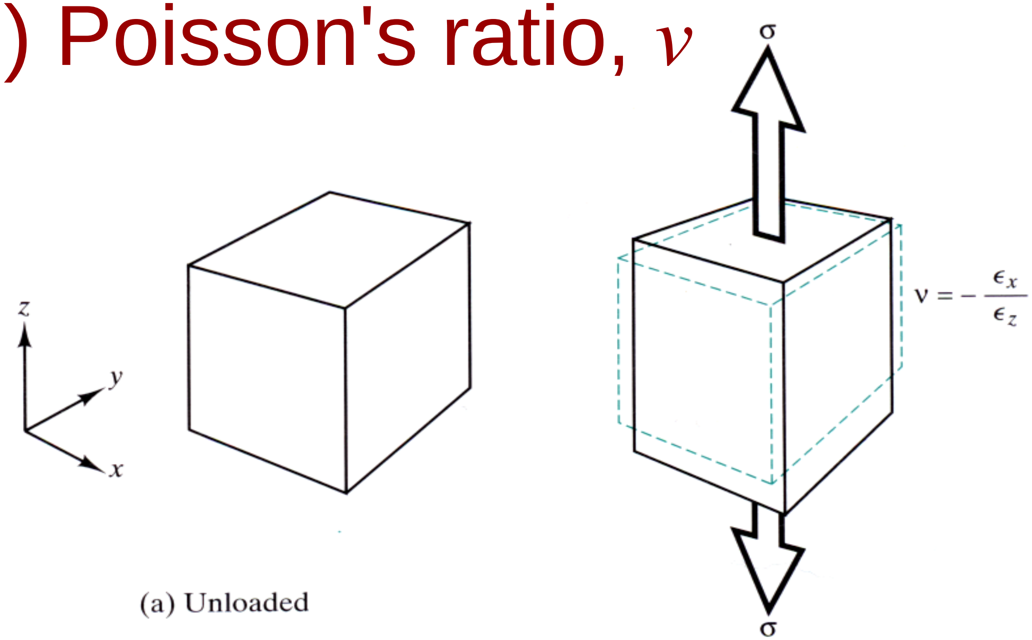
E is larger if E_o is larger

Young’s Moduli: Comparison



Based on data in Table B.2, *Callister & Rethwisch 9e.*
Composite data based on reinforced epoxy with 60 vol% of aligned carbon (CFRE), aramid (AFRE), or glass (GFRE) fibers.

(2) Poisson's ratio, ν



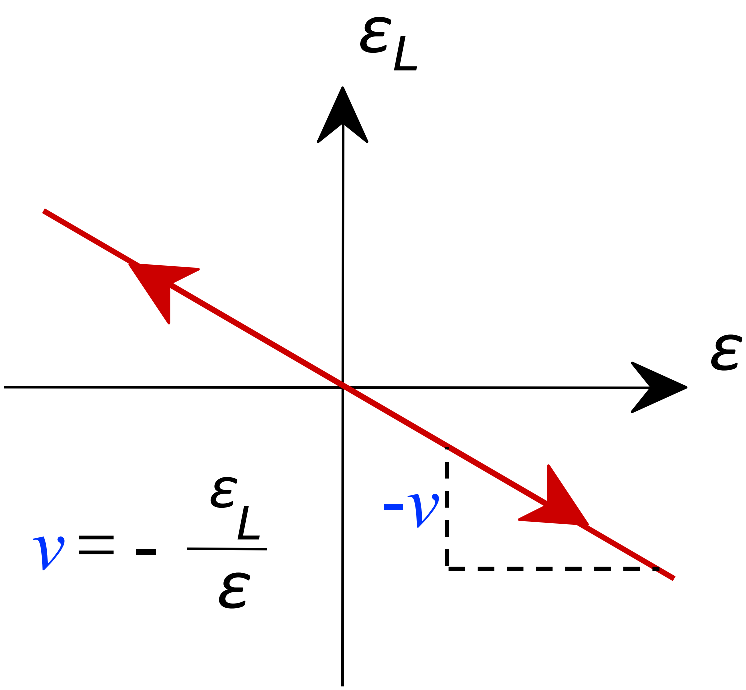
(a) Unloaded

(b) Loaded

Poisson's ratio

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

Estimation of ν



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

$\nu > 0.50$ density increases

$\nu < 0.50$ density decreases (voids form)

Measured values of Poisson's ratio

metals: $\nu \sim 0.33$
ceramics: $\nu \sim 0.25$
polymers: $\nu \sim 0.40$

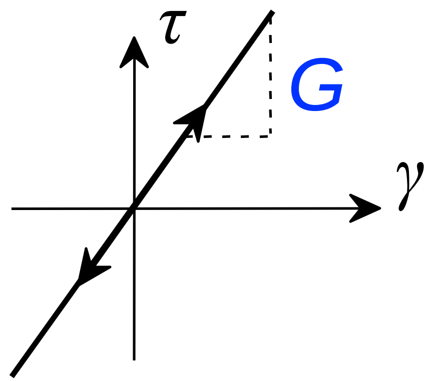
		ν
1.	Al_2O_3	0.26
2.	BeO	0.26
3.	CeO_2	0.27–0.31
4.	Cordierite ($2MgO \cdot 2Al_2O_3 \cdot 5SiO_2$)	0.31
5.	Mullite ($3Al_2O_3 \cdot 2SiO_2$)	0.25
6.	SiC	0.19
7.	Si_3N_4	0.24
8.	TaC	0.24
9.	TiC	0.19
10.	TiO_2	0.28
11.	Partially stabilized ZrO_2	0.23
12.	Fully stabilized ZrO_2	0.23–0.32
13.	Glass-ceramic ($MgO-Al_2O_3-SiO_2$)	0.24
14.	Borosilicate glass	0.2
15.	Glass from cordierite	0.26

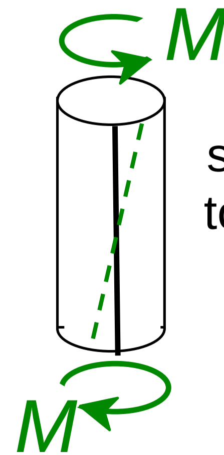
Source: Data from *Ceramic Source '86* and *Ceramic Source '87*, American Ceramic Society, Columbus, OH, 1985 and 1986.

(3) Other Elastic Properties

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

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

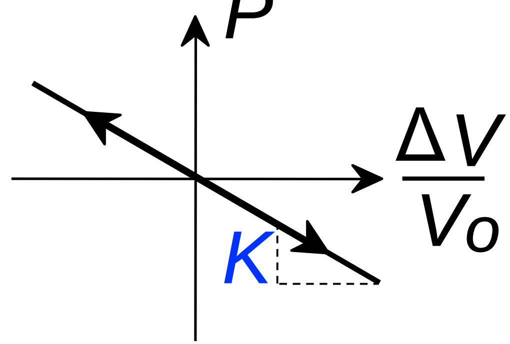


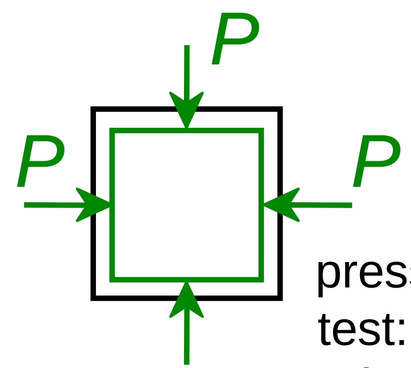


simple torsion test

- **Elastic Bulk modulus, K:**

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





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

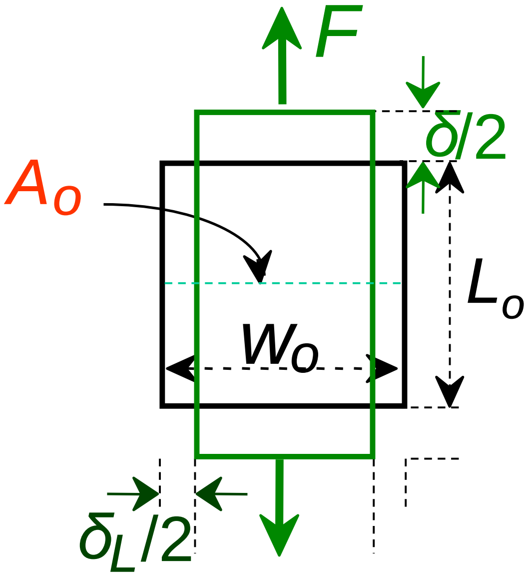
- **Special relations for isotropic materials:**

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

(4) Useful Linear Elastic Relationships

- **Simple tension:**

$$\delta = \frac{F L_o}{E A_o} \qquad \delta_L = -\nu \frac{F w_o}{E A_o}$$

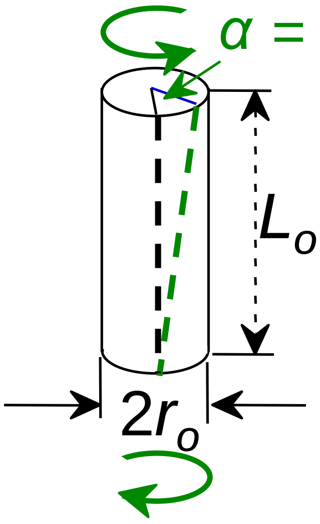


- **Simple torsion:**

$$\alpha = \frac{2 M L_o}{\pi r_o^4 G}$$

M = moment

α = angle of twist

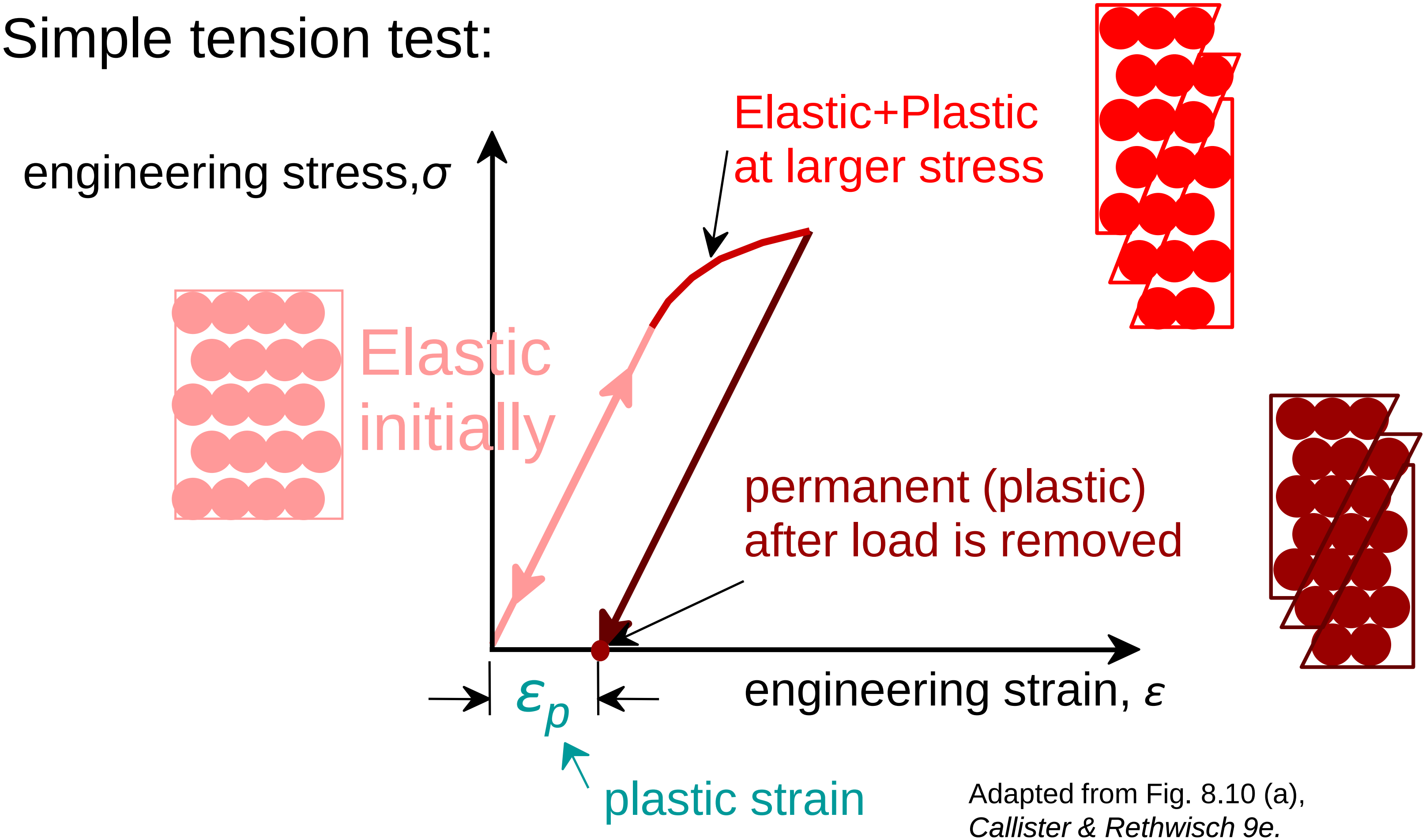


- Material, geometric, and loading parameters all contribute to deflection.
- Larger elastic moduli minimize elastic deflection.

Plastic (Permanent) Deformation

(at lower temperatures, i.e. $T < T_{melt}/3$)

- Simple tension test:

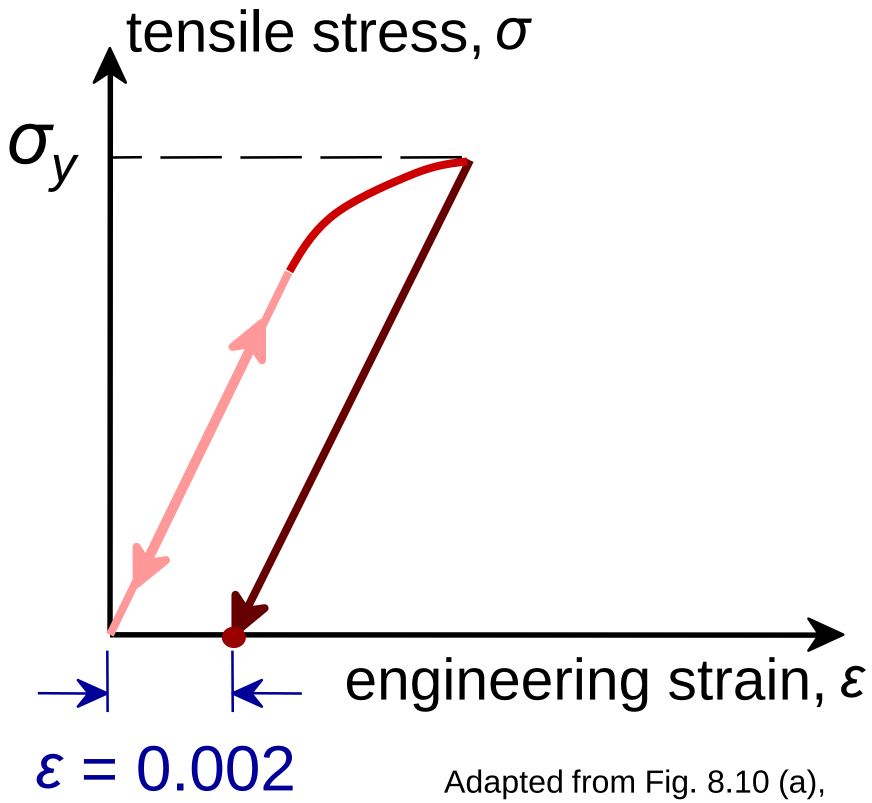


Adapted from Fig. 8.10 (a), *Callister & Rethwisch 9e.*

b. Yield Strength, σ_y

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

when $\varepsilon = 0.002$



Adapted from Fig. 8.10 (a), *Callister & Rethwisch 9e.*

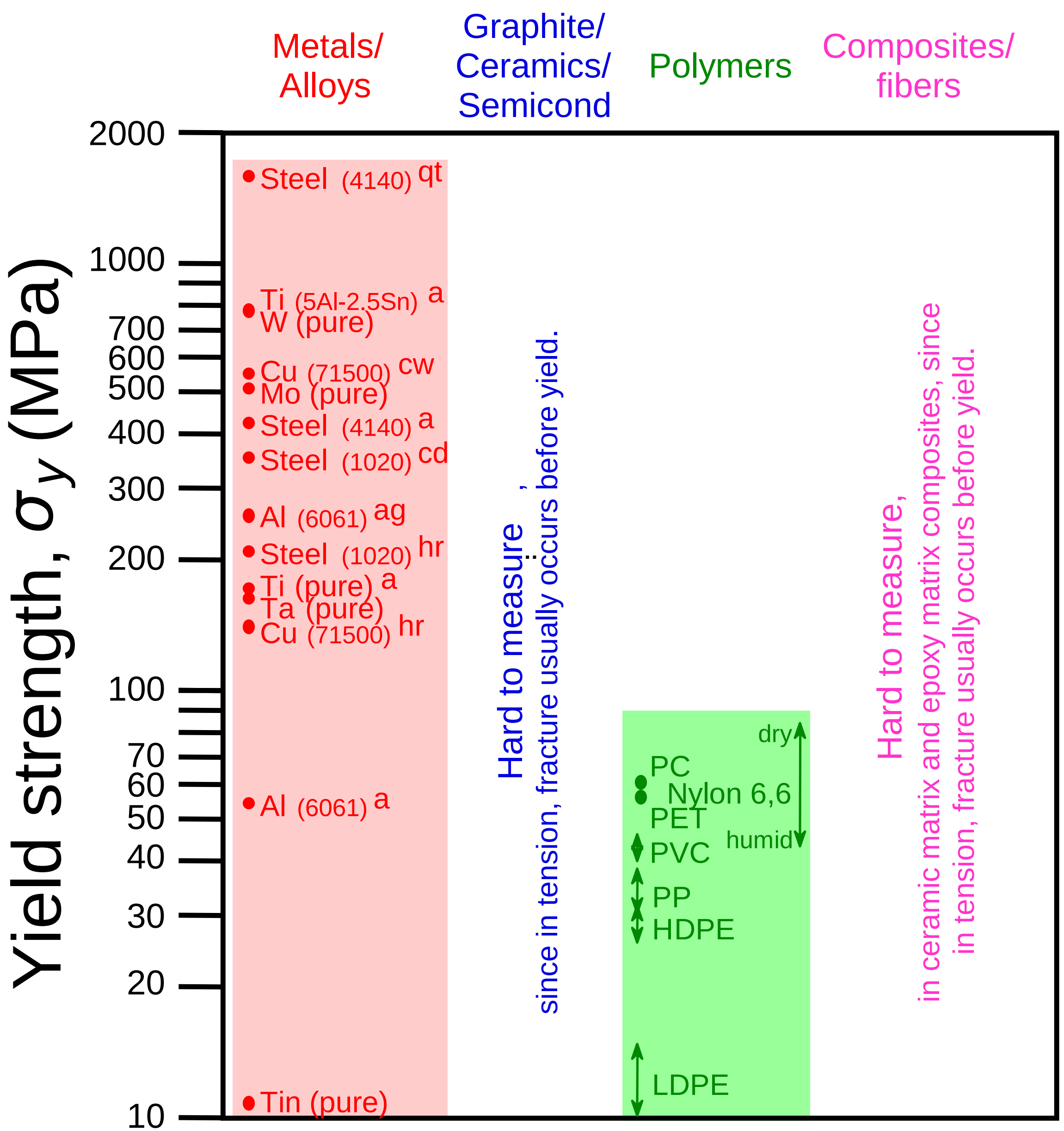
σ_y = yield strength

Note: for 2 inch sample

$\varepsilon = 0.002 = \Delta z/z$

$\therefore \Delta z = 0.004$ in

Yield Strength : Comparison



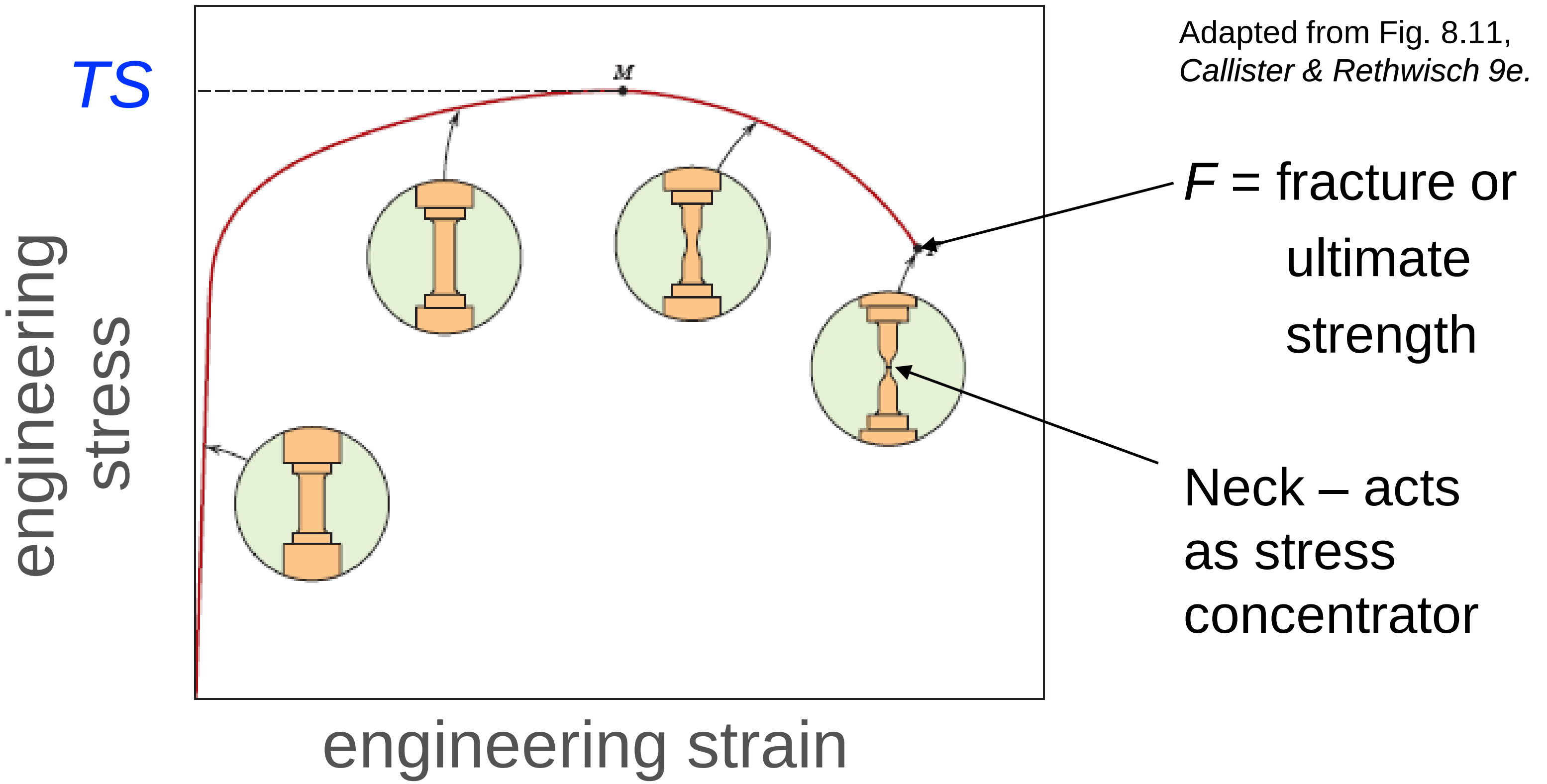
Room temperature values

Based on data in Table B.4, *Callister & Rethwisch 9e.*

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

c. Tensile Strength, TS

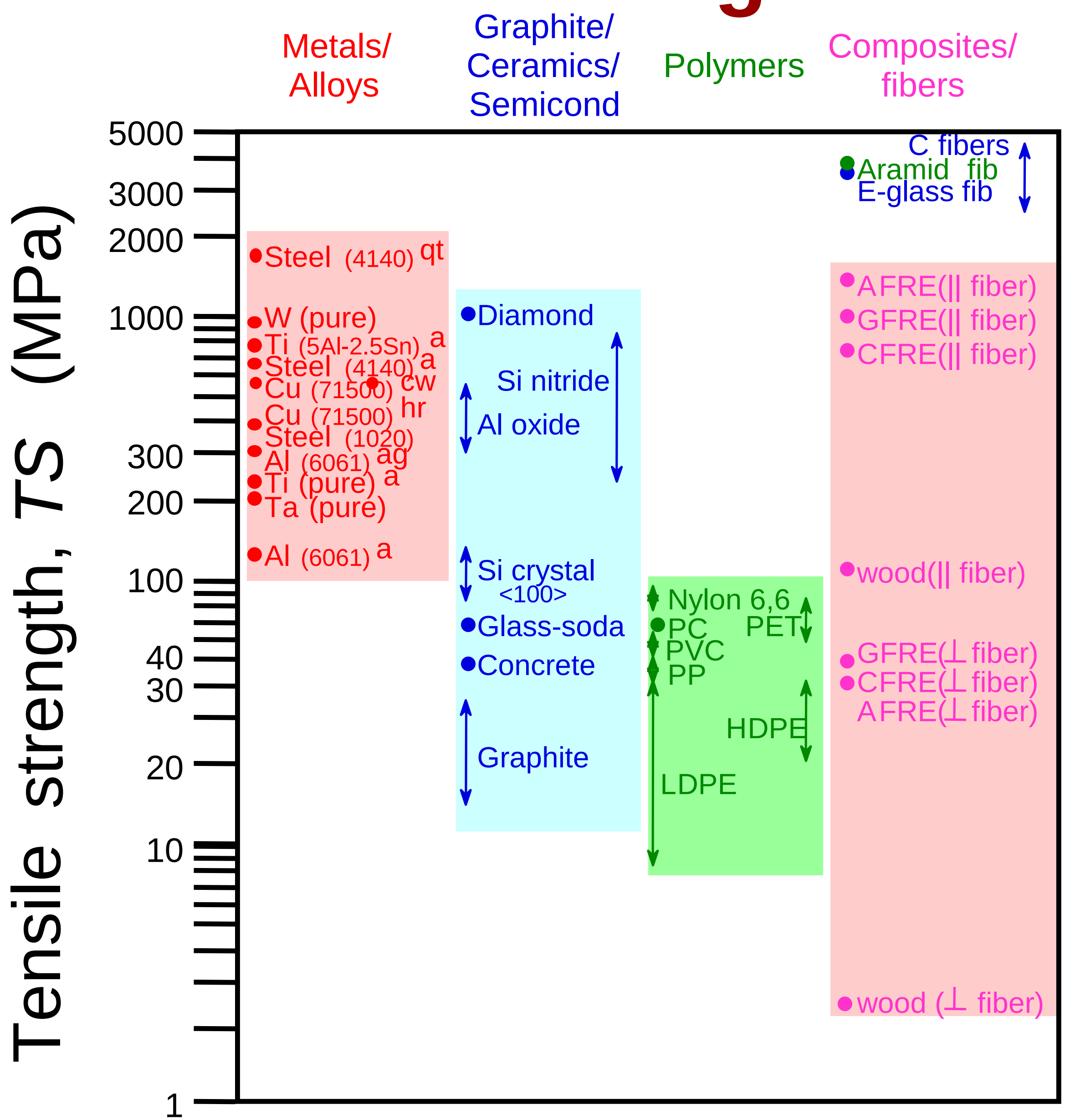
- Maximum stress on engineering stress-strain curve.



Adapted from Fig. 8.11, *Callister & Rethwisch 9e.*

- Metals: occurs when noticeable necking starts.
- Polymers: occurs when polymer backbone chains are aligned and about to break.

Tensile Strength: Comparison



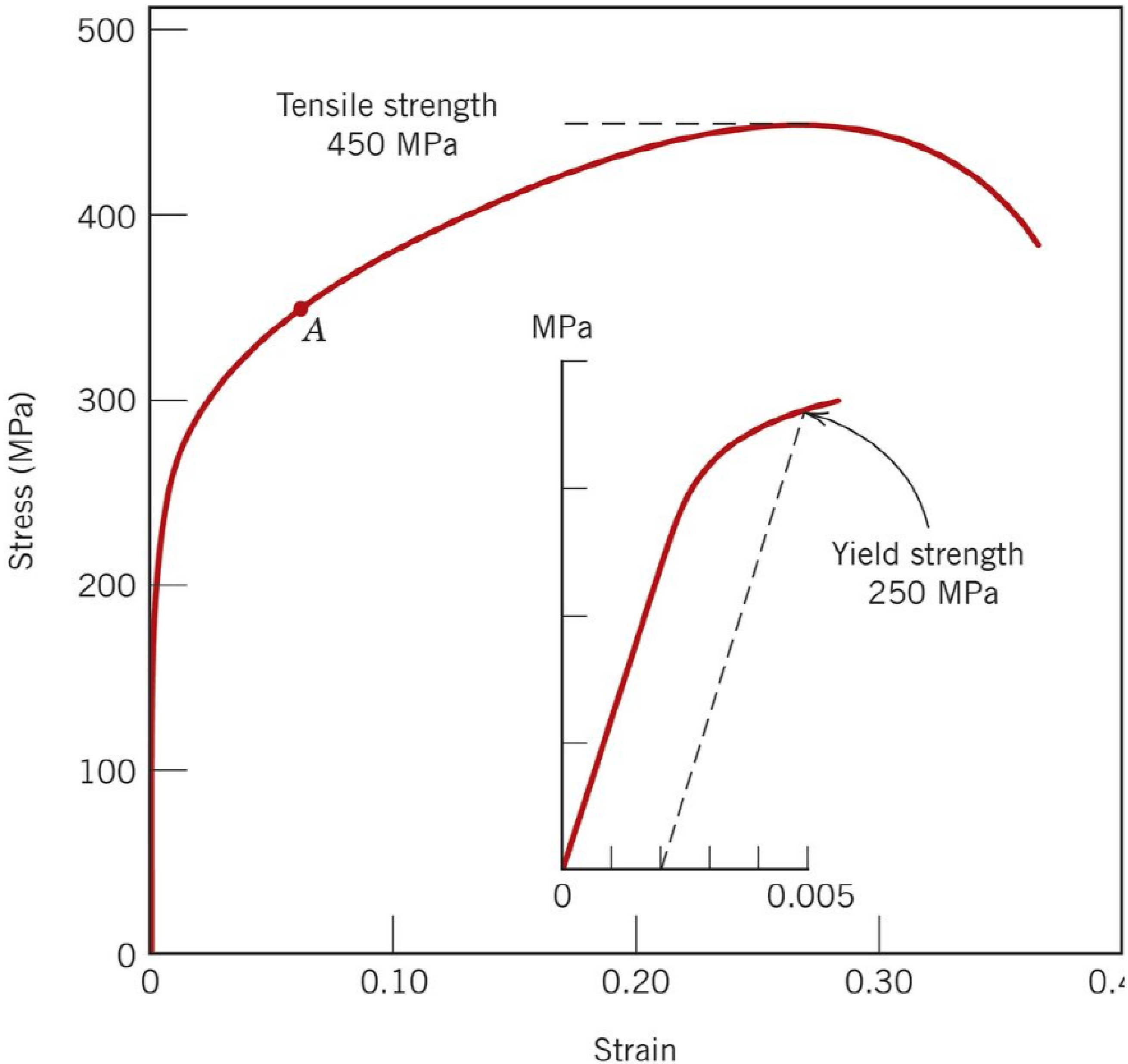
Room temperature values

Based on data in Table B4, *Callister & Rethwisch 9e.*

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

AFRE, GFRE, & CFRE = aramid, glass, & carbon fiber-reinforced epoxy composites, with 60 vol% fibers.

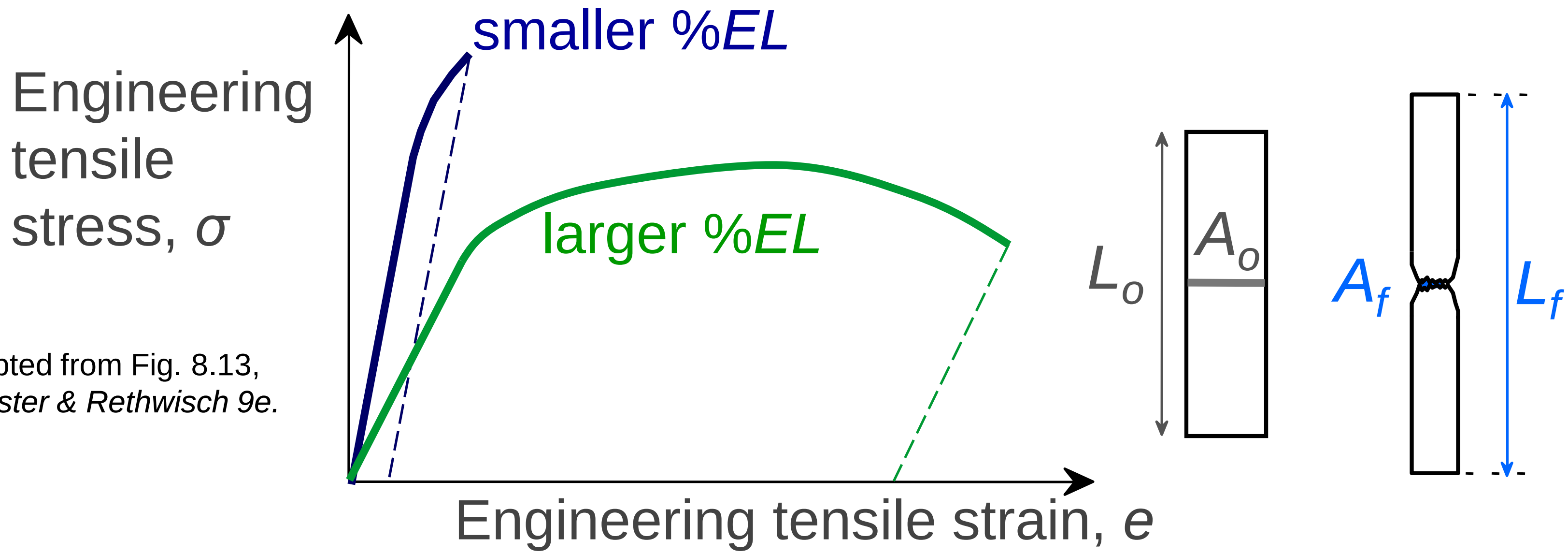
Figure 8.12 in the textbook



d. Ductility

- **Plastic tensile strain at failure**:

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



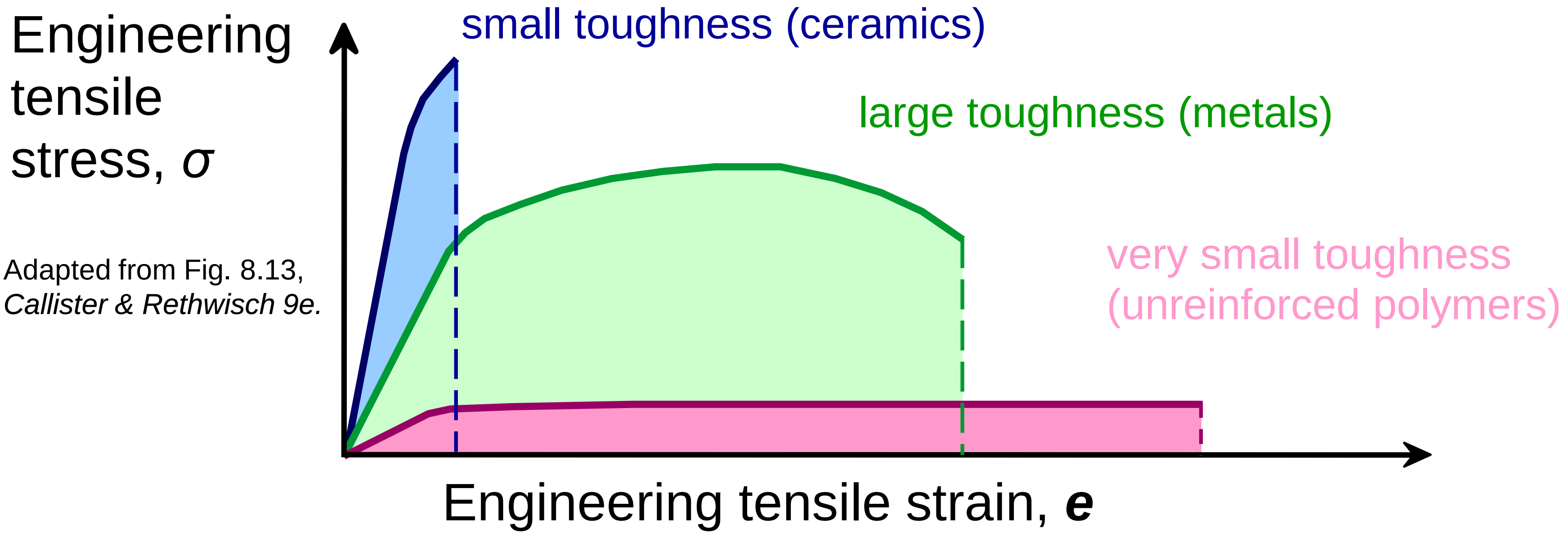
Adapted from Fig. 8.13, *Callister & Rethwisch 9e.*

- Another ductility measure:

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

e. Toughness

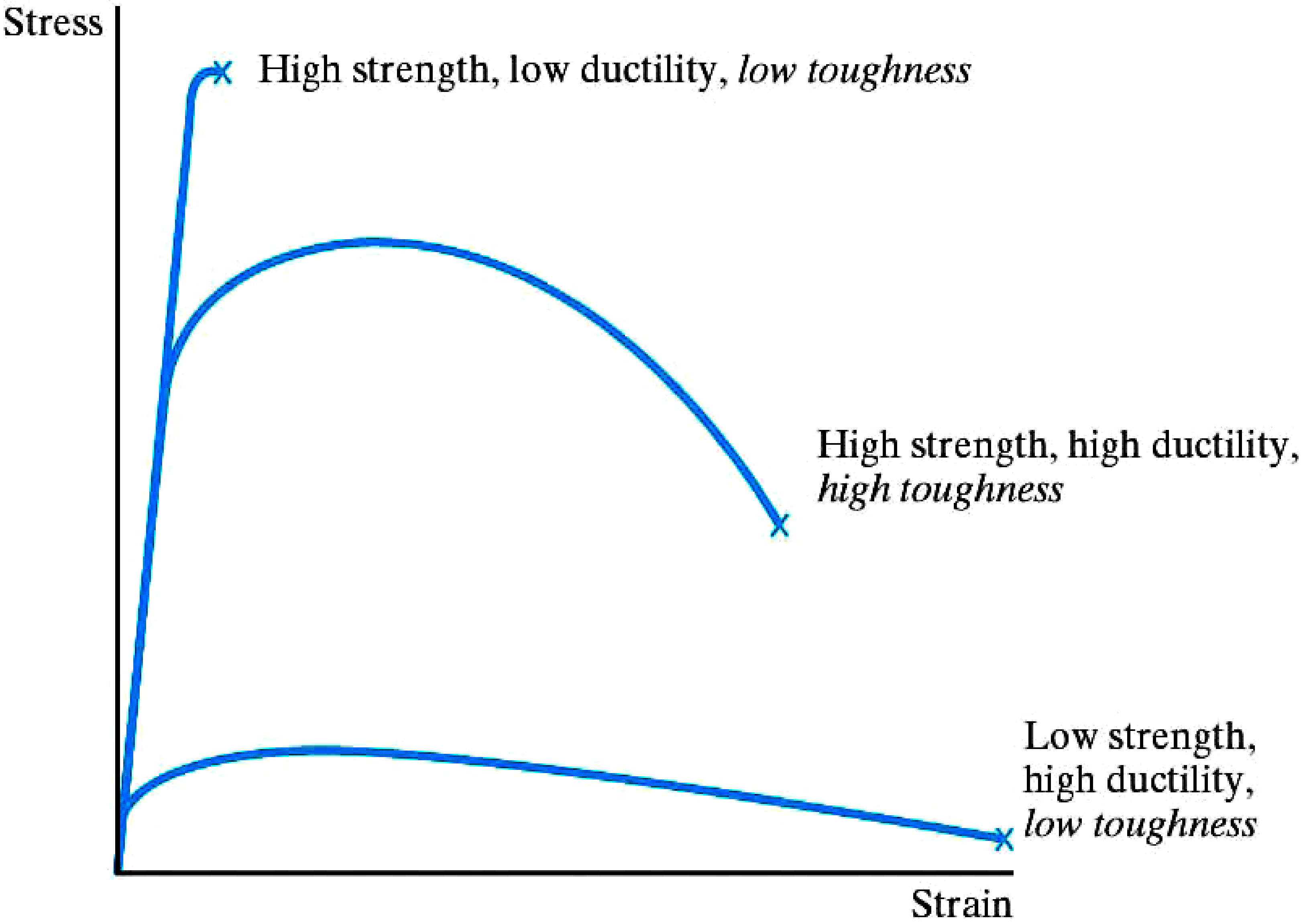
- **Energy to break a unit volume of material**
- Approximate by the area under the stress-strain curve.



Adapted from Fig. 8.13, *Callister & Rethwisch 9e.*

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

Tensile Test



f. Resilience, U_r

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

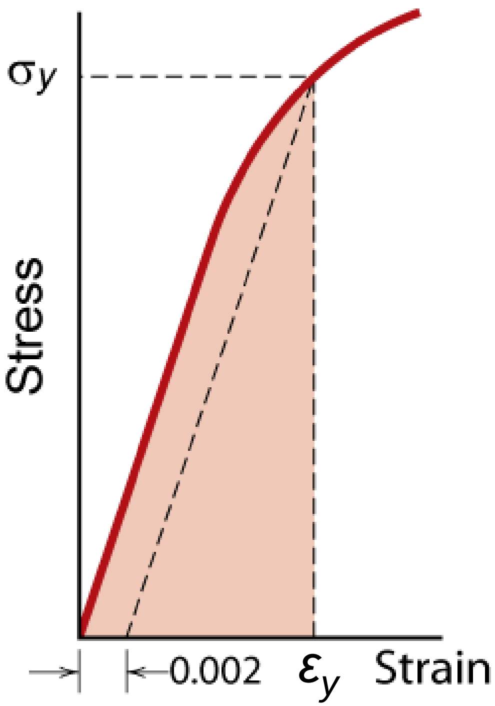


Fig. 8.15, *Callister & Rethwisch 9e.*

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

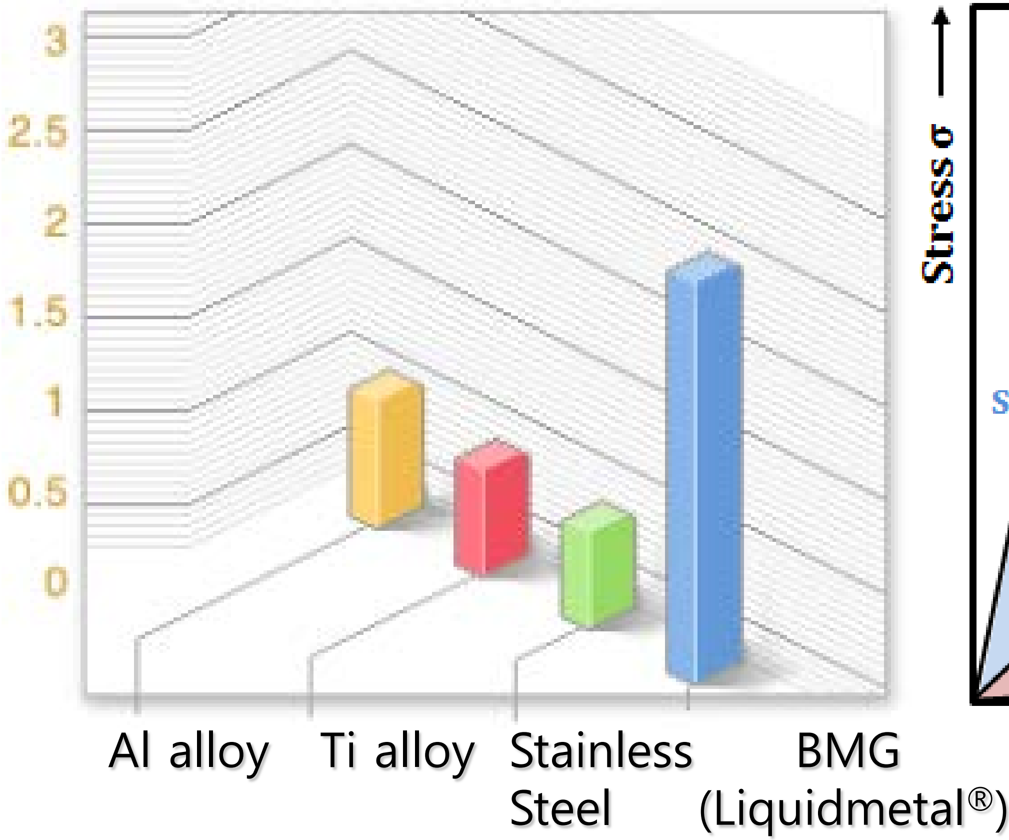
If we assume a linear stress-strain curve this simplifies to

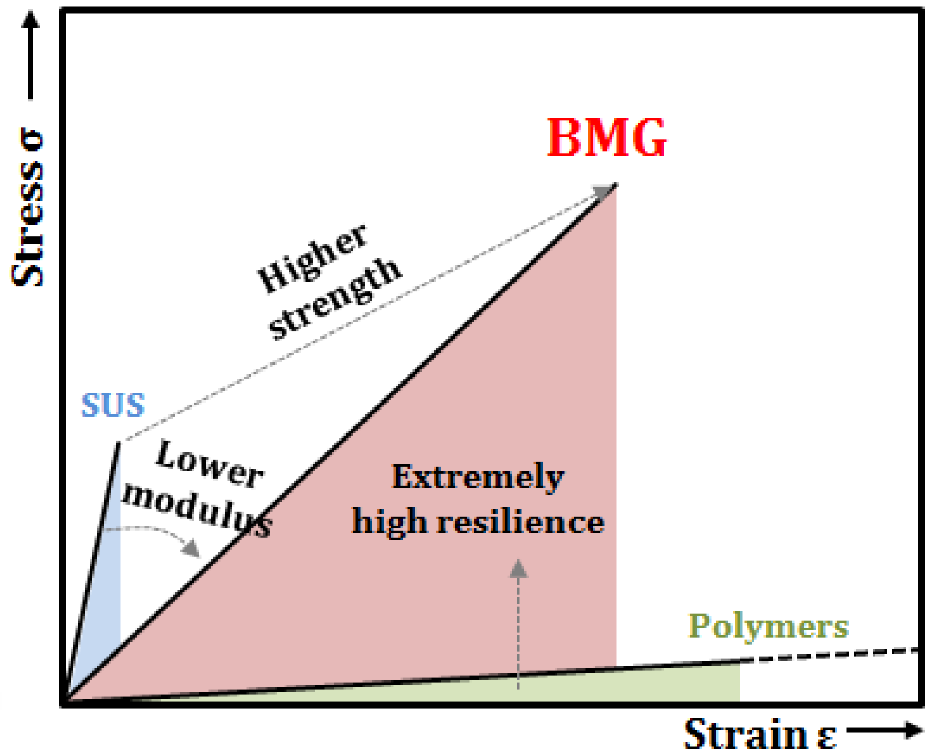
$$U_r \cong \frac{1}{2}\sigma_y \varepsilon_y$$

Large elastic strain limit of BMGs

Elastic Strain Limit

[as % of Original Shape]





* **Resilience: ability to return to the original form, position, etc.** → $U = \frac{\sigma_y 2}{2E}$

Large elastic strain limit of BMGs

VI. Elastic Strain Recovery

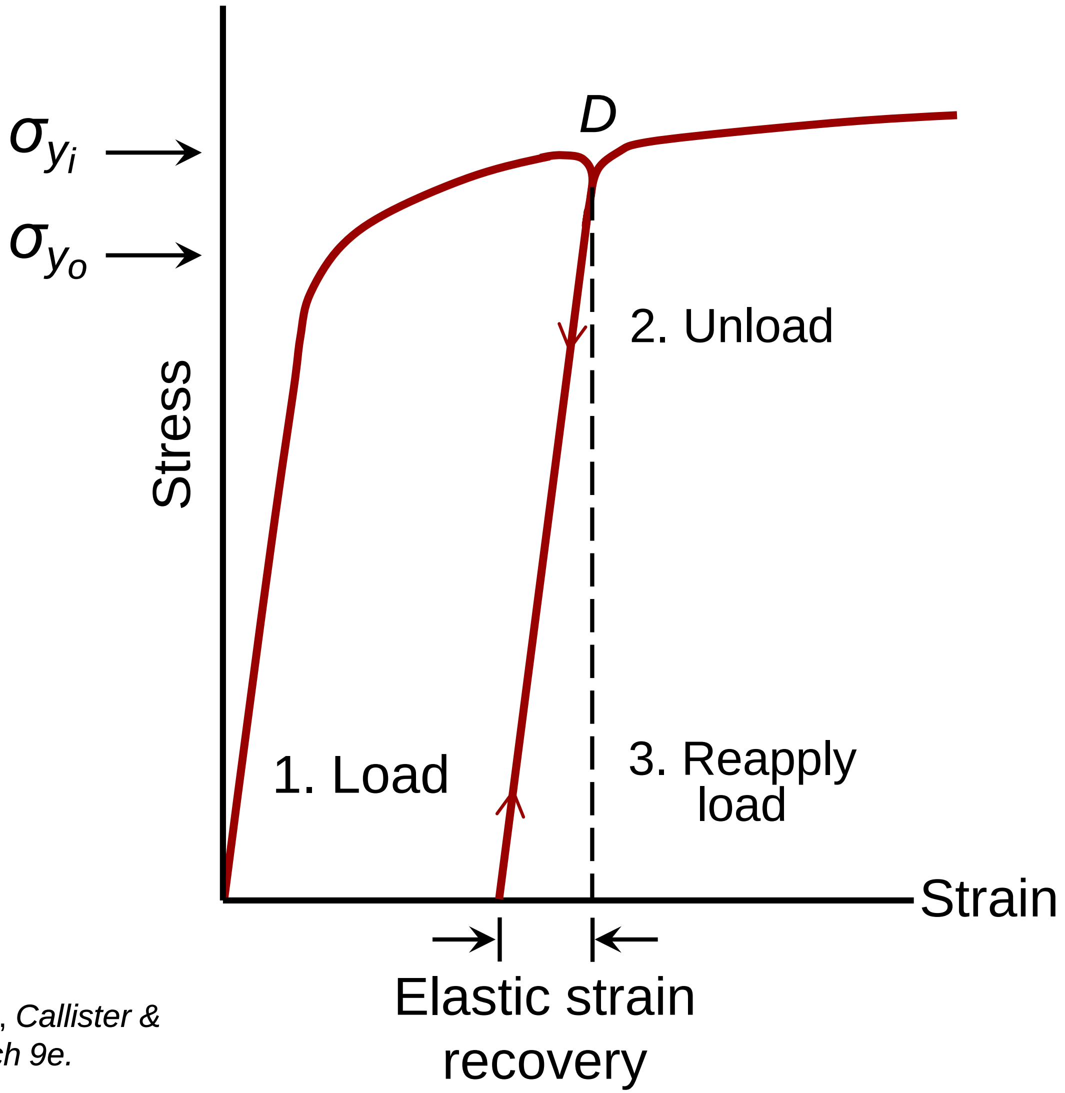
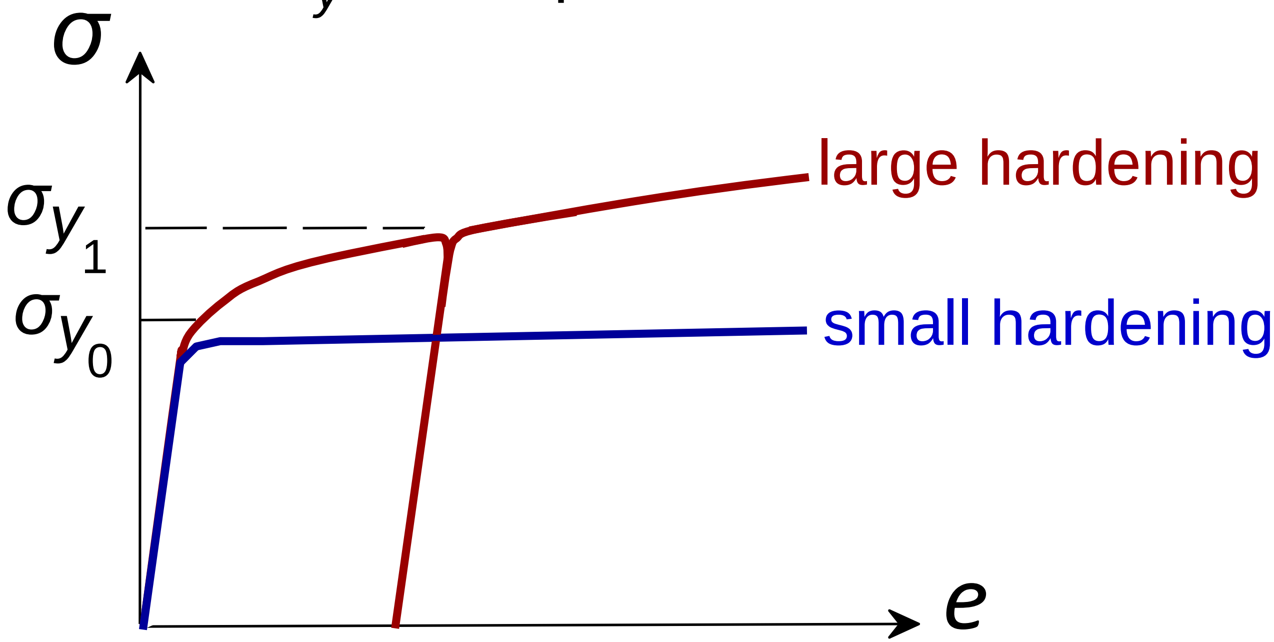


Fig. 8.17, *Callister & Rethwisch 9e.*

VII. Hardening

- An increase in σ_y due to plastic deformation.



- Curve fit to the stress-strain response:

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

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

"true" stress (F/A)

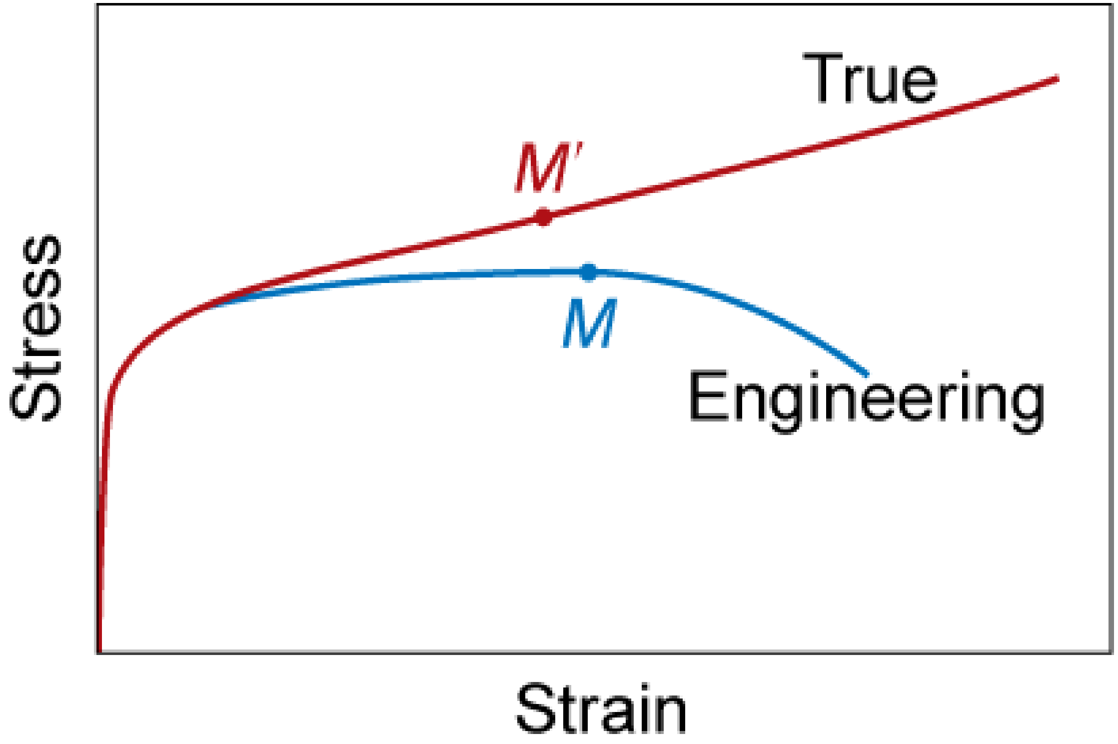
"true" strain: $\ln(\ell/\ell_o)$

VIII. True Stress & Strain

Note: *<u>Cross-sectional area</u>* changes when sample stretched

- True stress $\sigma_T = F/A_i$
- True strain $\epsilon_T = \ln\left(\ell_i/\ell_o\right)$

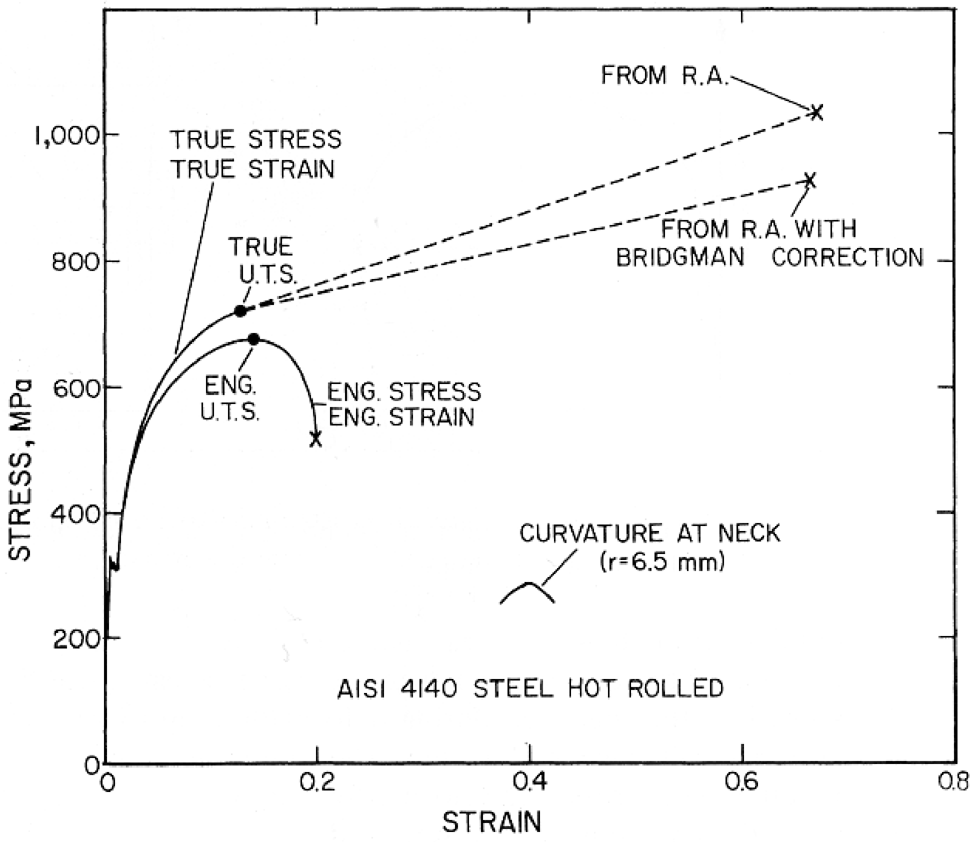
$$\sigma_T = \sigma\left(1+\epsilon\right)$$
$$\epsilon_T = \ln\left(1+\epsilon\right)$$



Adapted from Fig. 8.16,
Callister & Rethwisch 9e.

Necking – Work hardening

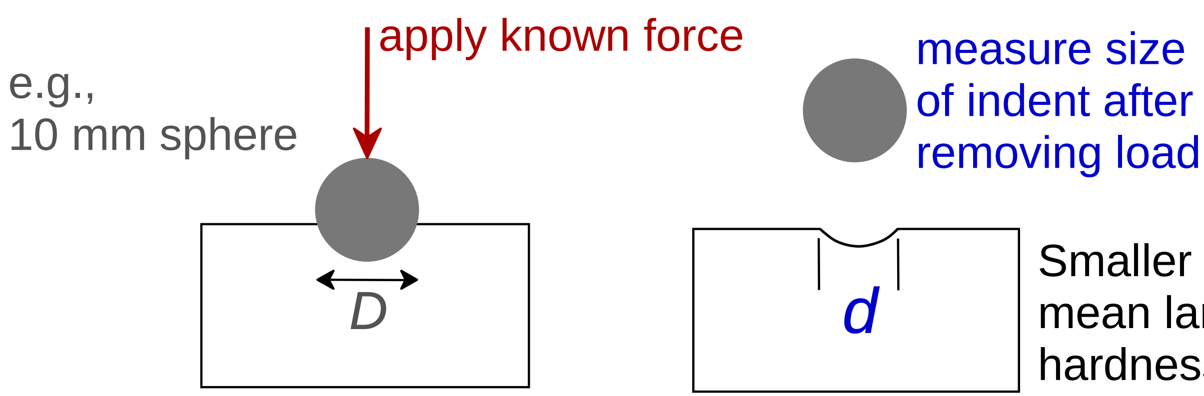
Represented as $\sigma = \sigma_0 + K\varepsilon^n$ Hollomon's eq



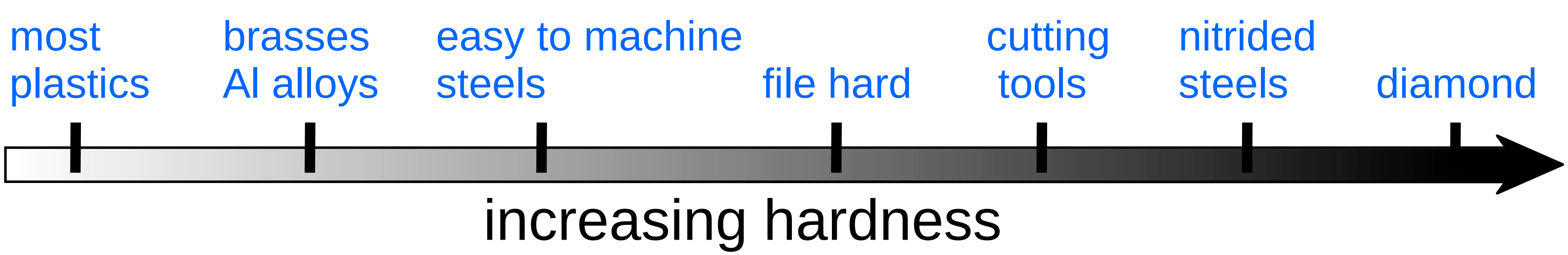
~~What is n? -> meaning from the relationship of stress-strain~~

IX. Hardness

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



Smaller indents mean larger hardness.



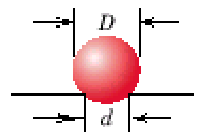
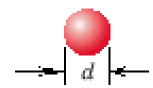
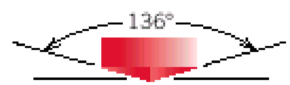
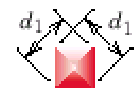
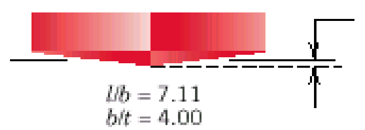
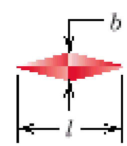
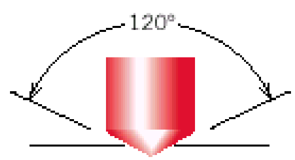
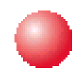
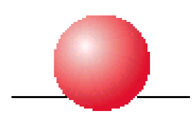
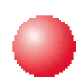
Hardness: Measurement

- 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=pounds per square inch) = 500 x HB
  - *TS* (MPa) = 3.45 x HB

Hardness: Measurement

Table 8.5 **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	$HB = \frac{2P}{\pi D[D - \sqrt{D^2 - d^2}]}$
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	
					

[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.

X. Variability in Material Properties

- Elastic modulus is material property
- Critical properties depend largely on sample flaws (defects, etc.). Large sample to sample variability.
- Statistics
  - Mean

$$\bar{x} = \frac{\sum^{n} x_n}{n}$$

  - Standard Deviation

$$s = \left[\frac{\sum^{n} \left(x_i - \bar{x} \right)^2}{n-1} \right]^{\frac{1}{2}}$$

where *n* is the number of data points

XI. Design or Safety Factors

- Design uncertainties mean we do not push the limit.
- Factor of safety, *N*

$$\sigma_{working} = \frac{\sigma_y}{N}$$

Often *N* is between 1.2 and 4

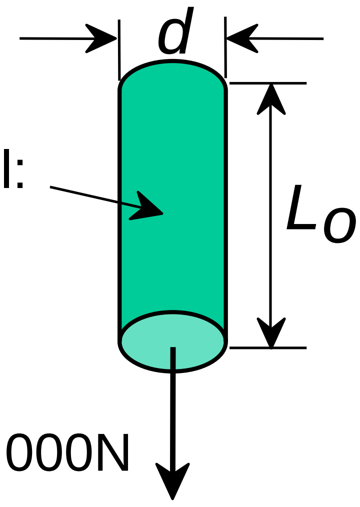
- Example: Calculate a diameter, *d*, to ensure that yield does not occur in the 1045 carbon steel rod below. Use a factor of safety of 5.

$$\sigma_{working} = \frac{\sigma_y}{N}$$

$$\frac{220{,}000\text{N}}{\pi\left(d^2/4\right)}$$

5

1045 plain carbon steel:
σ_y = 310 MPa
TS = 565 MPa



F = 220,000N

$d = 0.067$ m $= 6.7$ cm

Summary

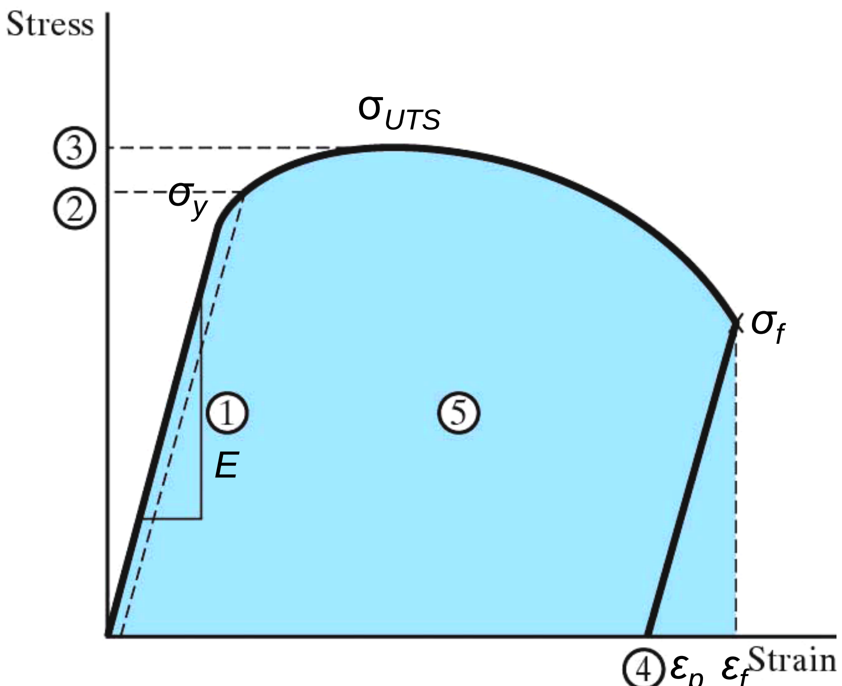
Chapter 8: Mechanical Properties of Metals

- 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.

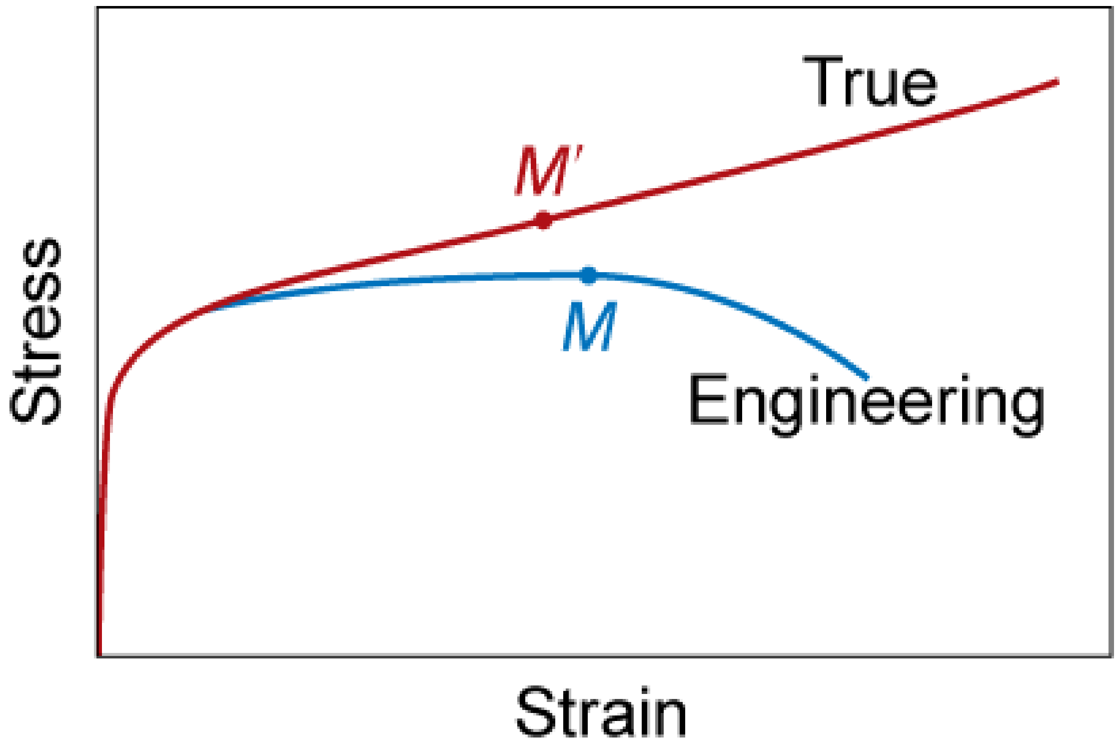
Deformation

- Elastic vs. Plastic region
- Key points

    1. Elastic modulus (=Young's modulus), E
    2. 0.2% (0.002 strain) yield stress, σ_y
    3. Ultimate yield stress, σ_{UTS}
    4. Ductility, ε_p
    5. Toughness → $\int \sigma d\varepsilon$
    6. Fracture stress, σ_f
    7. Fracture strain, ε_f



Engineering vs True Stress & Strain



Adapted from Fig. 8.16, *Callister & Rethwisch 9e.*

Variability in Material Properties : need to Statistics

Material design considering Safety factor:

$$\sigma_{working} = \frac{\sigma_y}{N}$$

Often *N* is between 1.2 and 4