Chemical Engineering 378

Science of Materials Engineering

Lecture 15

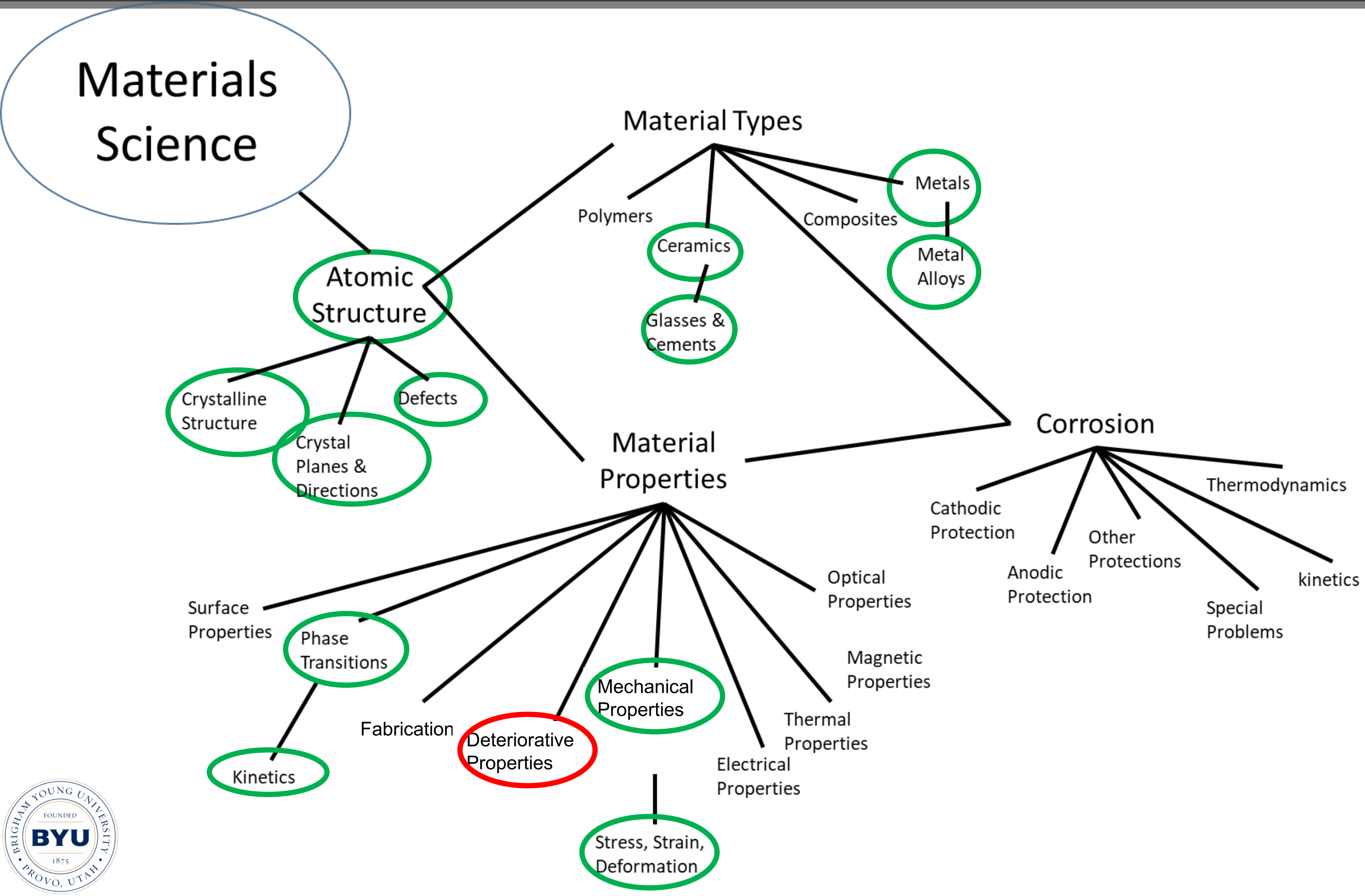
Failure and Fractures

Spiritual Thought

Moroni 7:48

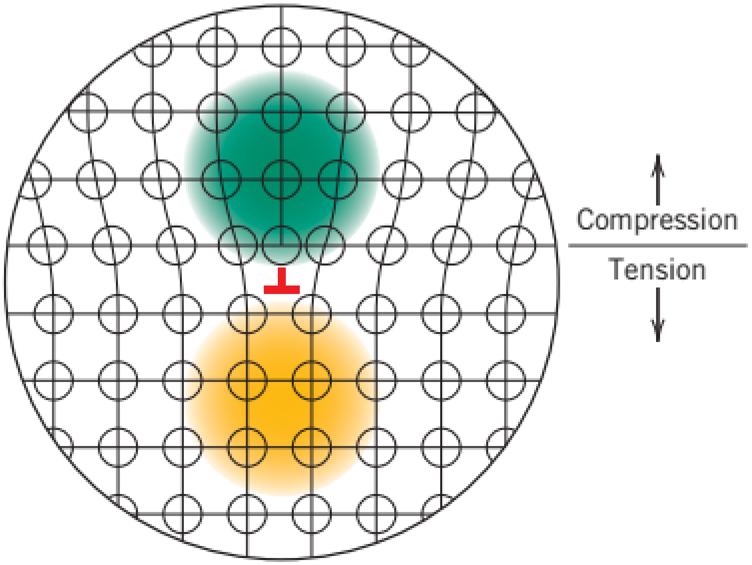
48. Wherefore, my beloved brethren, pray unto the Father with all the energy of heart, that ye may be filled with this love, which he hath bestowed upon all who are **true followers of his Son, Jesus Christ; that ye may become the sons of God…**

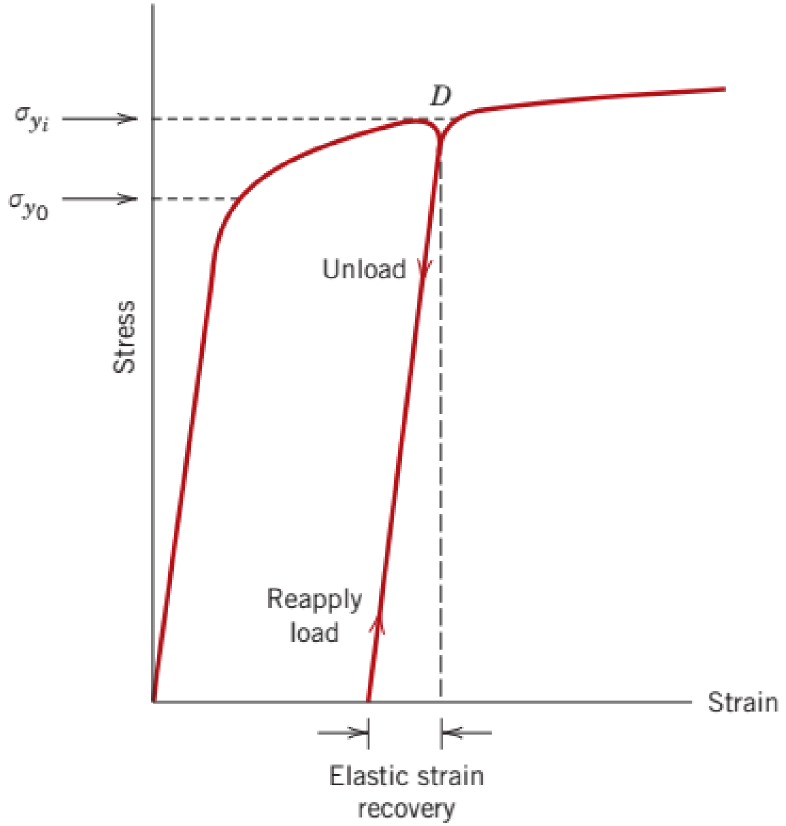
Materials Roadmap



Strain Hardening

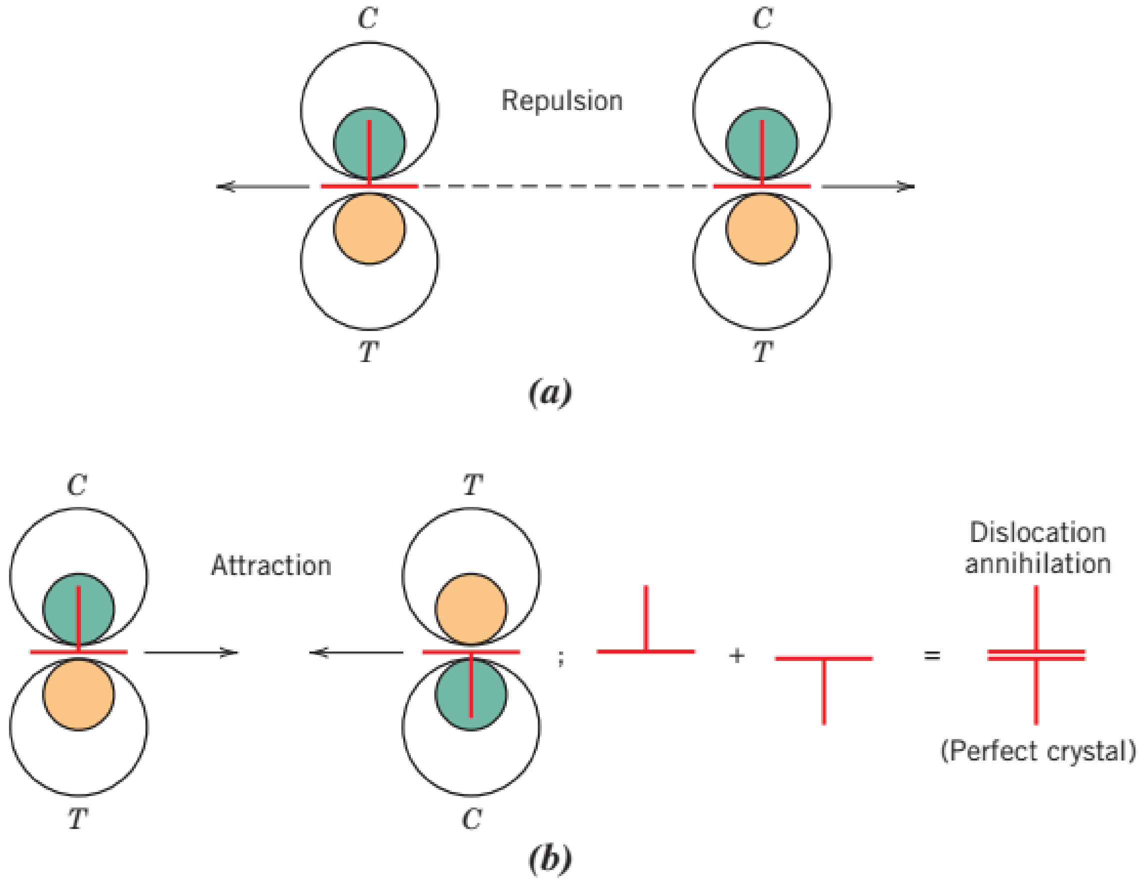
- Strain Hardening: The process by which ductile metal becomes harder as it is plasticly deformed.





Strain Hardening

Figure 7.5 (*a*) Two edge dislocations of the same sign and lying on the same slip plane exert a repulsive force on each other; *C* and *T* denote compression and tensile regions, respectively. (*b*) Edge dislocations of opposite sign and lying on the same slip plane exert an attractive force on each other. Upon meeting, they annihilate each other and leave a region of perfect crystal.
(Adapted from H. W. Hayden, W. G. Moffatt, and J. Wulff, *The Structure and Properties of Materials*, Vol. III, *Mechanical Behavior*, John Wiley & Sons, 1965. Reproduced with permission of Kathy Hayden.)



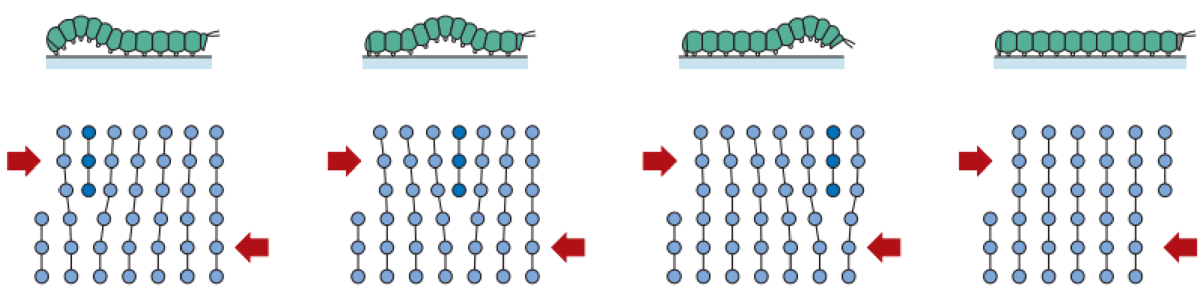


Figure 7.3 The analogy between caterpillar and dislocation motion.

Strain Hardening (cont.)
Dislocation Density and Cold Working

$$\text{Dislocation density} = \frac{\text{total dislocation length}}{\text{unit volume}}$$

– Dislocation density in undeformed metal

→ 10^5-10^6 mm^{-2}

– Dislocation density increases with increasing deformation

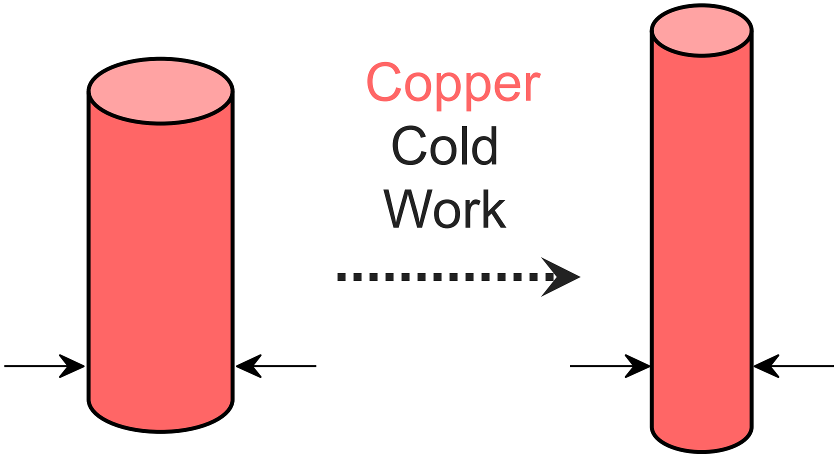
– Dislocation density in deformed (cold-worked) metal

→ 10^9-10^{10} mm^{-2}

Affect of Cold Work on Mechanical Properties

Example Problem:

Compute the yield and tensile strengths, and ductility for a cylindrical Cu specimen that has been cold worked by reducing its diameter from 15.2 mm to 12.2 mm.



D_o = 15.2 mm

D_d = 12.2 mm

% cold worked

$$\%CW = \left(\frac{A_0 - A_d}{A_0}\right) \times 100$$

Example Problem (cont.)

- Solution:

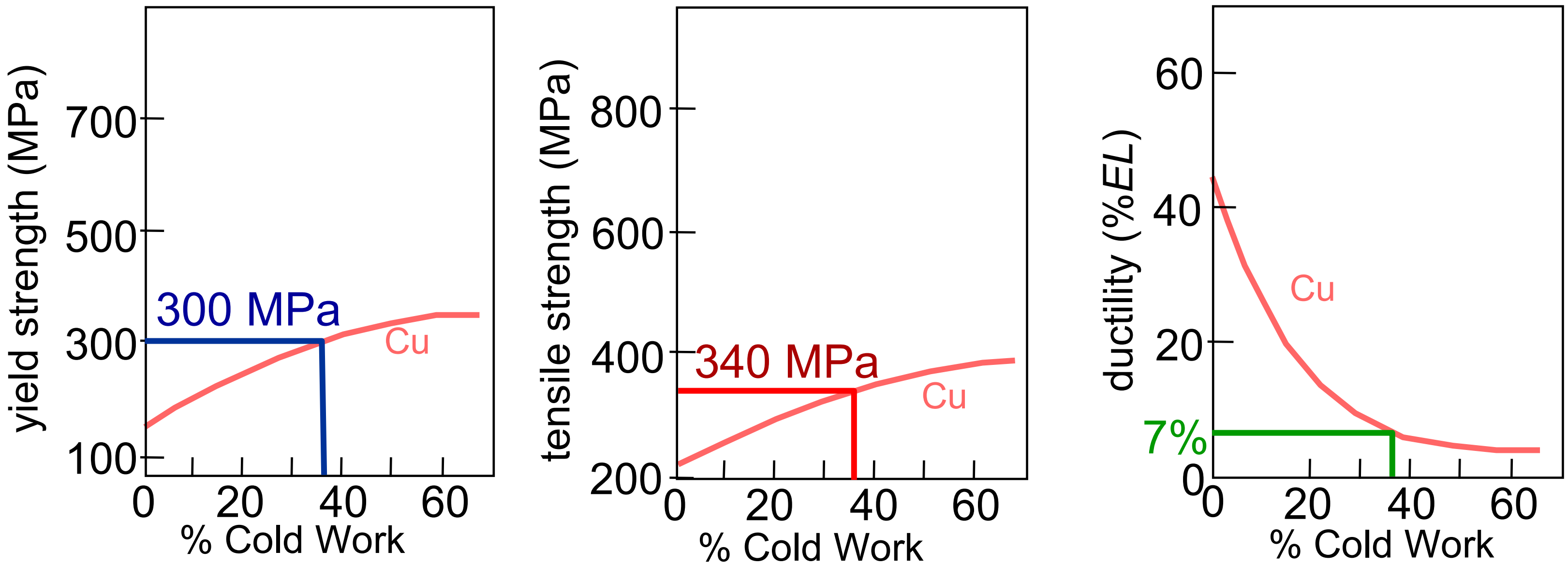
$$\%CW = \frac{\cancel{\pi}\left(\frac{D_o}{\cancel{2}}\right)^2 - \cancel{\pi}\left(\frac{D_d}{\cancel{2}}\right)^2}{\cancel{\pi}\left(\frac{D_o}{\cancel{2}}\right)^2} \text{ x } 100$$

$$= \frac{D_o^2 - D_d^2}{D_o^2} \text{ x } 100$$

$$\%CW = \frac{(15.2 \text{ mm})^2 - (12.2 \text{ mm})^2}{(15.2 \text{ mm})^2} \text{ x } 100 = 35.6\%$$

Example Problem (cont.)

- Yield and tensile strength, and ductility (%EL) are determined graphically as shown below for %CW = 35.6%



σ_y = 300 MPa

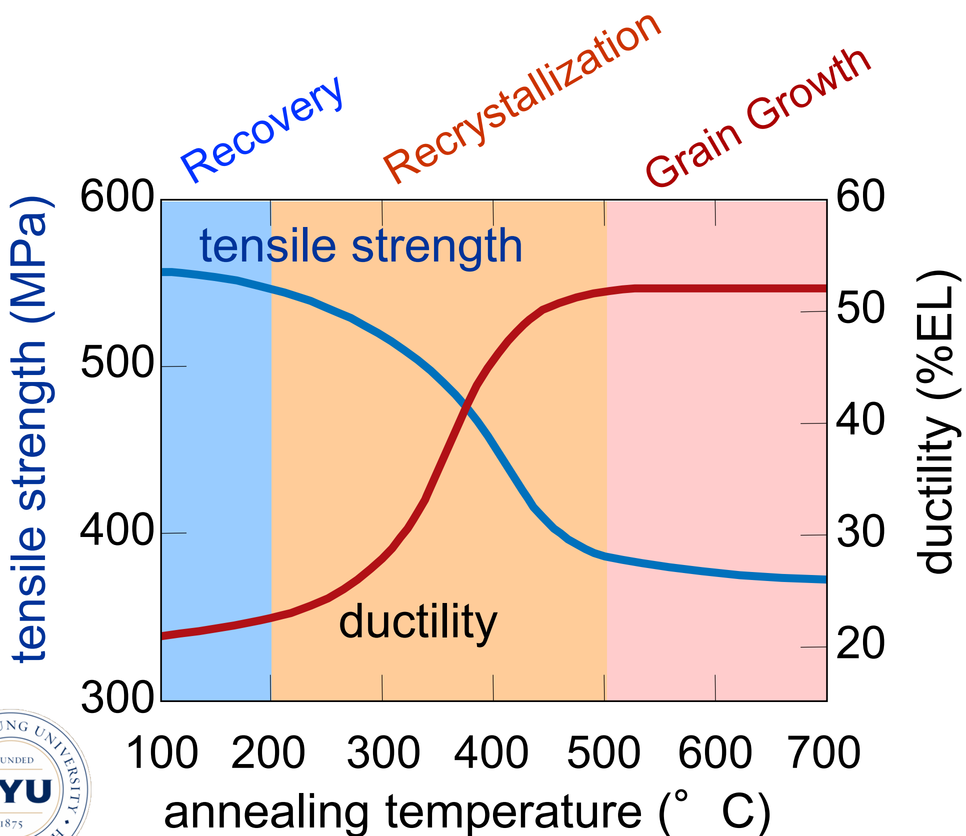
TS = 340 MPa

%*EL* = 7%

Fig. 7.19, *Callister & Rethwisch 10e.* [Adapted from *Metals Handbook: Properties and Selection: Irons and Steels*, Vol. 1, 9th edition, B. Bardes (Editor), 1978; and *Metals Handbook: Properties and Selection: Nonferrous Alloys and Pure Metals*, Vol. 2, 9th edition, H. Baker (Managing Editor), 1979. Reproduced by permission of ASM International, Materials Park, OH.]

Heat Treatment of Cold-Worked Metal Alloys

- Heat treating cold worked metals brings about changes in structure and properties
- As a result, effects of cold work are nullified!
- This type of heat treatment sometimes termed "annealing"
- 1 hour treatment at T_{anneal} decreases tensile strength & increases %EL



Three Annealing stages:

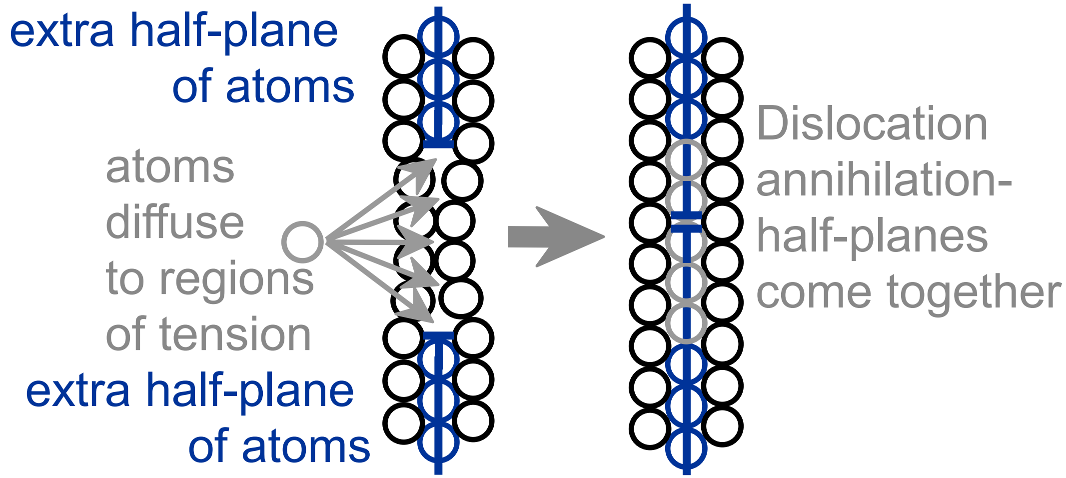
1. Recovery (100-200° C)
2. Recrystallization (200-500° C)
3. Grain Growth (> 500° C)

Fig. 7.22, *Callister & Rethwisch 10e.* (Adapted from G. Sachs and K. R. Van Horn, *Practical Metallurgy, Applied Metallurgy and the Industrial Processing of Ferrous and Nonferrous Metals and Alloys*, 1940. Reproduced by permission of ASM International, Materials Park, OH.)

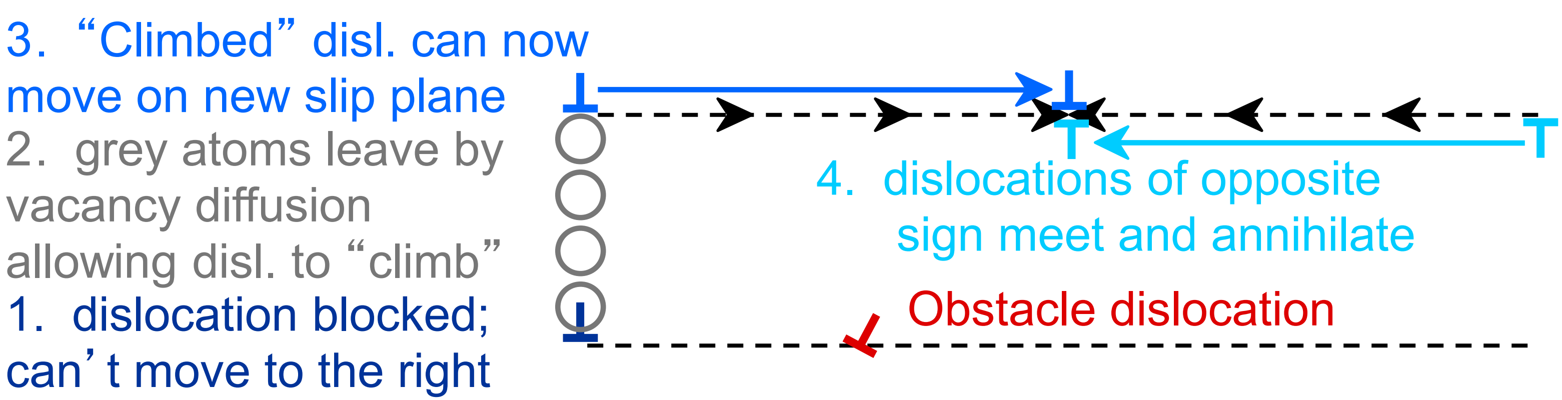
Recovery

During recovery – reduction in disl. density – annihilation of disl.

- Scenario 1

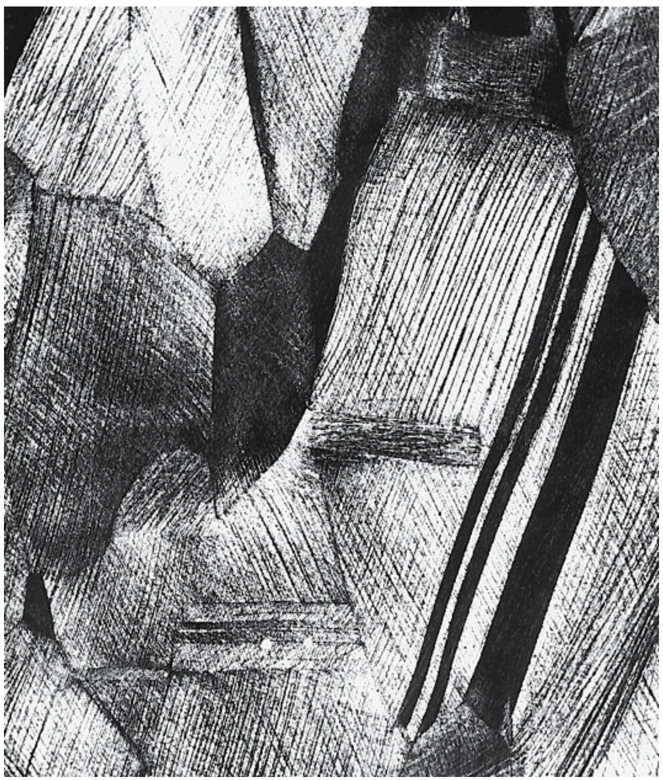


- Scenario 2



Recrystallization

- New grains form that:
  - -- have low dislocation densities
  - -- are small in size
  - -- consume and replace parent cold-worked grains.



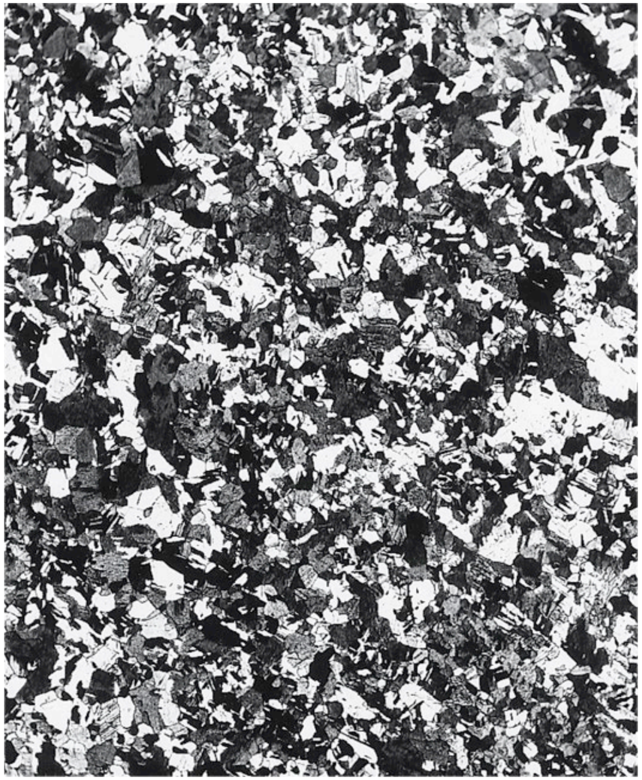
33%CW brass before heat treatment

After 4 sec. at 580° C

Adapted from Fig. 7.21 (a),(c), *Callister & Rethwisch 10e.* (Photomicrographs courtesy of J.E. Burke, General Electric Company.)

Recrystallization (cont.)

- All grains in cold-worked material have been consumed/replaced.



After 8 sec. at 580° C

Adapted from Fig. 7.21 (d), *Callister & Rethwisch 10e.* (Photomicrographs courtesy of J.E. Burke, General Electric Company.)

Recrystallization Temperature

T_R = recrystallization temperature = temperature at which recrystallization just reaches completion in 1 h.

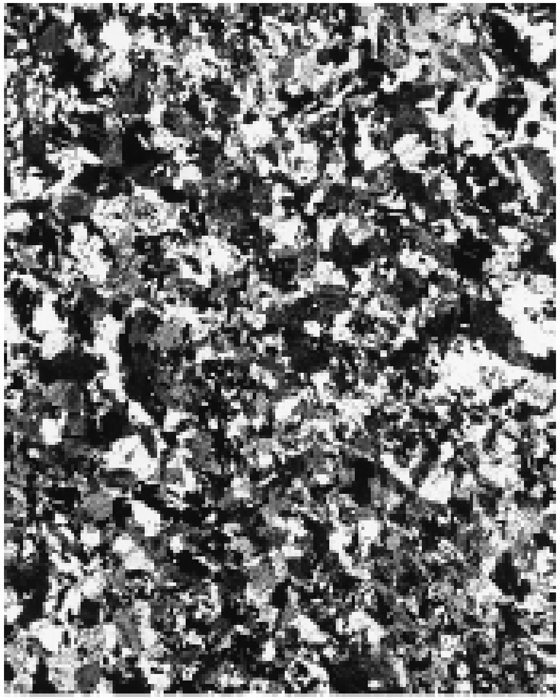
$$0.3T_m < T_R < 0.6T_m$$

For a specific metal/alloy, T_R depends on:

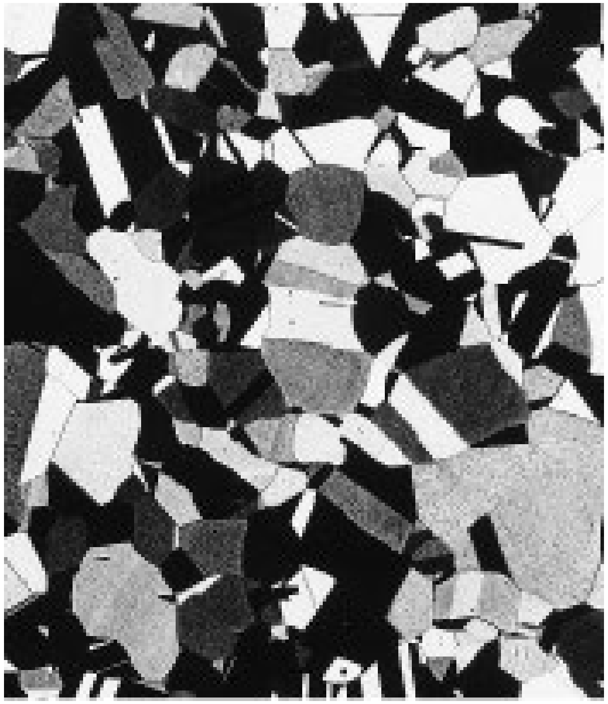
- %CW -- T_R decreases with increasing %CW
- Purity of metal -- T_R decreases with increasing purity

Grain Growth

- Grain growth occurs as heat treatment continues.
  - -- Average grain size increases
  - -- Small grains shrink (and ultimately disappear)
  - -- Large grains continue to grow



After 8 sec. at 580° C



After 15 min. at 580° C

Adapted from Fig. 9.21 (d),(e), *Callister & Rethwisch 10e.* (Photomicrographs courtesy of J.E. Burke, General Electric Company.)

Grain Growth (cont.)

- Empirical relationship—dependence of average grain size (*d*) on heat treating time (*t*):

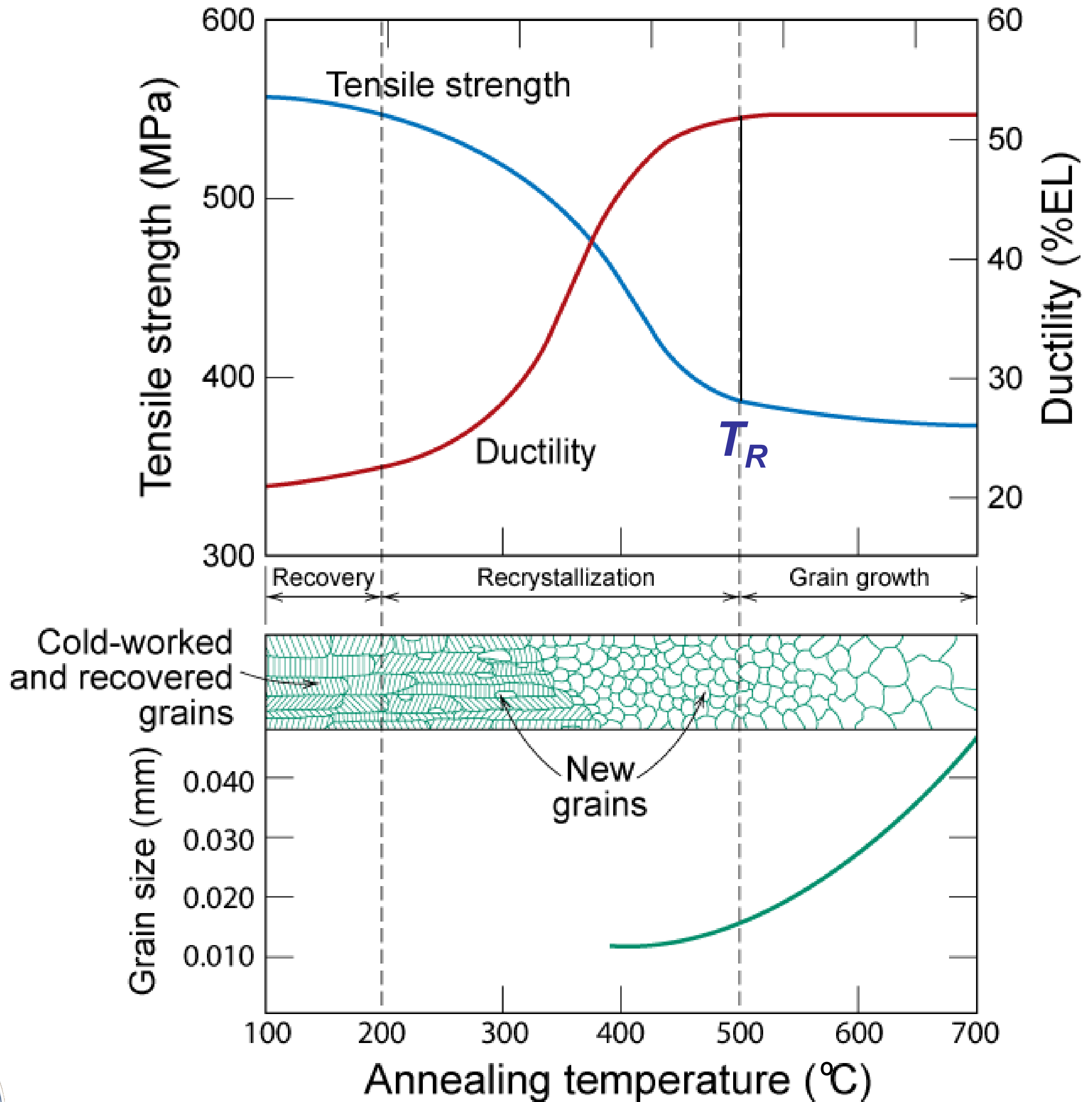
exponent typ. ~ 2

material constant
—depends on *T*
—independent of *t*

$$d^n - d_o^n = Kt$$

Initial average grain diam. before heat treatment

Recovery, Recrystallization, & Grain Growth

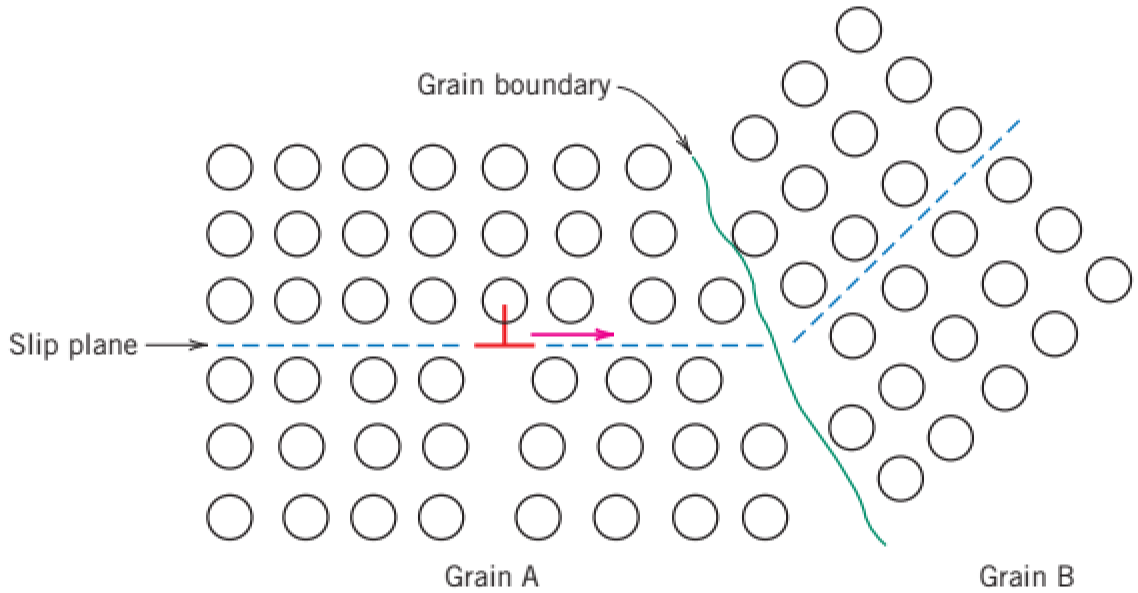


T_R = recrystallization temperature

annealing time = 1 h

Fig. 7.22, *Callister & Rethwisch 10e.*
(Adapted from G. Sachs and K. R. Van Horn, *Practical Metallurgy, Applied Metallurgy and the Industrial Processing of Ferrous and Nonferrous Metals and Alloys*, 1940. Reproduced by permission of ASM International, Materials Park, OH.)

Grain Size Effects Strength



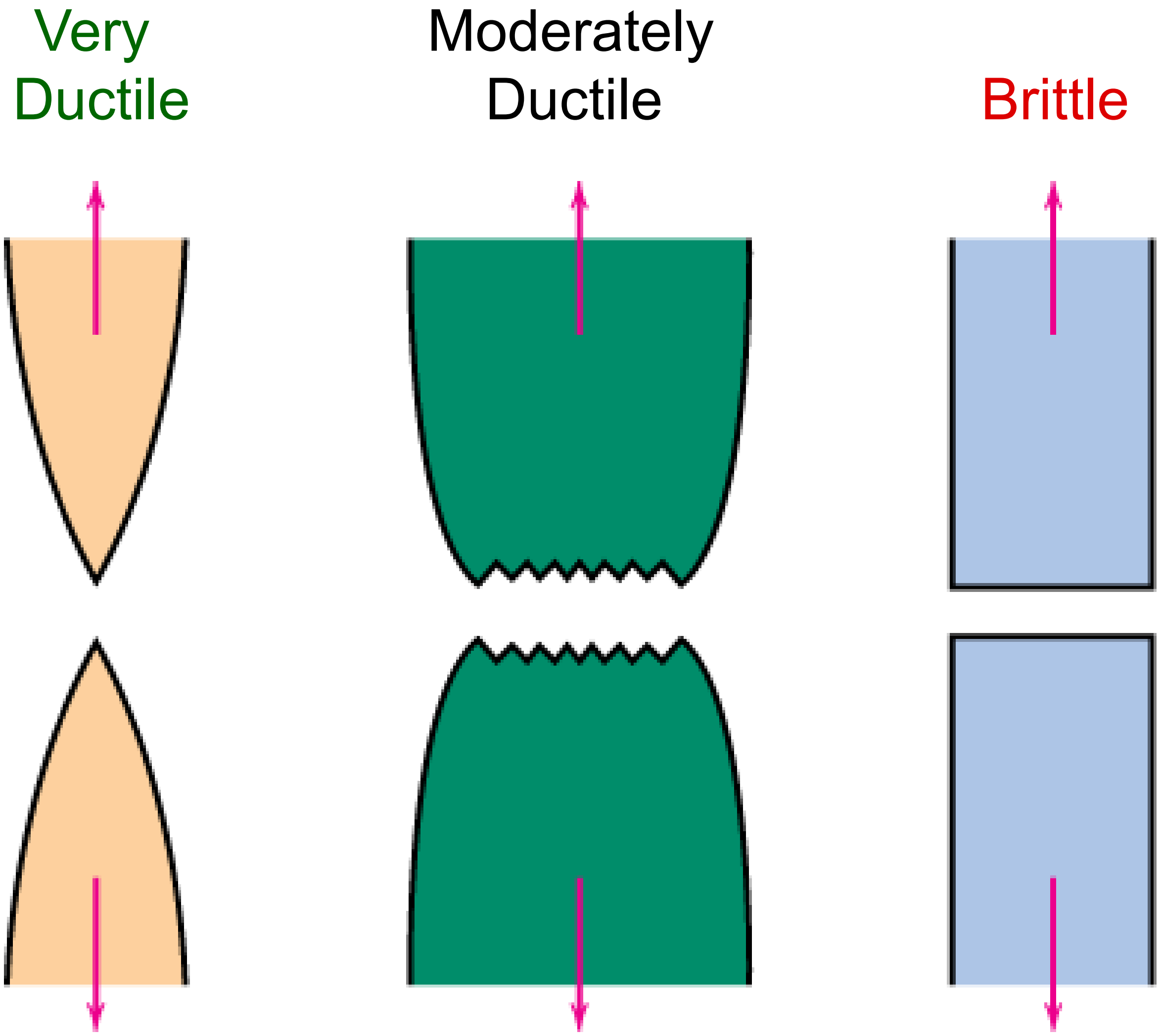
$$\sigma_y = \sigma_0 + k_y d^{-1/2}$$

Yield Strength

Average Grain Diameter

Material Property Constants

Fracture Profiles



Adapted from Fig. 8.1, *Callister & Rethwisch 10e.*

Fracture Surface Photographs

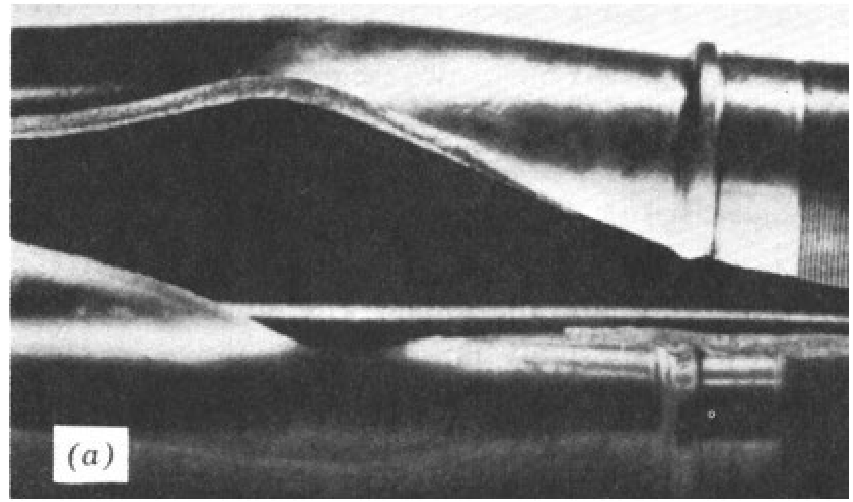
cup-and-cone fracture
- moderately ductile

brittle fracture
- totally brittle
- flat surfaces

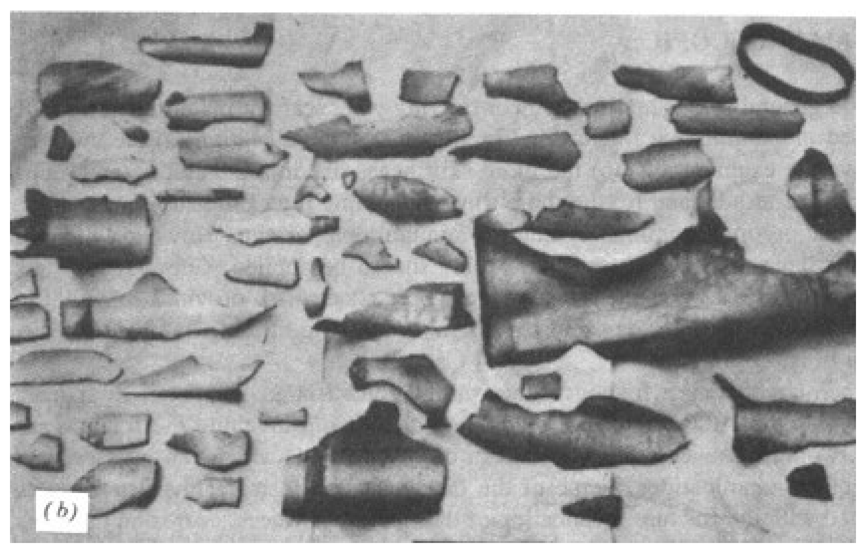
Fig. 8.3, *Callister & Rethwisch 10e.*

Examples of Ductile and Brittle Fracture of Pipes

- **Ductile fracture:**
  -- one piece
  -- large deformation

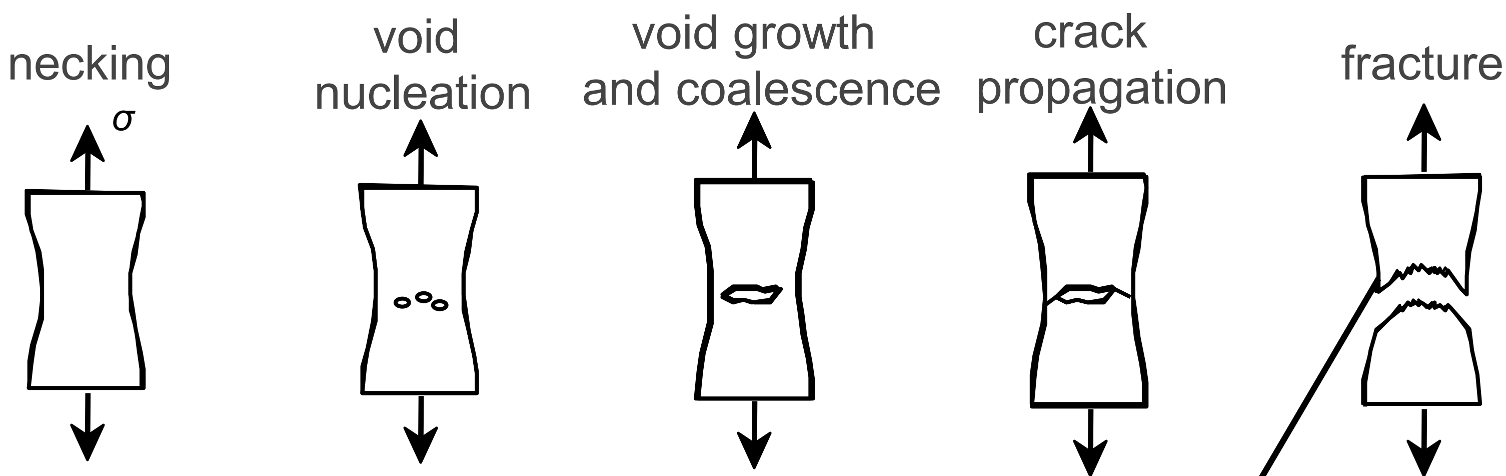


- **Brittle fracture:**
  -- many pieces
  -- small deformations

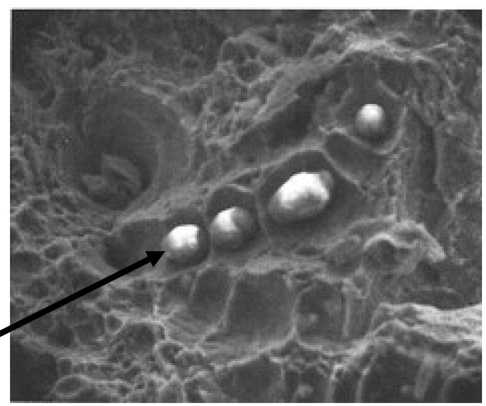


Figures from V.J. Colangelo and F.A. Heiser, *Analysis of Metallurgical Failures* (2nd ed.), Fig. 4.1(a) and (b), p. 66 John Wiley and Sons, Inc., 1987. Used with permission.

Stages of Moderately Ductile Failure

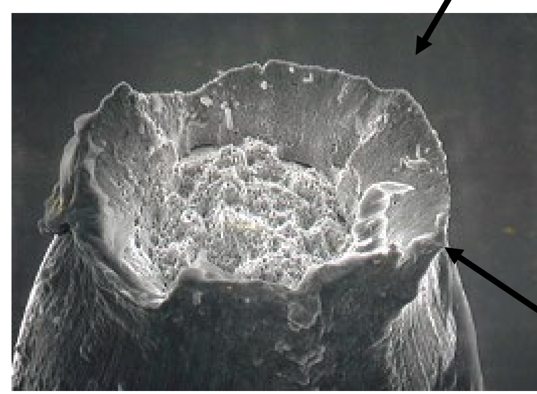


- Electron micrographs of fracture surfaces (steel)



particles serve as void nucleation sites.

From V.J. Colangelo and F.A. Heiser, *Analysis of Metallurgical Failures* (2nd ed.), Fig. 11.28, p. 294, John Wiley and Sons, Inc., 1987. (Orig. source: P. Thornton, *J. Mater. Sci.*, Vol. 6, 1971, pp. 347-56.)



Fracture surface of tire cord wire loaded in tension. Courtesy of F. Roehrig, CC Technologies, Dublin, OH. Used with permission.

cup and cone fracture surface

Brittle Failure Surface Photographs

- Brittle fracture surface displays V-shaped, chevron markings
- V features point to the crack initiation site

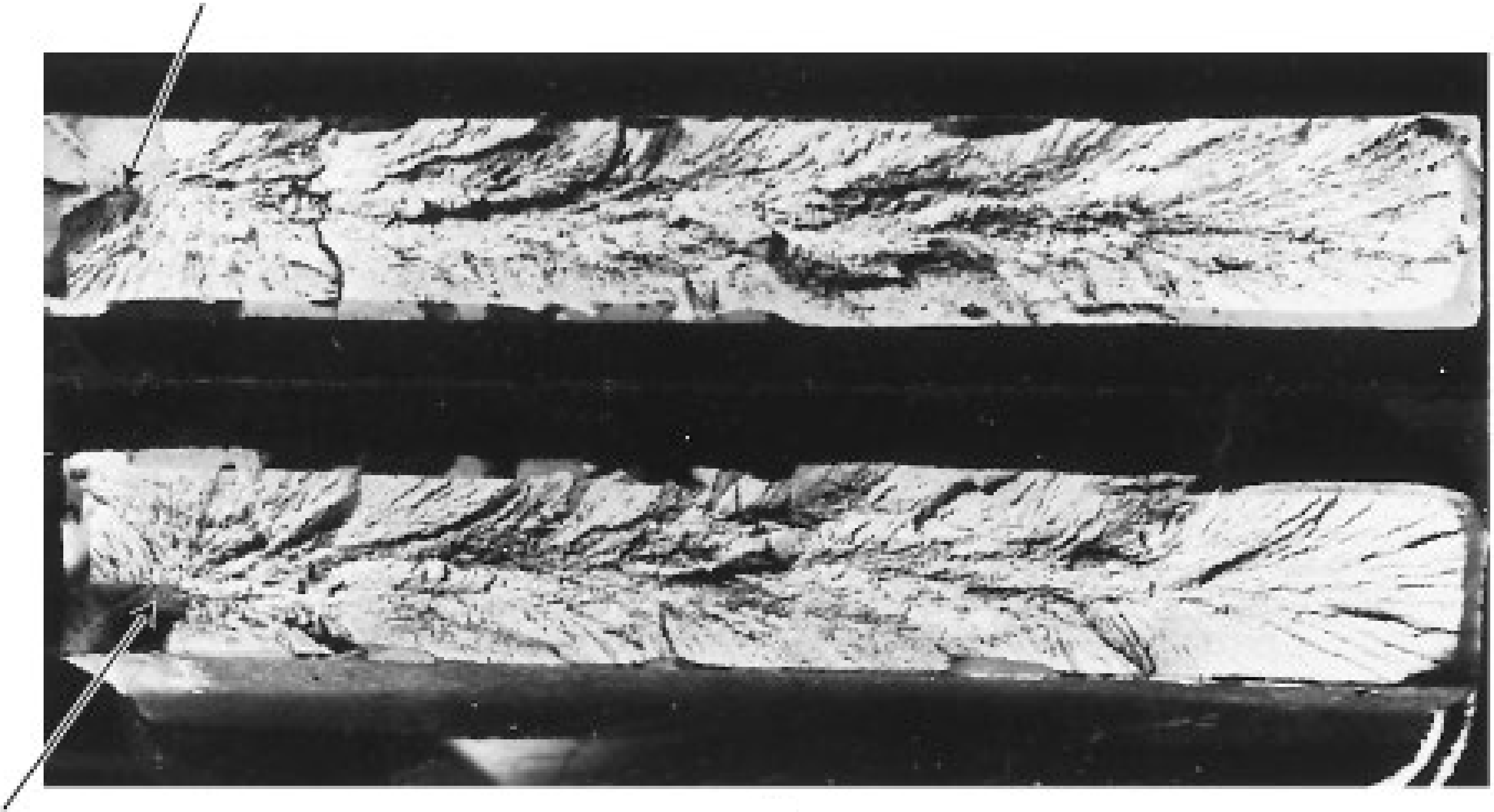
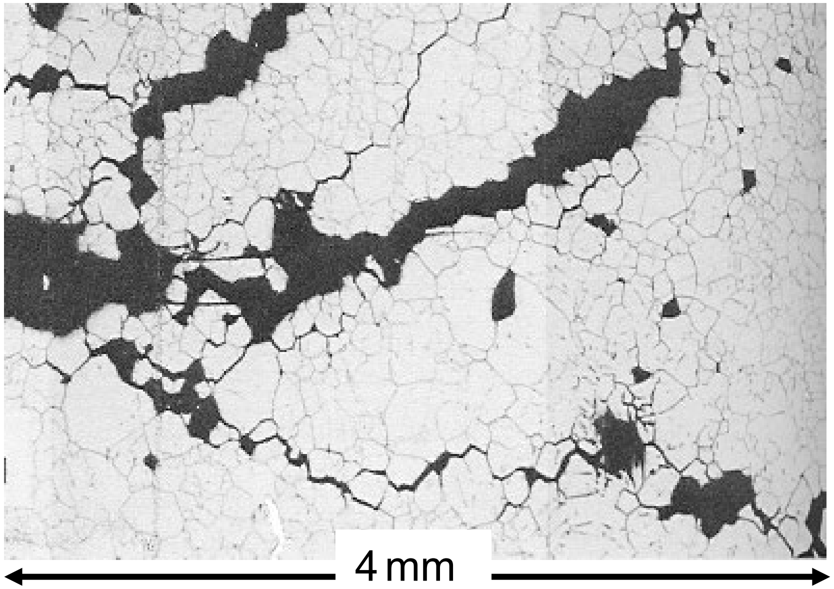


Fig. 8.5(a), *Callister & Rethwisch 10e.* [From R. W. Hertzberg, *Deformation and Fracture Mechanics of Engineering Materials*, 3rd edition. Copyright © 1989 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc. Photograph courtesy of Roger Slutter, Lehigh University.]

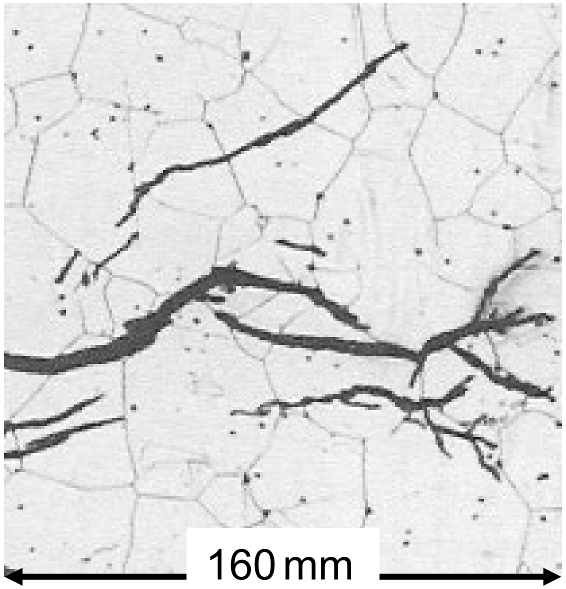
Photographs of Brittle Fracture Surfaces

- Intergranular crack propagation (between grains)



304 S. Steel (metal)
Reprinted w/permission from "Metals Handbook", 9th ed, Fig. 633, p. 650. Copyright 1985, ASM International, Materials Park, OH. (Micrograph by J.R. Keiser and A.R. Olsen, Oak Ridge National Lab.)

- Transgranular crack propagation (through grains)



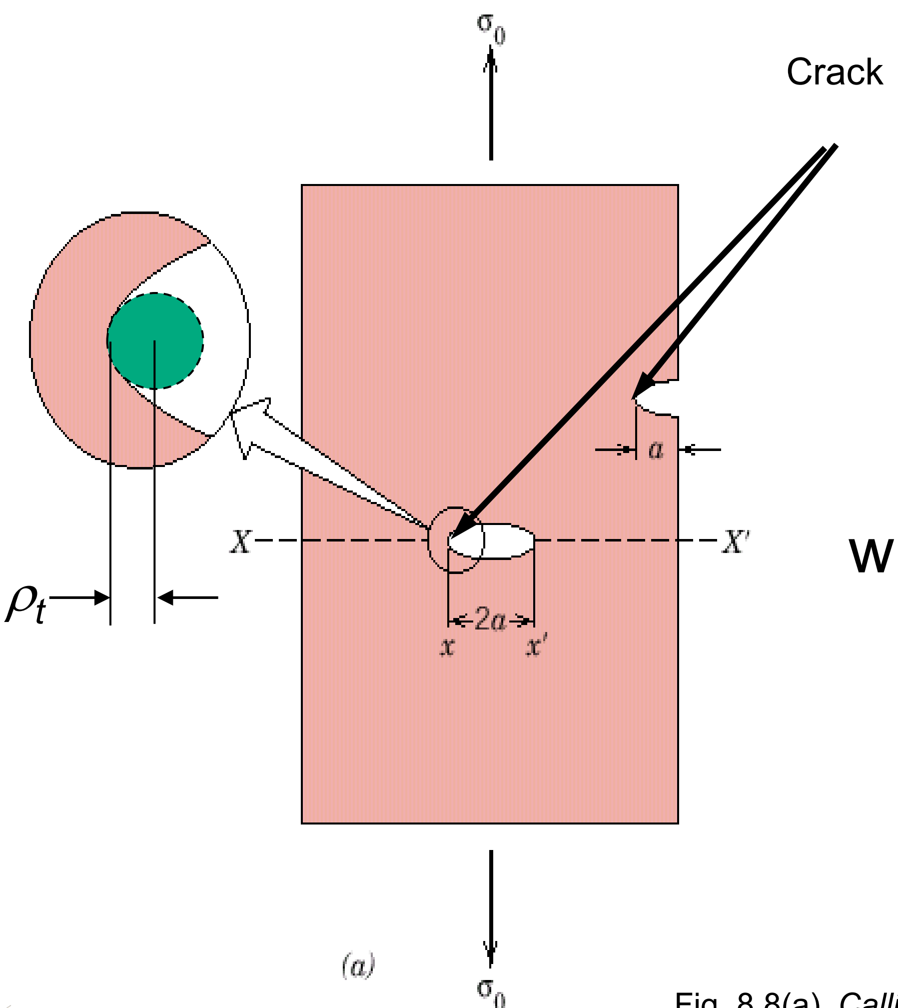
316 S. Steel (metal)
Reprinted w/ permission from "Metals Handbook", 9th ed, Fig. 650, p. 357. Copyright 1985, ASM International, Materials Park, OH. (Micrograph by D.R. Diercks, Argonne National Lab.)

Principles of Fracture Mechanics

- Fracture occurs as result of crack propagation
- Measured fracture strengths of most materials much lower than predicted by theory
  - microscopic flaws (cracks) always exist in materials
  - magnitude of applied tensile stress amplified at the tips of these cracks

Fracture Mechanics (cont.)

Flaws are Stress Concentrators!



$$\sigma_m = 2\sigma_o\left(\frac{a}{\rho_t}\right)^{1/2}$$

where

ρ_t = radius of curvature

σ_o = applied stress

σ_m = stress at crack tip

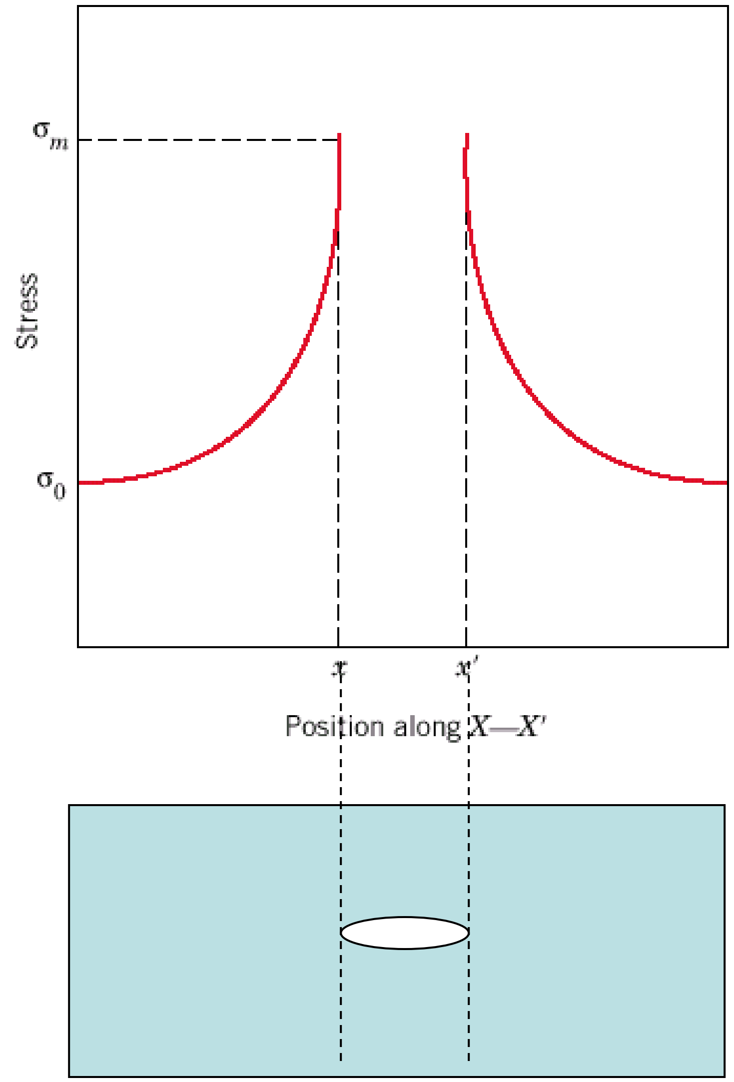
Fig. 8.8(a), *Callister & Rethwisch 10e.*

Fracture Mechanics (cont.)

Stress Concentration at Crack Tip

K_t = stress concentration factor

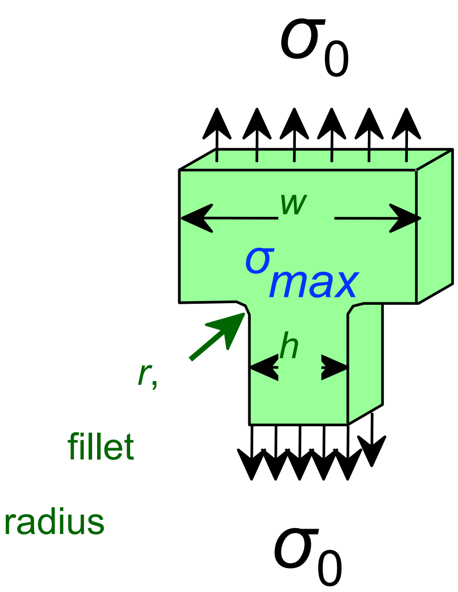
$$K_t = \frac{\sigma_m}{\sigma_o}$$



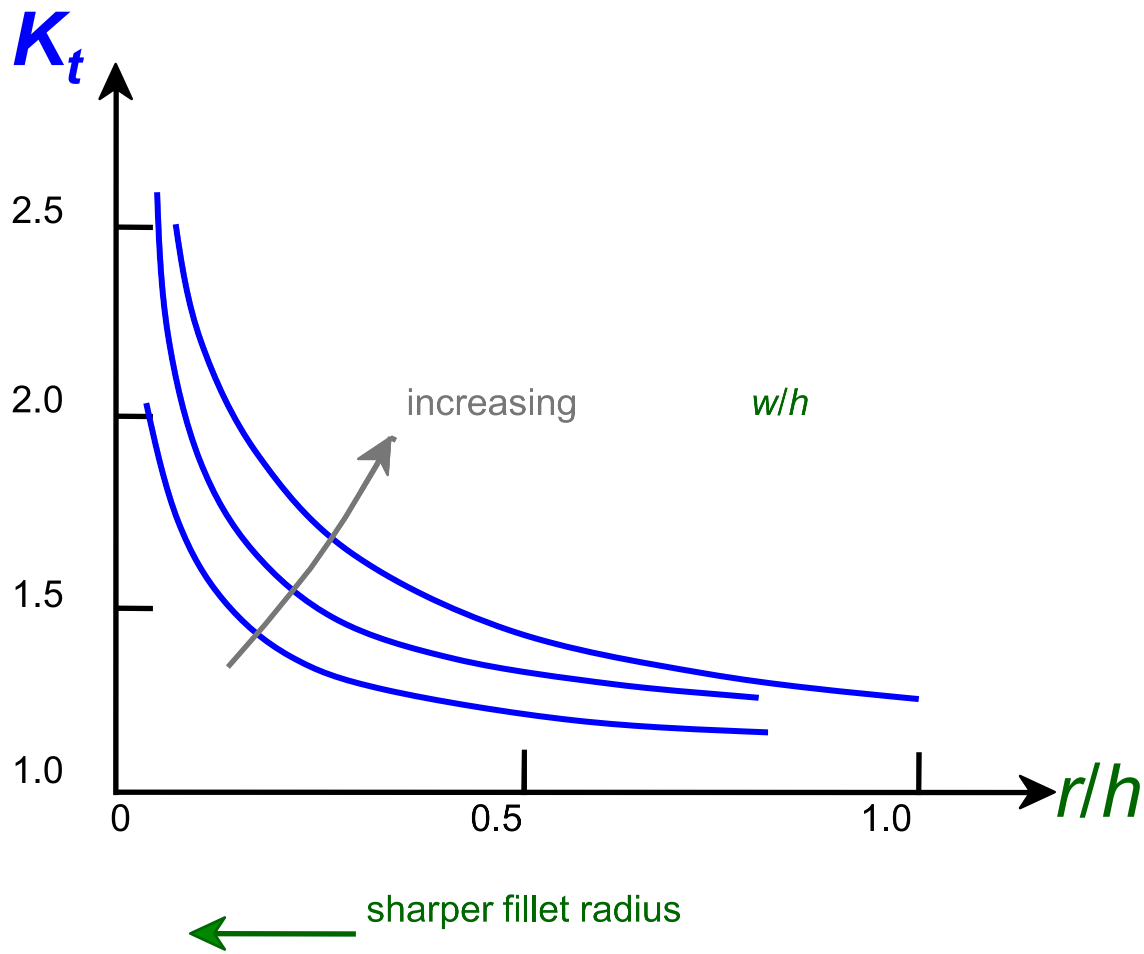
Adapted from Fig. 8.8(b), *Callister & Rethwisch 10e.*

Fracture Mechanics (cont.)

- **Avoid sharp corners!**

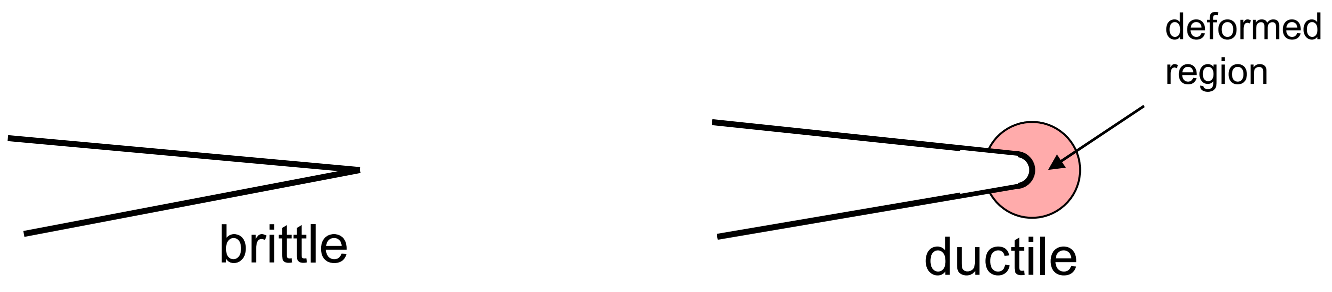


Adapted from Fig. 8.2W(c), *Callister 6e.*
(Fig. 8.2W(c) is from G.H. Neugebauer, *Prod. Eng.* (NY), Vol. 14, pp. 82-87 1943.)



Crack Propagation

- Stress concentration higher for sharp cracks—propagate at lower stresses than cracks with blunt tips
- For ductile materials—plastic deformation at crack tip when stress reaches yield strength—tip blunted—lowers stress conc.



Criterion for Crack Propagation

Critical stress for crack propagation (σ_c) of brittle materials

$$\sigma_c = \left(\frac{2E\gamma_s}{\pi a} \right)^{1/2}$$

where

- σ_c = crack-tip stress
- E = modulus of elasticity
- γ_s = specific surface energy
- a = one half length of internal crack

For ductile materials replace γ_s with $\gamma_s + \gamma_p$ where γ_p is plastic deformation energy

- materials have numerous cracks with different lengths and orientations
- crack propagation (and fracture) occurs when $\sigma_m > \sigma_c$ for crack with lowest σ_c
- Largest, most highly stressed cracks grow first!