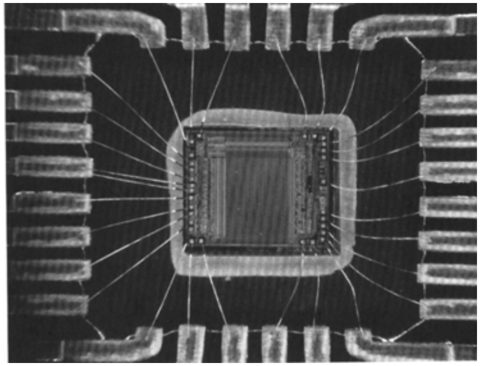
CHAPTER 8:
Mechanical failure

ISSUES TO ADDRESS...

- 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?
- How do loading rate, loading history, and temperature affect the failure stress?

Ship-cyclic loading from waves.

Adapted from Fig. 8.0, *Callister 6e.* (Fig. 8.0 is by Neil Boenzi, *The New York Times*.)



Computer chip-cyclic thermal loading.

Adapted from Fig. 18.11W(b), *Callister 6e.* (Fig. 18.11W(b) is courtesy of National Semiconductor Corporation.)

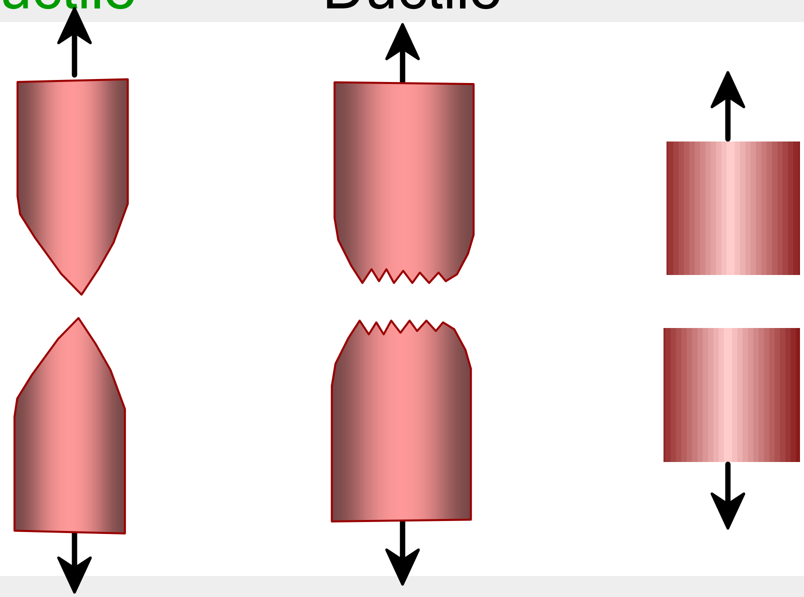
Hip implant-cyclic loading from walking.

Adapted from Fig. 17.19(b), *Callister 6e.*

Ductile vs brittle failure

- Classification:

Fracture behavior:	Very Ductile	Moderately Ductile	Brittle



Adapted from Fig. 8.1, *Callister 6e.*

%AR or %EL :	Large	Moderate	Small

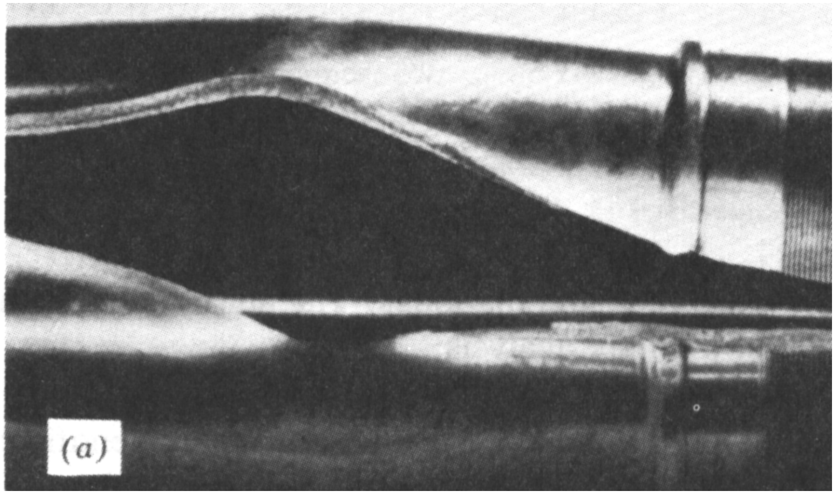
- Ductile fracture is desirable!

Ductile: warning before fracture

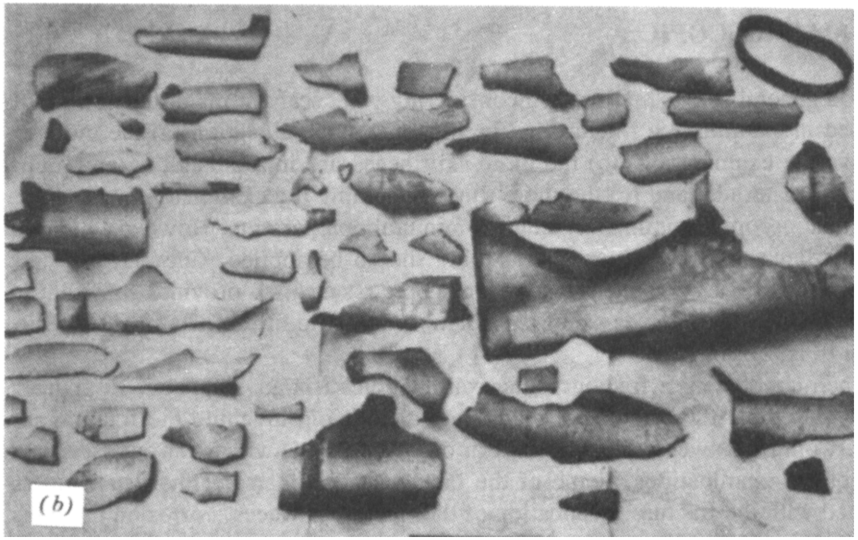
Brittle: No warning

Ex: Failure of a pipe

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



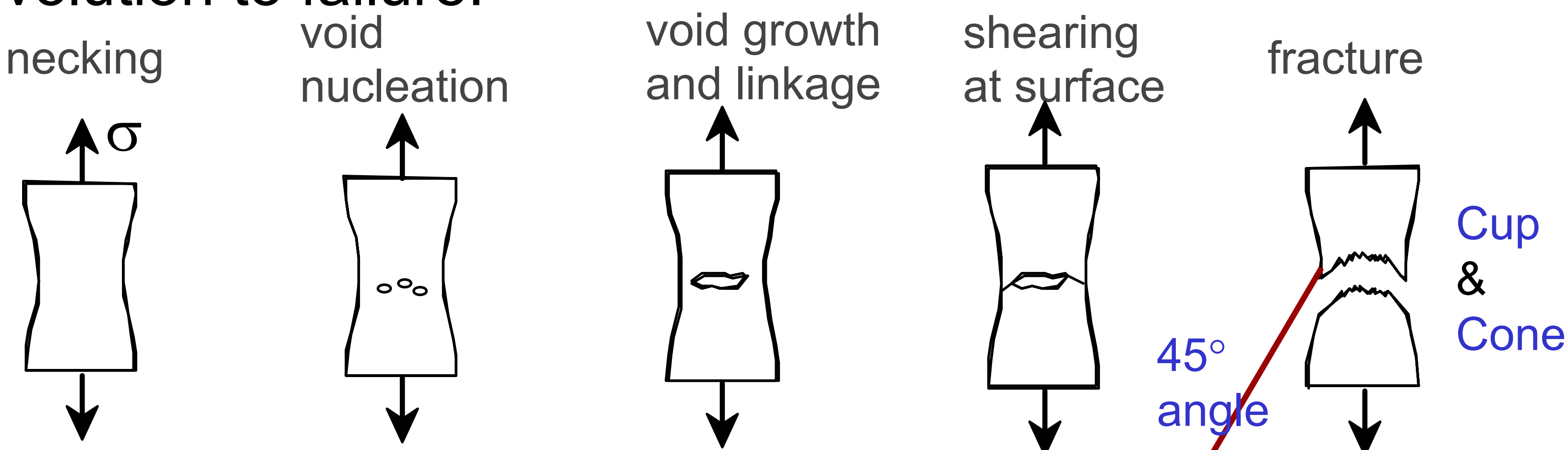
- Brittle failure:
  --many pieces
  --small deformation



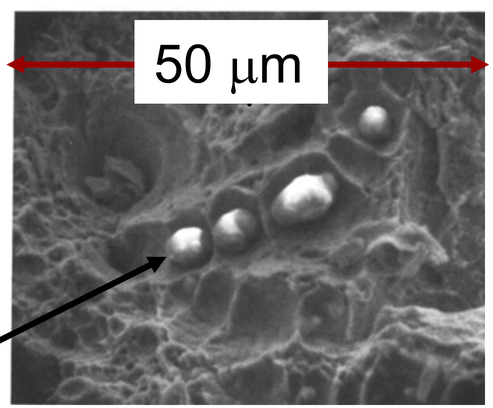
Figures from V.J. Colangelo and F.A. Heiser, *Analysis of Metallurgical Failures* (2nd ed.), Fig. 4.1(a) and (b), p. 66 John Wiley and Sons, Inc., 1987. Used with permission.

Moderately ductile failure

- Evolution to failure:

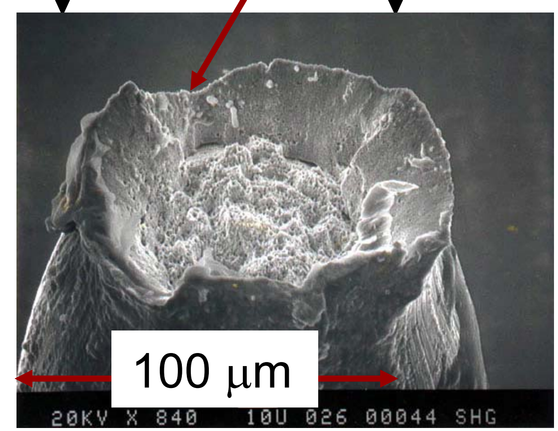


- Resulting fracture surfaces (steel)



particles serve as void nucleation sites.

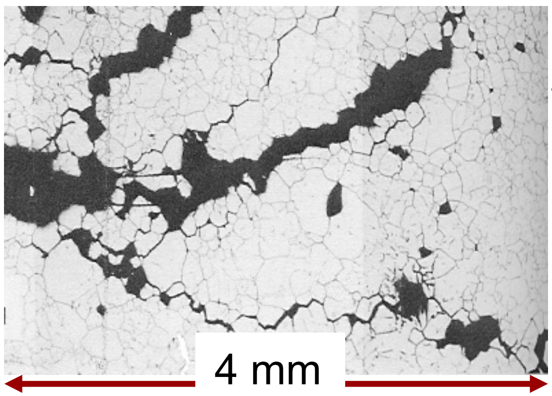
From V.J. Colangelo and F.A. Heiser, *Analysis of Metallurgical Failures* (2nd ed.), Fig. 11.28, p. 294, John Wiley and Sons, Inc., 1987. (Orig. source: P. Thornton, *J. Mater. Sci*., Vol. 6, 1971, pp. 347-56.)



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

Brittle fracture surfaces

- Intergranular (between grains)
- Intragranular (within grains)

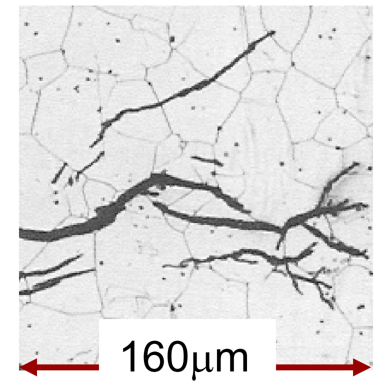


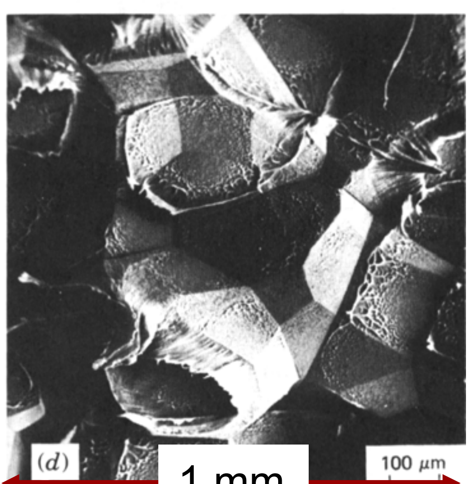
304 S. Steel (metal)

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.)

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.)





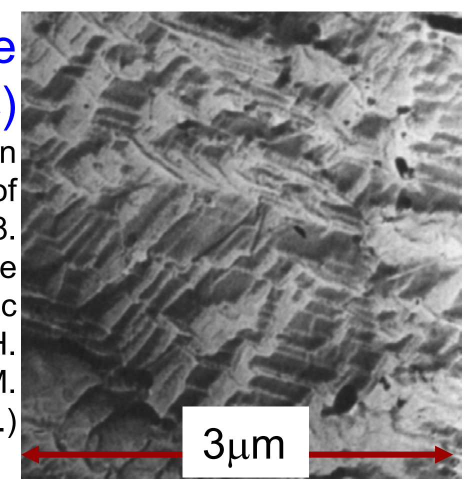
Polypropylene (polymer)

Reprinted w/ permission from R.W. Hertzberg, "Defor-mation and Fracture Mechanics of Engineering Materials", (4th ed.) Fig. 7.35(d), p. 303, John Wiley and Sons, Inc., 1996.

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

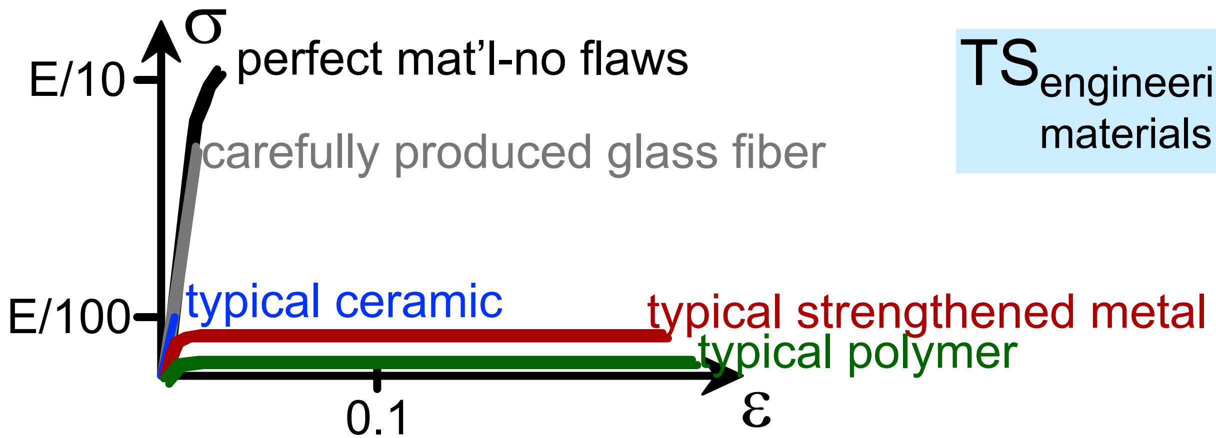
Al Oxide (ceramic)

Reprinted w/ permission from "Failure Analysis of Brittle Materials", p. 78. Copyright 1990, The American Ceramic Society, Westerville, OH. (Micrograph by R.M. Gruver and H. Kirchner.)



Ideal vs real materials

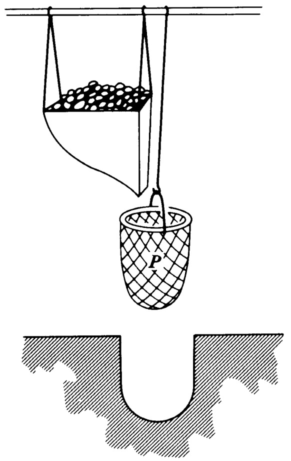
• Stress-strain behavior (Room T):



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

• DaVinci (500 yrs ago!) observed...
  --the longer the wire, the smaller the load to fail it.

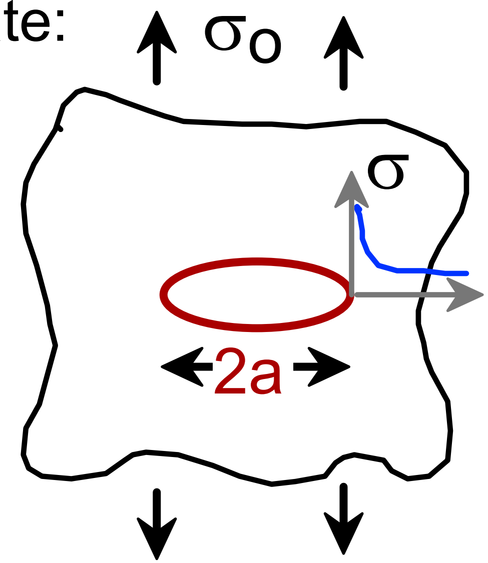
• Reasons:
  --flaws cause premature failure.
  --Larger samples are more flawed!



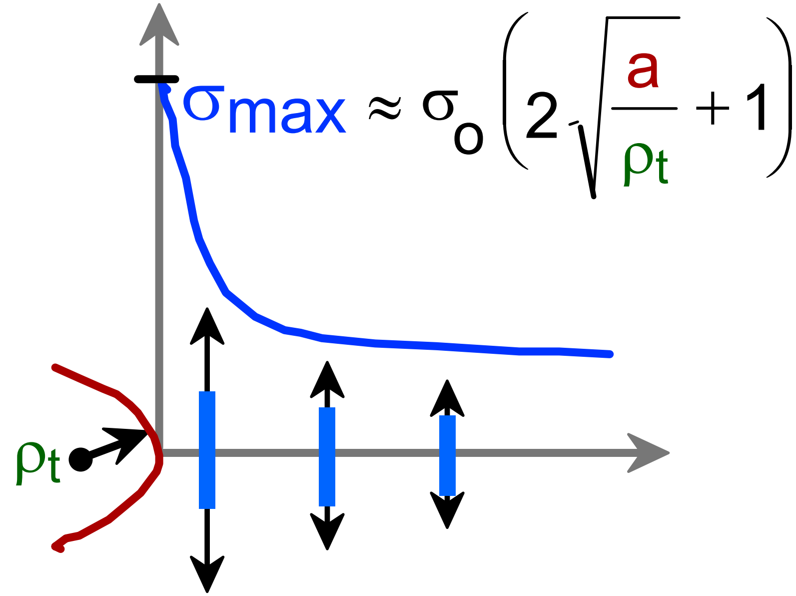
Reprinted w/ permission from R.W. Hertzberg, "Deformation and Fracture Mechanics of Engineering Materials", (4th ed.) Fig. 7.4. John Wiley and Sons, Inc., 1996.

Flaws are stress concentrators!

- Elliptical hole in a plate:



- Stress distrib. in front of a hole:

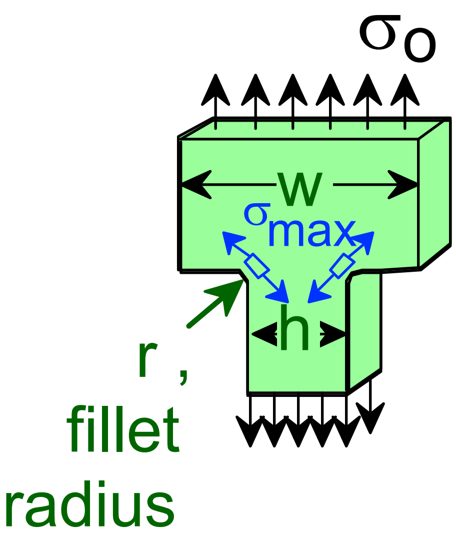


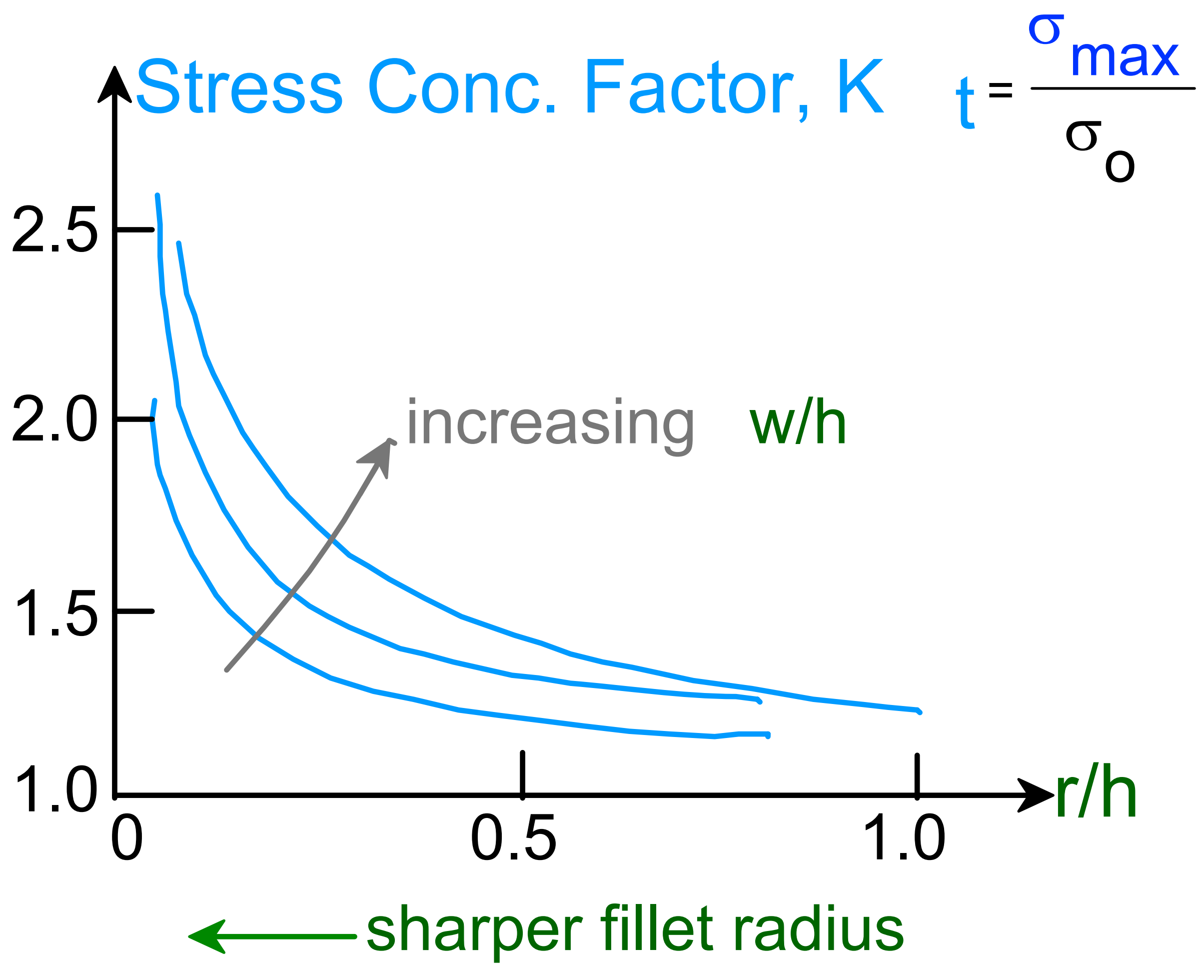
- Stress conc. factor: $K_t = \sigma_{max} / \sigma_o$

- Large K_t promotes failure:

Engineering fracture design

- Avoid sharp corners!

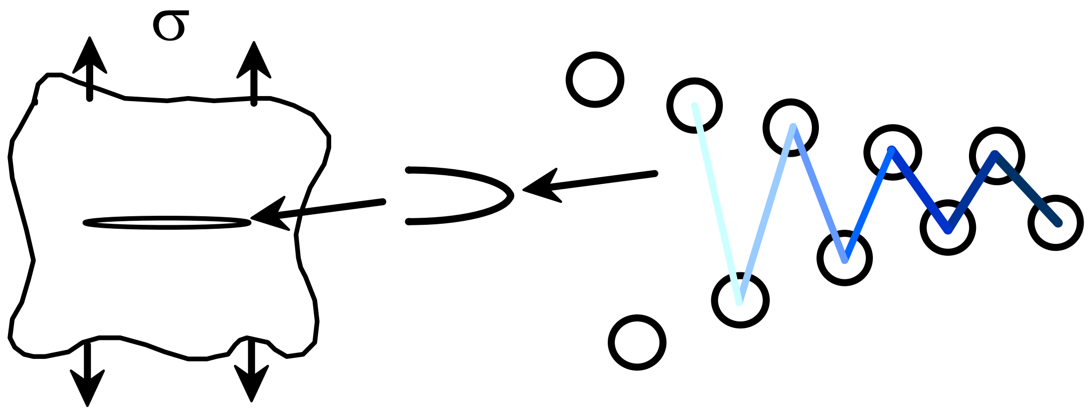




Adapted from Fig. 8.2W(c), *Callister 6e.* (Fig. 8.2W(c) is from G.H. Neugebauer, *Prod. Eng.* (NY), Vol. 14, pp. 82-87 1943.)

When does a crack propagate?

- ρ_t at a crack tip is very small!



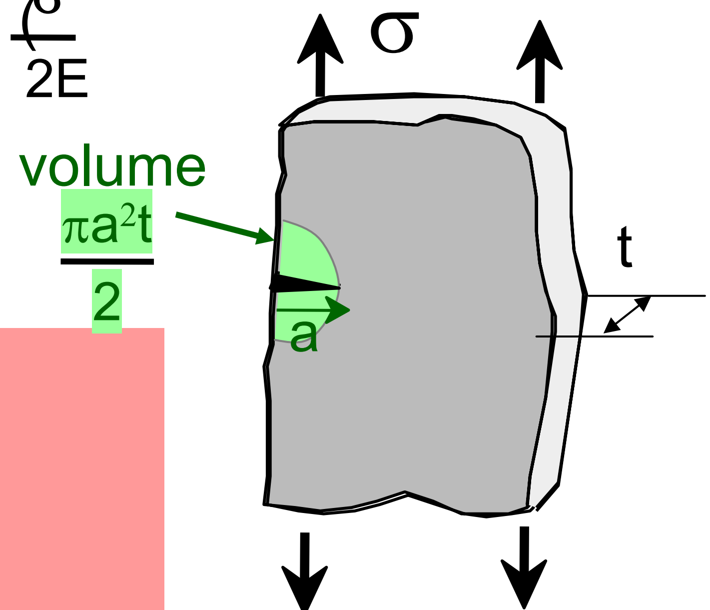
- Result: crack tip stress is very large.

    - Crack propagates when: the tip stress is large enough to make crack unstable (?):

When does a crack propagate?

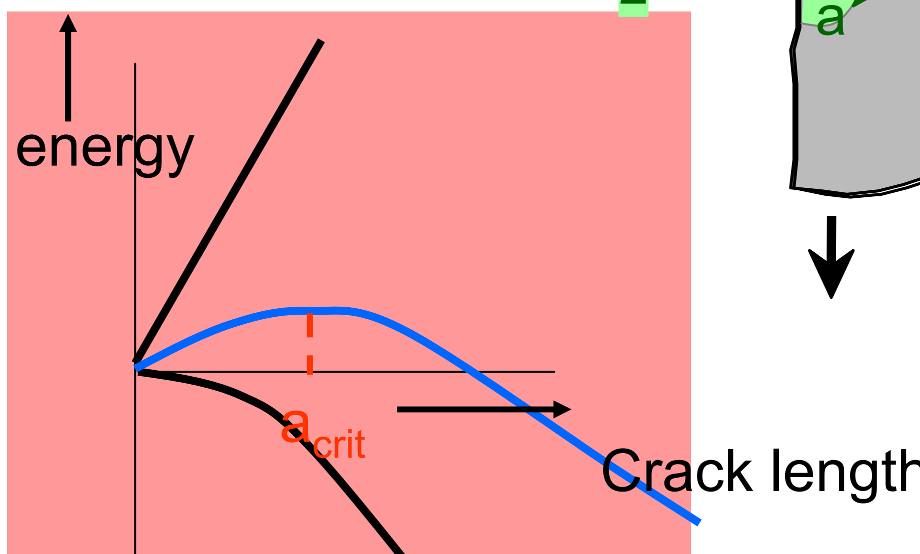
Strain energy $U_s = U_o + V_o(\frac{\sigma^2}{2E}) - \frac{\pi a^2 t}{2}(\frac{\sigma^2}{2E})$

Energy of a crack $U_{crack} = 2\gamma a t$



Total energy = Strain energy + Energy of the crack

Crack will propagate if energy decreases, i.e. crack length is greater than a_{crit}



$\sigma \sqrt{2\pi a_{crit}} > \sqrt{2\gamma E}$

$\sigma \sqrt{2\pi a} > K_{IC}$

Geometry, load, & material

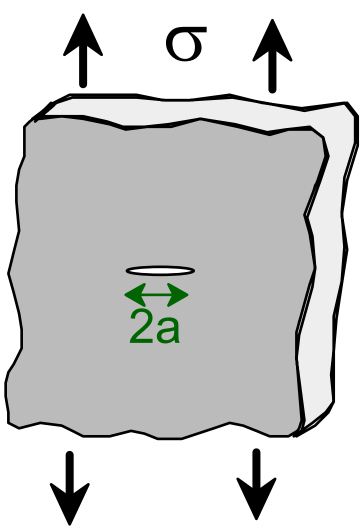
- Condition for crack propagation:

$$K \geq K_c$$

Stress Intensity Factor:
--Depends on load & geometry.

Fracture Toughness:
--Depends on the material, temperature, environment, & rate of loading.

- Values of K for some standard loads & geometries:



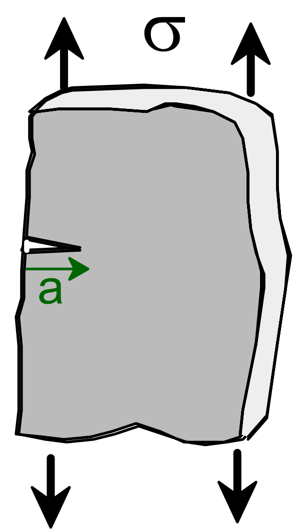
$$K = \sigma\sqrt{\pi a}$$

units of K:

$MPa\sqrt{m}$

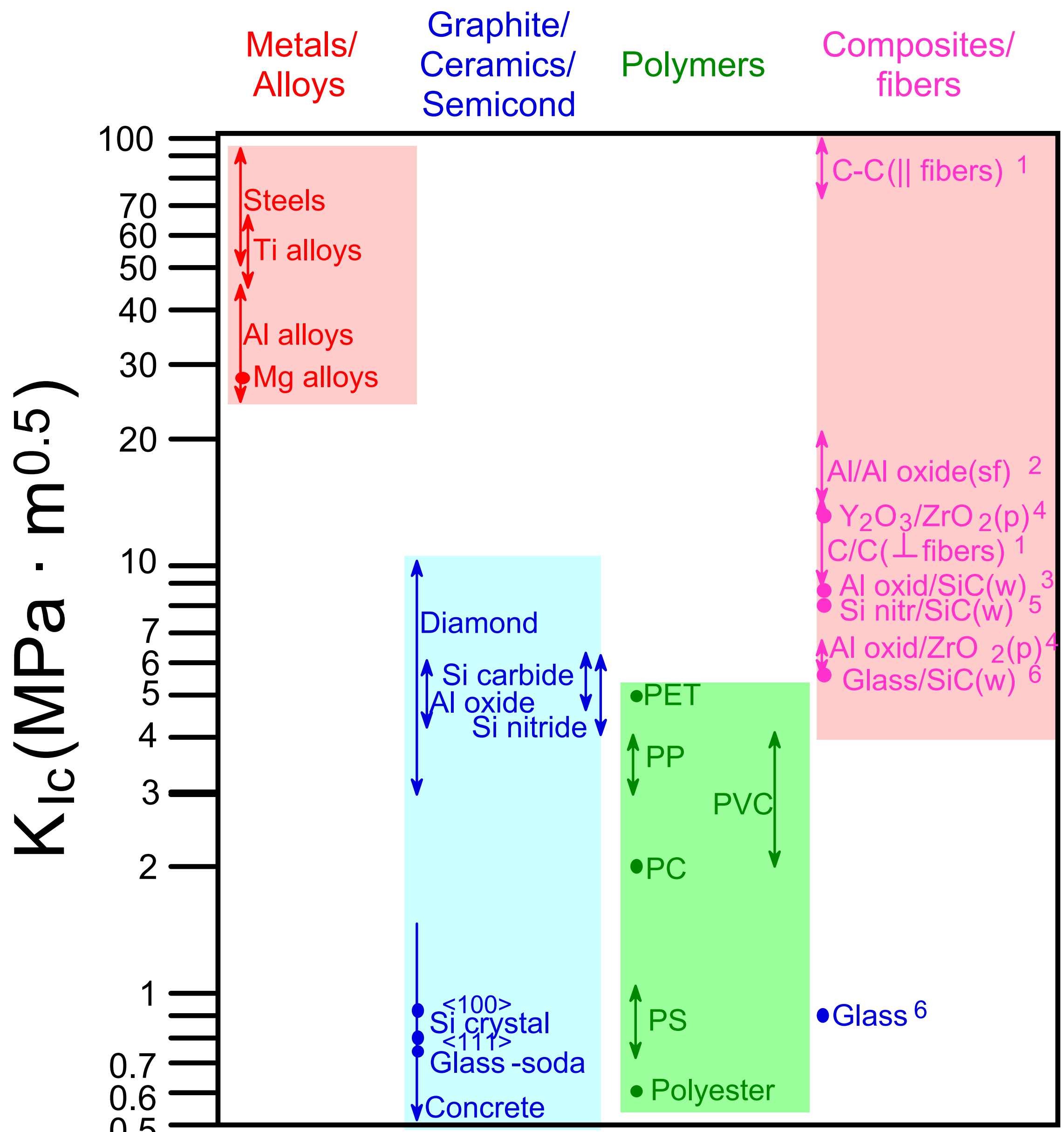
or $ksi\sqrt{in}$

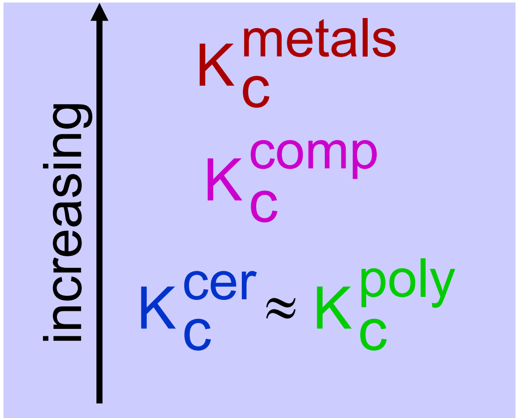
Adapted from Fig. 8.8, *Callister 6e.*



$$K = 1.1\sigma\sqrt{\pi a}$$

Fracture toughness





Based on data in Table B5, *Callister 6e*.

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

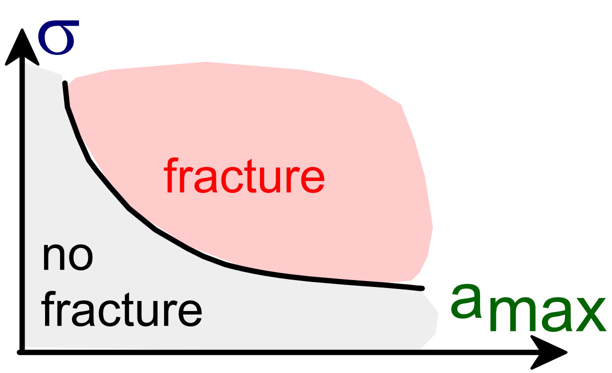
1. (55vol%) *ASM Handbook*, Vol. 21, ASM Int., Materials Park, OH (2001) p. 606.
2. (55 vol%) Courtesy J. Cornie, MMC, Inc., Waltham, MA.
3. (30 vol%) P.F. Becher et al., *Fracture Mechanics of Ceramics*, Vol. 7, Plenum Press (1986). pp. 61-73.
4. Courtesy CoorsTek, Golden, CO.
5. (30 vol%) S.T. Buljan 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: $K \geq K_c$, where $K = Y\sigma\sqrt{\pi a}$
- Largest, most stressed cracks grow first!

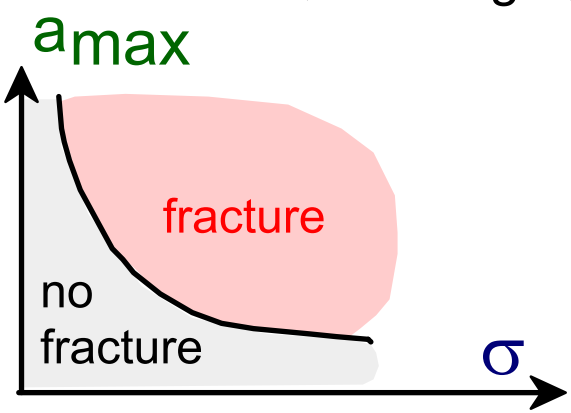
--Result 1: Max flaw size dictates design stress.

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



--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

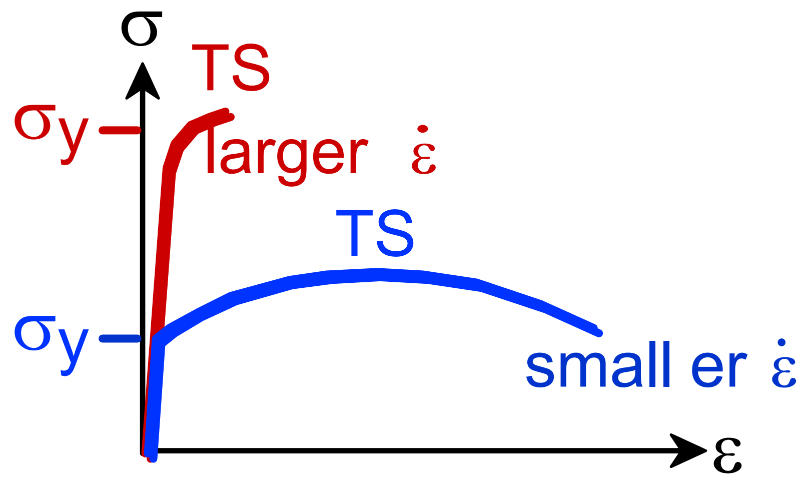
$$\left(\sigma_c\sqrt{a_{max}}\right)_A = \left(\sigma_c\sqrt{a_{max}}\right)_B$$

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

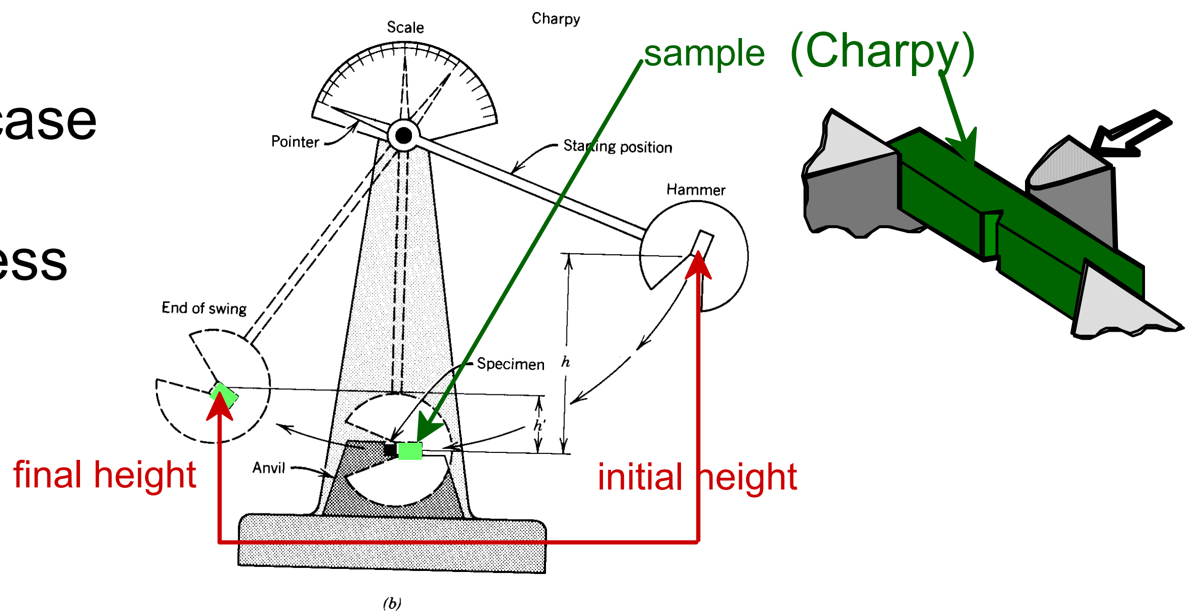
- Reducing flaw size pays off!

Loading rate

- Increased loading rate...
  --increases σ_y and TS
  --decreases %EL
- Why? An increased rate gives less time for disl. to move past obstacles.



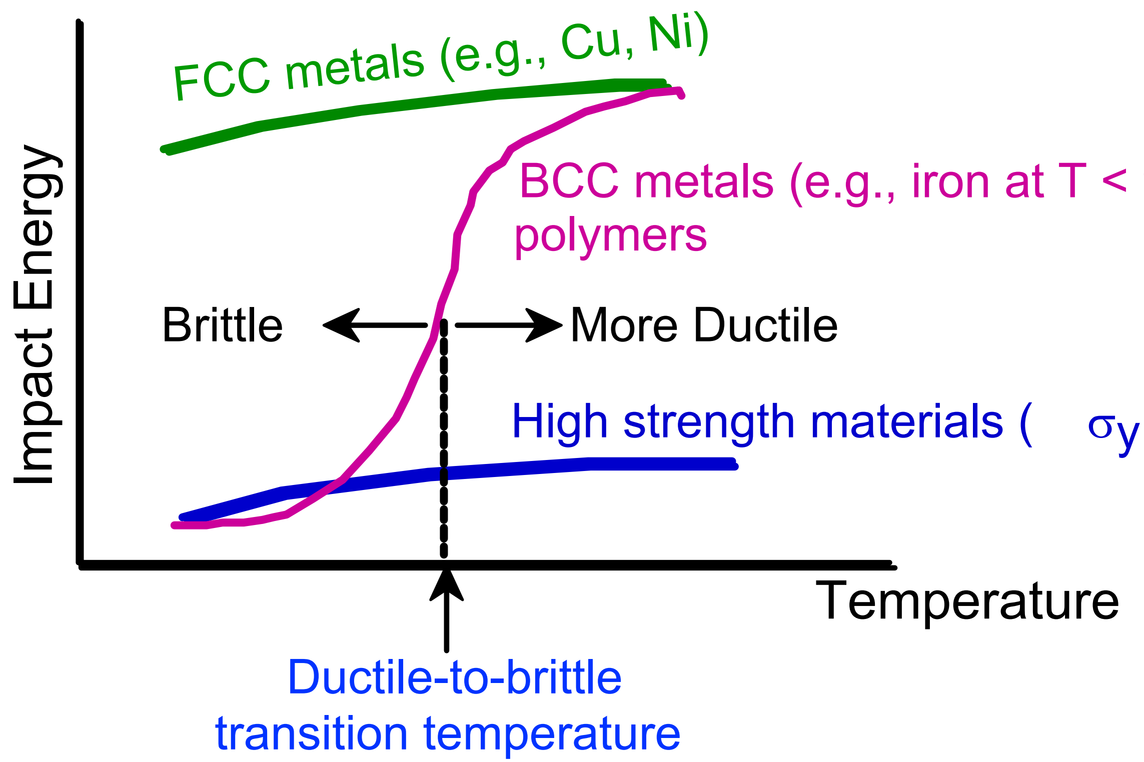
- Impact loading:
  --severe testing case
  --more brittle
  --smaller toughness



Adapted from Fig. 8.11(a) and (b), *Callister 6e.* (Fig. 8.11(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)...



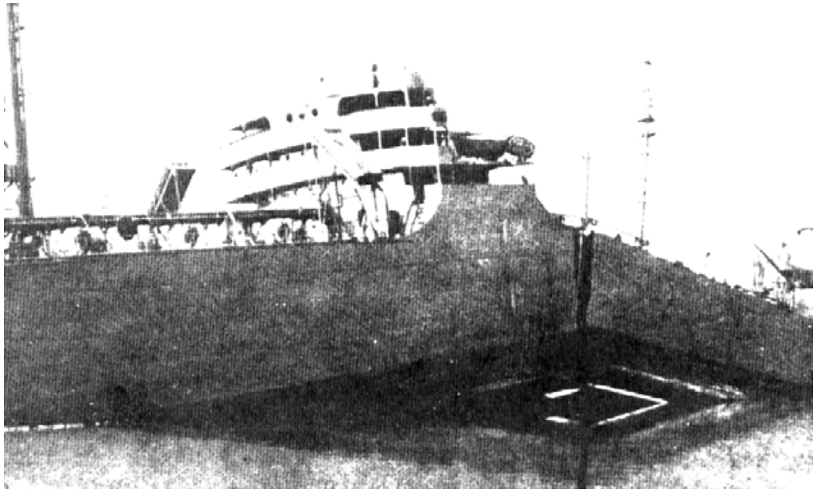
Adapted from C. Barrett, W. Nix, and A.Tetelman, *The Principles of Engineering Materials*, Fig. 6-21, p. 220, Prentice-Hall, 1973. Electronically reproduced by permission of Pearson Education, Inc., Upper Saddle River, New Jersey.

Design strategy: stay above the DBTT!

- Pre-WWII: The Titanic

Reprinted w/ permission from R.W. Hertzberg, "Deformation and Fracture Mechanics of Engineering Materials", (4th ed.) Fig. 7.1(a), p. 262, John Wiley and Sons, Inc., 1996. (Orig. source: Dr. Robert D. Ballard, *The Discovery of the Titanic*.)

- WWII: Liberty ships

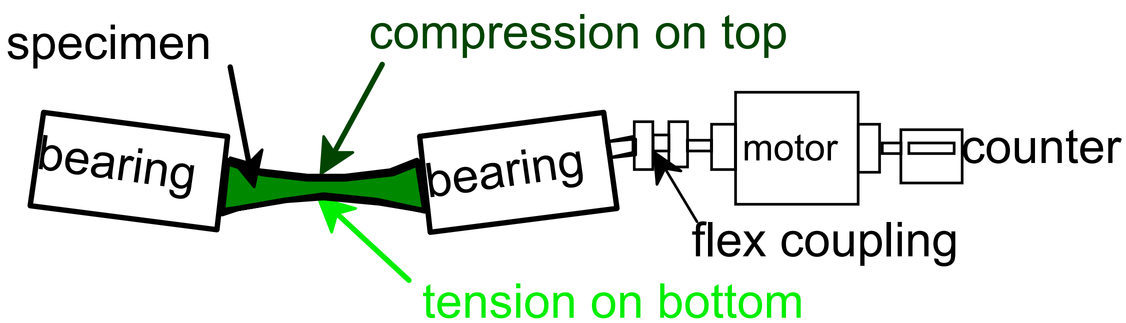


Reprinted w/ permission from R.W. Hertzberg, "Deformation and Fracture Mechanics of Engineering Materials", (4th ed.) Fig. 7.1(b), p. 262, John Wiley and Sons, Inc., 1996. (Orig. source: Earl R. Parker, "Behavior of Engineering Structures", Nat. Acad. Sci., Nat. Res. Council, John Wiley and Sons, Inc., NY, 1957.)

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

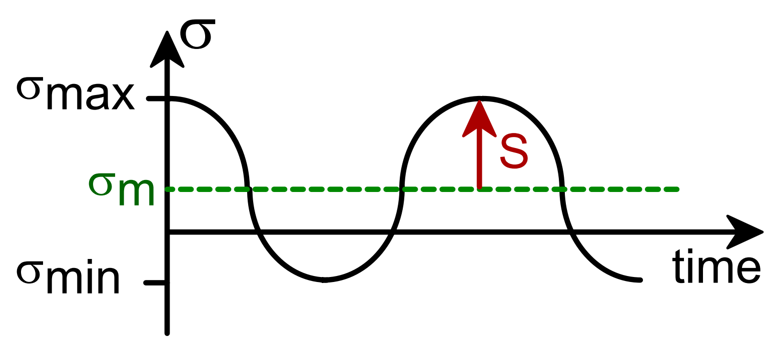
Fatigue

- **Fatigue** = failure under cyclic stress.



Adapted from Fig. 8.16, *Callister 6e.* (Fig. 8.16 is from *Materials Science in Engineering*, 4/E by Carl. A. Keyser, Pearson Education, Inc., Upper Saddle River, NJ.)

- Stress varies with time.
  --key parameters are S and σ_m

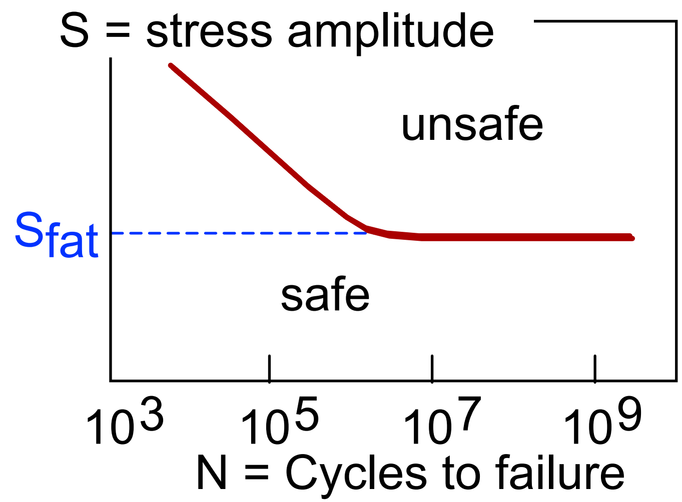


- Key points: Fatigue...
  --can cause part failure, even though $\sigma_{max} < \sigma_c$.
  --causes ~ 90% of mechanical engineering failures.

Fatigue design parameters
S-N curve

- Fatigue limit, S_{fat}:
  --no fatigue if $S < S_{fat}$

  (Endurance limit)

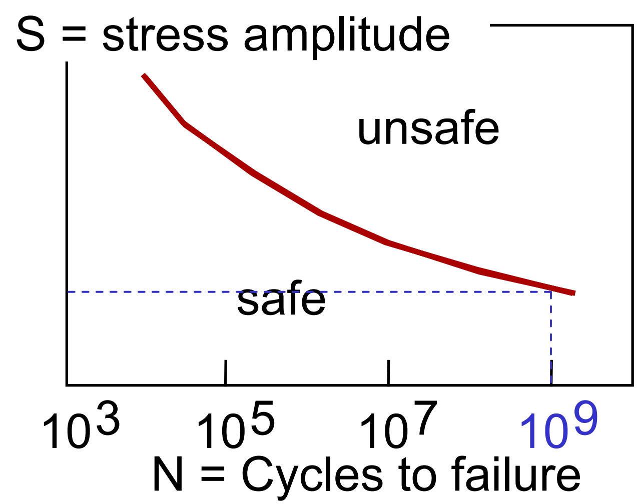


case for steel (typ.)

Adapted from Fig. 8.17(a), *Callister 6e.*

- Sometimes, the fatigue limit is zero!

Fatigue strength



case for Al (typ.)

Adapted from Fig. 8.17(b), *Callister 6e.*

Fatigue life

Fatigue mechanism

- Crack grows *incrementally*

$$\frac{da}{dN} = \left(\Delta K\right)^m$$

typ. 1 to 6

$$\sim \left(\Delta\sigma\right)\sqrt{a}$$

increase in crack length per loading cycle

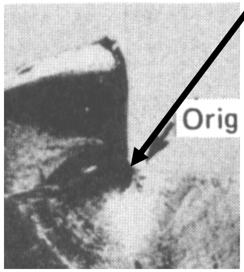
- Failed rotating shaft

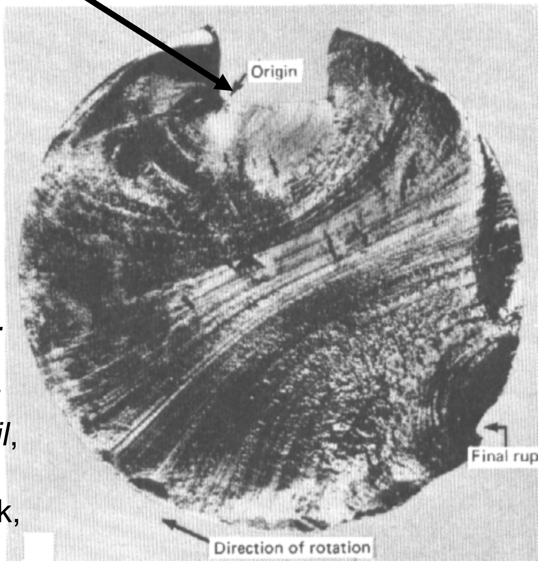
  --crack grew even though

  $K_{max} < K_c$

  --crack grows faster if
  - $\Delta\sigma$ increases
  - crack gets longer
  - loading freq. increases.

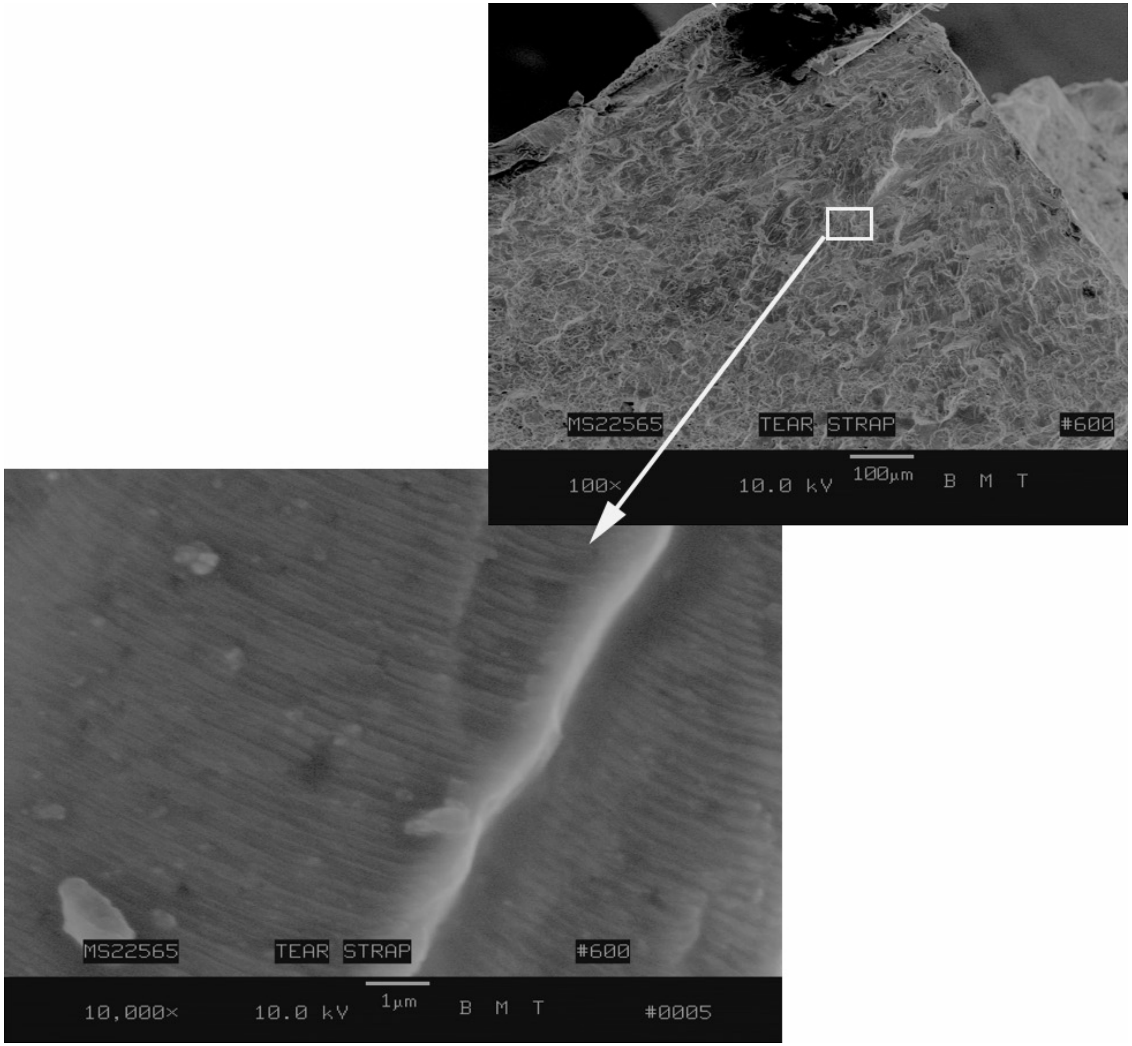
crack origin





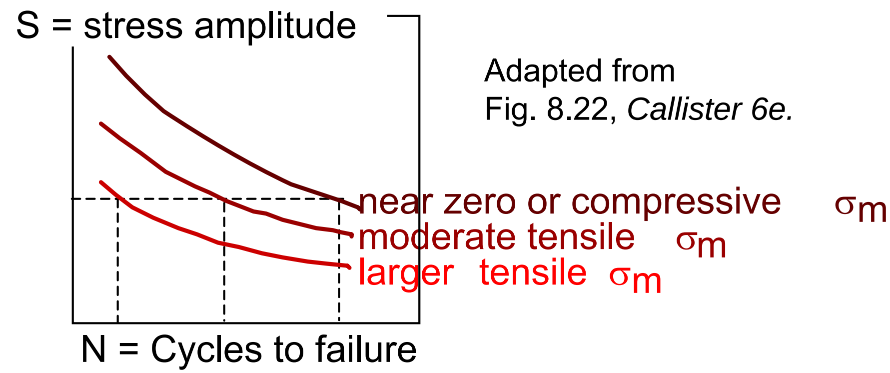
Adapted from Fig. 8.19, *Callister 6e.* (Fig. 8.19 is from D.J. Wulpi, *Understanding How Components Fail*, American Society for Metals, Materials Park, OH, 1985.)

Fatigue striations in Al



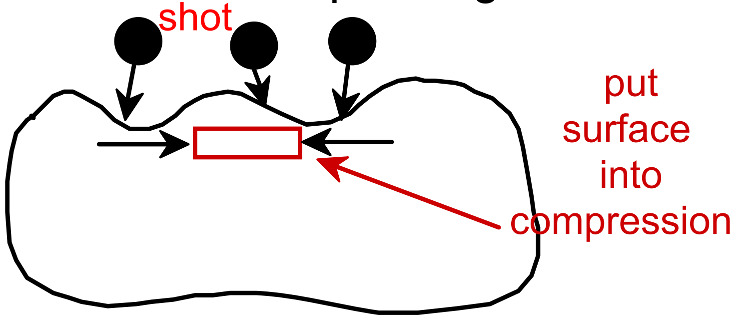
Improving fatigue life

1. Impose a compressive surface stress (to suppress surface cracks from growing)

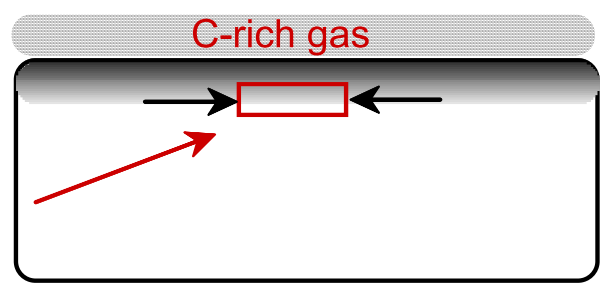


Adapted from Fig. 8.22, *Callister 6e.*

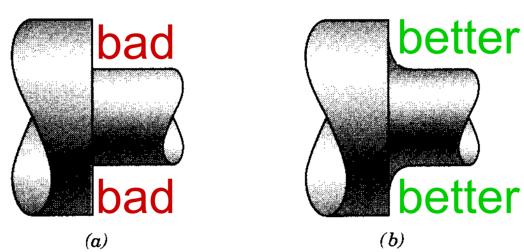
--Method 1: shot peening



--Method 2: carburizing



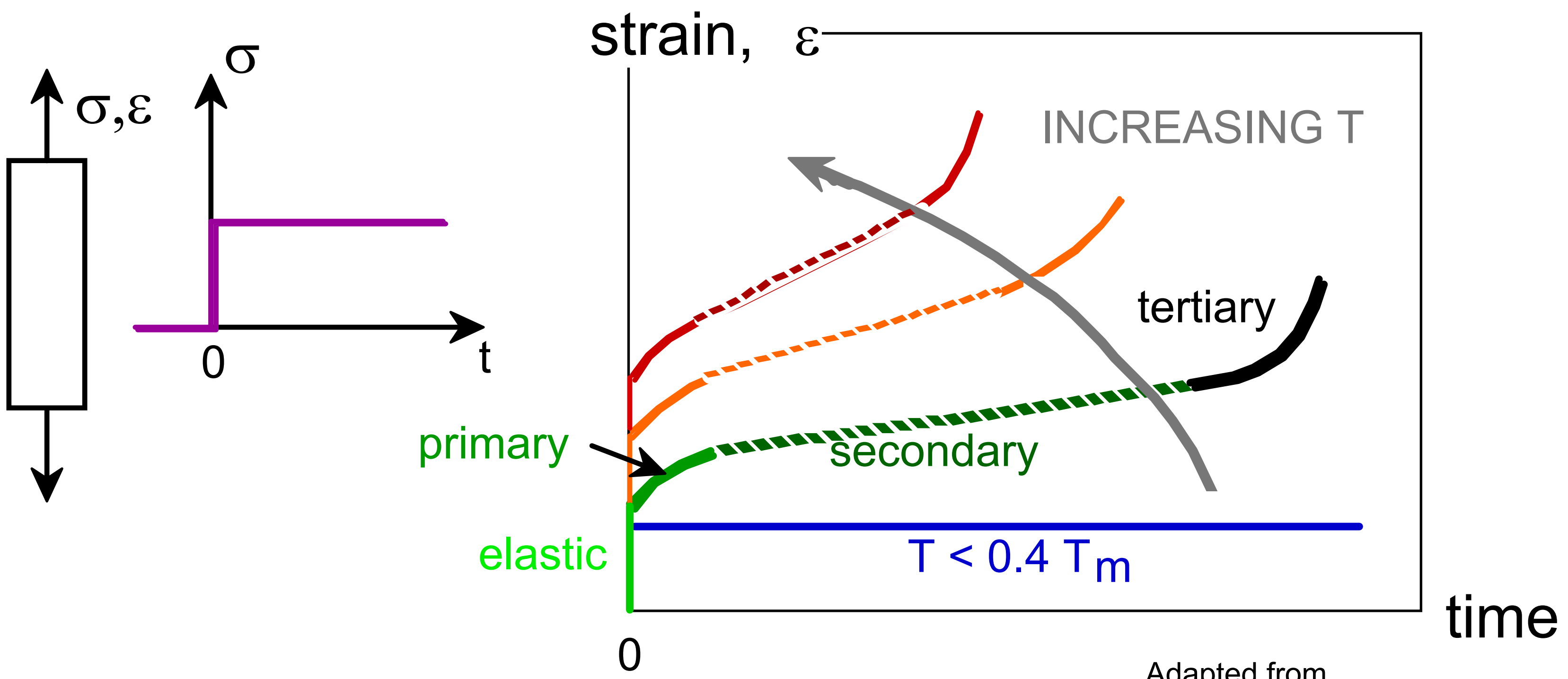
2. Remove stress concentrators.



Adapted from Fig. 8.23, *Callister 6e.*

Creep

- Occurs at elevated temperature, $T > 0.4\ T_{melt}$
- Deformation changes with time.



Adapted from Figs. 8.26 and 8.27, *Callister 6e.*

Secondary creep

- Most of component life spent here.
- Strain rate is constant at a given T, σ
  --strain hardening is balanced by recovery

$$\dot{\varepsilon}_s = K_2 \sigma^n \exp\left(-\frac{Q_c}{RT}\right)$$

strain rate → $\dot{\varepsilon}_s$

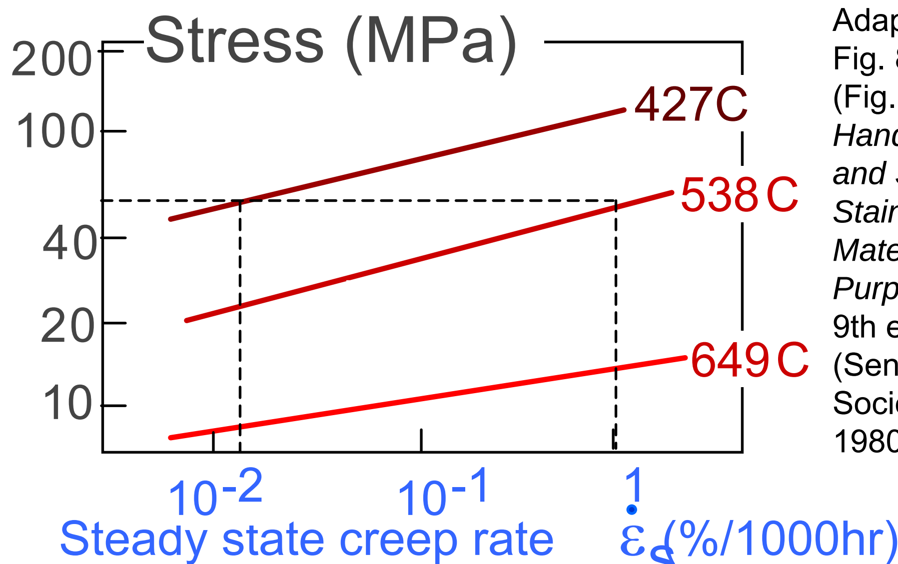
material const. → K_2

applied stress → σ

stress exponent (material parameter) → n

activation energy for creep (material parameter) → Q_c

- Strain rate increases for larger T, σ



Adapted from Fig. 8.29, *Callister 6e.* (Fig. 8.29 is from *Metals Handbook: Properties and Selection: Stainless Steels, Tool Materials, and Special Purpose Metals*, Vol. 3, 9th ed., D. Benjamin (Senior Ed.), American Society for Metals, 1980, p. 131.)

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:

-for noncyclic σ and $T < 0.4T_m$, failure stress decreases with:

increased maximum flaw size,
decreased T,
increased rate of loading.

-for cyclic σ:

cycles to fail decreases as $\Delta\sigma$ increases.

-for higher T ($T > 0.4T_m$):

time to fail decreases as σ or T increases.