Mechanical Properties

ISSUES TO ADDRESS...

- Stress and strain: Normalized force and displacements. What are they? Why not use *load* and elongation/*deformation*?

$$\sigma = F / A_0 \qquad \varepsilon = \Delta\ell / \ell_0$$

- Elastic behavior: When loads are small, how much deformation occurs? What materials deform least?

$$Young's\ Modulus: \quad E \quad [GPa]$$

- Plastic behavior: At what point do *dislocations* cause *permanent deformation*? What materials are most resistant to permanent deformation?

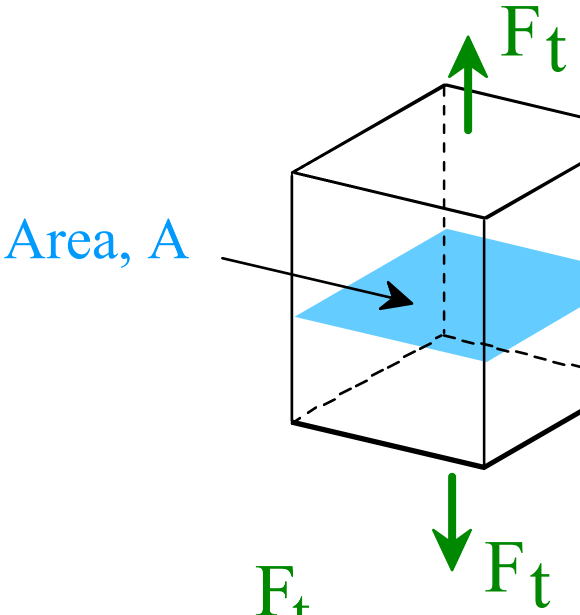
$$Yield\ Strength: \quad \sigma_{YS} \quad [GPa]\,(permanent\ deformation)$$

$$Ulitmate\ Tensile\ Strength: \quad \sigma_{TS} \quad [GPa]\,(fracture)$$

- Toughness and ductility: What are they and how do we measure them?

Engineering Stress

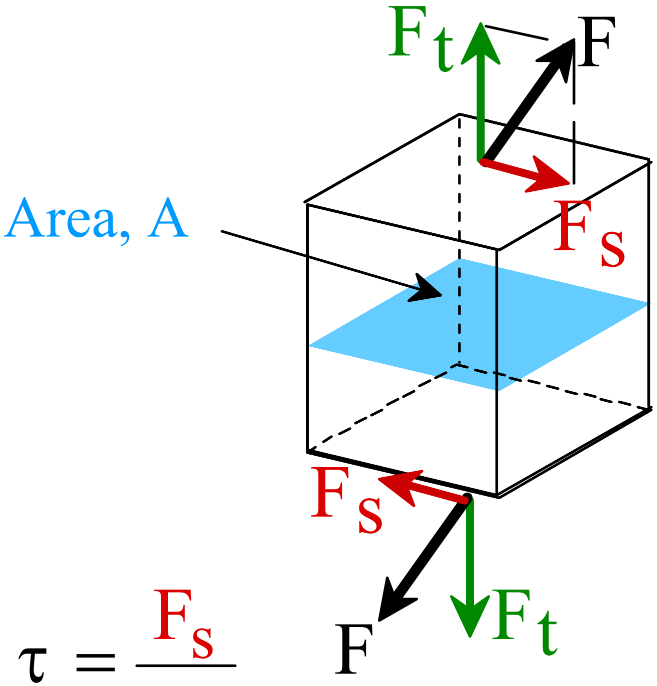
- Tensile stress, σ:



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

original area
before loading

- Shear stress, τ:

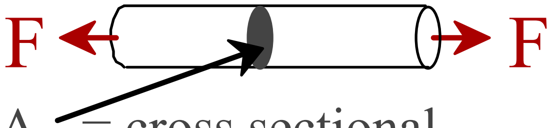


$$\tau = \frac{F_s}{A_o}$$

Stress has units:
N/m^2 (or lb$_f$/in^2)

Common States of Stress

- Simple tension: cable



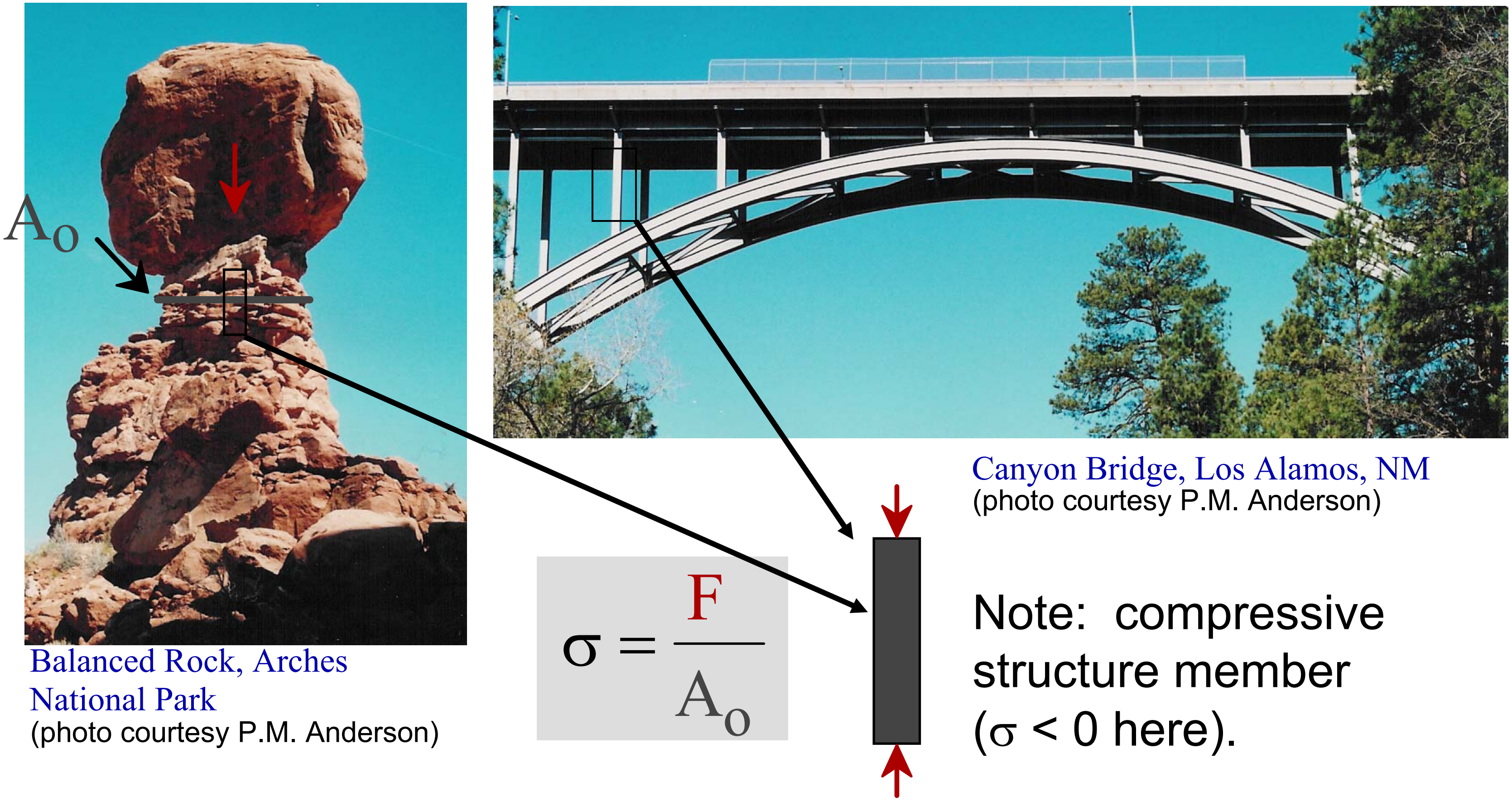
A_o = cross sectional Area (when unloaded)

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

Ski lift (photo courtesy P.M. Anderson)

Common States of Stress

- Simple compression:



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

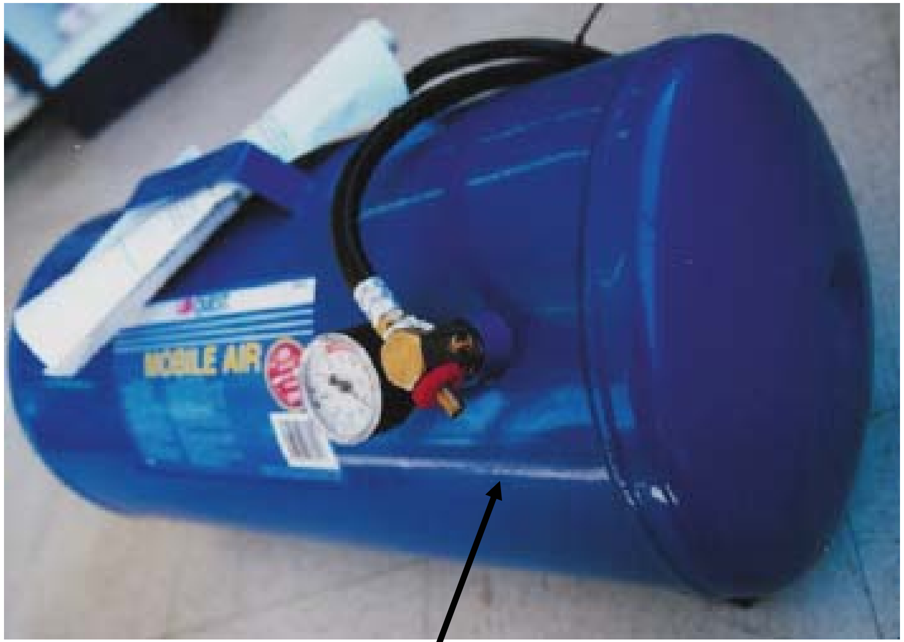
Canyon Bridge, Los Alamos, NM
(photo courtesy P.M. Anderson)

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

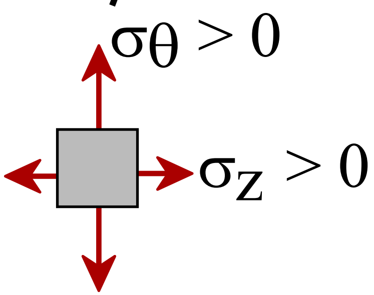
Note: compressive structure member ($\sigma < 0$ here).

Common States of Stress

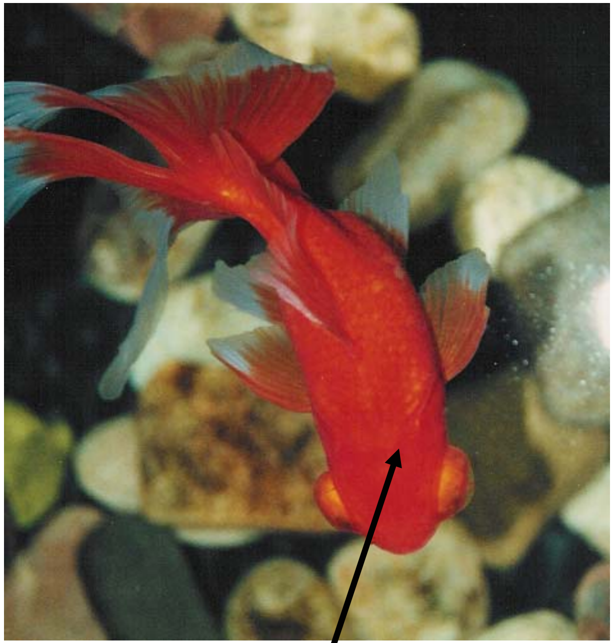
- Bi-axial tension:



Pressurized tank
(photo courtesy
P.M. Anderson)

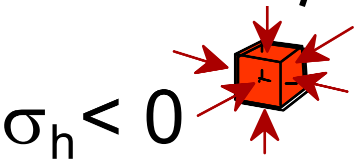


- Hydrostatic compression:



Fish under water

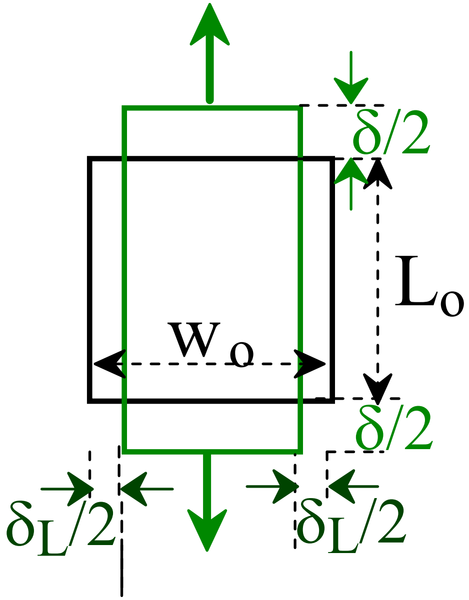
(photo courtesy
P.M. Anderson)



Engineering Strain

- Tensile strain:

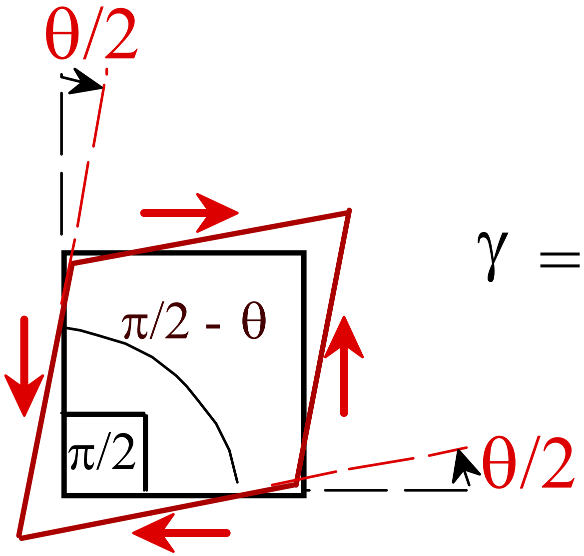
$$\varepsilon = \frac{\delta}{L_o}$$



- Lateral (width) strain:

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

- Shear strain:

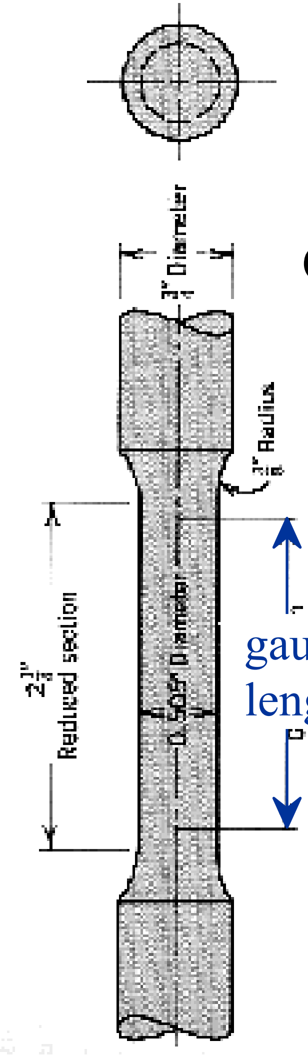


$$\gamma = \tan\,\theta$$

Strain is always dimensionless.

Strain Testing

- Tensile specimen

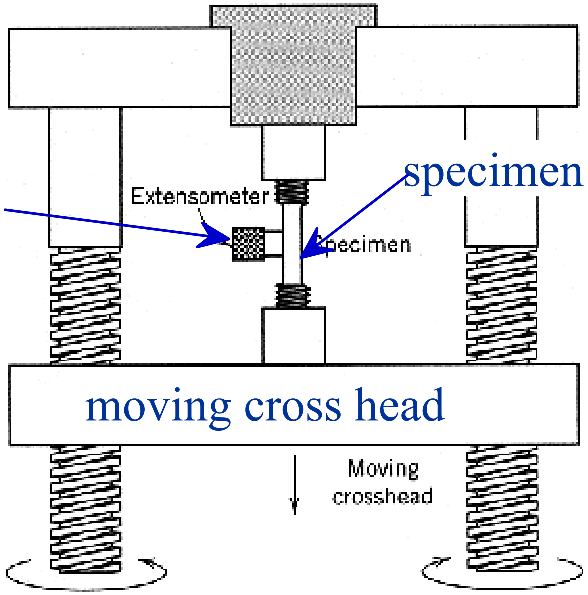


Adapted from Fig. 6.2, *Callister 6e.*

Often 12.8 mm x 60 mm

gauge length = (portion of sample with reduced cross section)

- Tensile test machine



load cell

extensometer

specimen

moving cross head

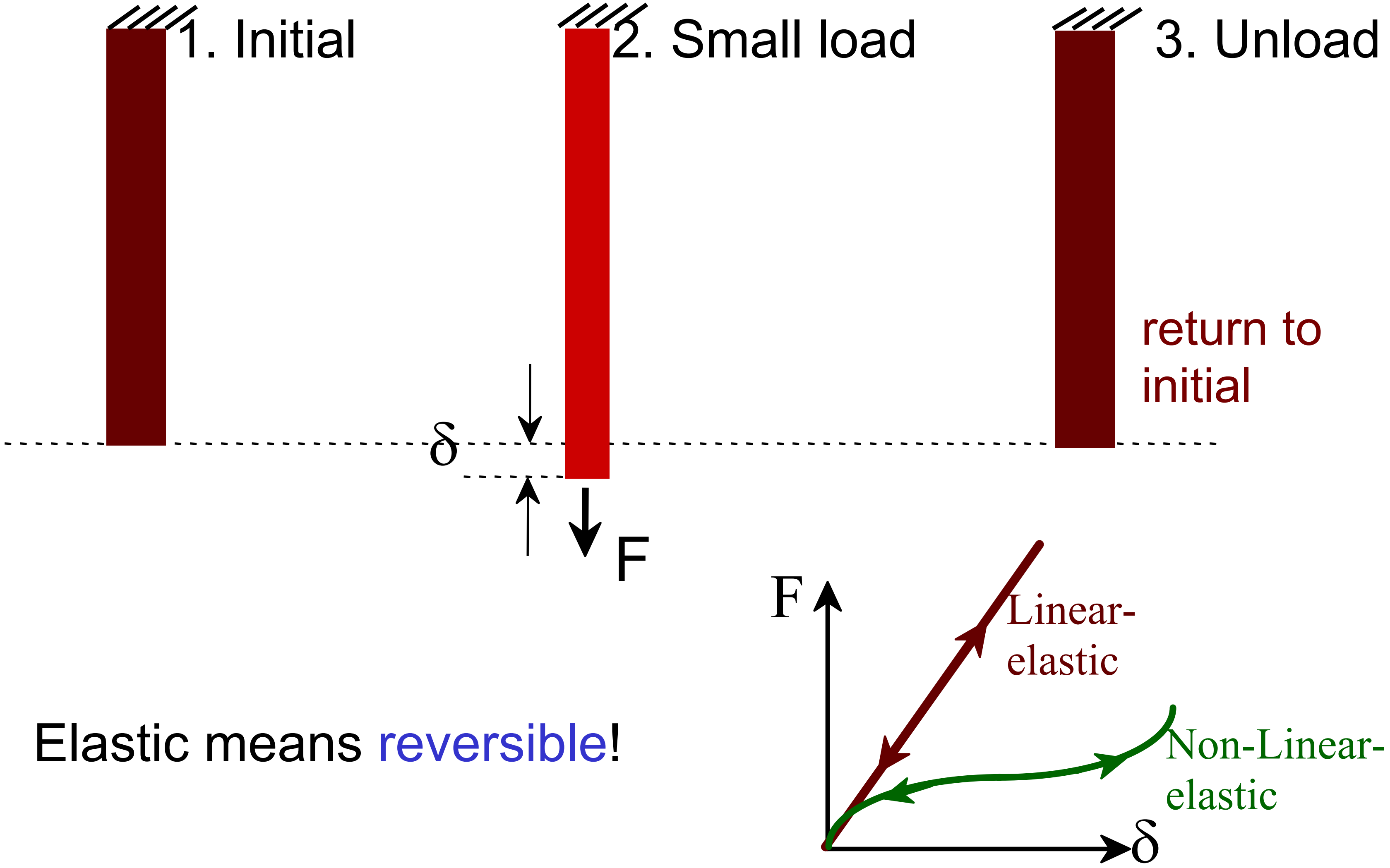
Adapted from Fig. 6.3, *Callister 6e.*

- Other types:

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

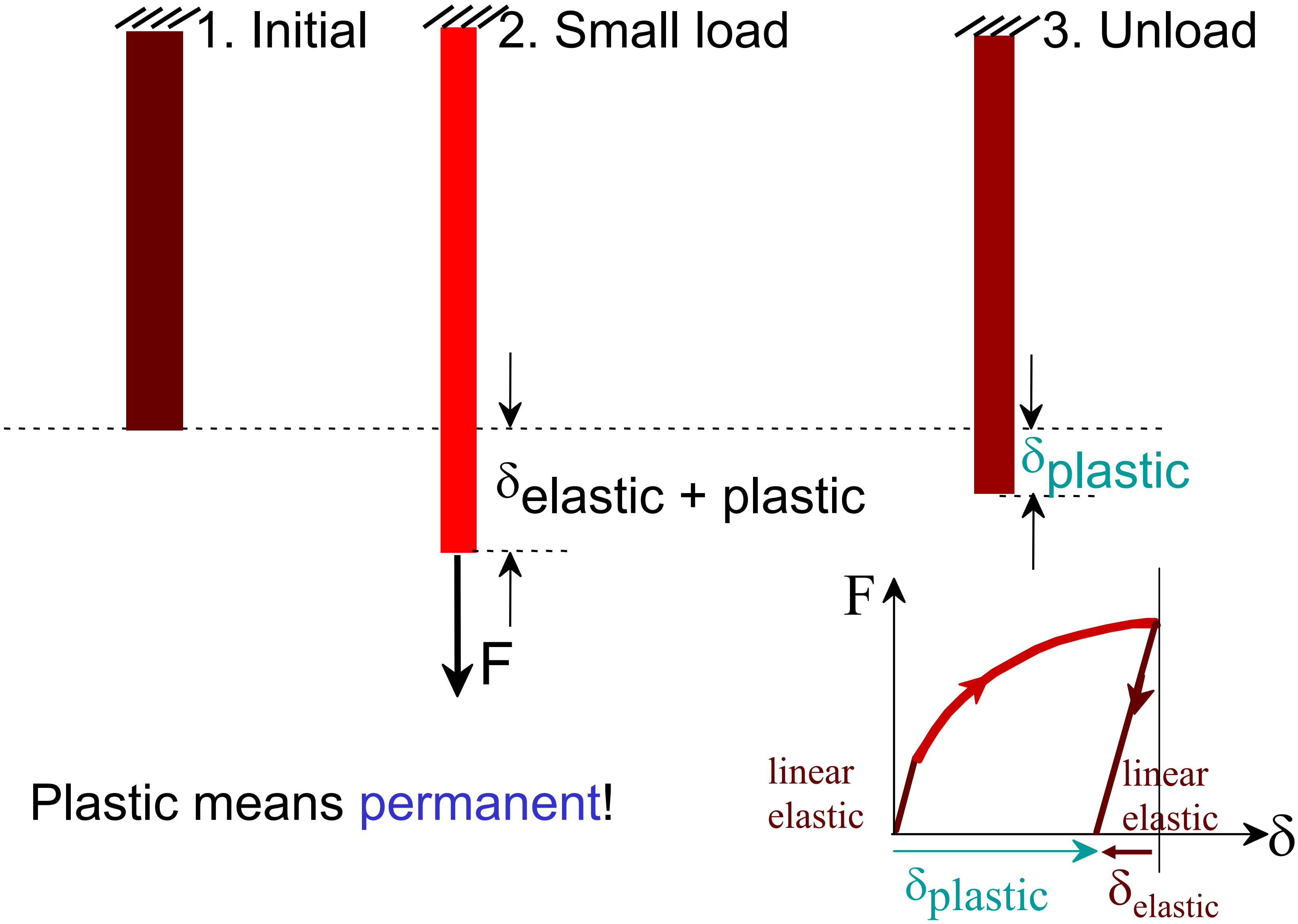
  -torsion: cylindrical tubes, shafts.

Elastic Deformation



Elastic means reversible!

Plastic Deformation

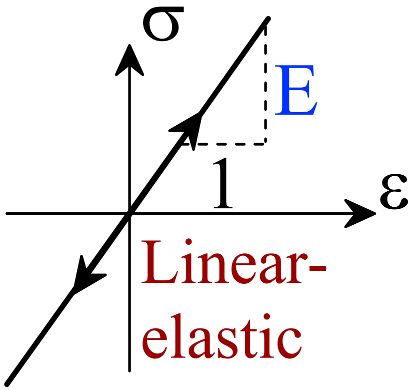


Plastic means permanent!

Linear Elasticity

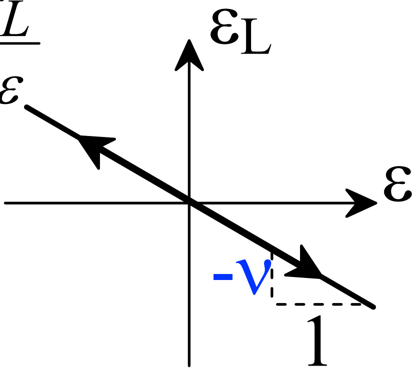
- Modulus of Elasticity, E:
  (also known as Young's modulus)

- Hooke's Law: $\sigma = E\,\varepsilon$

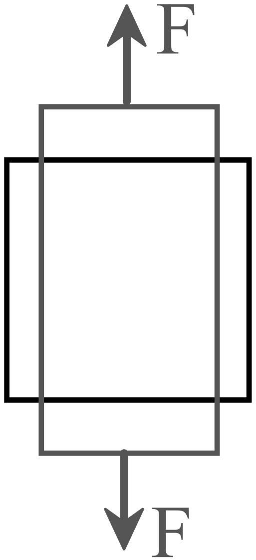


- Poisson's ratio, ν:

$$\nu = -\frac{width\ strain}{axial\ strain} = -\frac{\Delta w / w}{\Delta \ell / \ell} = -\frac{\varepsilon_L}{\varepsilon}$$



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

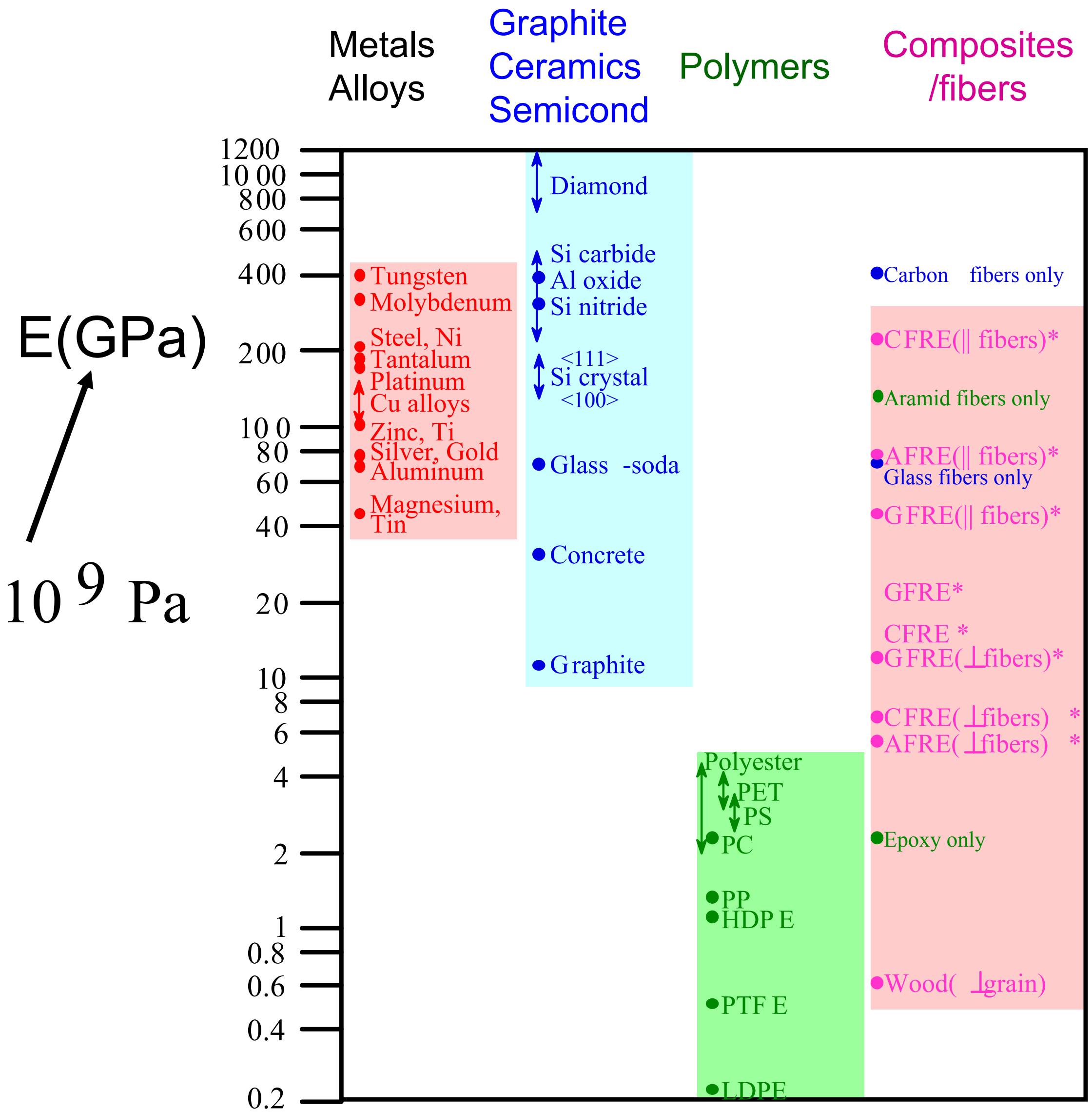


simple
tension
test

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

Why does ν have minus sign?

Young’s Modulus, E



$E_{ceramics}$

$> E_{metals}$

$>> E_{polymers}$

Based on data in Table B2, *Callister 6e*.

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

Poisson Ratio: materials specific

Metals:	Ir	W	Ni	Cu	Al	Ag	Au
	0.26	0.29	0.31	0.34	0.34	0.38	0.42

generic value ~ 1/3

Solid Argon: 0.25

Covalent Solids:	Si	Ge	Al_2O_3	TiC
	0.27	0.28	0.23	0.19

generic value ~ 1/4

Ionic Solids: MgO 0.19

Silica Glass: 0.20

Polymers: Network (Bakelite) 0.49 Chain (PE) 0.40

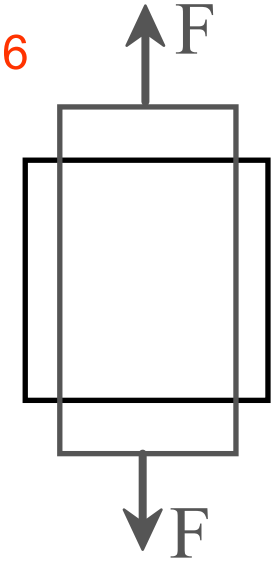
Elastomer: Hard Rubber (Ebonite) 0.39 (Natural) 0.49

Example: Hooke's Law

- Hooke's Law: $\sigma = E\,\varepsilon$

Copper sample (305 mm long) is pulled in tension with stress of 276 MPa. If deformation is elastic, what is elongation?

For Cu, E = 110 GPa.



simple tension test

$$\sigma = E\varepsilon = E\left(\frac{\Delta\ell}{\ell_0}\right) \quad \Rightarrow \quad \Delta\ell = \frac{\sigma\ell_0}{E}$$

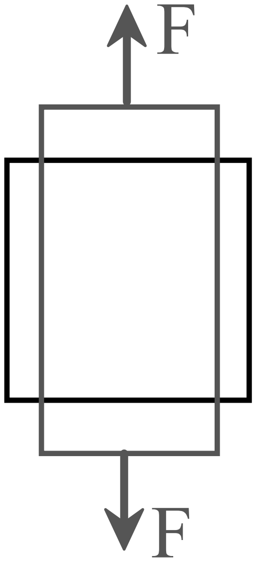
$$\Delta\ell = \frac{(276 MPa)(305 mm)}{110x10^3 MPa} = 0.77 mm$$

Hooke's law involves axial (parallel to applied tensile load) elastic deformation.

Example: Poisson Effect

Tensile stress is applied along cylindrical brass rod (10 mm diameter). Poisson ratio is $\nu = 0.34$ and $E = 97$ GPa.

- Determine load needed for 2.5×10^{-3} mm change in diameter if the deformation is entirely elastic?



simple tension test

Width strain: (note reduction in diameter)

$$\varepsilon_x = \Delta d/d = -(2.5\times10^{-3}\text{ mm})/(10\text{ mm}) = -2.5\times10^{-4}$$

Axial strain: Given Poisson ratio

$$\varepsilon_z = -\varepsilon_x/\nu = -(-2.5\times10^{-4})/0.34 = +7.35\times10^{-4}$$

Axial Stress: $\sigma_z = E\varepsilon_z = (97\times10^3\text{ MPa})(7.35\times10^{-4}) = 71.3$ MPa.

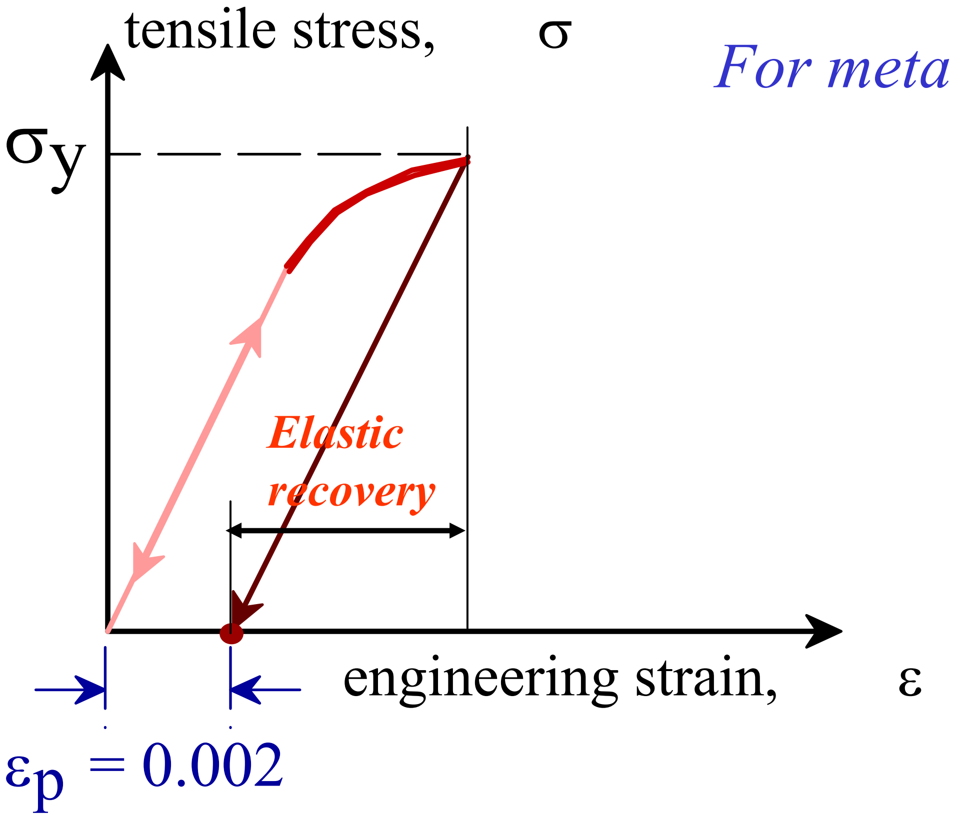
Required Load: $F = \sigma_z A_0 = (71.3\text{ MPa})\pi(5\text{ mm})^2 = 5600$ N.

Yield Strength, σ_{YS}

- Stress where *noticeable* plastic deformation occurs.

when $\varepsilon_p = 0.002$

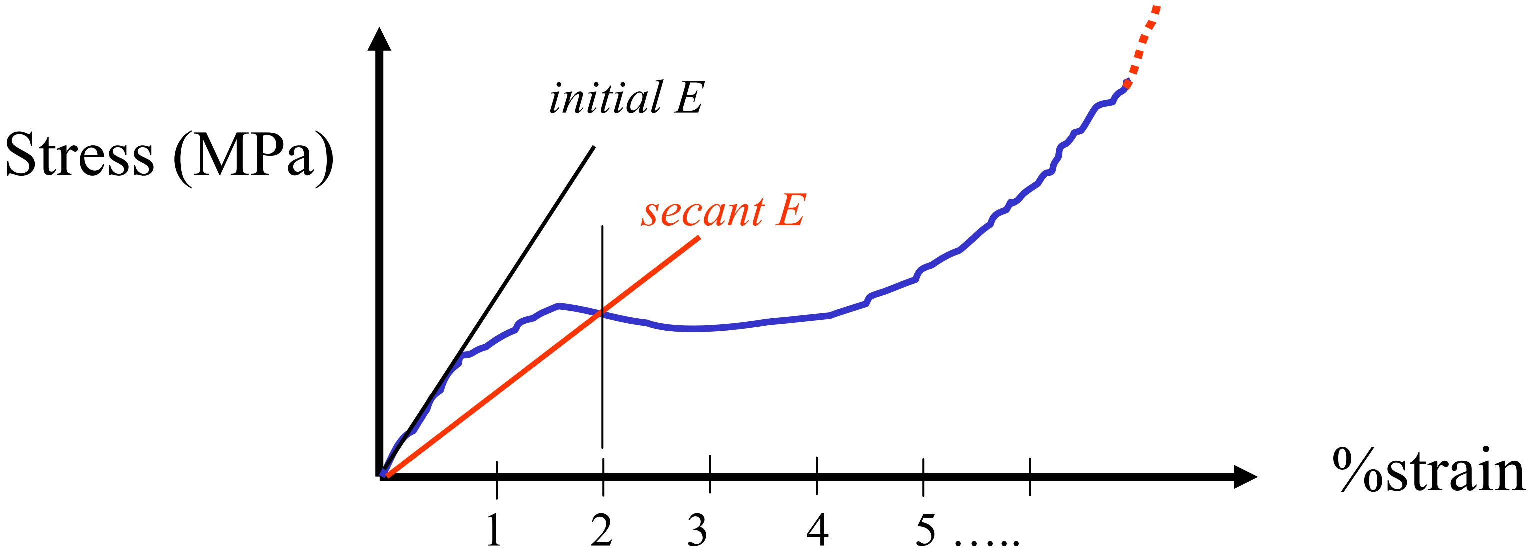
For metals agreed upon 0.2%



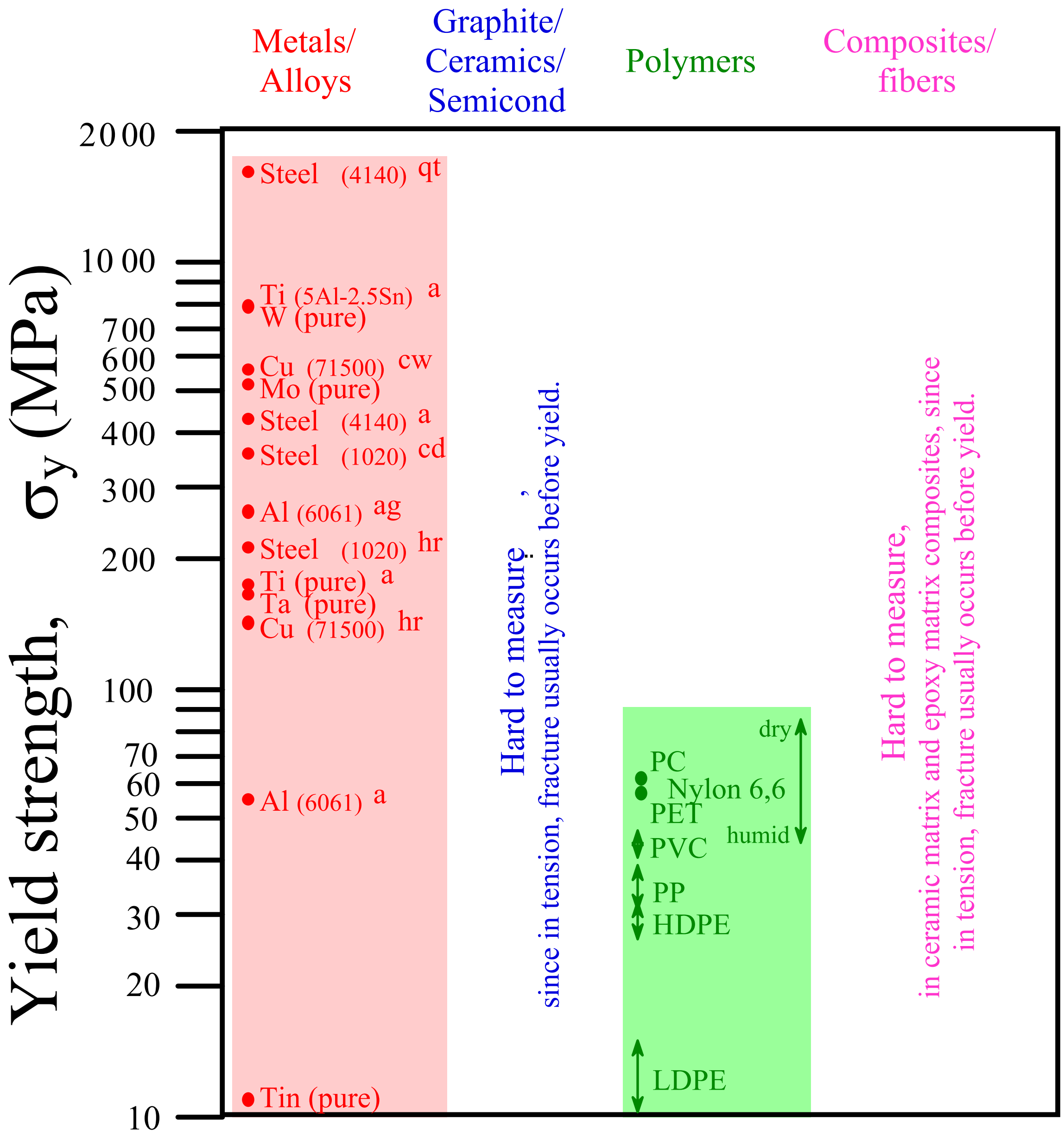
Polymers: Secant Modulus

- Secant Modulus is effective modulus at 2% strain.

- Modulus of polymer changes with *time* and *strain-rate*.
  - must report strain-rate $d\varepsilon/dt$ for polymers.
  - must report fracture strain ε_f **before** fracture.



Compare Yield Strength, σ_{YS}



σ_y(ceramics)

$>>\sigma_y$(metals)

$>>\sigma_y$(polymers)

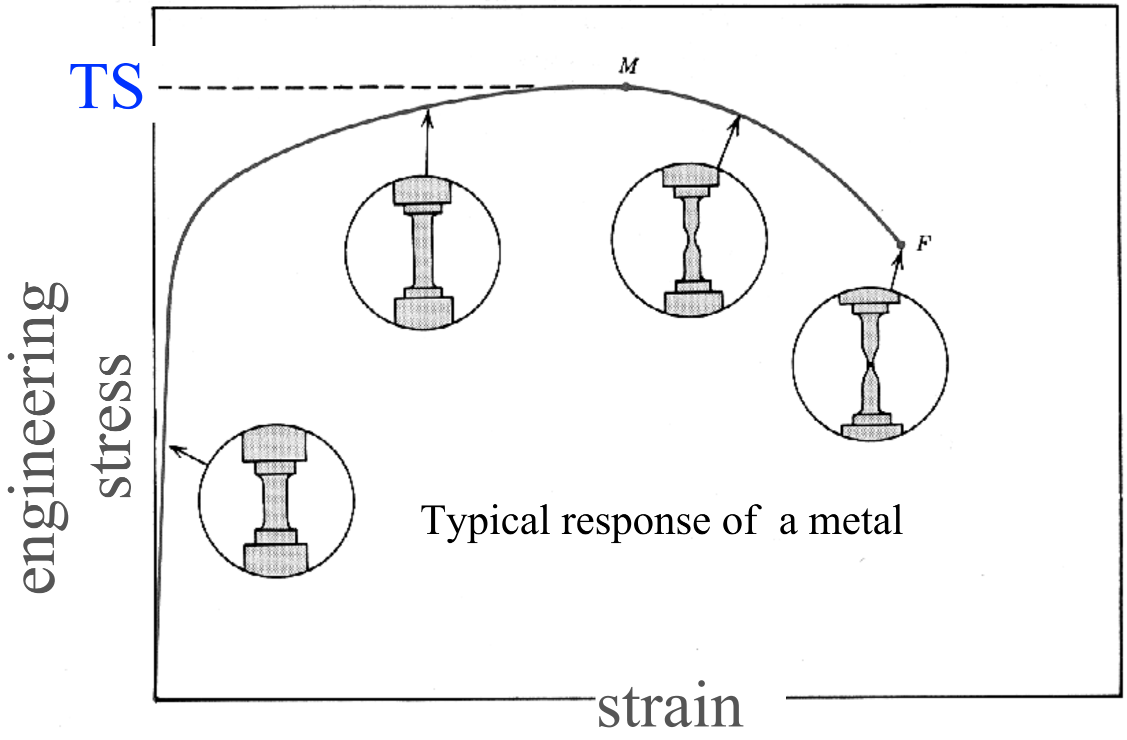
Room T values

Based on data in Table B4, *Callister 6e*.

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

(Ultimate) Tensile Strength, σ_{TS}

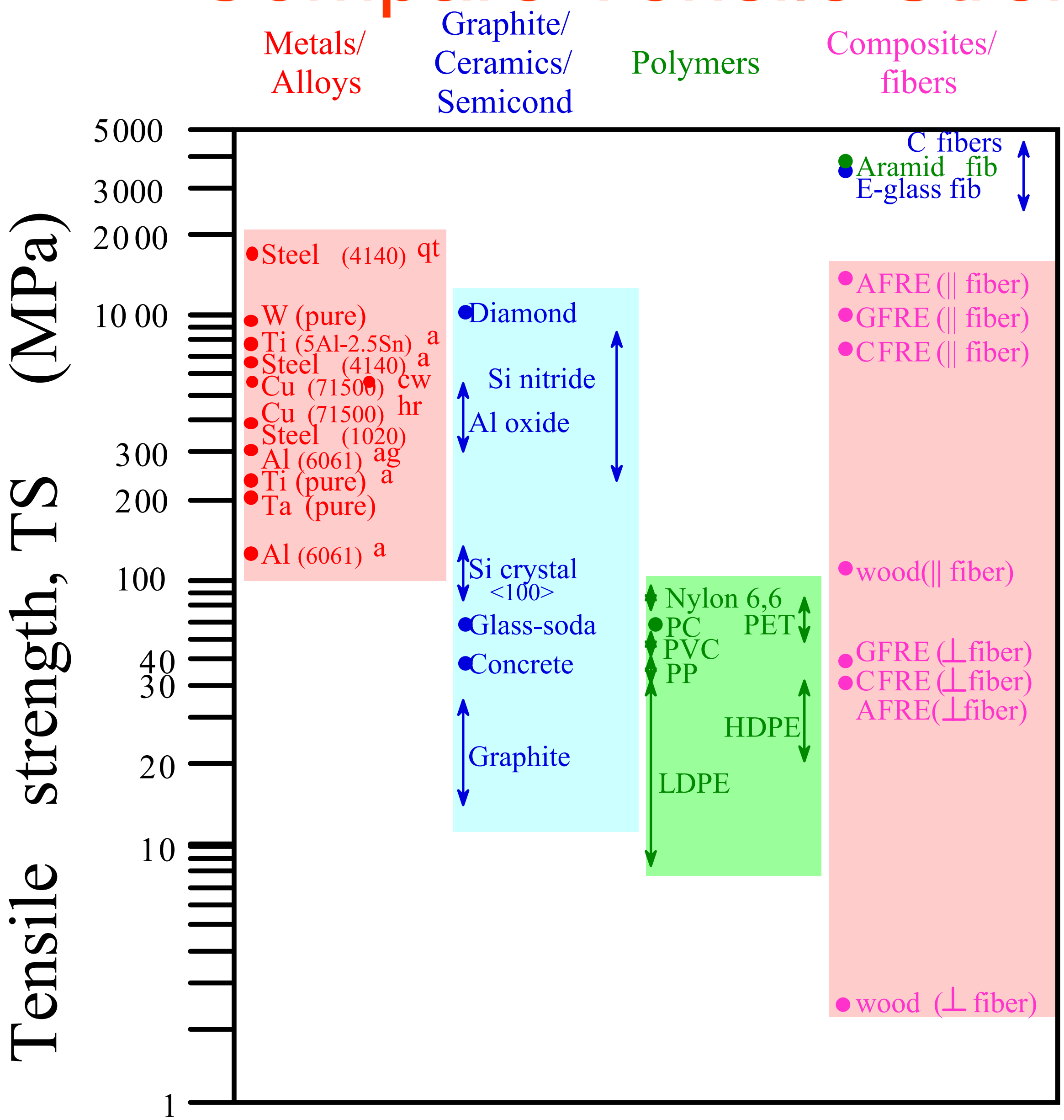
- Maximum possible engineering stress in tension.



Adapted from Fig. 6.11, *Callister 6e.*

- Metals: occurs when necking starts.
- Ceramics: occurs when crack propagation starts.
- Polymers: occurs when polymer backbones are aligned and about to break.

Compare Tensile Strength, σ_{TS}



TS (ceram)

~TS (met)

~ TS (comp)

>> TS (poly)

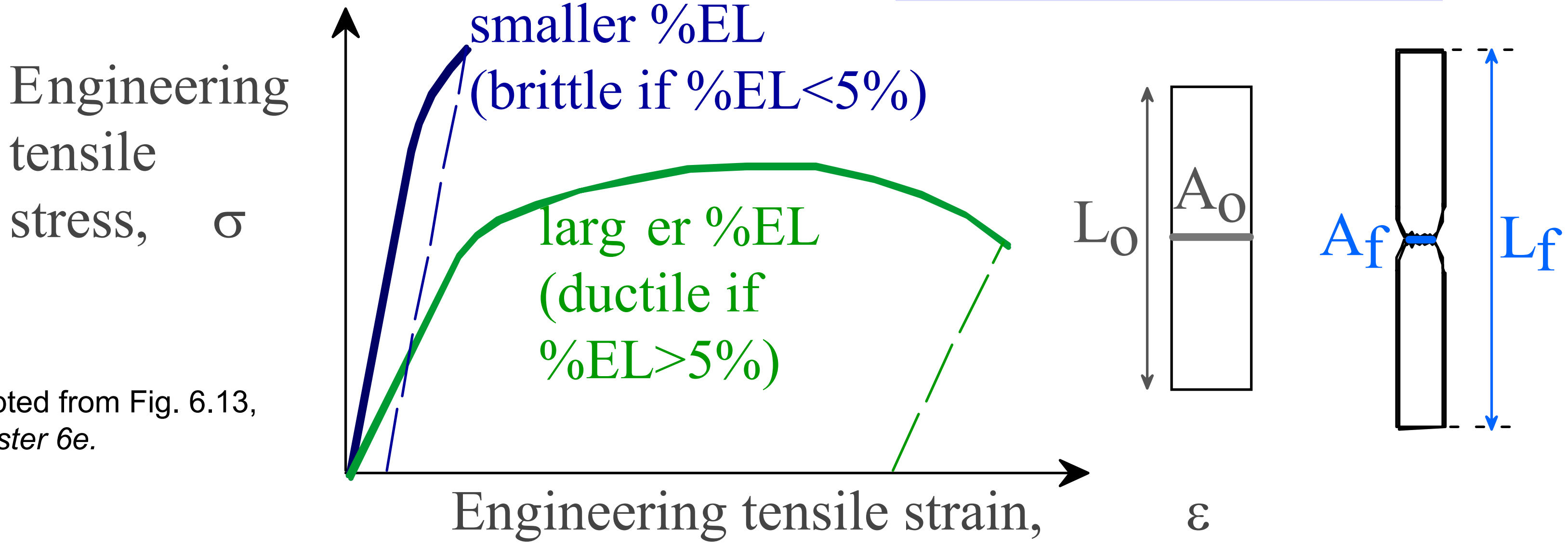
Room T values

Based on data in Table B4, *Callister 6e*.

Ductility or %EL

- Plastic tensile strain at failure:

$$\%EL = \frac{L_f - L_o}{L_o} x100$$



Adapted from Fig. 6.13, *Callister 6e.*

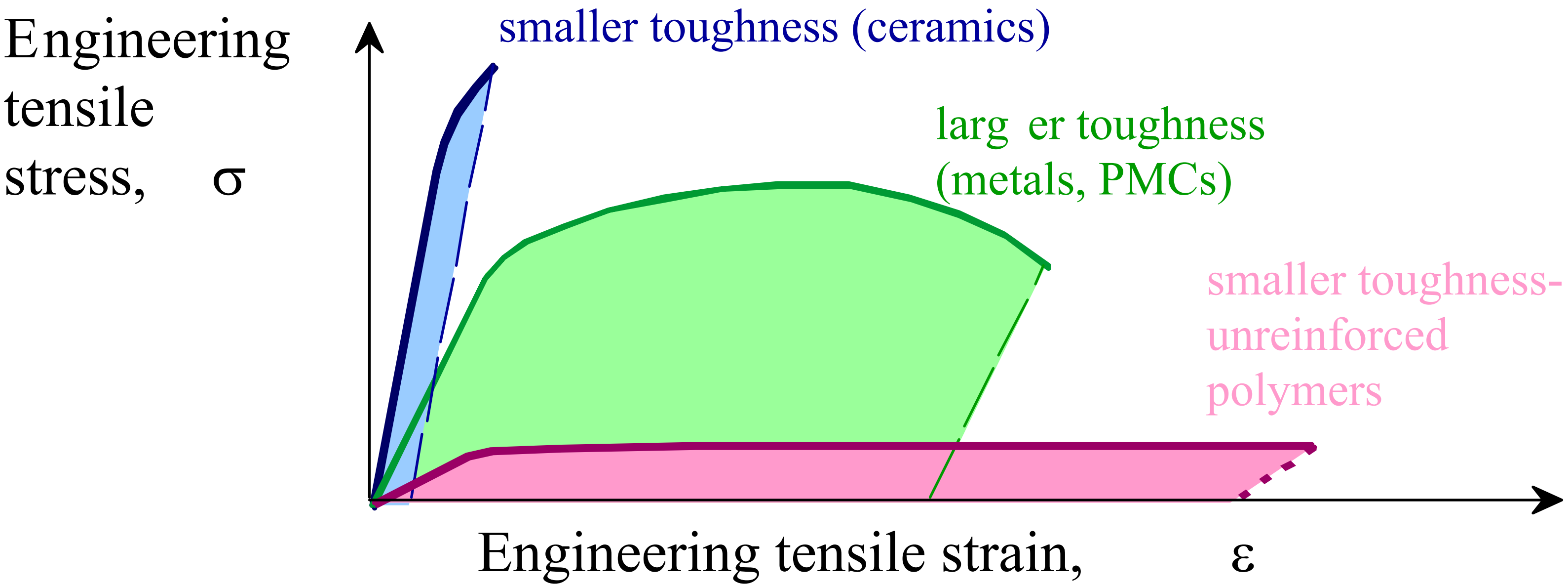
- Another ductility measure:

$$\%AR = \frac{A_o - A_f}{A_o} x100$$

- Note: %AR and %EL are often comparable.
  - Reason: crystal slip does not change material volume.
  - %AR > %EL possible if internal voids form in neck.

Toughness

- Energy to break a unit volume of material,
  or absorb energy to fracture.
- Approximate as area under the stress-strain curve.



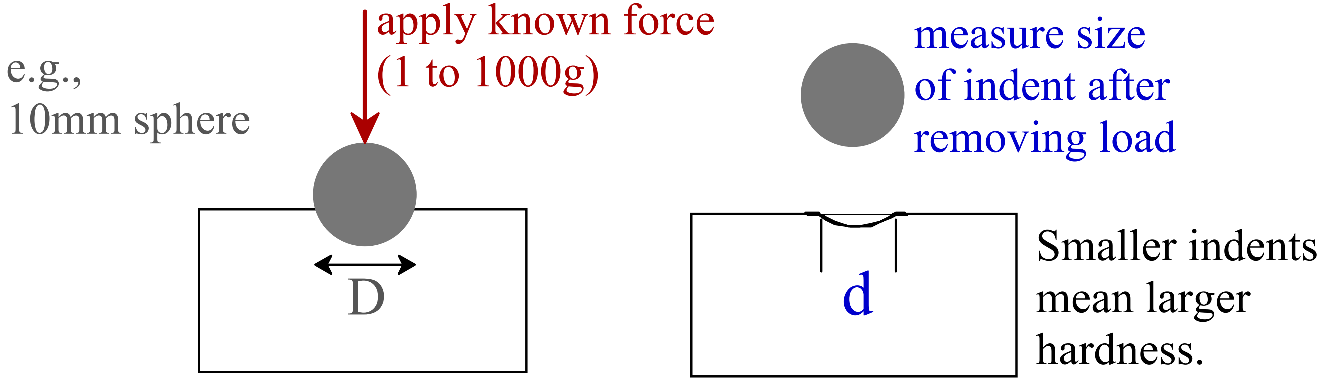
Resilience is capacity to absorb energy when deformed *elastically* and *recover* all energy when unloaded.

Hardness

- Resistance to permanently indenting the surface.
- Large hardness means:

  --resistance to plastic deformation or cracking in compression.

  --better wear properties.



e.g., 10mm sphere

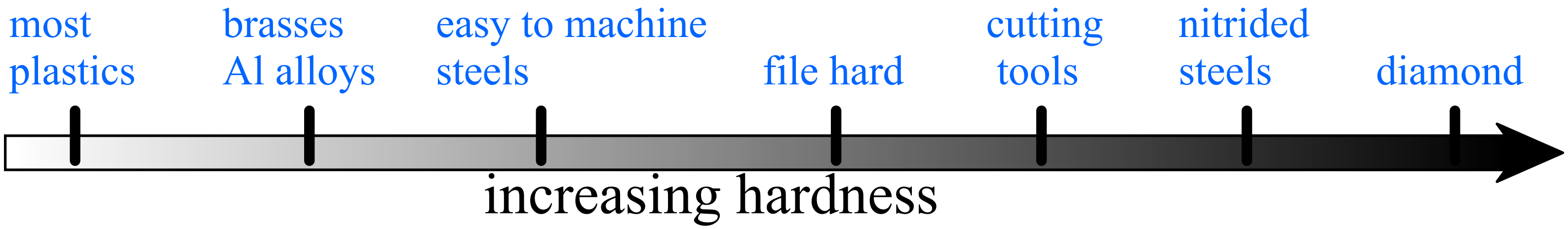
apply known force (1 to 1000g)

D

measure size of indent after removing load

d

Smaller indents mean larger hardness.



most plastics

brasses Al alloys

easy to machine steels

file hard

cutting tools

nitrided steels

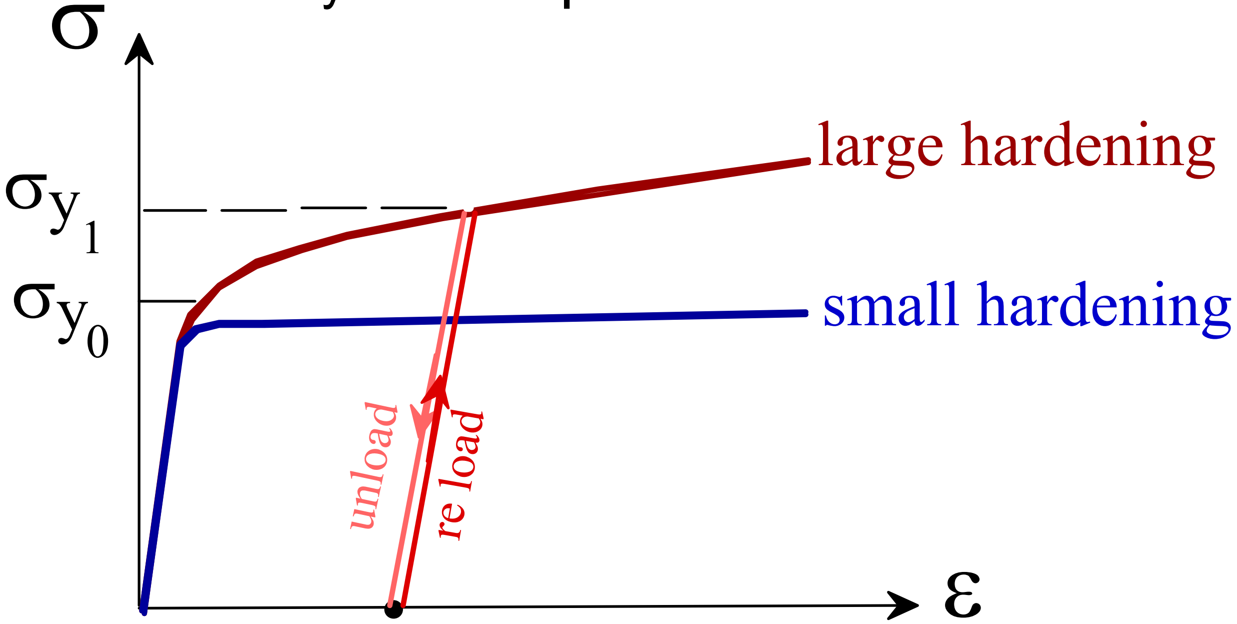
diamond

increasing hardness

Adapted from Fig. 6.18, *Callister 6e.*

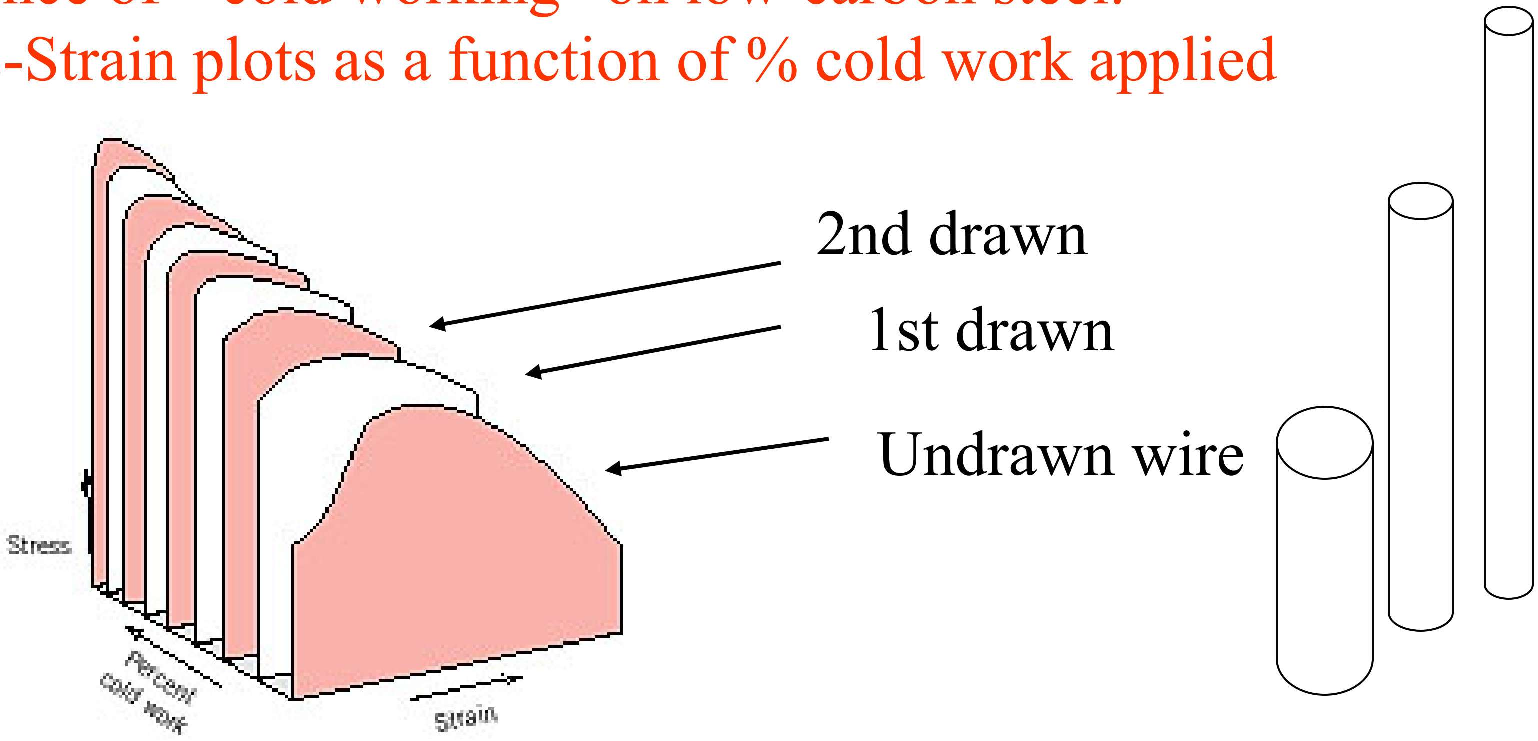
Hardening

- An increase in σ_y due to plastic deformation.



Using Work-Hardening

Influence of “cold working” on low-carbon steel.
Stress-Strain plots as a function of % cold work applied



Processing: Forging, Rolling, Extrusion, Drawing,…

- Each draw of the wire *decreases* ductility, *increases* YS.
- Use drawing to strengthen and thin “aluminum” soda can.

Design Safety Factors

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

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

Often N is between 1.2 and 4

- Ex: Calculate diameter, d, to ensure that no yielding occurs in the 1045 carbon steel rod for an applied load of 220 kN. Use safety factor of 5.

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

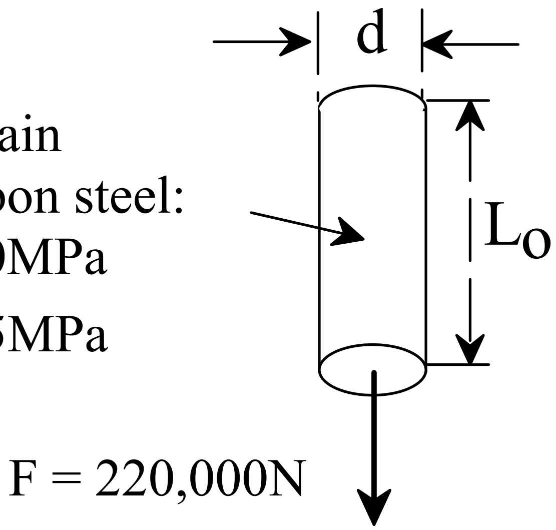
$$\boxed{\frac{220,000N}{\pi\left(d^2/4\right)}}$$

5

1045 plain carbon steel:

σ_y=310MPa

TS=565MPa



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 σy.
- Toughness: The energy needed to break a unit volume of material.
- Ductility: The plastic strain at failure.

Viscoelastic Behaivor of Polymers

Perfectly elastic (Hookean)

$$\sigma = \text{constant} \times \varepsilon$$

(Energy stored, it can be recovered, e.g. metals.)
(Some thermosets like epoxies exhibit close to linear elastic behavior.)

Perfectly viscous (Newtonian)

$$\tau = \text{constant} \times \dot{\gamma}$$

(Energy completely dissipated, it can not be recovered, e.g. water.)

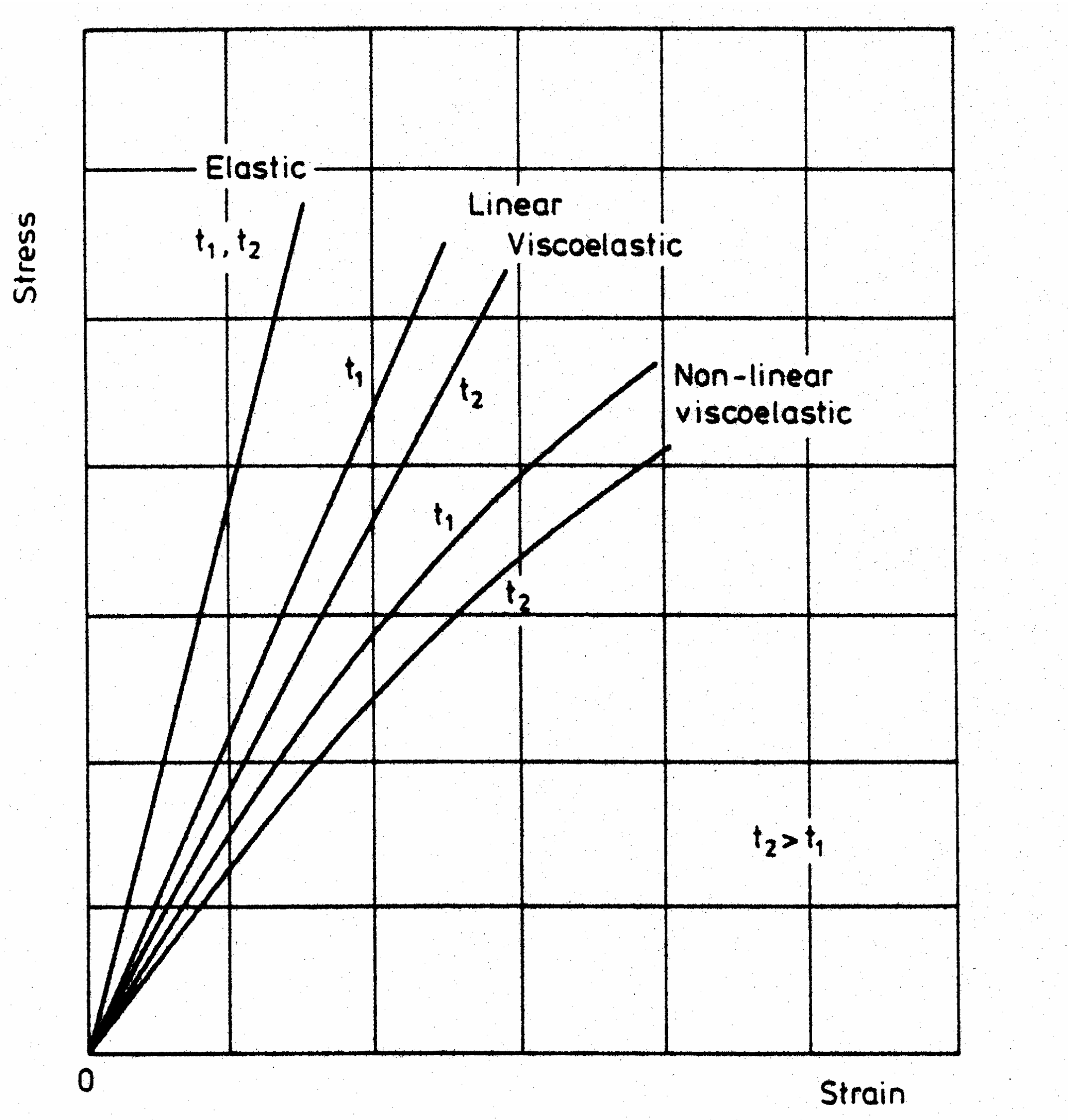
Viscoelastic

Non-linear viscoelasticity: $\sigma = f(\varepsilon, t)$

Linear viscoelasticity: $\sigma = \varepsilon \cdot f(t)$

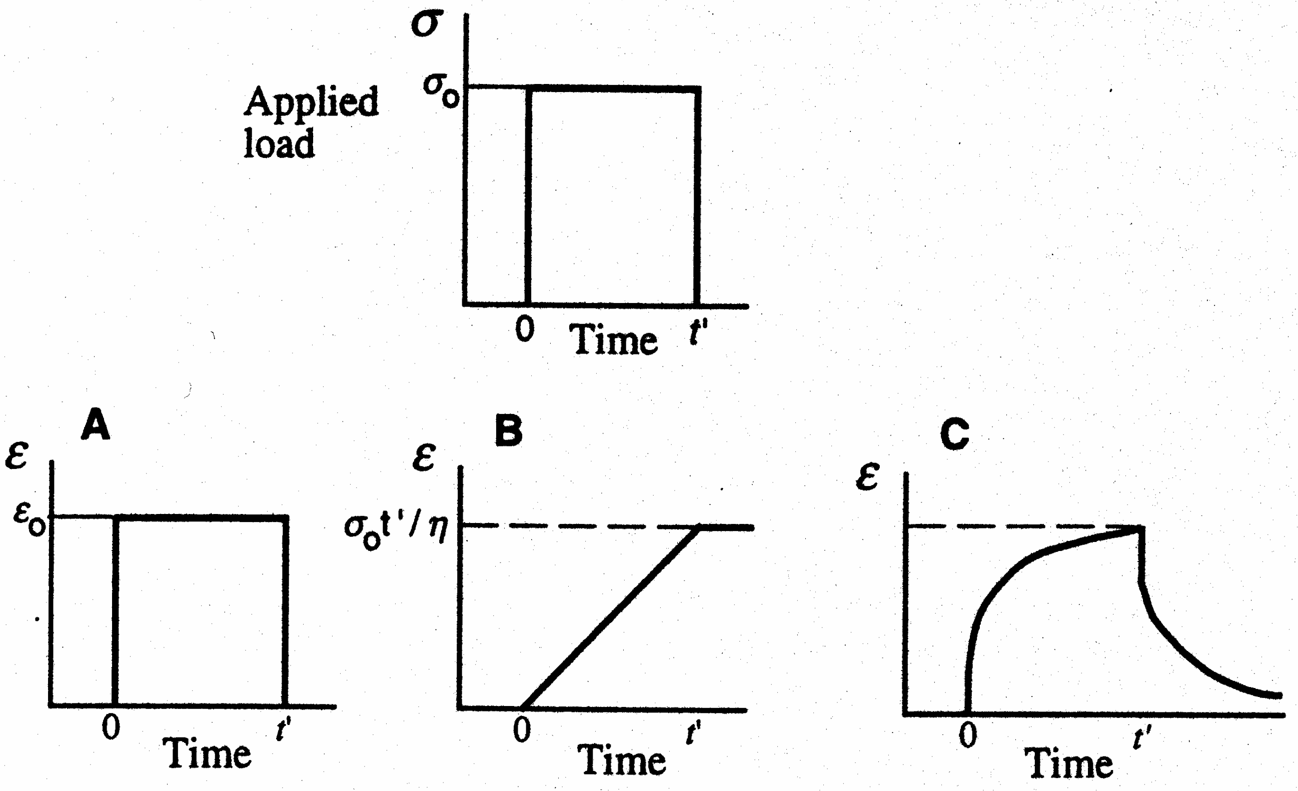
(For a fixed elapsed time, the stress is directly proportional to the strain, e.g. most polymers.)

Viscoelastic Behavior of Polymers (Cont.)



[Plastics Engineering, 2nd Ed., R. J. Crawford, Pergamon Press, Oxford, 1987]

Viscoelastic Behavior of Polymers (Cont.)



A, elastic; **B**, viscous; and **C**, viscoelastic

[Polymer Science and Technology, Joel R. Fried, Prentice Hall, Englewood Cliffs, 1995]

Viscoelastic Behavior of Polymers (Cont.)

The most characteristic features of viscoelastic materials are that they exhibit:

Creep: a time dependent strain response to a constant stress

and

Relaxation: a time dependent stress response to a constant strain

and

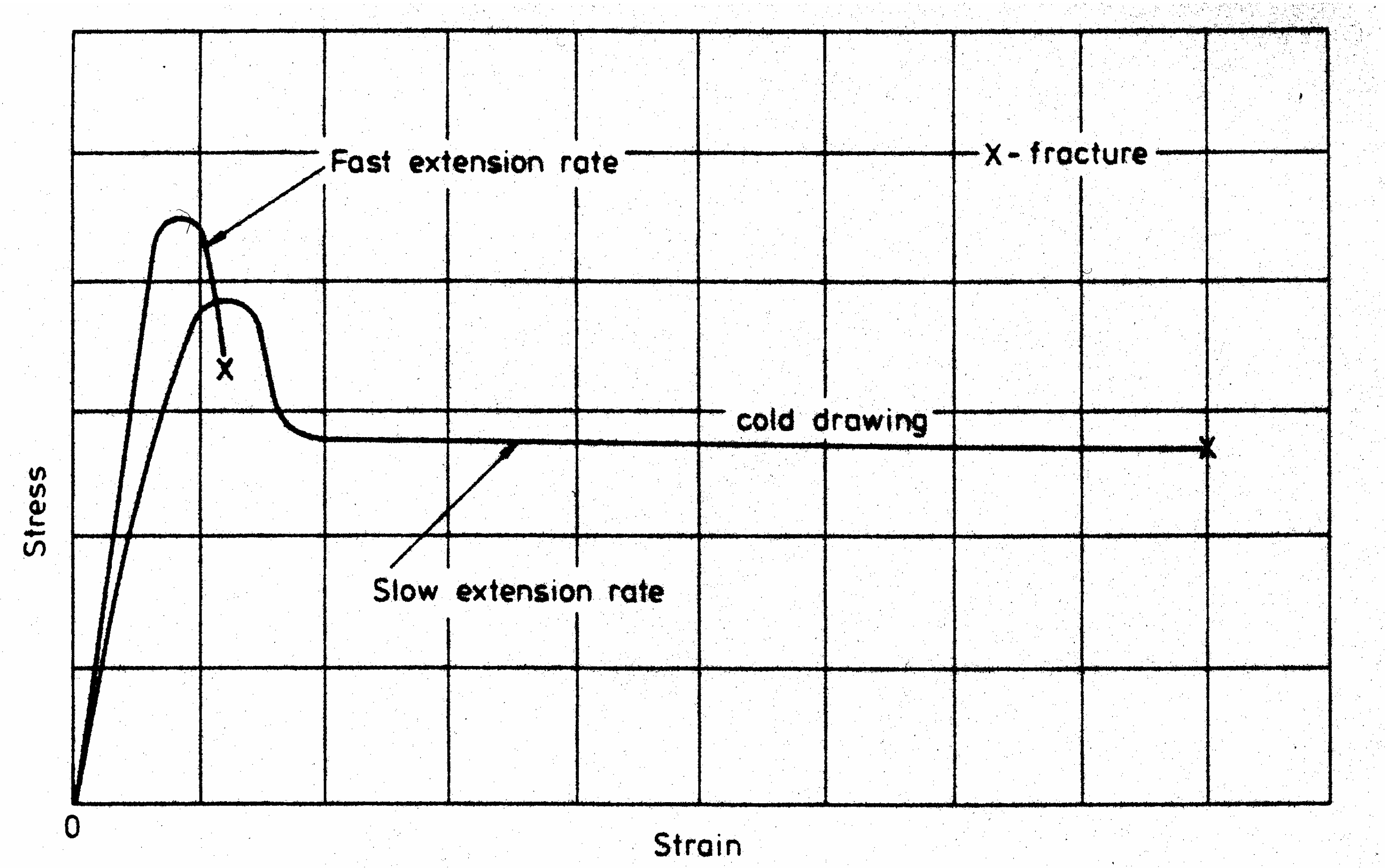
when the applied stress is removed the materials have the ability to recover slowly over a period of time.

These effects can also be observed in metals but the difference is that in plastics they occur at room temperature whereas in metals they only occur at very high temperatures

Short-Term Testing of Plastics

Results of a single short-term test should only be used as a means of quality control – not as design data

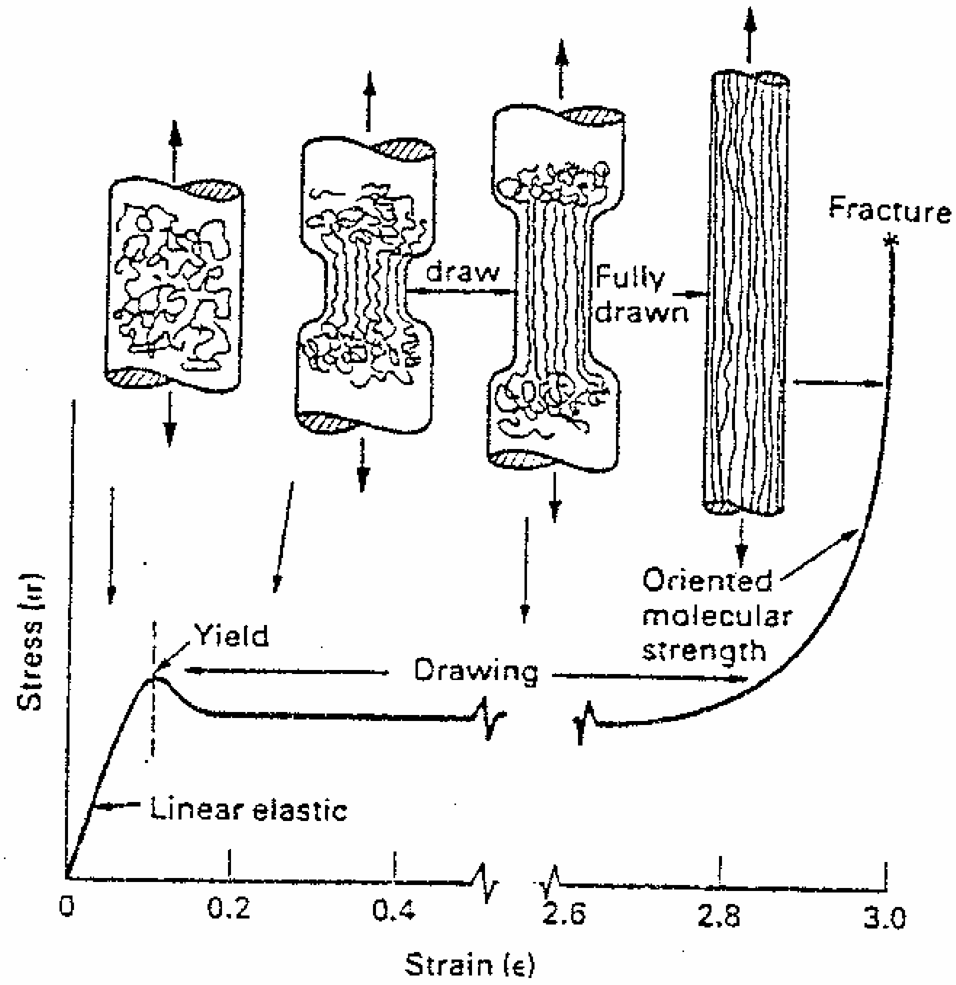
Typical tensile behavior of unplasticized PVC



Short-Term Testing of Plastics (Cont.)

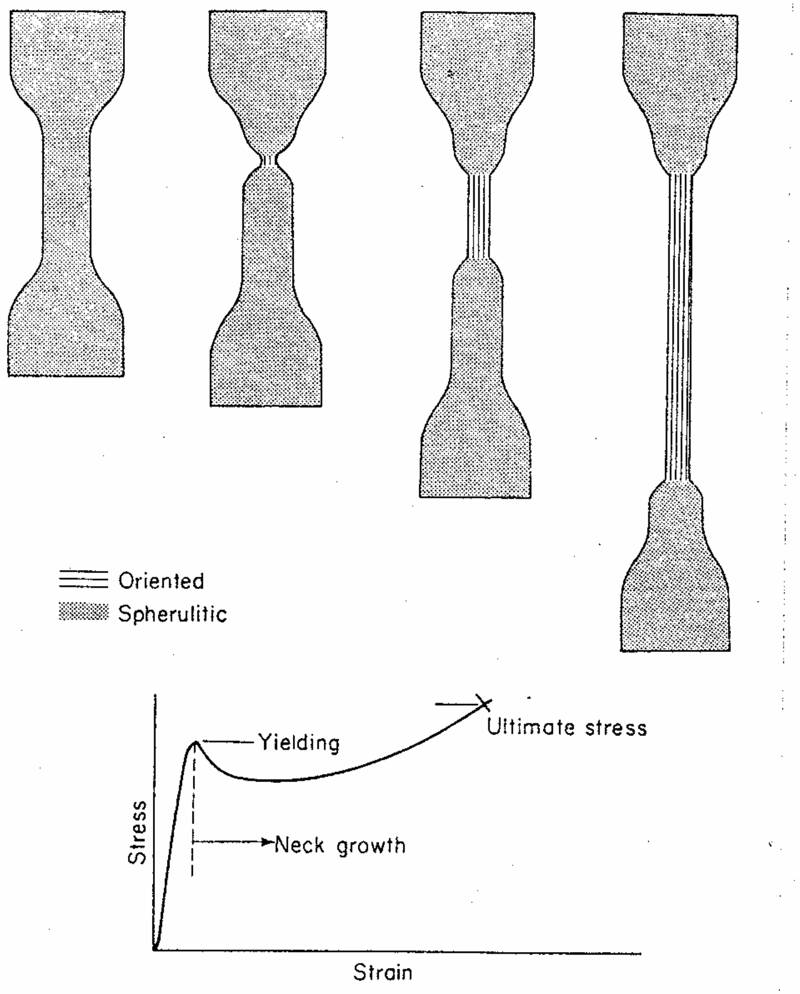
Cold drawing of an amorphous polymer

At low extension rates the molecular chains in the plastic have time to align themselves under the influence of the applied stress



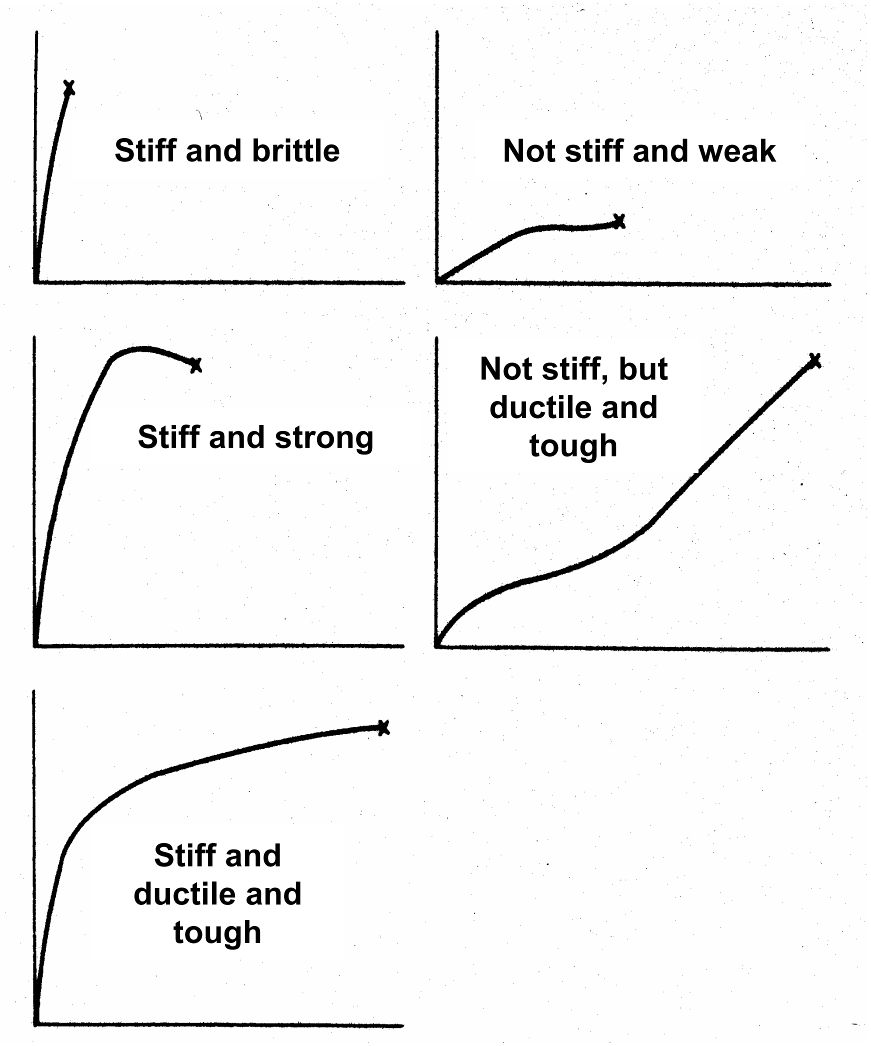
Short-Term Testing of Plastics (Cont.)

Cold drawing (Cont.) - Successive stages in the drawing (elongation) of a spherulitic (semi-crystalline) polymer



Short-Term Testing of Plastics (Cont.)

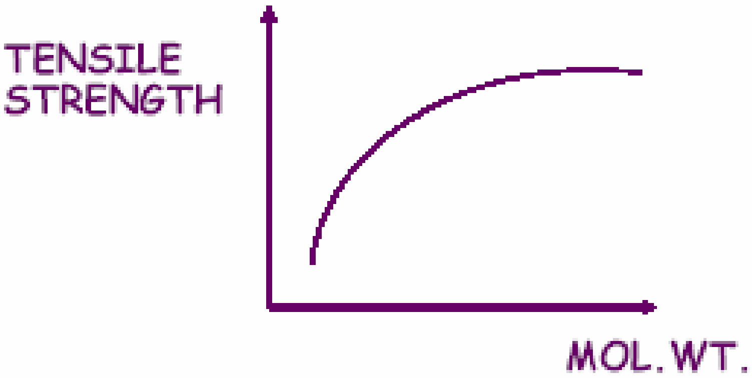
Types of stress-strain curves

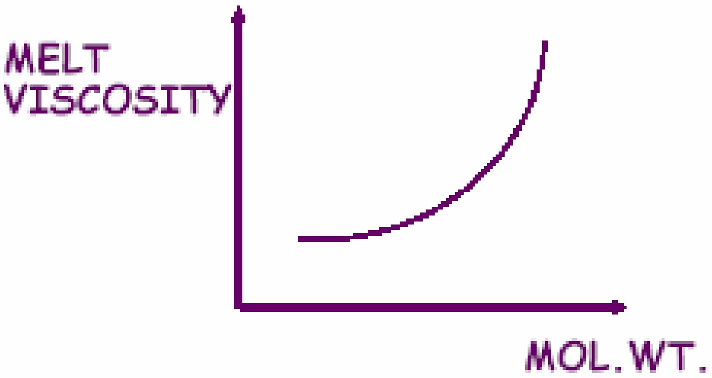


[Principles of Polymer Systems, 4th Ed., Ferdinand Rodriguez, Taylor & Francis, Washington, 1996]

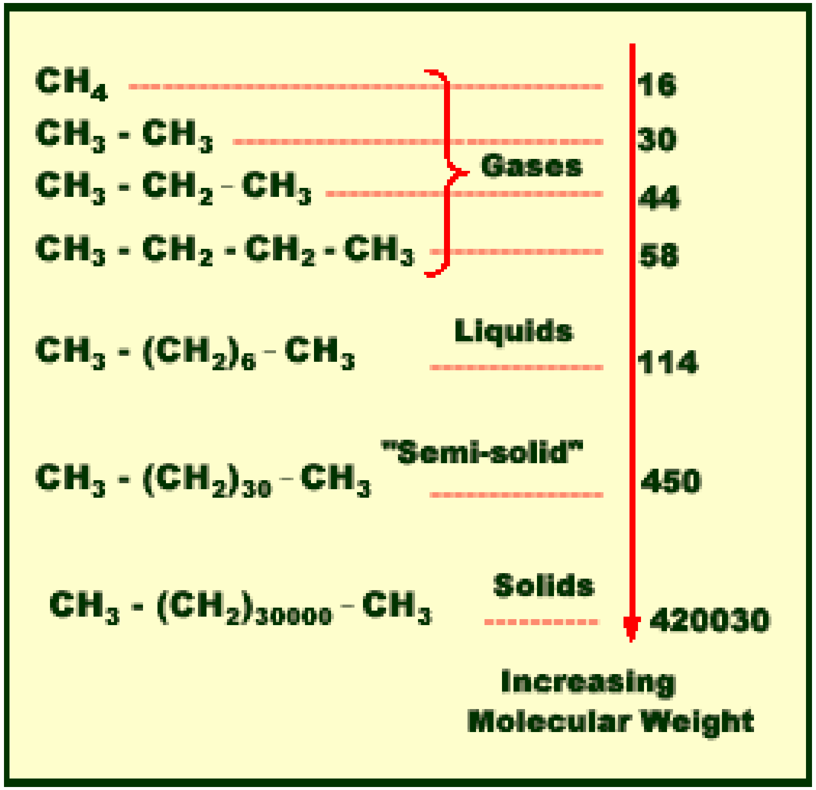
Effect of Molecular Weight of Polymers on Their Strength

There is no direct effect but for many polymers it has been observed that tensile strength increases with M_w.





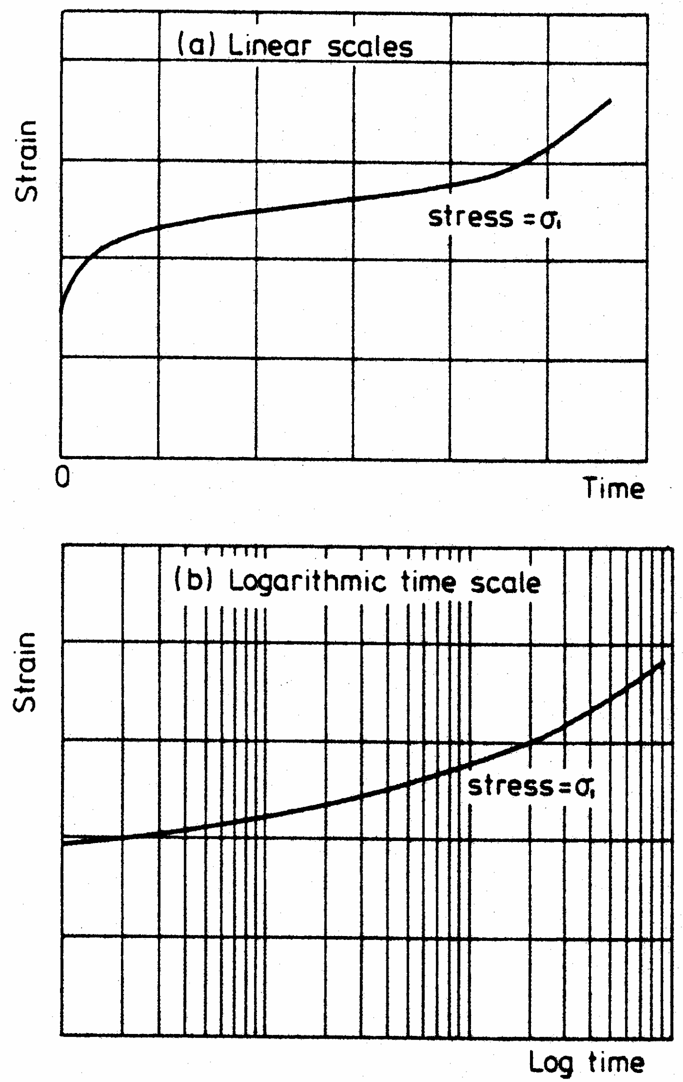
Molecular Weight of Polymers



States at room temperature.

Long-Term Testing of Plastics

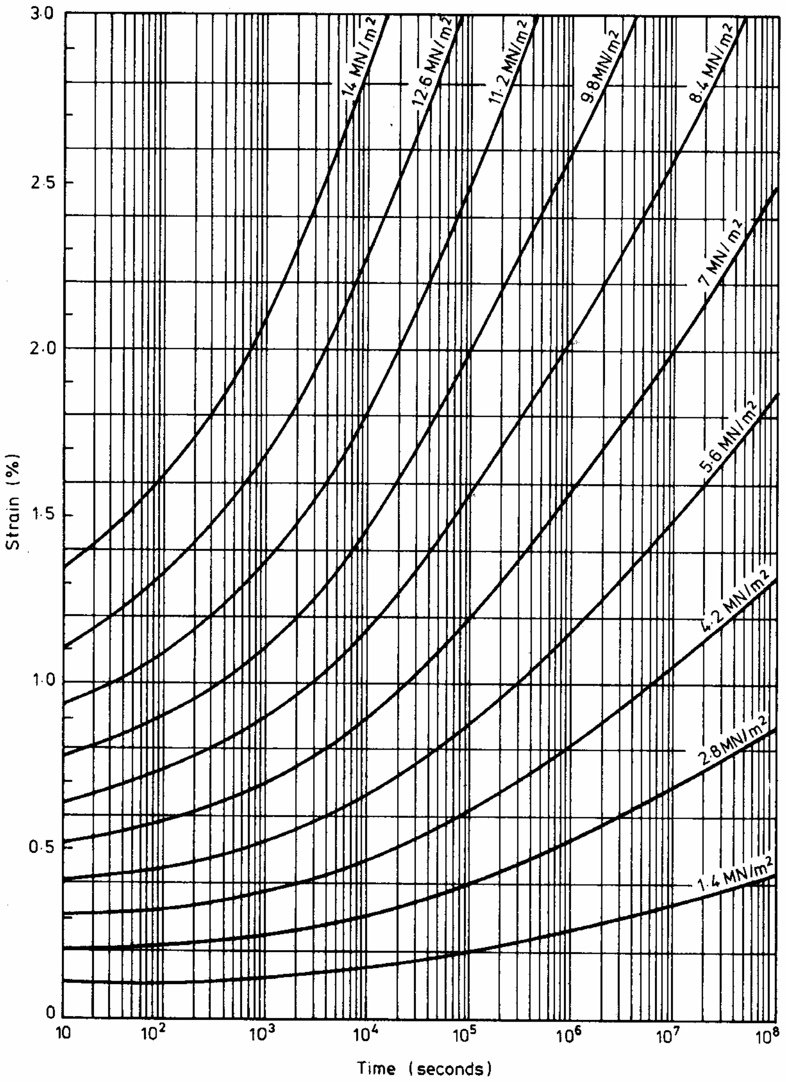
Typical creep curves



[Plastics Engineering, 2nd Ed., R. J. Crawford, Pergamon Press, Oxford, 1987]

Long-Term Testing of Plastics (Cont.)

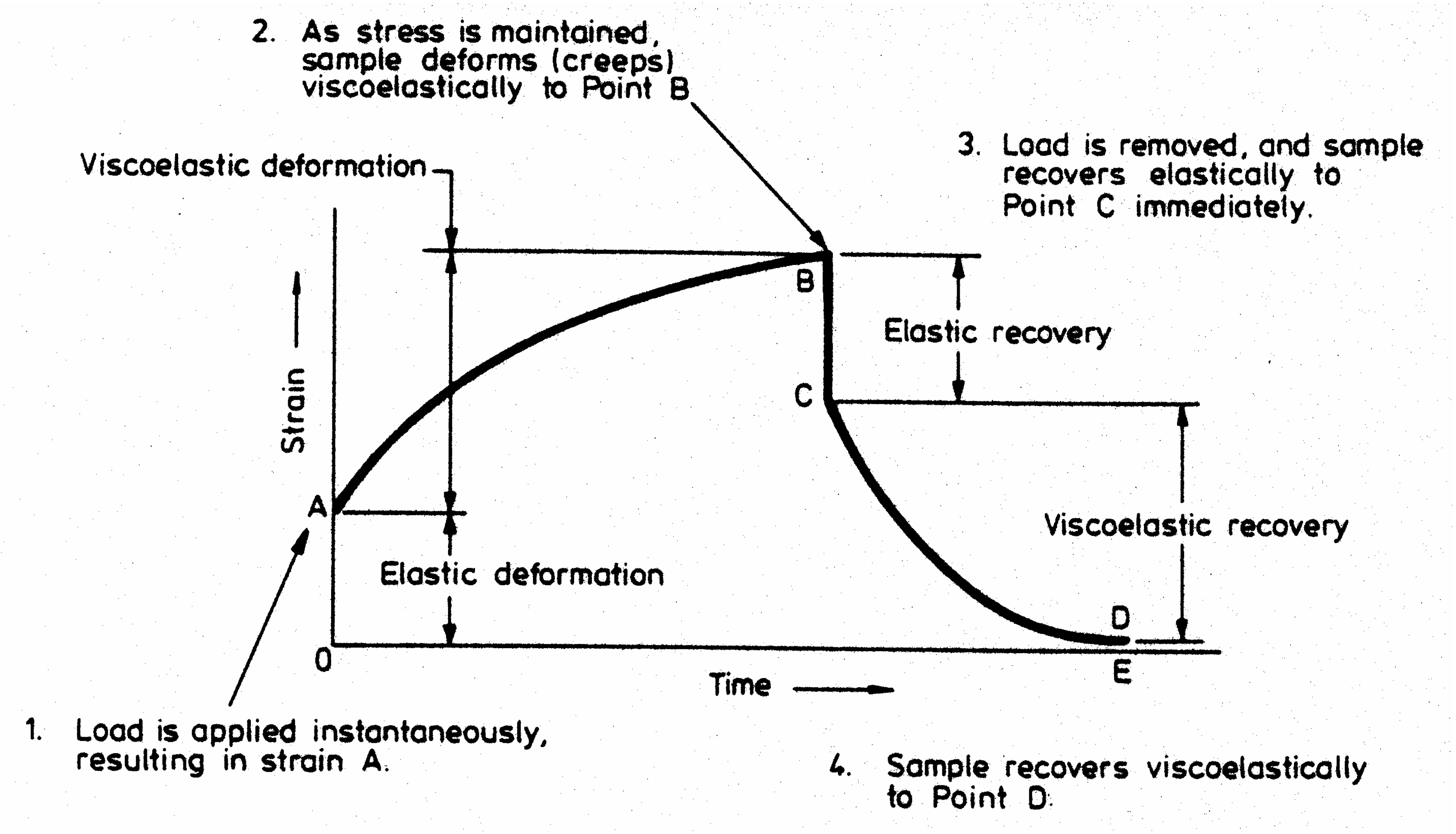
Creep curves for polypropylene at 20°C (density 909 kg/m^3)



[Plastics Engineering, 2nd Ed., R. J. Crawford, Pergamon Press, Oxford, 1987]

Long-Term Testing of Plastics (Cont.)

Typical creep and recovery behavior of a plastic



1. Load is applied instantaneously, resulting in strain A.
2. As stress is maintained, sample deforms (creeps) viscoelastically to Point B
3. Load is removed, and sample recovers elastically to Point C immediately.
4. Sample recovers viscoelastically to Point D.

[Plastics Engineering, 2nd Ed., R. J. Crawford, Pergamon Press, Oxford, 1987]

References

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2. R. J. Crawford, Plastics Engineering, 2nd Ed., Pergamon Press, Oxford, 1987.

3. Polymer Science and Technology, Joel R. Fried, Prentice Hall, Englewood Cliffs, 1995.

4. Web site of Prof. Duane D. Johnson at University of Illinois at Urbana-Champaign

5. Callister, W. D., Jr., Materials Science and Engineering – An Introduction, 4thEd., John Wiley & Sons, New York, 1997.