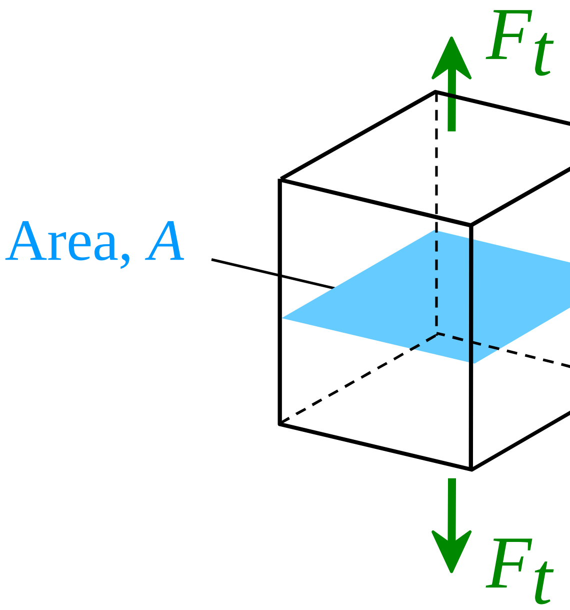
Chapter 8:
Mechanical Properties

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?

Engineering Stress

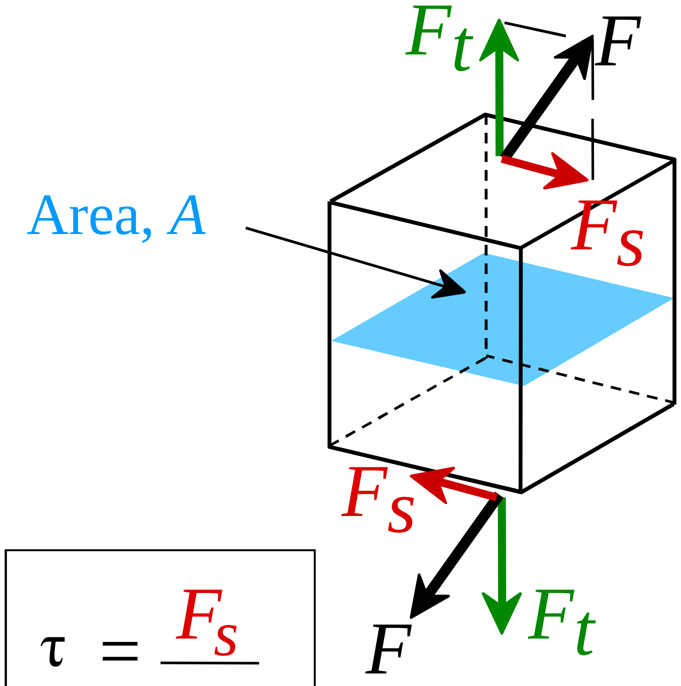
- Tensile stress, σ :



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

original area before loading

- Shear stress, τ :



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

∴ Stress has units: N/m^2 or lb_f/in^2

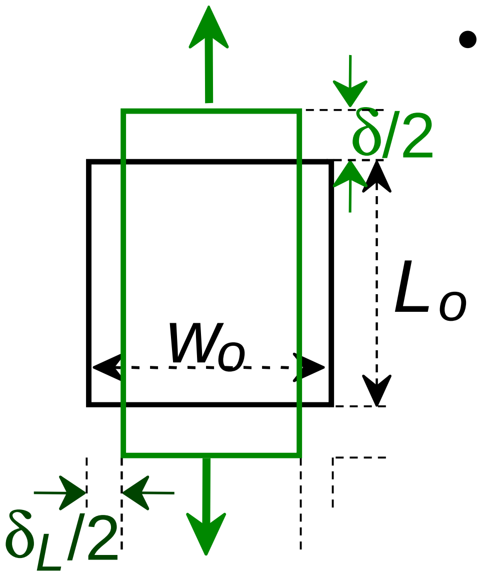
Engineering Strain

- **Tensile strain:**

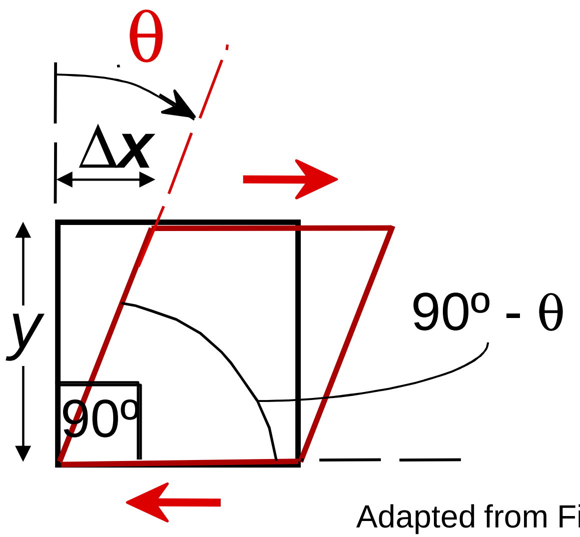
$$\varepsilon = \frac{\delta}{L_o}$$

- **Lateral strain:**

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



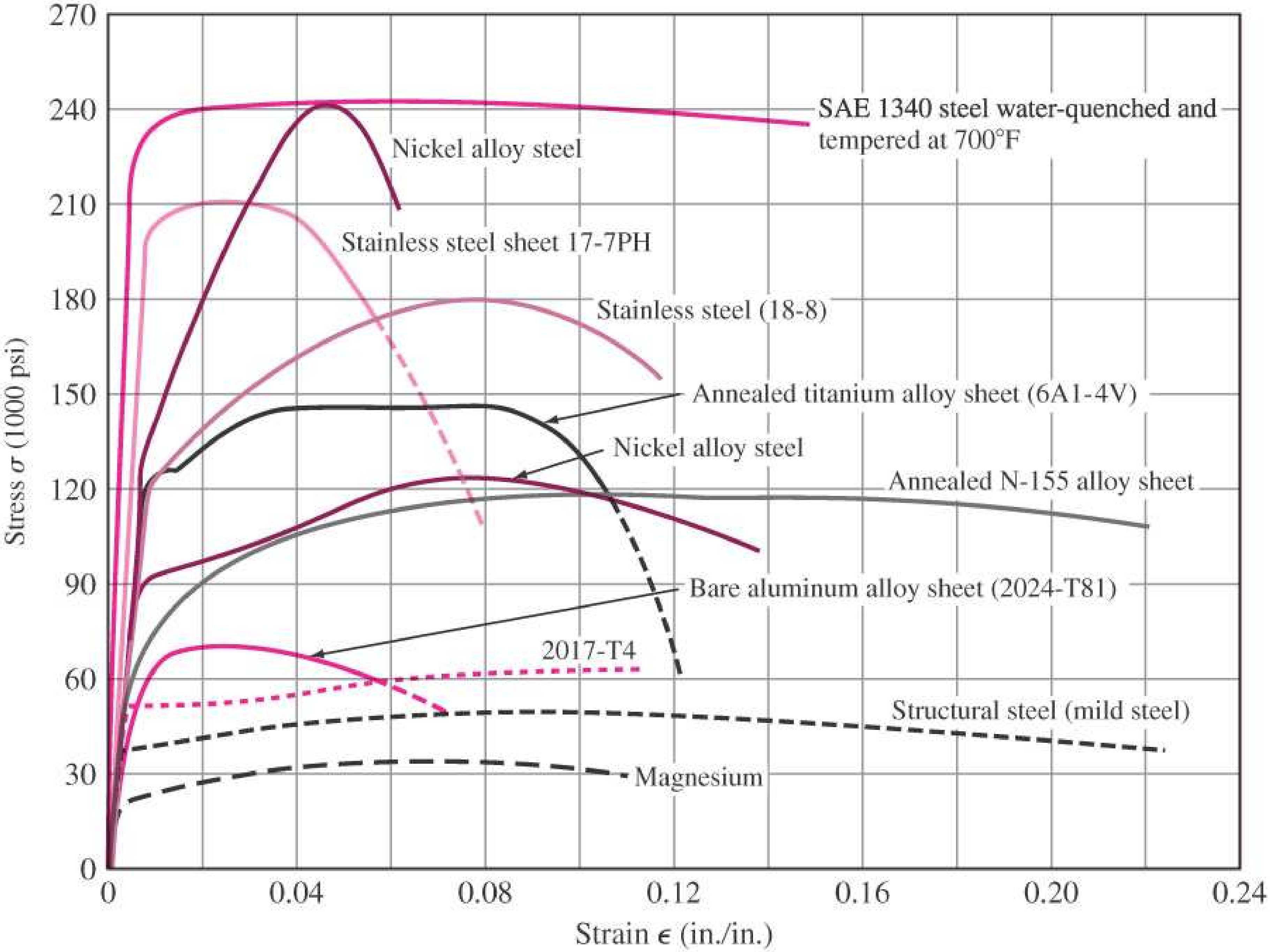
- **Shear strain:**



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

Strain is always dimensionless.

Adapted from Fig. 6.1 (a) and (c), *Callister 7e.*



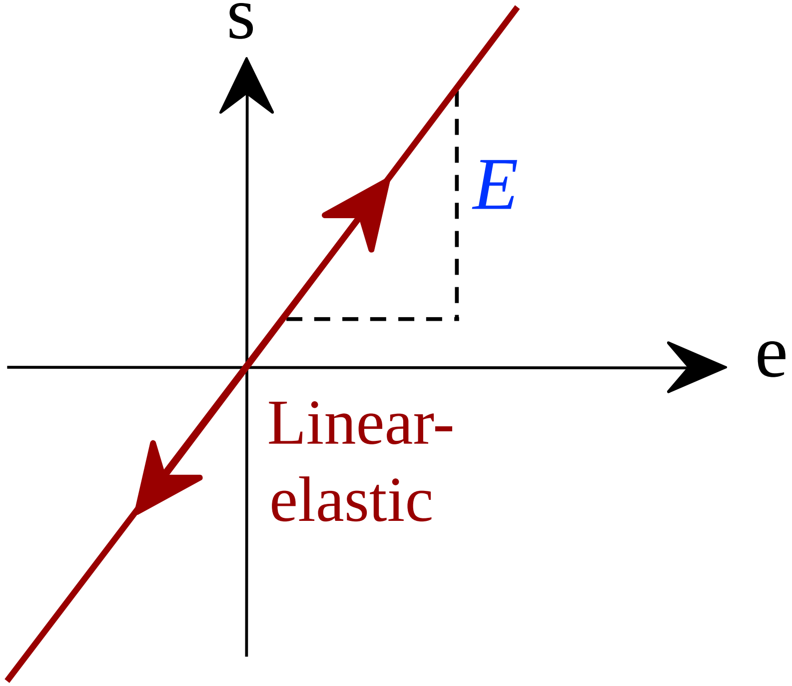
270
240
210
180
150
120
90
60
30
0
Stress σ (1000 psi)
0
0.04
0.08
0.12
0.16
0.20
0.24
Strain ϵ (in./in.)
SAE 1340 steel water-quenched and tempered at 700°F
Nickel alloy steel
Stainless steel sheet 17-7PH
Stainless steel (18-8)
Annealed titanium alloy sheet (6A1-4V)
Nickel alloy steel
Annealed N-155 alloy sheet
Bare aluminum alloy sheet (2024-T81)
2017-T4
Structural steel (mild steel)
Magnesium

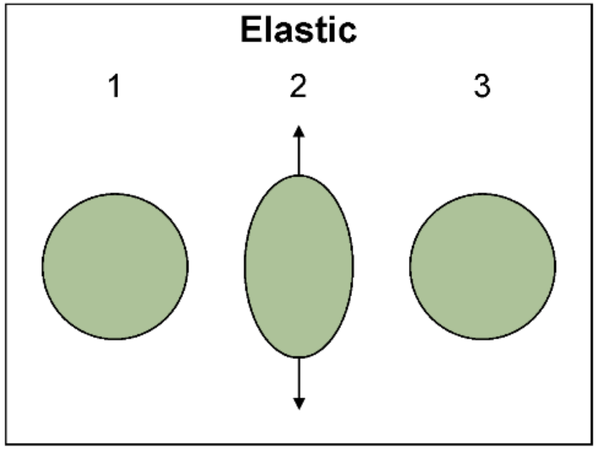
Linear Elastic Properties

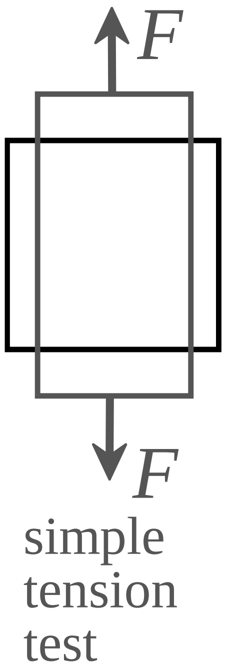
- **Modulus of Elasticity, *E*:**
  (also known as Young's modulus)

- **Hooke's Law:**

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







https://commons.wvc.edu/rdawes/g101ocl/Basics/earthquakes.html

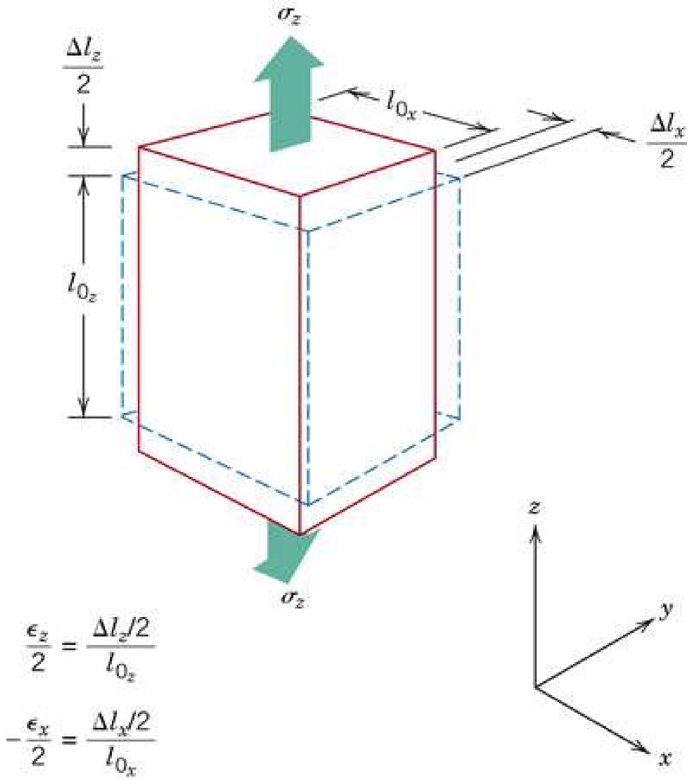
Poisson's ratio, n

- **Poisson's ratio, ν:**

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

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

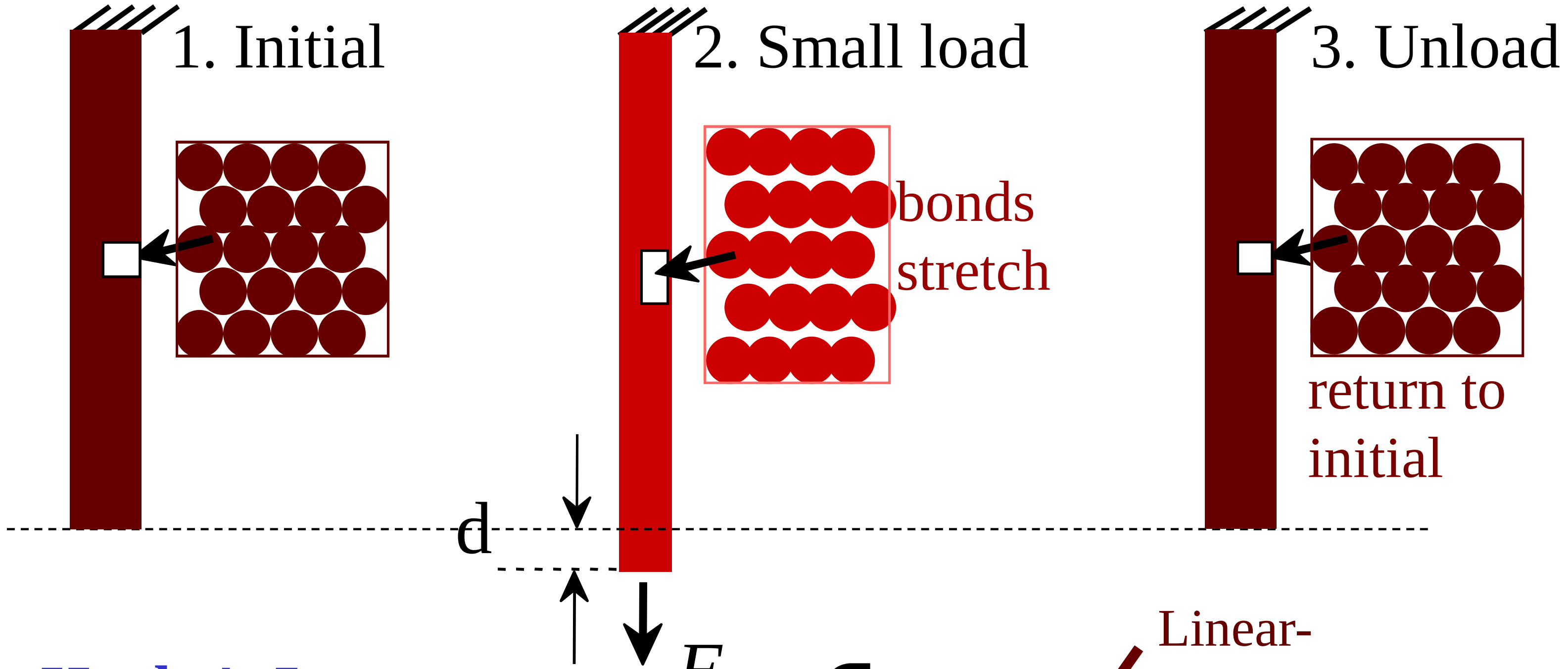
Units:
E: [GPa] or [psi]
ν: dimensionless



– ν > 0.50 density increases

– ν < 0.50 density decreases (voids form)

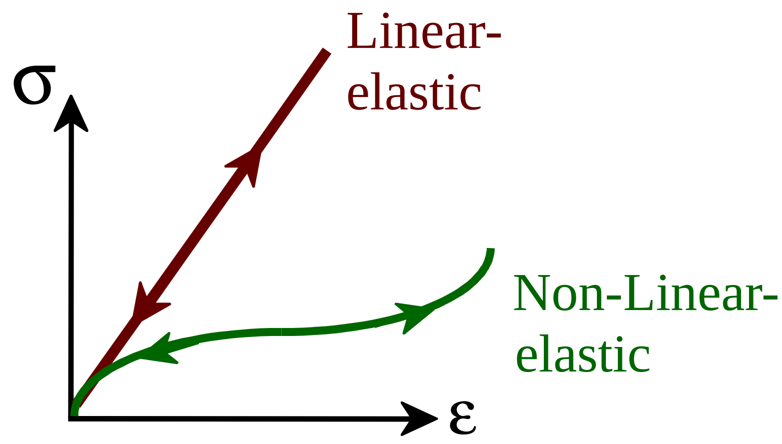
Elastic Deformation



- **Hooke's Law**:

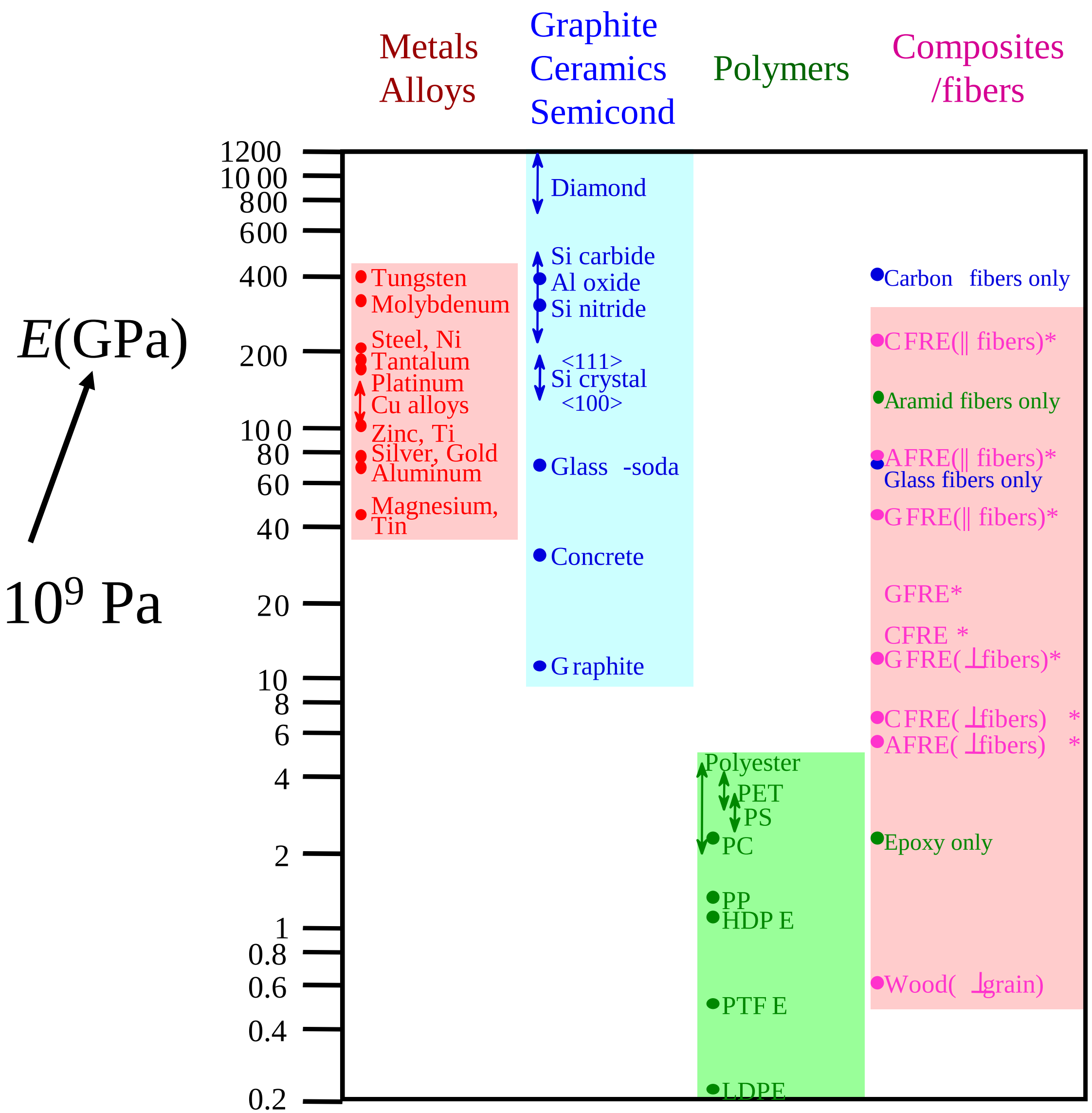
$$\sigma = E\,\varepsilon$$

$$\sigma = \frac{F}{A} \qquad \varepsilon = \frac{\delta}{L_o}$$



Elastic means reversible!

Young's Moduli: Comparison

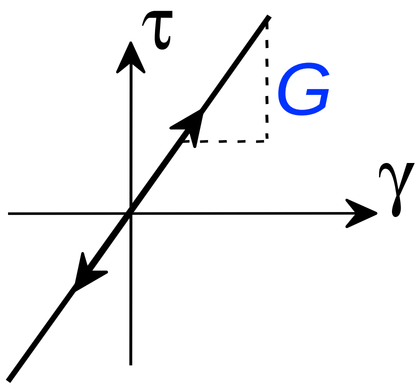


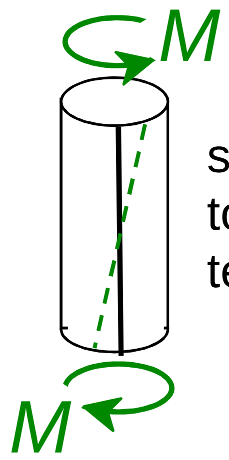
Based on data in Table B2, *Callister 7e*.
Composite data based on reinforced epoxy with 60 vol% of aligned carbon (CFRE), aramid (AFRE), or glass (GFRE) fibers.

Other Elastic Properties

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

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

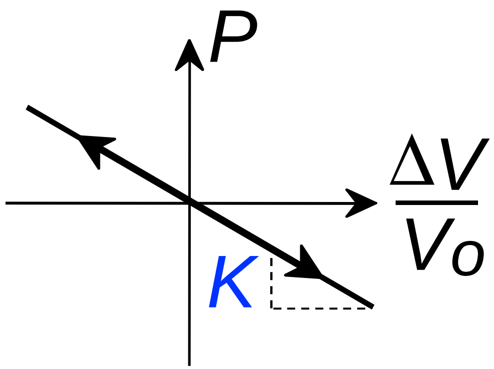


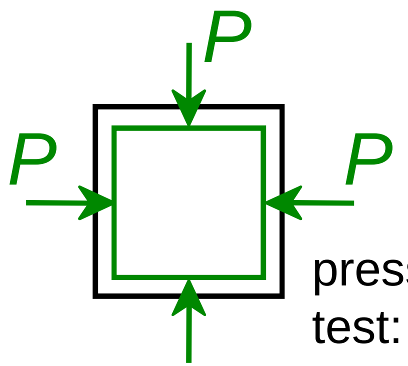


simple
torsion
test

- **Elastic Bulk modulus, K:**

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





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

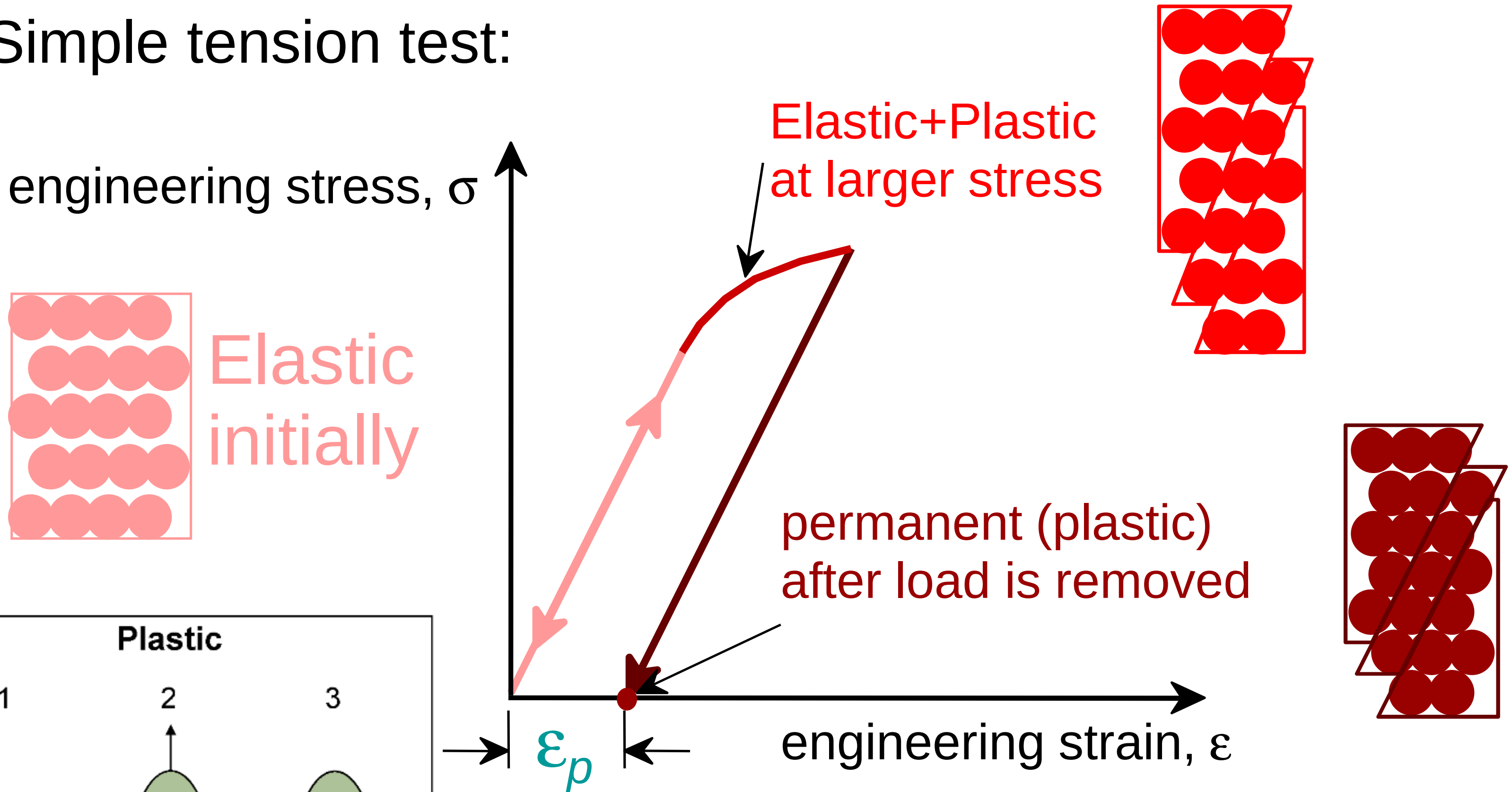
- **Special relations for isotropic materials:**

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

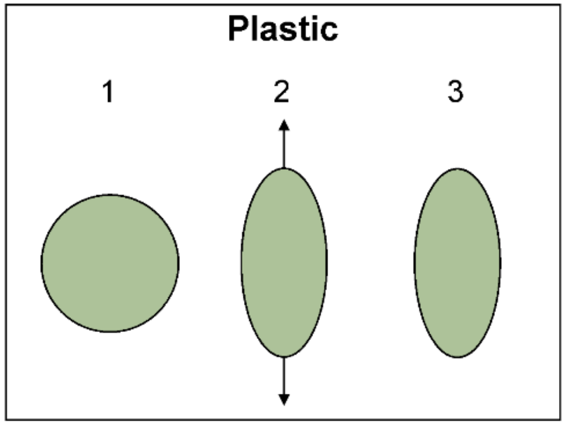
Plastic (Permanent) Deformation

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

- Simple tension test:

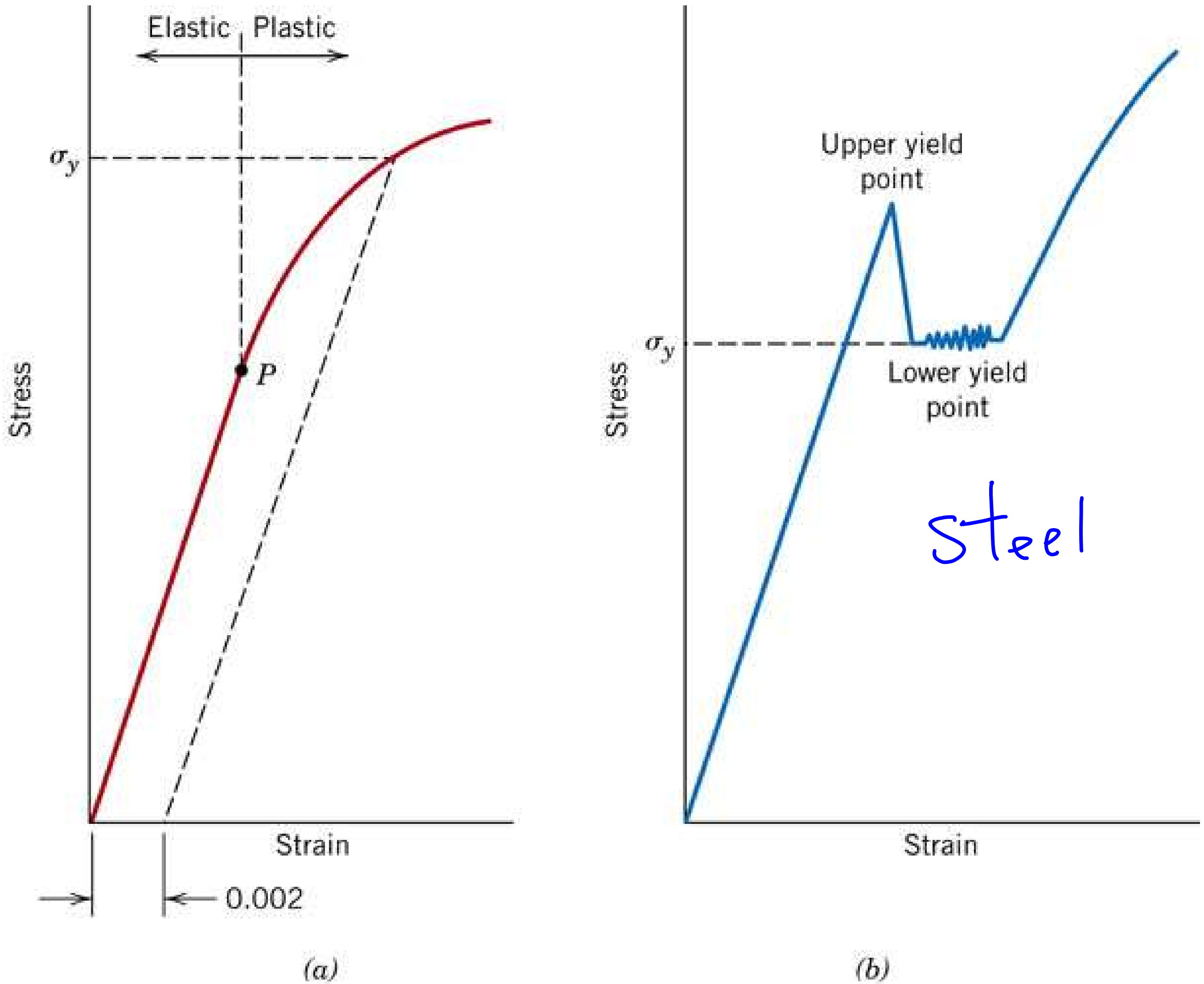


Adapted from Fig. 6.10 (a), *Callister 7e.*



https://commons.wvc.edu/rdawes/g101ocl/Basics/earthquakes.html

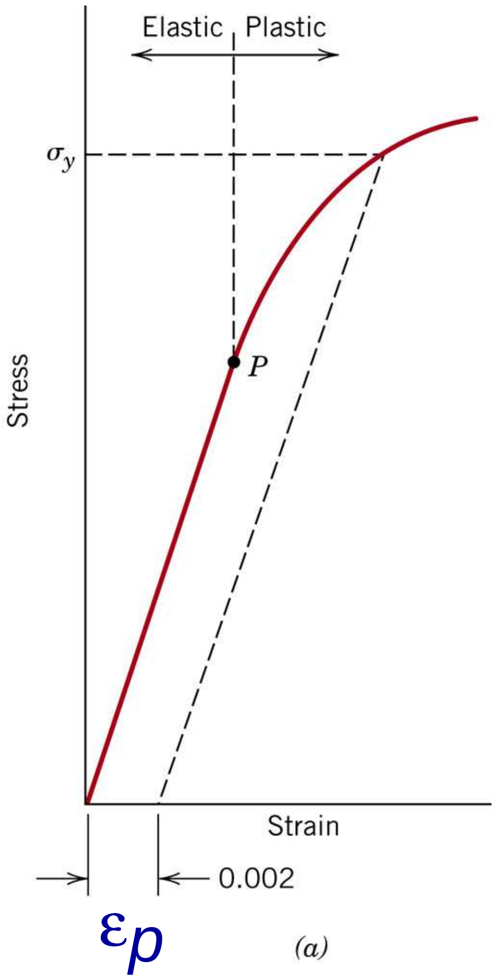
Figure 6.10



Elastic
Plastic
σ_y
P
Stress
Strain
0.002
(a)
Upper yield
point
σ_y
Lower yield
point
Stress
Strain
Steel
(b)

Yield Strength, σ_y

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



when ε_p = 0.2%

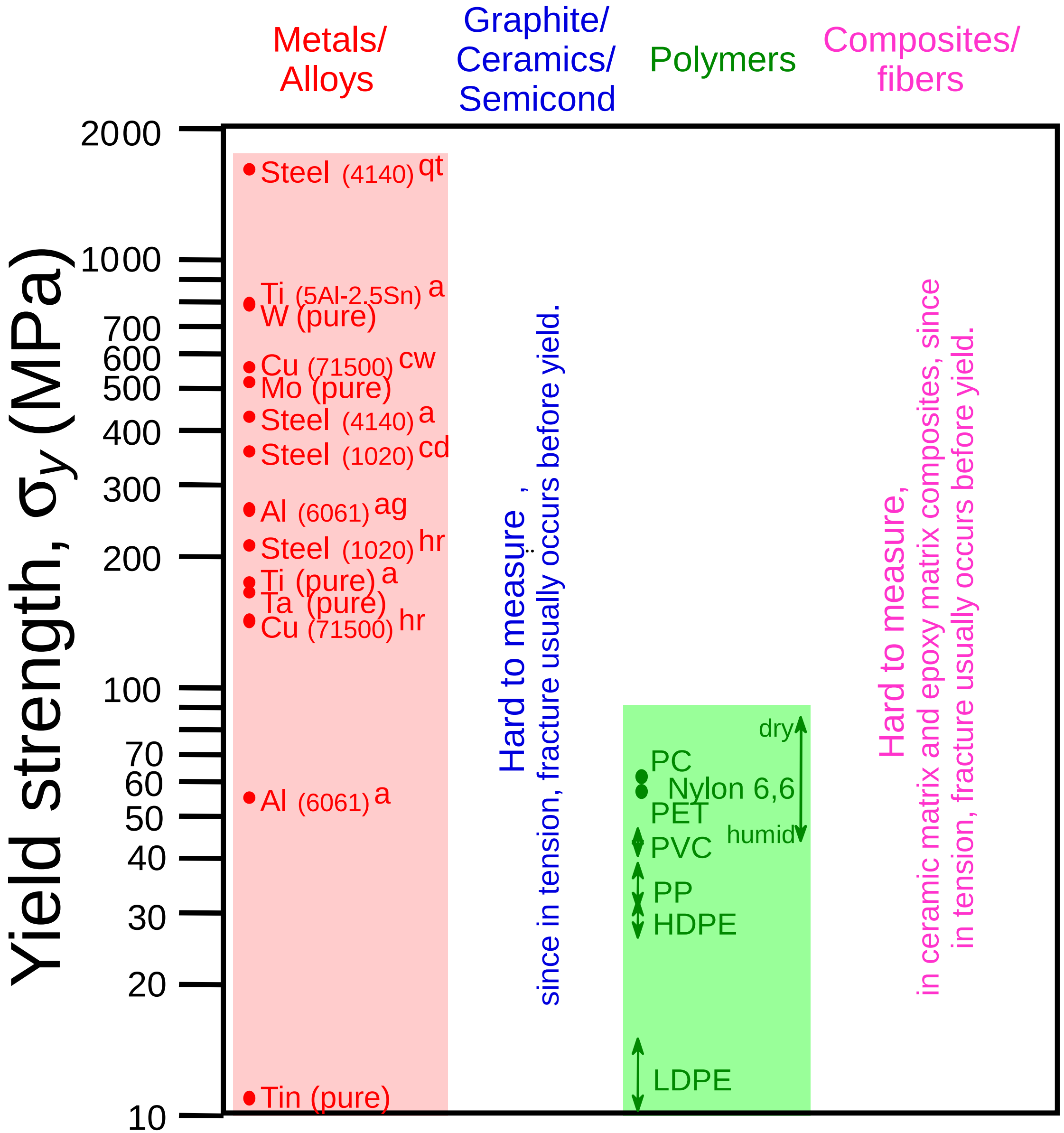
σ_y = yield strength

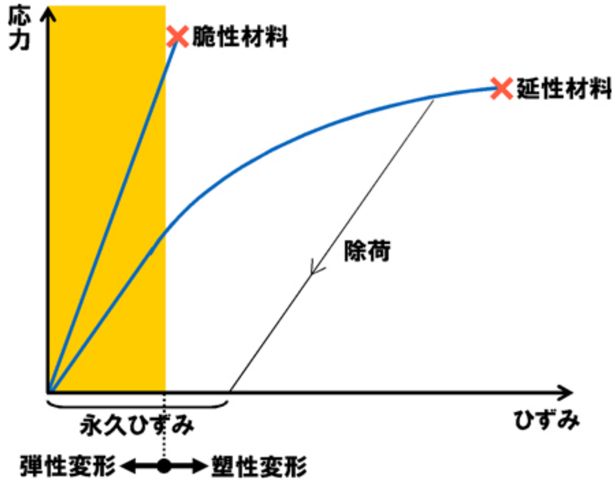
Note: for 2 inch sample

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

$\therefore\ \Delta z = 0.004$ in

Yield Strength : Comparison





Room *T* values

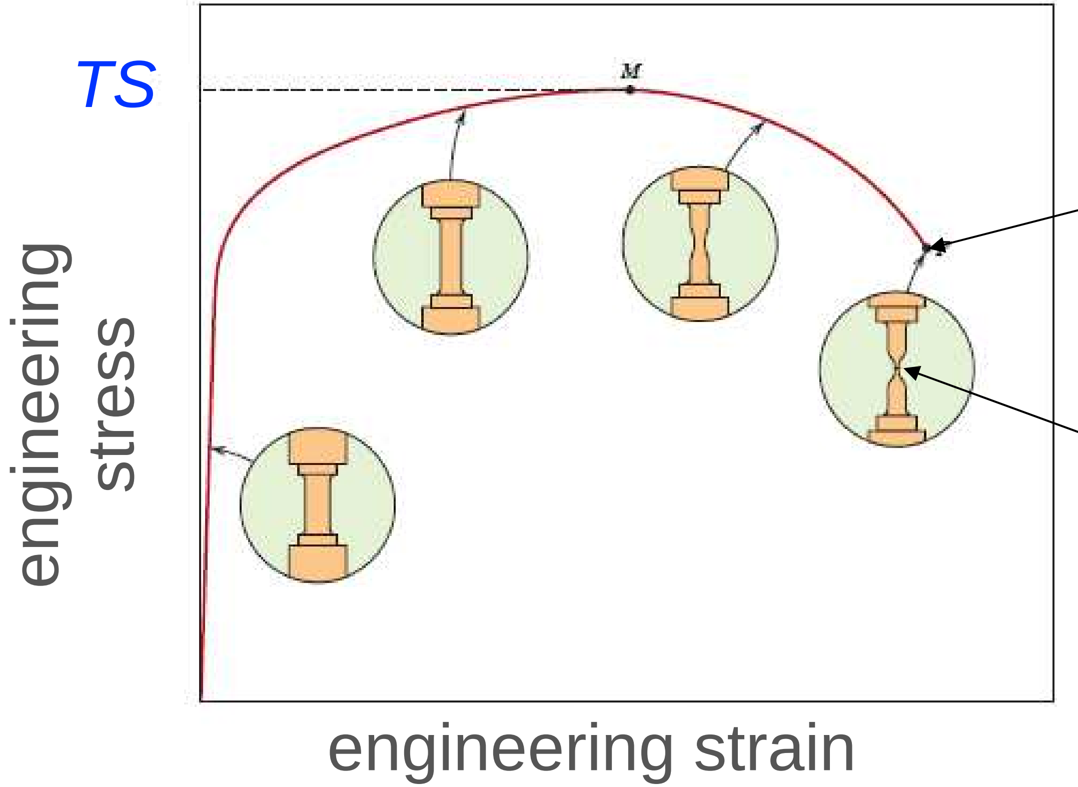
Based on data in Table B4, *Callister 7e*.

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

http://monoist.atmarkit.co.jp/mn/articles/0806/30/news113.html

Tensile Strength, TS

- Maximum stress on engineering stress-strain curve.



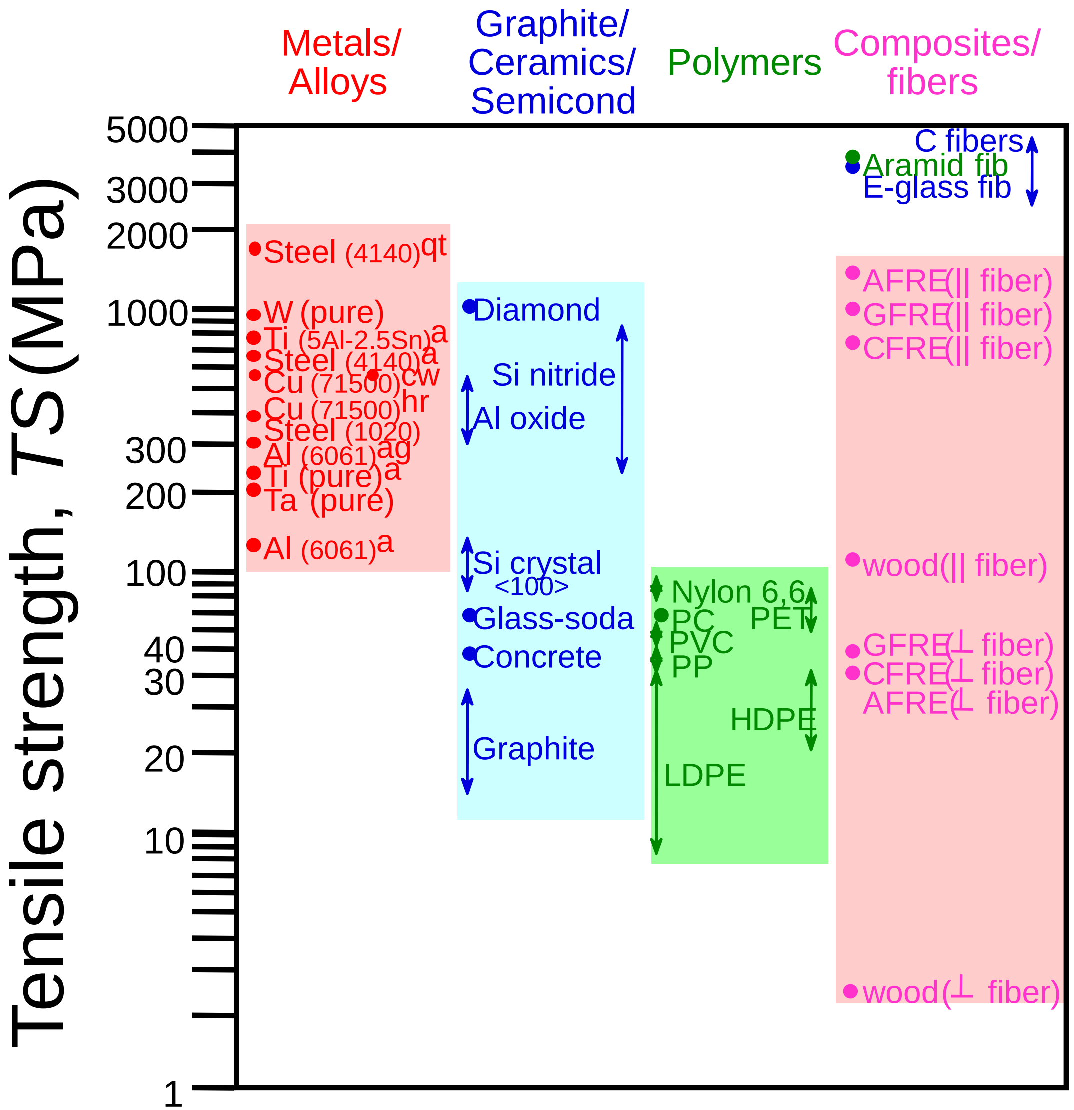
Adapted from Fig. 6.11, *Callister 7e.*

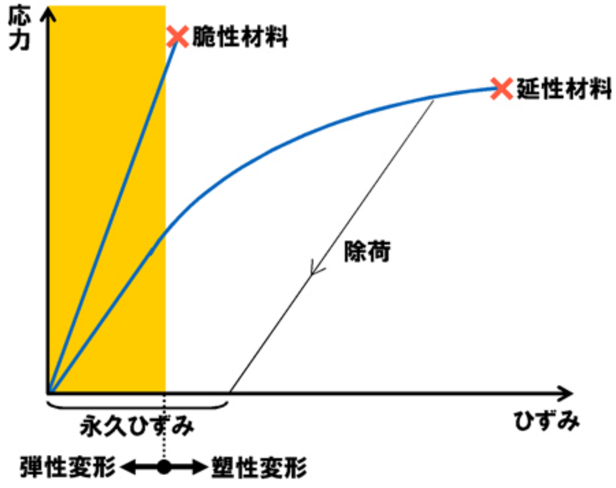
F = fracture or ultimate strength

Neck – acts as stress concentrator

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

Tensile Strength : Comparison



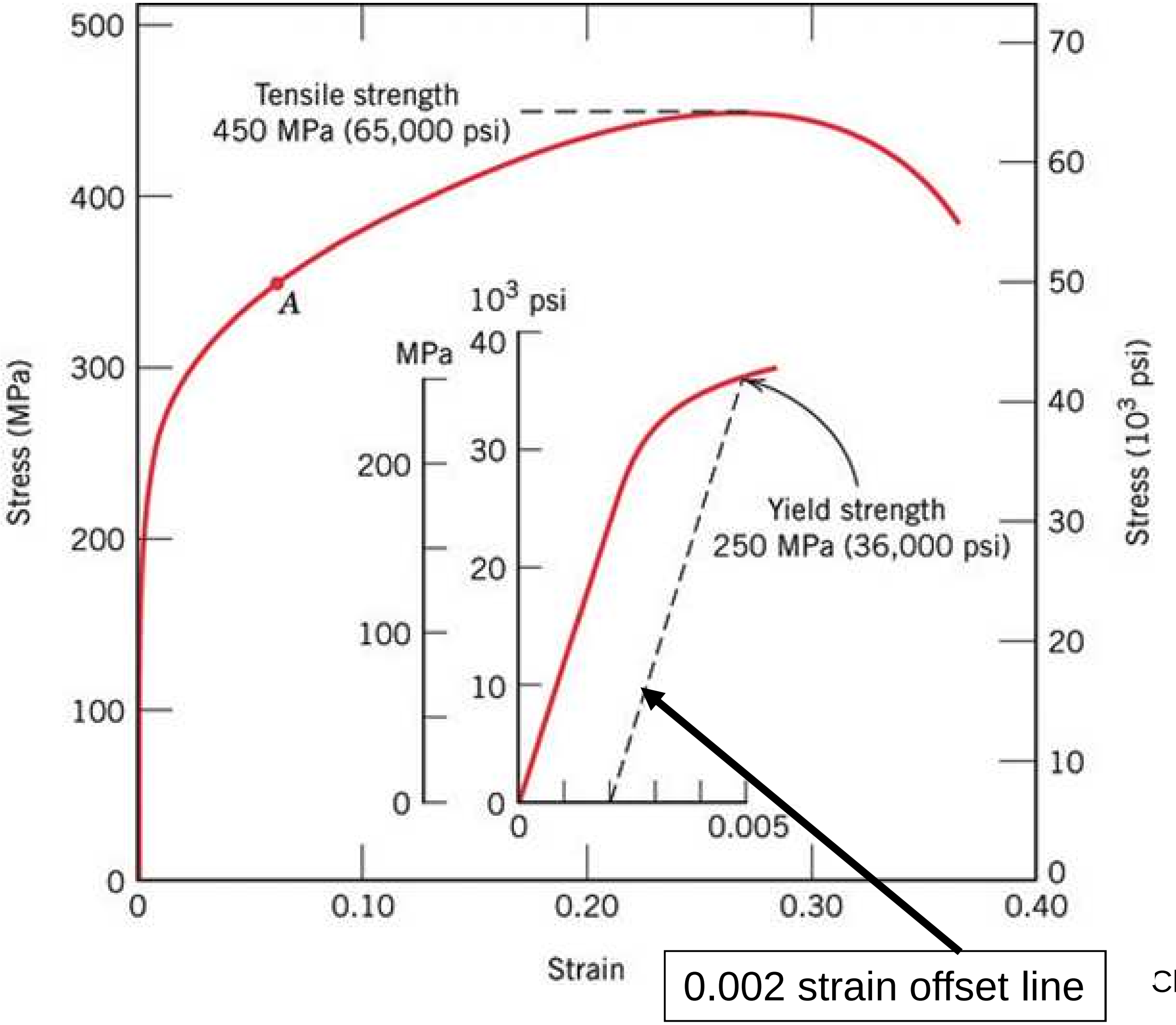


Based on data in Table B4, *Callister 7e*.

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.

http://monoist.atmarkit.co.jp/mn/articles/0806/30/news113.html

Mechanical Property Determinations from Stress-Strain Plot (Example 6.3)



Solution (6.3)

rise over the run, or the change in stress divided by the corresponding change in strain; in mathematical terms,

$$E = \text{slope} = \frac{\Delta\sigma}{\Delta\epsilon} = \frac{\sigma_2 - \sigma_1}{\epsilon_2 - \epsilon_1} \tag{6.10}$$

Inasmuch as the line segment passes through the origin, it is convenient to take both σ_1 and ϵ_1 as zero. If σ_2 is arbitrarily taken as 150 MPa, then ϵ_2 will have a value of 0.0016. Therefore,

$$E = \frac{(150 - 0)\ \text{MPa}}{0.0016 - 0} = 93.8\ \text{GPa}$$

which is very close to the value of 97 GPa given for brass in Table 6.1.

(b) The 0.002 strain offset line is constructed as shown in the inset; its intersection with the stress–strain curve is at approximately 250 MPa, which is the yield strength 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 Figure 6.12, 450 MPa. Solving for F, the maximum load, yields

$$F = \sigma A_0 = \sigma\left(\frac{d_0}{2}\right)^2 \pi$$

$$= (450 \times 10^6\ \text{N/m}^2)\left(\frac{12.8 \times 10^{-3}\ \text{m}}{2}\right)^2 \pi = 57{,}900\ \text{N}$$

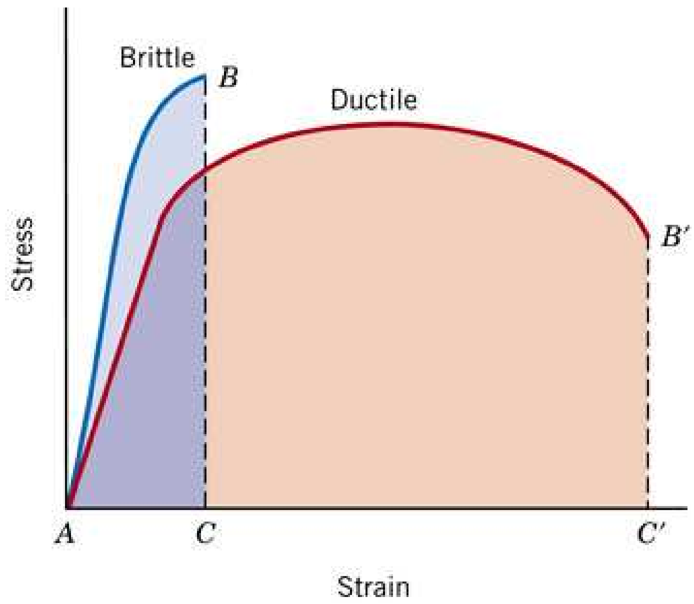
(d) To compute the change in length, Δl, in Equation 6.2, it is first necessary to determine the strain that is produced by a stress of 345 MPa. This is accomplished by locating the stress point on the stress–strain curve, point A, and reading the corresponding strain from the strain axis, which is approximately 0.06. Inasmuch as $l_0 = 250$ mm, we have

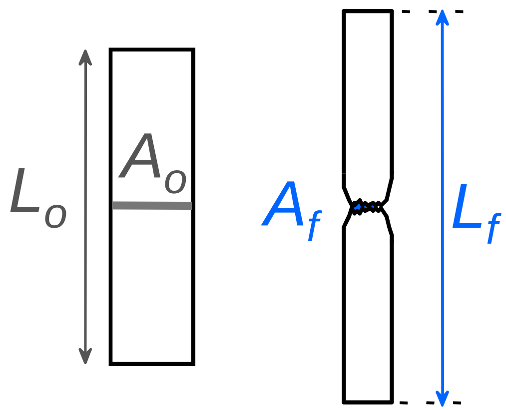
$$\Delta l = \epsilon l_0 = (0.06)(250\ \text{mm}) = 15\ \text{mm}$$

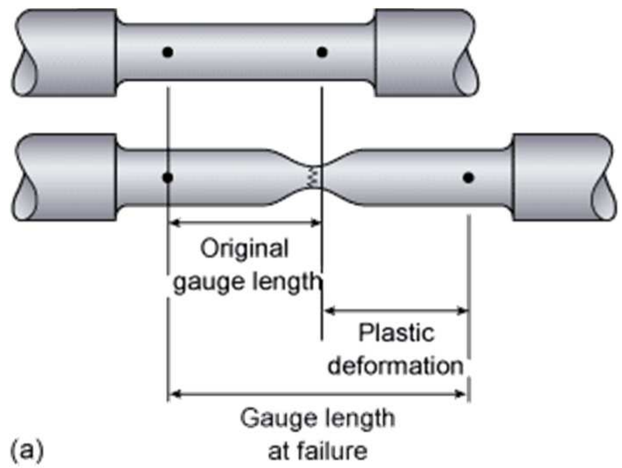
Ductility

- Plastic tensile strain at failure:

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







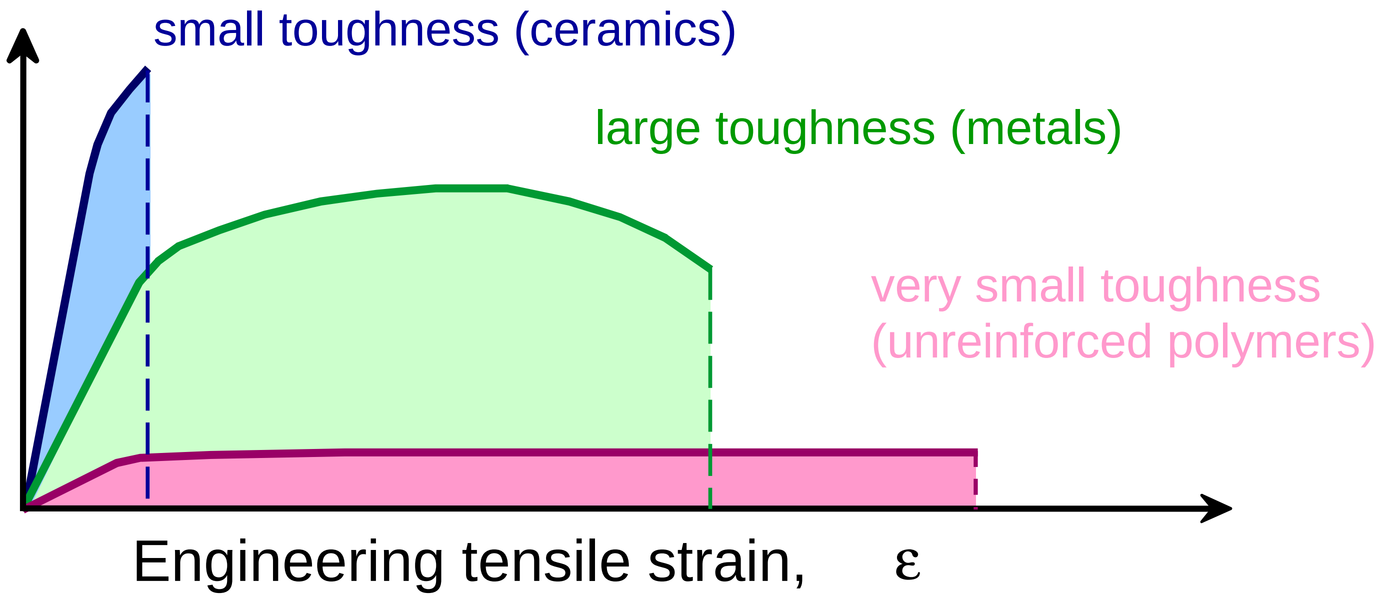
- Another ductility measure:

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

http://hsc.csu.edu.au/engineering_studies/application/lift/3210/index.html

Toughness

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

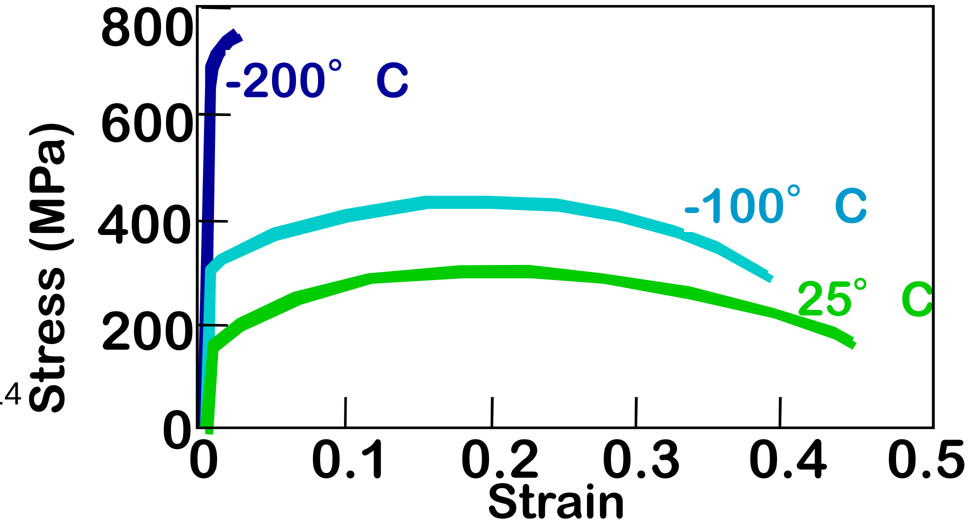


Adapted from Fig. 6.13, *Callister 7e.*

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

σ-ε Behavior vs. Temperature

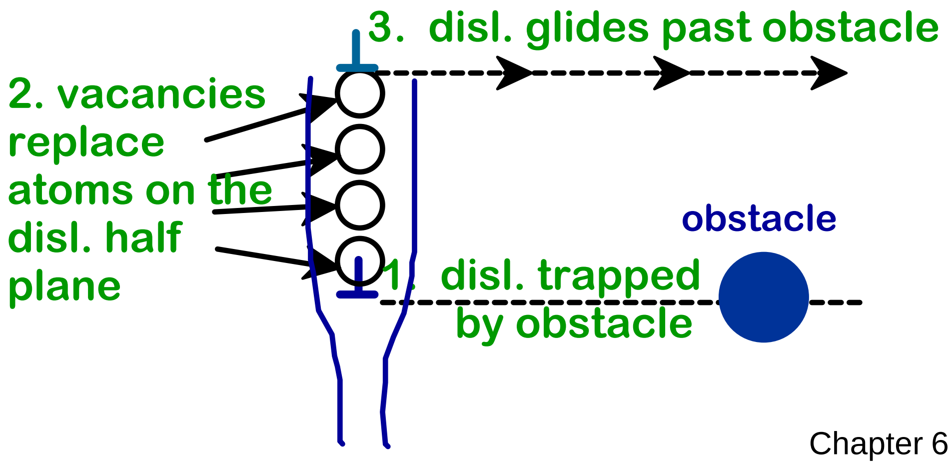
- Results for polycrystalline iron:



Adapted from Fig. 6.14 *Callister 6e.*

- σ_y and **TS *decrease*** with increasing test temperature.
- **%EL *increases*** with increasing test temperature.

- Why? Vacancies help dislocations past obstacles.

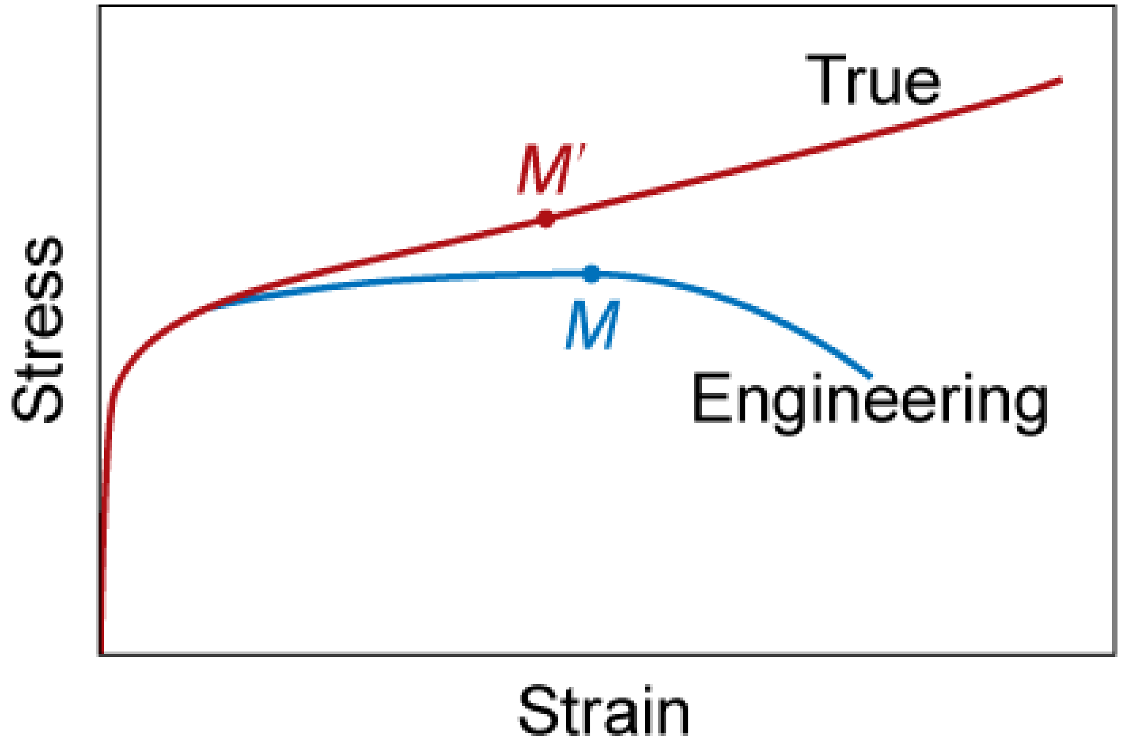


True Stress & Strain

Note: S.A. changes when sample stretched

- True stress $\sigma_T = F/A_i$
- True Strain $\varepsilon_T = \ln(\ell_i/\ell_o)$

$$\boxed{\begin{aligned}\sigma_T &= \sigma(1+\varepsilon)\\ \varepsilon_T &= \ln(1+\varepsilon)\end{aligned}}$$



Adapted from Fig. 6.16, *Callister 7e.*

Example 6.4

Ductility and True-Stress-at-Fracture Computations

A cylindrical specimen of steel having an original diameter of 12.8 mm is tensile-tested to fracture and found to have an engineering fracture strength σ_f of 460 MPa. If its cross-sectional diameter at fracture is 10.7 mm, determine:

(a) The ductility in terms of percent reduction in area

(b) The true stress at fracture

Solution

(a) Ductility is computed using Equation 6.12, as

$$\%\text{RA} = \frac{\left(\frac{12.8\text{ mm}}{2}\right)^2 \pi - \left(\frac{10.7\text{ mm}}{2}\right)^2 \pi}{\left(\frac{12.8\text{ mm}}{2}\right)^2 \pi} \times 100$$

$$= \frac{128.7\text{ mm}^2 - 89.9\text{ mm}^2}{128.7\text{ mm}^2} \times 100 = 30\%$$

(b) True stress is defined by Equation 6.15, where in this case the area is taken as the fracture area A_f. However, the load at fracture must first be computed from the fracture strength as

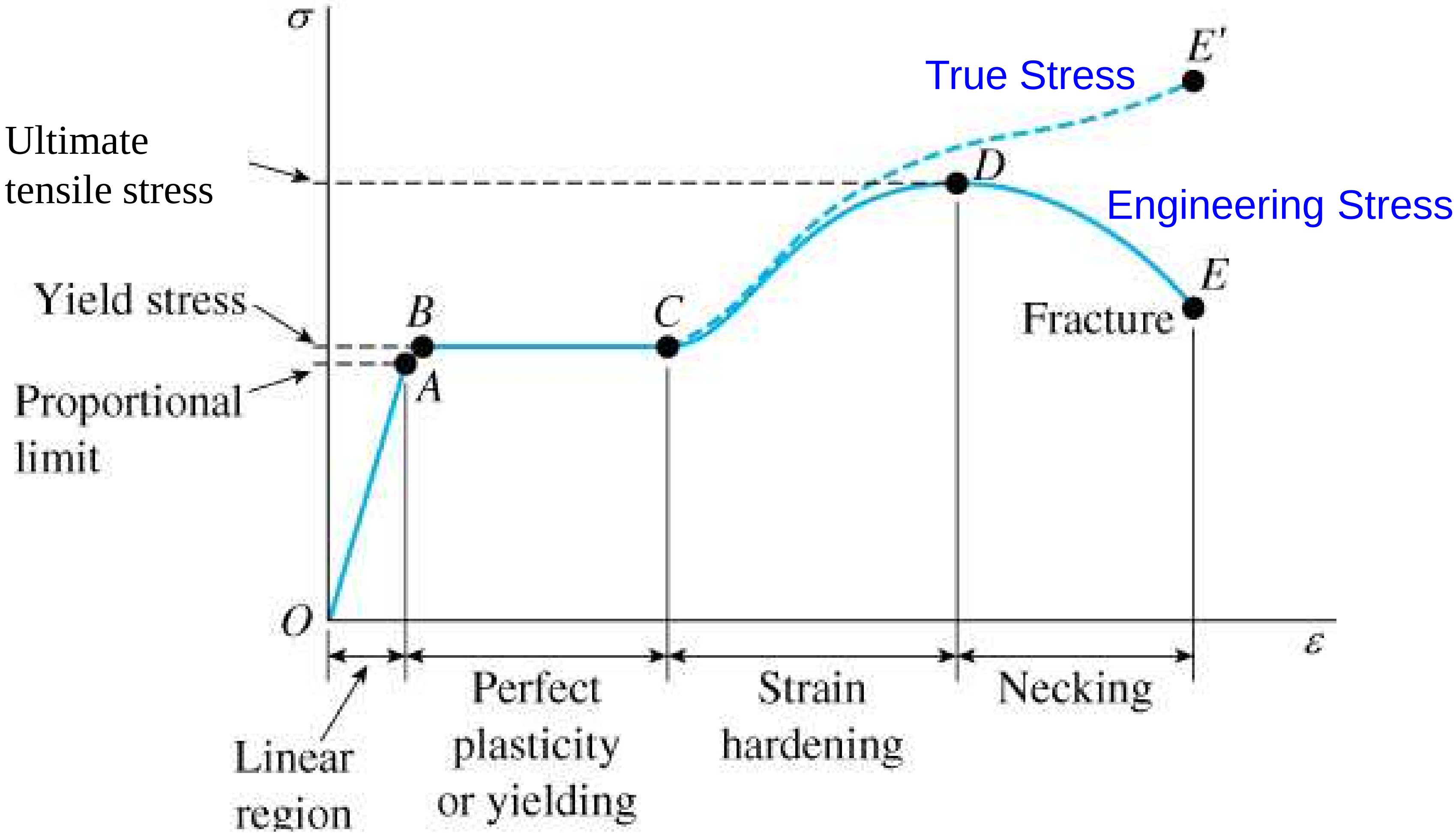
$$F = \sigma_f A_0 = (460 \times 10^6\text{ N/m}^2)(128.7\text{ mm}^2)\left(\frac{1\text{ m}^2}{10^6\text{ mm}^2}\right) = 59{,}200\text{ N}$$

Thus, the true stress is calculated as

$$\sigma_T = \frac{F}{A_f} = \frac{59{,}200\text{ N}}{(89.9\text{ mm}^2)\left(\frac{1\text{ m}^2}{10^6\text{ mm}^2}\right)}$$

$$= 6.6 \times 10^8\text{ N/m}^2 = 660\text{ MPa}$$

Stress-Strain Diagram



- For most purposes, engineering stresses and strains are used.
- Necking: plastic instability, localized plastic deformation

Design or Safety Factors

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

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

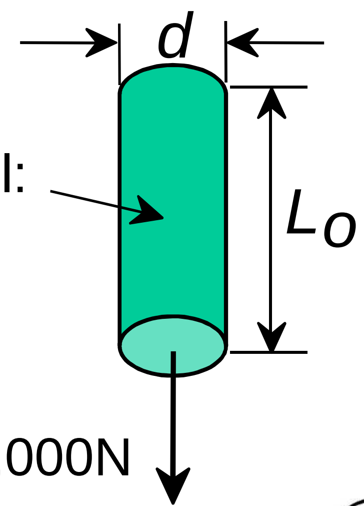
Often N is between 1.2 and 4

- 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.

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

$$\frac{220{,}000N}{\pi\left(d^2/4\right)} \qquad 5$$

1045 plain carbon steel:
$\sigma_y = 310$ MPa
$TS = 565$ MPa

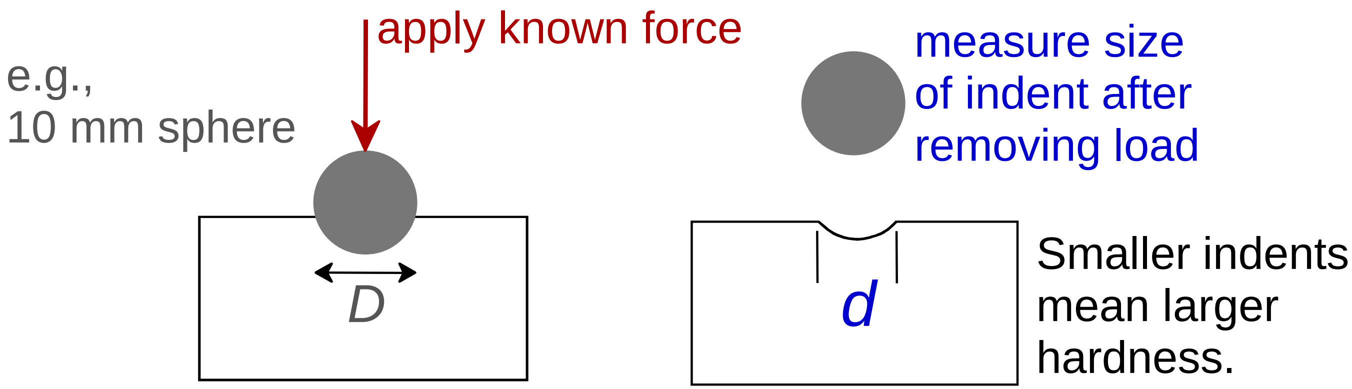


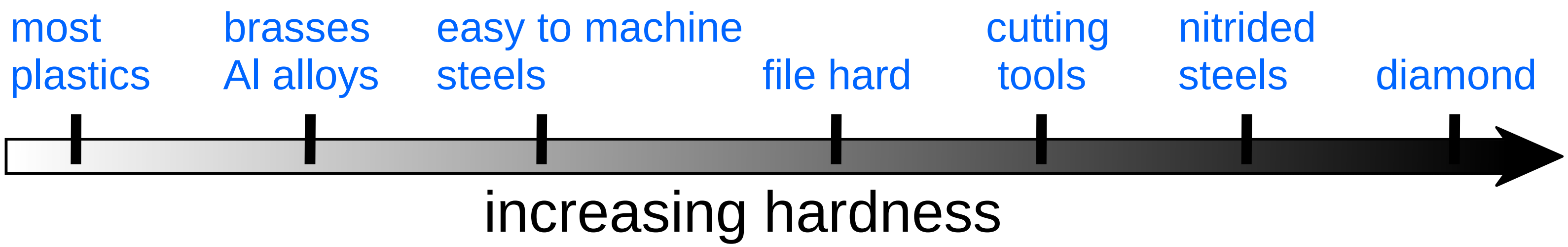
$F = 220{,}000$N

$$\boxed{d = 0.067 \text{ m} = 6.7 \text{ cm}}$$

Hardness

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





Hardness Testing

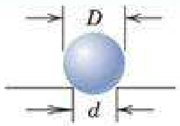
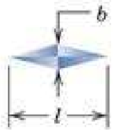
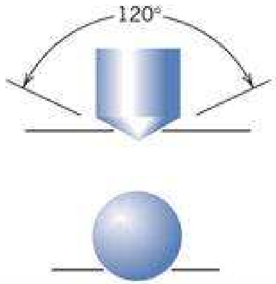
- Several common types of hardness test.
- Gives a measure of strength and wear resistance.
- The hardness is affected by work hardening of the material around the indentation.
- Various scales depend on the penetration device shape.

  Brinell, Vickers, Knoop, Rockwell.

Hardness Testers

Hardness: Measurement

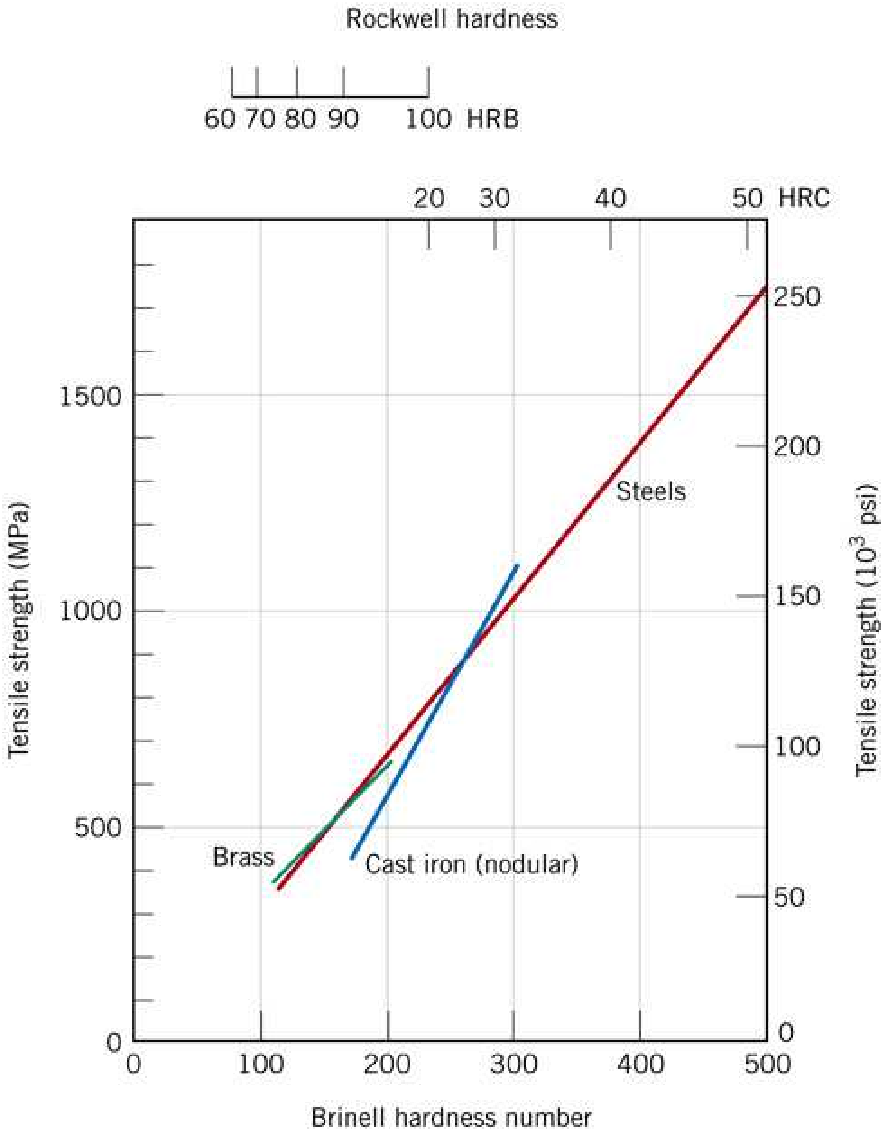
Table 6.5 Hardness-Testing Techniques

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, whereas 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.

Hardness v.s. Tensile Strength



TS(MPa)=3.45 X HB

Summary

- **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 or ν).
- **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.

- **Resilience, Temperature, Hardness, Safety Factor**