Diffusion

Diffusion - Mass transport by atomic motion

Mechanisms

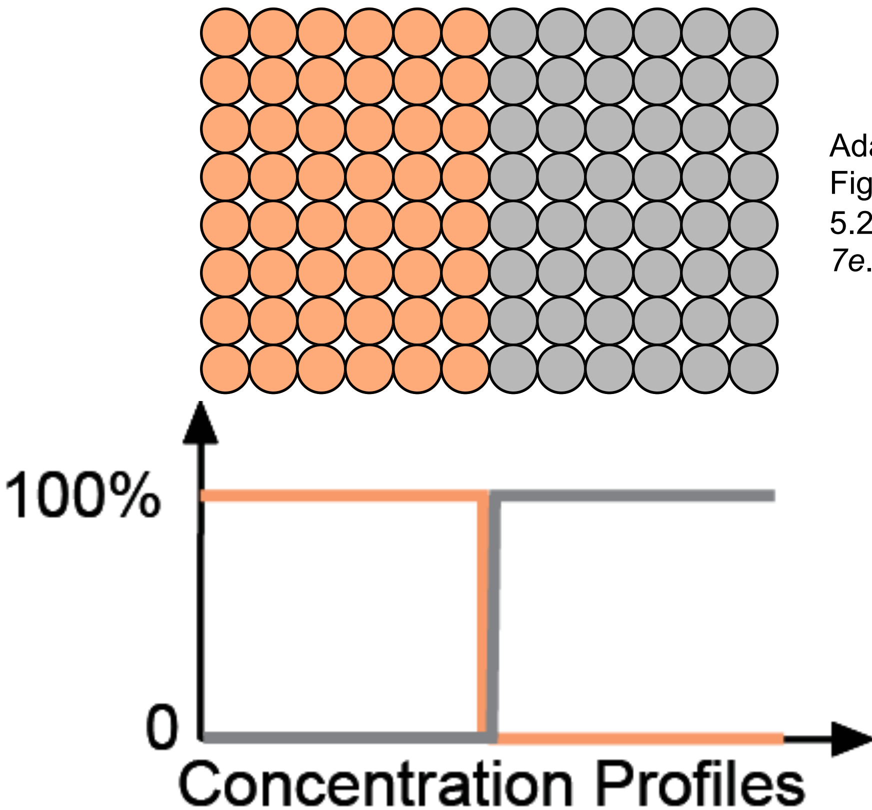
- Gases & Liquids – random (Brownian) motion
- Solids – vacancy diffusion or interstitial diffusion

Interdiffusion: In an alloy, atoms tend to migrate from regions of high conc. to regions of low conc.

Self-diffusion: In an elemental solid, atoms also migrate.

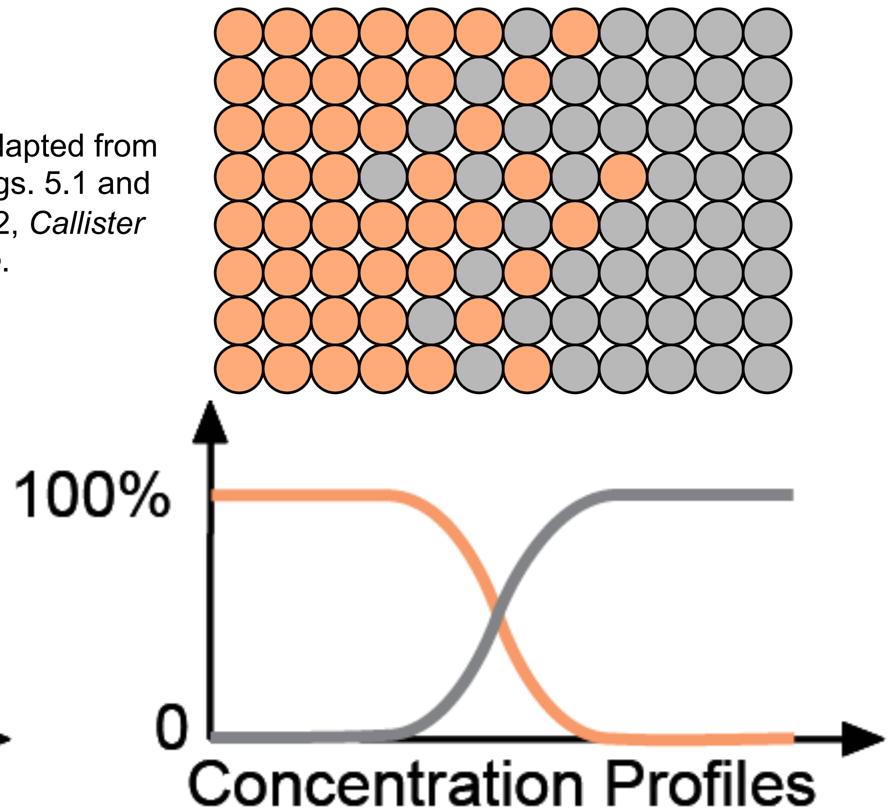
Interdiffusion

Initially



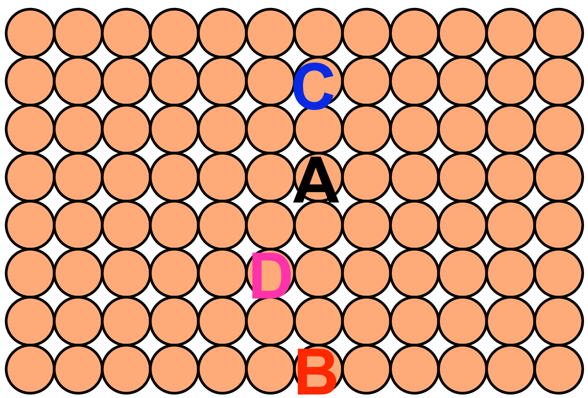
Adapted from Figs. 5.1 and 5.2, *Callister 7e*.

After some time

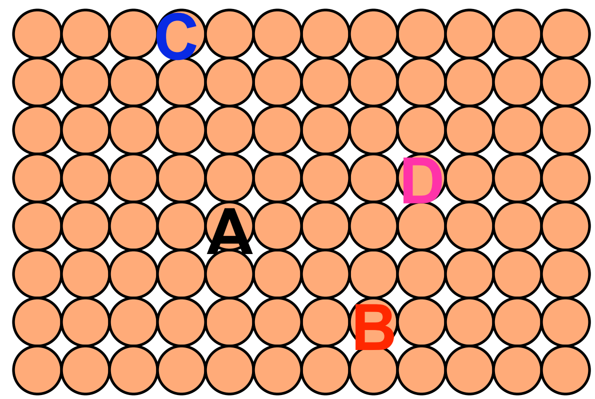


Self-diffusion

Label some atoms



After some time

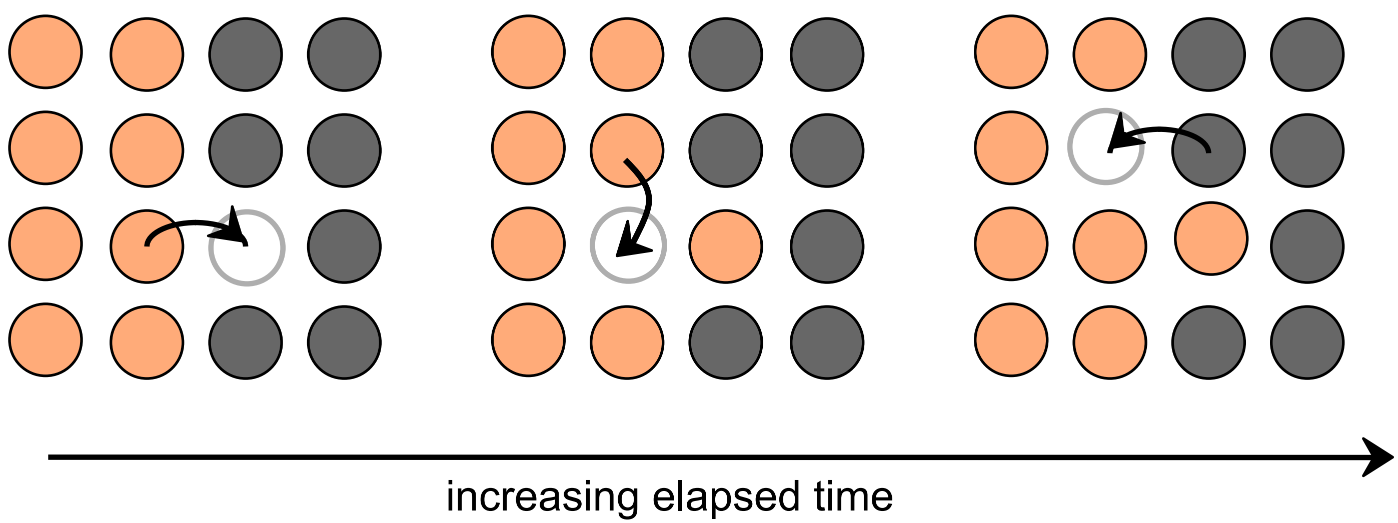


Diffusion mechanisms

Conditions:

Vacancy Diffusion:

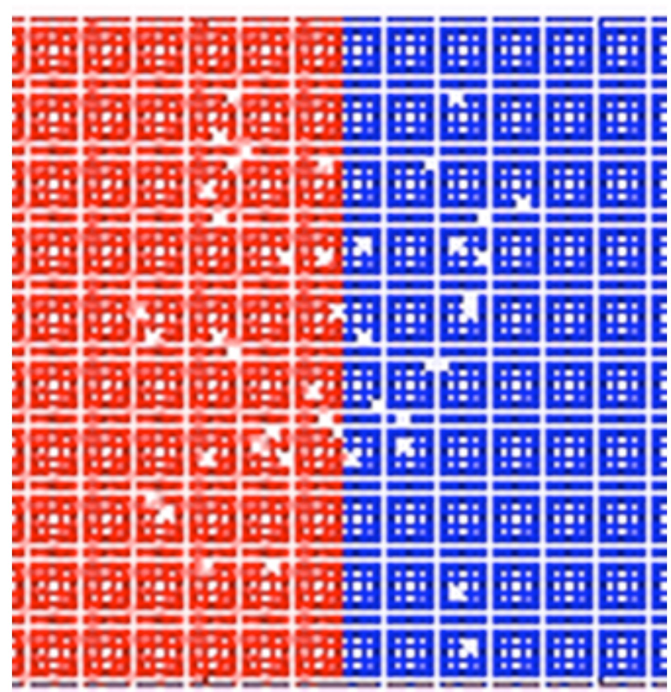
- atoms exchange with vacancies
- applies to substitutional impurities atoms
- rate depends on:
  --number of vacancies
  --activation energy to exchange.



Diffusion simulation

- Simulation of interdiffusion across an interface:

- Rate of substitutional diffusion depends on:
  --vacancy concentration
  --frequency of jumping.



(Courtesy P.M. Anderson)

Diffusion flux

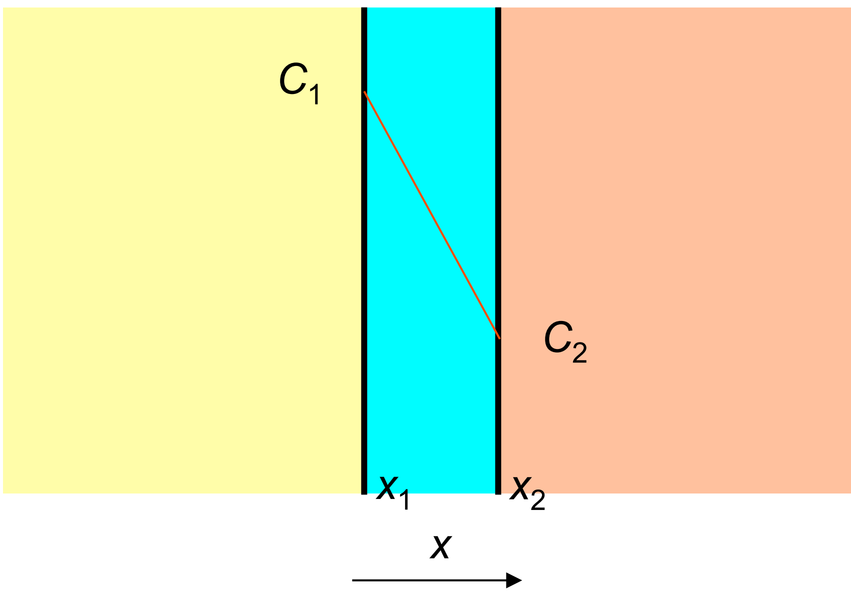
How do we quantify the amount or rate of diffusion?

Measured empirically

- Make thin film (membrane) of known surface area
- Impose concentration gradient
- Measure how fast atoms or molecules diffuse through the membrane

Steady-state diffusion

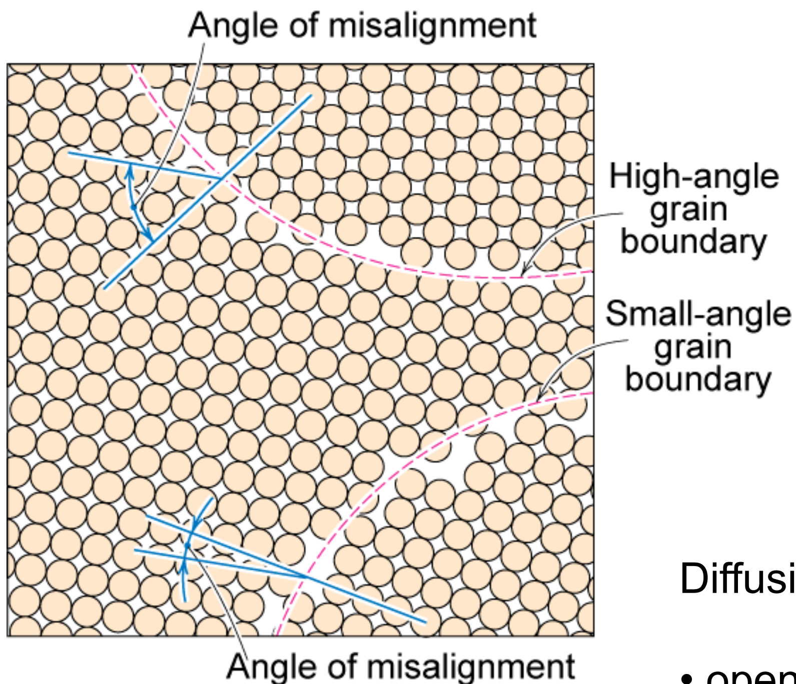
Flux proportional to concentration gradient = $\dfrac{dC}{dx}$



Diffusion and temperature

- Diffusion coefficient increases with increasing *T*.

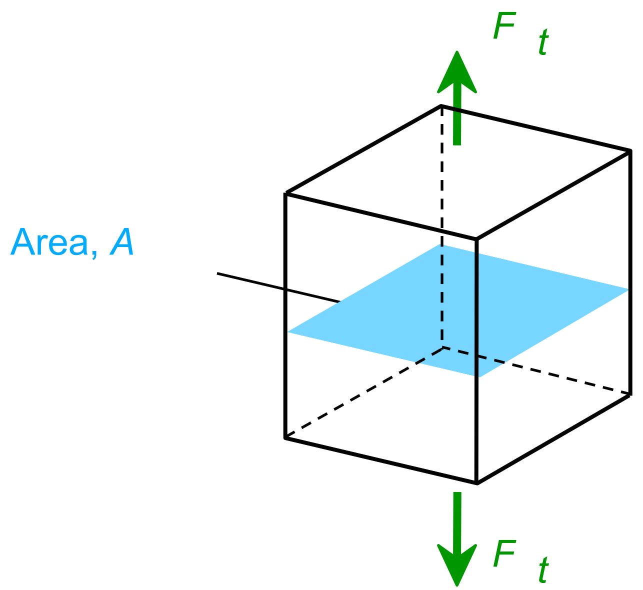
Diffusion paths



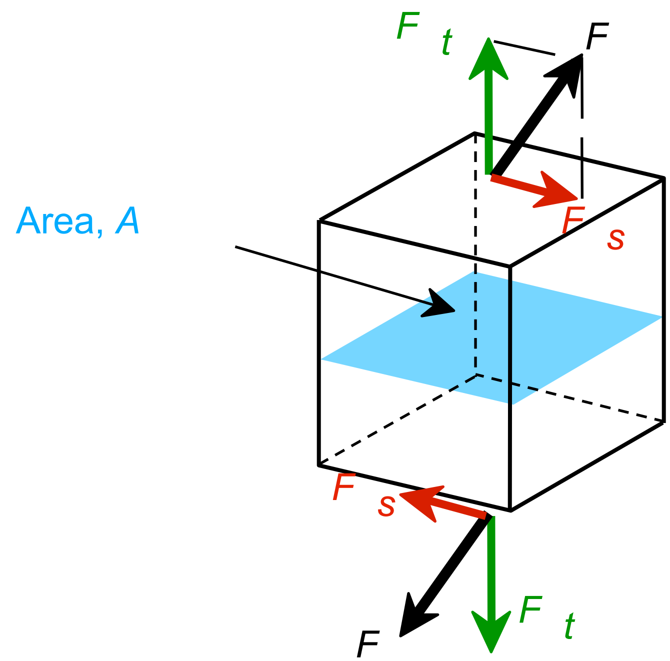
Diffusion FASTER for...	Diffusion SLOWER for...
• open crystal structures	• close-packed structures
• materials w/secondary bonding	• materials w/covalent bonding
• smaller diffusing atoms	• larger diffusing atoms
• lower density materials	• higher density materials

Engineering stress

- Tensile stress, σ:

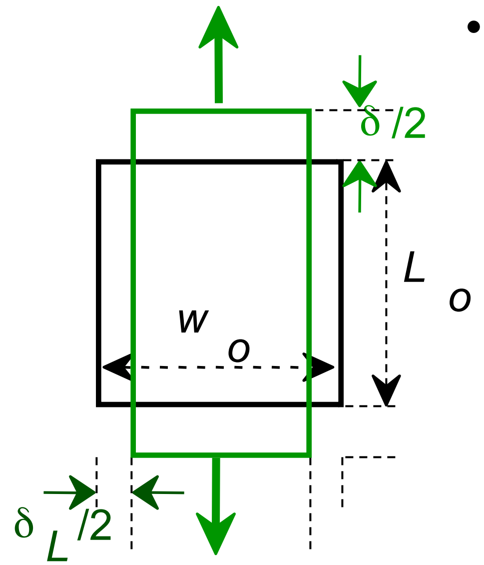


- Shear stress, τ:



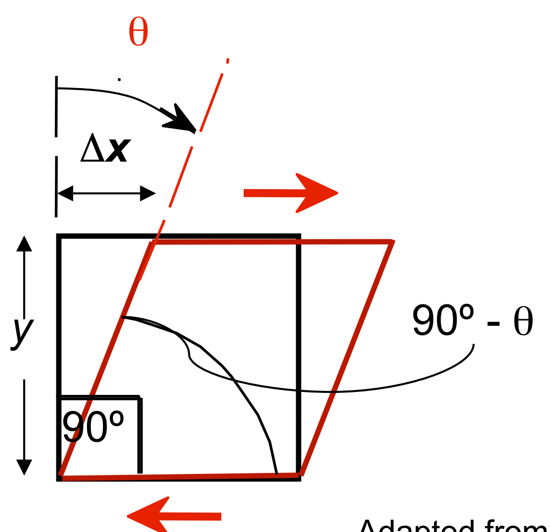
Engineering strain

- **Tensile strain:**



- **Lateral strain:**

- **Shear strain:**

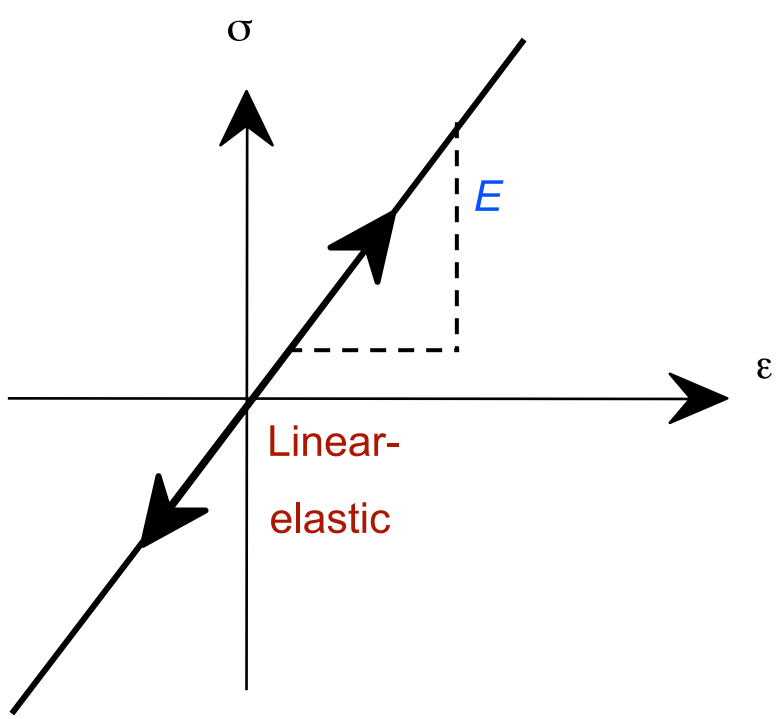


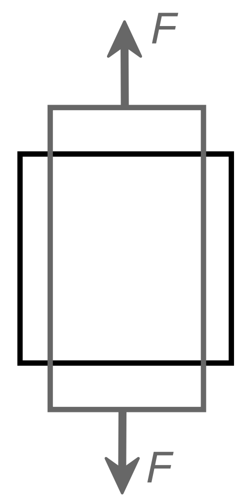
$\gamma = \Delta x / y = \tan \theta$

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

Engineering strain

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

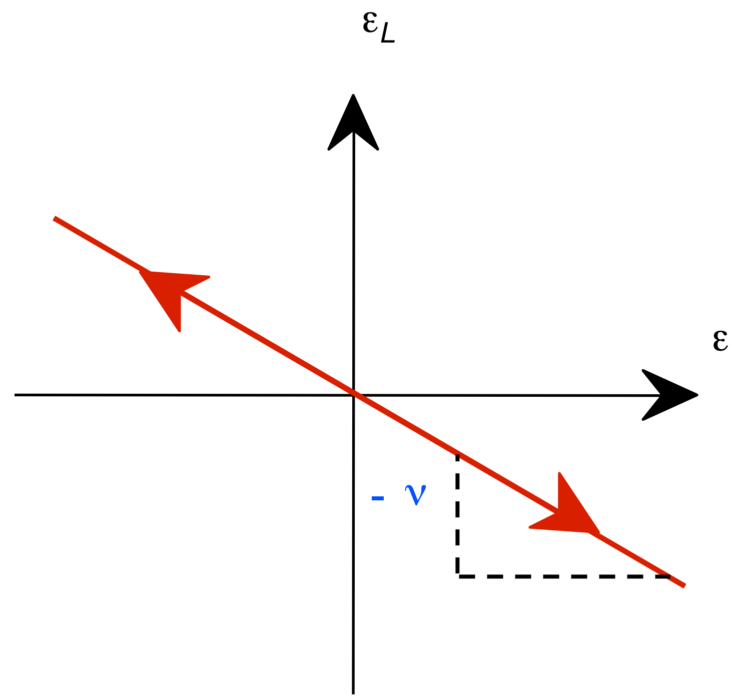




simple
tension
test

Elastic properties of materials

- **Poisson's ratio, ν:**

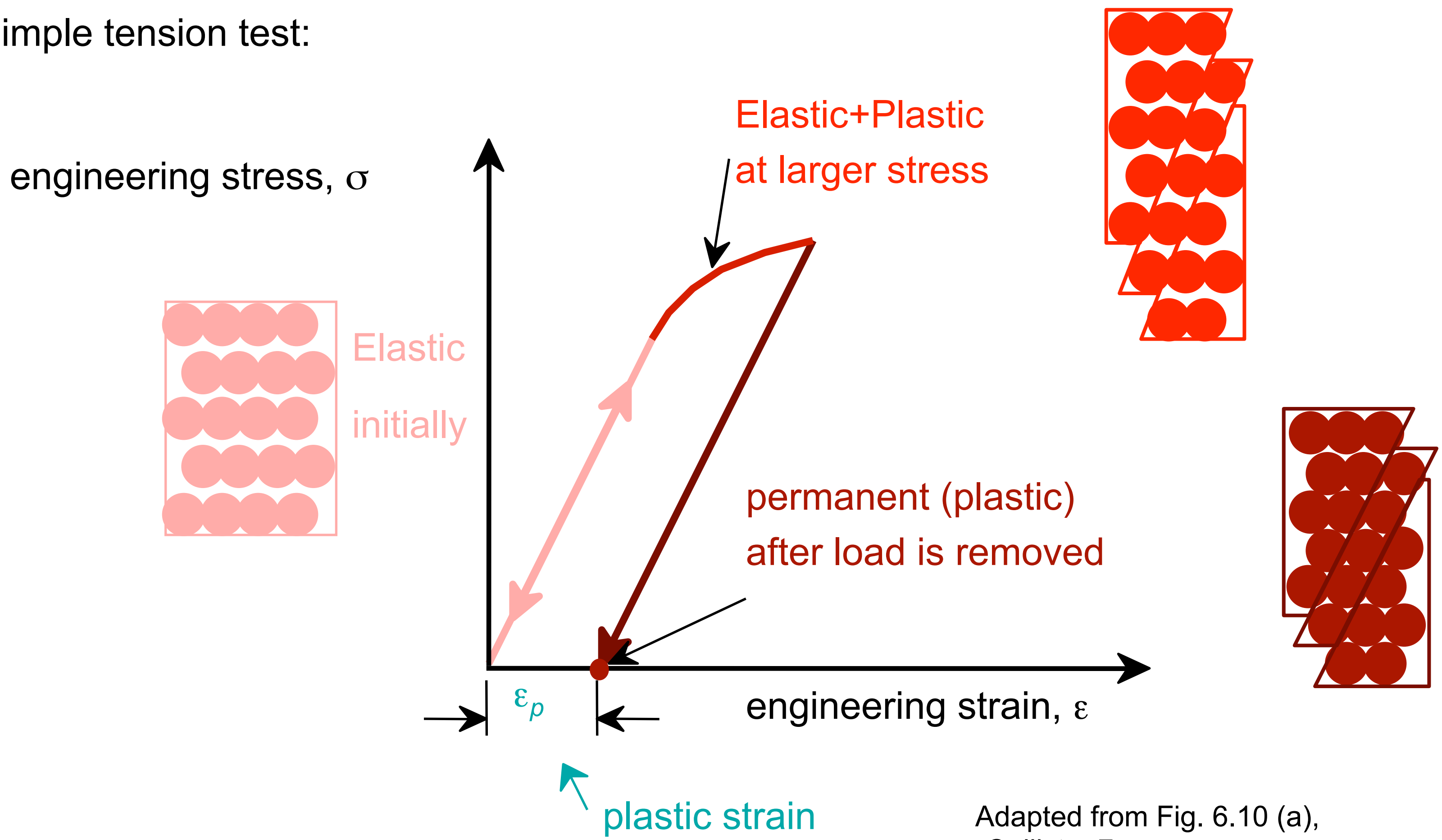


–ν > 0.50 density increases

–ν < 0.50 density decreases
(voids form)

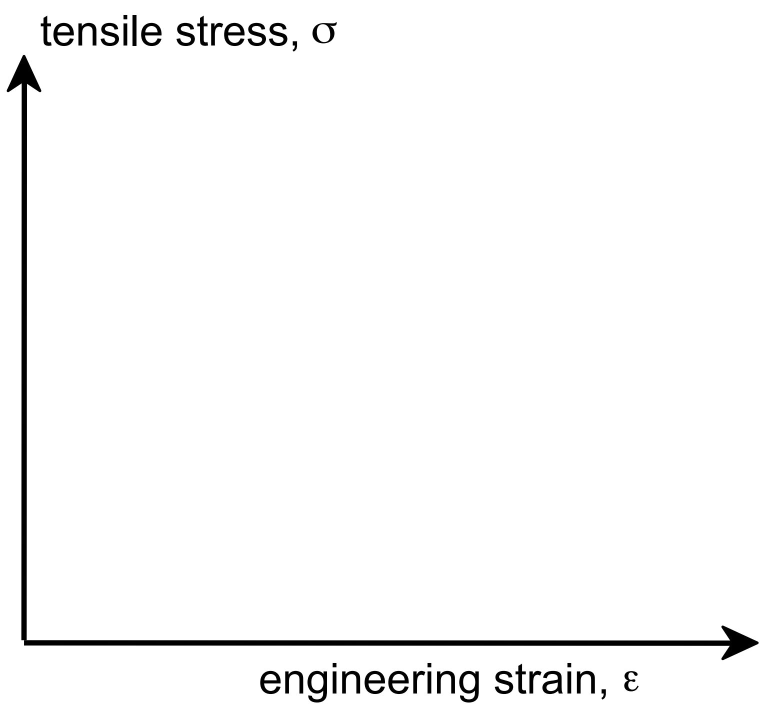
Plastic deformation

- Simple tension test:



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

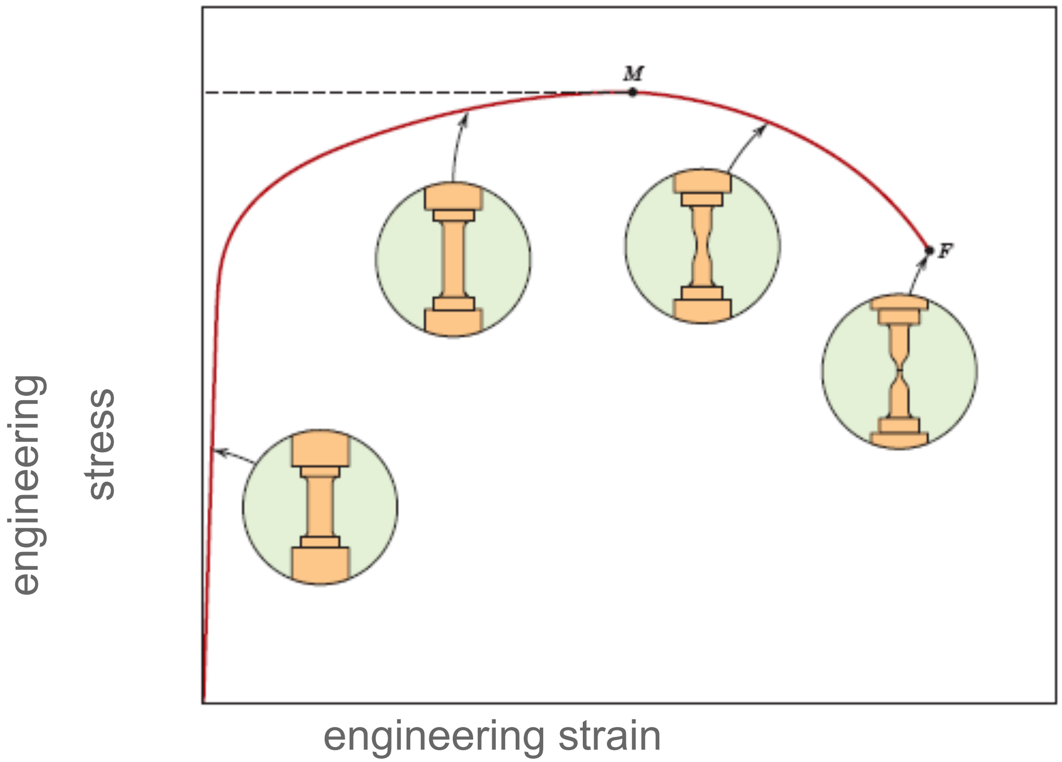
Yield strength, σ_y



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

Tensile strength, TS

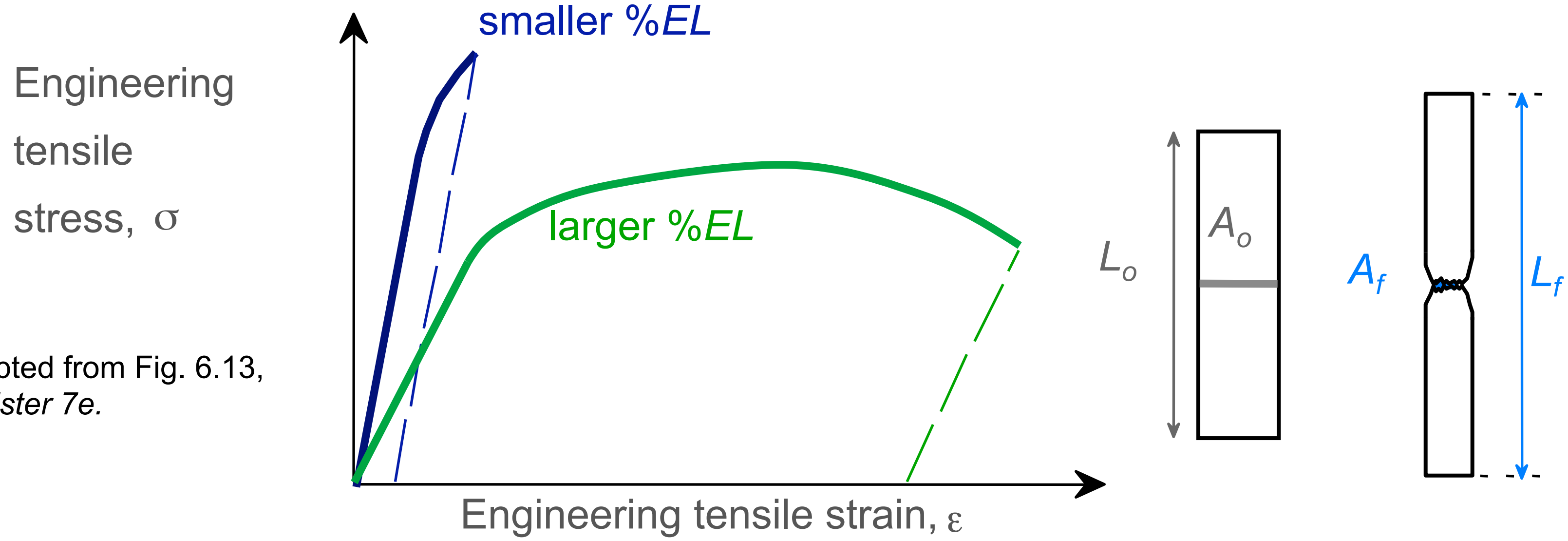
- Maximum stress on engineering stress-strain curve.



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

Ductility

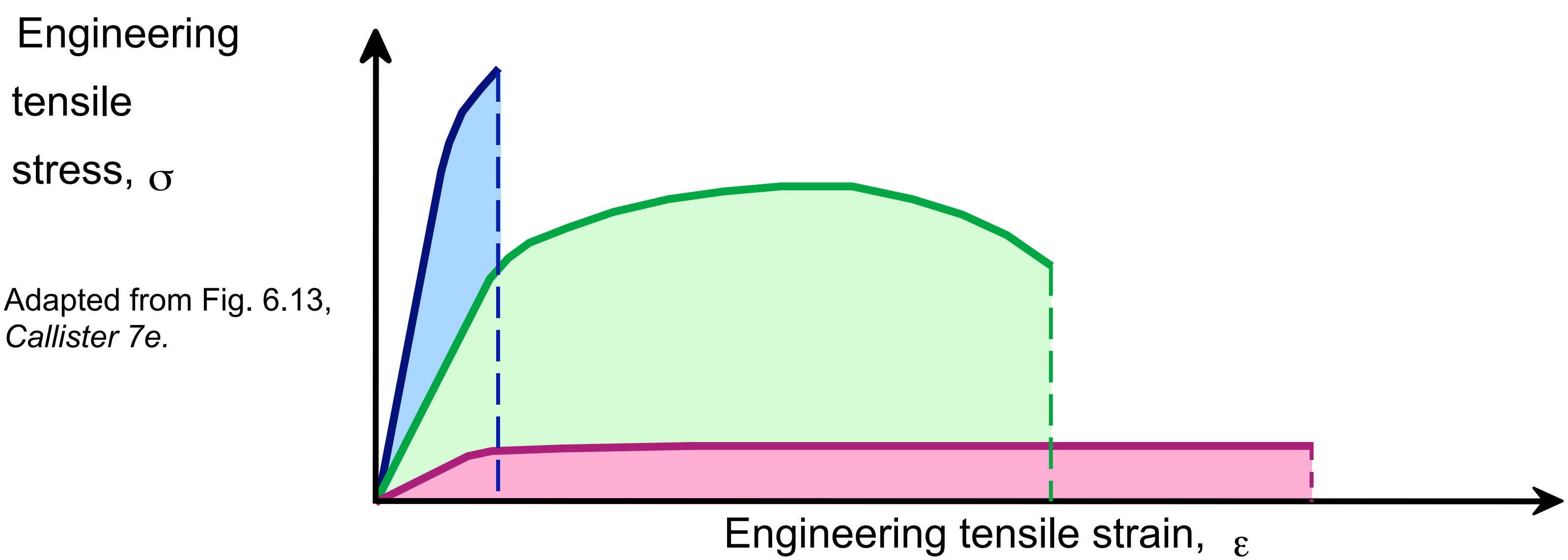
- Plastic tensile strain at failure:



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

Toughness

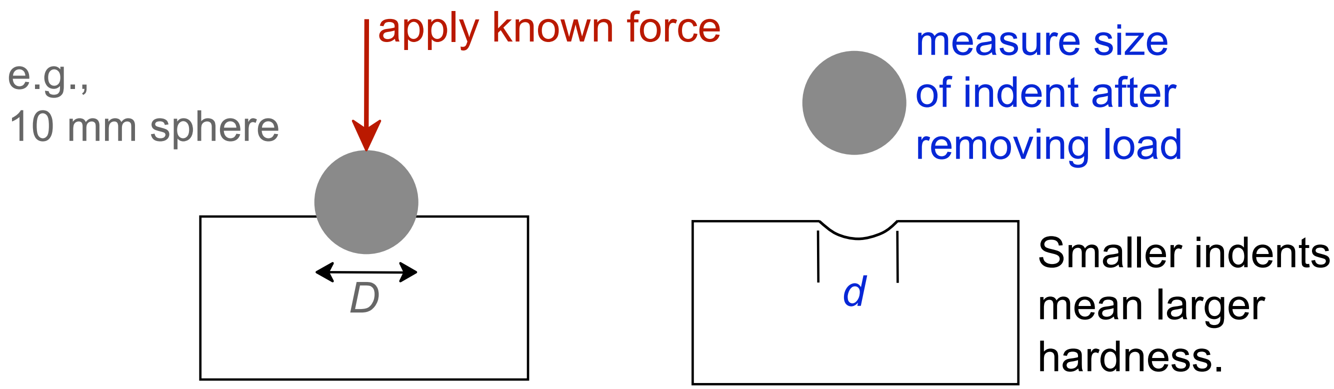
- Energy to break a unit volume of material
- Approximate by the area under the stress-strain curve.

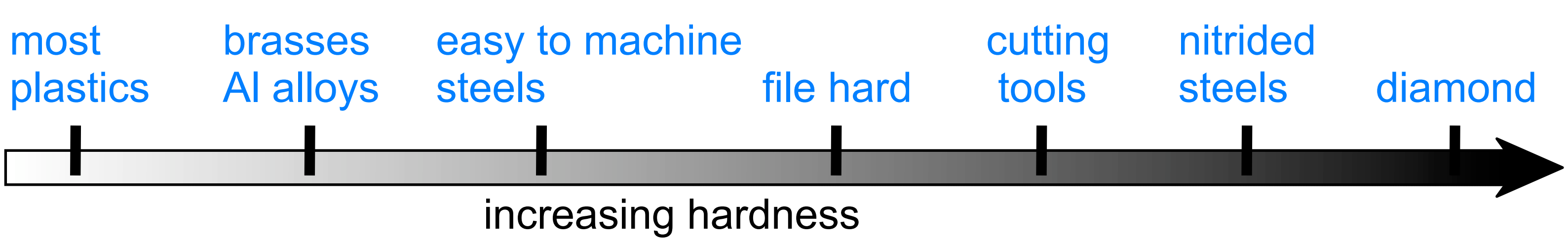


Adapted from Fig. 6.13, *Callister 7e.*

Hardness

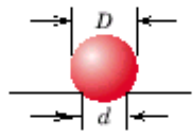
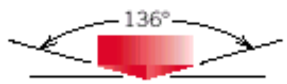
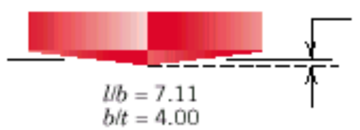
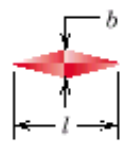
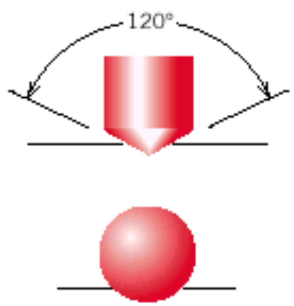
- Resistance to permanently indenting the surface.
- Large hardness means:
  --resistance to plastic deformation or cracking in compression.
  --better wear properties.





Hardness Measurement

Table 6.5 **Hardness Testing Techniques**

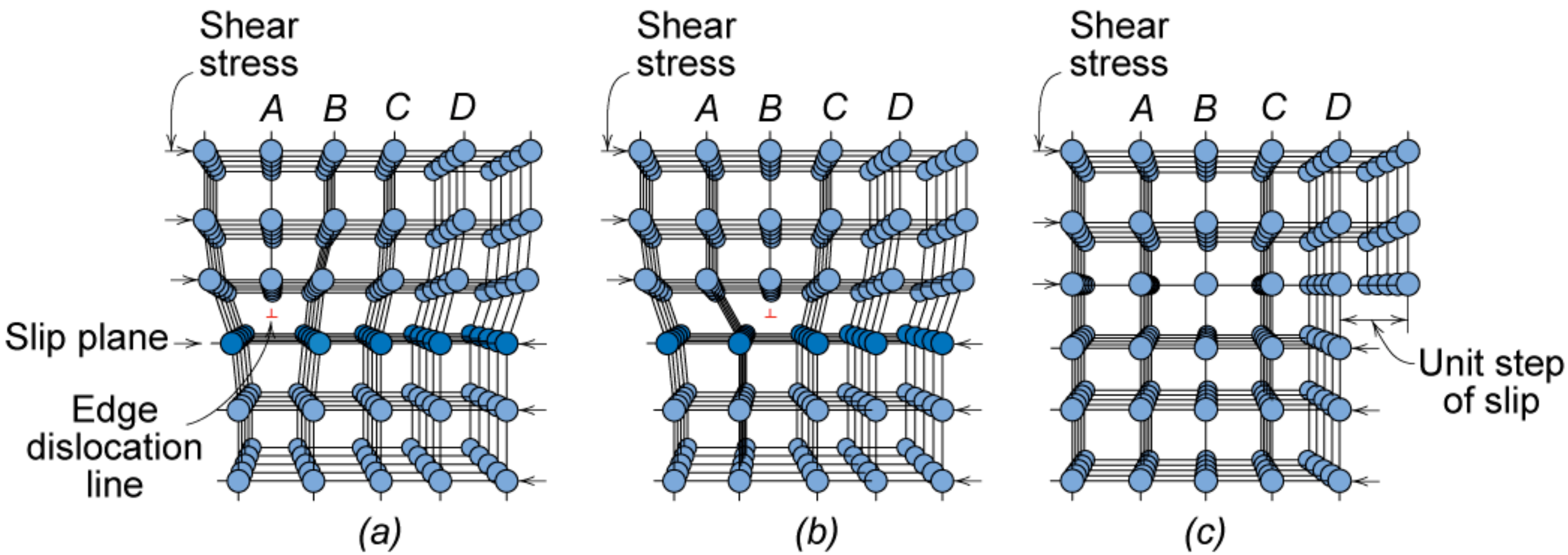
Test	Indenter	Shape of Indentation: Side View	Shape of Indentation: Top View	Load	Formula for Hardness Number[a]
Brinell	10-mm sphere of steel or tungsten carbide			P	$HB = \dfrac{2P}{\pi D[D - \sqrt{D^2 - d^2}]}$
Vickers microhardness	Diamond pyramid			P	$HV = 1.854P/d_1^2$
Knoop microhardness	Diamond 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.

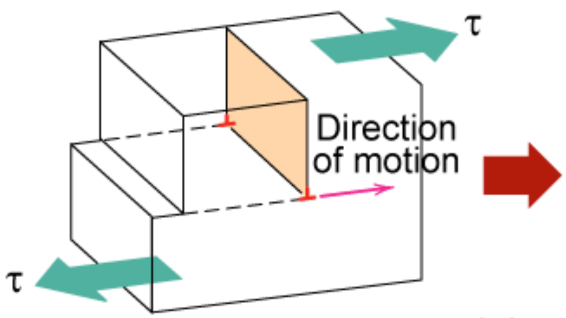
Dislocation and plastic deformation

- Cubic & hexagonal metals - plastic deformation by plastic shear or slip where one plane of atoms slides over adjacent plane by defect motion (dislocations).



Adapted from Fig. 7.1, *Callister 7e.*

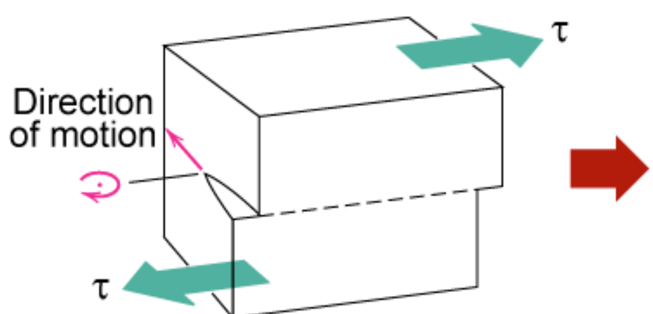
Dislocation motion



(a)

Edge dislocation

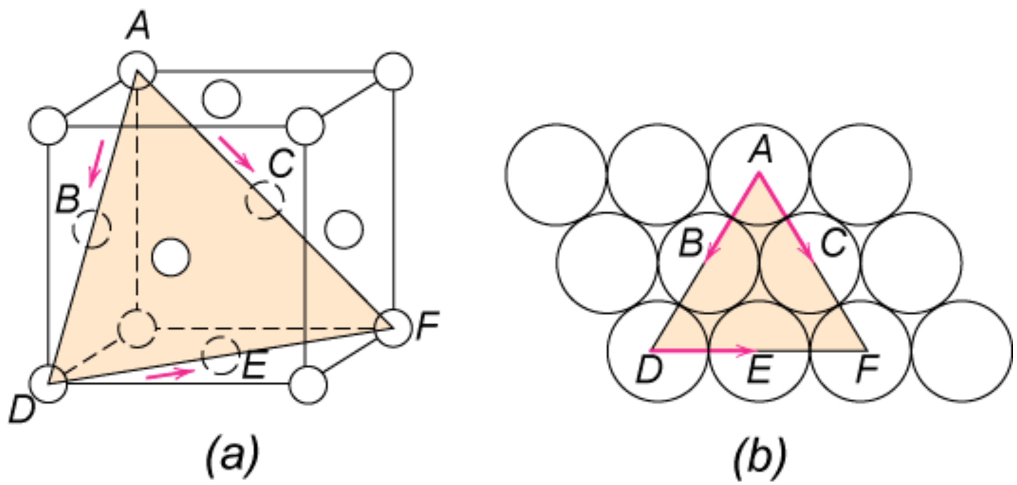
Adapted from Fig. 7.2, *Callister 7e.*



(b)

Screw dislocation

Deformation mechanisms

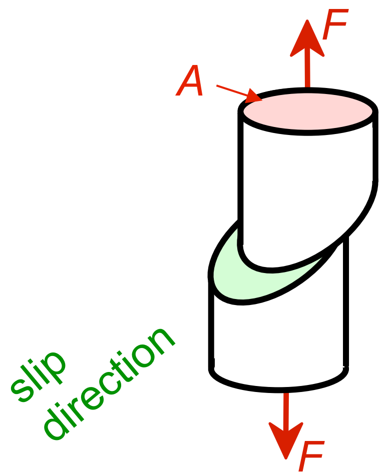


Adapted from Fig. 7.6, *Callister 7e.*

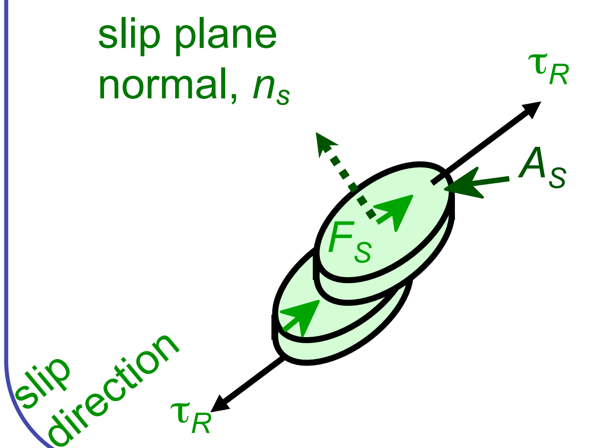
Slip in single crystals

- Crystals slip due to a resolved shear stress, τ_R.
- Applied tension can produce such a stress.

Applied **tensile** stress:

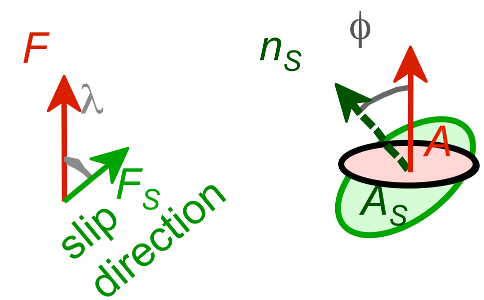


Resolved shear stress:



Relation between

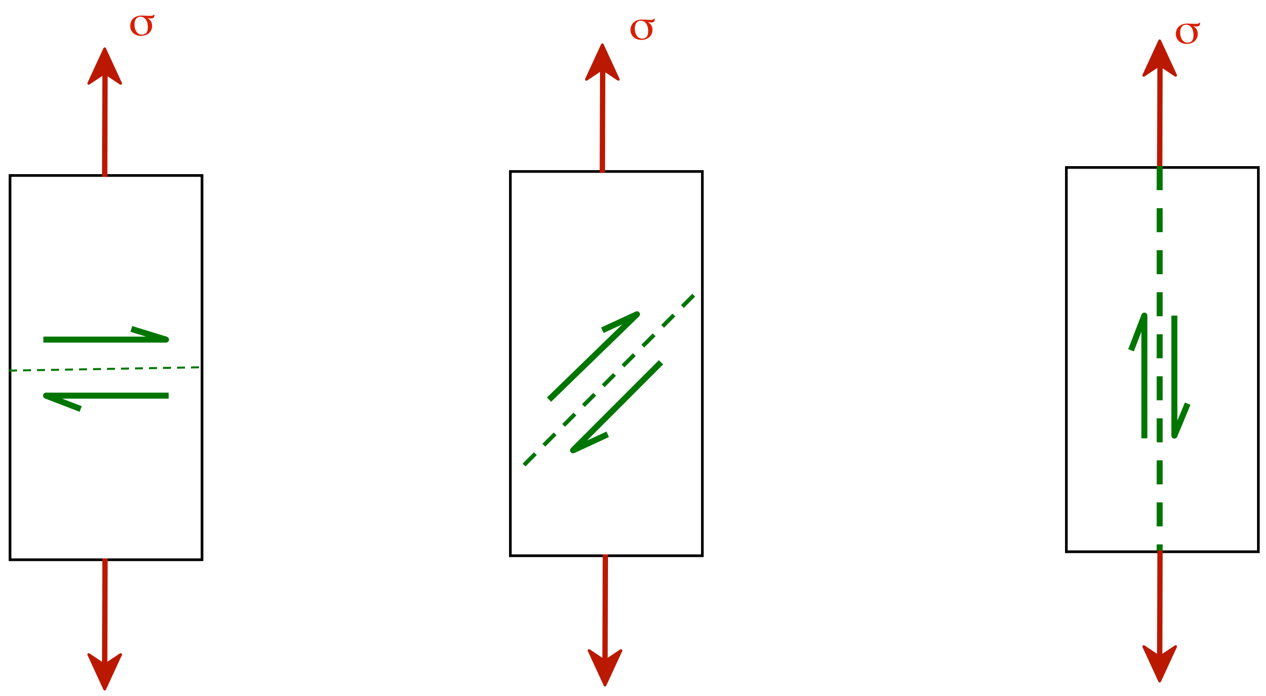
σ and τ_R



Critical resolved shear stress

- Condition for dislocation motion:

- Crystal orientation can make it easy or hard to move dislocation



Slip motion in polycrystals

- Stronger - grain boundaries pin deformations

- Slip planes & directions (λ, ϕ) change from one crystal to another.

- τ_R will vary from one crystal to another.

- The crystal with the largest τ_R yields first.

- Other (less favorably oriented) crystals yield later.

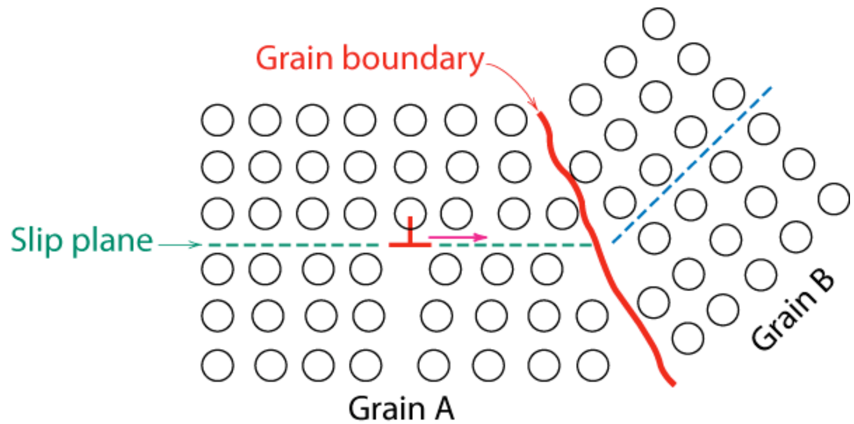
Adapted from Fig. 7.10, *Callister 7e.* (Fig. 7.10 is courtesy of C. Brady, National Bureau of Standards [now the National Institute of Standards and Technology, Gaithersburg, MD].)

Strategies for strengthening: grain size reduction

- Grain boundaries are barriers to slip.

- Barrier "strength” increases with increasing angle of misorientation.

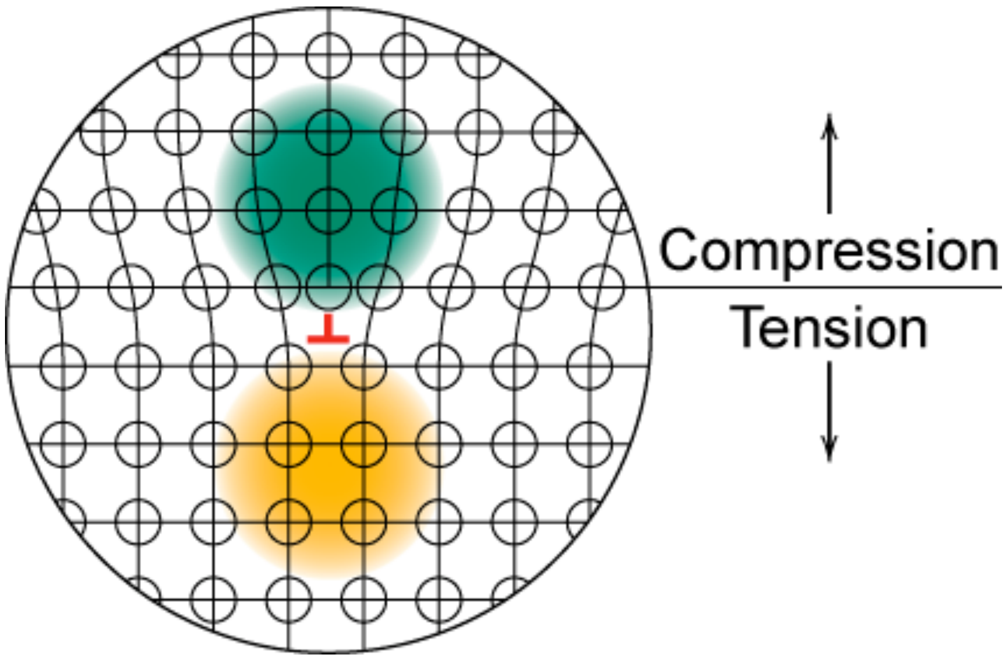
- Smaller grain size: more barriers to slip.



Adapted from Fig. 7.14, *Callister 7e.*
(Fig. 7.14 is from *A Textbook of Materials Technology*, by Van Vlack, Pearson Education, Inc., Upper Saddle River, NJ.)

- Hall-Petch Equation:

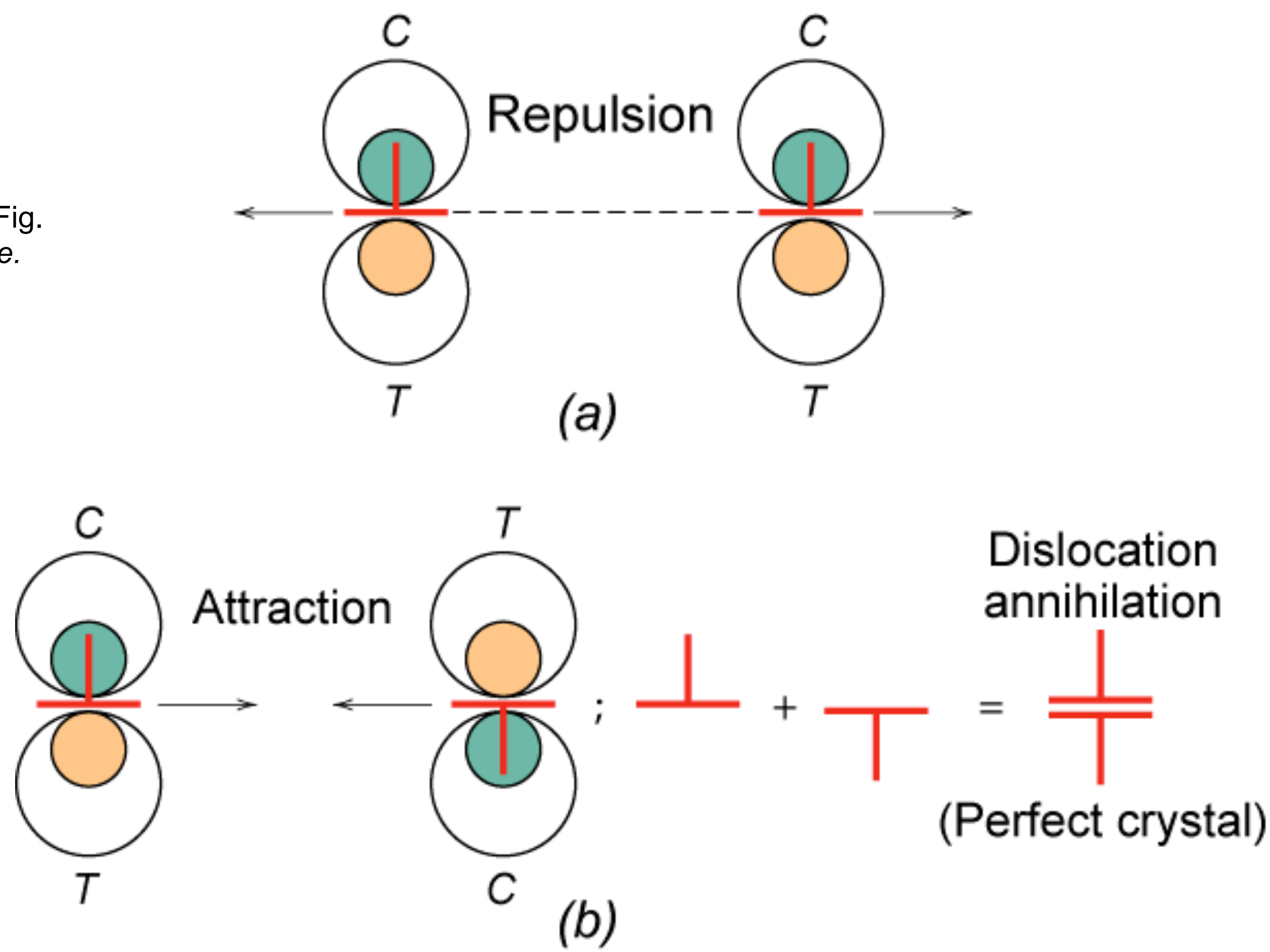
Strategies for strengthening: solid solutions



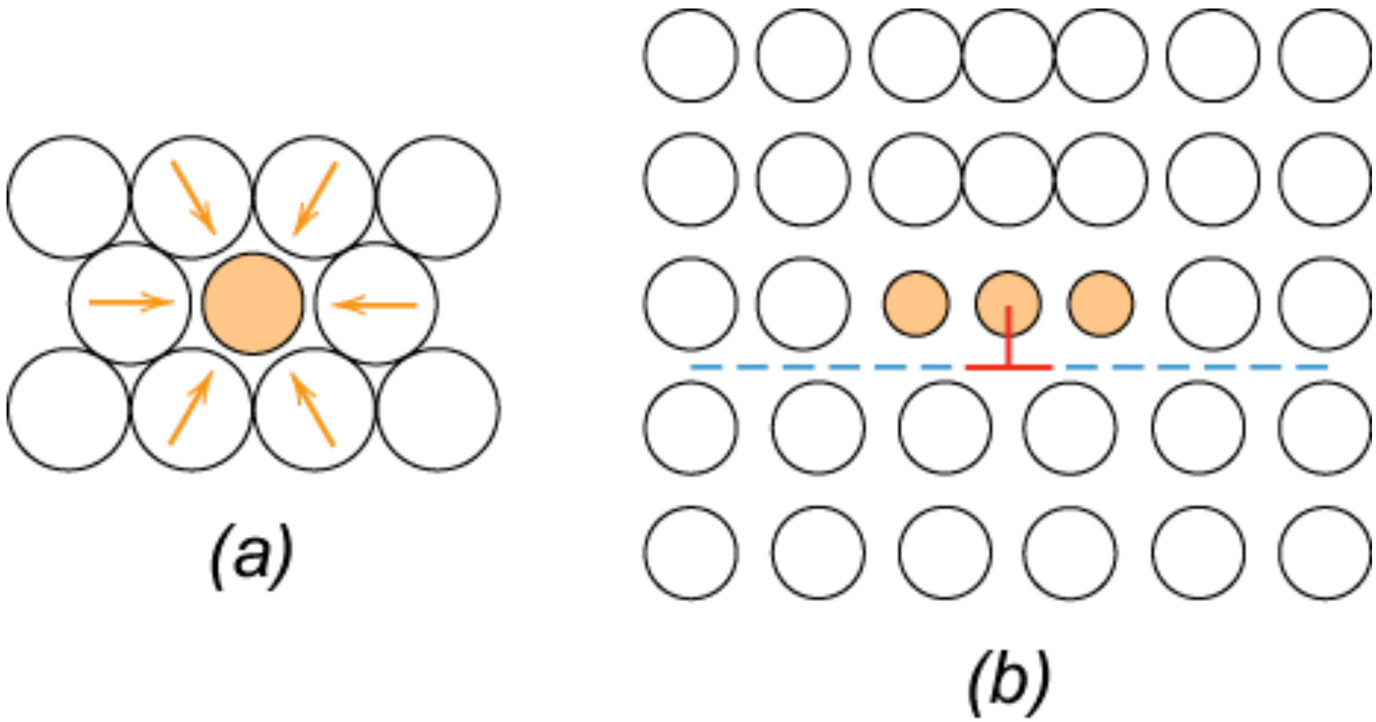
Adapted from Fig. 7.4, *Callister 7e.*

Effects of stress at dislocations

Adapted from Fig. 7.5, *Callister 7e.*

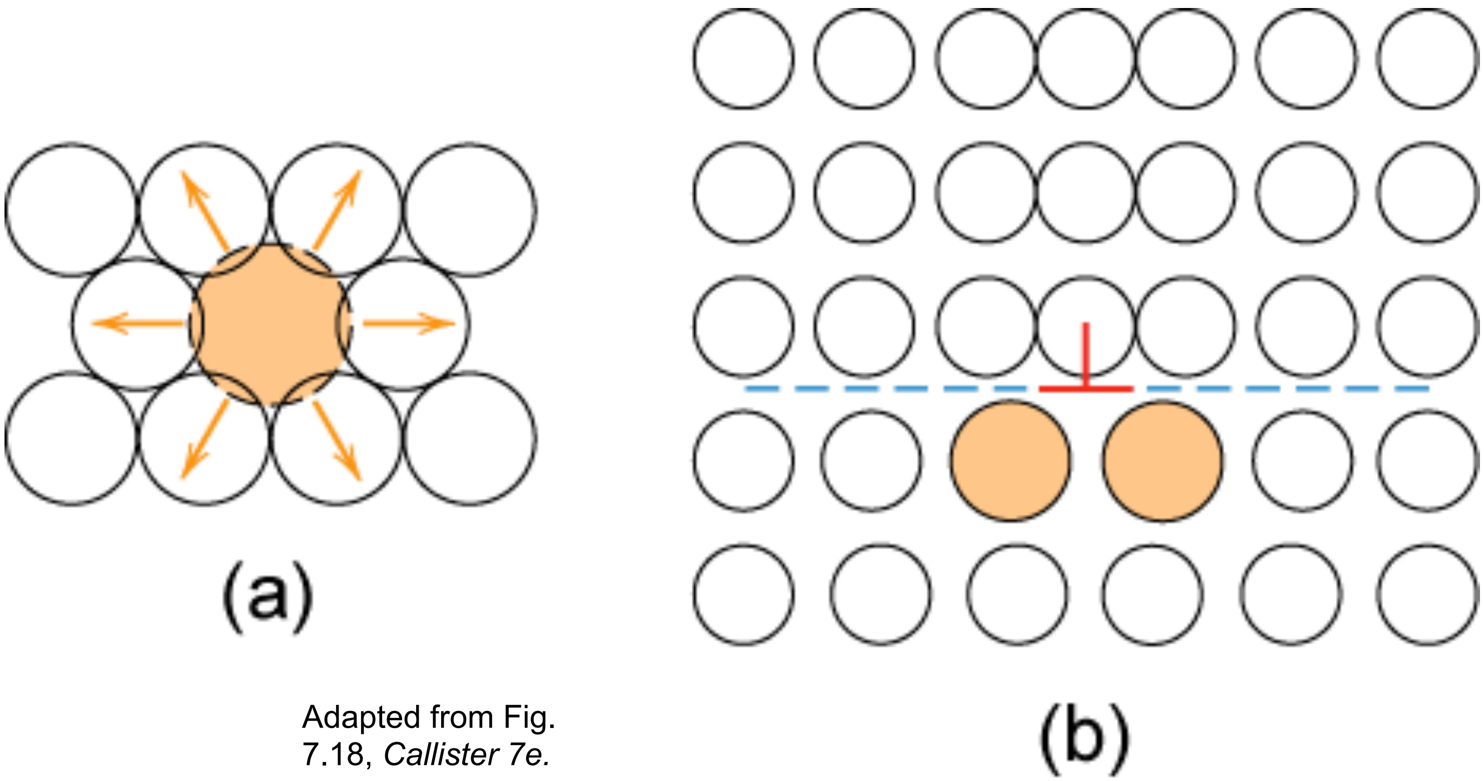


Strengthening by alloying



Adapted from Fig. 7.17, *Callister 7e.*

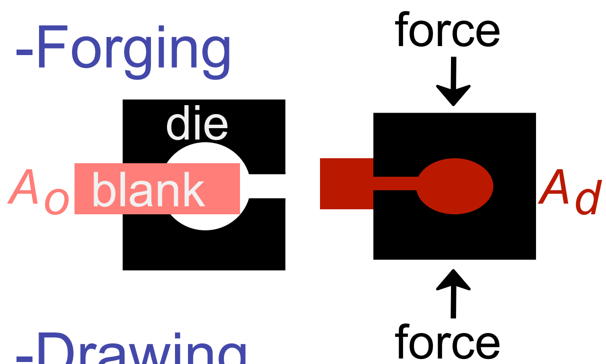
Strengthening by alloying

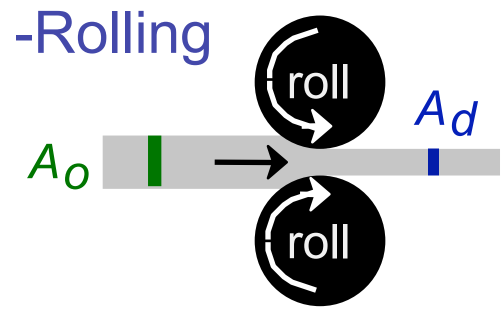


Adapted from Fig. 7.18, *Callister 7e.*

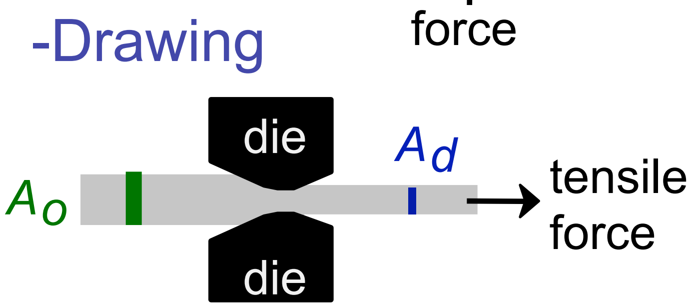
Strategies for strengthening: Cold work (%CW)

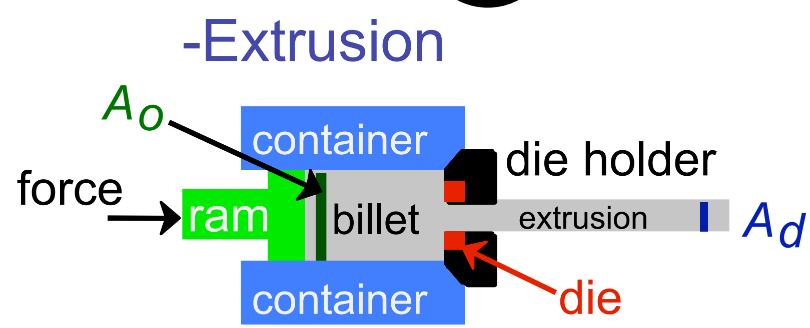
- Room temperature deformation.
- Common forming operations change the cross sectional area:





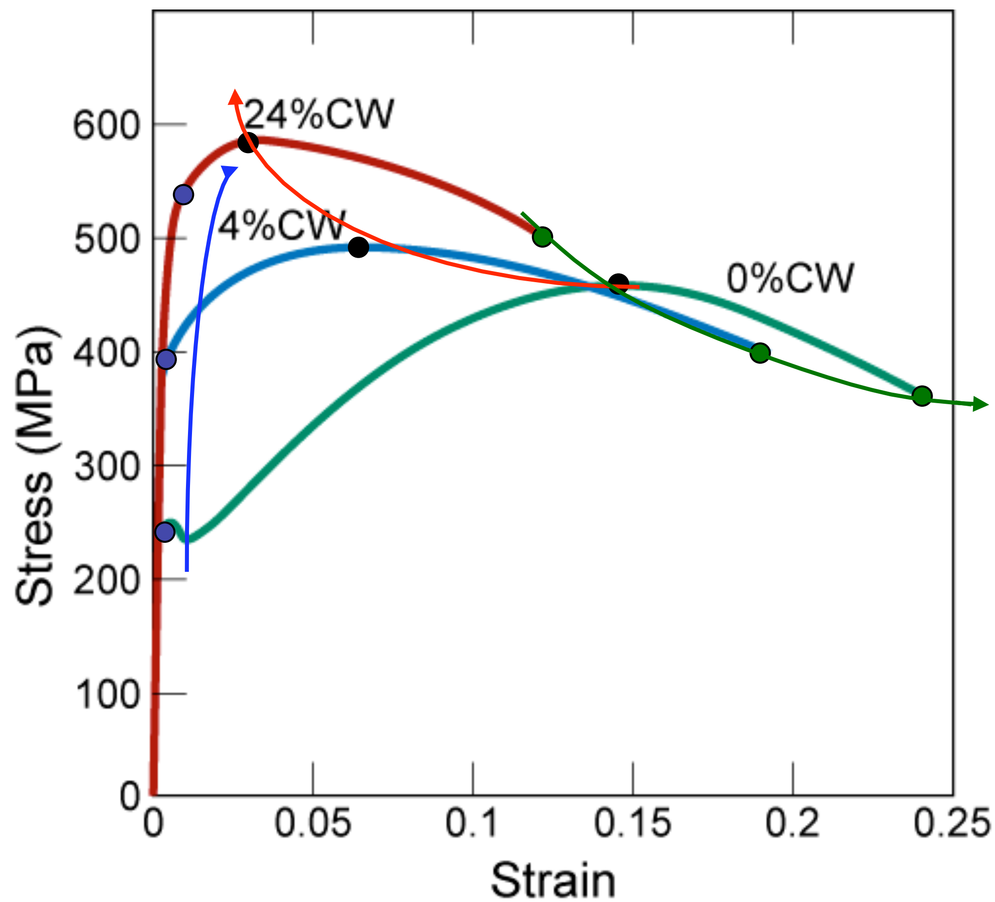
Adapted from Fig. 11.8, *Callister 7e.*





Impact of cold work

As cold work is increased



Adapted from Fig. 7.20, *Callister 7e.*