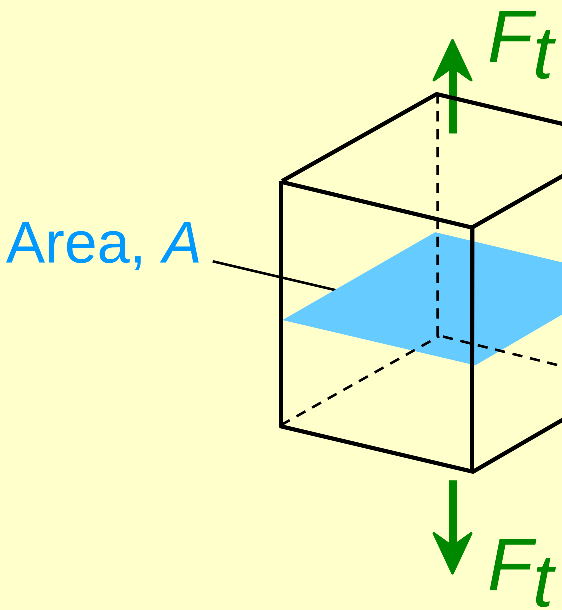
Chapter 6: Behavior Of Material Under Mechanical Loads = Mechanical Properties.

- Stress and strain:
  - What are they and why are they used instead of load and deformation
- Elastic behavior:
  - Recoverable Deformation of small magnitude
- Plastic behavior:
  - Permanent deformation We must consider which materials are most resistant to permanent deformation?
- Toughness and ductility:
  - Defining how much energy that a material can take before failure. How do we measure them?
- Hardness:
  - How we measure hardness and its relationship to material strength

Engineering Stress:

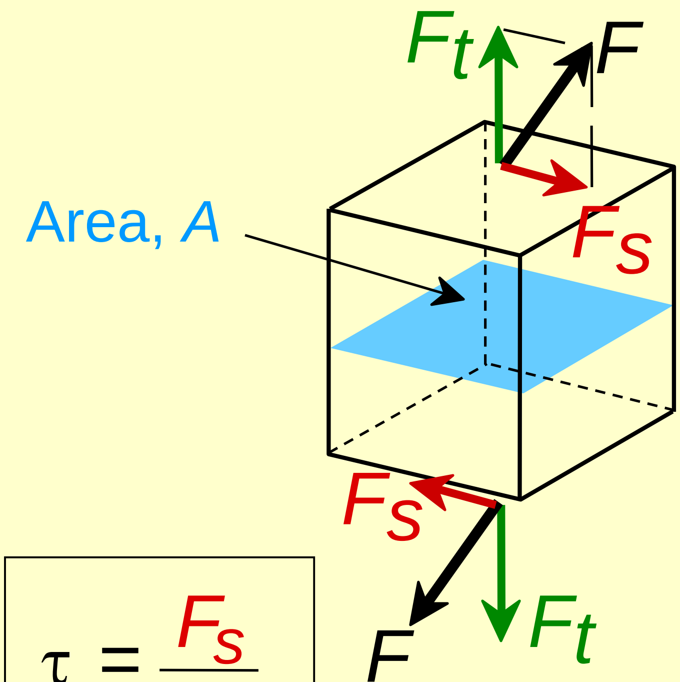
- Tensile stress, σ:



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

original area before loading

- Shear stress, τ:



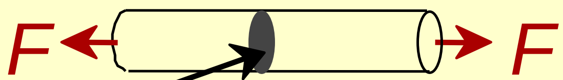
$$\tau = \frac{F_s}{A_o}$$

$\therefore$ Stress has units:
N/m^2 (Mpa) or $lb_f/in2$

we can also see the symbol 's' used for engineering stress

Common States of Stress

- **Simple tension: cable**

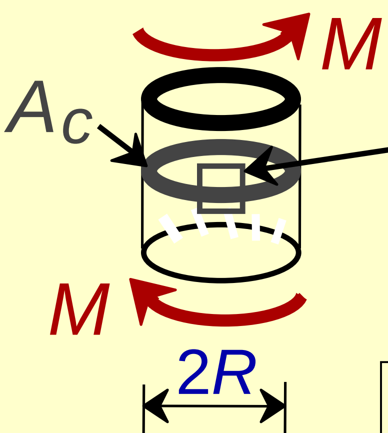


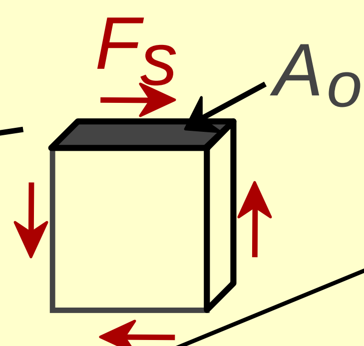
A_o = cross sectional area (when unloaded)

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

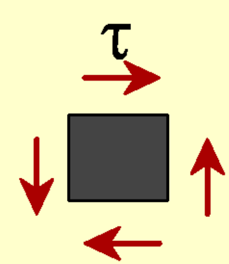
Ski lift (photo courtesy P.M. Anderson)

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





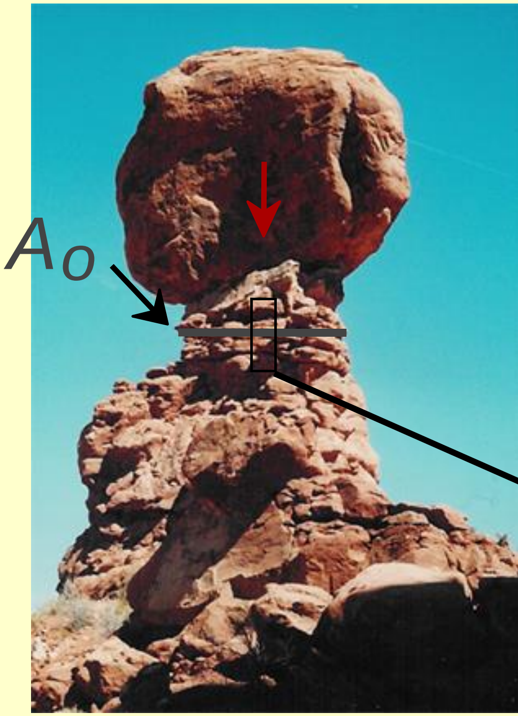
$$\tau = \frac{F_s}{A_o}$$



Note: $\tau = M/A_cR$ here.
Where M is the "Moment" A_c shaft area & R shaft radius

OTHER COMMON STRESS STATES (1)

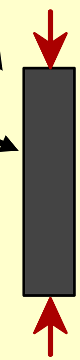
- **Simple compression:**



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

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

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

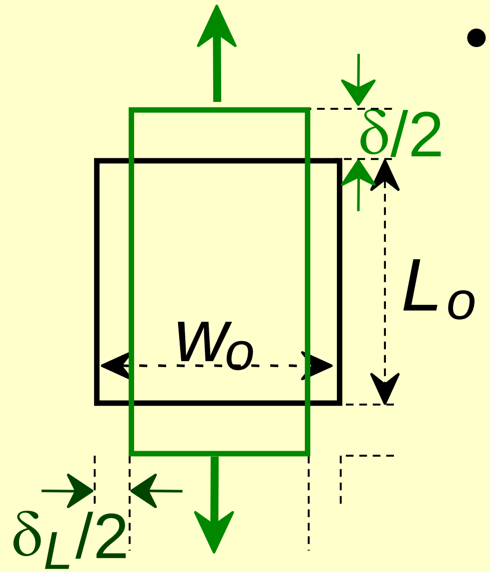


Note: compressive structure member ($\sigma < 0$ here).

Engineering Strain:

- **Tensile strain:**

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



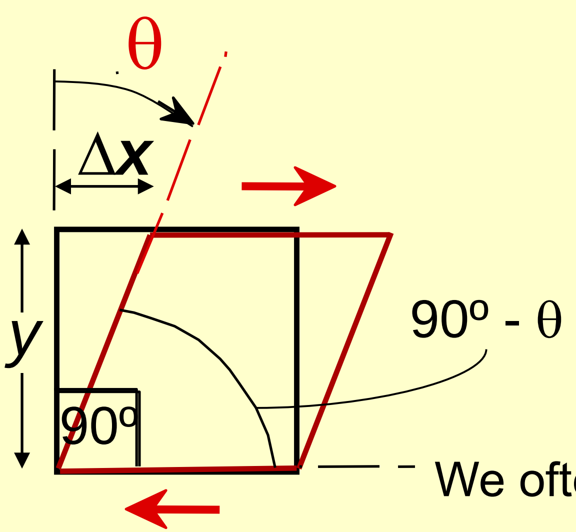
- **Lateral strain:**

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

Here: The Black Outline is Original, Green is after application of load

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

- **Shear strain:**



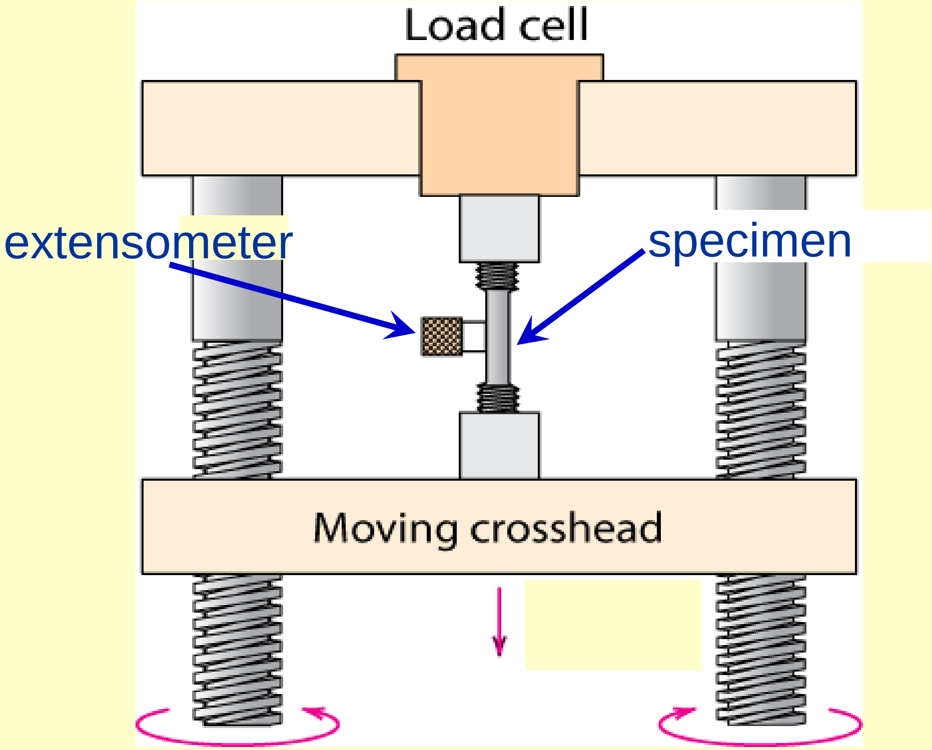
$$\gamma = \Delta x / y = \tan\theta$$

Strain is always Dimensionless!

We often see the symbol 'e' used for engineering strain

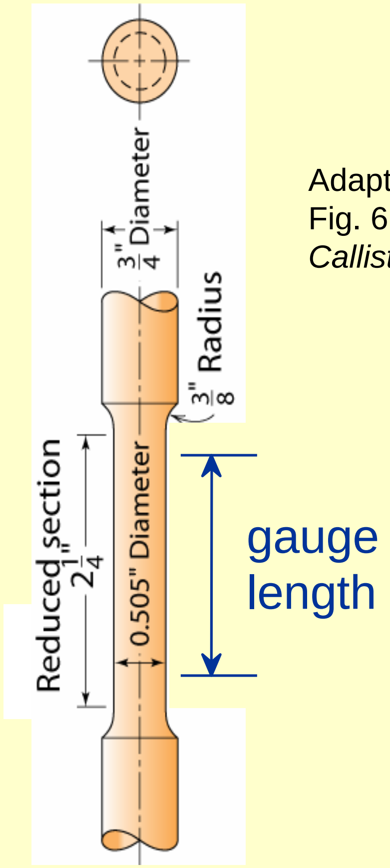
Stress-Strain: Testing Uses Standardized methods developed by ASTM for Tensile Tests it is ASTM E8

- **Typical tensile test machine**



Adapted from Fig. 6.3, *Callister 7e.* (Fig. 6.3 is 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.)

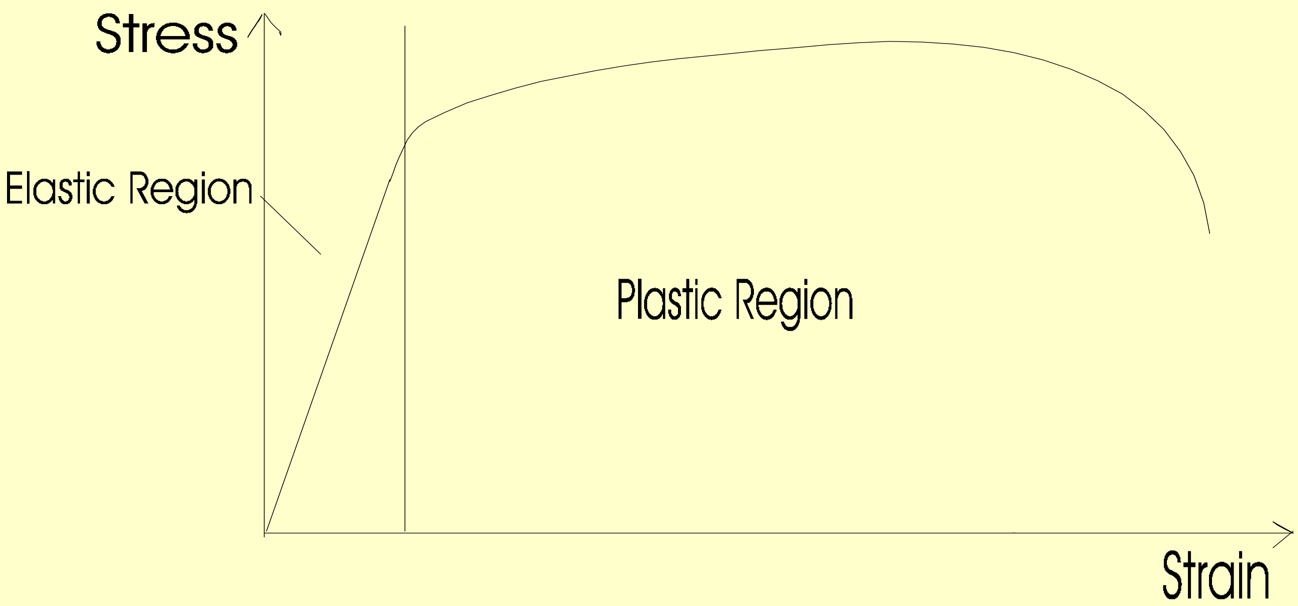
- **Typical tensile specimen (ASTM A-bar)**



Adapted from Fig. 6.2, *Callister 7e.*

The Engineering Stress - Strain curve Divided into 2 regions

ELASTIC | **PLASTIC**



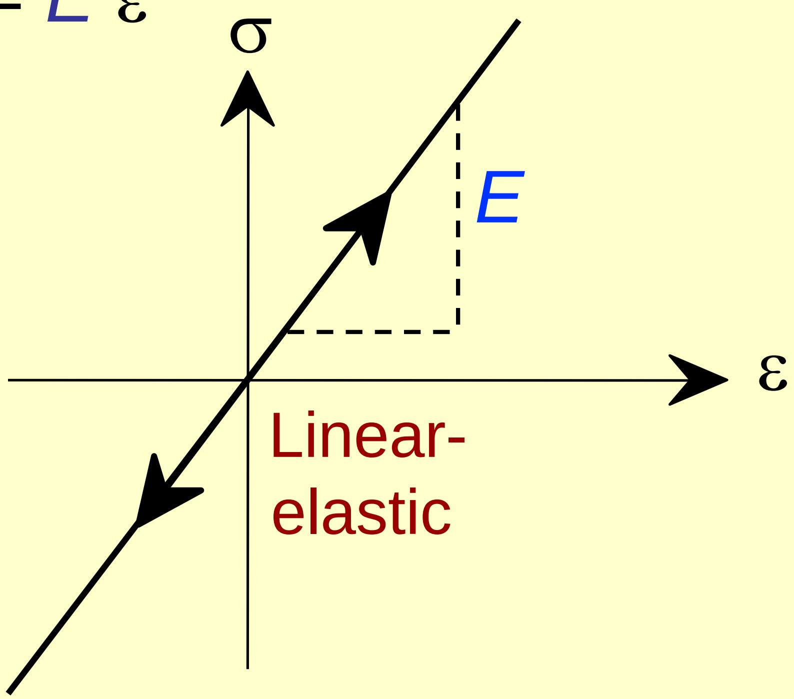
Linear: Elastic Properties

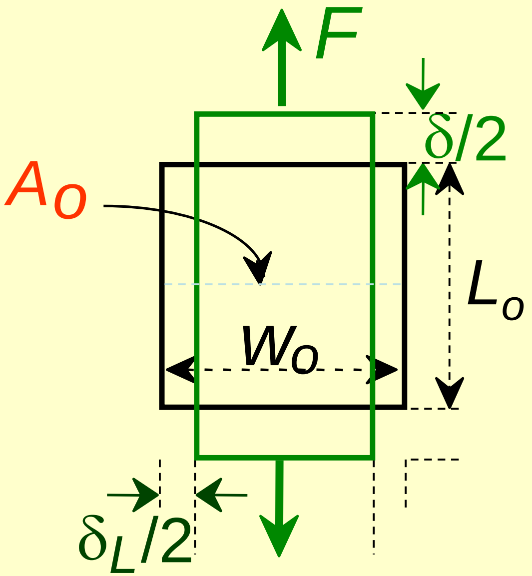
- **Modulus of Elasticity, *E*:**
  (also known as Young's modulus)

Units:
E: [GPa] or [psi]
σ: in [Mpa] or [psi]
ε: [m/m or mm/mm] or [in/in]

- **Hooke's Law:**

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





Here: The Black Outline is Original, Green is after application of load

Solving:

$$\sigma = F/A_0 = 66700N / \left(16.5*10^{-3}\right)^2 = 244.995MPa$$

$$\varepsilon = \Delta L / L_0 = 0.43mm / 125mm = 0.00344$$

Because we are to assume all deformation is recoverable, Hooke's Law can be assumed:

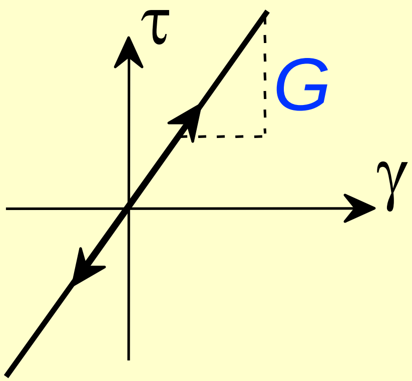
$$\sigma = E*\varepsilon \Rightarrow E = \sigma/\varepsilon = 244.995MPa / 0.00344$$

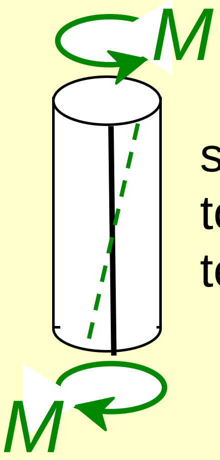
$$E = 71219.6\ MPa = 71.2\ GPa$$

Other Elastic Properties

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

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

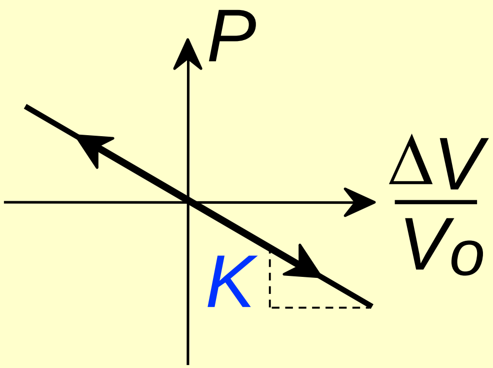


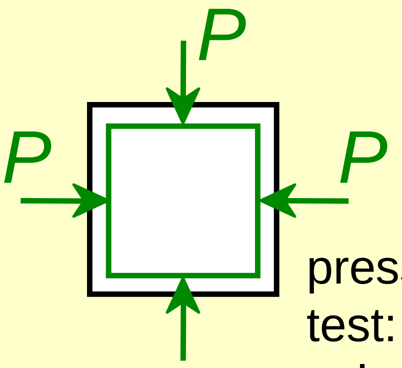


simple torsion test

- **Elastic Bulk modulus, K:**

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





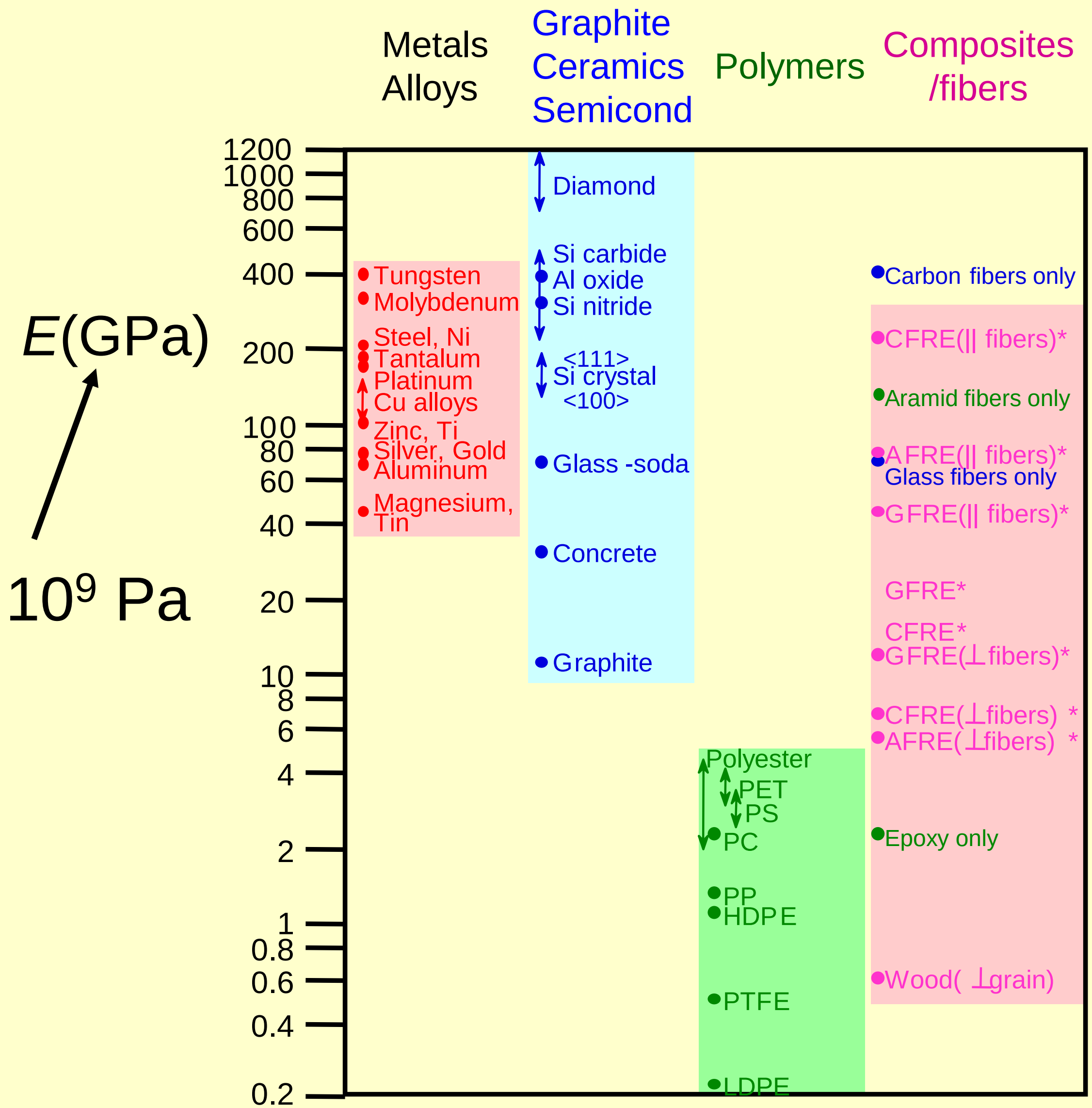
pressure test: Init. vol $=V_o$. Vol chg. $=\Delta V$

- **Special relations for *isotropic materials*:**

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

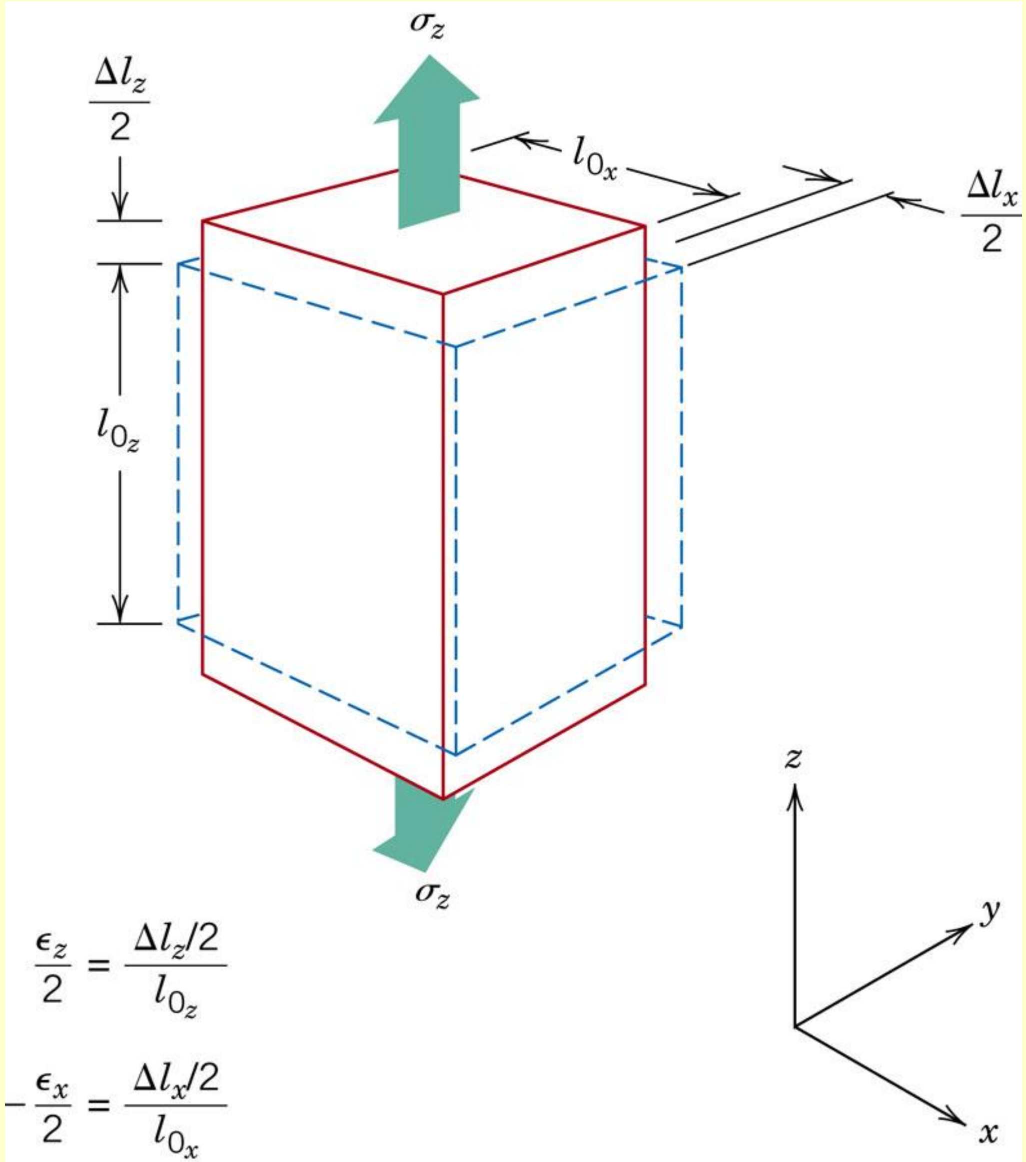
E is Modulus of Elasticity
ν is Poisson's Ratio

Young's Moduli: Comparison



Based on data in Table B2, *Callister 7e*.

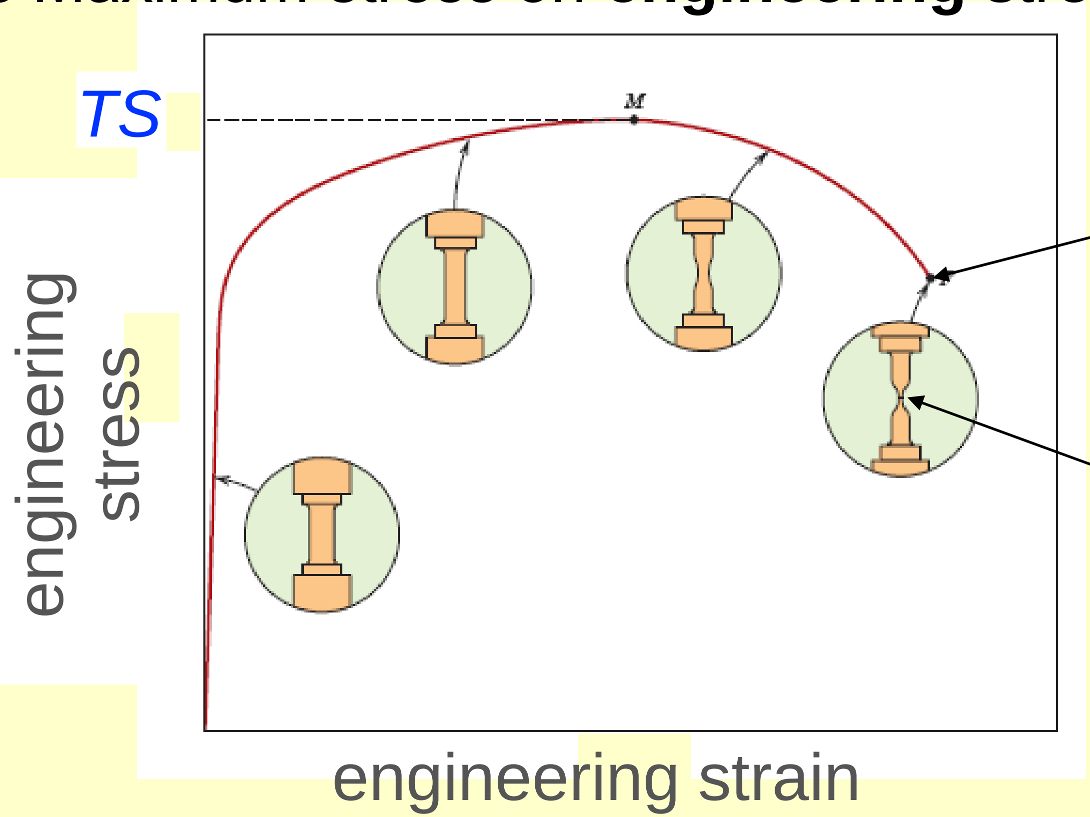
Composite data based on reinforced epoxy with 60 vol% of aligned carbon (CFRE), aramid (AFRE), or glass (GFRE) fibers.



σ_z
$\frac{\Delta l_z}{2}$
l_{0_x}
$\frac{\Delta l_x}{2}$
l_{0_z}
σ_z
z
y
x
$\frac{\epsilon_z}{2} = \frac{\Delta l_z/2}{l_{0_z}}$
$-\frac{\epsilon_x}{2} = \frac{\Delta l_x/2}{l_{0_x}}$

Tensile Strength, TS

- TS is Maximum stress on **engineering** stress-strain curve.



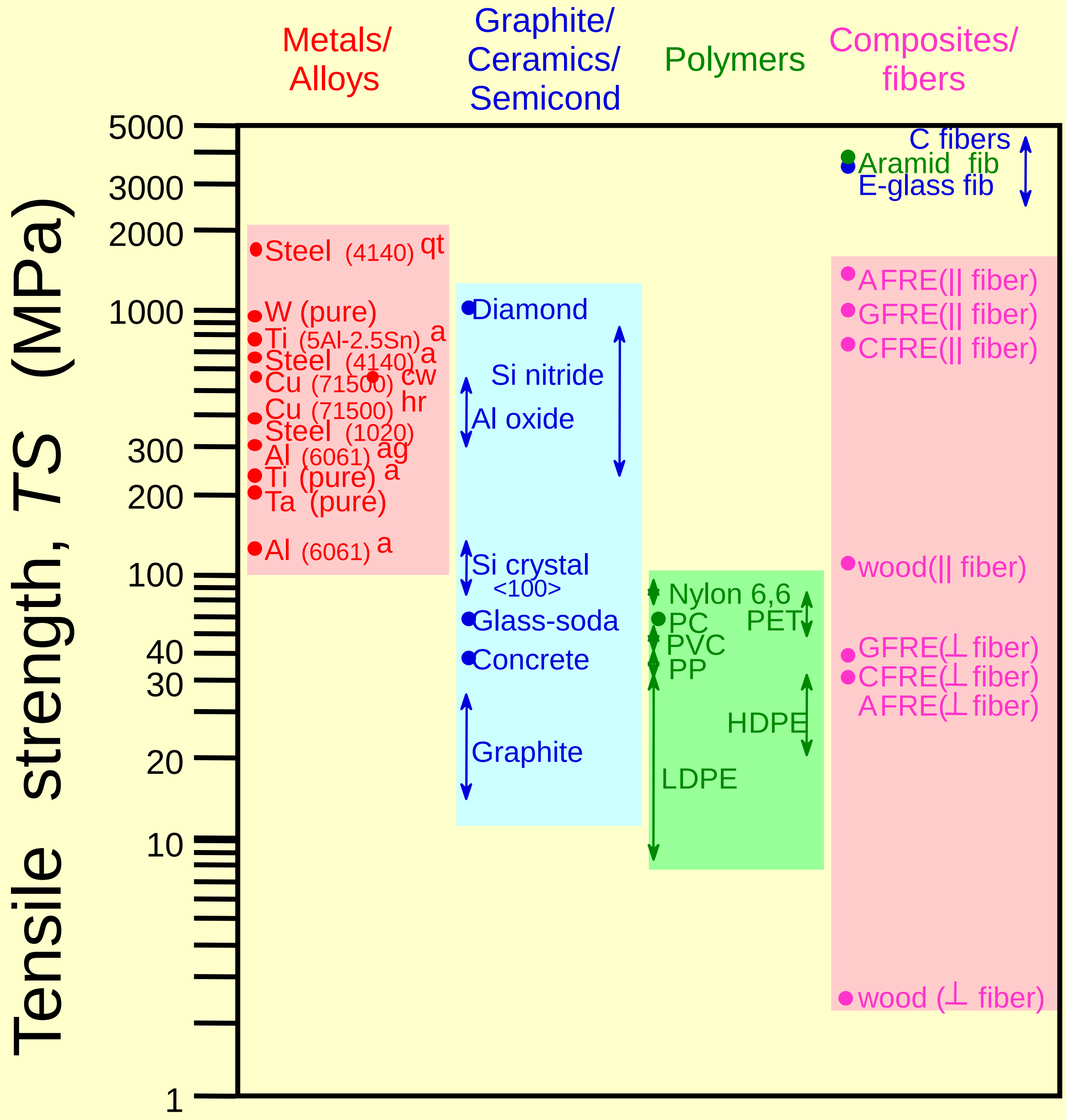
Adapted from Fig. 6.11, *Callister 7e.*

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



Room Temp. values

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

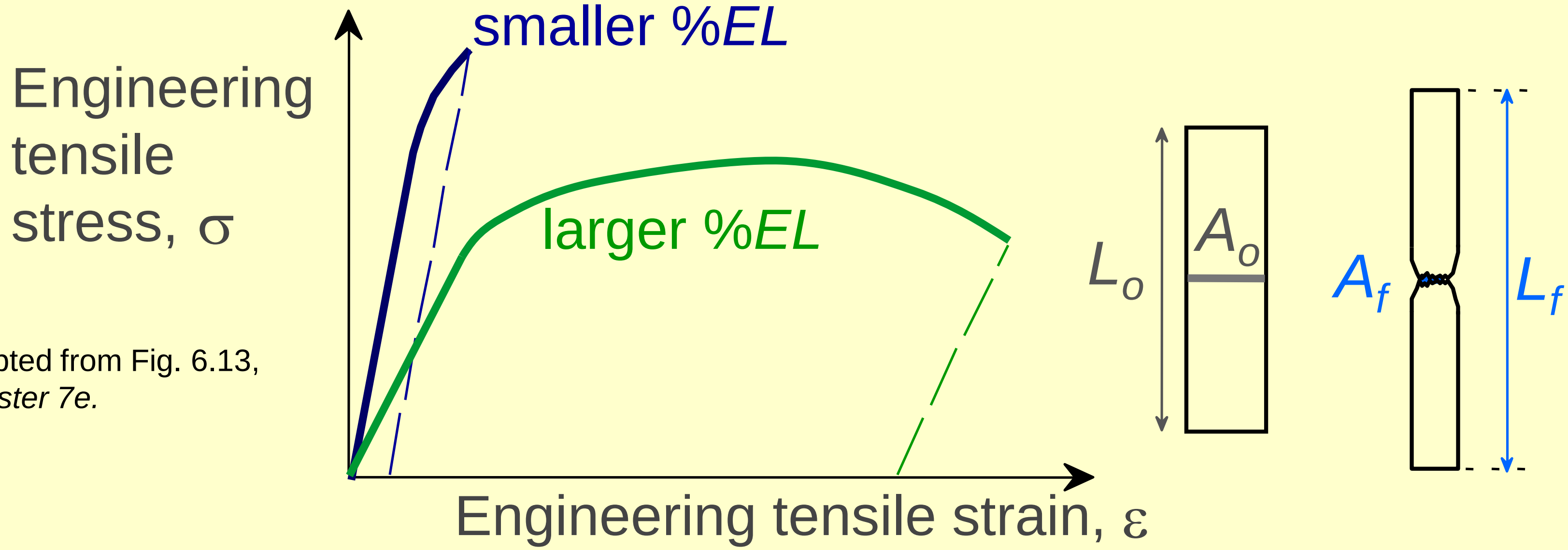
a = annealed
hr = hot rolled
ag = aged
cd = cold drawn
cw = cold worked
qt = quenched & tempered

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

Ductility

- Plastic tensile strain at failure:

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



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

- Another ductility measure:

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

Lets Try one (like Problem 6.29)

GIVENS:

Load (N)	len. (mm)	len. (m)	∆l
0	50.8	0.0508	0
12700	50.825	0.050825	2.5E-05
25400	50.851	0.050851	5.1E-05
38100	50.876	0.050876	7.6E-05
50800	50.902	0.050902	0.000102
76200	50.952	0.050952	0.000152
89100	51.003	0.051003	0.000203
92700	51.054	0.051054	0.000254
102500	51.181	0.051181	0.000381
107800	51.308	0.051308	0.000508
119400	51.562	0.051562	0.000762
128300	51.816	0.051816	0.001016
149700	52.832	0.052832	0.002032
159000	53.848	0.053848	0.003048
160400	54.356	0.054356	0.003556
159500	54.864	0.054864	0.004064
151500	55.88	0.05588	0.00508
124700	56.642	0.056642	0.005842

Leads to the following computed Stress/Strains:

e stress (Pa)	e str (MPa)	e. strain
0	0	0
98694715.7	98.694716	0.000492
197389431	197.38943	0.001004
296084147	296.08415	0.001496
394778863	394.77886	0.002008
592168294	592.16829	0.002992
692417257	692.41726	0.003996
720393712	720.39371	0.005
796551839	796.55184	0.0075
837739398	837.7394	0.01
927885752	927.88575	0.015
997049766	997.04977	0.02
1163354247	1163.3542	0.04
1235626755	1235.6268	0.06
1246506488	1246.5065	0.07
1239512374	1239.5124	0.08
1177342475	1177.3425	0.1
969073311	969.07331	0.115

$$\sigma = F / A_0$$

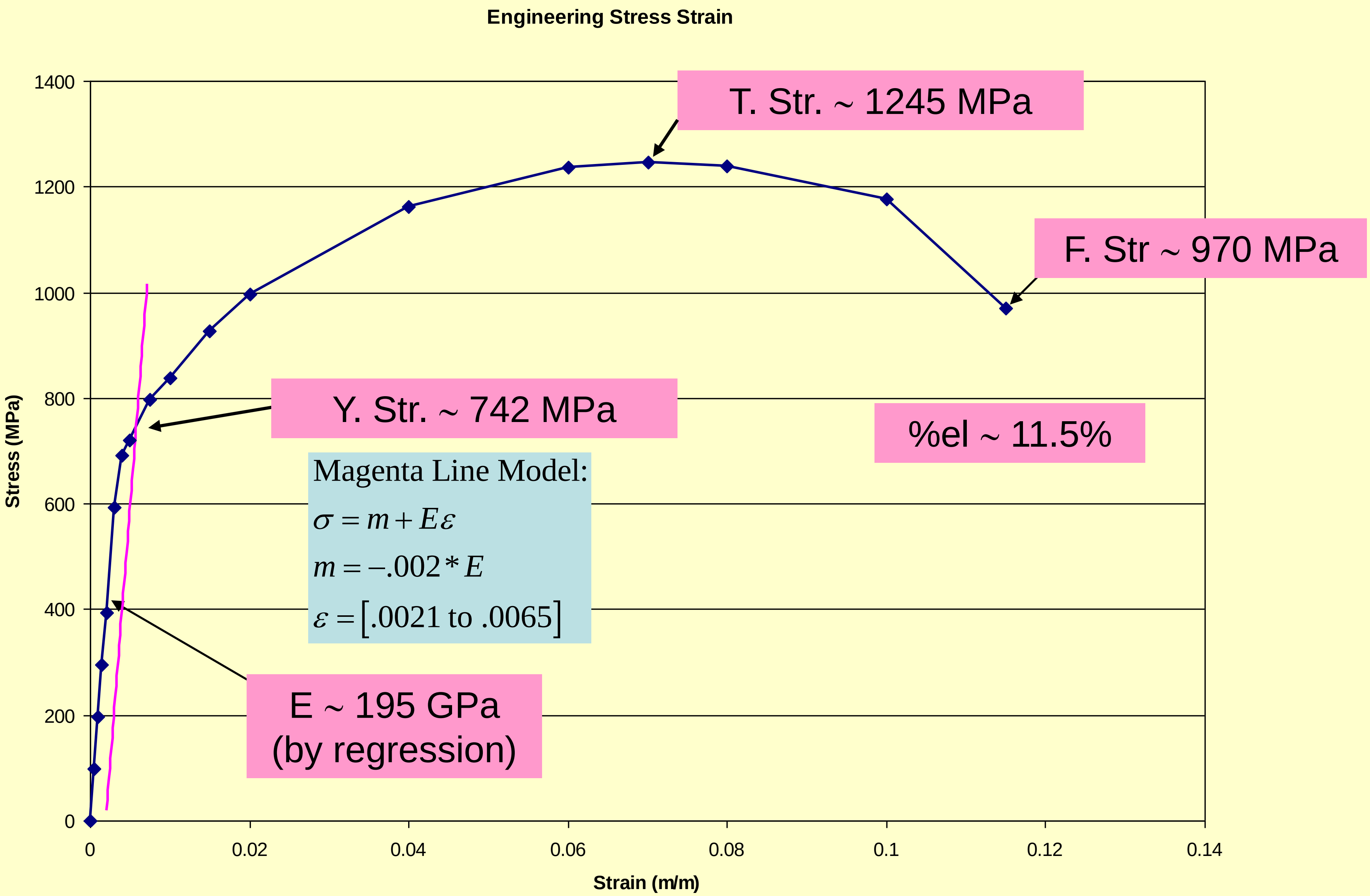
A_0 use m^2 if F in Newtons; in^2 if F in lb_f

results in Pa (MPa) or psi (ksi)

and

$$\varepsilon = \Delta l / l_0$$

Leads to the Eng. Stress/Strain Curve:



TOUGHNESS

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

High toughness = High yield strength and ductility

Important Factors in determining Toughness:

1. Specimen Geometry & 2. Method of load application

Dynamic (high strain rate) loading condition (Impact test)

1. Specimen with notch- Notch toughness

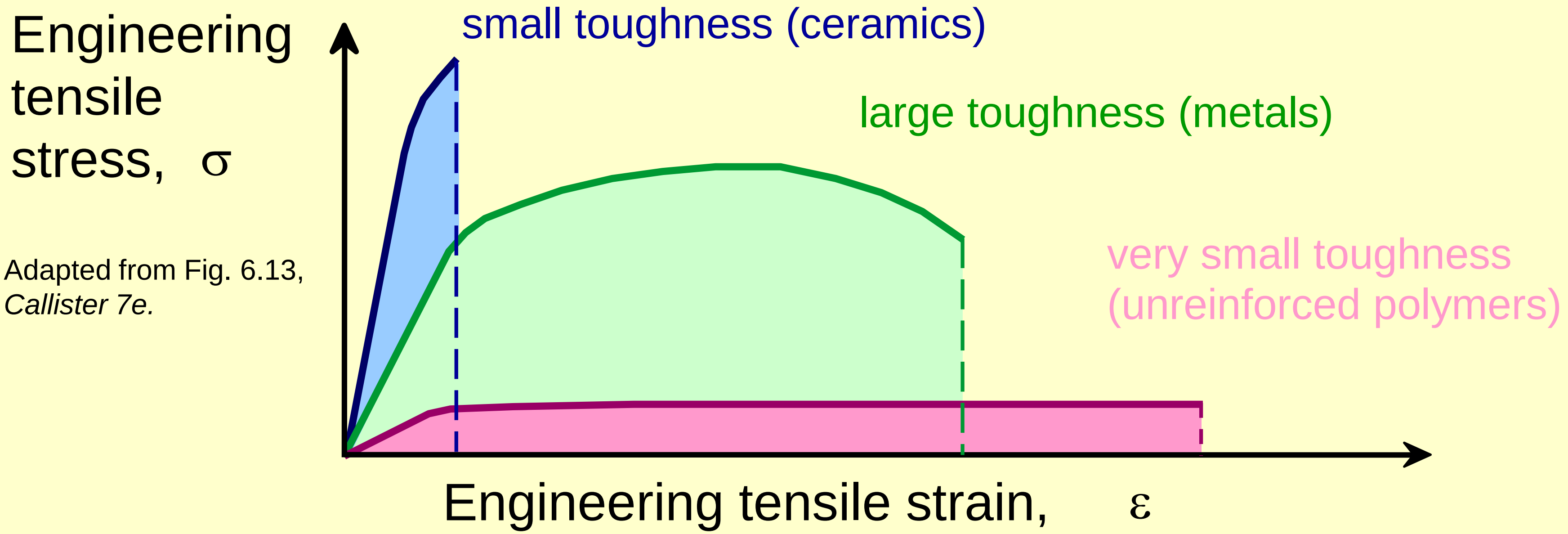
2. Specimen with crack- Fracture toughness

Static (low strain rate) loading condition (tensile stress-strain test)

1. Area under stress vs strain curve up to the point of fracture.

Toughness

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

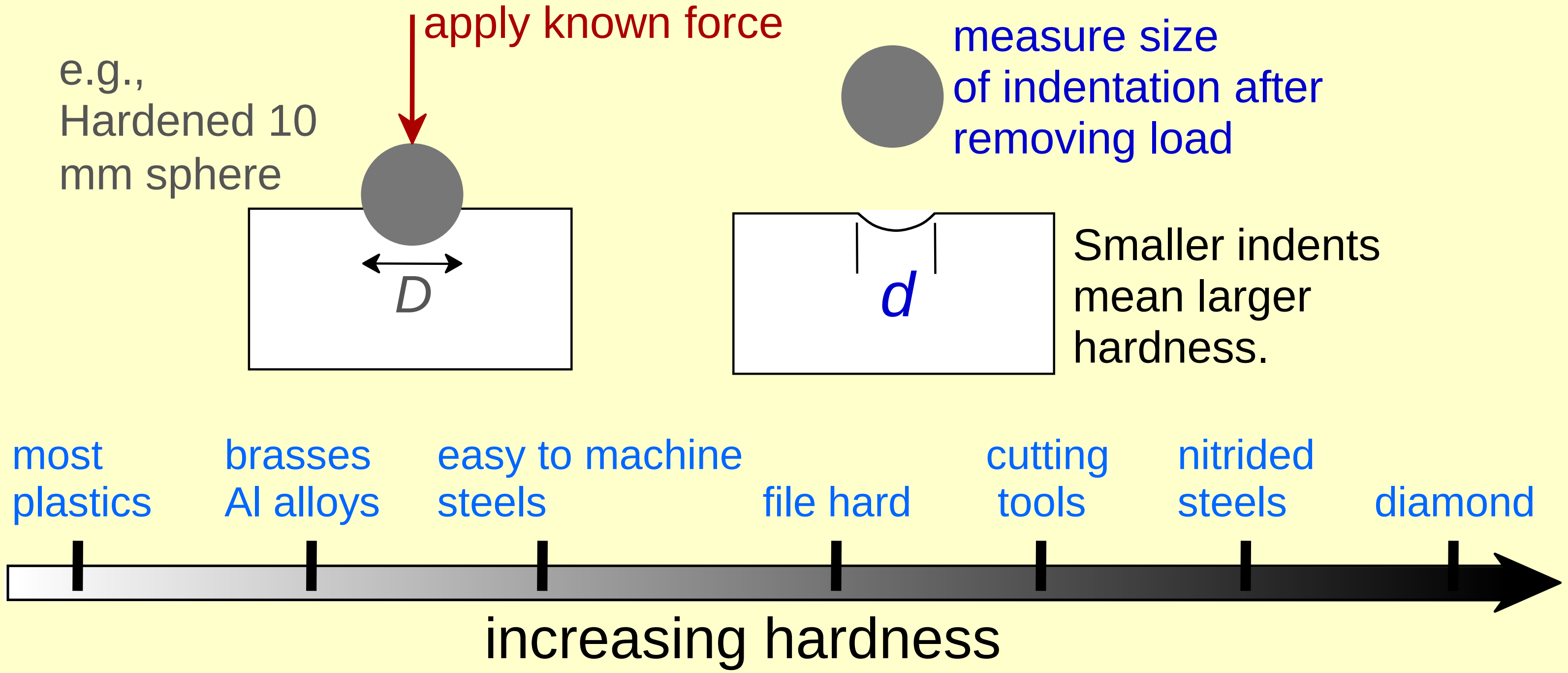


Adapted from Fig. 6.13, *Callister 7e.*

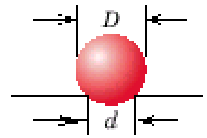
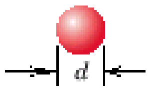
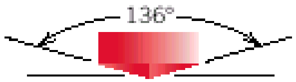
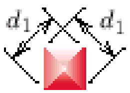
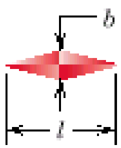
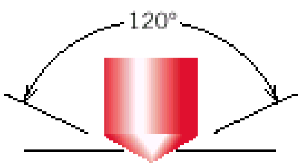
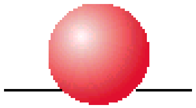
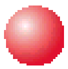
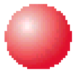
Brittle fracture: elastic energy
Ductile fracture: elastic + plastic energy

Hardness

- Resistance to permanently (plastically) indenting the surface of a product.
- Large hardness means:
  --resistance to plastic deformation or cracking in compression.
  --better wear properties.



Hardness: Common Measurement Systems

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.

Callister Table 6.5

Comparing Hardness Scales:

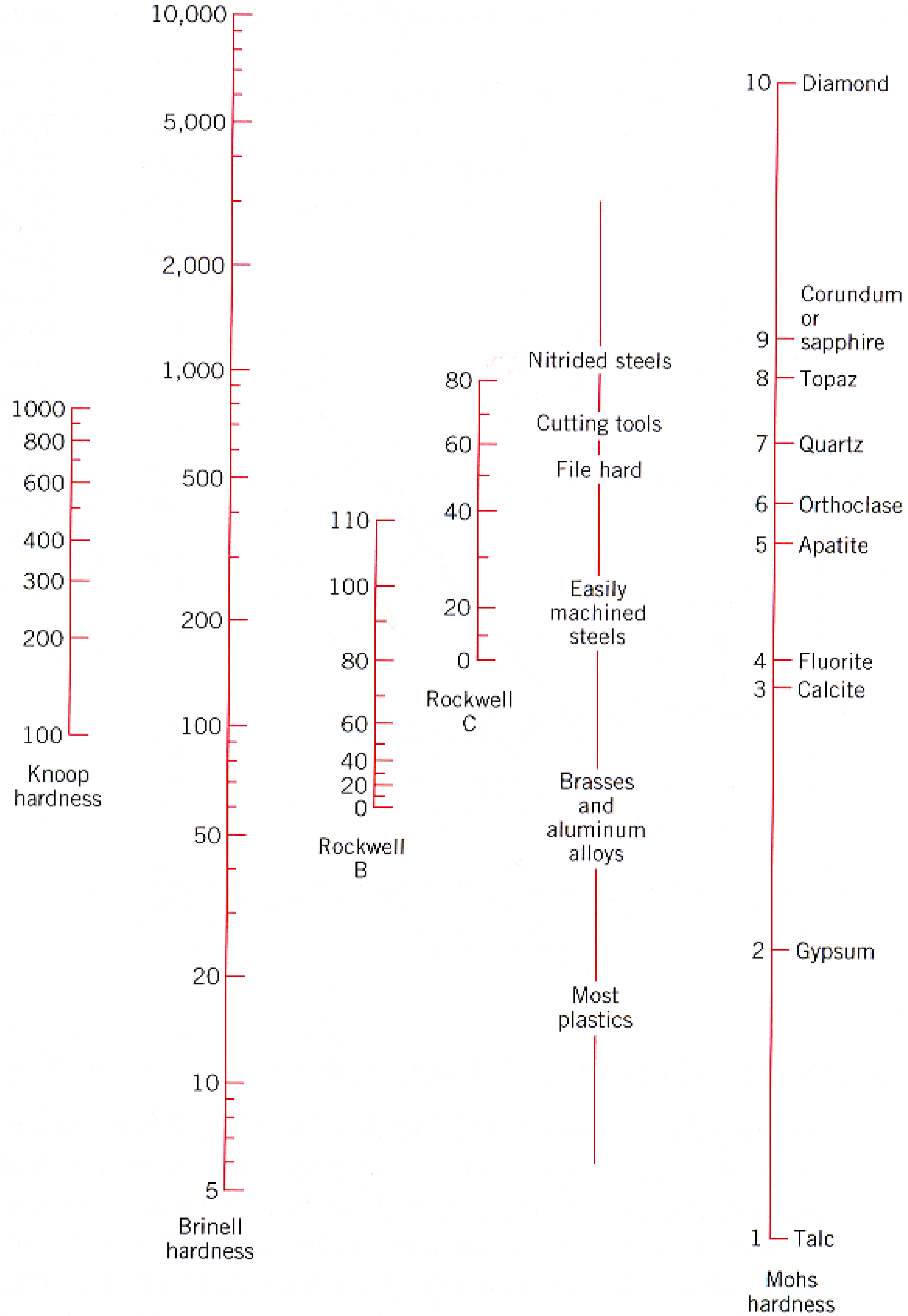


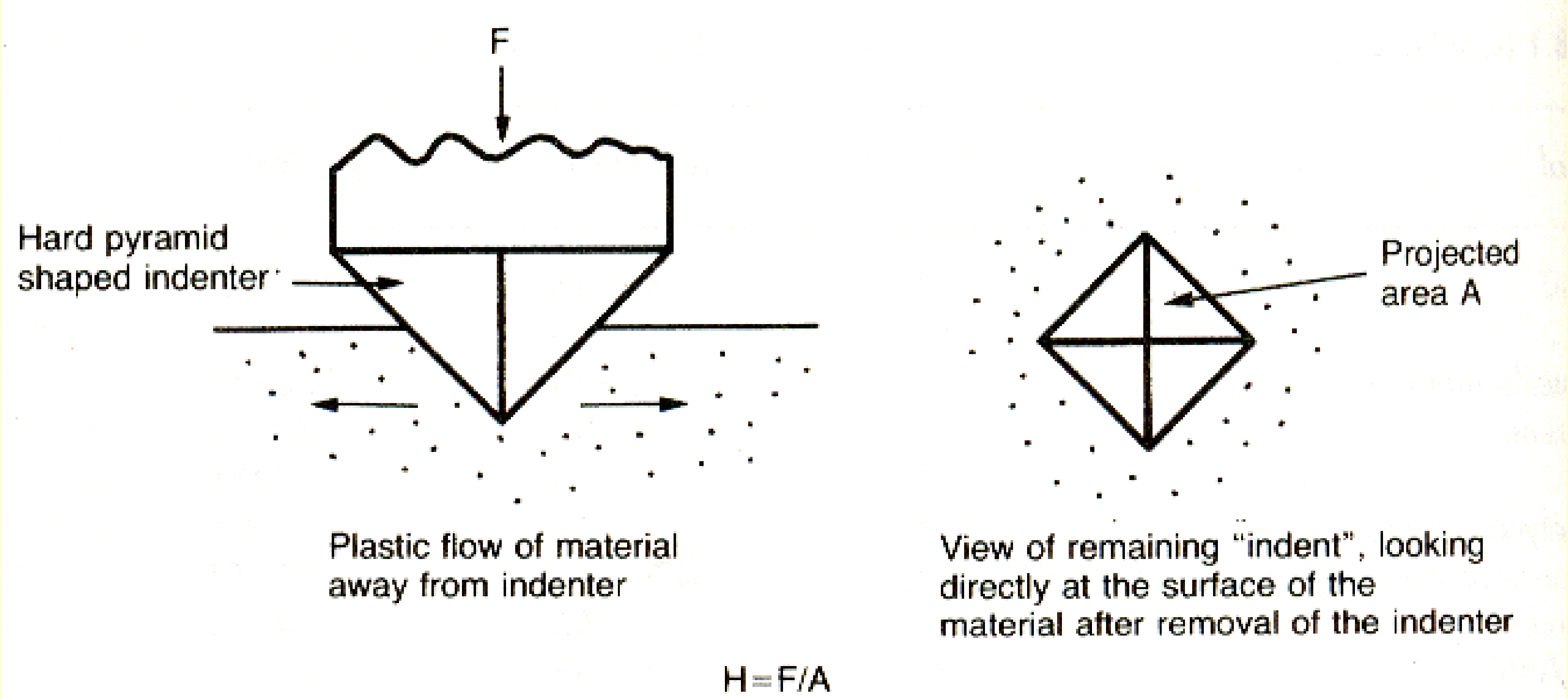
FIGURE 6.18 Comparison of several hardness scales. (Adapted from G. F. Kinney, *Engineering Properties and Applications of Plastics*, p. 202. Copyright © 1957 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)

Inaccuracies in Rockwell (Brinell) hardness measurements may occur due to:

- **An indentation is made too near a specimen edge.**
- **Two indentations are made too close to one another.**
- **Specimen thickness should be at least ten times the indentation depth.**
- **Allowance of at least three indentation diameters between the center on one indentation and the specimen edge, or to the center of a second indentation.**
- **Testing of specimens stacked one on top of another is not recommended.**
- **Indentation should be made into a smooth flat surface.**

Correlation Between Hardness and Tensile Strength

Both measures the resistance to plastic deformation of a material.



The hardness test for yield strength.

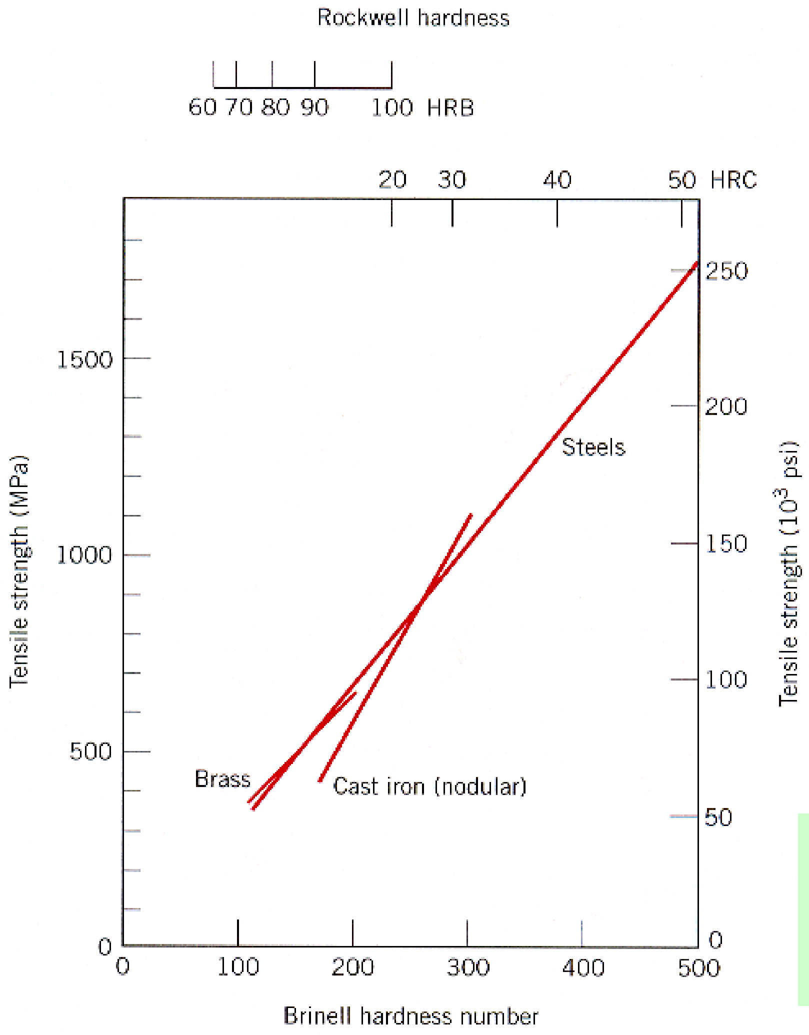


FIGURE 6.19 Relationships between hardness and tensile strength for steel, brass, and cast iron. (Data taken from *Metals Handbook: Properties and Selection: Irons and Steels,* Vol. 1, 9th edition, B. Bardes, Editor, American Society for Metals, 1978, pp. 36 and 461; and *Metals Handbook: Properties and Selection: Nonferrous Alloys and Pure Metals,* Vol. 2, 9th edition, H. Baker, Managing Editor, American Society for Metals, 1979, p. 327.)

HB = Brinell Hardness

***TS* (psia) = 500 x HB**

***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).
- 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.