Chapter 8: Mechanical Failure

Topics

- How do flaws in a material initiate failure?
- How is fracture resistance quantified; how do different material classes compare?
- How do we estimate the stress to fracture?

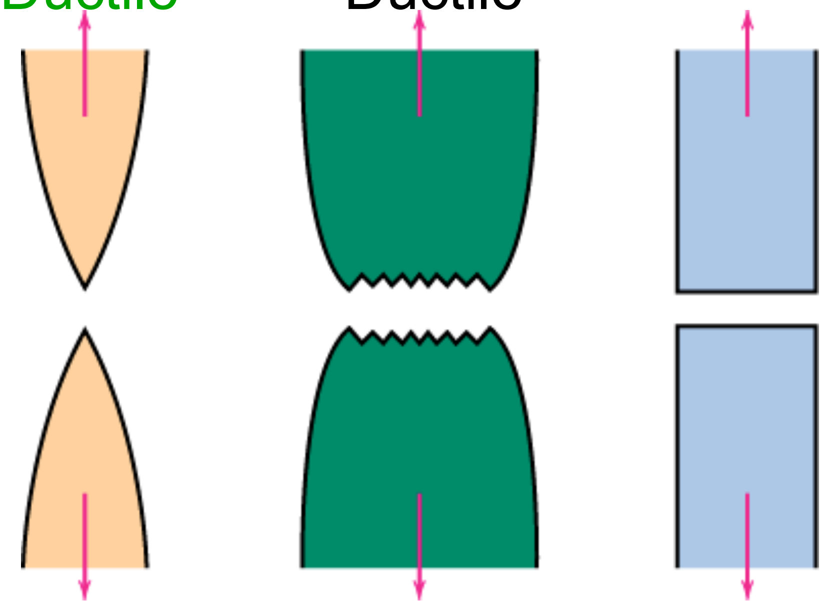
Fracture mechanisms

- Ductile fracture
  - Occurs with plastic deformation
- Brittle fracture
  - Little or no plastic deformation
  - Catastrophic

Ductile vs Brittle Failure

• Classification:

Fracture behavior:	Very Ductile	Moderately Ductile	Brittle
%*AR* or %*EL*	Large	Moderate	Small



Adapted from Fig. 8.1, *Callister 7e.*

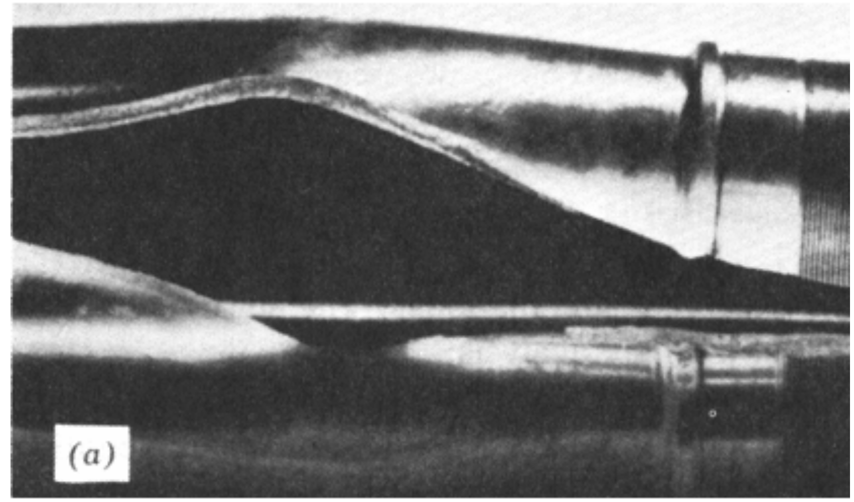
• Ductile fracture is usually desirable!

Ductile: warning before fracture

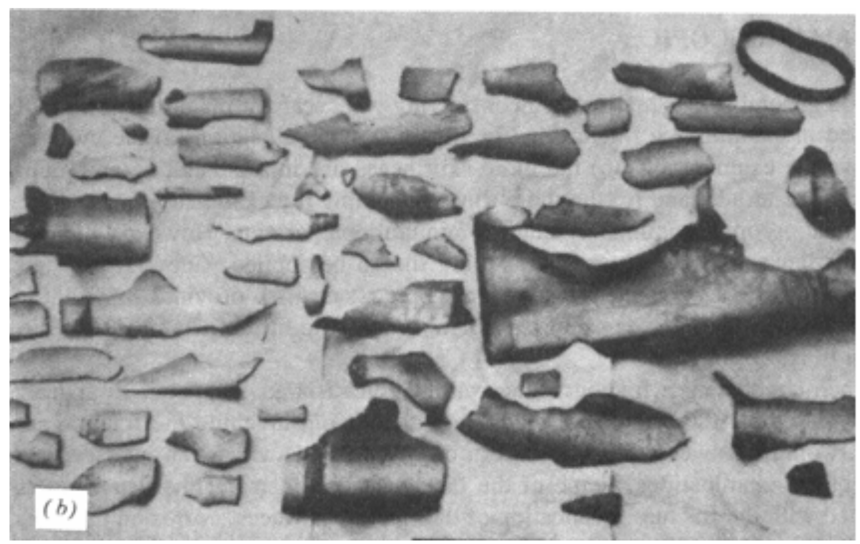
Brittle: No warning

Example: Failure of a Pipe

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



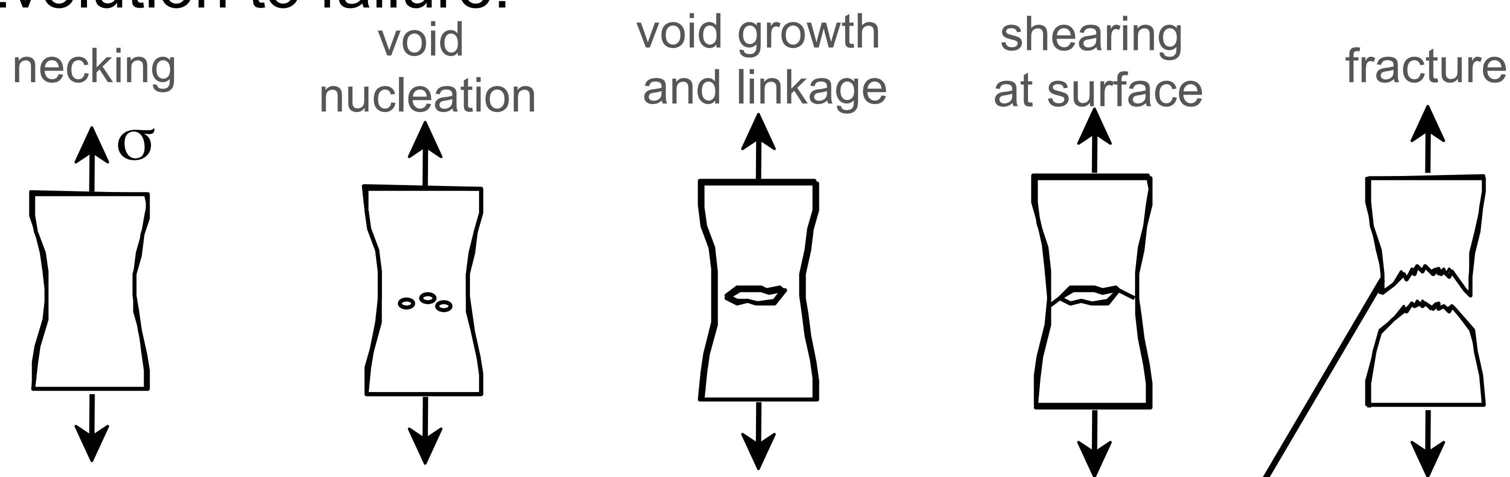
- **Brittle failure:**
  --many pieces
  --small deformation



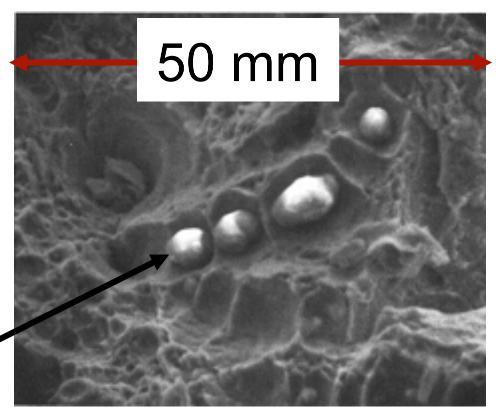
Figures from V.J. Colangelo and F.A. Heiser, *Analysis of Metallurgical Failures* (2nd ed.), Fig. 4.1(a) and (b), p. 66 John Wiley and Sons, Inc., 1987. Used with permission.

Moderately Ductile Failure

- Evolution to failure:

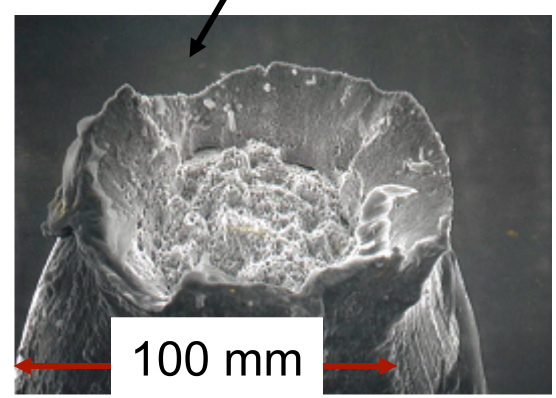


- Resulting fracture surfaces (steel)



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.

Ductile vs. Brittle Failure

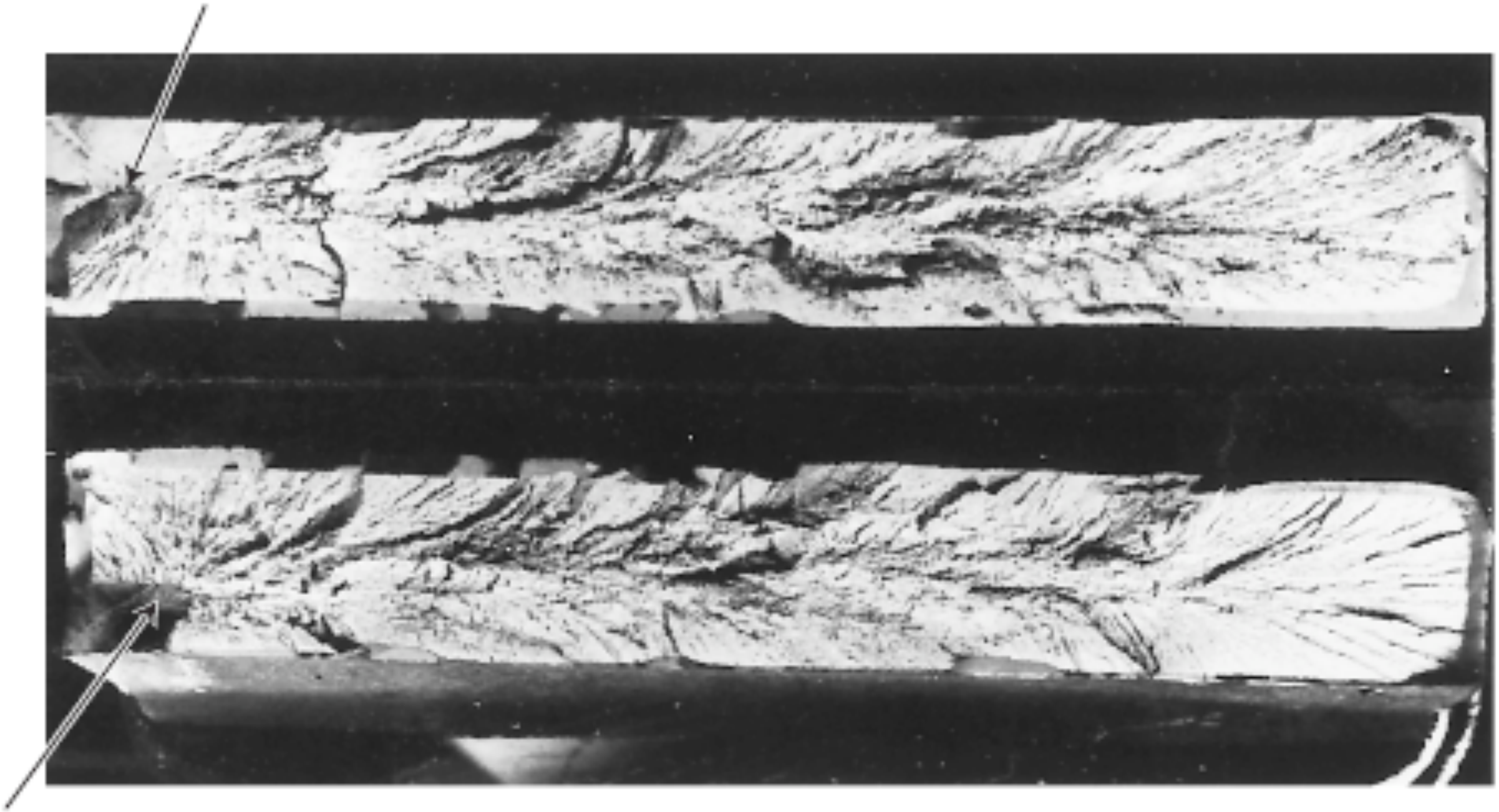
cup-and-cone fracture

brittle fracture

Adapted from Fig. 8.3, *Callister 7e.*

Brittle Failure

Arrows indicate pt at which failure originated

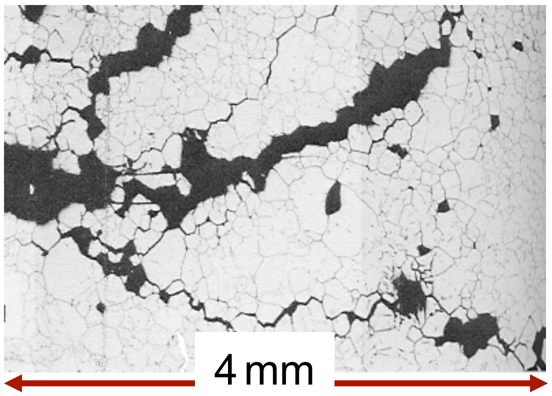


Adapted from Fig. 8.5(a), *Callister 7e.*

Brittle Fracture Surfaces

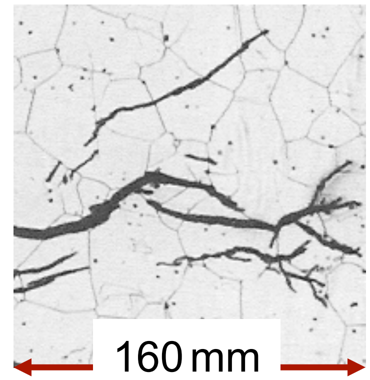
- Intergranular (between grains)

304 S. Steel (metal)

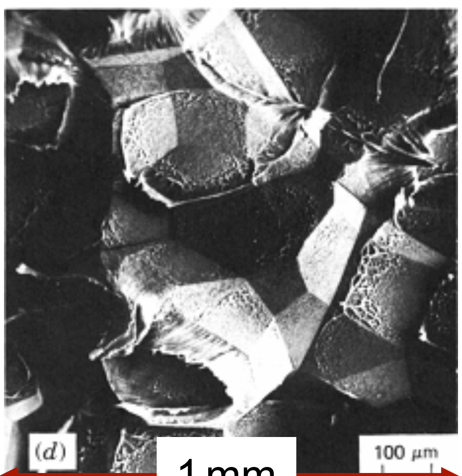


- Intragranular (within grains)

316 S. Steel (metal)

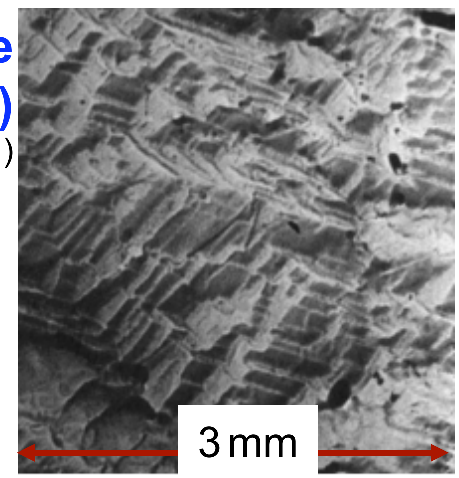


Polypropylene (polymer)



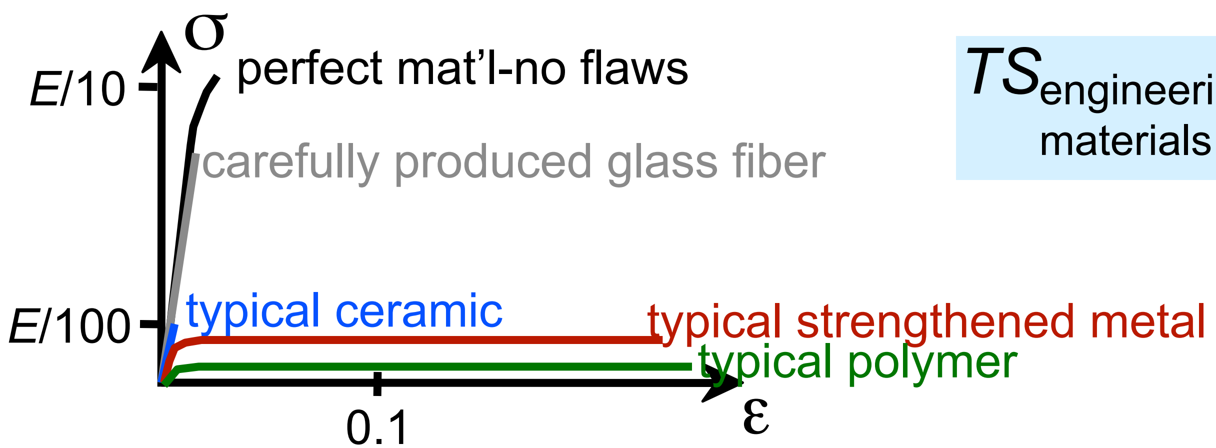
(Orig. source: K. Friedrick, *Fracture 1977*, Vol. 3, ICF4, Waterloo, CA, 1977, p. 1119.)

Al Oxide (ceramic)
)



Ideal vs Real Materials

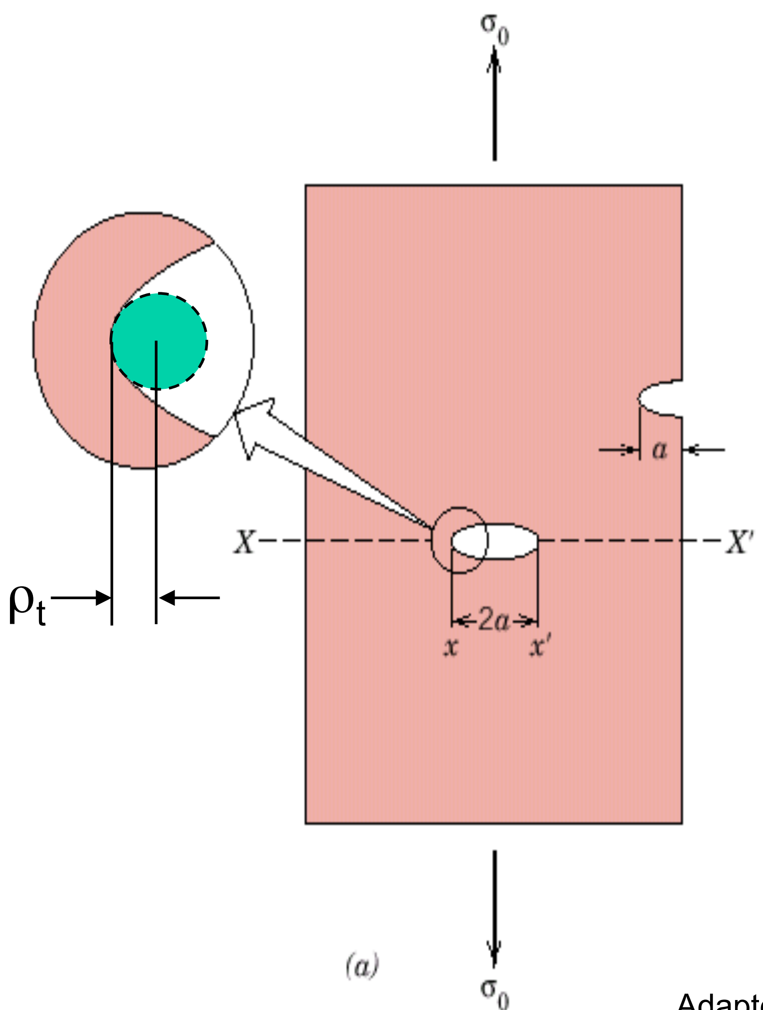
- Stress-strain behavior (Room *T*):



$TS_{\text{engineering materials}} \ll TS_{\text{perfect materials}}$

- DaVinci (500 yrs ago!) observed...
  -- the longer the wire, the smaller the load for failure.
- Reasons:
  -- flaws cause premature failure.
  -- Larger samples contain more flaws!

Flaws are Stress Concentrators!



Results from crack propagation

- Griffith Crack

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

where

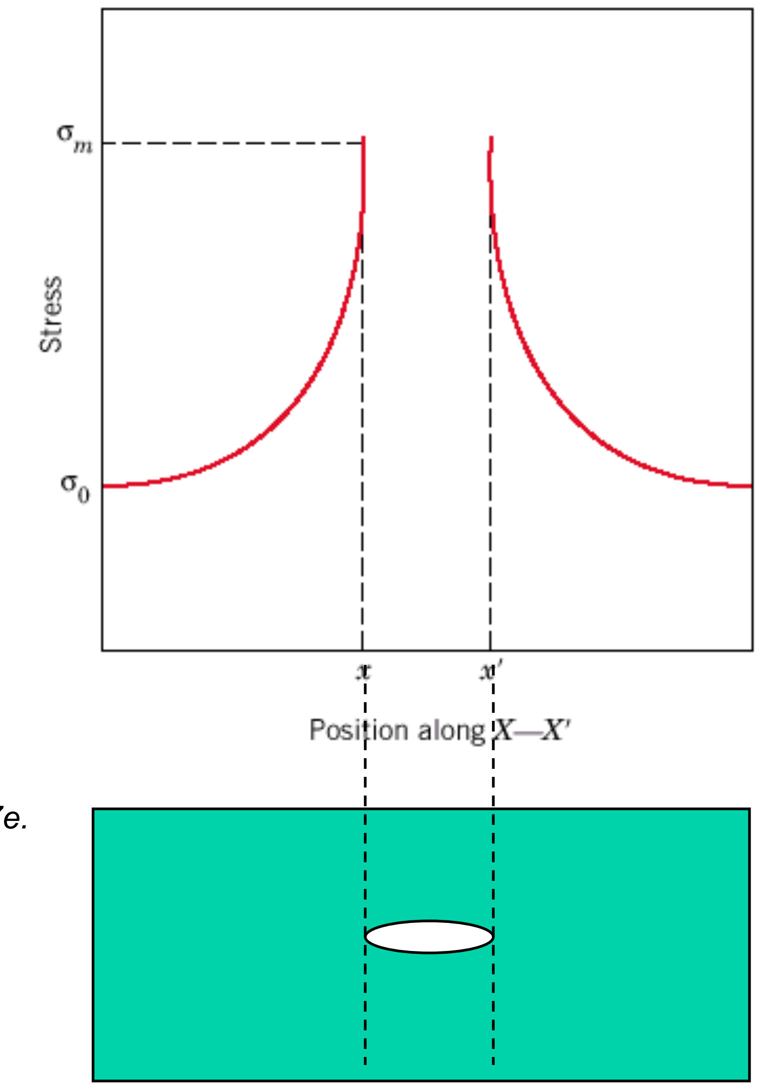
ρ_t = radius of curvature

σ_o = applied stress

σ_m = stress at crack tip

Adapted from Fig. 8.8(a), *Callister 7e.*

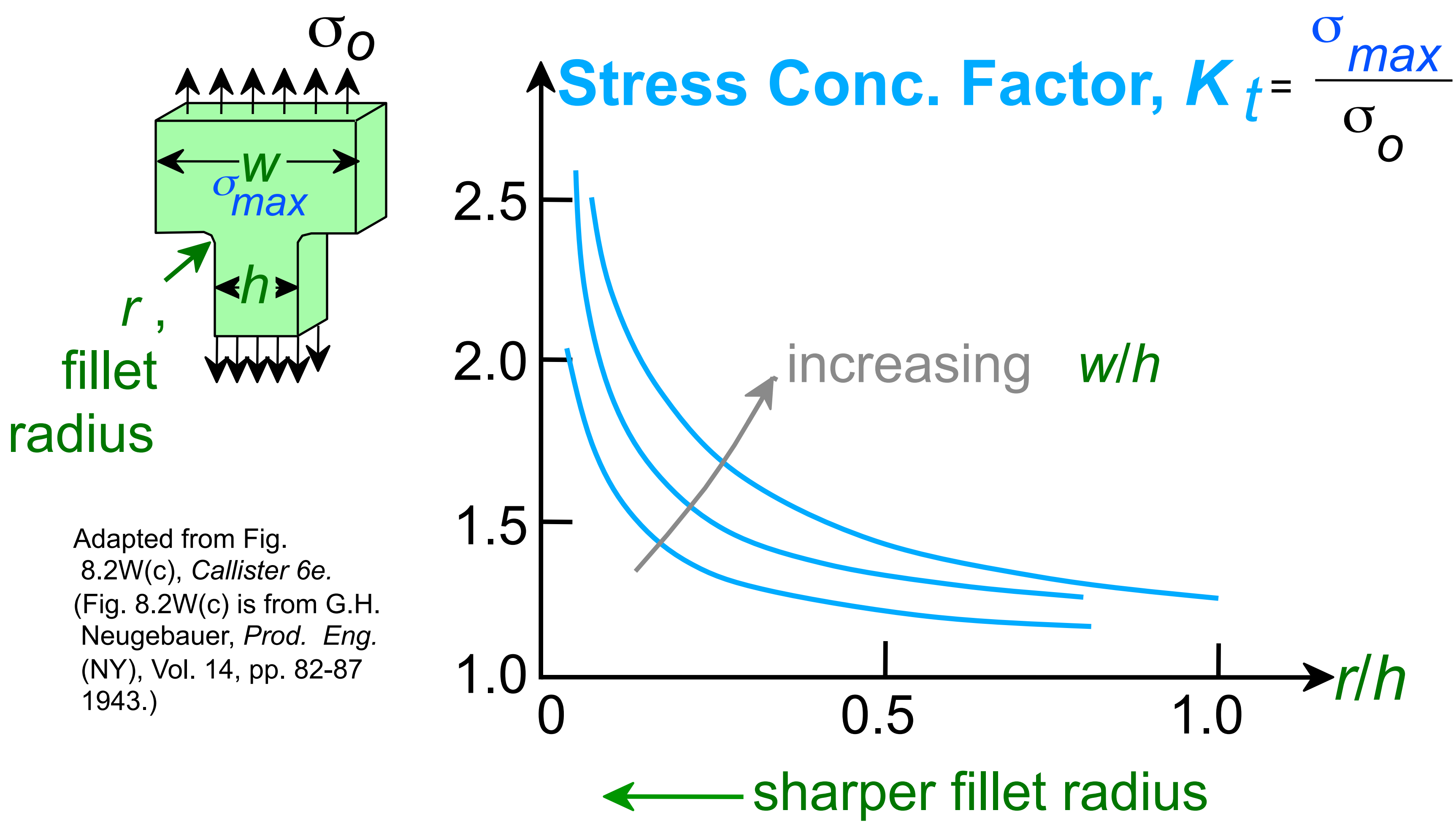
Concentration of Stress at Crack Tip



Adapted from Fig. 8.8(b), *Callister 7e.*

Engineering Fracture Design

- **Avoid sharp corners!**

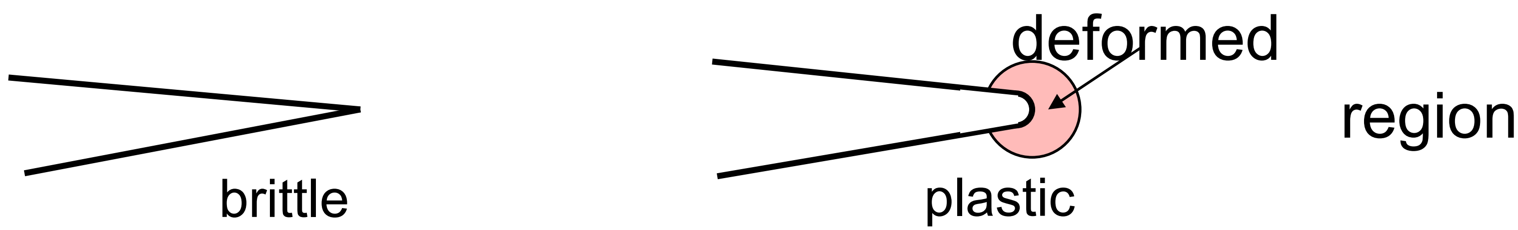


Adapted from Fig. 8.2W(c), *Callister 6e.* (Fig. 8.2W(c) is from G.H. Neugebauer, *Prod. Eng.* (NY), Vol. 14, pp. 82-87 1943.)

Crack Propagation

Cracks propagate due to sharpness of crack tip

- A plastic material deforms at the tip, “blunting” the crack.



Energy balance on the crack

- Elastic strain energy-
  - energy stored in material as it is elastically deformed
  - this energy is released when the crack propagates
  - creation of new surfaces requires energy

When Does a Crack Propagate?

Crack propagates if above critical stress

i.e., $\sigma_m > \sigma_c$

or $K_t > K_c$

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

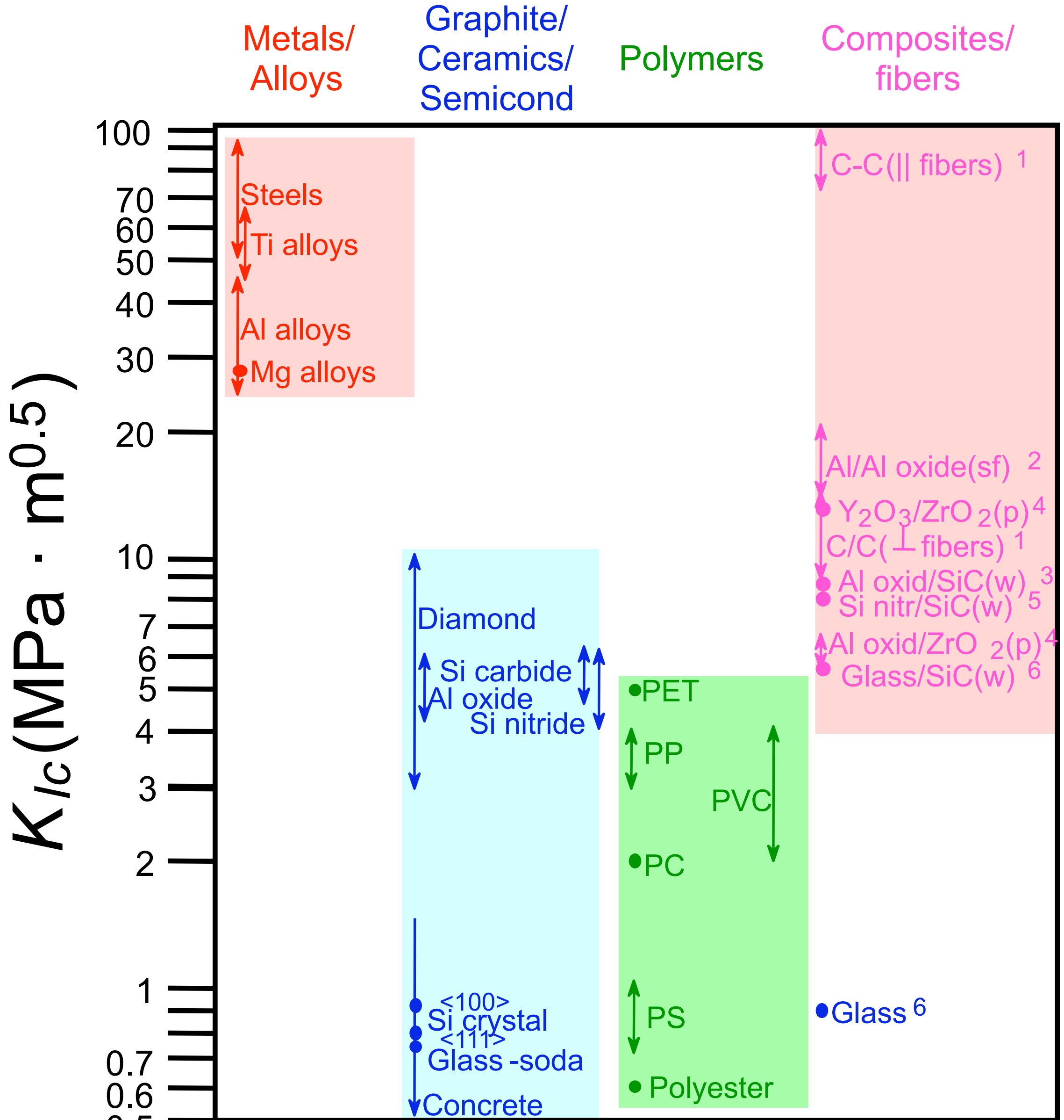
where

- E = modulus of elasticity
- γ_s = specific surface energy
- a = one half length of internal crack
- $K_c = \sigma_c/\sigma_0$

For ductile => replace γ_s by $\gamma_s + \gamma_p$

where γ_p is plastic deformation energy

Fracture Toughness



Based on data in Table B5, *Callister 7e*.

Composite reinforcement geometry is: f = fibers; sf = short fibers; w = whiskers; p = particles. Addition data as noted (vol. fraction of reinforcement):

1. (55vol%) *ASM Handbook*, Vol. 21, ASM Int., Materials Park, OH (2001) p. 606.
2. (55 vol%) Courtesy J. Cornie, MMC, Inc., Waltham, MA.
3. (30 vol%) P.F. Becher et al., *Fracture Mechanics of Ceramics*, Vol. 7, Plenum Press (1986). pp. 61-73.
4. Courtesy CoorsTek, Golden, CO.
5. (30 vol%) S.T. Buljan et al., "Development of Ceramic Matrix Composites for Application in Technology for Advanced Engines Program", ORNL/Sub/85-22011/2, ORNL, 1992.
6. (20vol%) F.D. Gace et al., *Ceram. Eng. Sci. Proc.*, Vol. 7 (1986) pp. 978-82.

Design Against Crack Growth

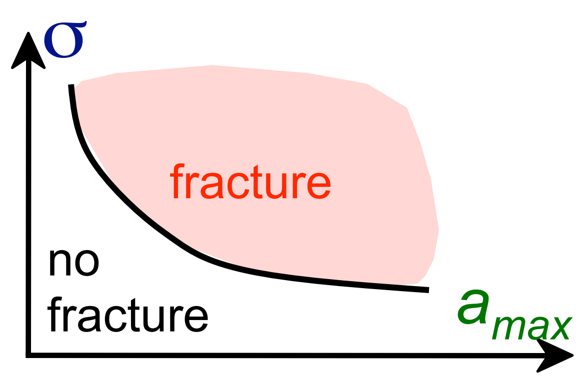
- Crack growth condition:

$$K \geq K_c = Y\sigma\sqrt{\pi a}$$

- Largest, most stressed cracks grow first!

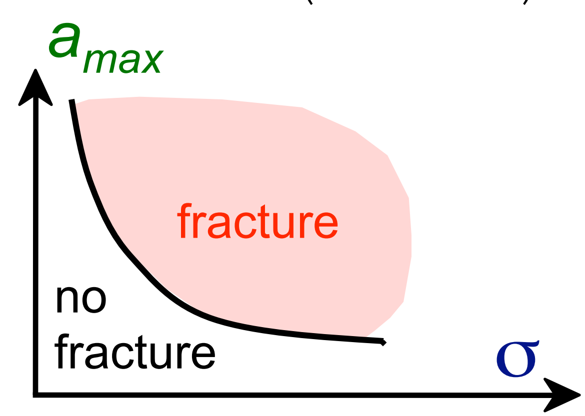
--Result 1: Max. flaw size dictates design stress.

$$\sigma_{design} < \frac{K_c}{Y\sqrt{\pi a_{max}}}$$



--Result 2: Design stress dictates max. flaw size.

$$a_{max} < \frac{1}{\pi}\left(\frac{K_c}{Y\sigma_{design}}\right)^2$$



Design Example: Aircraft Wing

- Material has K_c = 26 MPa-m$^{0.5}$
- Two designs to consider...

Design A
  --largest flaw is 9 mm
  --failure stress = 112 MPa

Design B
  --use same material
  --largest flaw is 4 mm
  --failure stress = ?

- Use...

$$\sigma_c = \frac{K_c}{Y\sqrt{\pi a_{max}}}$$

- Key point: Y and K_c are the same in both designs.

--Result:

112 MPa, 9 mm, 4 mm

$$\left(\sigma_c\sqrt{a_{max}}\right)_A = \left(\sigma_c\sqrt{a_{max}}\right)_B$$

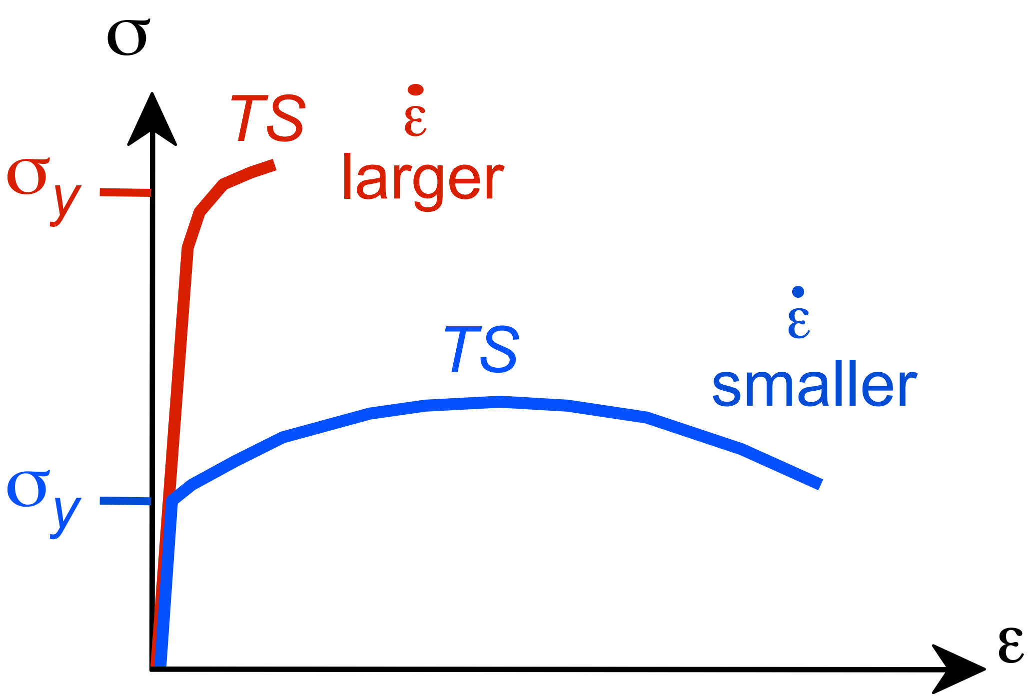
Answer: $(\sigma_c)_B = 168\text{ MPa}$

- Reducing flaw size pays off!

Loading Rate

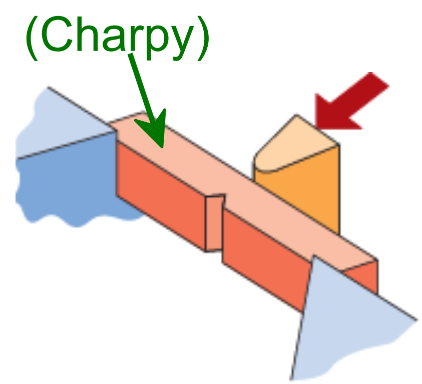
- Increased loading rate...
  -- increases σ_y and *TS*
  -- decreases %*EL*

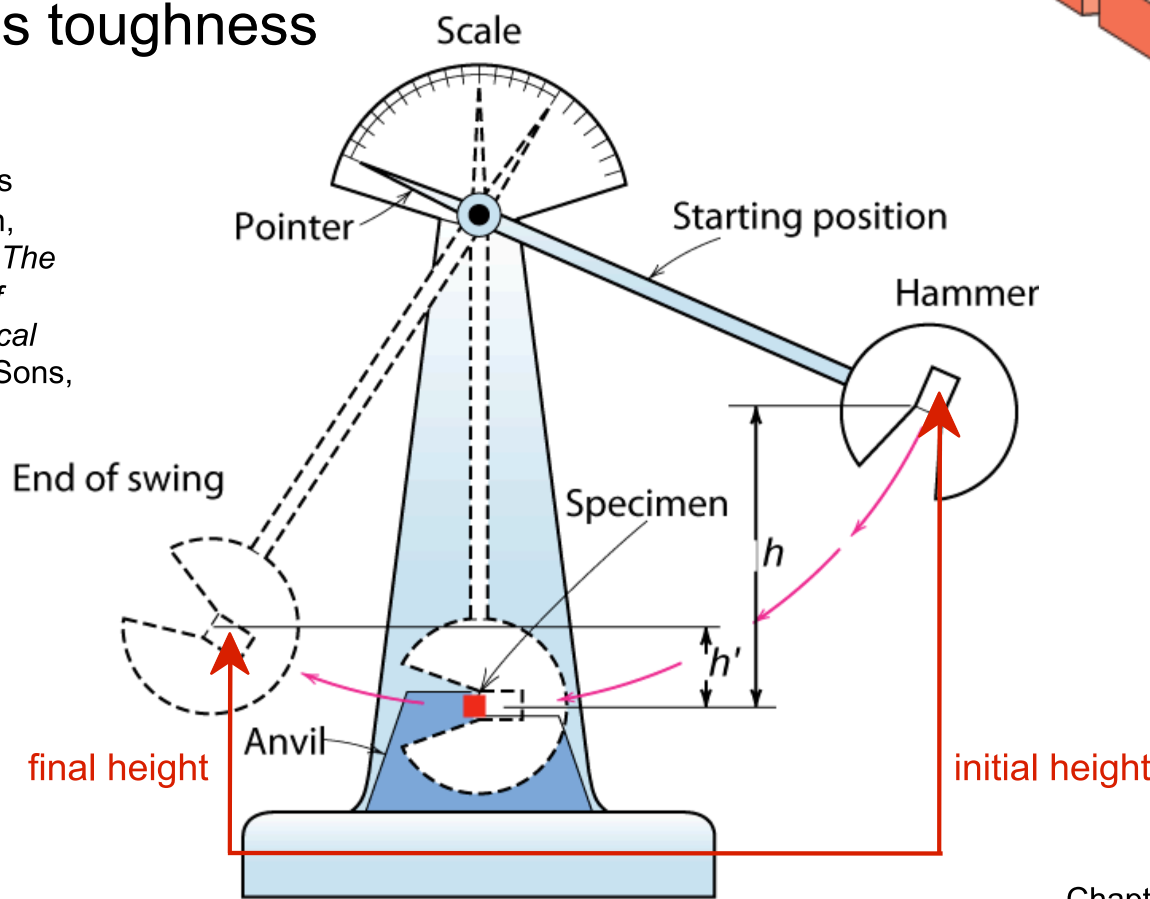
- Why? An increased rate gives less time for dislocations to move past obstacles.



Impact Testing

- Impact loading:
  - -- severe testing case
  - -- makes material more brittle
  - -- decreases toughness

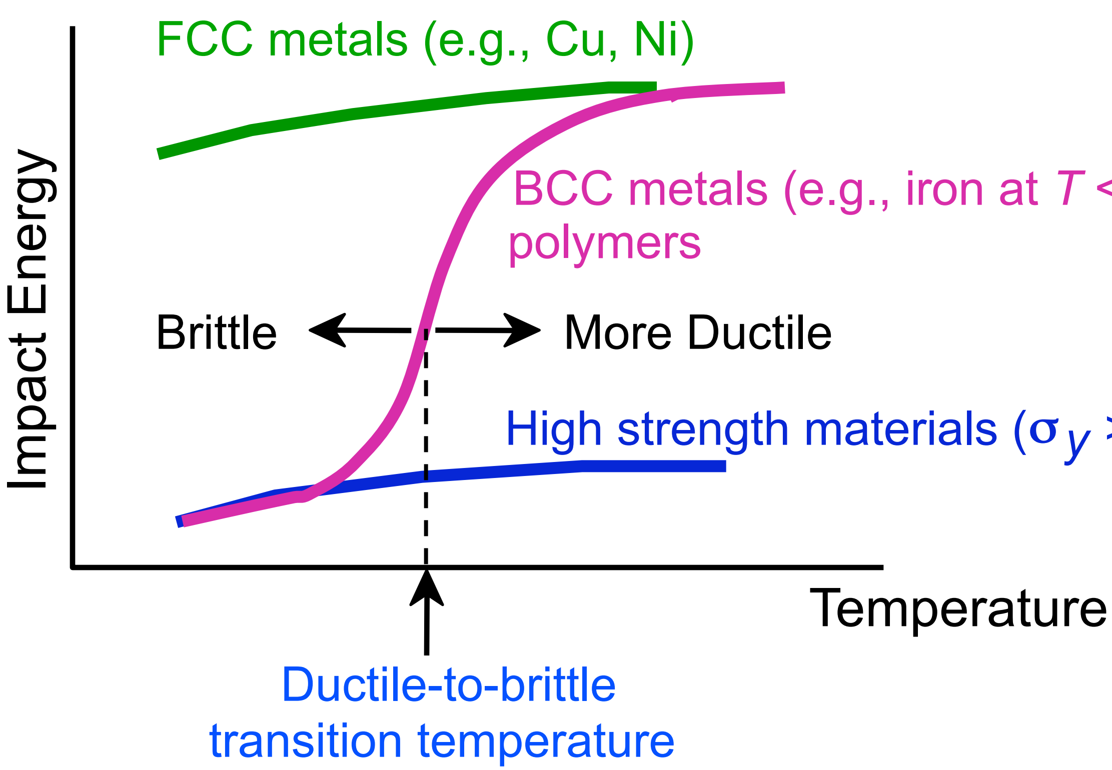




Adapted from Fig. 8.12(b), *Callister 7e.* (Fig. 8.12(b) is adapted from H.W. Hayden, W.G. Moffatt, and J. Wulff, *The Structure and Properties of Materials*, Vol. III, *Mechanical Behavior*, John Wiley and Sons, Inc. (1965) p. 13.)

Temperature

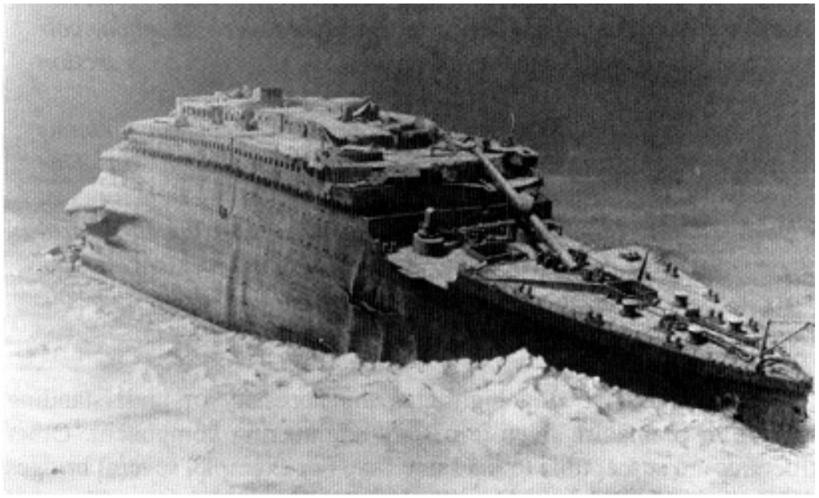
- **Increasing temperature...**
  --increases %*EL* and K_c
- **Ductile-to-Brittle Transition Temperature (DBTT)...**



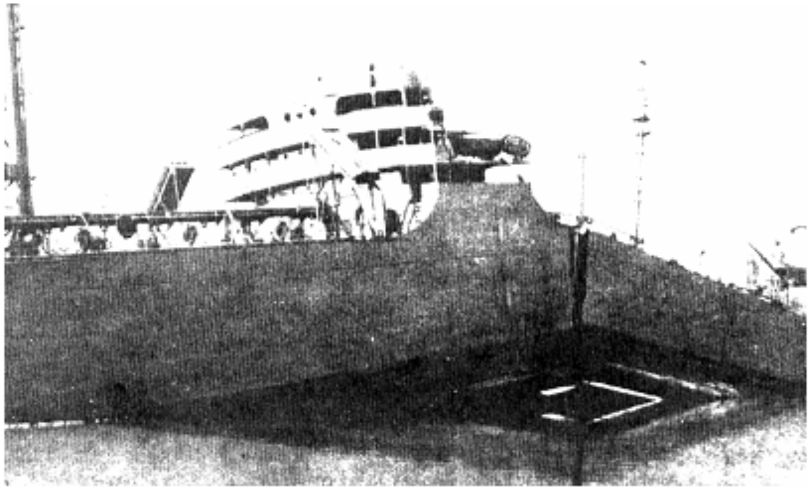
Adapted from Fig. 8.15, *Callister 7e.*

Design Strategy: Stay Above The DBTT!

- **Pre-WWII: The Titanic**



- **WWII: Liberty ships**



- Problem: Used a type of steel with a DBTT ~ Room temp.

SUMMARY

- Engineering materials don't reach theoretical strength.
- Flaws produce stress concentrations that cause premature failure.
- Sharp corners produce large stress concentrations and premature failure.
- Failure type depends on *T* and stress.