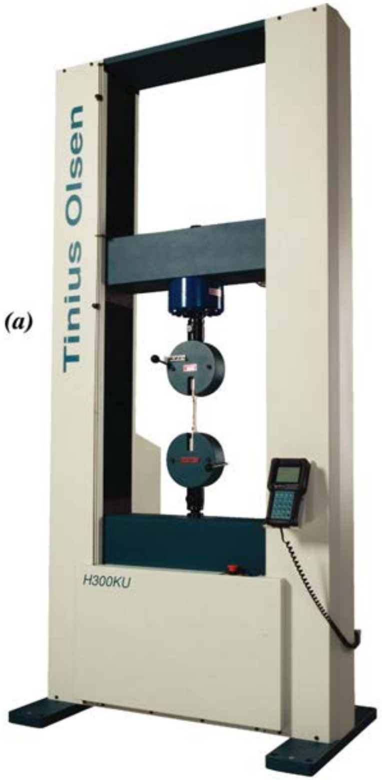
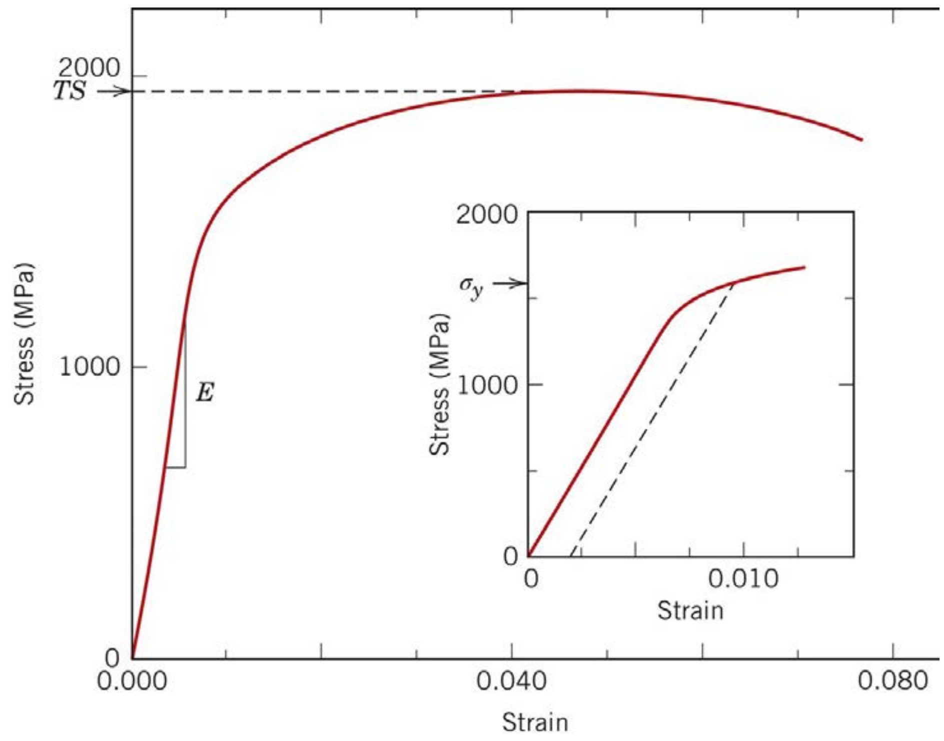
(a)



Model H300KU Universal Testing Machine by Tinius Olsen



(b)

Main suspender cables

Vertical suspender cables

(c)

Chapter 7: Mechanical Properties

ISSUES TO ADDRESS...

- When a metal is exposed to **mechanical forces**, what parameters are used to express force magnitude and degree of deformation?

彈性 塑性

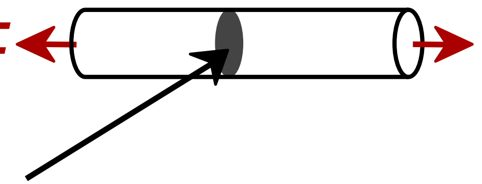
- What is the distinction between **elastic** and **plastic** deformations?

- How are the following mechanical characteristics of metals measured?
  - (a) **Strength**
  - (b) **Ductility** 延展性
  - (c) **Hardness**

- What parameters are used to quantify these properties?

Common States of Stress（應力）

- **Simple tension**: **cable**



F ← → *F* = force

A_o = cross-sectional area of cable (with no load)

Ski lift (photo courtesy P.M. Anderson)
滑雪電纜車

Tensile stress = σ

拉伸應力

材料展延 ⇒ 形變

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

F: 垂直試片橫截面的瞬間作用負荷

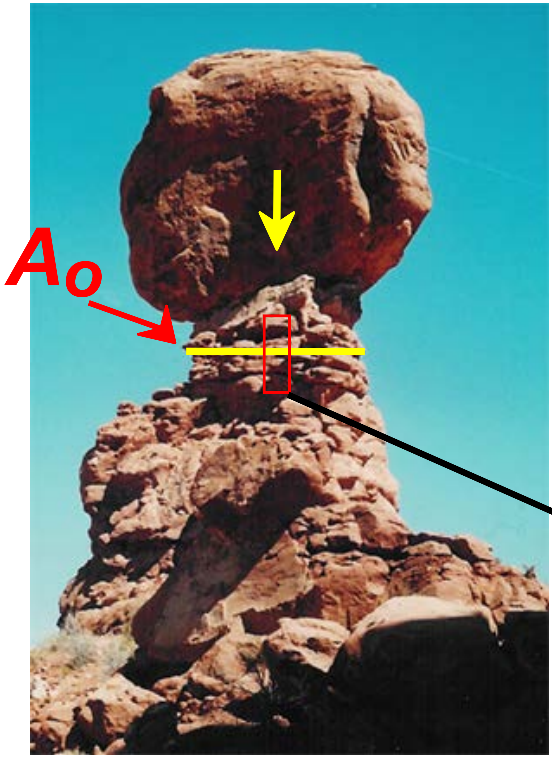
A0:負荷作用前，原來橫截面面積

Units for stress:

MPa = 10^6 Pa = 10^6 N/m^2 or lb$_f$/in^2

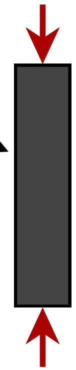
OTHER COMMON STRESS STATES (i)

- **Simple compression:** 壓縮應力



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

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

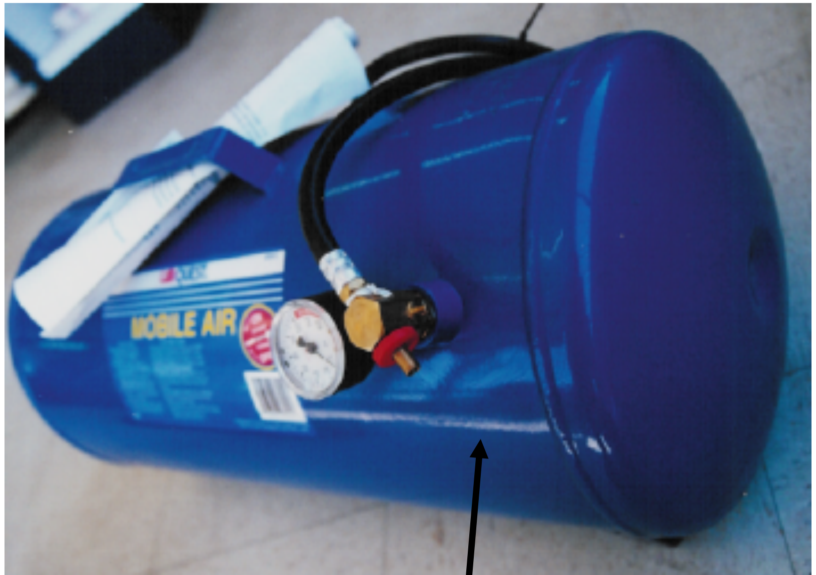


Note: structure members are under compression ($F < 0$ and $\sigma < 0$).

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

OTHER COMMON STRESS STATES (ii)

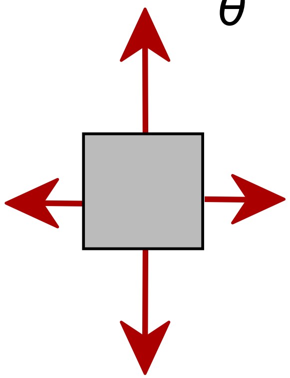
- **Bi-axial tension:**



Pressurized tank

(photo courtesy
P.M. Anderson)

$\sigma_\theta > 0$



$\sigma_z > 0$

水合壓力

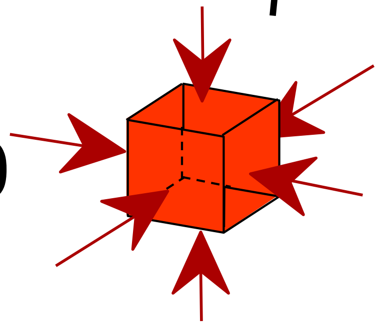
- **Hydrostatic compression:**

非單方向

(photo courtesy
P.M. Anderson)

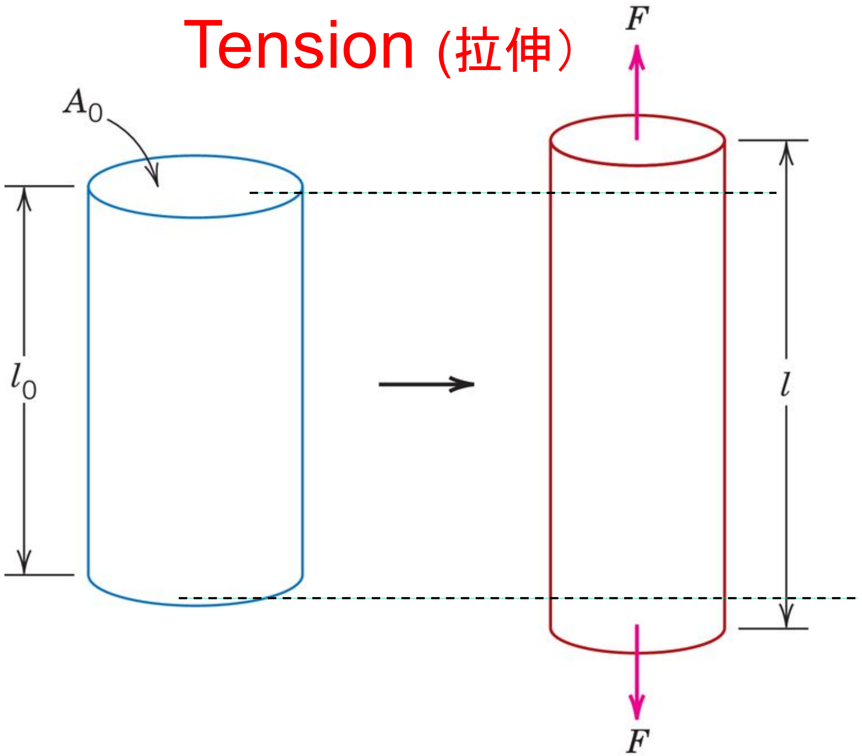
Fish under water

$\sigma_h < 0$



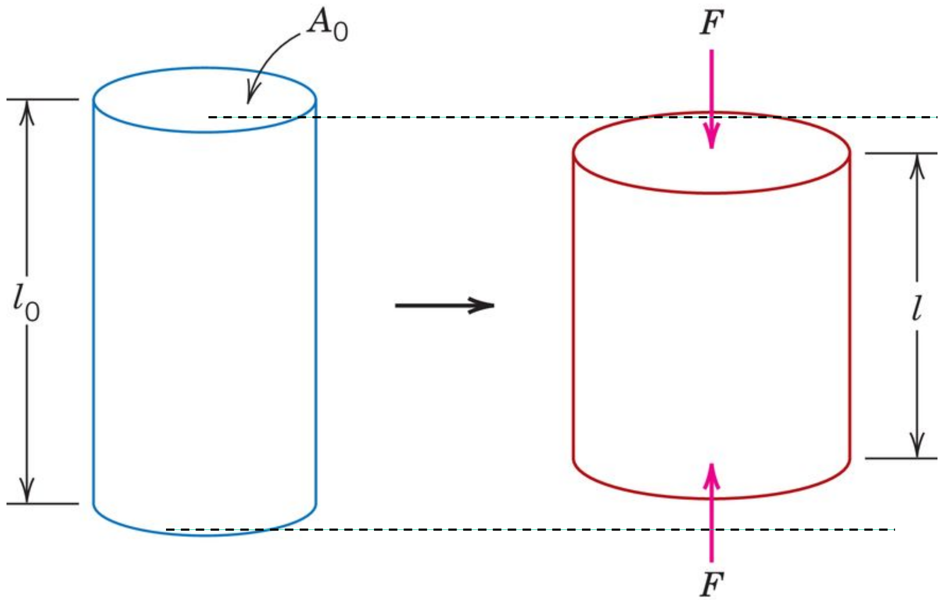
Common States of Stress（應力）

Tension (拉伸)



(a)

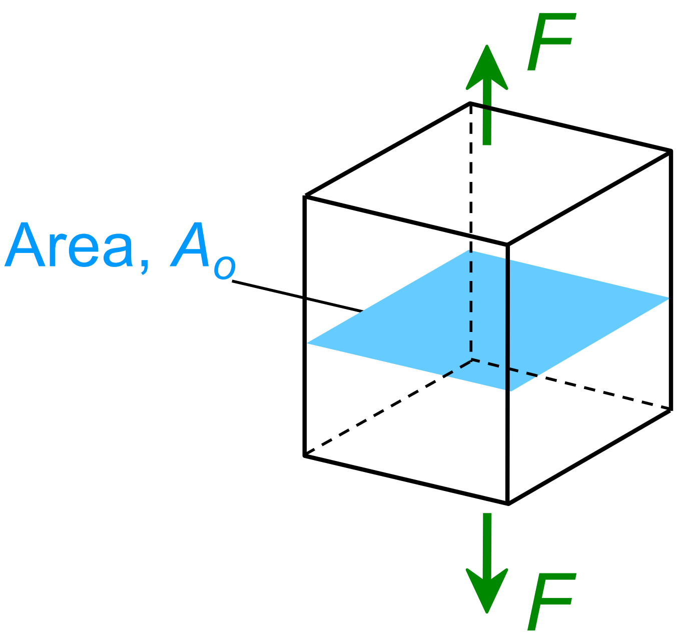
Compression (壓縮)



(b)

Engineering **Stress**（應力）

- **Tensile** stress, σ:

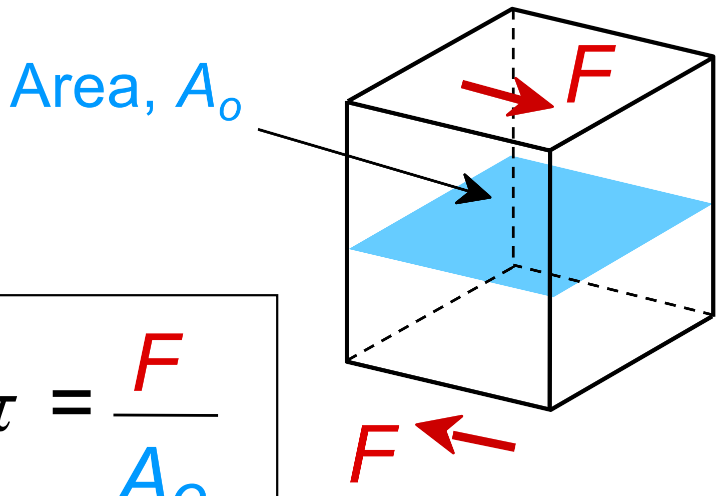


$$\sigma = \frac{F}{A_o}$$

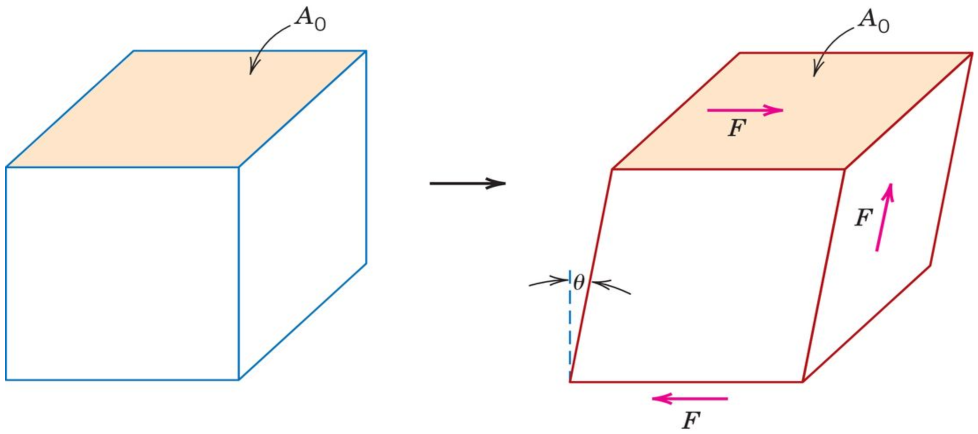
original cross-sectional area before loading

- **Shear** stress, τ:

剪力：平行於作用面



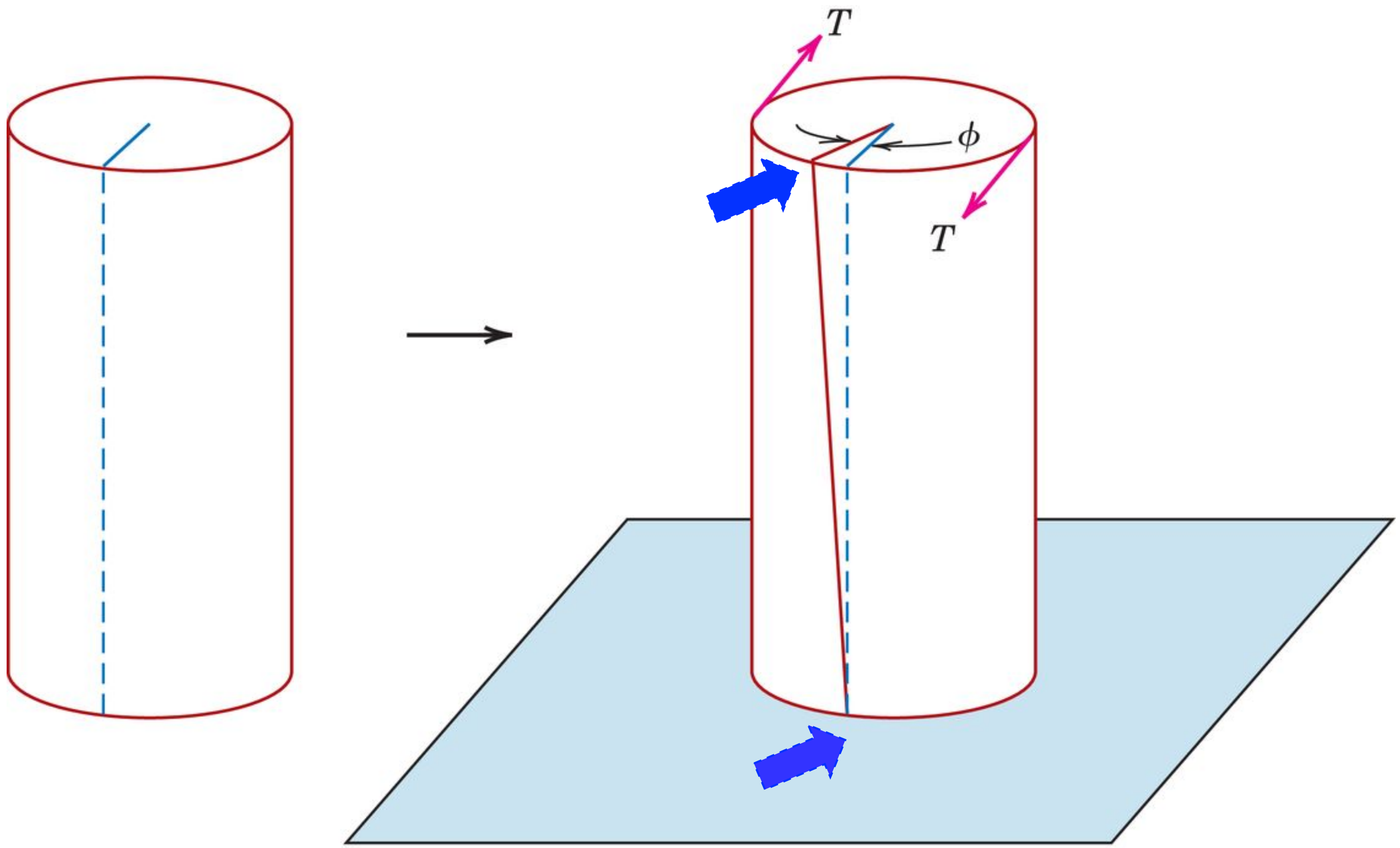
$$\tau = \frac{F}{A_o}$$



(c)

Common States of Stress（應力）

剪切和扭轉試驗（Shear and Torsional Tests）

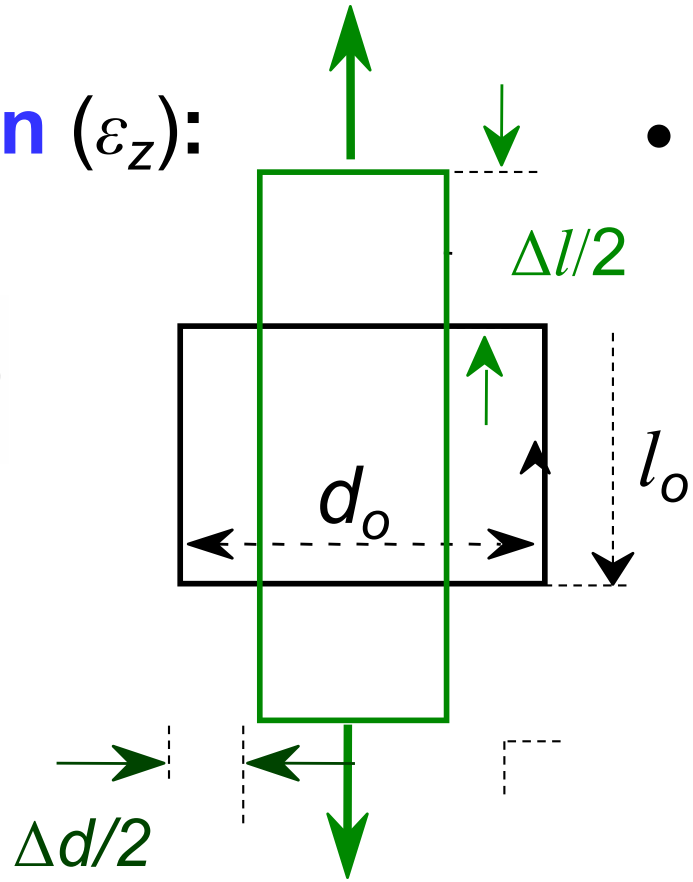


(d)

Engineering Strain (應變)

- **Tensile strain** (ε_z):

$$\varepsilon_z = \frac{\Delta l}{l_o} \qquad \frac{l_i - l_0}{l_0}$$



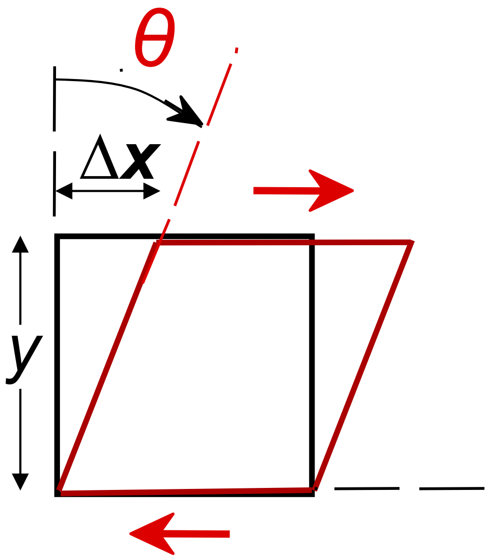
- **Lateral strain** (ε_x):

$$\varepsilon_x = \frac{-\Delta d}{d_o}$$

Engineering Strain（應變）

- **Shear strain** (γ):

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

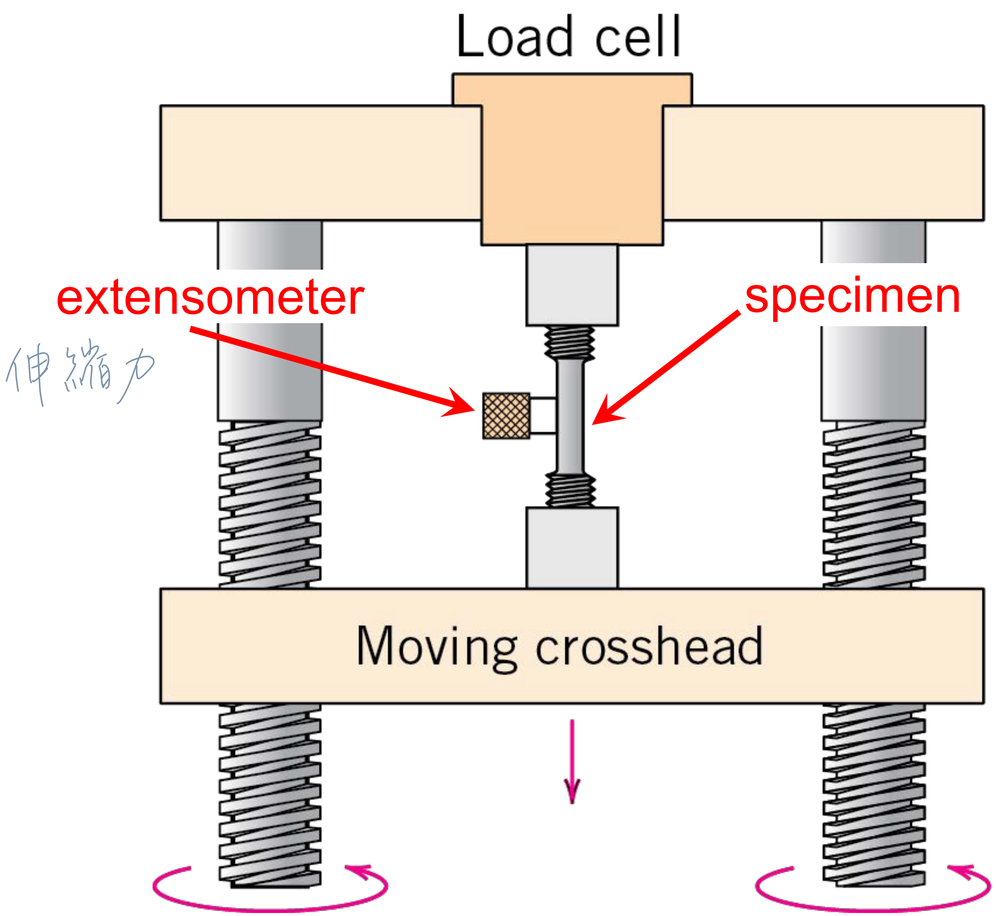


$\gamma = \Delta x / y = \tan\theta$

Both tensile and shear strain are dimensionless

Stress-Strain Testing

- **Typical tensile test machine**



- **Typical tensile specimen**

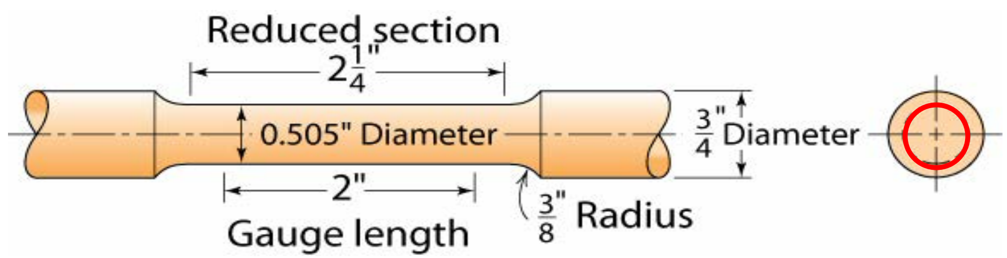
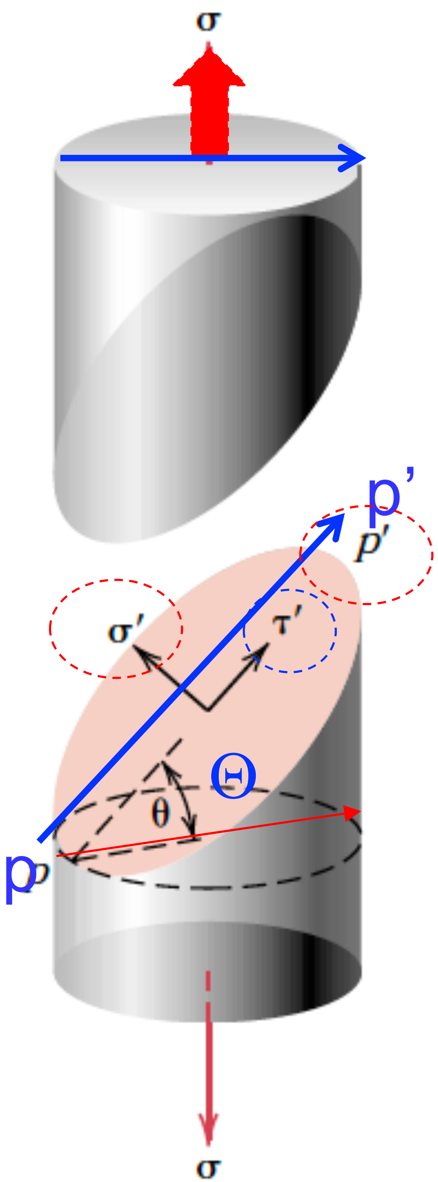
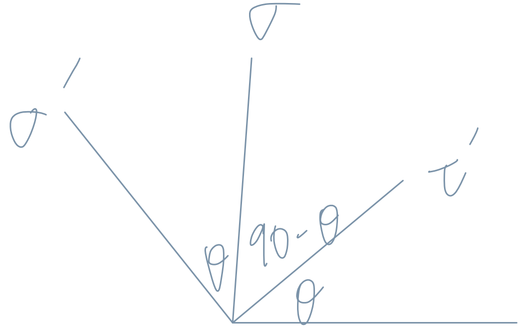


Fig. 7.3, *Callister & Rethwisch 5e.*
(Taken from H.W. Hayden, W.G. Moffatt, and J. Wulff, *The Structure and Properties of Materials*, Vol. III, *Mechanical Behavior*, p. 2, John Wiley and Sons, New York, 1965.)

Geometric Considerations of The Stress State

壓力狀態的幾何考量





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

$$\sigma' = \sigma \cos^2 \theta = \sigma \left(\frac{1 + \cos 2\theta}{2} \right) \qquad (7.4a)$$

$$\tau' = \sigma \sin \theta \cos \theta = \sigma \left(\frac{\sin 2\theta}{2} \right) \qquad (7.4b)$$

$\sigma = \frac{F}{A}$ $\qquad$ $\sigma' = \frac{F \times \cos\theta}{A \times \frac{1}{\cos\theta}}$

Linear Elastic Properties（線性彈性變形）

- **Elastic deformation** is **nonpermanent** and **reversible**!
  - generally valid at small deformations
  - linear stress strain curve

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

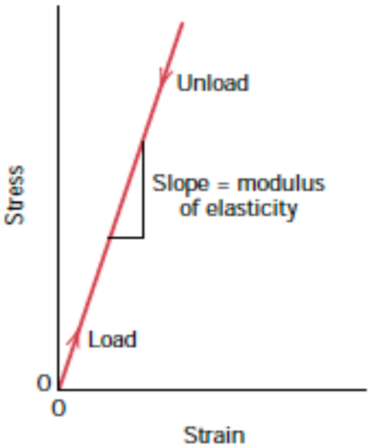
材料

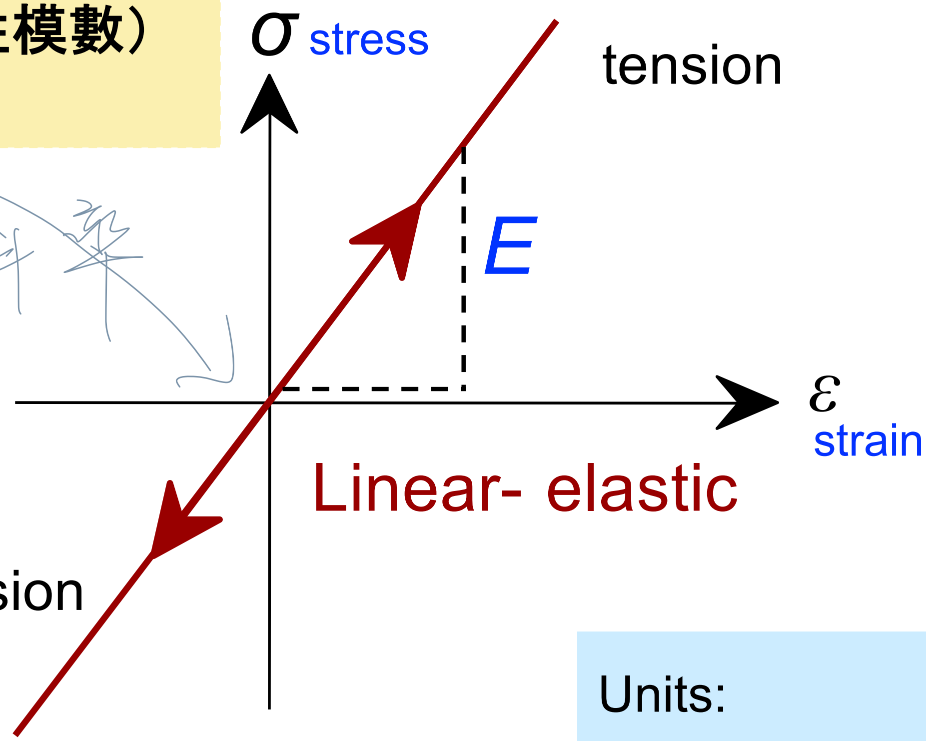
斜率

- **Hooke's Law:**

$$E = \frac{\sigma}{\varepsilon}$$

產生形變的力



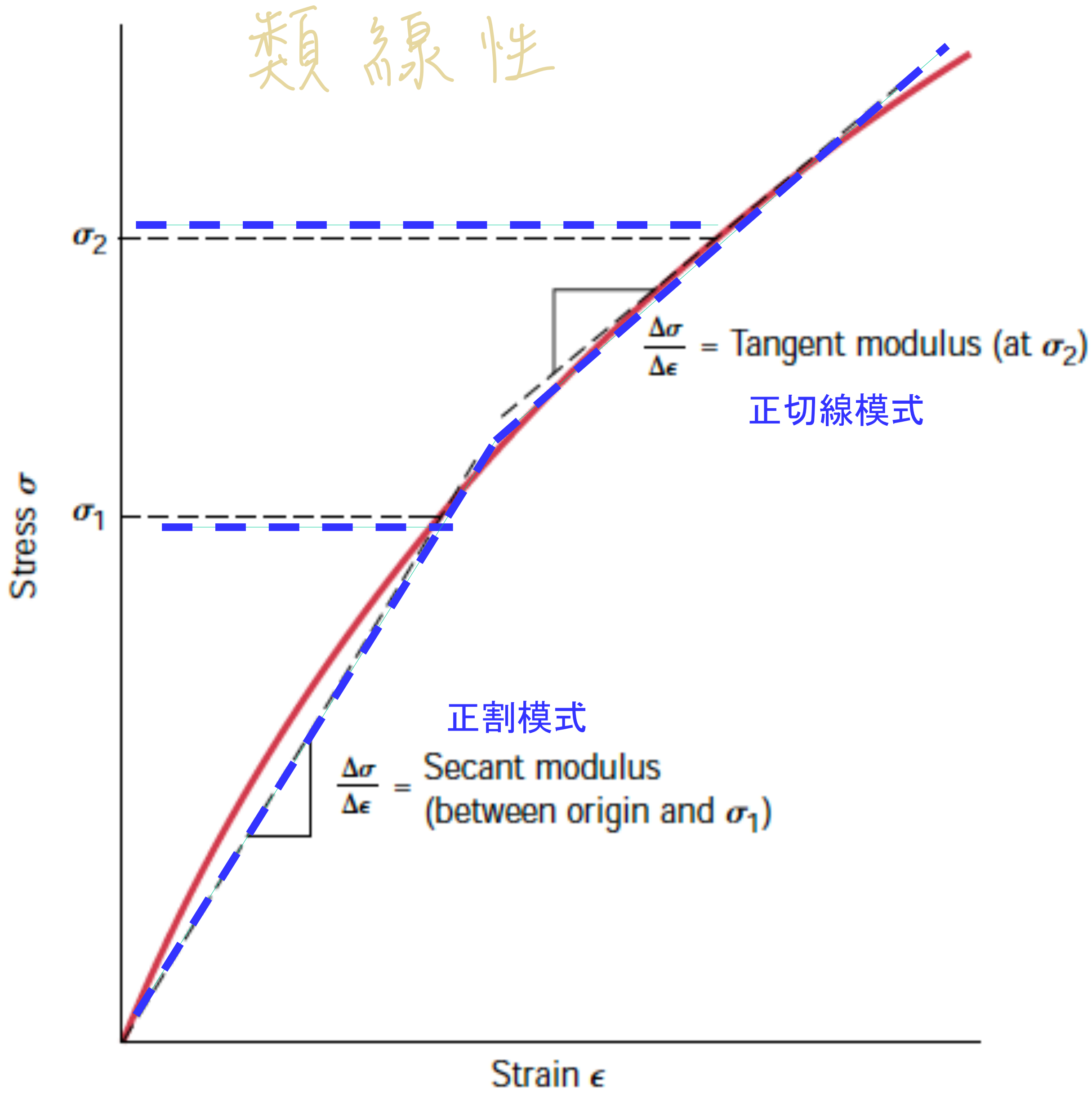


Units:

E: [GPa] or [psi]

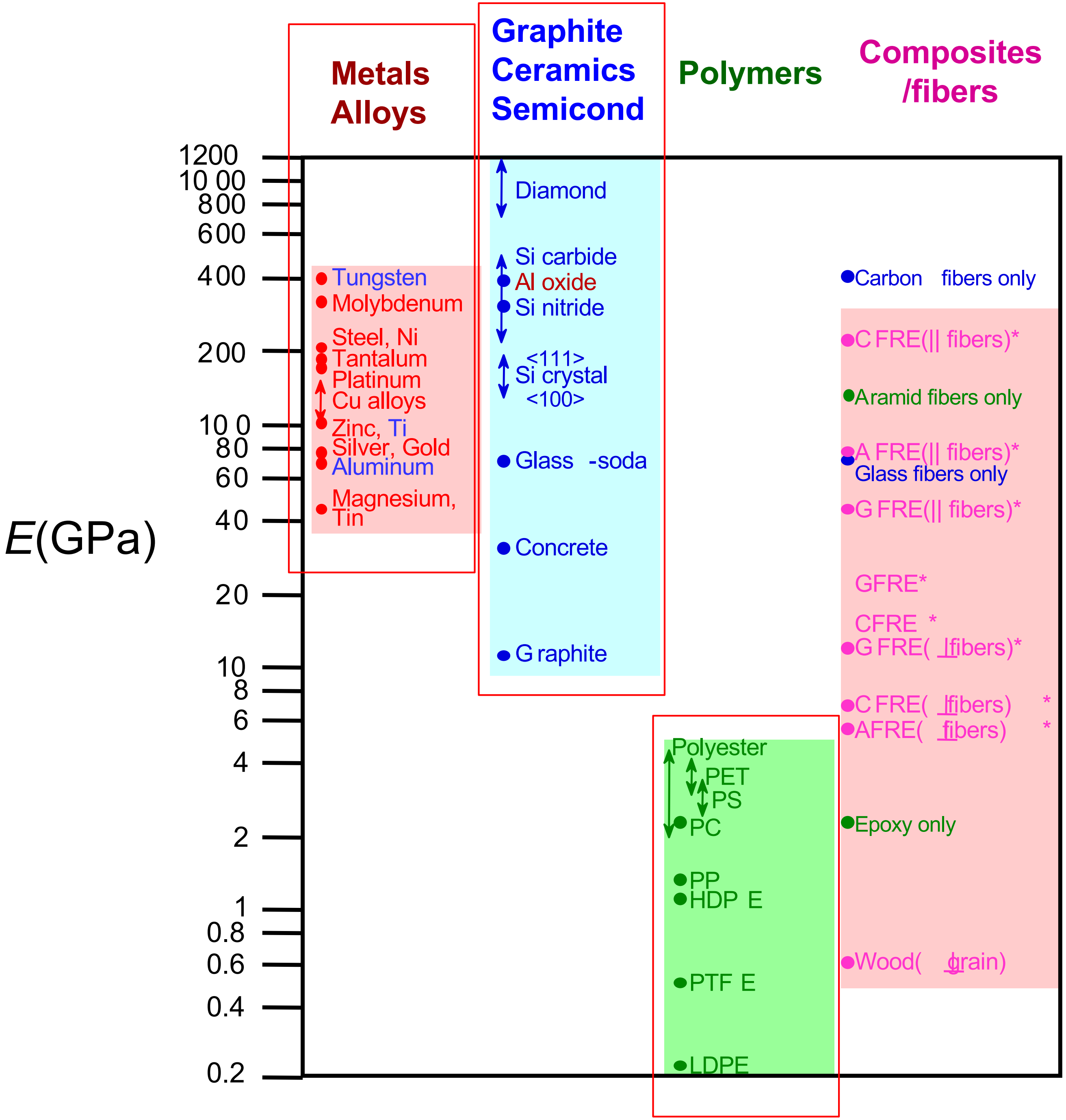
1 GPa = 10^9 Pa

Some material has Nonlinear elastic behavior



金屬
高分子

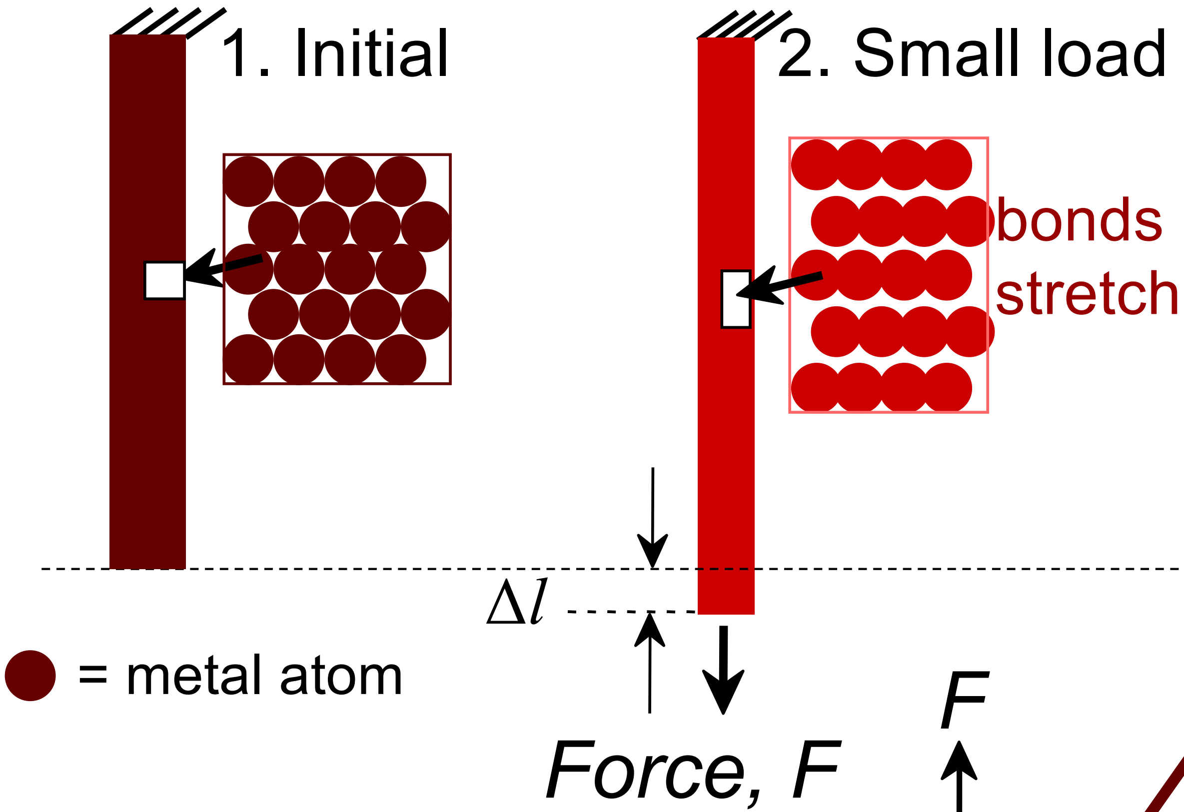
Elastic Modulus – Comparison of Material Types

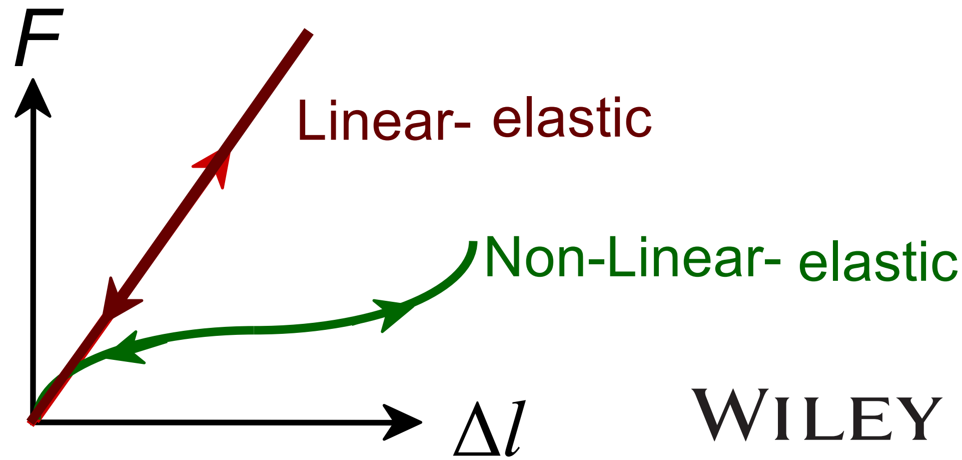


Composite data based on reinforced epoxy with 60 vol% of aligned carbon (CFRE), aramid (AFRE), or glass (GFRE) fibers.

Elastic Deformation（彈性變形）

Atomic configurations—before, during, after load (force) application





Elastic deformation is nonpermanent and reversible!

Influence of Bonding Forces

- Elastic modulus depends on interatomic bonding forces
- Modulus proportional to **slope** of inter-atomic force (F)-inter-atomic separation curve (r)

$$E \propto \left(\frac{dF}{dr}\right)_{r_0}$$

距離小→原子作用力大
↓
楊氏係數大

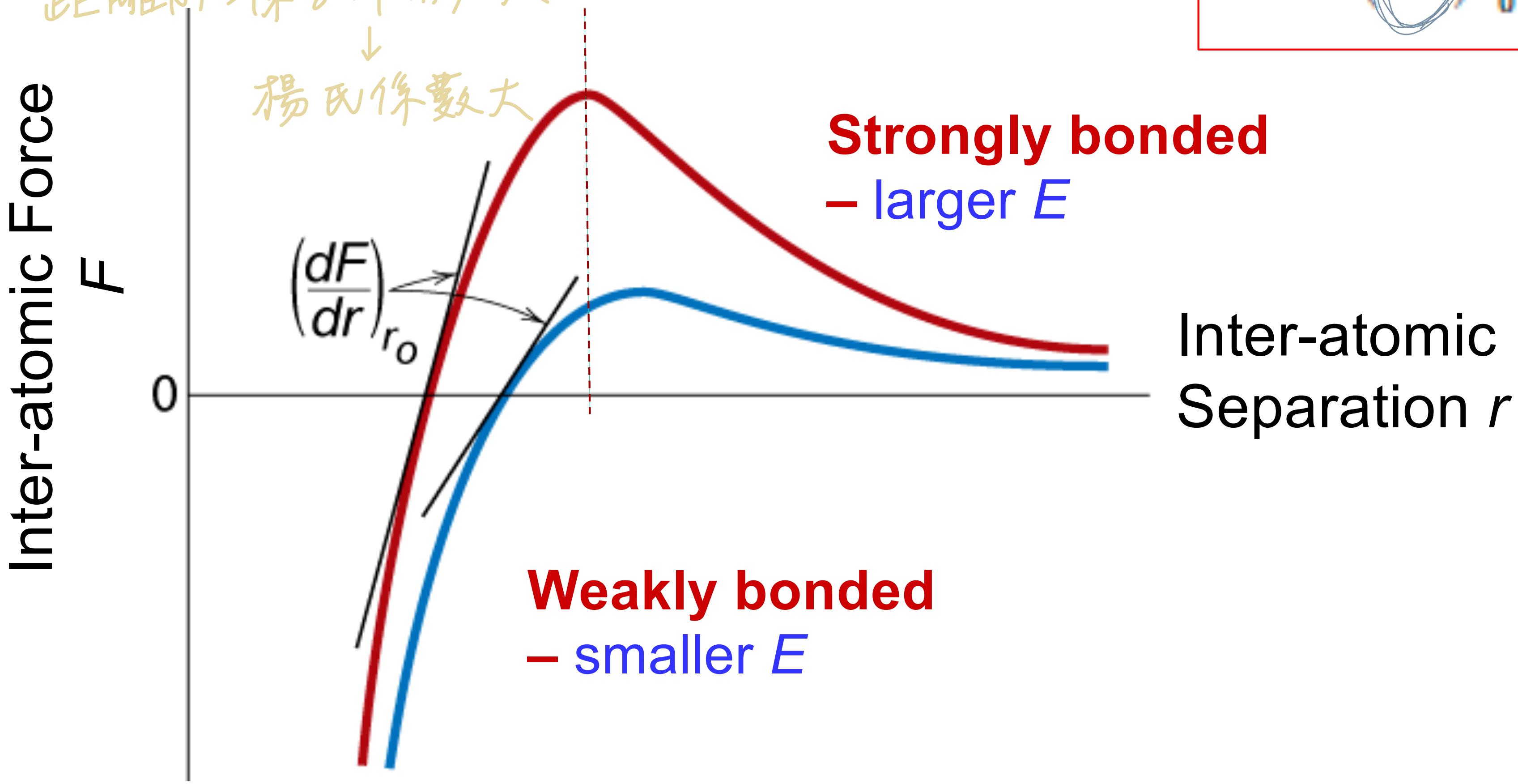
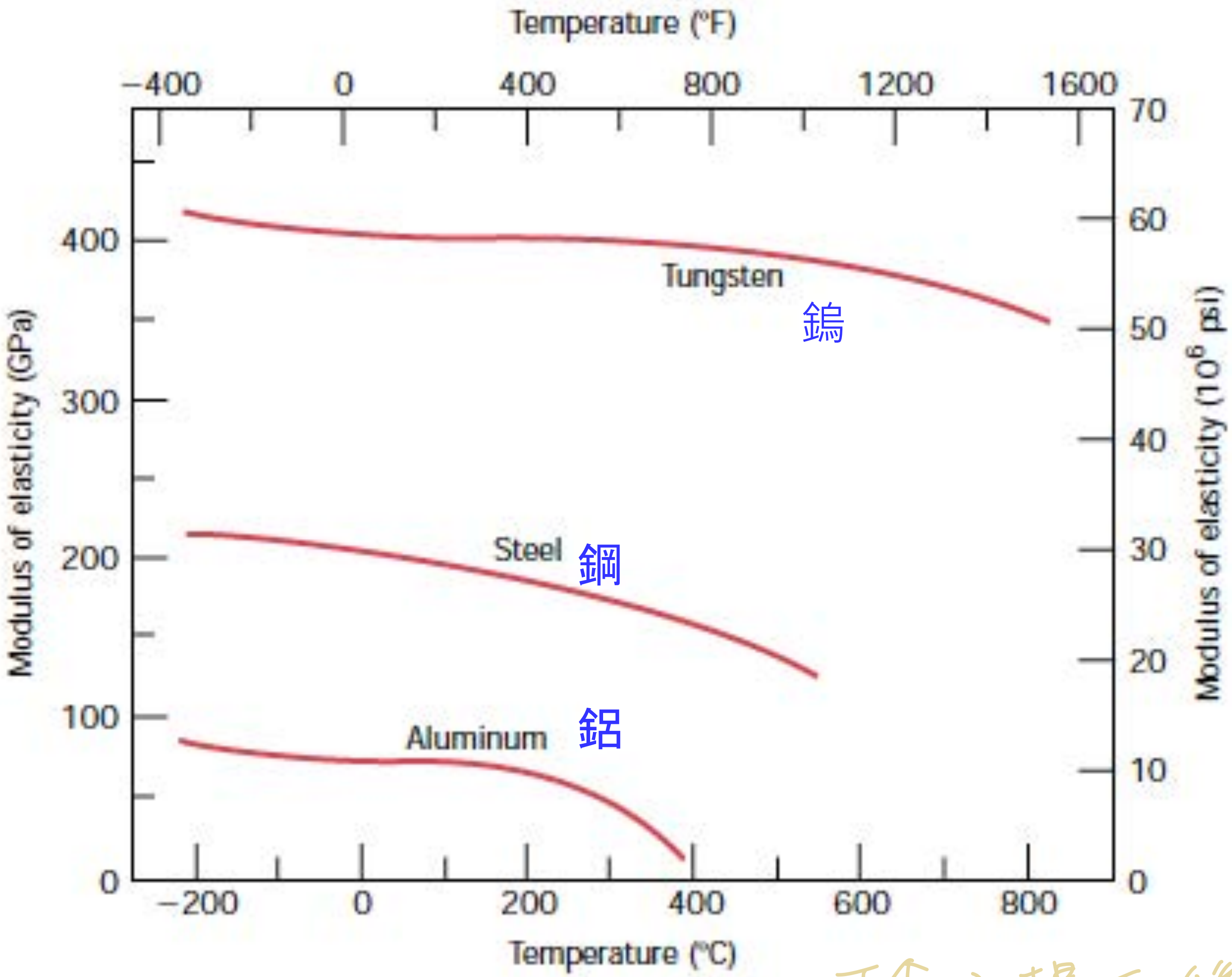


Fig. 7.7, *Callister & Rethwisch 5e.*

Temperature increased, modulus decreased



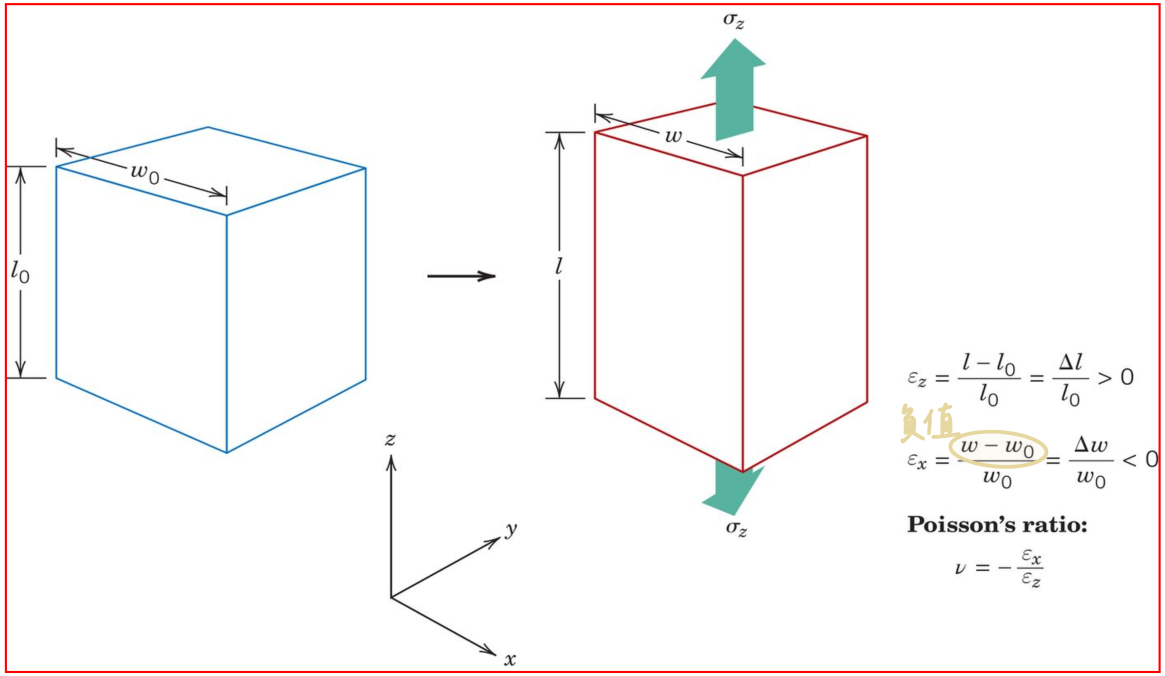
T↑ ⇒ 楊氏係數↓

Poisson‘s ratio（浦松比）

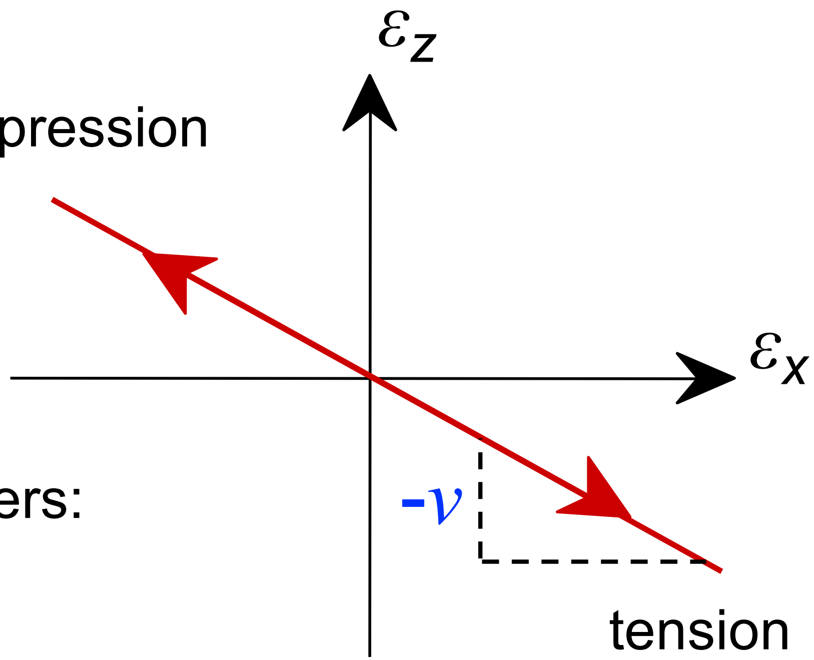
- **Poisson's ratio, ν:**

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

x axial 和 Z axial的 應變比值



Units ν:
dimensionless
無量綱 無因次



ceramics: $\nu \sim 0.25$

metals: $\nu \sim 0.33$

polymers: $\nu \sim 0.40$

For most metals, ceramics and polymers:

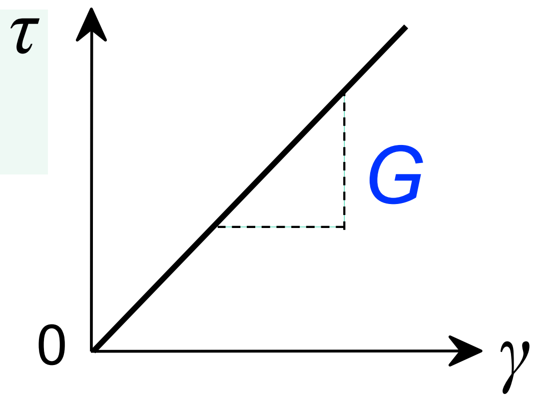
$0.15 < \nu \leq 0.50$

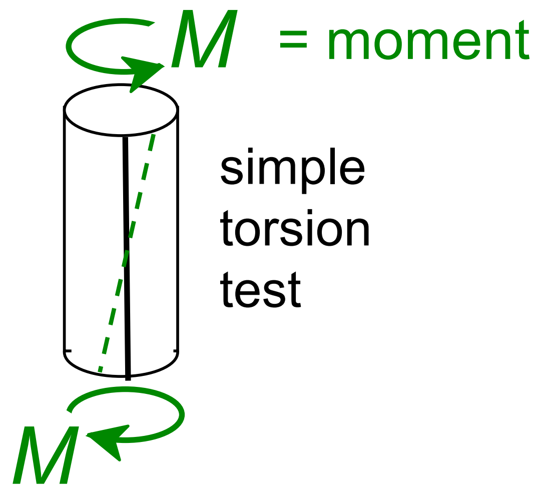
Other Elastic Properties

- **Elastic Shear modulus, G:**

G: shear modulus

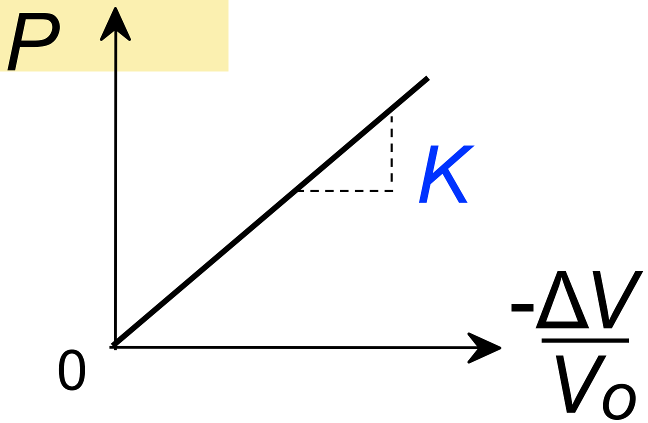
$$\tau = G\gamma$$

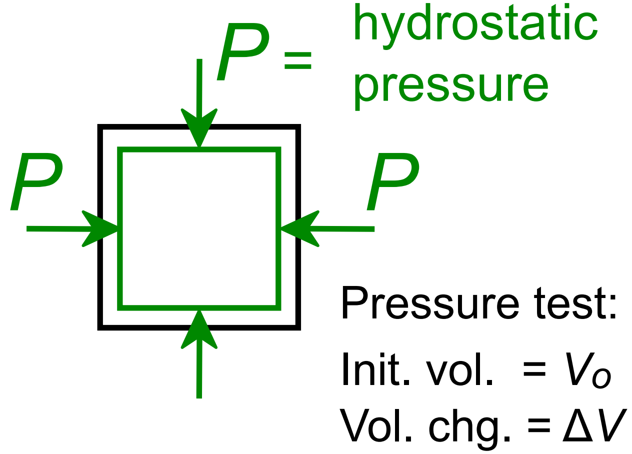




- **Elastic Bulk modulus, K:**

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





- Elastic constant relationships for **isotropic** materials:

等向材料

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

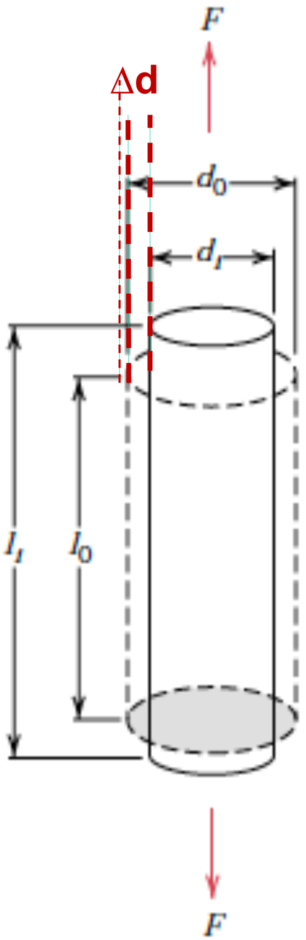
A tensile stress is to be applied along the long axis of a cylindrical brass rod that has a diameter of 10 mm (0.4 in.). Determine the magnitude of the load required to produce a 2.5×10^{-3} mm (10^{-4} in.) change in diameter if the deformation is entirely elastic.

d_0 Δd

Solution

This deformation situation is represented in the accompanying drawing.

Δd, of 2.5×10^{-3} mm



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

$$\epsilon_x = \frac{\Delta d}{d_0} = \frac{d_i - d_0}{d_0}$$

For the strain in the x direction

$$E = \frac{\sigma}{\varepsilon_z}$$

$$\boxed{\epsilon_x = \frac{\Delta d}{d_0} = \frac{-2.5 \times 10^{-3}\ \text{mm}}{10\ \text{mm}} = -2.5 \times 10^{-4}}$$

$$F = \frac{(-\Delta d)\, E A_0}{d_0 \times V}$$

For the strain in the z direction

$$\boxed{\epsilon_z = -\frac{\epsilon_x}{\nu} = -\frac{(-2.5 \times 10^{-4})}{0.34} = 7.35 \times 10^{-4}}$$

表

From Table 7-1

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

$$\boxed{\sigma = \epsilon_z E = (7.35 \times 10^{-4})(97 \times 10^3\ \text{MPa}) = 71.3\ \text{MPa}}$$

The applied force

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

原始截面積

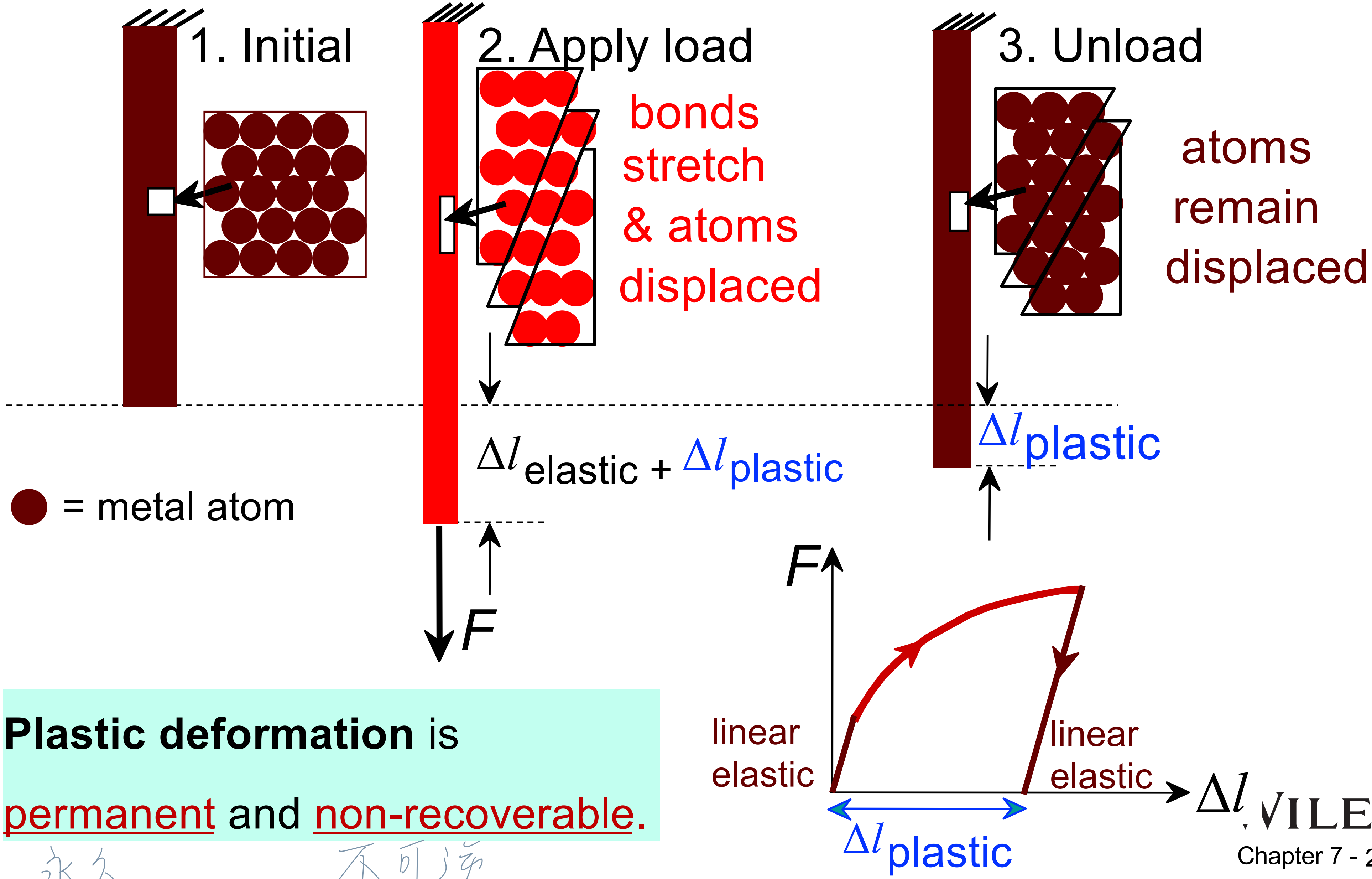
$$= (71.3 \times 10^6\ \text{N/m}^2)\left(\frac{10 \times 10^{-3}\ \text{m}}{2}\right)^2 \pi = 5600\ \text{N}\ (1293\ \text{lb}_f)$$

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

https://www.youtube.com/watch?v=tuOlM3P7ygA

Mechanical Behavior - Metals

Plastic Deformation (塑性變形) (Metals)



Plastic deformation is

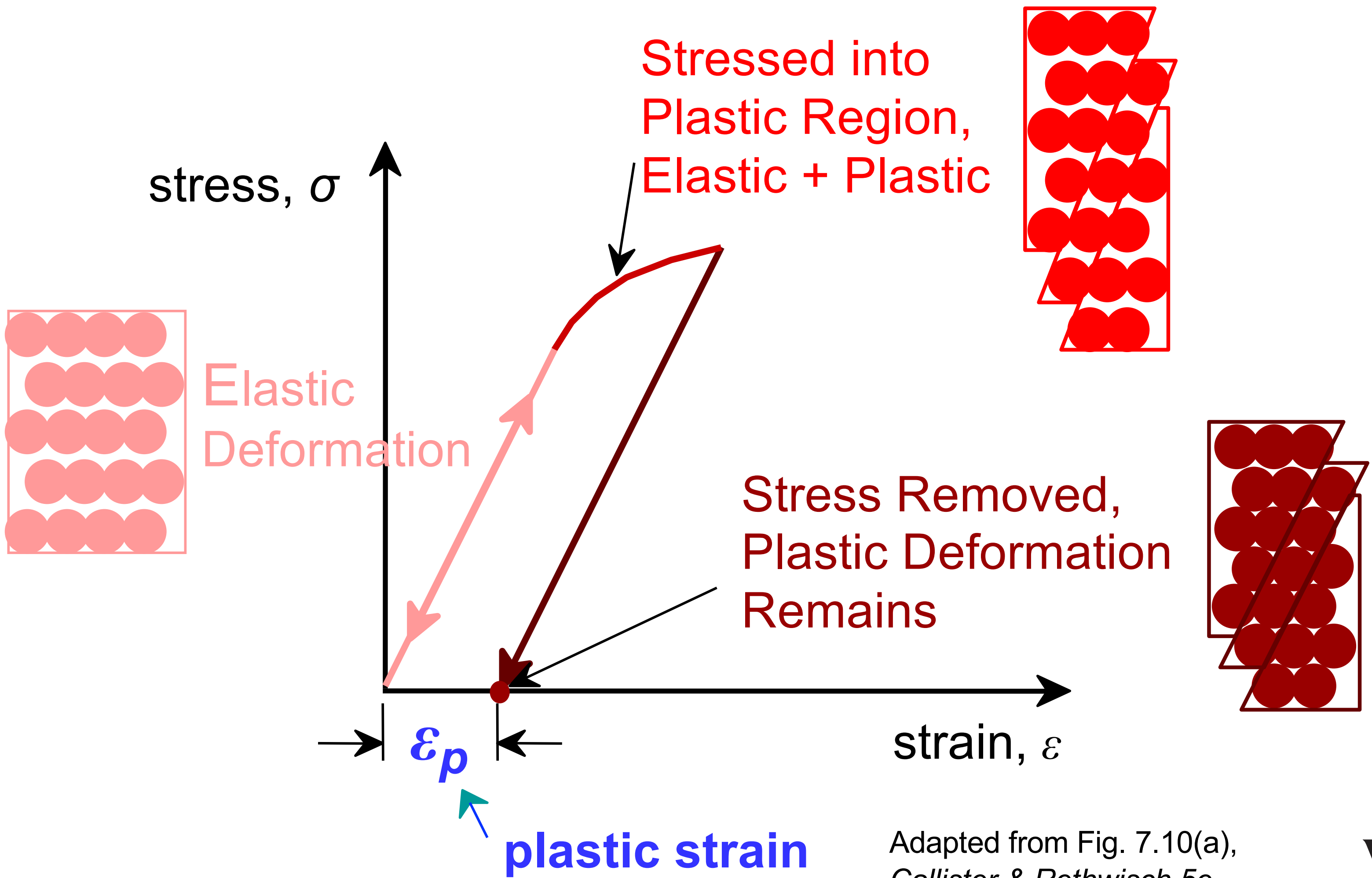
permanent and non-recoverable.

永久 不可逆

WILEY

Plastic Deformation（塑性變形）

- Plastic Deformation is permanent and nonrecoverable
- Stress-strain plot for simple tension test:



Adapted from Fig. 7.10(a), *Callister & Rethwisch 5e.*

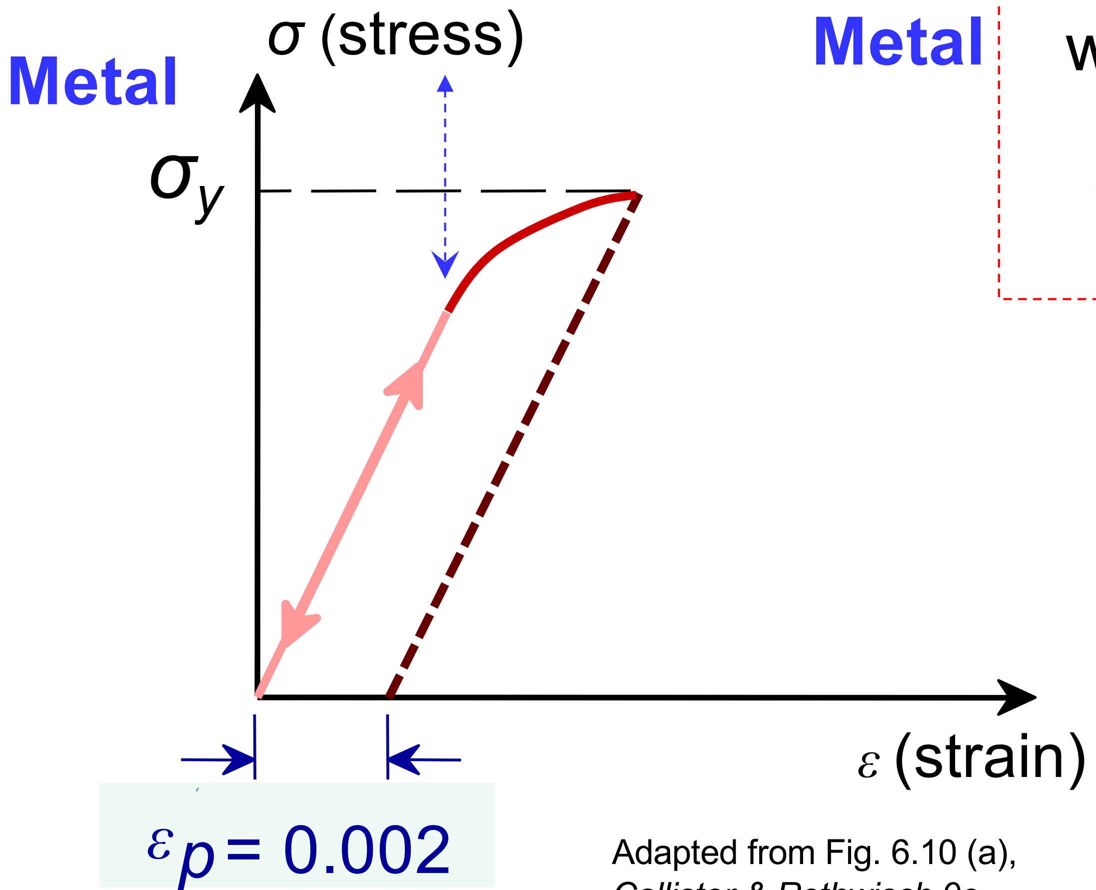
Yield Strength（降伏強度）

- Transition from elastic to plastic deformation is **gradual**

逐漸的

- Yield strength = **stress** at which *noticeable* plastic deformation has occurred

明顯的塑性變化



Adapted from Fig. 6.10 (a), *Callister & Rethwisch 9e.*

Metal

when $\varepsilon_p = 0.002$ (0.2%)

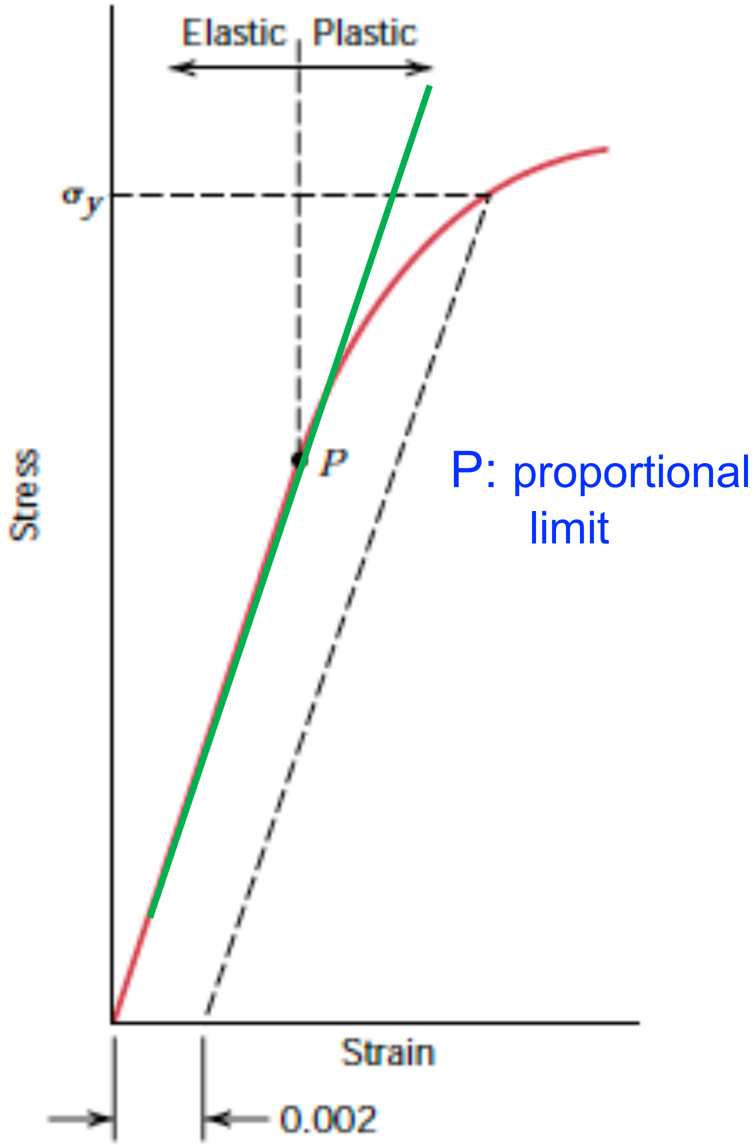
σ_y = yield strength

Note: for 5 cm sample

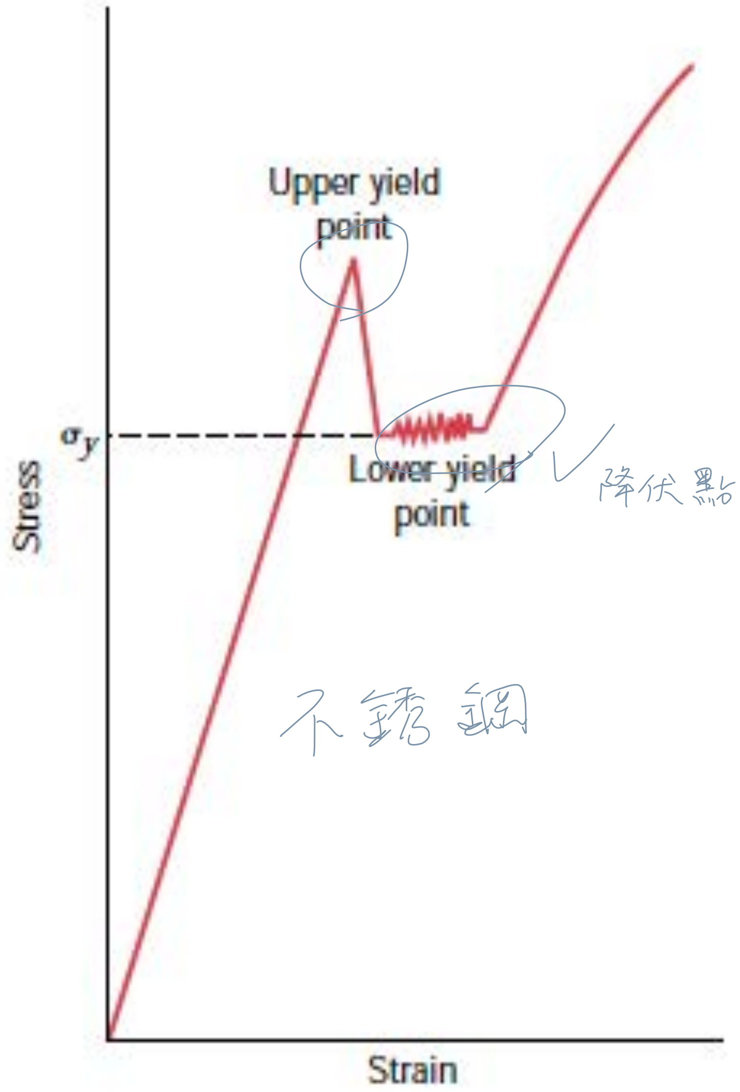
$\varepsilon = 0.002 = \Delta z/z$

$\Delta z = 0.01$ cm

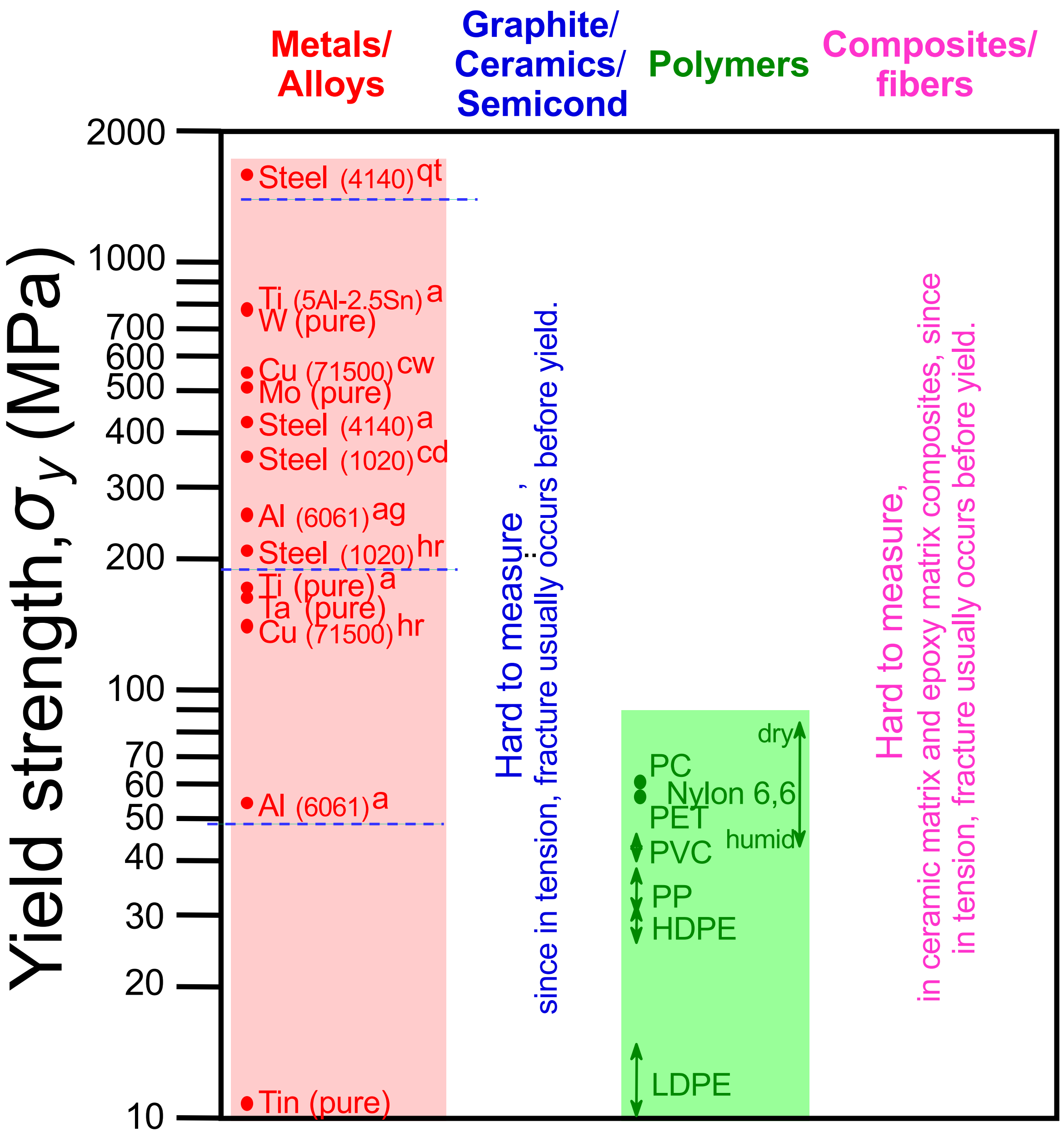
Typical stress–strain behavior for a metal



The stress–strain behavior found for some steels demonstrating the yield point phenomenon.



Yield Strength – Comparison of Material Types



Room temperature values

Based on data in Table B.4, *Callister & Rethwisch 5e.*

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

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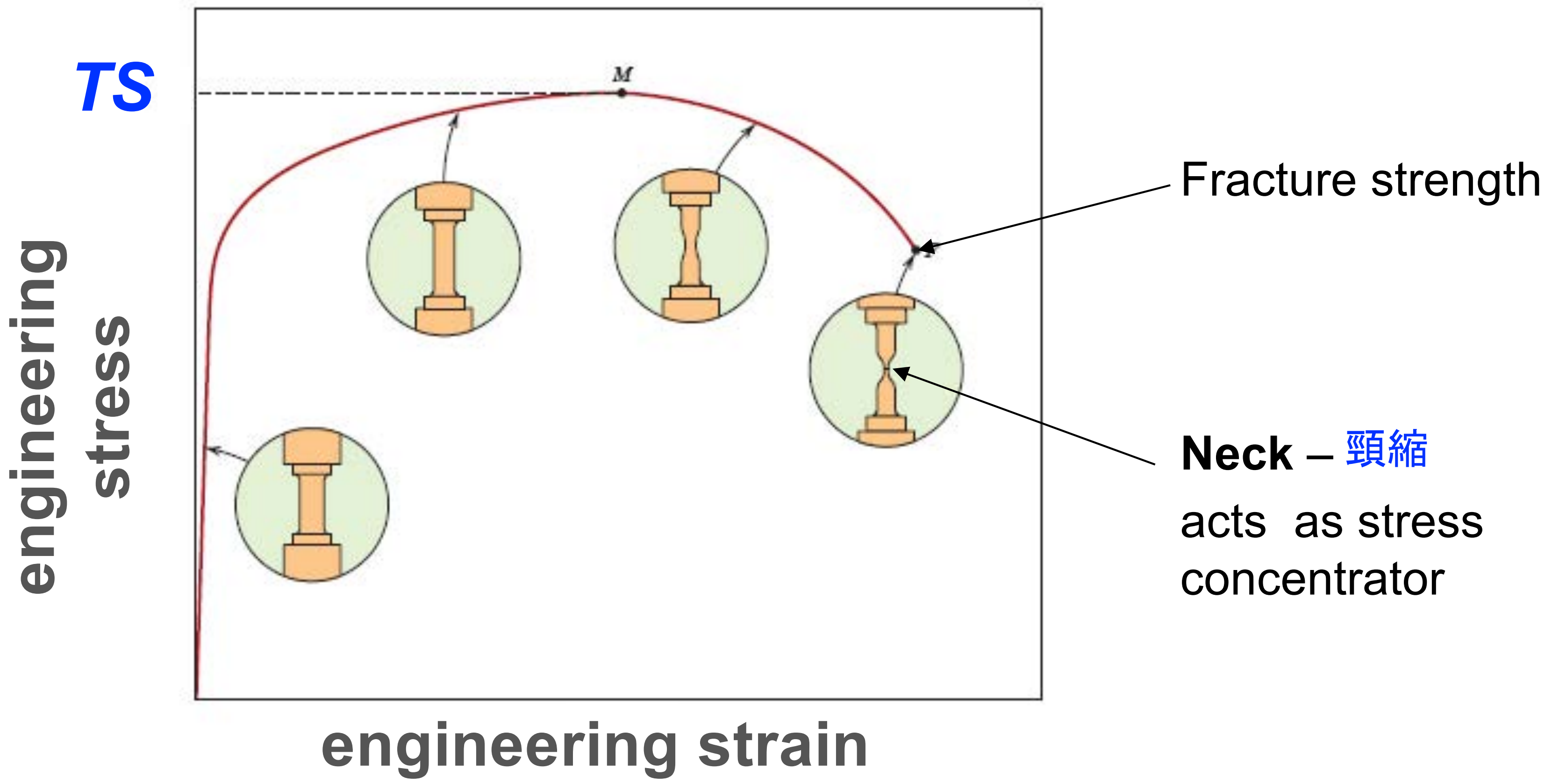
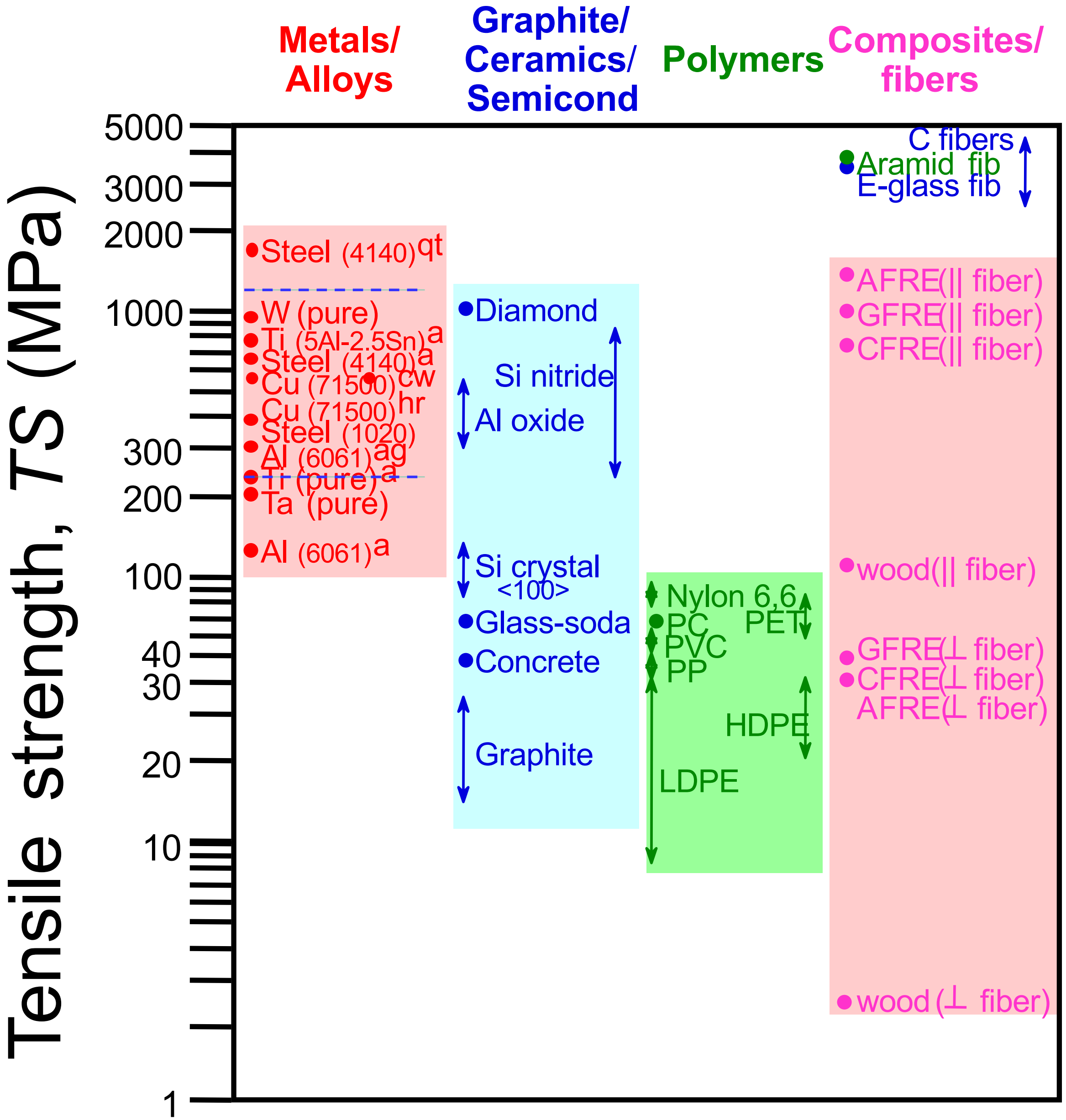
Tensile Strength（抗拉強度）

• **Tensile strength (*TS*) =** **maximum stress** on engineering stress-strain curve.



• Metals: Maximum on <u>stress-strain curve</u> appears at the onset of noticeable **necking**

Tensile Strength: Comparison of Material Types



Room temperature values

Based on data in Table B4, *Callister & Rethwisch 5e.*

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

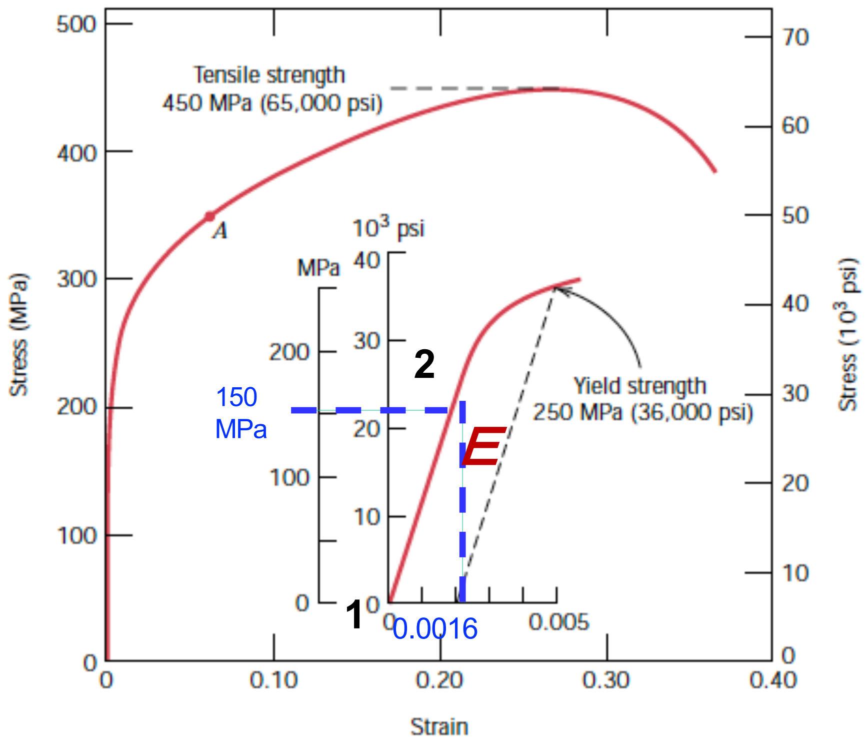
AFRE, GFRE, & CFRE = aramid, glass, & carbon fiber-reinforced epoxy composites, with 60 vol% fibers.

From the tensile stress–strain behavior for the brass specimen shown in Figure 7.12, determine the following:

係數

(a) The modulus of elasticity.

(b) The yield strength at a strain offset of 0.002.

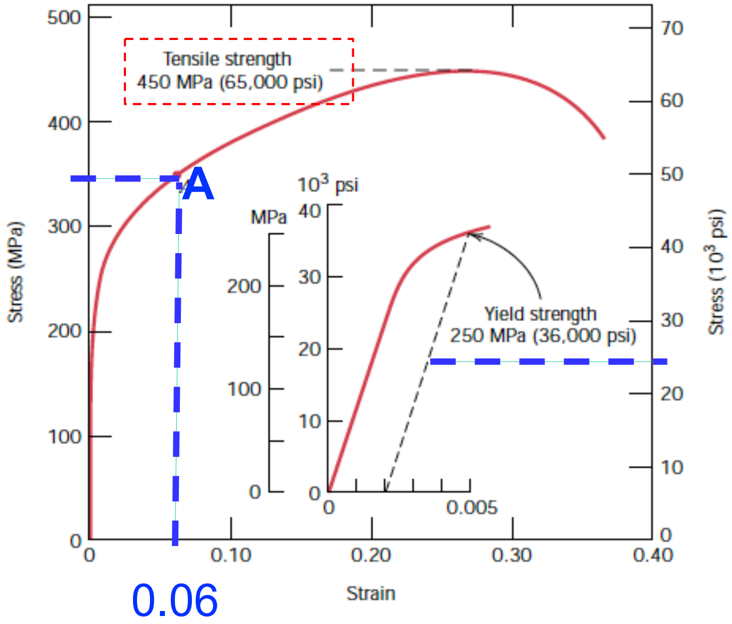


$$E = \text{slope} = \frac{\Delta\sigma}{\Delta\epsilon} = \frac{\sigma_2 - \sigma_1}{\epsilon_2 - \epsilon_1} \tag{7.10}$$

$$E = \frac{(150 - 0)\ \text{MPa}}{0.0016 - 0} = 93.8\ \text{GPa}\ (13.6 \times 10^6\ \text{psi})$$

(b) The 0.002 strain offset line is constructed as sho
tion with the stress–strain curve is at approxima
which is the yield strength of the brass.

(c) The maximum load that can be sustained by th
using Equation 7.1, in which σ is taken to be the te
7.12, 450 MPa (65,000 psi). Solving for F, the maxi



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

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

$$= (450 \times 10^6\ \mathrm{N/m^2}) \left(\frac{12.8 \times 10^{-3}\ \mathrm{m}}{2}\right)^2 \pi = 57{,}900\ \mathrm{N}\ (13{,}000\ \mathrm{lb_f})$$

(d) To compute the change in length, Δl, in Equation 7.2, 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

$$\Delta l = \epsilon l_0 = (0.06)(250\ \mathrm{mm}) = 15\ \mathrm{mm}\ (0.6\ \mathrm{in.})$$

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

Ductility（延展性）

- **Ductility = amount of plastic deformation at failure:**
- Specification of ductility

-- **Percent elongation**（%EL）:（伸長率）

l_f: fracture length

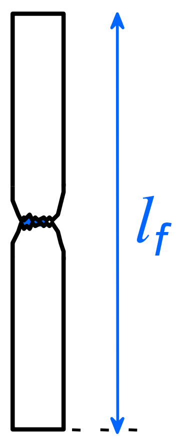
-- **Percent reduction in area**（%RA）:（ 斷面收縮率 ）

A_f: cross-sectional area

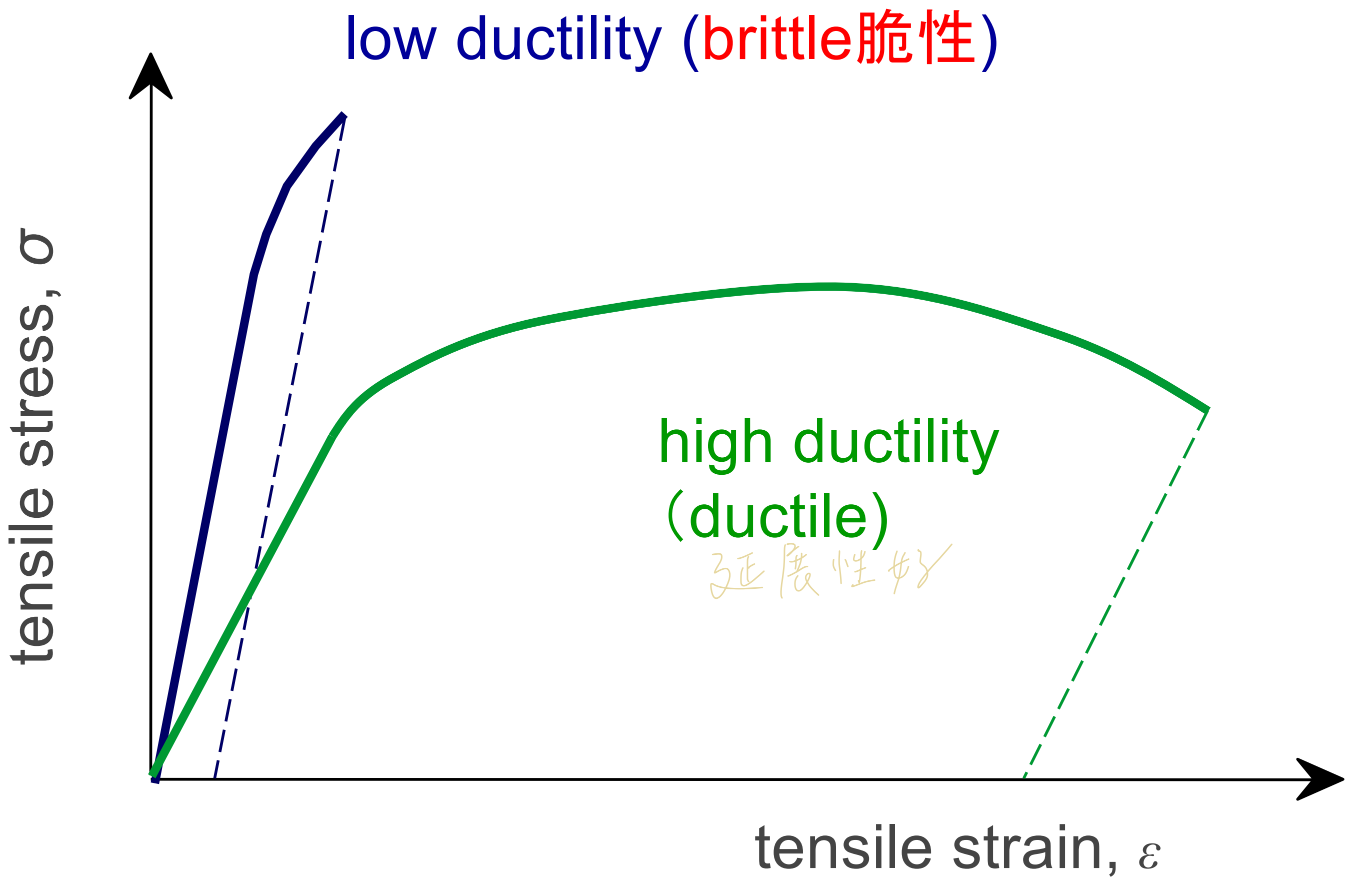
at the point of fracture

$$\%EL = \frac{l_f - l_o}{l_o} \times 100$$

$$\%RA = \frac{A_0 - A_f}{A_0} \times 100$$



- Brittle materials are approximately considered to be those having a fracture strain < 5%.



Material	Yield Strength MPa	Yield Strength ksi	Tensile Strength MPa	Tensile Strength ksi	Ductility, %EL [in 50 mm (2 in.)][a]
		Metal Alloys[b]			
Molybdenum	565	82	655	95	35
Titanium	450	65	520	75	25
Steel (1020)	180	26	380	55	25
Nickel	138	20	480	70	40
Iron	130	19	262	38	45
Brass (70 Cu–30 Zn)	75	11	300	44	68
Copper	69	10	200	29	45
Aluminum	35	5	90	13	40
		Ceramic Materials[c]			
Zirconia (ZrO_2)[d]	—	—	800–1500	115–215	—
Silicon nitride (Si_3N_4)	—	—	250–1000	35–145	—
Aluminum oxide (Al_2O_3)	—	—	275–700	40–100	—
Silicon carbide (SiC)	—	—	100–820	15–120	—
Glass–ceramic (Pyroceram)	—	—	247	36	—
Mullite ($3Al_2O_3$–$2SiO_2$)	—	—	185	27	—
Spinel ($MgAl_2O_4$)	—	—	110–245	16–36	—
Fused silica (SiO_2)	—	—	110	16	—
Magnesium oxide (MgO)[e]	—	—	105	15	—
Soda–lime glass	—	—	69	10	—
		Polymers			
Nylon 6,6	44.8–82.8	6.5–12	75.9–94.5	11.0–13.7	15–300
Polycarbonate (PC)	62.1	9.0	62.8–72.4	9.1–10.5	110–150
Poly(ethylene terephthalate) (PET)	59.3	8.6	48.3–72.4	7.0–10.5	30–300
Poly(methyl methacrylate) (PMMA)	53.8–73.1	7.8–10.6	48.3–72.4	7.0–10.5	2.0–5.5
Poly(vinyl chloride) (PVC)	40.7–44.8	5.9–6.5	40.7–51.7	5.9–7.5	40–80
Phenol-formaldehyde	—	—	34.5–62.1	5.0–9.0	1.5–2.0
Polystyrene (PS)	25.0–69.0	3.63–10.0	35.9–51.7	5.2–7.5	1.2–2.5
Polypropylene (PP)	31.0–37.2	4.5–5.4	31.0–41.4	4.5–6.0	100–600
Polyethylene—high density (HDPE)	26.2–33.1	3.8–4.8	22.1–31.0	3.2–4.5	10–1200
Polytetrafluoroethylene (PTFE)	13.8–15.2	2.0–2.2	20.7–34.5	3.0–5.0	200–400
Polyethylene—low density (LDPE)	9.0–14.5	1.3–2.1	8.3–31.4	1.2–4.55	100–650

[a]For polymers, percent elongation at break.
[b]Property values are for metal alloys in an annealed state.
[c]The tensile strength of ceramic materials is taken as flexural strength (Section 7.10).
[d]Partially stabilized with 3 mol% Y_2O_3.
[e]Sintered and containing approximately 5% porosity.

Table_7-2

Stress–strain behavior for iron at three temperatures

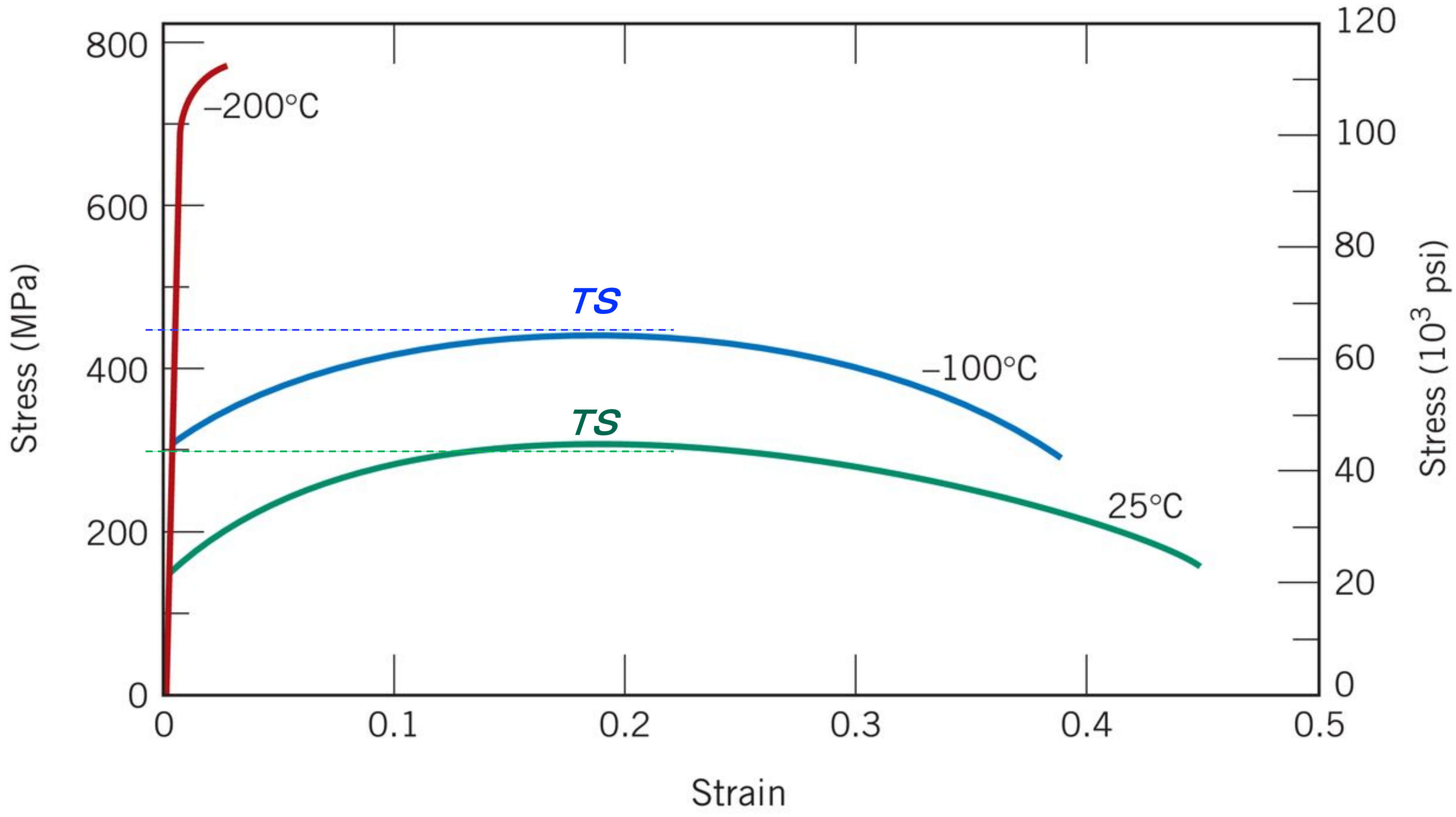


FIGURE 7.14
Engineering stress–strain behavior for iron at three temperatures.

Resilience（彈性能）

- **Resilience—ability of a material to <u>absorb energy during elastic deformation</u>**
- Energy recovered when load released
- Resilience specified by modulus of resilience, U_r（彈性能係數）

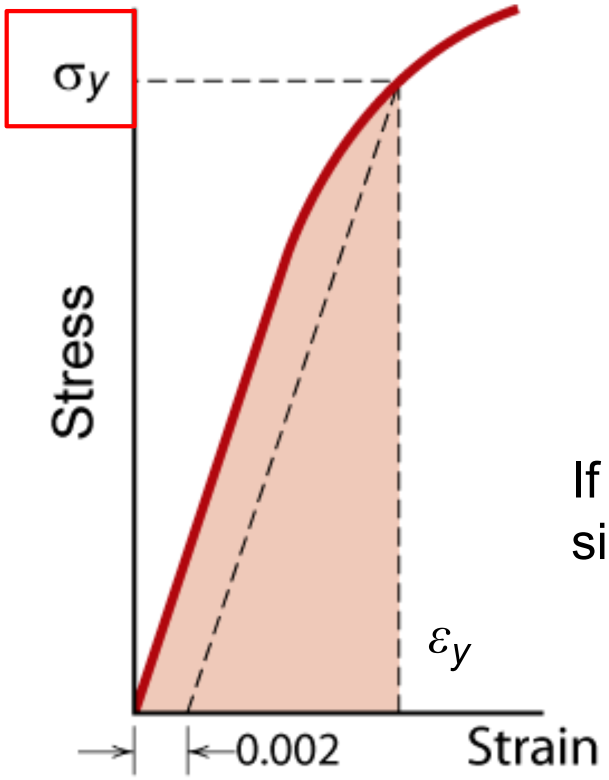


Fig. 7.15, *Callister & Rethwisch 5e.*

降伏點受應力的狀態

U_r = Area under stress-strain curve to yielding $= \int_0^{\varepsilon_y} \sigma \, d\varepsilon$

未受應力的狀態

If assume a linear stress-strain curve this simplifies to

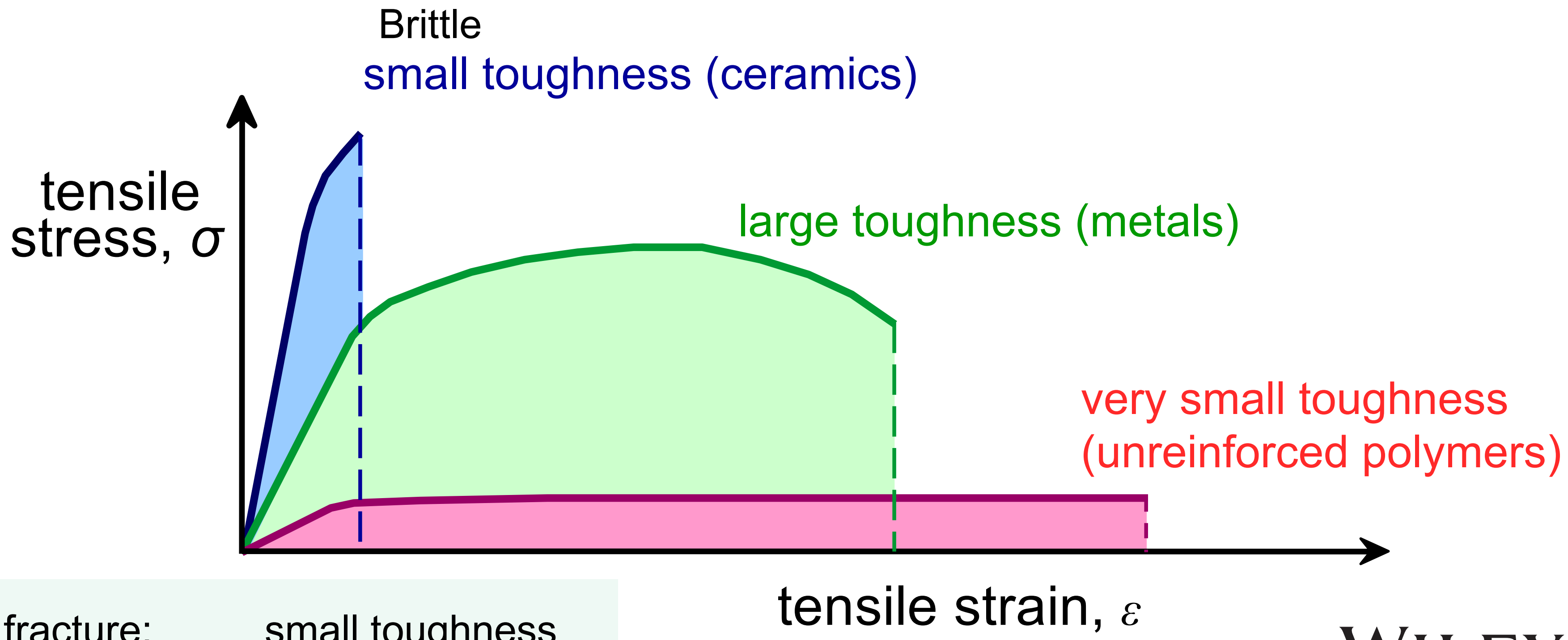
降伏點的應變

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

線性彈性行為下的彈性能係數

Toughness (韧性)

- Toughness of a material is expressed in several contexts
- Toughness = amount of energy absorbed before **fracture**
- Approximate by area under the stress-strain curve — units of energy per unit volume



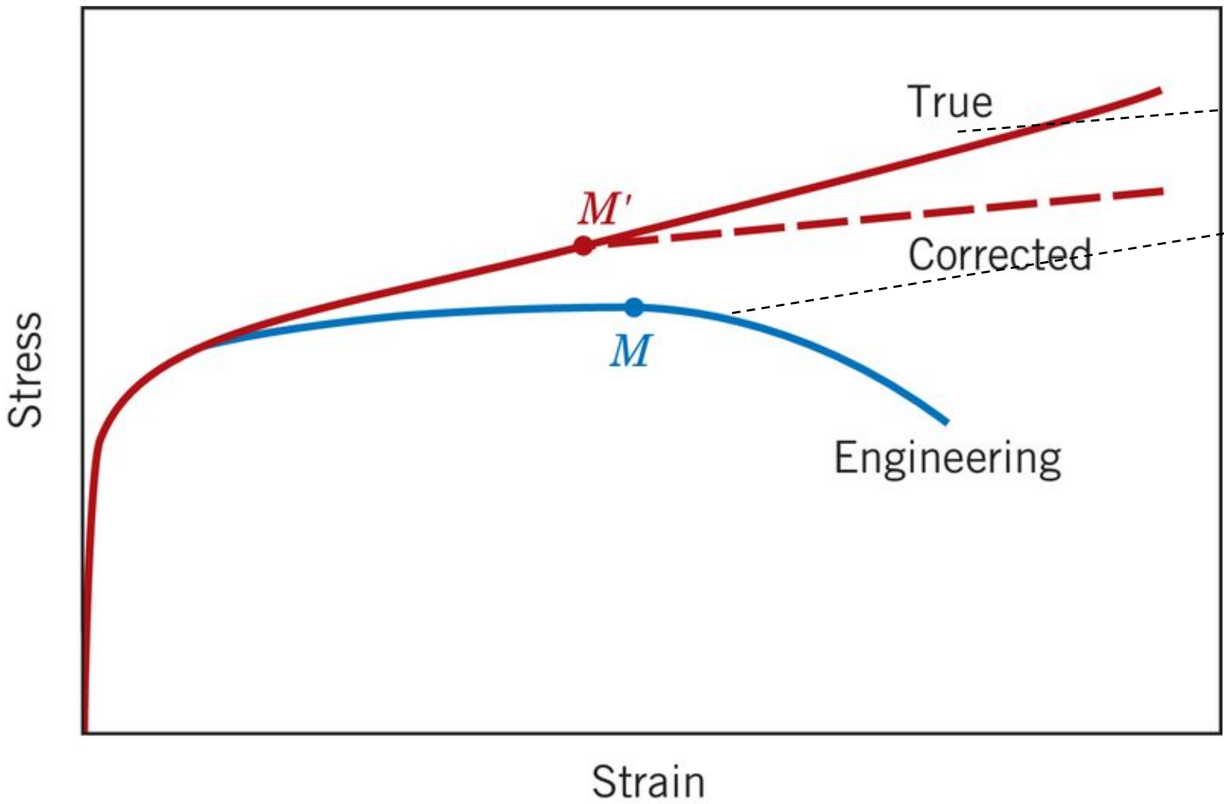
Brittle fracture:	small toughness
Ductile fracture:	large toughness

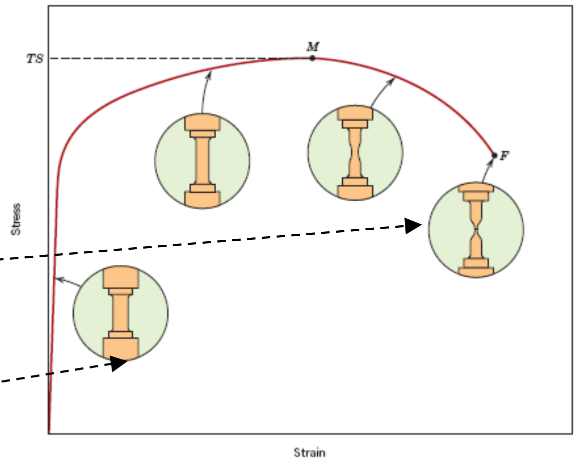
WILEY

True Stress & Strain

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

where A_i = instantaneous cross-sectional area





Adapted from Fig. 7.16, *Callister & Rethwisch 5e.*

Conversion Equations: valid only to the **onset of necking** 緊縮

$$\sigma_T = \sigma\left(1+\varepsilon\right)$$

$$\varepsilon_T = \ln\left(1+\varepsilon\right)$$

Ductility and True-stress-at-Fracture Computations

圓形

A cylindrical specimen of steel having an original diameter of 12.8 mm (0.505 in.) is tensile tested to fracture 斷裂 and found to have an engineering fracture strength σ_f of 460 MPa (67,000 psi).
If its cross-sectional diameter at fracture is 10.7 mm (0.422 in.), determine:

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

$$\left(\frac{12.8}{2}\right)^2$$

(a) Ductility is computed using Equation 7.12, as

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

Af

Ao

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

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

(b) The true stress at fracture.

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

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

Thus, the true stress is calculated as

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

$$= 6.6 \times 10^8\ \mathrm{N/m^2} = \underline{660\ \mathrm{MPa}}\ (95{,}700\ \mathrm{psi})$$

Elastic Strain Recovery

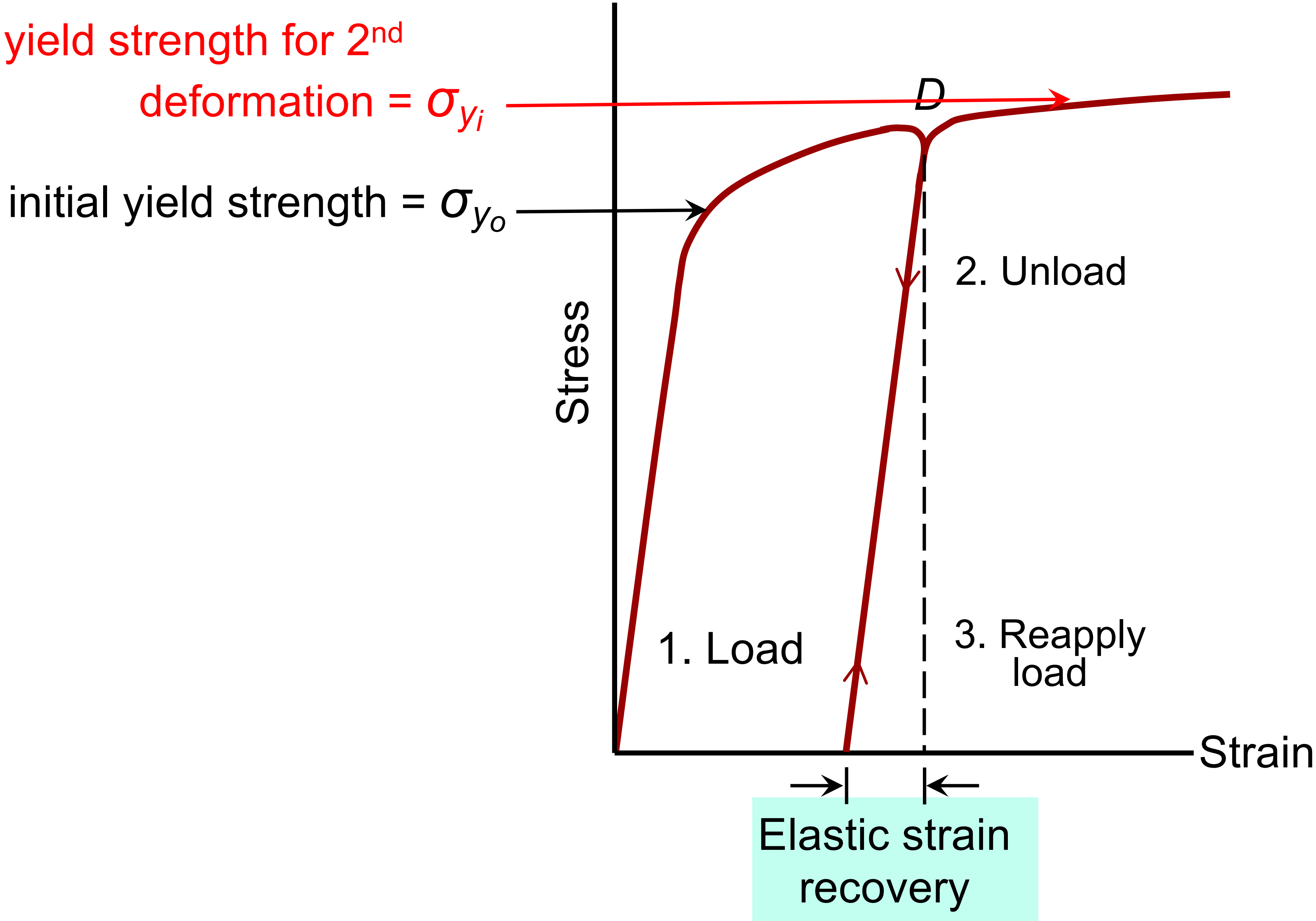


Fig. 7.17, *Callister & Rethwisch 5e.*

彈性形變恢復

MECHANICAL BEHAVIOR—
Ceramics

Ceramic materials are more brittle than metals.
Why is this so?

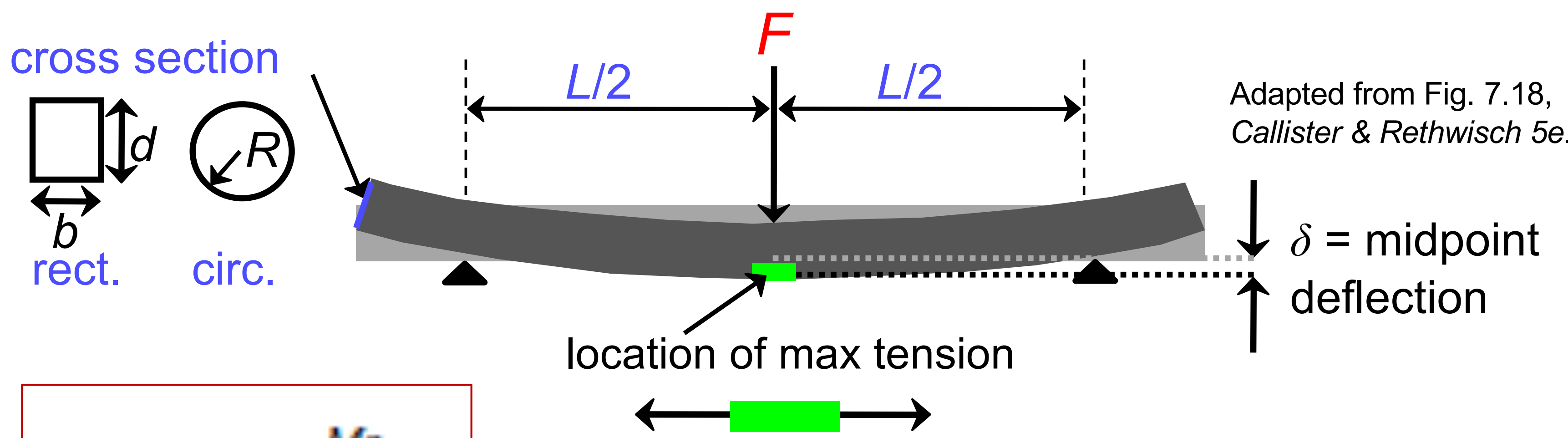
- Consider mechanism of deformation
  - In crystalline, by dislocation motion
  - In highly ionic solids, dislocation motion is difficult
    - few slip systems
    - resistance to motion of ions of like charge (e.g., anions) past one another

Flexural Tests – Measurement of Elastic Modulus

抗彎強度

CERAMICS

- Room *T* behavior is usually elastic, with brittle failure.
- **3-Point Bend Testing** often used. 三點負荷彎曲測試
  -- tensile tests are difficult for brittle materials.



Adapted from Fig. 7.18, *Callister & Rethwisch 5e.*

$$\boxed{\sigma = \text{stress} = \frac{Mc}{I}}$$

where M = maximum bending moment 最大彎矩
c = distance from center of specimen to outer fibers 試片中心到外緣位置
I = moment of inertia of cross section 截面的慣性矩
F = applied load 作用力

	M	c	I	σ
Rectangular	$\frac{FL}{4}$	$\frac{d}{2}$	$\frac{bd^3}{12}$	$\frac{3FL}{2bd^2}$
Circular	$\frac{FL}{4}$	R	$\frac{\pi R^4}{4}$	$\frac{FL}{\pi R^3}$

Flexural Tests – Measurement of Flexural Strength（抗彎強度）

- **Flexural strength (F_f):**

CERAMICS

  - The stress at fracture using this flexure test.
  - an important mechanical parameter for brittle ceramics.

$$\sigma_{fs} = \frac{3F_f L}{2bd^2} \quad \text{(rect. cross section)}$$

$$\sigma_{fs} = \frac{F_f L}{\pi R^3} \quad \text{(circ. cross section)}$$

F_f: loaded at fracture

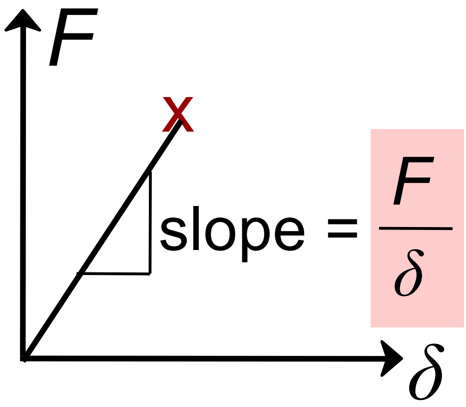
L: distance between point

- Typical values:

Material	σ_{fs} (MPa)
Si nitride	250-1000
Si carbide	100-820
Al oxide	275-700
glass (soda-lime)	69

Data from Table 7.2, *Callister & Rethwisch*

- **Determine elastic modulus（E）according to:**



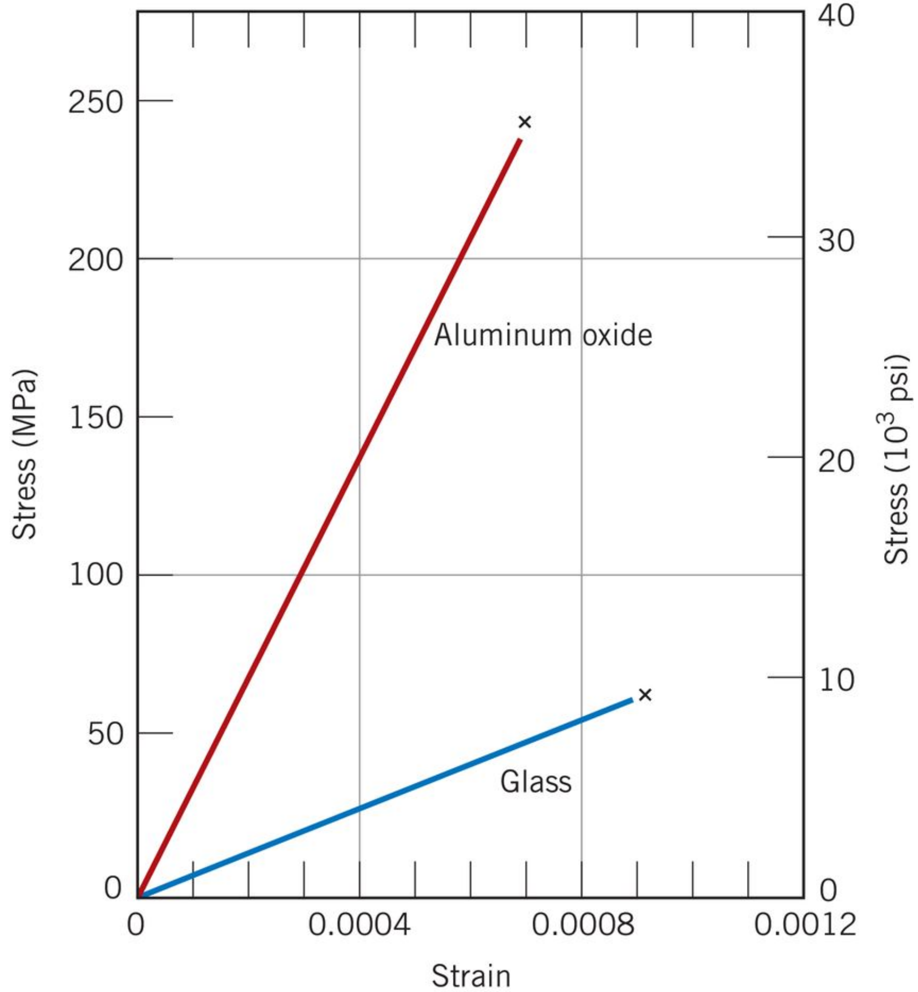
$$E = \frac{F}{\delta}\frac{L^3}{4bd^3} \quad \text{(rectangle cross section)}$$

$$E = \frac{F}{\delta}\frac{L^3}{12\pi R^4} \quad \text{(circle cross section)}$$

linear-elastic behavior

- **Flexural strength**: the **stress at fracture** using this flexure test, modulus of rupture, fracture strength, or the bend strength,
- an important mechanical parameter for brittle ceramics.

Flexural Tests – Measurement of Elastic Modulus



Typical stress–strain behavior to fracture for aluminum oxide and glass.

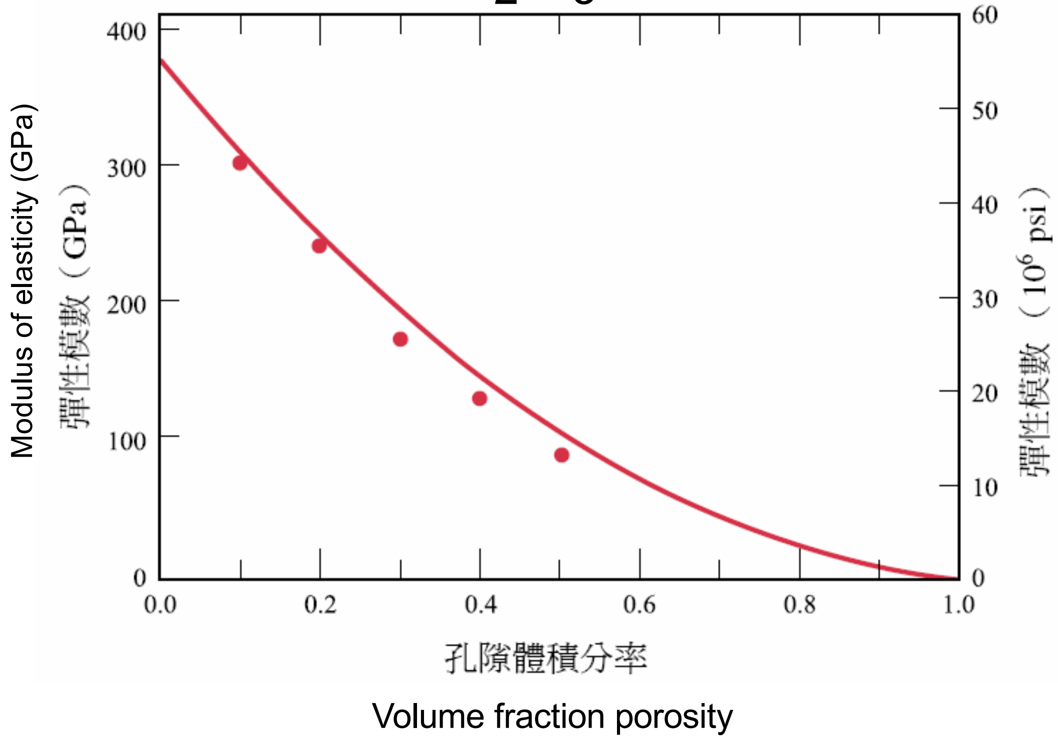
- Typical values:

Material	σ_{fs} (MPa)	E (GPa)
Si nitride	250-1000	304
Si carbide	100-820	345
Al oxide	275-700	393
glass (soda-lime)	69	69

Data from Table 7.2, *Callister & Rethwisch 5e.*

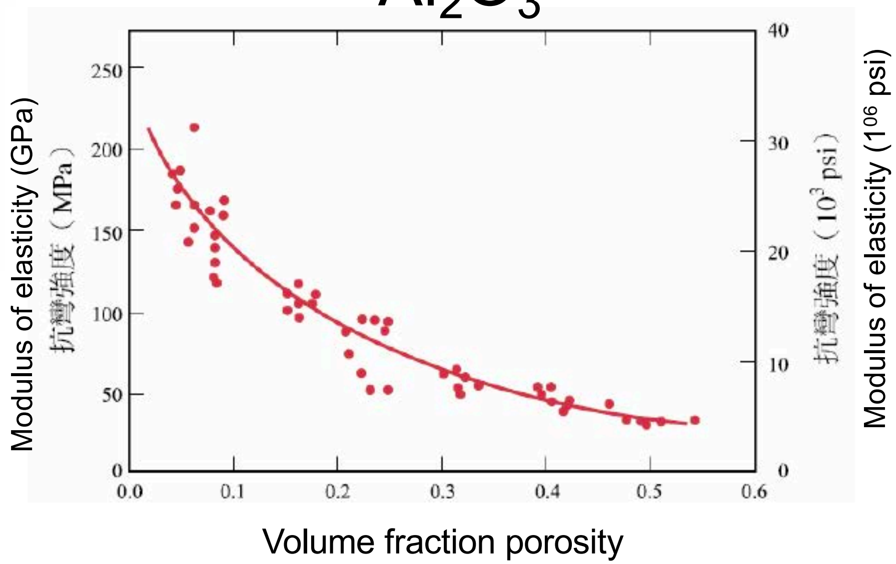
Influence of Porosity on The Mechanical Properties of Ceramics）

Al_2O_3



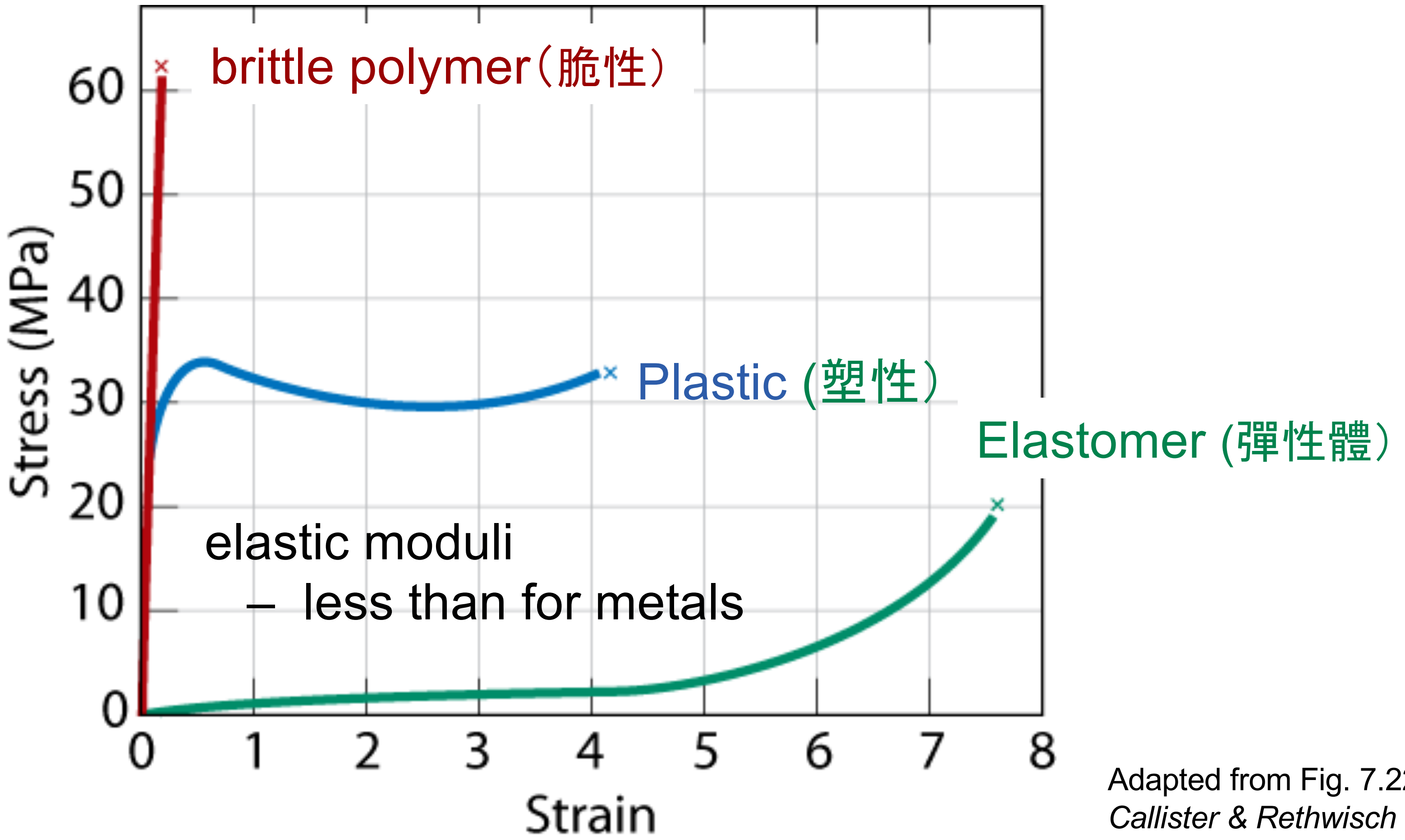
$$E = E_0\,(1 - 1.9P + 0.9P^2) \quad (7.21)$$

Al_2O_3



$$\sigma_{fs} = \sigma_0 \exp(-nP)$$

Mechanical Properties of Polymers – Stress-Strain Behavior



Adapted from Fig. 7.22, *Callister & Rethwisch 5e.*

- Fracture strengths of polymers ~ 10% of those for metals
- Deformation strains for polymers > 1000%
  - for most metals, deformation strains < 10%

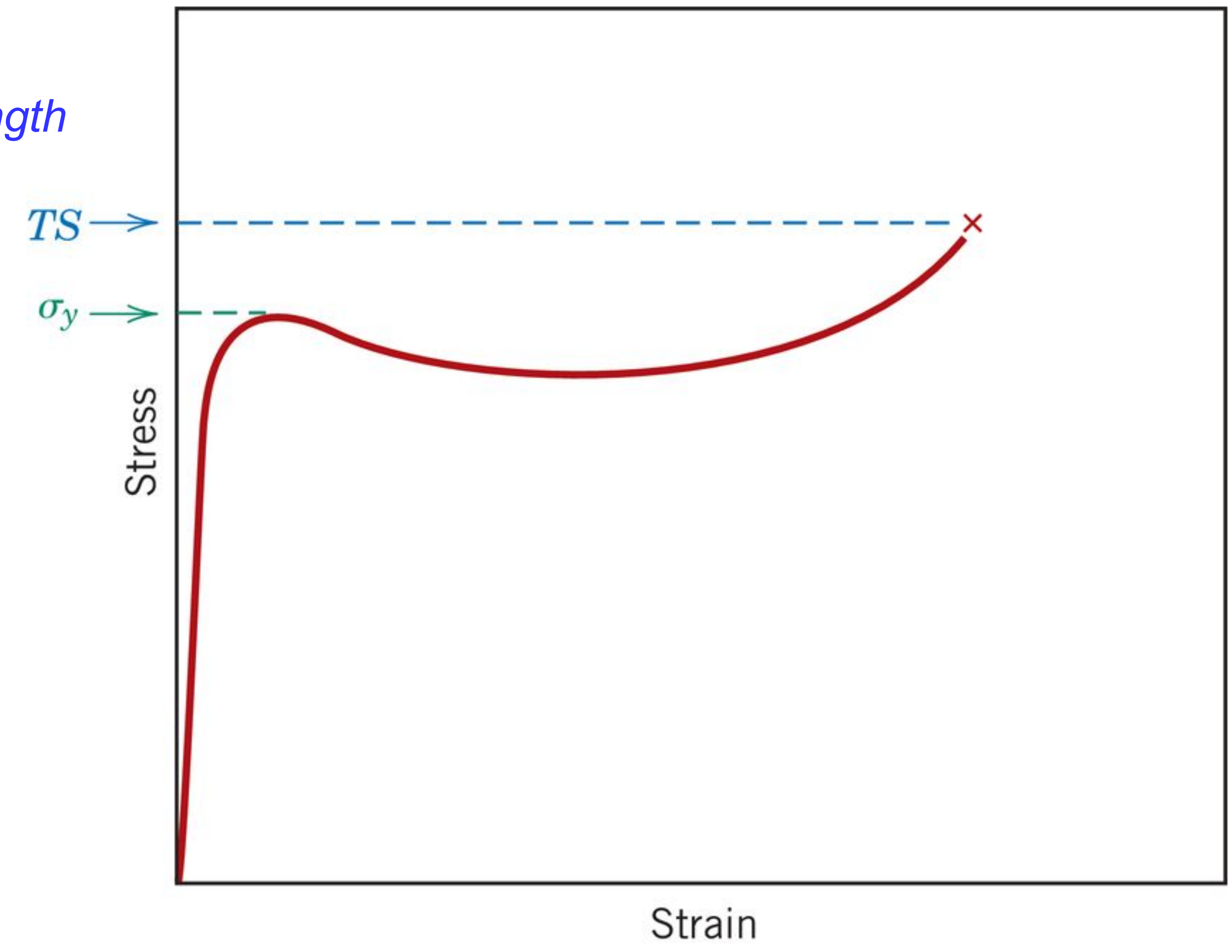
Mechanical Properties of Polymers

Plastic polymer

Stress-strain curve

Tensile strength (TS)

Yield strength



Material	Yield Strength MPa	Yield Strength ksi	Tensile Strength MPa	Tensile Strength ksi	Ductility, %EL [in 50 mm (2 in.)][a]
		Metal Alloys[b]			
Molybdenum	565	82	655	95	35
Titanium	450	65	520	75	25
Steel (1020)	180	26	380	55	25
Nickel	138	20	480	70	40
Iron	130	19	262	38	45
Brass (70 Cu–30 Zn)	75	11	300	44	68
Copper	69	10	200	29	45
Aluminum	35	5	90	13	40
		Ceramic Materials[c]			
Zirconia (ZrO_2)[d]	—	—	800–1500	115–215	—
Silicon nitride (Si_3N_4)	—	—	250–1000	35–145	—
Aluminum oxide (Al_2O_3)	—	—	275–700	40–100	—
Silicon carbide (SiC)	—	—	100–820	15–120	—
Glass–ceramic (Pyroceram)	—	—	247	36	—
Mullite ($3Al_2O_3$–$2SiO_2$)	—	—	185	27	—
Spinel ($MgAl_2O_4$)	—	—	110–245	16–36	—
Fused silica (SiO_2)	—	—	110	16	—
Magnesium oxide (MgO)[e]	—	—	105	15	—
Soda–lime glass	—	—	69	10	—
		Polymers			
Nylon 6,6	44.8–82.8	6.5–12	75.9–94.5	11.0–13.7	15–300
Polycarbonate (PC)	62.1	9.0	62.8–72.4	9.1–10.5	110–150
Poly(ethylene terephthalate) (PET)	59.3	8.6	48.3–72.4	7.0–10.5	30–300
Poly(methyl methacrylate) (PMMA)	53.8–73.1	7.8–10.6	48.3–72.4	7.0–10.5	2.0–5.5
Poly(vinyl chloride) (PVC)	40.7–44.8	5.9–6.5	40.7–51.7	5.9–7.5	40–80
Phenol-formaldehyde	—	—	34.5–62.1	5.0–9.0	1.5–2.0
Polystyrene (PS)	25.0–69.0	3.63–10.0	35.9–51.7	5.2–7.5	1.2–2.5
Polypropylene (PP)	31.0–37.2	4.5–5.4	31.0–41.4	4.5–6.0	100–600
Polyethylene—high density (HDPE)	26.2–33.1	3.8–4.8	22.1–31.0	3.2–4.5	10–1200
Polytetrafluoroethylene (PTFE)	13.8–15.2	2.0–2.2	20.7–34.5	3.0–5.0	200–400
Polyethylene—low density (LDPE)	9.0–14.5	1.3–2.1	8.3–31.4	1.2–4.55	100–650

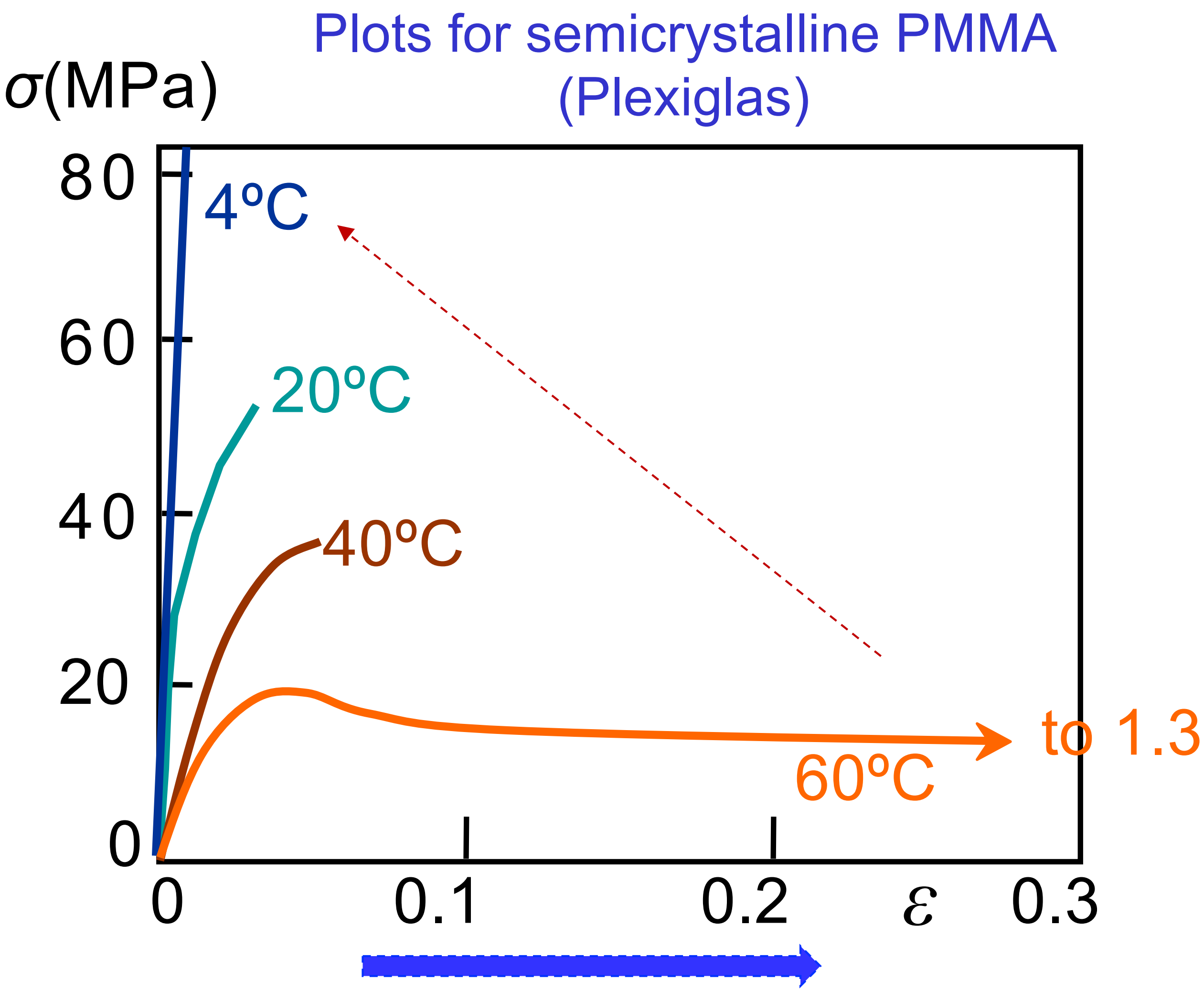
[a]For polymers, percent elongation at break.
[b]Property values are for metal alloys in an annealed state.
[c]The tensile strength of ceramic materials is taken as flexural strength (Section 7.10).
[d]Partially stabilized with 3 mol% Y_2O_3.
[e]Sintered and containing approximately 5% porosity.

Table_7-2

Influence of *Temperature* & Strain Rate on Thermoplastics

- Decreasing *T*...
  -- increases *E*
  -- increases *TS*
  -- decreases %*EL*

- Increasing strain rate...
  -- same effects as decreasing *T*.

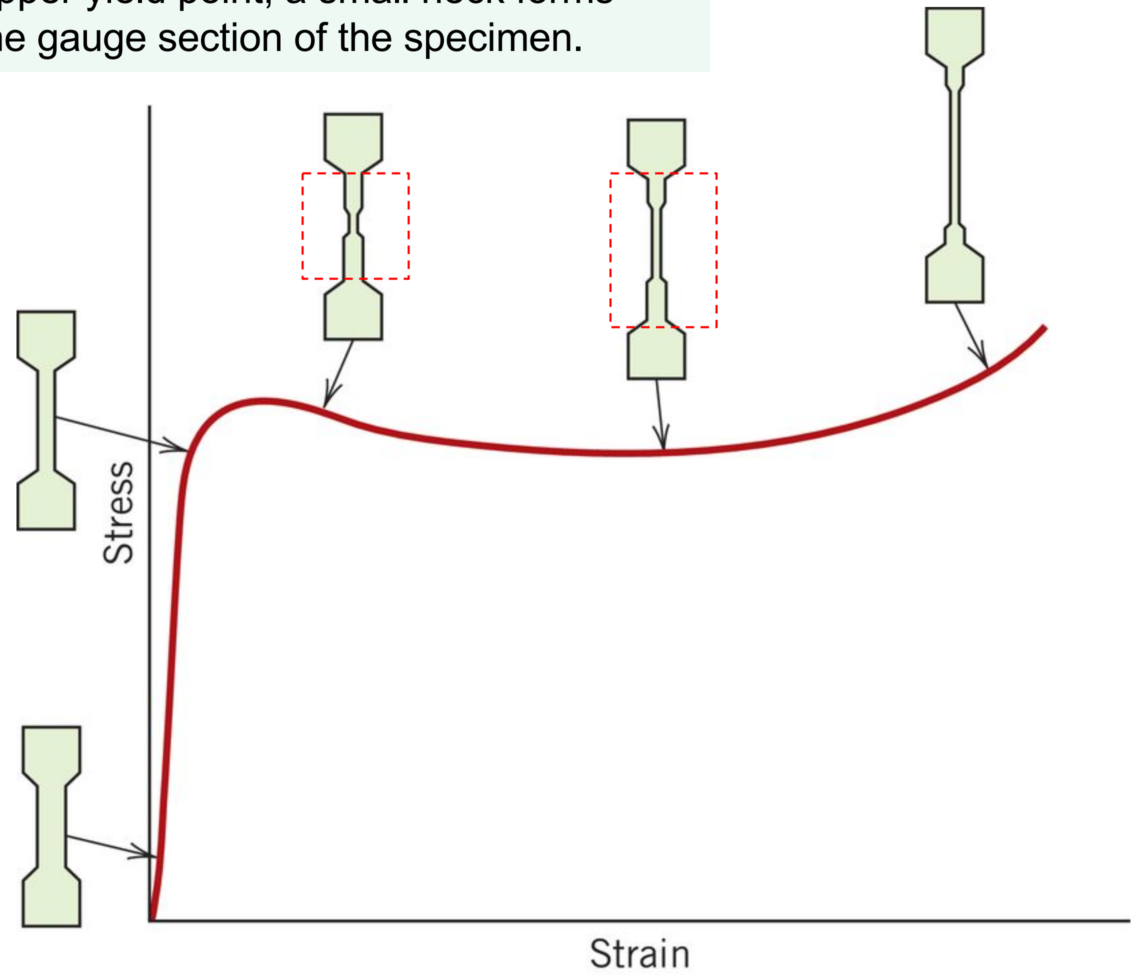


polymethyl methacrylate（PMMA）
聚甲基丙烯酸甲酯

Macroscopic Deformation

Semi-crystalline polymer

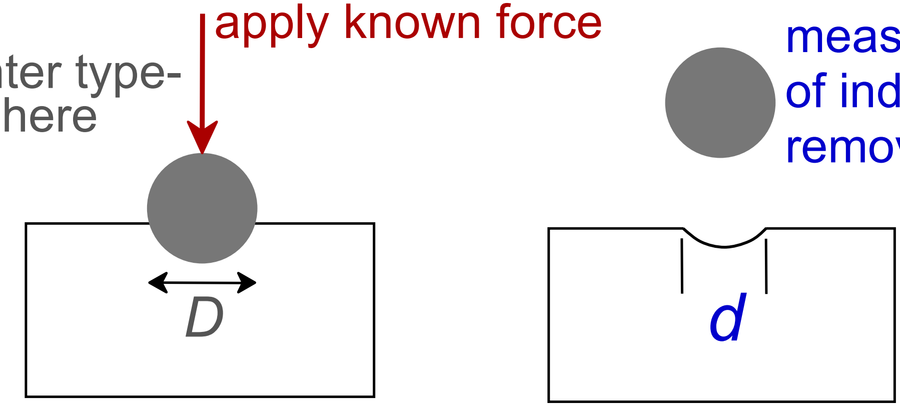
At the upper yield point, a small neck forms within the gauge section of the specimen.



Hardness（硬度）

不考硬度

- Measure of resistance to surface plastic deformation — dent or scratch.
- Large hardness means:
  -- high resistance to deformation from compressive loads.
  -- better wear properties.



Measurement of Hardness

Rockwell Hardness（洛氏硬度）

- Several scales—combination of load magnitude, indenter size

	Indenters	Loads	
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

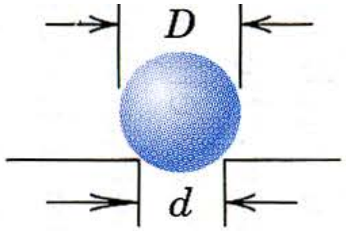
- Examples:
  - Rockwell A Scale – 60 kg load/diamond indenter
  - Superficial Rockwell 15T Scale – 15 kg load/ 1/16 in. indenter
- Rockwell hardness designation: (hardness reading) HR
- Examples: 57 **HRA**; 63 **HR15T**
- Hardness range for each scale: 0–130 HR;
  useful range: 20–100 HR

Measurement of Hardness (cont.)

Brinell Hardness勃氏硬度

- Single scale
- Brinell hardness designation: (hardness reading) HB

10-mm sphere
of steel or
tungsten carbide



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

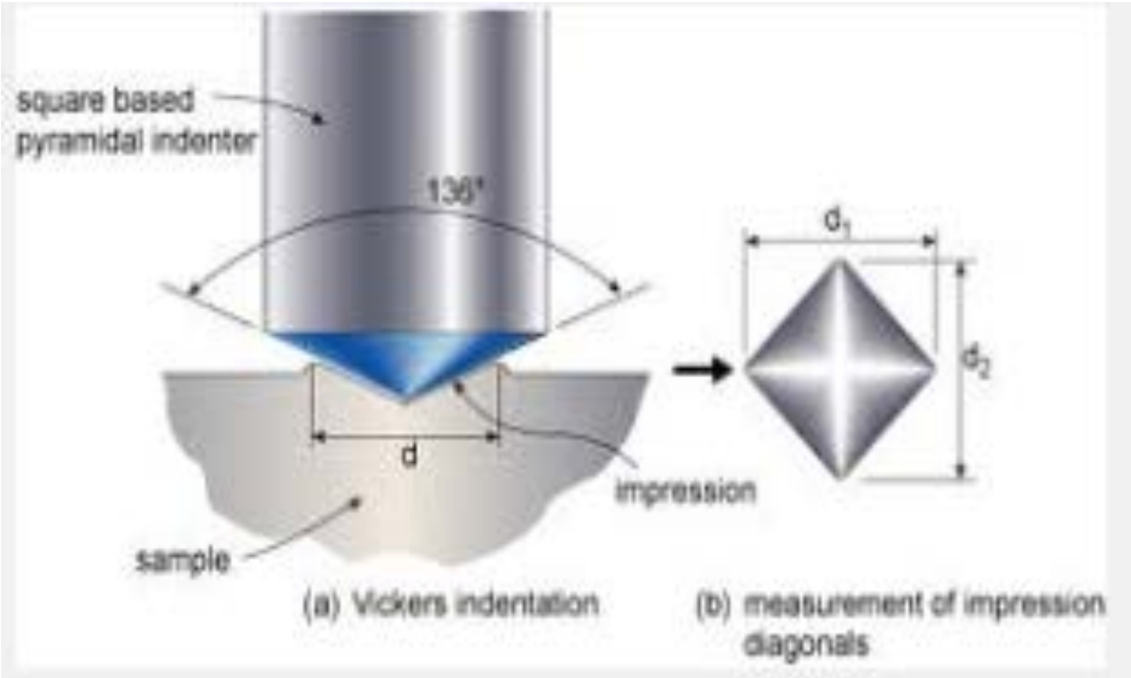
- P = load (kg)
- 500 kg $\leq P \leq$ 3000 kg (50 kg increments)

- **Relationships—Brinell hardness & tensile strength**
  - TS (psia) = 500 x HB
  - TS (MPa) = 3.45 x HB

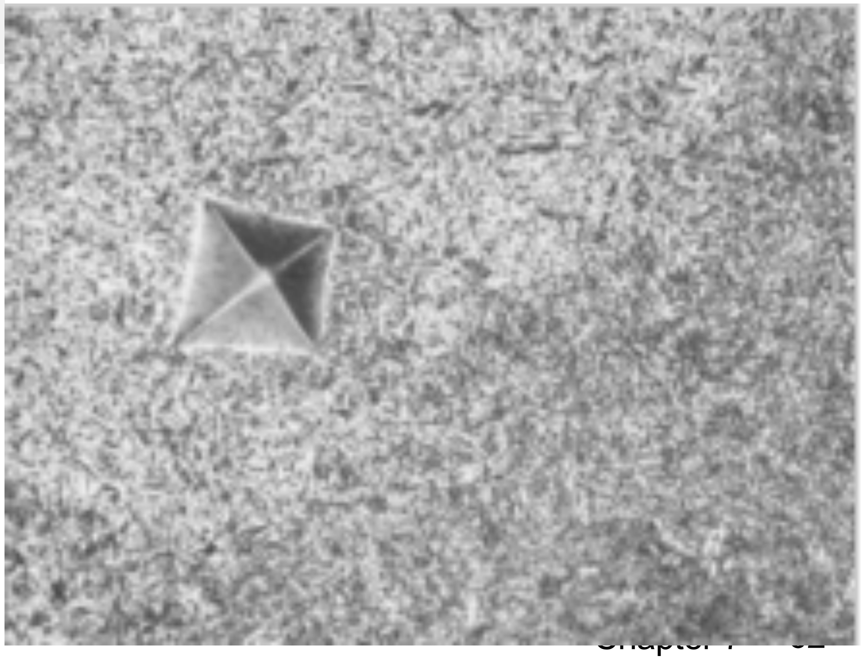
Knoop and Vickers Microhardness Tests
諾普和維氏微小硬度試驗

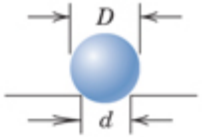
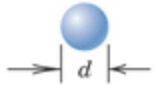
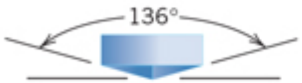
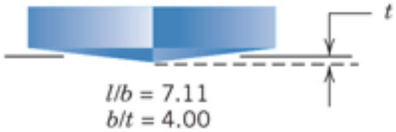
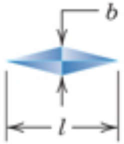
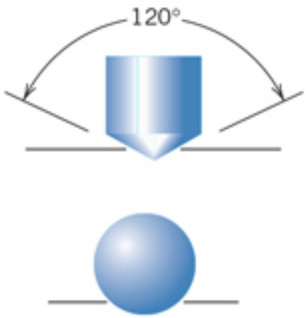
- Knoop and Vickers (also called diamond pyramid).
- For each test a **very small diamond indenter** having pyramidal geometry is forced into the surface of the specimen.
- Applied loads are much smaller（ranging 1 - 1000 g).
- The resulting impression is observed under a microscope and measured;
- This measurement is then converted into a hardness number.
- Careful specimen surface preparation (grinding and polishing) may be necessary to ensure a well-defined indentation that may be accurately measured.
- The Knoop and Vickers hardness numbers are designated by **HK** and **HV**, respectively,
- Both are well suited for measuring the hardness of small, selected specimen regions; furthermore, Knoop is used for testing brittle materials such as ceramics.

Hardness（硬度）



square based
pyramidal indenter
136°
d_1
d_2
d
impression
sample
(a) Vickers indentation
(b) measurement of impression
diagonals



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	$\mathrm{HB} = \dfrac{2P}{\pi D\left[D - \sqrt{D^2 - d^2}\right]}$
Vickers microhardness	Diamond pyramid			P	$\mathrm{HV} = 1.854P/d_1^2$
Knoop microhardness	Diamond pyramid			P	$\mathrm{HK} = 14.2\ P/l^2$
Rockwell and superficial Rockwell	Diamond cone; $\frac{1}{16}$-, $\frac{1}{8}$-, $\frac{1}{4}$-, $\frac{1}{2}$- in. diameter tungsten carbide 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 and 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.

Rockwell Hardness Scales

Scale Symbol	*Indenter*	*Major Load (kg)*
A	Diamond	60
B	$\frac{1}{16}$-in. ball	100
C	Diamond	150
D	Diamond	100
E	$\frac{1}{8}$-in. ball	100
F	$\frac{1}{16}$-in. ball	60
G	$\frac{1}{16}$-in. ball	150
H	$\frac{1}{8}$-in. ball	60
K	$\frac{1}{8}$-in. ball	150

Superficial Rockwell Hardness Scales

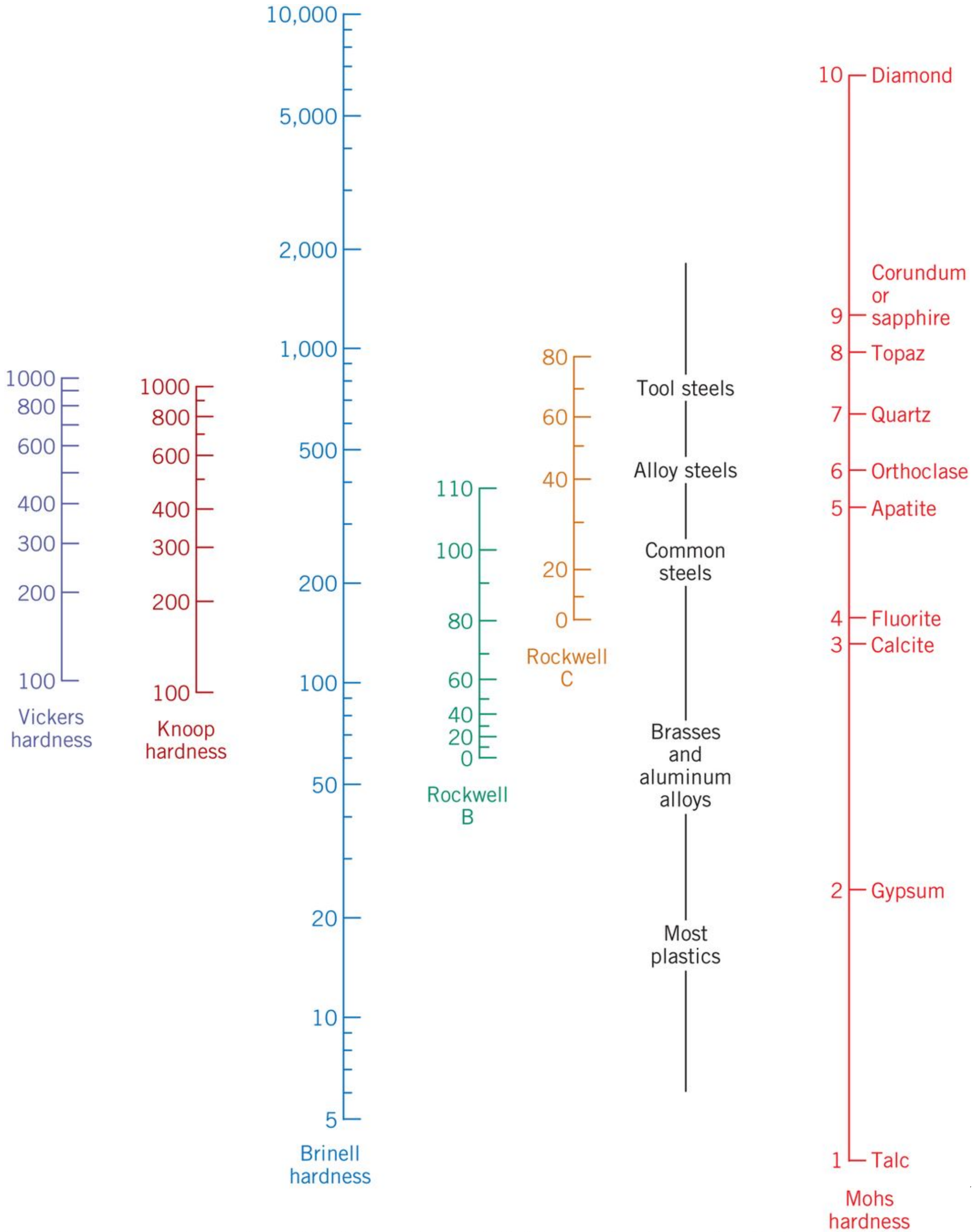
Table 7.5b Superficial Rockwell Hardness Scales

Scale Symbol	*Indenter*	*Major Load (kg)*
15N	Diamond	15
30N	Diamond	30
45N	Diamond	45
15T	$\frac{1}{16}$ in. ball	15
30T	$\frac{1}{16}$ in. ball	30
45T	$\frac{1}{16}$ in. ball	45
15W	$\frac{1}{8}$ in. ball	15
30W	$\frac{1}{8}$ in. ball	30
45W	$\frac{1}{8}$ in. ball	45

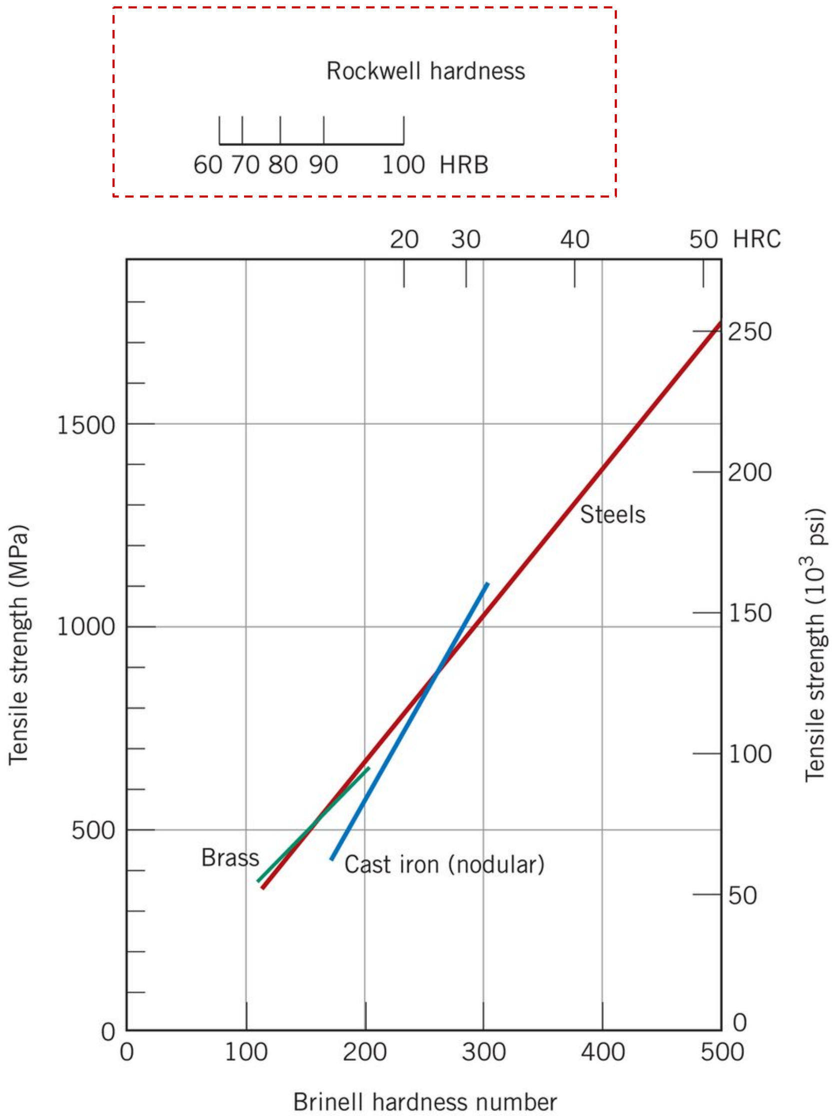
Hardness Conversion

$$TS\,(\mathrm{MPa}) = 3.45 \times \mathrm{HB}$$

$$TS\,(\mathrm{psi}) = 500 \times \mathrm{HB}$$



Adapted with permission from ASM International, *ASM Handbook: Mechanical Testing and Evaluation*, Volume 8, 2000, pg. 936.



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.

Relationships between hardness and tensile strength for steel, brass, and cast iron.

Design/Safety Factors

- Because of design uncertainties allowances must be made to protect against unanticipated failure.

- For structural applications, to protect against possibility of failure—use working stress, σ_w, and a factor of safety, N

$$\sigma_w = \frac{\boxed{\sigma_y}}{N}$$

yield strength

Depending on application, N is between 1, 2 and 4

Design/Safety Factors

Example Problem:

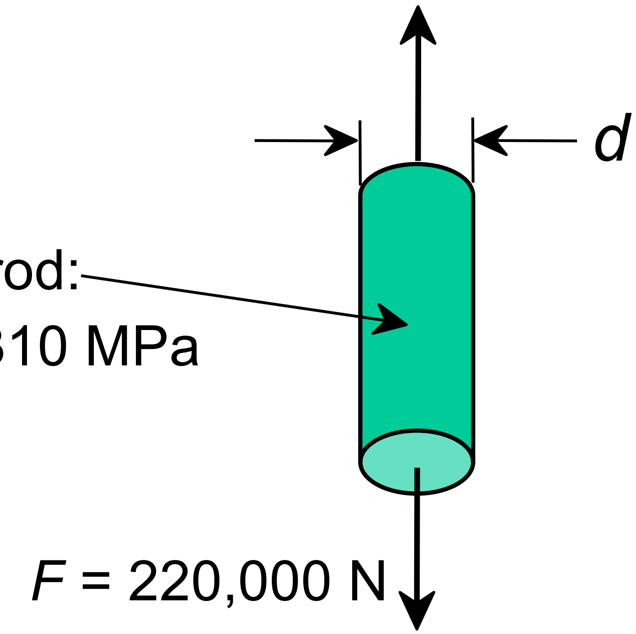
A cylindrical rod, to be constructed from a steel that has a yield strength of 310 MPa, is to withstand a load of 220,000 N without yielding. Assuming a value of 4 for *N*, specify a suitable bar diameter.

$$\sigma_w = \frac{\sigma_y}{N}$$

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

4

Steel rod:
σ_y = 310 MPa



Solving for the rod diameter *d* yields

$$\boxed{d = 0.060\ \text{m} = 60\ \text{mm}}$$

A tensile-testing apparatus is to be constructed that must withstand a maximum load of 220,000 N (50,000 lb_f). The design calls for two cylindrical support posts, each of which is to support half of the maximum load. Furthermore, plain-carbon (1045) steel ground and polished shafting rounds are to be used; the minimum yield and tensile strengths of this alloy are 310 MPa (45,000 psi) and 565 MPa (82,000 psi), respectively. Specify a suitable diameter for these support posts.

$$\sigma_w = \frac{\sigma_y}{N}$$

$$= \frac{310 \text{ MPa}}{5} = 62 \text{ MPa (9000 psi)}$$

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

$$d = 2\sqrt{\frac{F}{\pi \sigma_w}}$$

$$= 2\sqrt{\frac{110{,}000 \text{ N}}{\pi (62 \times 10^6 \text{ N/m}^2)}}$$

$$= 4.75 \times 10^{-2} \text{ m} = 47.5 \text{ mm (1.87 in.)}$$

$$A_0 = \left(\frac{d}{2}\right)^2 \pi = \frac{F}{\sigma_w}$$

Therefore, the diameter of each of the two rods should be 47.5 mm or 1.87 in.

Stress-strain curves of Metal

A materials is loaded above its strength, it deforms plastically or fractures

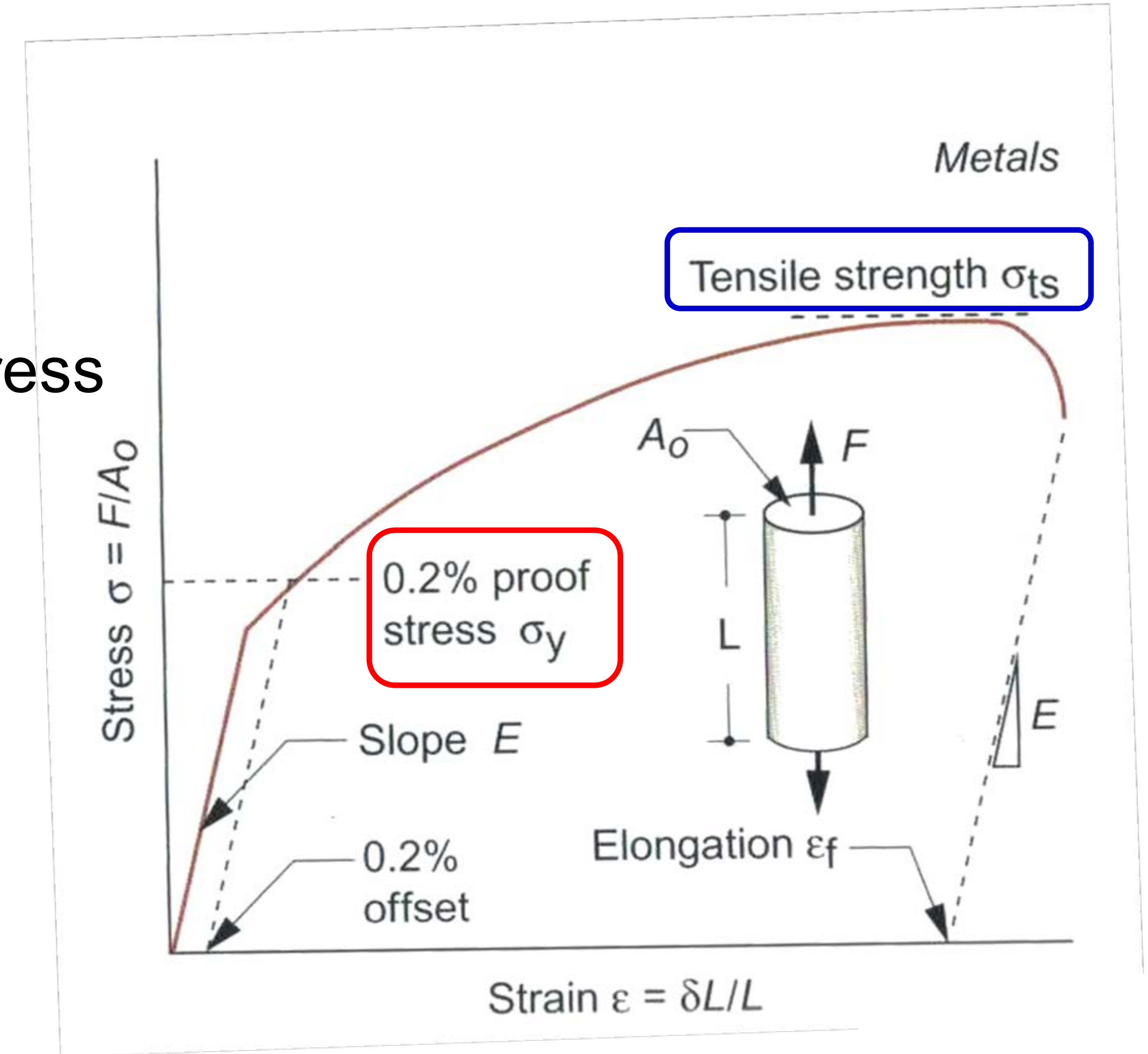
Yield strength

- 0.2% proof stress

σ_{γ}

Tensile strength

σ_{ts}



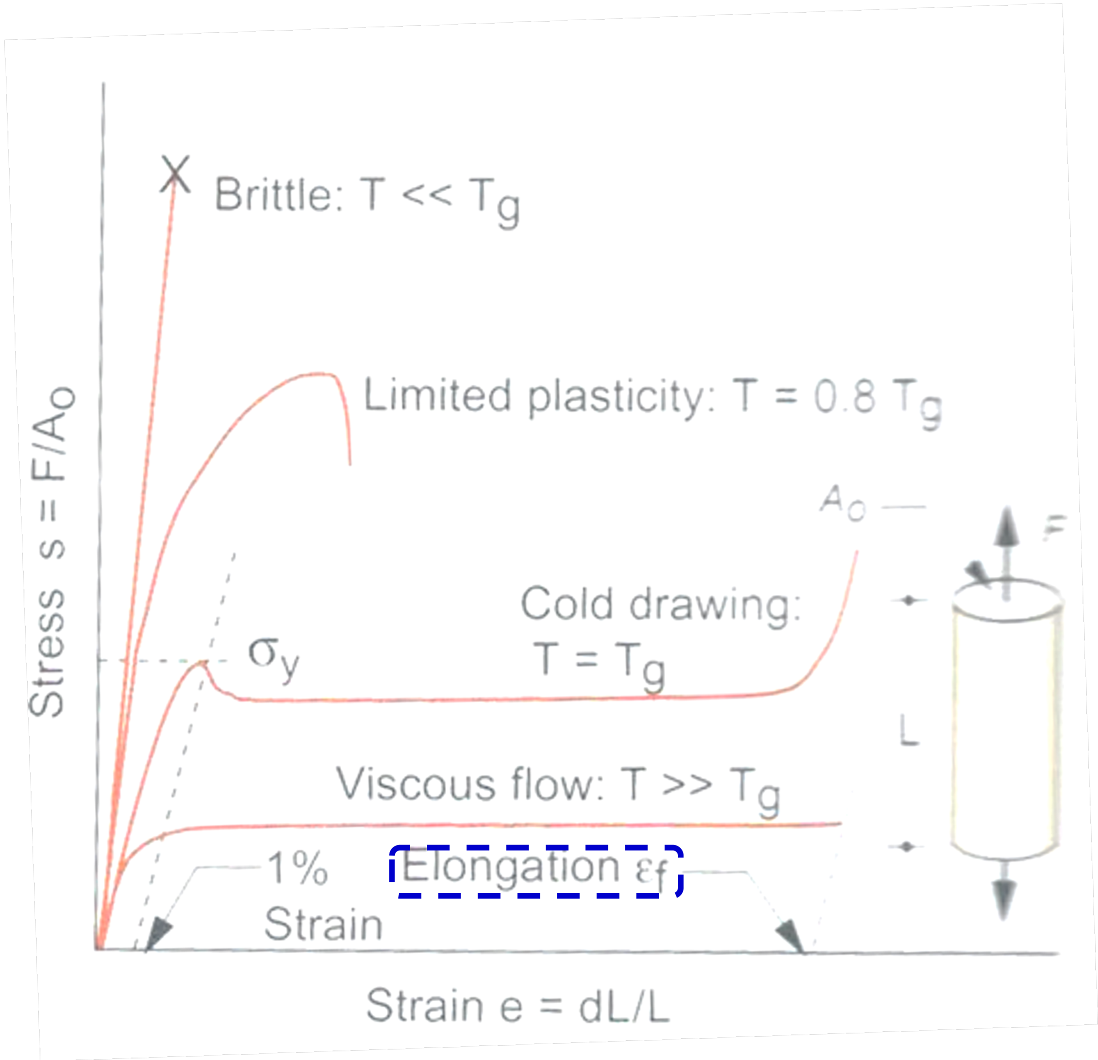
Stress-strain curves of Polymer

Yield strength - 1% strain

σ_γ

Ductility

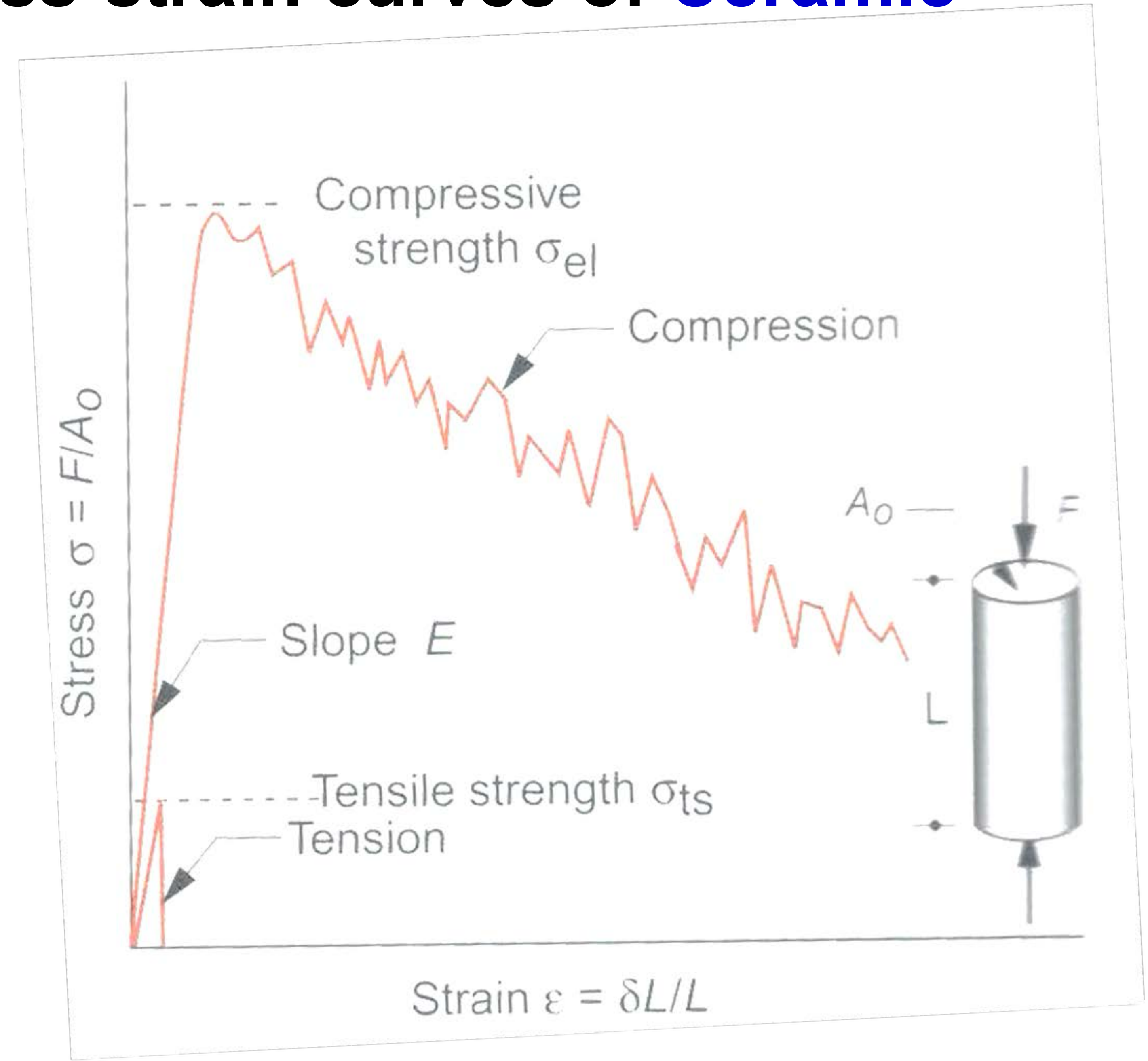
A measure of how much plastic strain a material can tolerate



Elongation ε_f

the tensile strain at break

Stress-strain curves of Ceramic



Summary

- Applied mechanical force — normalized to **stress**

- Degree of deformation — normalized to **strain**

- **Elastic deformation**:
  –– **non-permanent**; occurs at low levels of stress
  –– stress-strain behavior is **linear**

- **Plastic deformation**
  –– **permanent**; occurs at higher levels of stress
  –– stress-strain behavior is nonlinear

- **Stiffness** - a material's **resistance to elastic deformation**
  - elastic (or Young's) modulus

Summary (cont.)

- **Strength** - a material's resistance to plastic deformation
  yield and tensile strengths

- **Ductility** - amount of plastic deformation at failure percent
  elongation, reduction in area

- **Hardness** - **resistance to localized surface deformation**
  & compressive stresses

  - Rockwell, Brinell hardnesses