M. Sc. Bionics Engineering

Università di Pisa

Sant'Anna Scuola Universitaria Superiore Pisa

IMT Scuola Alti Studi Lucca

Advanced Materials for Bionics

Lecture 4: Mechanical Properties

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AY 2024-25

L4 - 07.10.2024

QUESTIONS

- When a material is exposed to mechanical forces, what parameters are used to express force magnitude and degree of deformation?
- What is the distinction between elastic and plastic deformations?
- How are the following mechanical characteristics of materials measured?
  - Stiffness
  - Strength
  - Ductility
  - Hardness
- What parameters are used to quantify these properties?
- How the different classes of materials are deformed ? How this is connected with their bonding/internal structure?

4.1

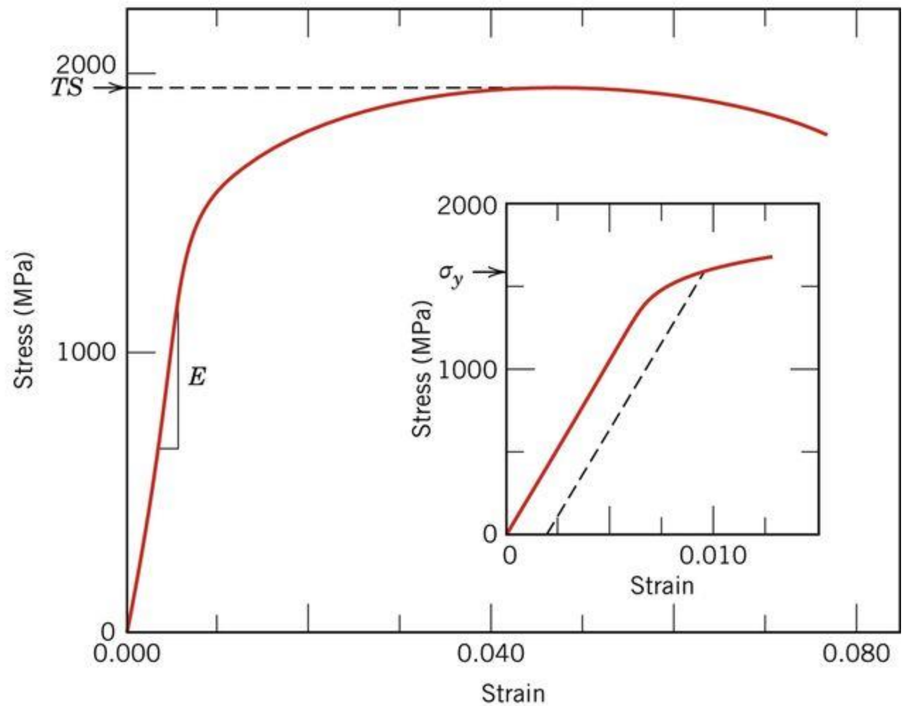
Intro and definitions

MECHANICAL TESTS

familiar with this?

Steel

(a)



(b)

STRESS-STRAIN TESTING

Typical tensile test machine

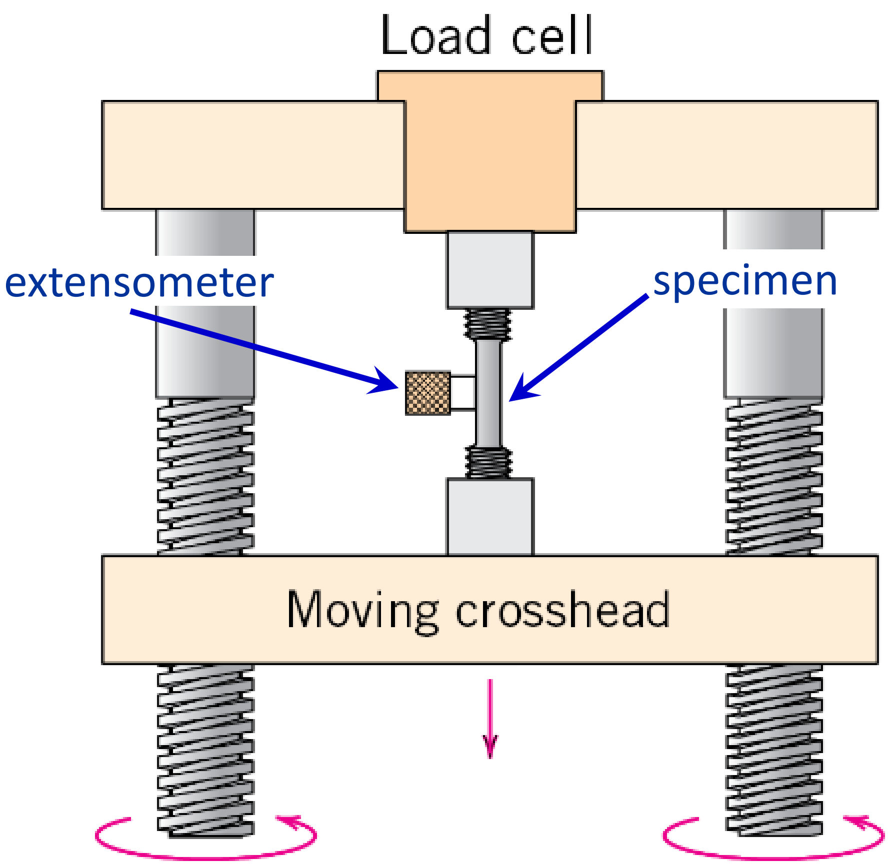


Fig. 6.3, *Callister & Rethwisch 10e.*

Typical tensile specimen (e.g. metal)

standard «dogbone» specimen

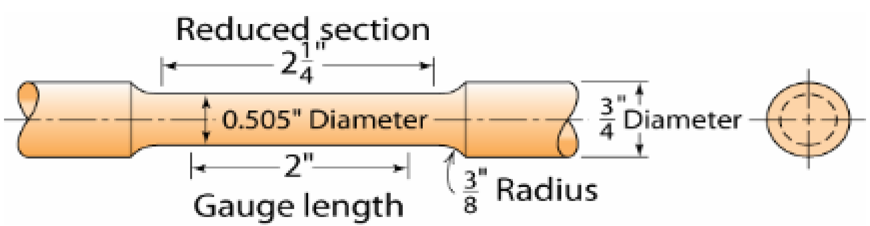


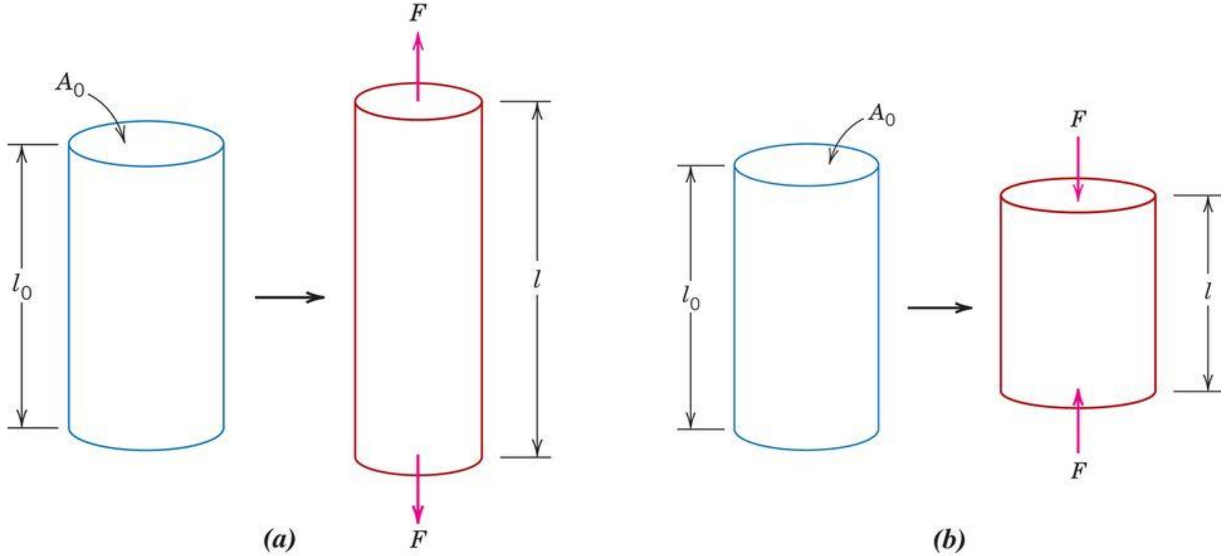
Fig. 6.2, *Callister & Rethwisch 10e.*

also rectangular section

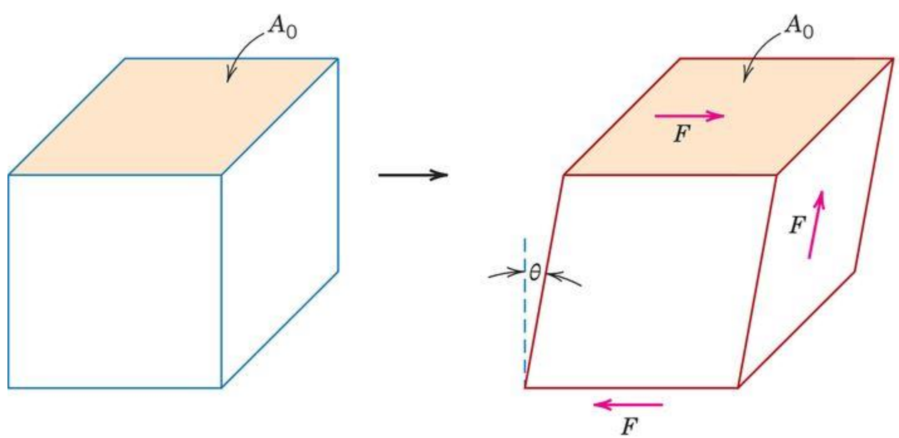
STRESS/STRAIN CONCEPTS

3 principal ways in which a load may be applied

TENSION



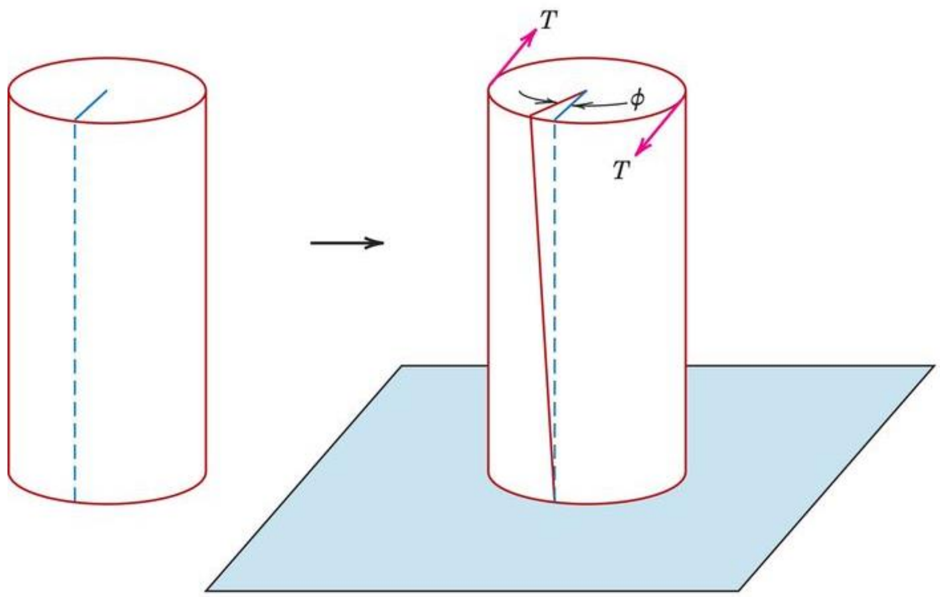
COMPRESSION



SHEAR

STRESS/STRAIN CONCEPTS

another type (connected to shear)

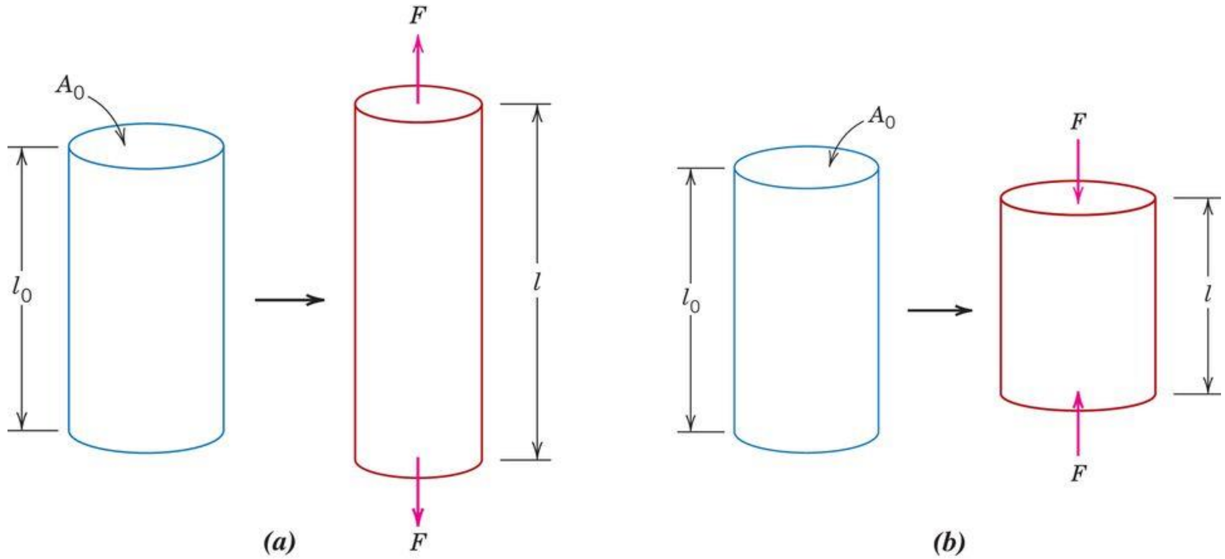


(d)

TORSION

TENSION/COMPRESSION

TENSION



COMPRESSION

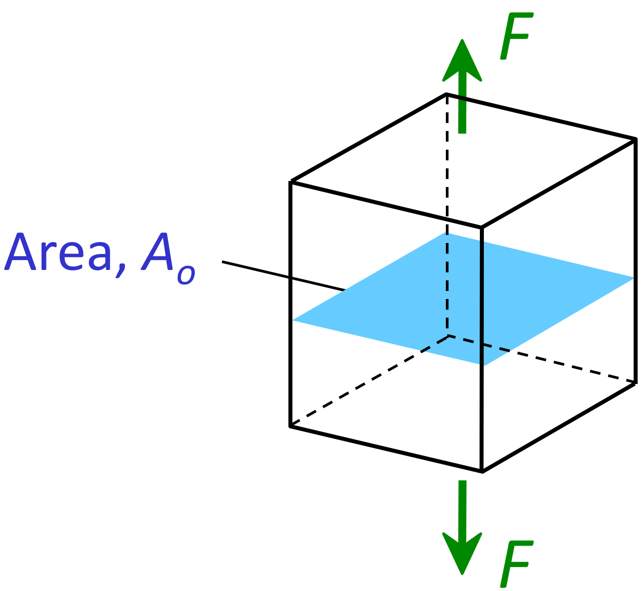
Tensile
(or compressive)
stress

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

conventionally:
in compression F < 0 → σ < 0

Engineering Stress

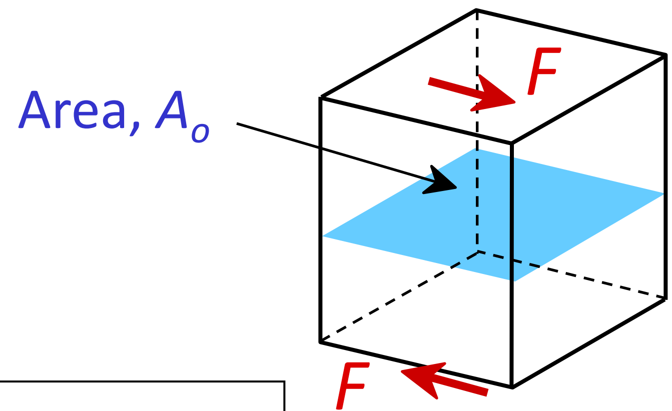
- Tensile stress, σ:



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

original cross-sectional area before loading

- Shear stress, τ:



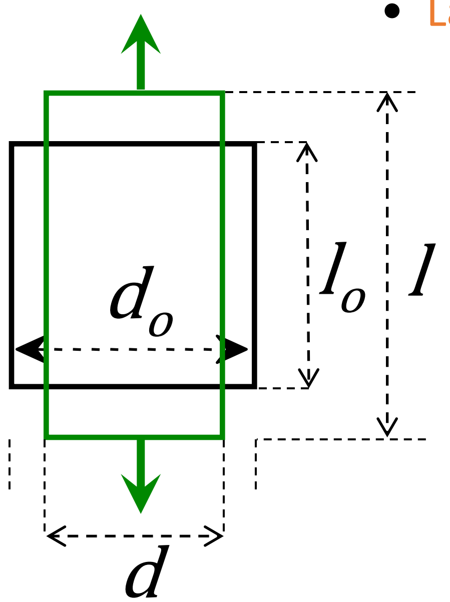
$$\tau = \frac{F}{A_o}$$

Units for stress:
MPa = 10^6 Pa = 10^6 N/m^2

Engineering Strain

- Tensile strain (ε_z):

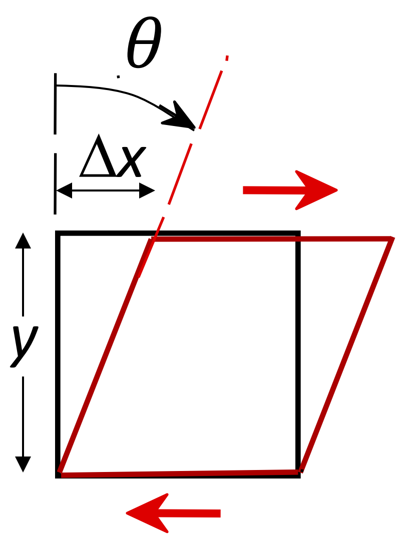
$$\varepsilon_Z = \frac{l - l_0}{l_0} = \frac{\Delta l}{l_0}$$



- Lateral strain (ε_x):

$$\varepsilon_X = \frac{d - d_0}{d_0} = \frac{\Delta d}{d_0}$$

- Shear strain (γ):



$$\gamma = \frac{\Delta x}{y} = \tan\theta$$

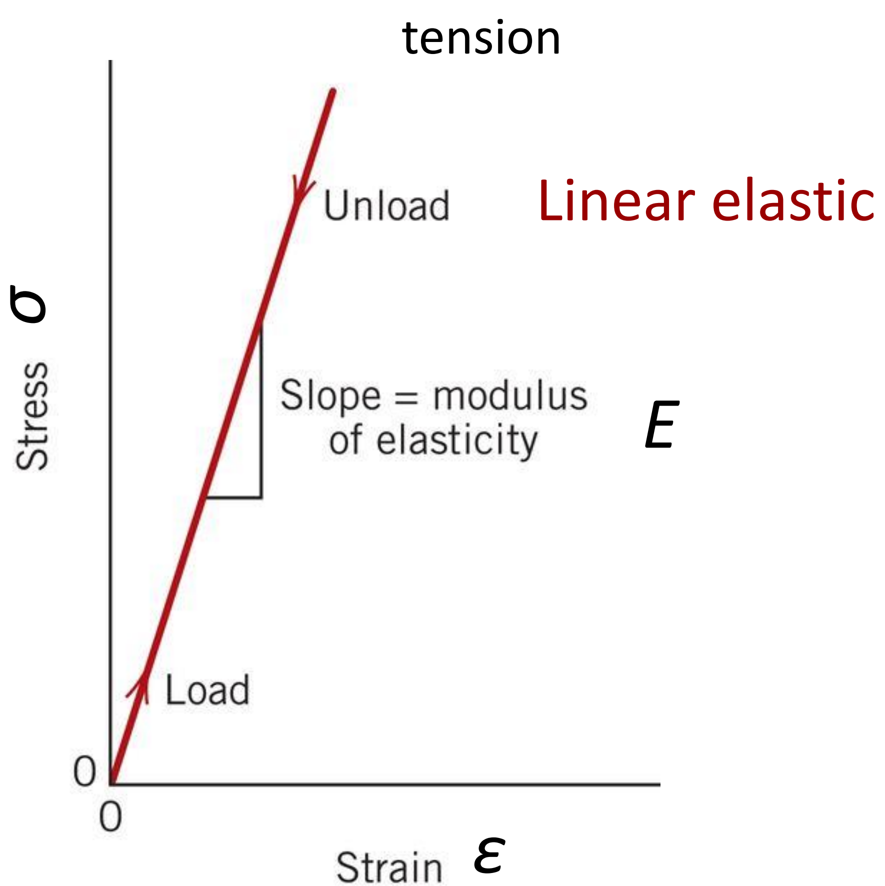
dimensionless

4.2

STRESS-STRAIN BEHAVIOUR: ELASTIC DEFORMATIONS

Linear Elastic Properties

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



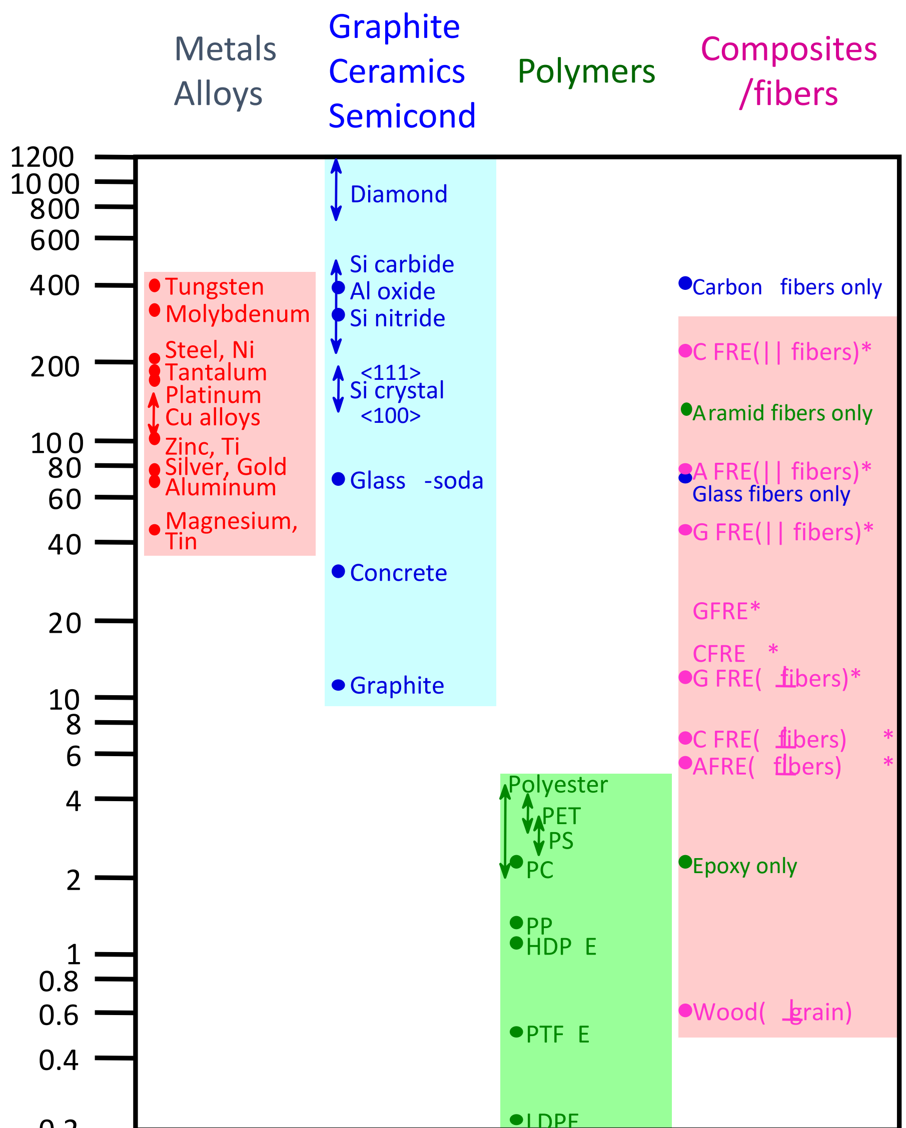
- **Modulus of Elasticity, *E*:**
  (Young's modulus)

- **Hooke's Law:**

$$\sigma = E\varepsilon$$

Units:
E: [Pa] = [N m^{-2}]

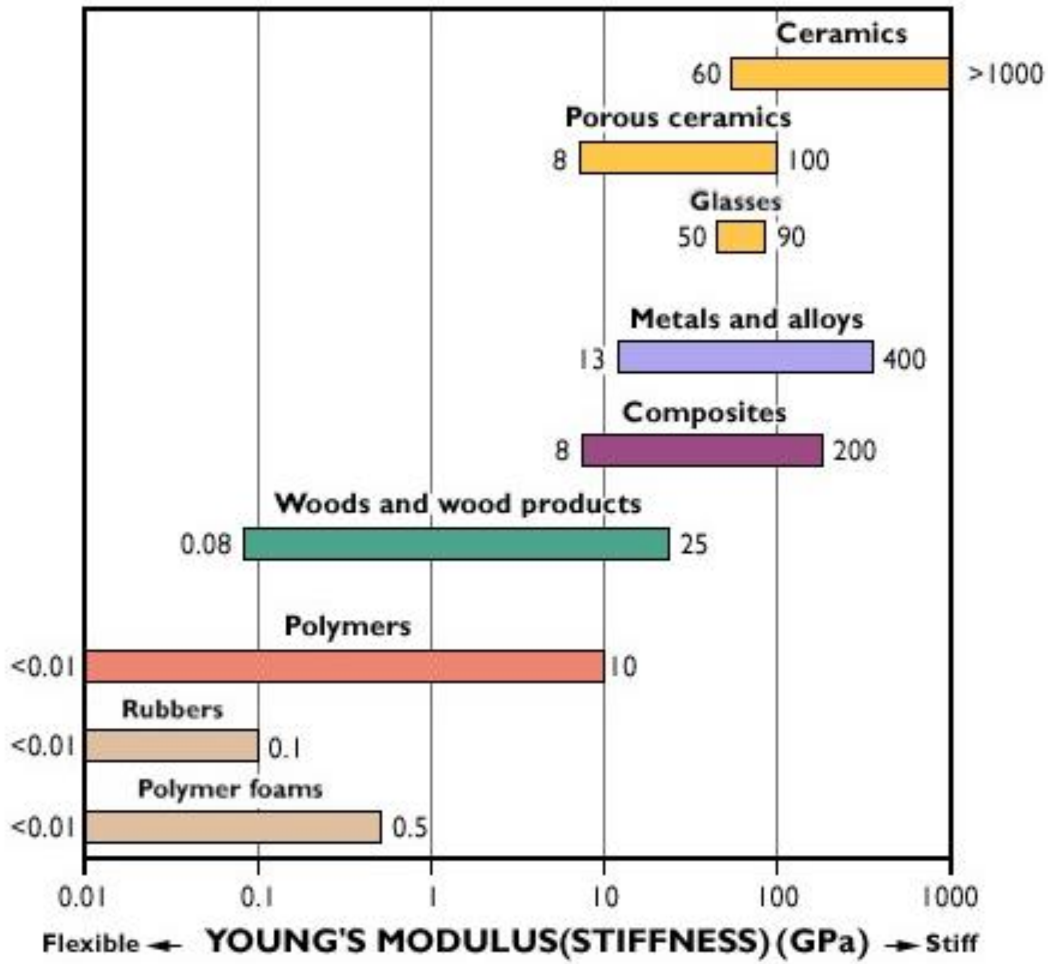
E – Comparison of Material Types



Based on data in Table B.2, *Callister & Rethwisch 10e.*

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

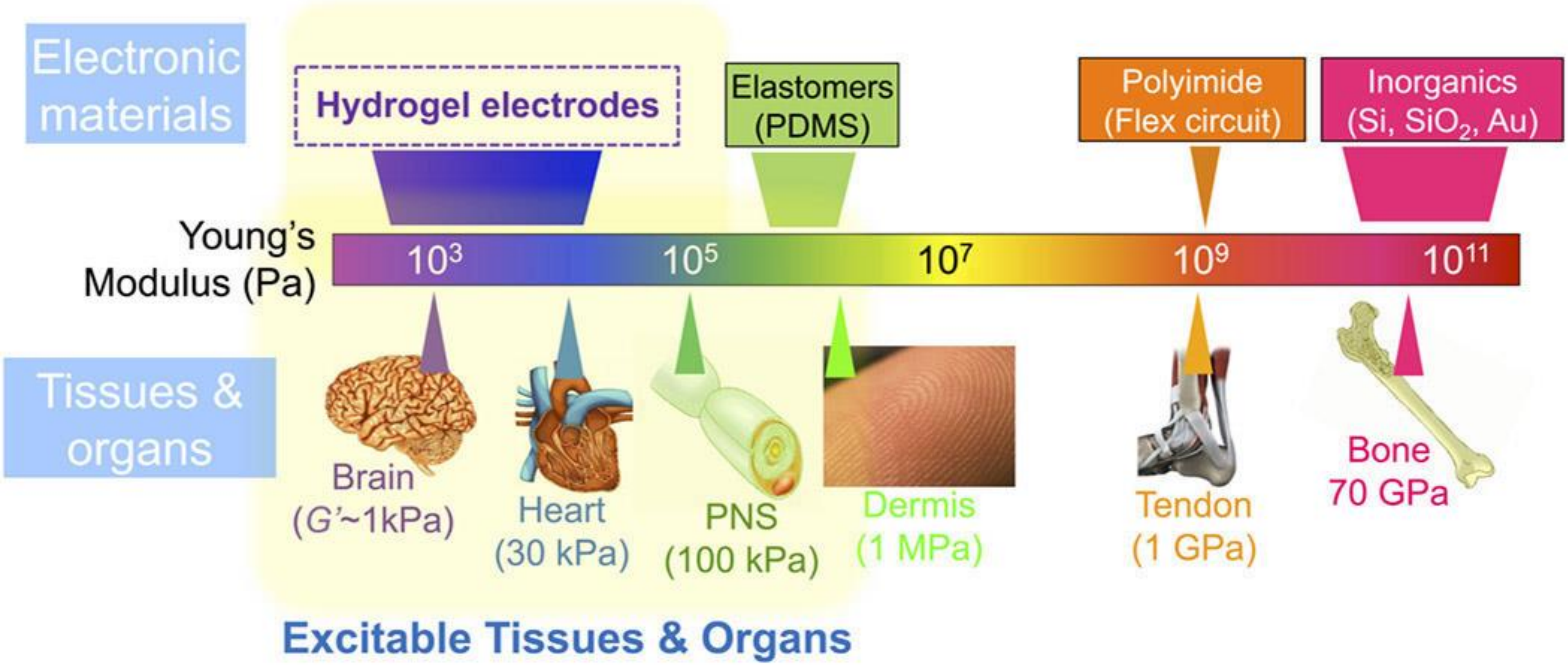
E – Comparison of Material Types



http://www-materials.eng.cam.ac.uk/

RANGE OF E AND BIONICS

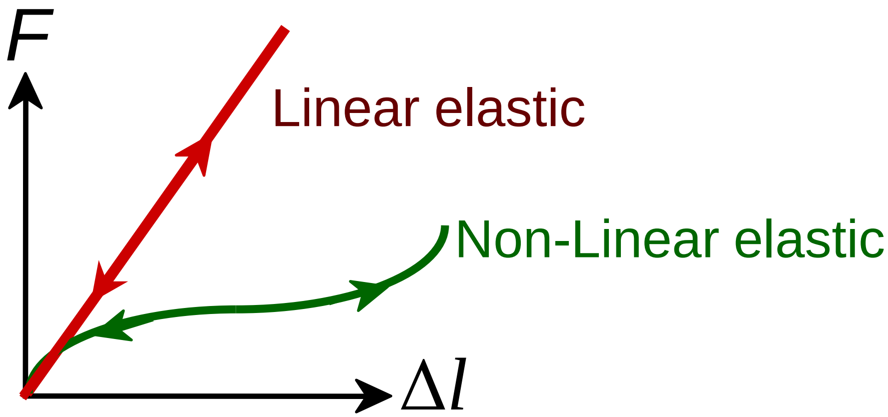
Young's moduli of a range of biological and electronic materials.

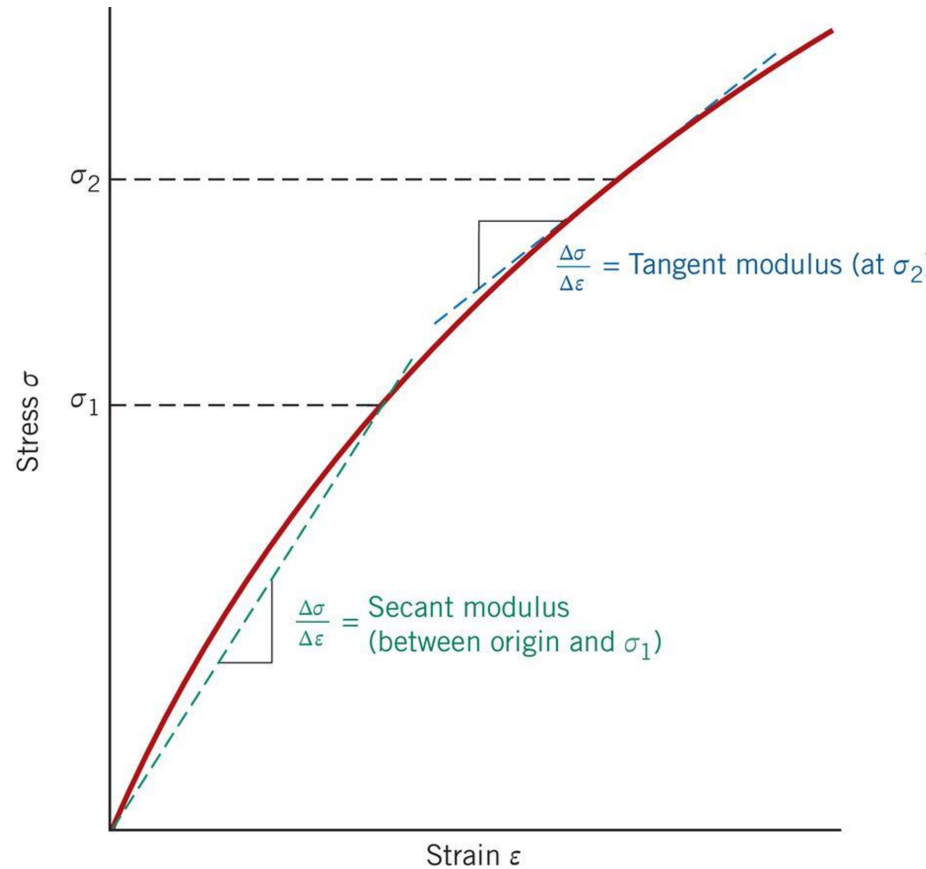


Materials and microfabrication processes for next-generation brain-machine devices

C. Bettinger et al. 2016 – SPIE NEWS

NON-LINEAR ELASTIC DEFORMATION

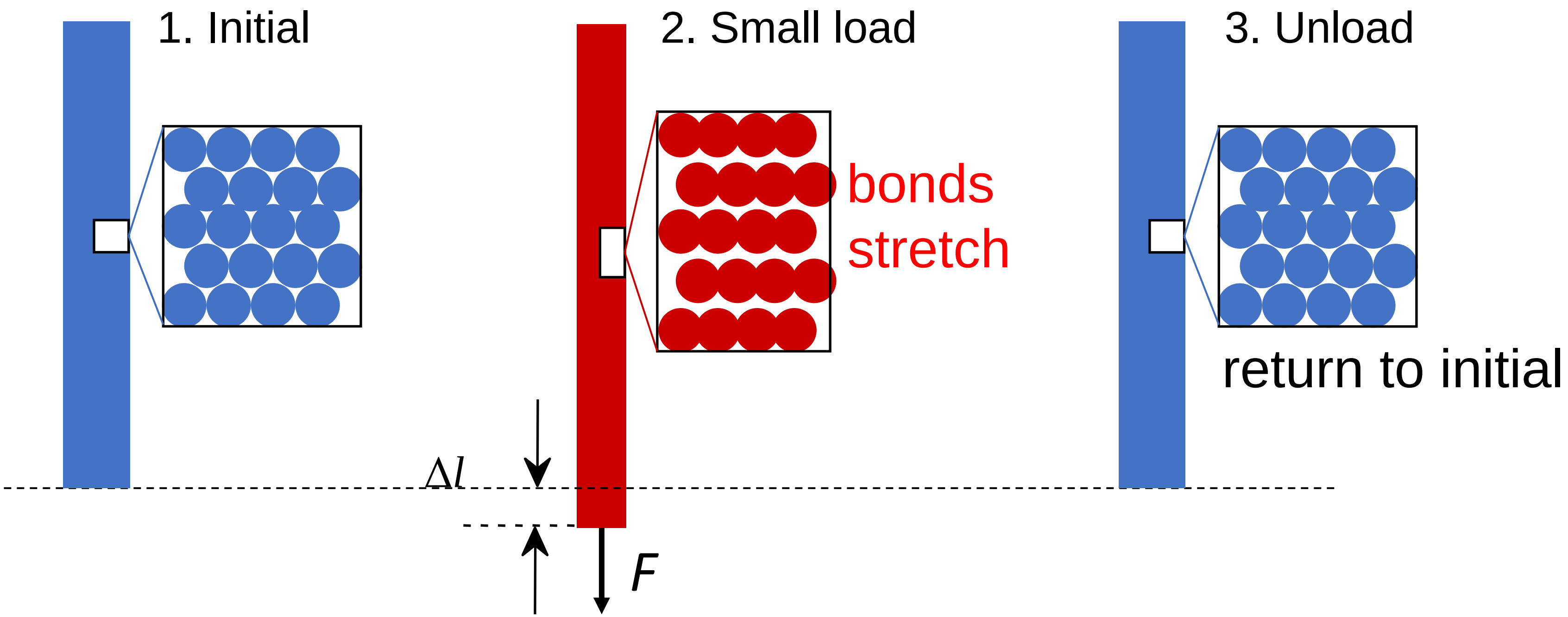




- non linear
- fully reversible

ELASTIC DEFORMATION

Metals



- elastic deformation is nonpermanent and reversible
- small variations of interatomic distances
- E measures the resistance against separation

INFLUENCE OF BONDING FORCES

Elastic modulus depends on interatomic bonding forces

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

F: interatomic bonding force

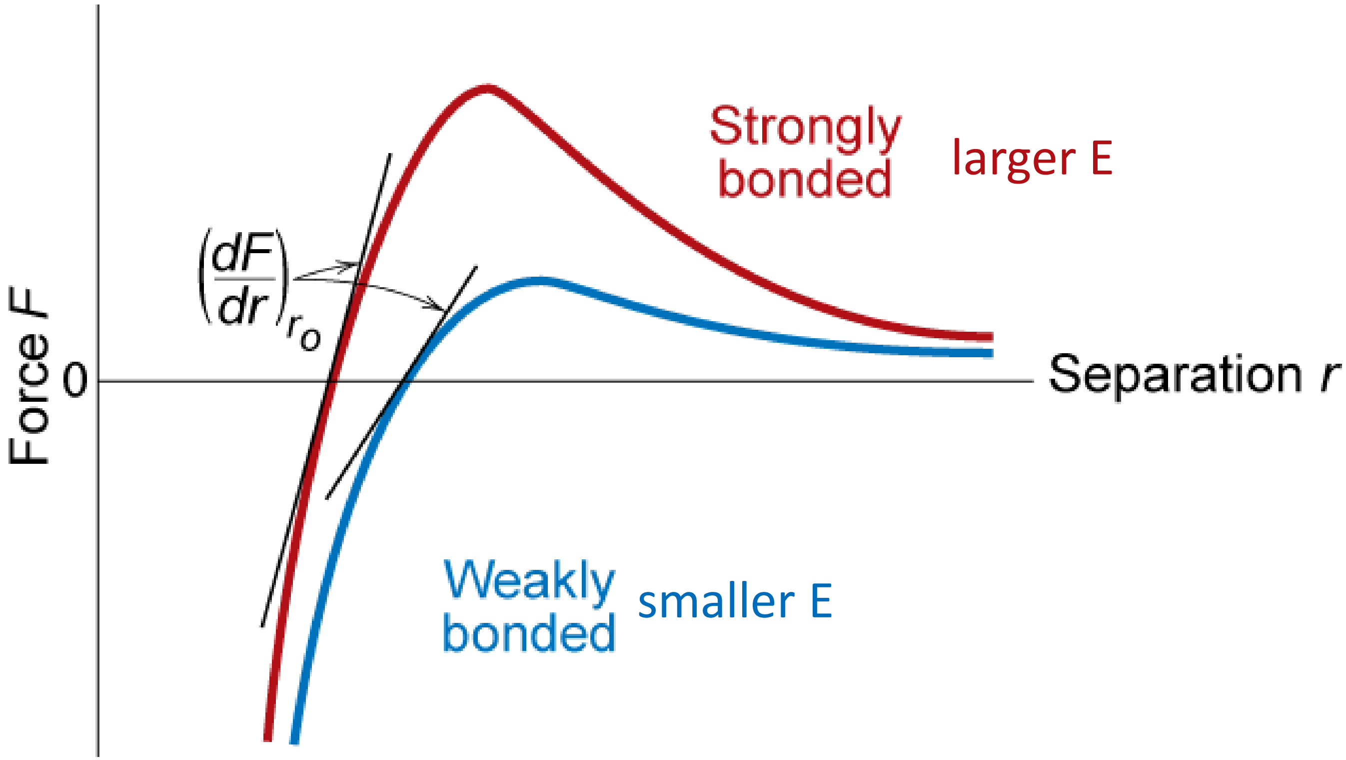
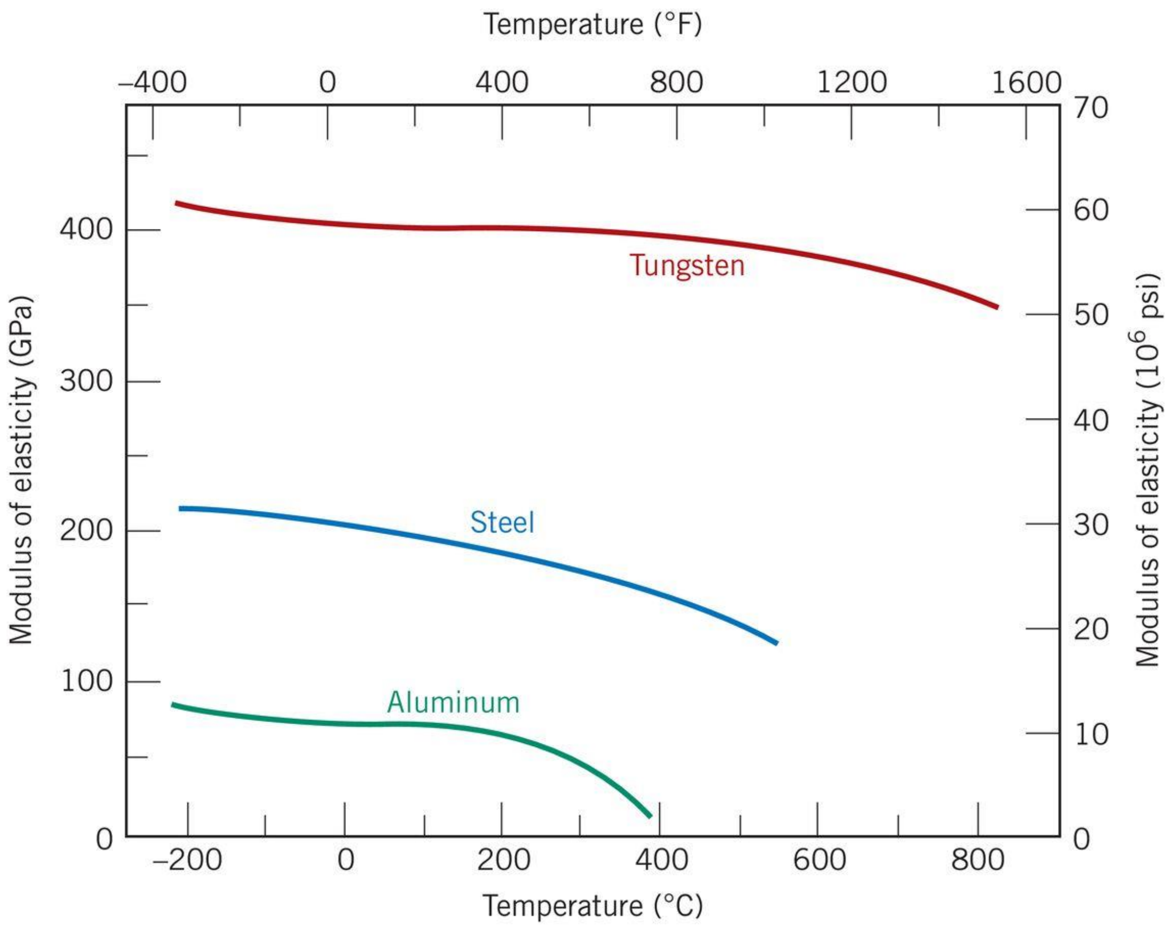


Fig. 6.7, *Callister & Rethwisch 10e.*

Influence of Temperature on E

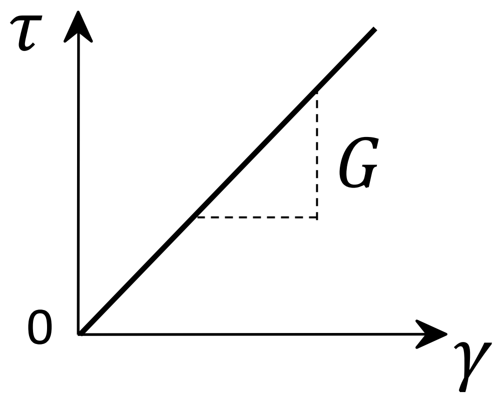


Adapted from K. M. Ralls, T. H. Courtney, and J. Wulff, *Introduction to Materials Science and Engineering*. Copyright © 1976 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.

Other Elastic Properties

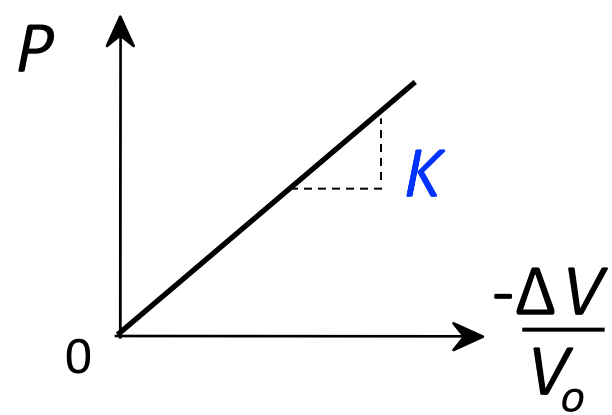
- Elastic Shear modulus, G:

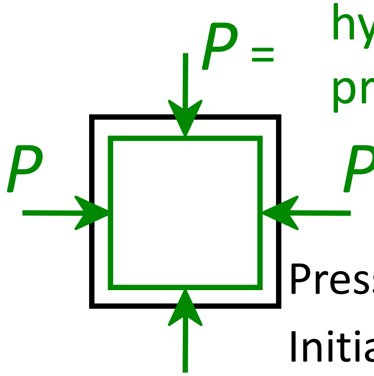
$$\tau = G\gamma$$



- Elastic Bulk modulus, K:

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





RECAP: YOUNG'S MODULUS

YOUTUBE VIDEO – The efficient engineer Channel
"Understanding Young's modulus" (06:42)

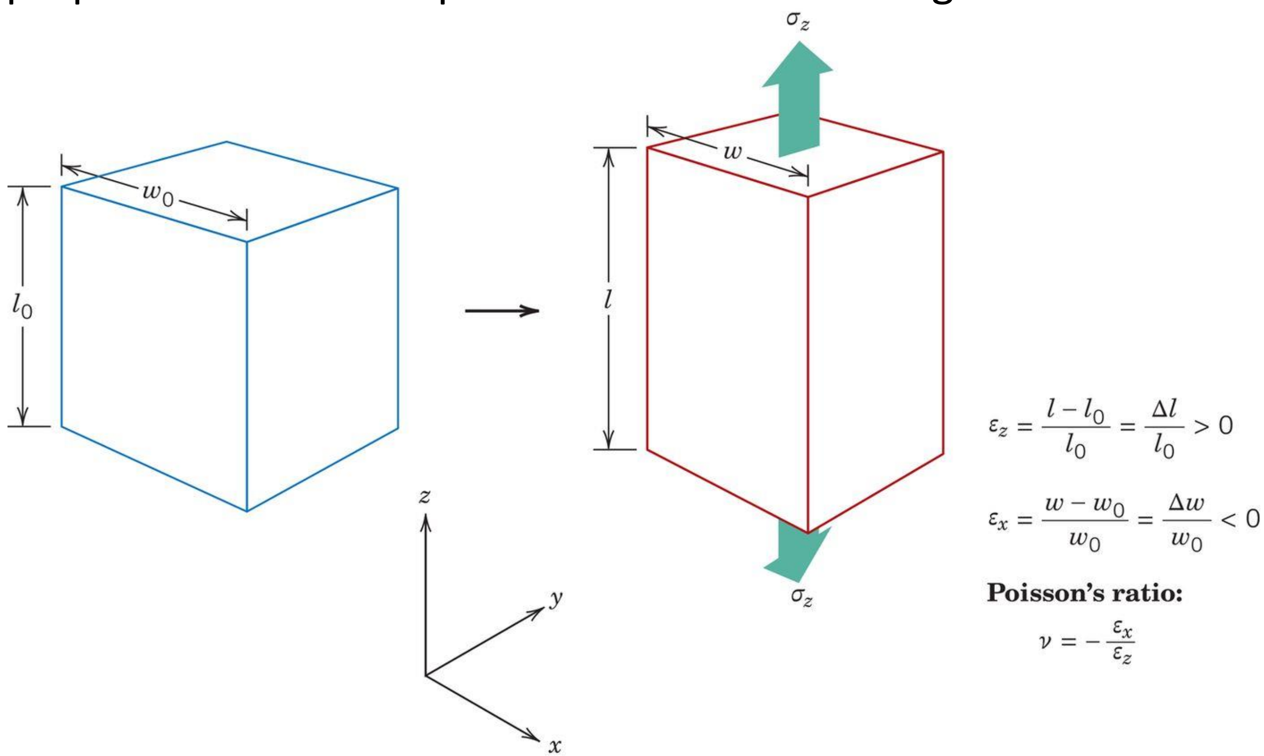
https://youtu.be/DLE-ieOVFjI

POISSON'S RATIO

deformation in directions perpendicular to the specific direction of loading

- Poisson's ratio, ν:

$$\nu = -\frac{\varepsilon_{trans}}{\varepsilon_{axial}} = -\frac{\varepsilon_x}{\varepsilon_z}$$



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

rubber: $\nu \approx 0.50$

For most metals, ceramics and polymers:

$0.15 < \nu \leq 0.50$

Units:
ν: dimensionless

Poisson's ratio

isotropic materials:

$$E = 2G(1 + \nu)$$
$$E = 3K(1 - 2\nu)$$

for most metals $G = 0.4E$ if the value of one modulus is known, ν may be approximately estimated

anisotropic materials: elastic behavior (E) varies with crystallographic direction

characterized only by the specification of several elastic constants, depending on characteristics of the crystal structure

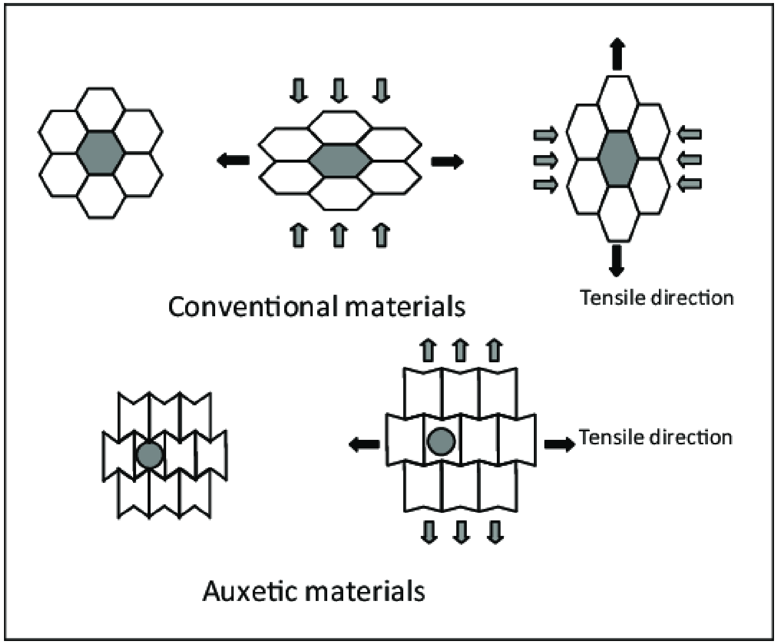
RECAP: POISSON'S RATIO

YOUTUBE VIDEO – The efficient engineer Channel
"Understanding Poisson's ratio" (09:46)

https://youtu.be/tuOlM3P7ygA

Negative Poisson's ratio- Auxetic Materials

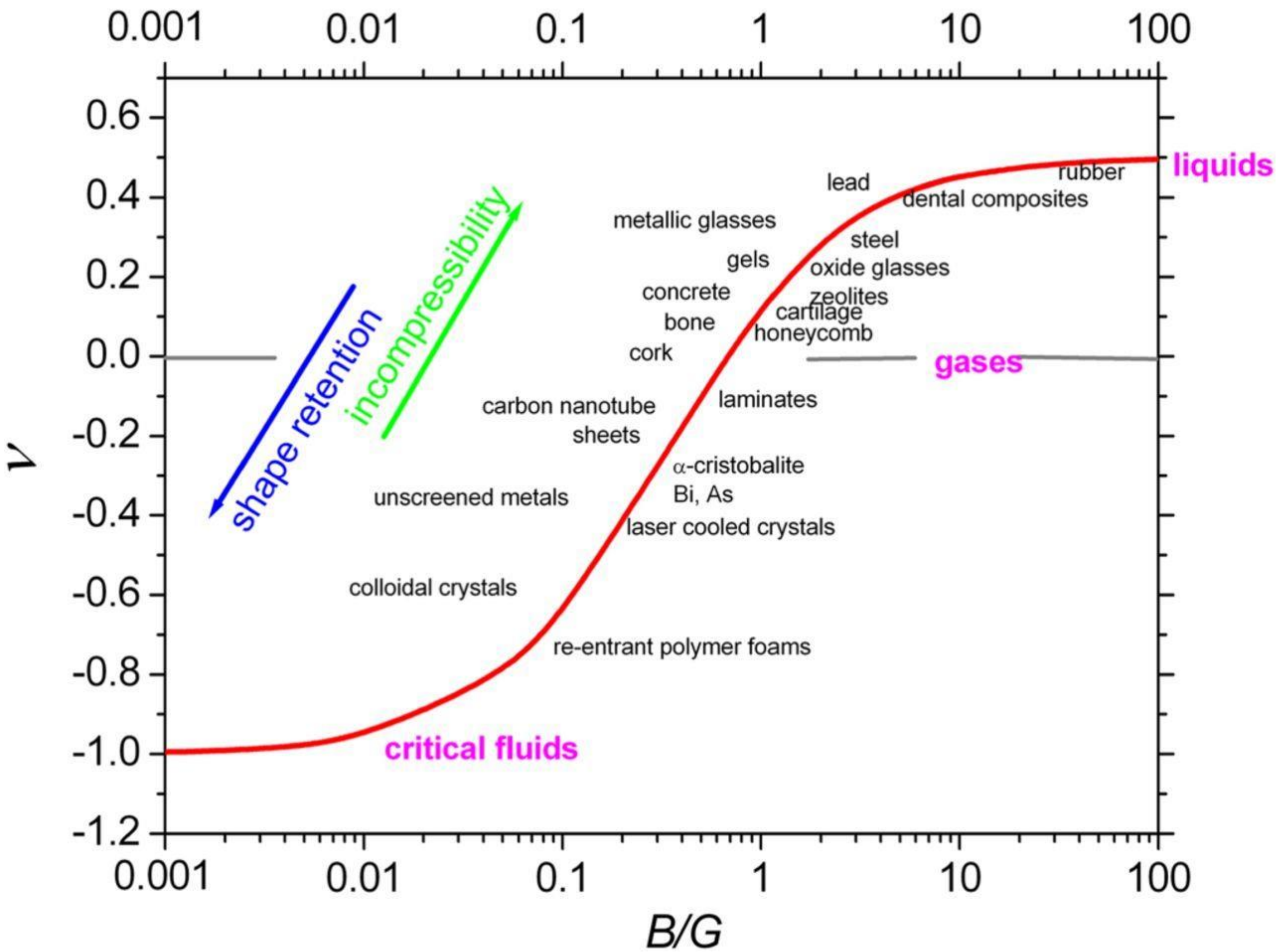
auxetic materials: $\nu < 0$ expand along transversal direction during tensile extension



blood vessel stents based on auxetic structures
https://lgg.epfl.ch/

SEMINAR TOPIC	AUXETIC Materials & Structures in BIOMEDICINE

POISSON'S RATIO



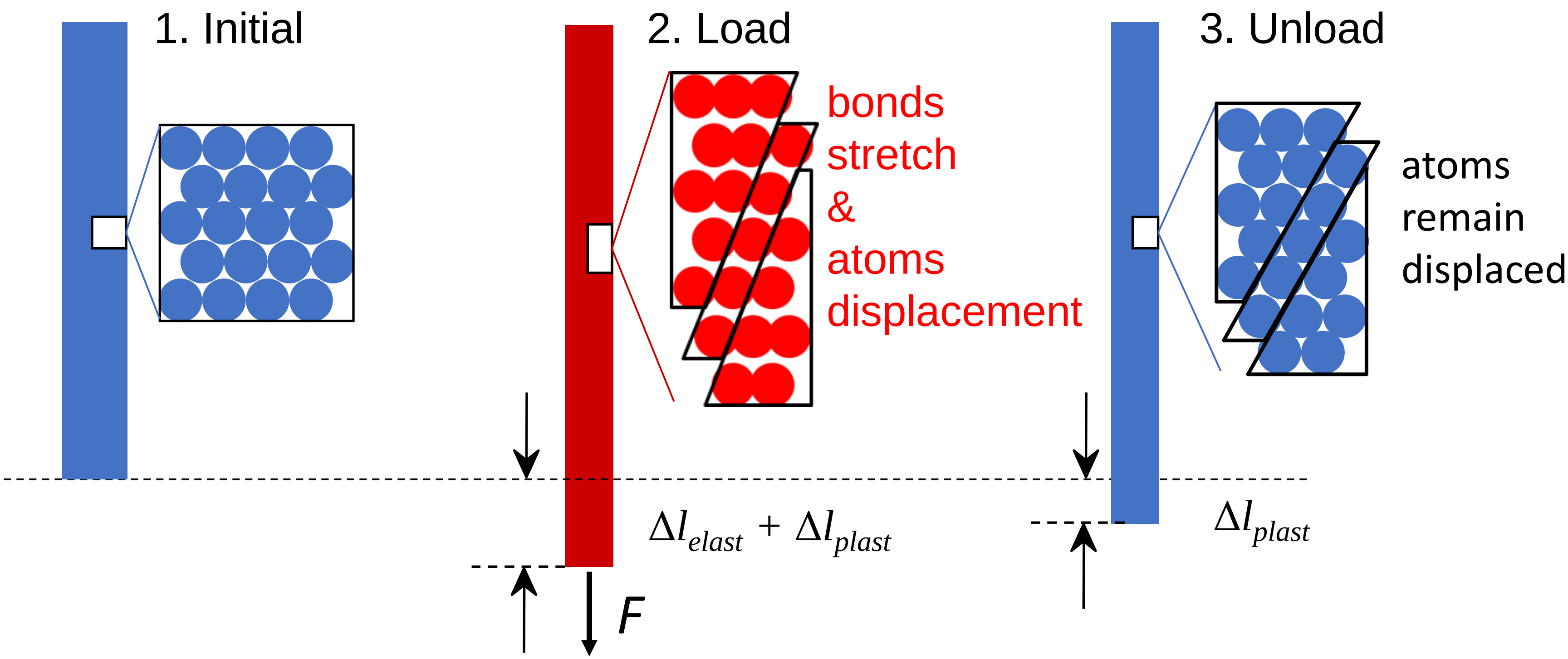
G. N. Greaves Royal Soc. J. Hist Sci. 67,1,37-58, DOI: (10.1098/rsnr.2012.0021)

4.3

STRESS-STRAIN BEHAVIOUR:
PLASTIC DEFORMATIONS, TENSILE PROPERTIES

Plastic Deformation

Metals

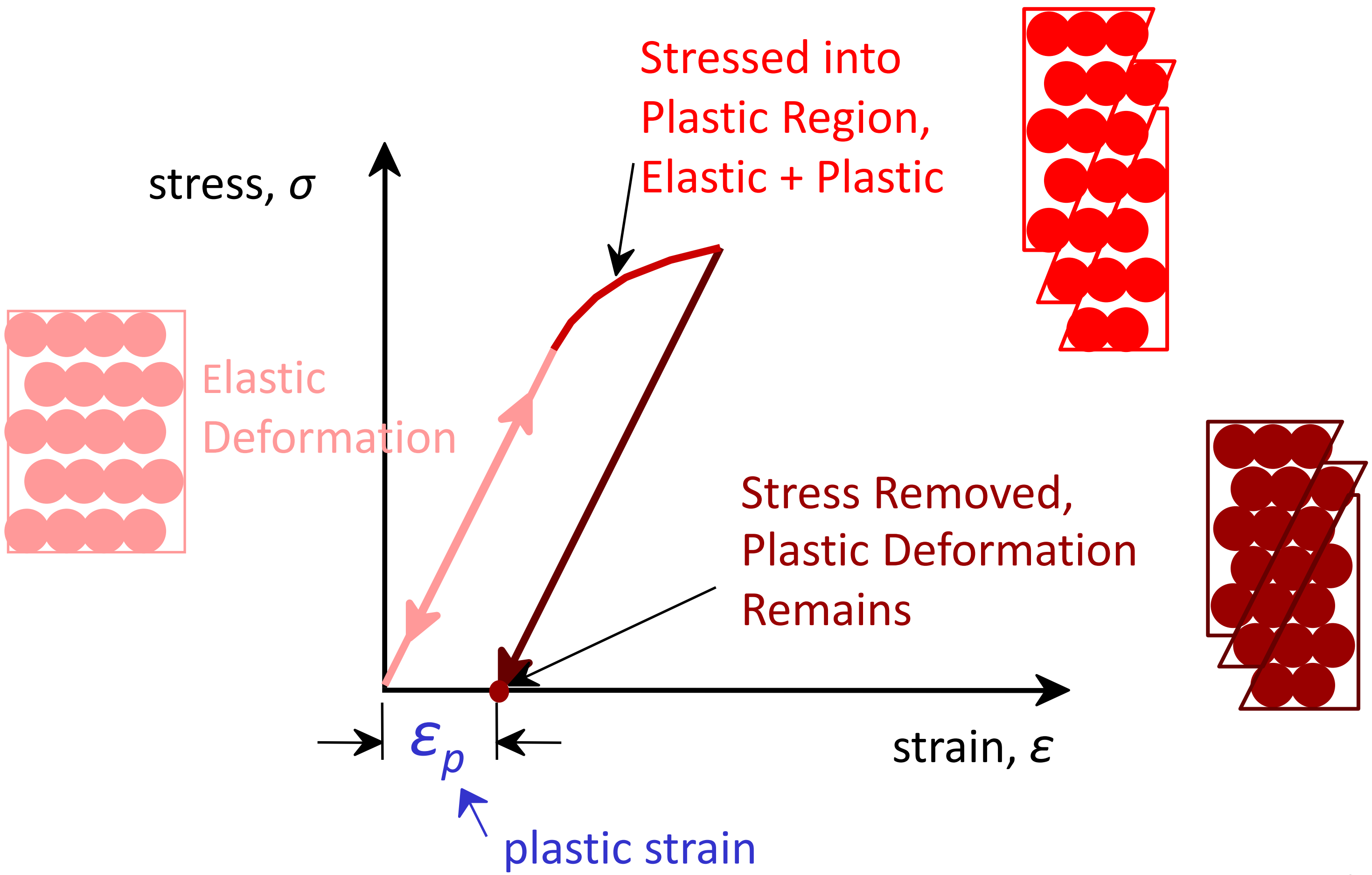


- only partial recovery (elastic)
- plastic deformation is permanent and non-reversible

NB! in crystalline solids: dislocations
in amorphous solids: viscous flux (more in following lectures)

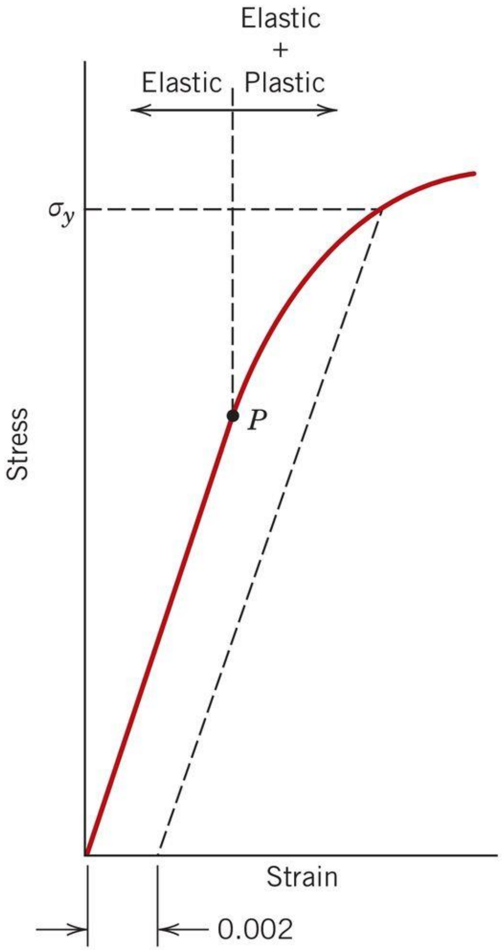
PLASTIC DEFORMATION

- Stress-strain plot for simple tension test:



Adapted from Fig. 6.10 (a), *Callister & Rethwisch 10e.*

YIELD STRENGTH

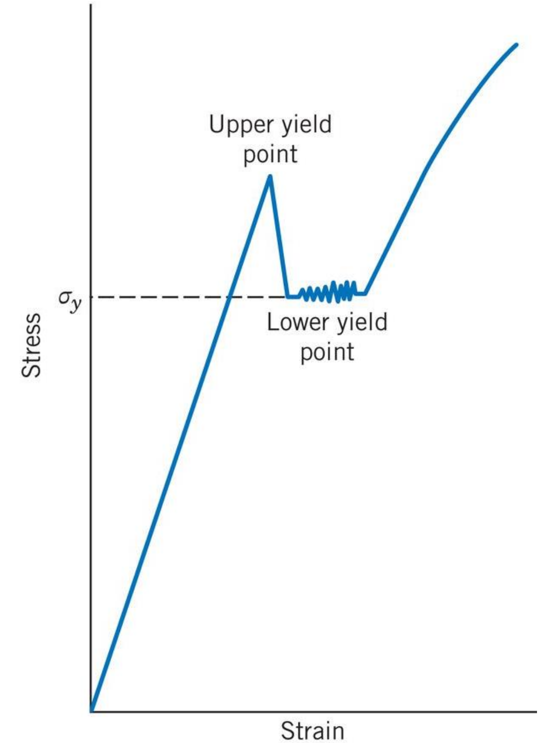


- Transition from elastic to plastic deformation is gradual
- Yield strength = stress at which *noticeable* plastic deformation has occurred

σ_y : yield strength

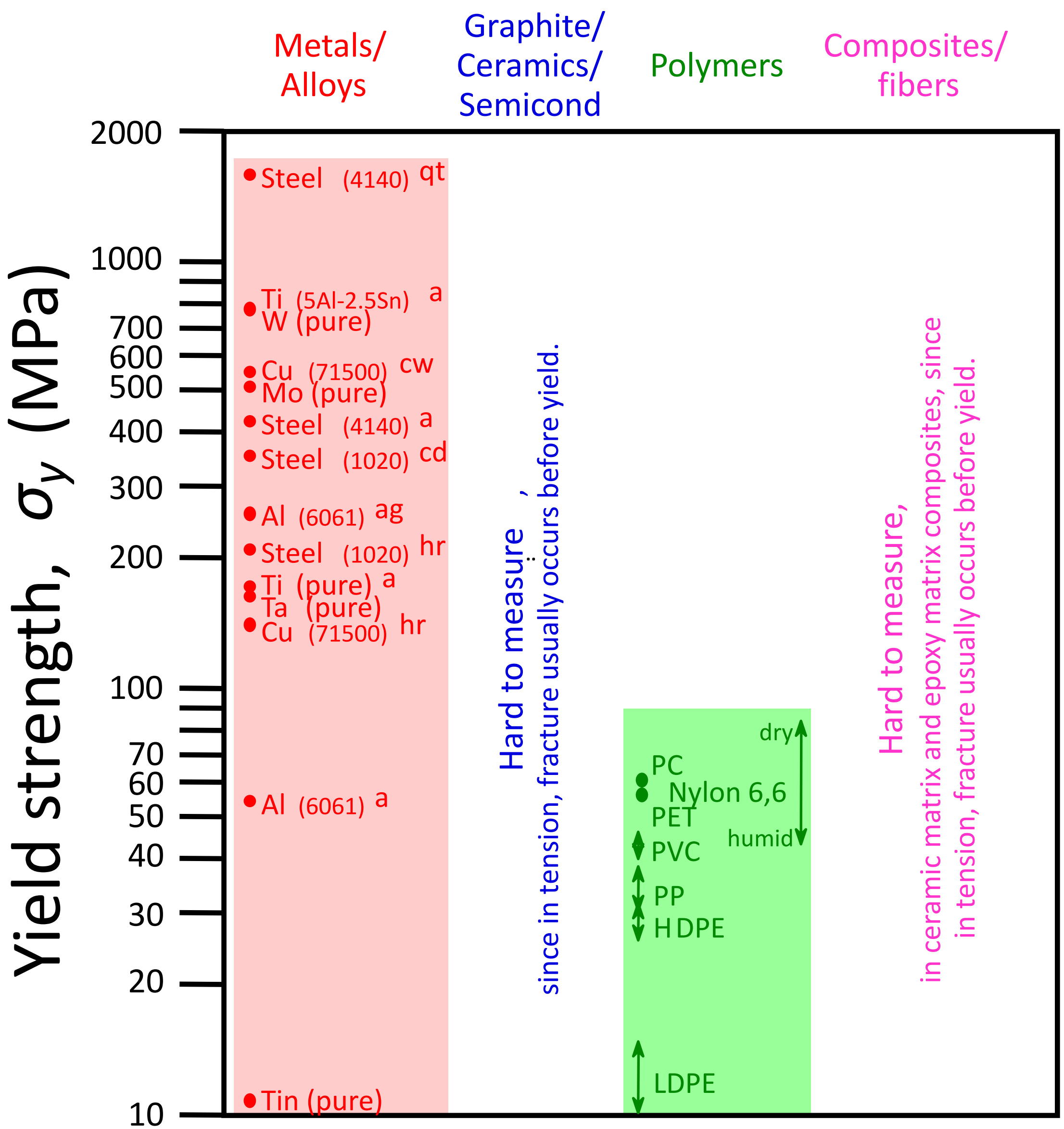
P: proportionality limit

Some steels



e.g. $\Delta l = 0.01$ cm for $l_0 = 5$ cm sample

YIELD STRENGTH – COMPARISON OF MATERIAL TYPES

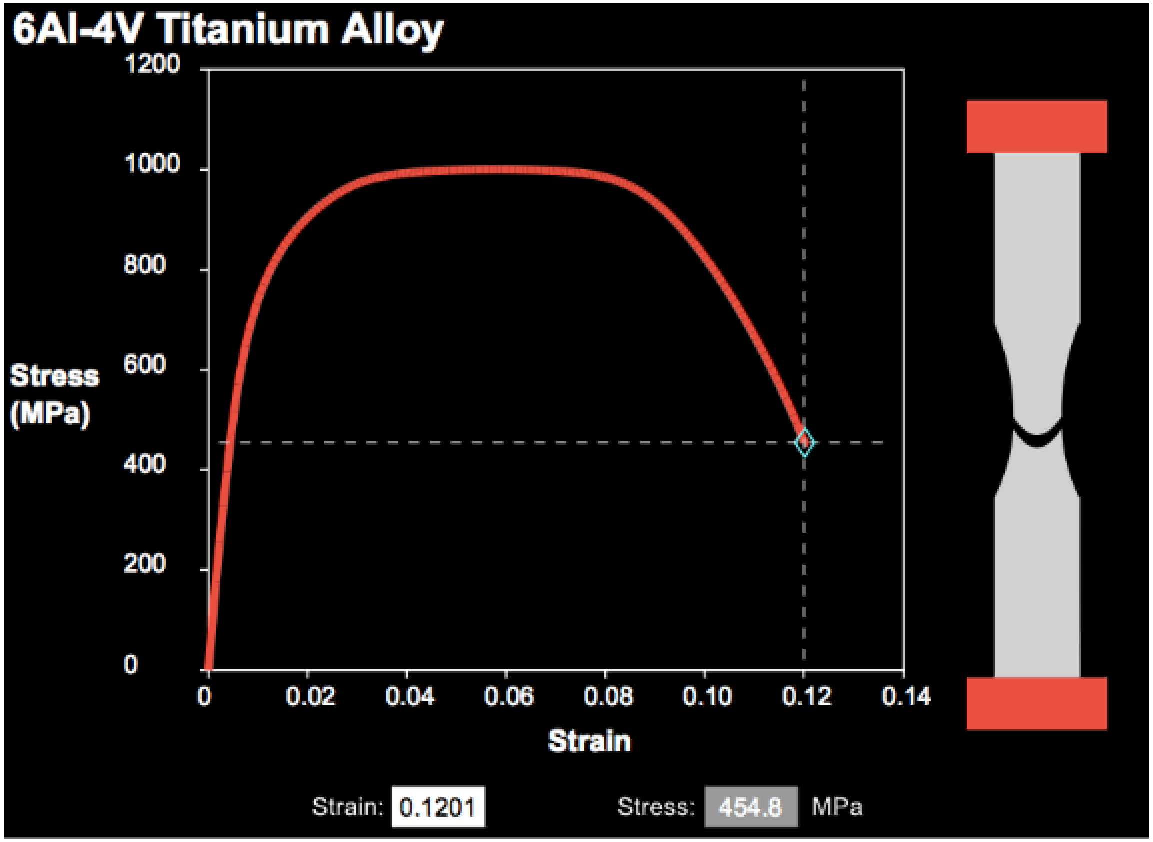


Room temperature values

Based on data in Table B.4, *Callister & Rethwisch 10e.*

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

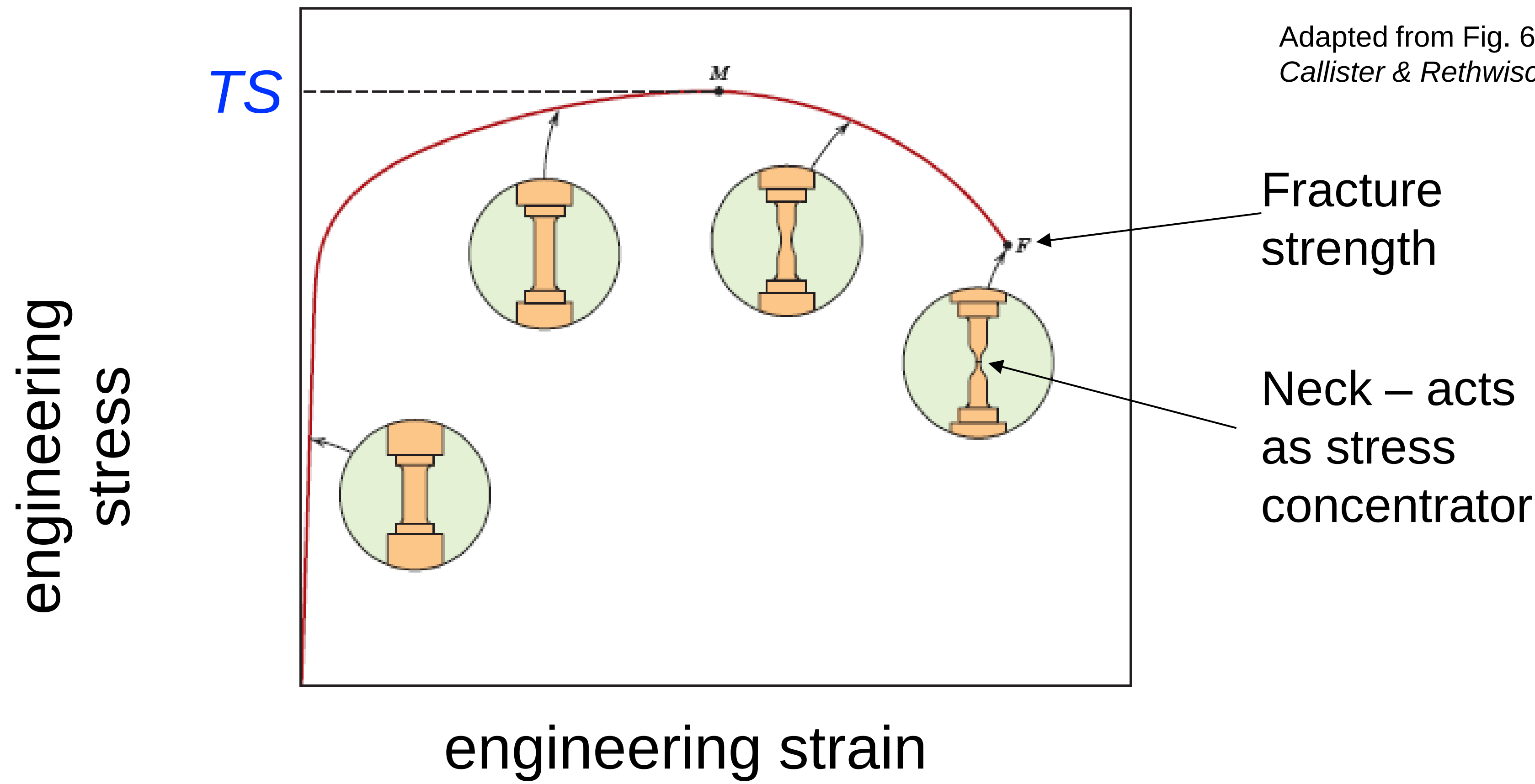
VMSE: Virtual Tensile Testing



[Wiley - VMSE TENSILE TESTING]

TENSILE STRENGTH

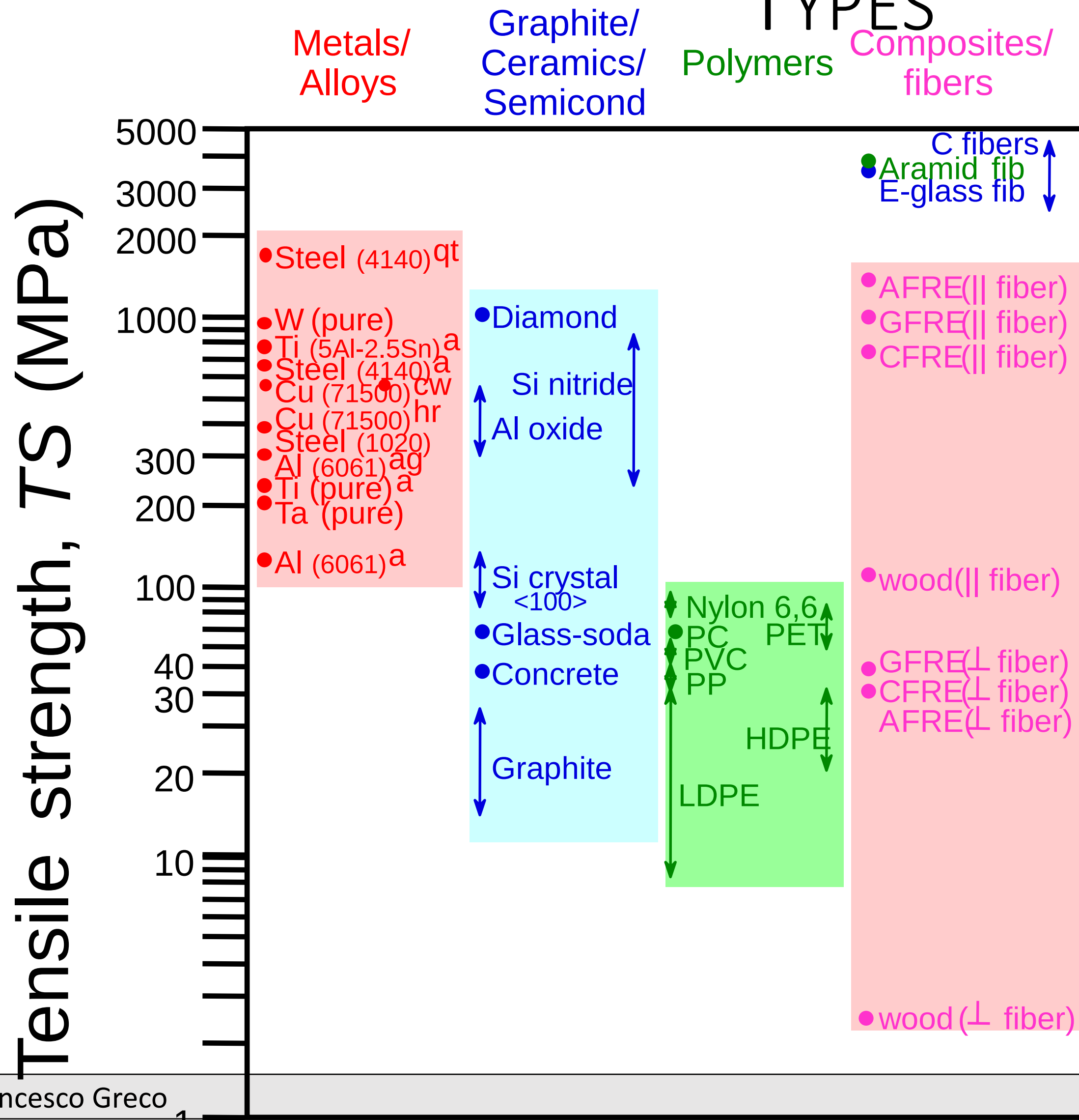
- Tensile strength (*TS*) (it. "resistenza a trazione")= max. stress on engineering stress-strain curve.



Adapted from Fig. 6.11, *Callister & Rethwisch 10e.*

- Metals: Maximum on stress-strain curve appears at the onset of necking

Tensile Strength: Comparison of Material Types



Room temperature values

Based on data in Table B4, *Callister & Rethwisch 10e.*

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

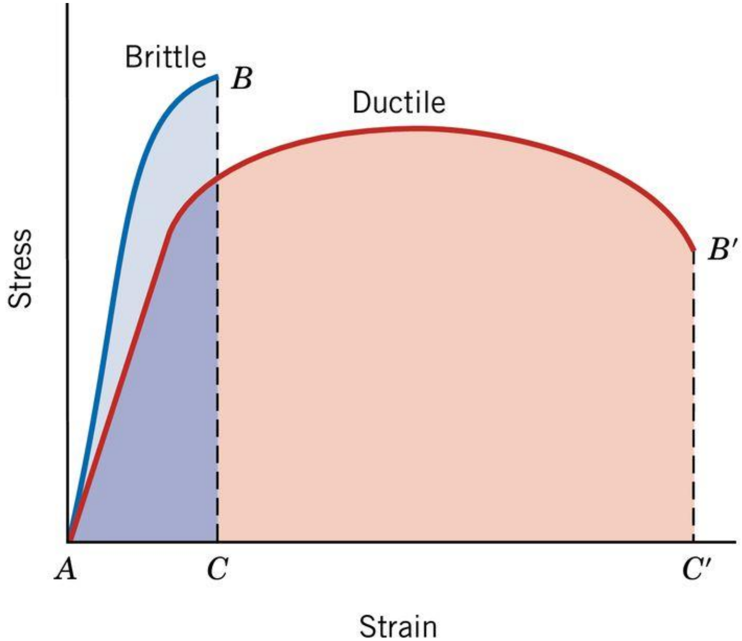
- Ductility = amount of plastic deformation at failure

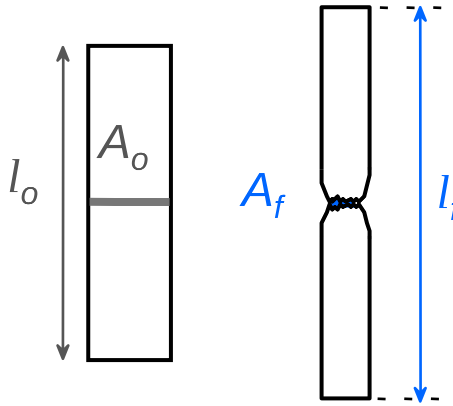
- Ductility, as percent elongation

$$\%EL = \frac{l_f - l_0}{l_0} \times 100$$

- Ductility, as percent reduction in area

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



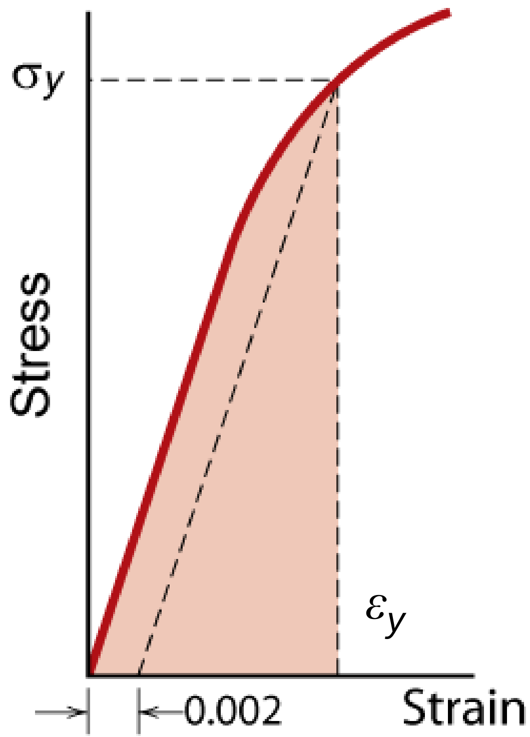


Resilience

Resilience—ability to absorb energy during elastic deformation , energy recovered when load released

Modulus of resilience, U_r

U_r = Area under stress-strain curve to yielding



$$U_r = \int_0^{\varepsilon_y} \sigma d\varepsilon$$

assuming a linear stress-strain curve simplifies to

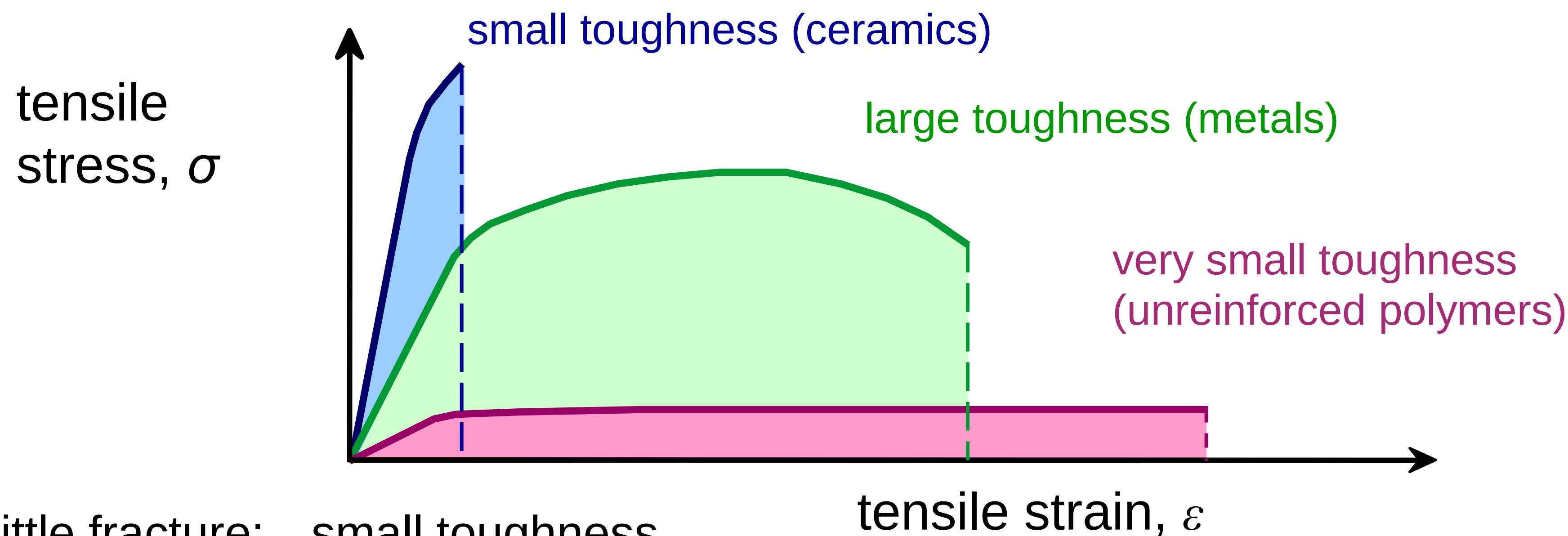
$$U_r \cong \frac{1}{2}\sigma_y \varepsilon_y = \frac{\sigma_y^2}{2E}$$

resilient materials:
high σ_y , low E
alloys for springs!

TOUGHNESS

- Toughness (it.: tenacità) of a material is expressed in several contexts amount of energy absorbed before fracture

- Approximate by area under the stress-strain curve— [J/m^3]

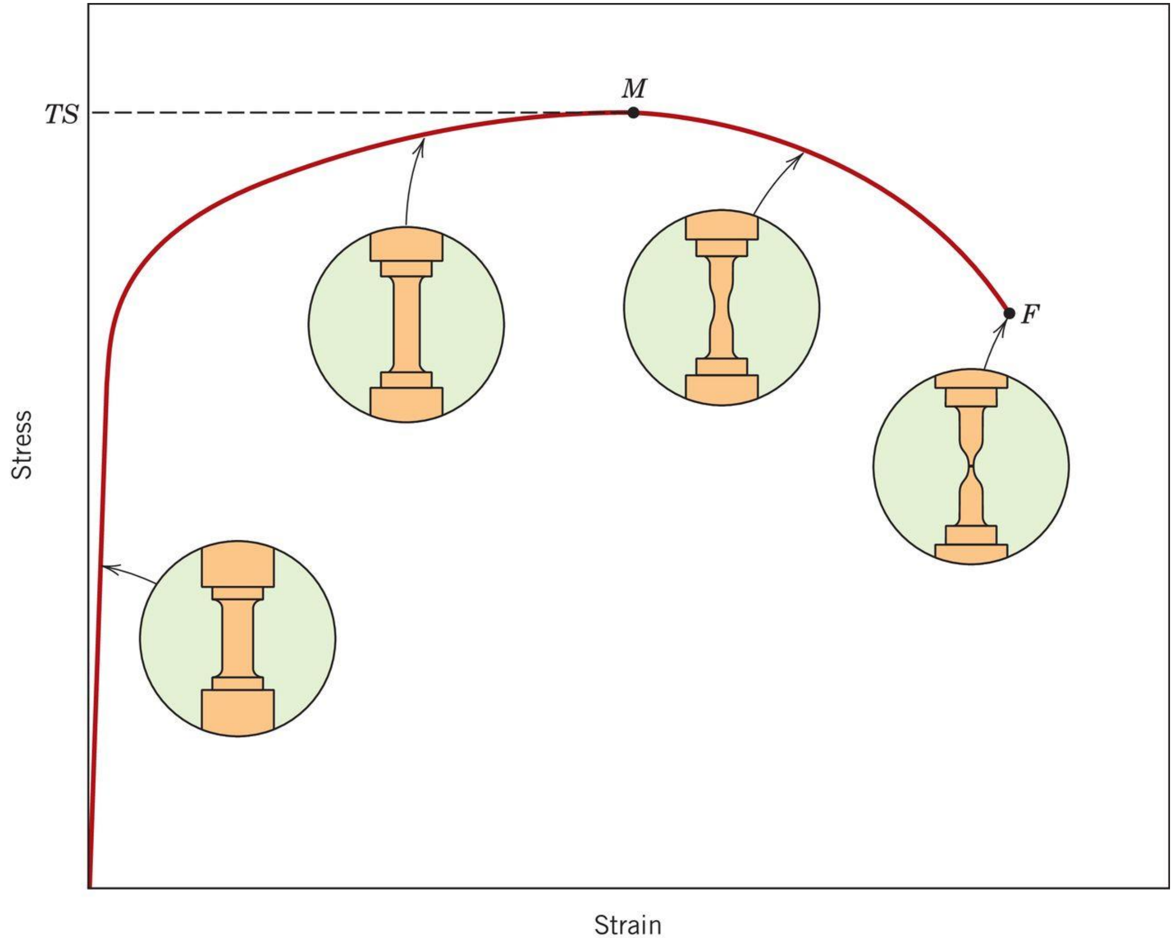


Brittle fracture: small toughness
Ductile fracture: large toughness

37

TRUE STRESS & STRAIN

- after point M (TS) the curve decreases → the material is weaker?
- influence of necking



True Stress & Strain

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

A_i = instantaneous cross-sectional area

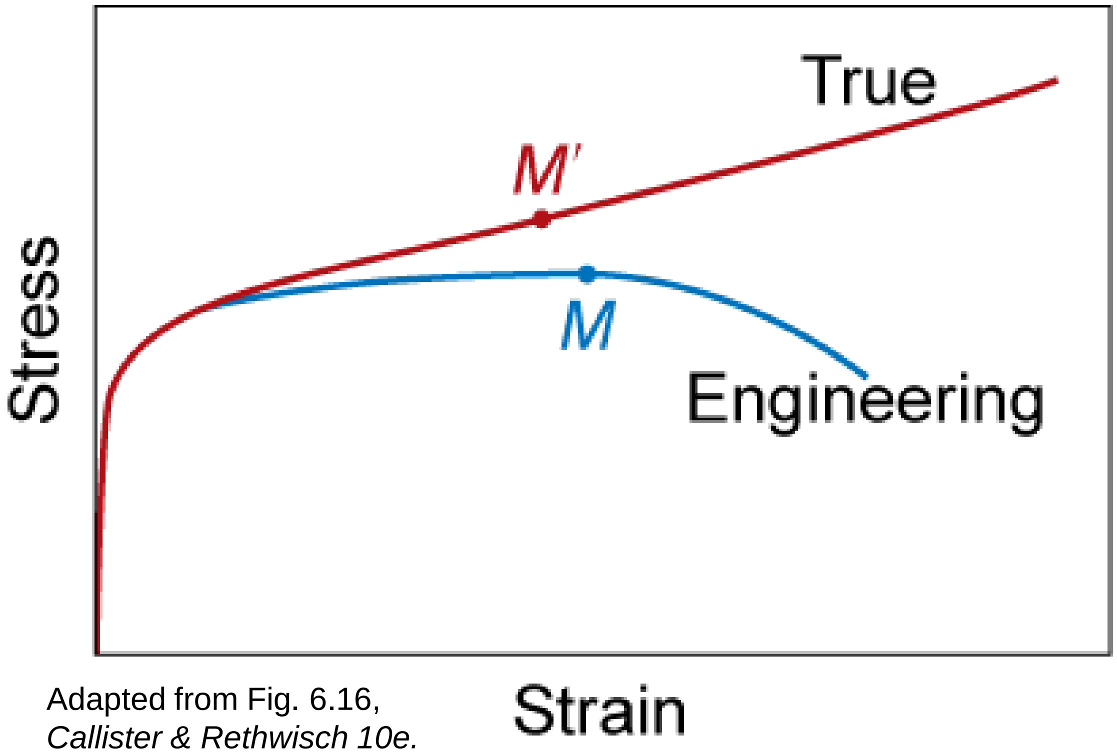
True strain $\varepsilon_T = ln\left({}^{l_i}/_{l_0}\right)$

if no change in volume

$$A_i l_i = A_0 l_0$$

Conversion Equations: valid only to the onset of necking

$$\boxed{\begin{aligned} s_T &= s(1+e) \\ e_T &= \ln(1+e) \end{aligned}}$$



Adapted from Fig. 6.16, *Callister & Rethwisch 10e.*

Elastic Strain Recovery

yield strength for 2nd deformation = σ_{y_i} →

initial yield strength = σ_{y_o} →

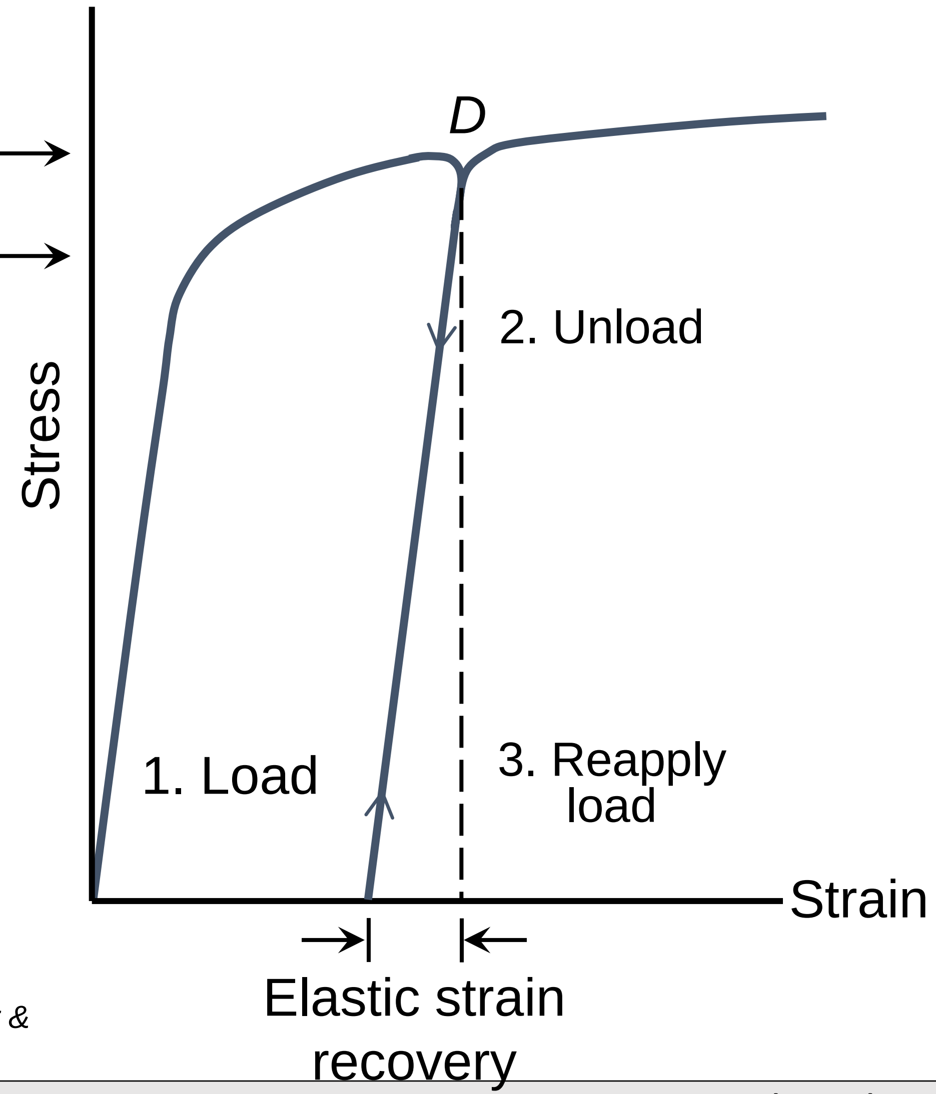
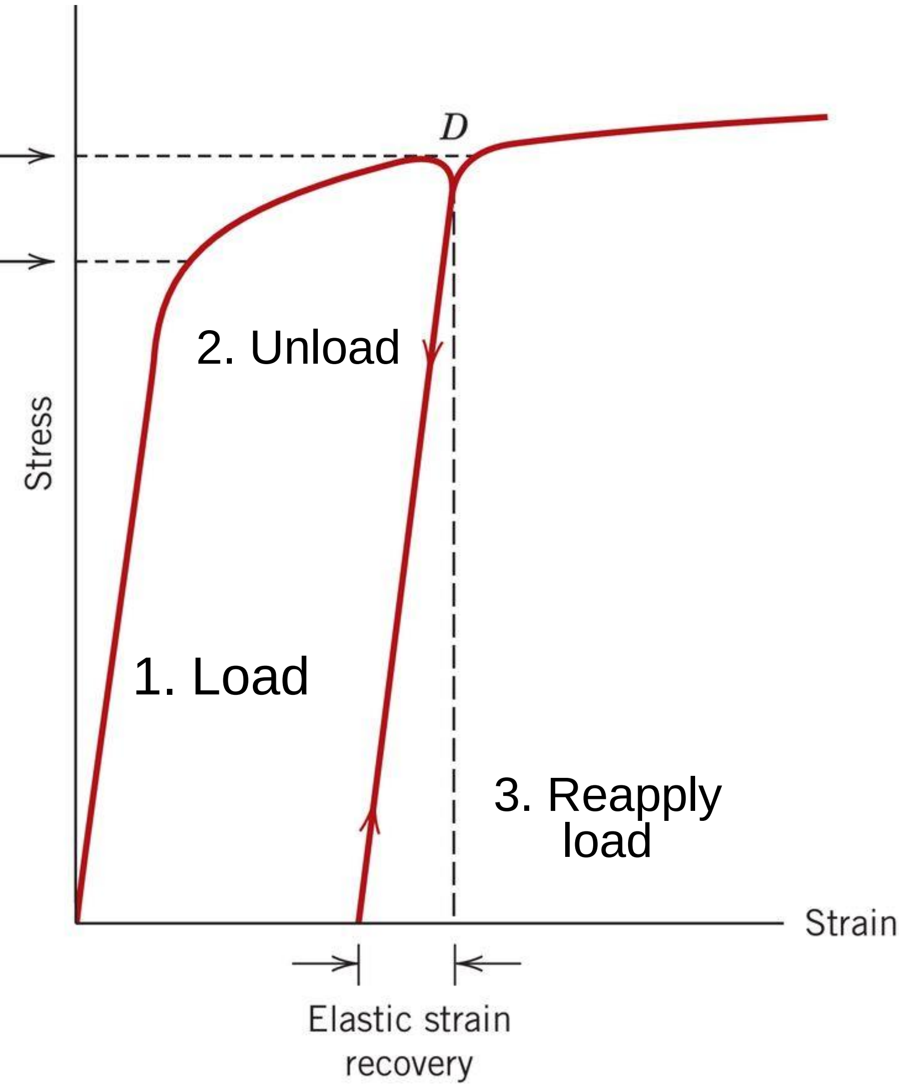


Fig. 6.17, *Callister & Rethwisch 10e.*

Elastic Strain Recovery

yield strength for 2nd deformation = σ_{y_i}

initial yield strength = σ_{y_0}



RECAP: STRENGTH, DUCTILITY, TOUGHNESS

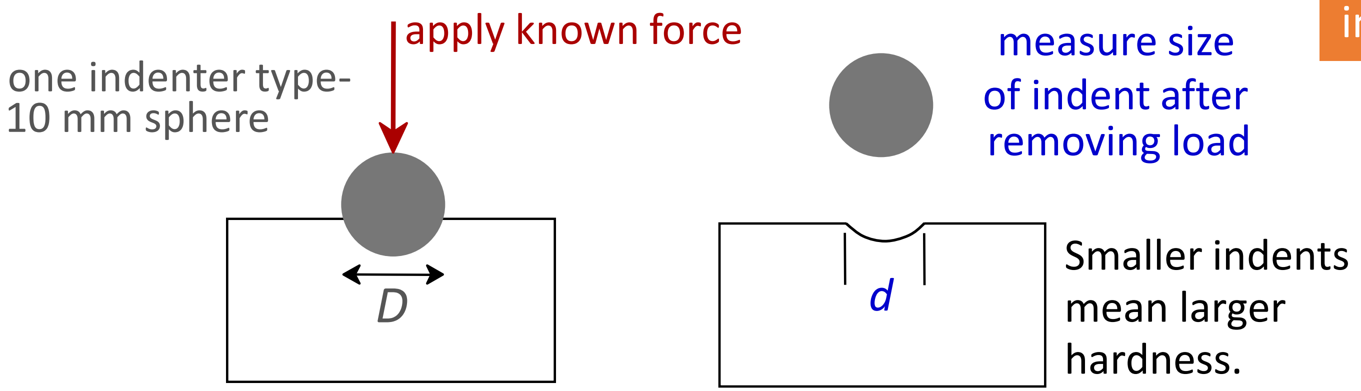
YOUTUBE VIDEO – The efficient engineer Channel “Understanding Materials’ strength, ductility, toughness” (07:19)

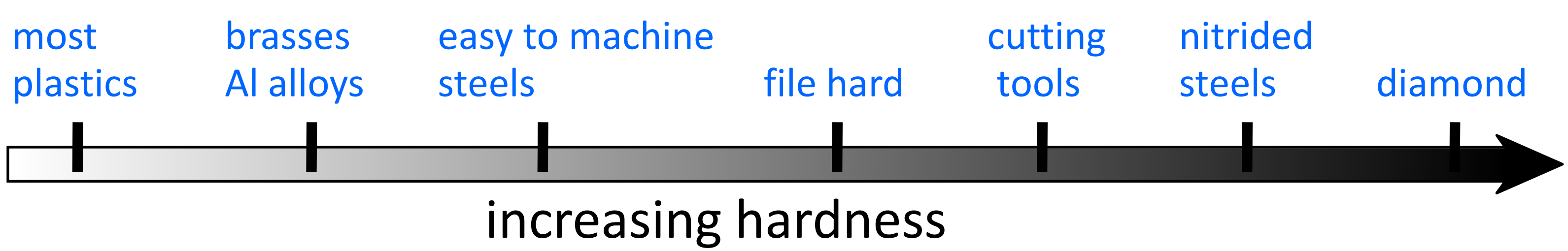
https://youtu.be/WSRqJdT2COE

HARDNESS

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

More on hardness in additional slides





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

SUMMARY

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

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

- Ductility—amount of plastic deformation at failure
  ——percents elongation, reduction in area

- Hardness—resistance to localized surface deformation
  & compressive stresses
  ——Rockwell, Brinell hardnesses

SUMMARY L4

L4.1 • Stress/Strain: Intro and Definitions

L4.2 • Elastic deformations

L4.3 • Plastic Deformations, Tensile Properties

Additional Resources, Readings

YOUTUBE videos:

- The Efficient Engineer Channel – PLAYLIST «Understanding Materials properties»
  3 Episodes
  - Young's Modulus
  - Strength, Ductility, Toughness
  - Poisson's ratio
- Real Engineering Channel- Ep. Material Properties , Ep. Aluminium , Ep. Titanium

Readings:

- Callister Rethwisch – Chapter 6

PLUS:

- Greaves G. Neville 2013 Poisson's ratio over two centuries: challenging hypotheses *Notes Rec.* **67** 37–58 http://doi.org/10.1098/rsnr.2012.0021

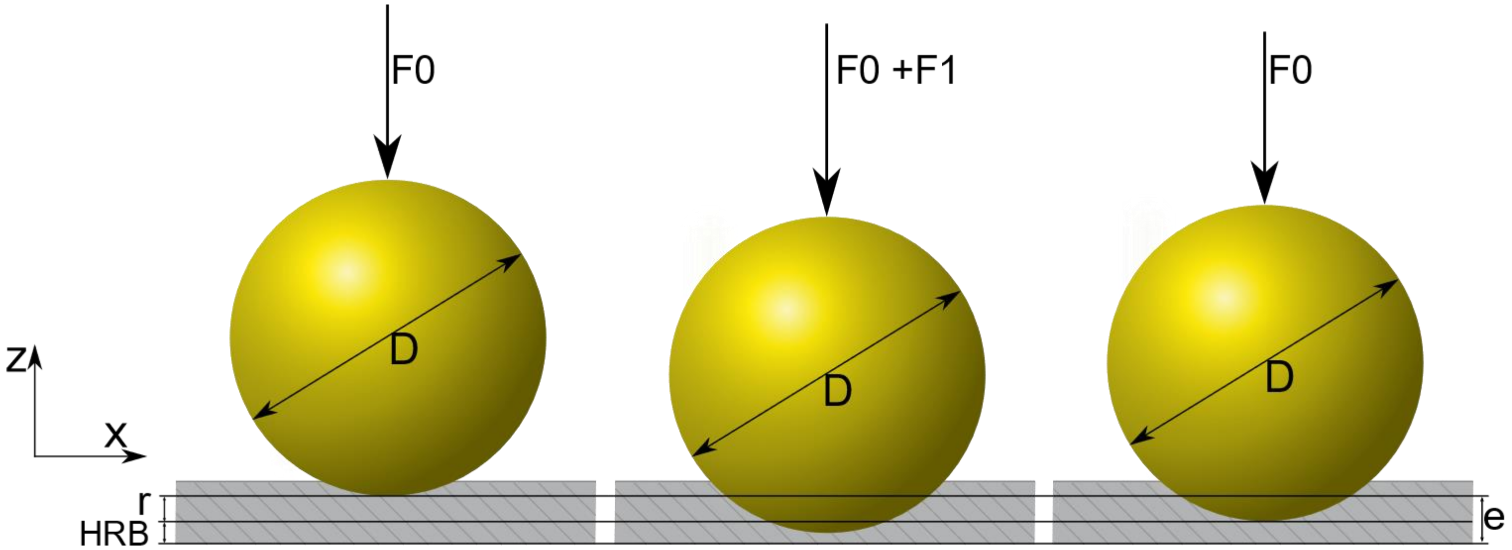
ADDITIONAL SLIDES: HARDNESS

Measurement of Hardness

Rockwell Hardness - HR

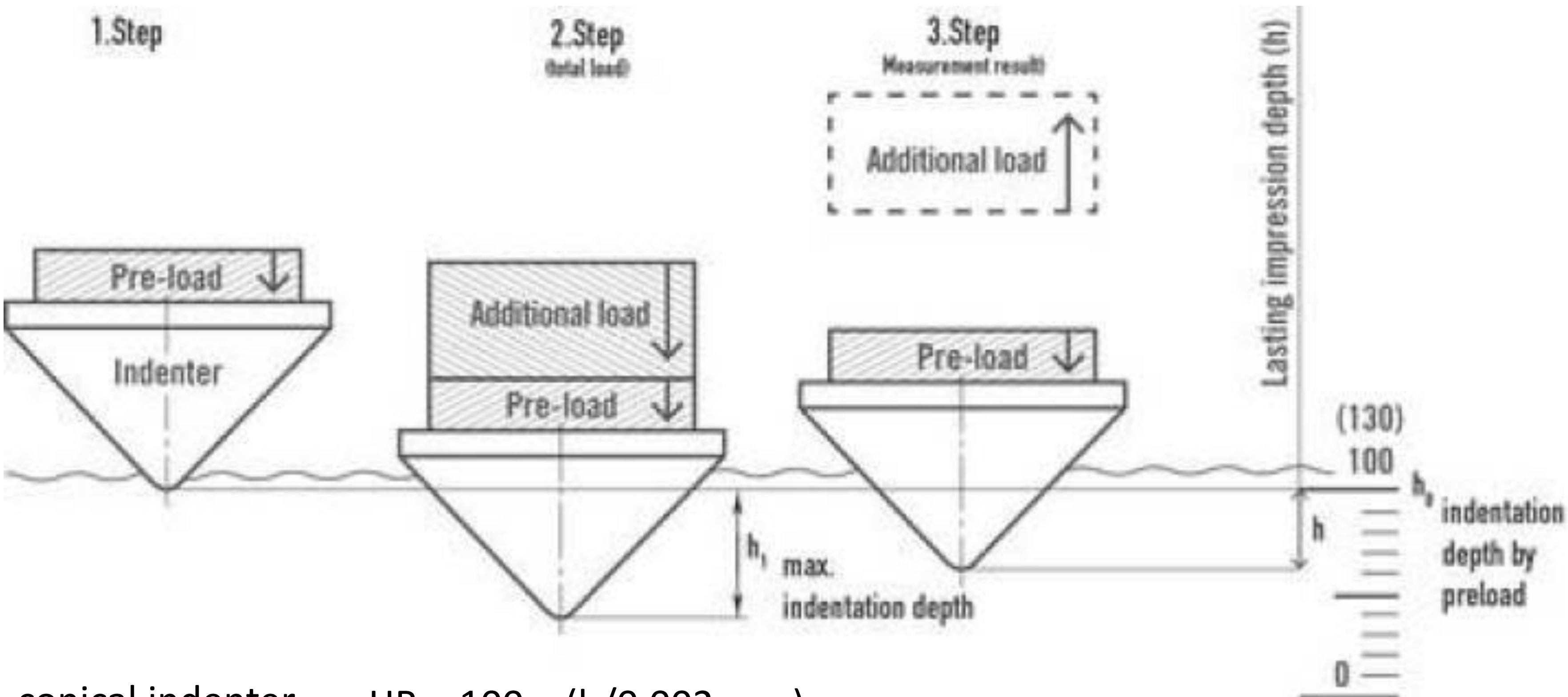
INDENTERS: ASTM E18, diamond spheroconical or tungsten carbide balls

1. Apply a small load F0 (preload)
2. Apply additional load F1 dwell time (typ 4 s)
3. Remove load F1



Measurement of Hardness

Rockwell Hardness - HR



conical indenter $HR = 100 - (h/0.002\ mm)$

spherical indenter $HR = 130 - (h/0.002\ mm)$

h in mm

Measurement of Hardness

Rockwell Hardness - HR

- 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

ROCKWELL HARDNESS SCALES

Table 6.6a 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

Table 6.6b Superficial Rockwell Hardness Scales

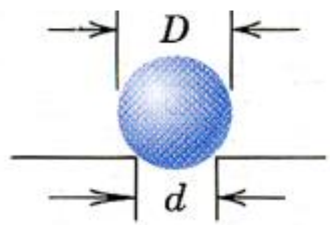
Scale Symbol	Indenter	Major Load (kg)
15N	Diamond	15
30N	Diamond	30
45N	Diamond	45
15T	$\frac{1}{16}$-in. ball	15
30T	$\frac{1}{16}$-in. ball	30
45T	$\frac{1}{16}$-in. ball	45
15W	$\frac{1}{8}$-in. ball	15
30W	$\frac{1}{8}$-in. ball	30
45W	$\frac{1}{8}$-in. ball	45

Measurement of Hardness
Brinell Hardness

Single scale

Brinell hardness designation: (hardness reading) HB

10-mm sphere
of steel or
tungsten carbide

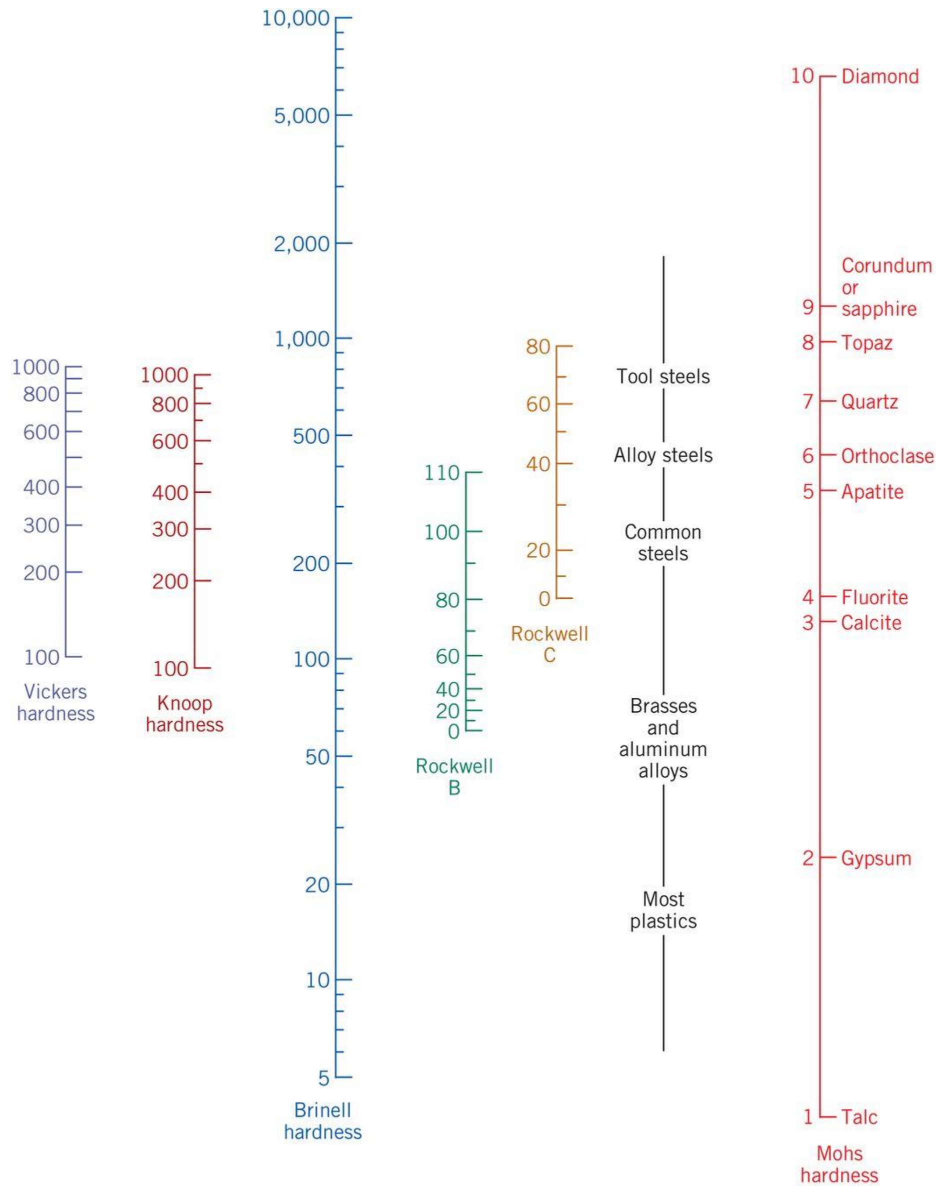


$$HB = \frac{2P}{\pi D[D - \sqrt{D^2 - d^2}]}$$

- P = load (kg)
- 500 kg ≤ P ≤ 3000 kg (500 kg increments)

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

COMPARISON OF VARIOUS HARDNESS SCALES



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