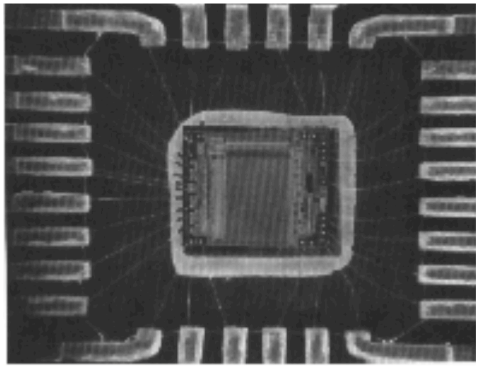
CHAPTER 8: MECHANICAL FAILURE

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.)

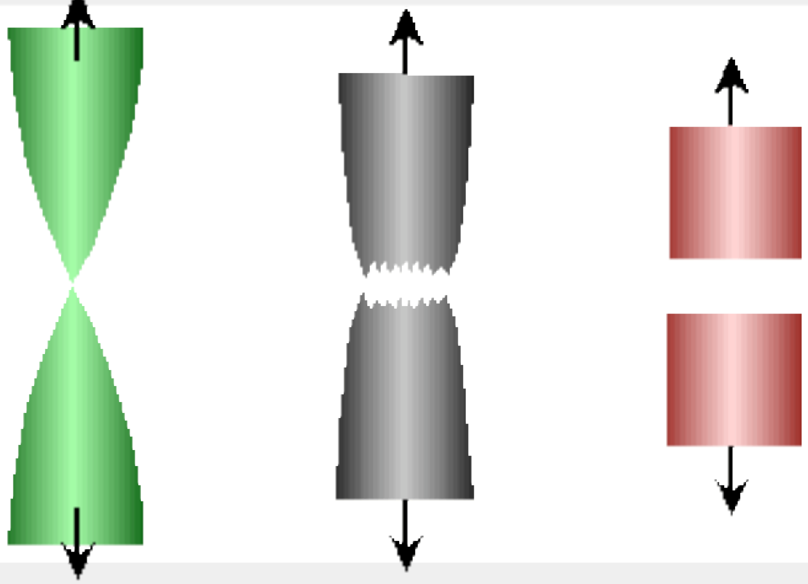
Hip implant-cyclic loading from walking.

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

DUCTILE VS BRITTLE FAILURE

- Classification:

Fracture behavior:	Very Ductile	Moderately Ductile	Brittle



%AR or %EL:	Large	Moderate	Small

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

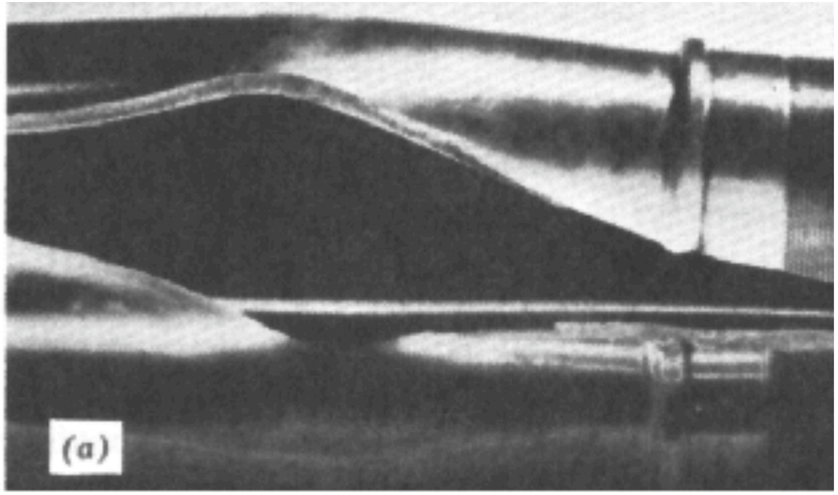
- Ductile fracture is desirable!

Ductile: warning before fracture

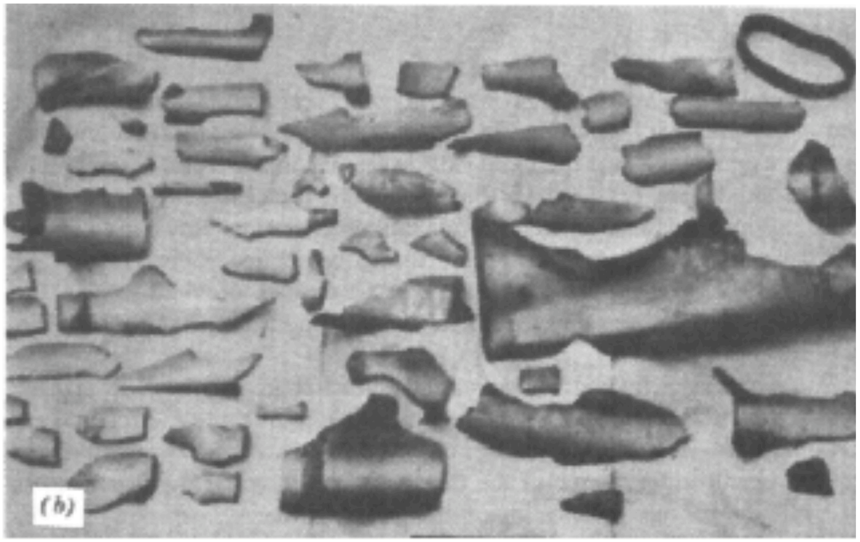
Brittle: No warning

EX: FAILURE OF A PIPE

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



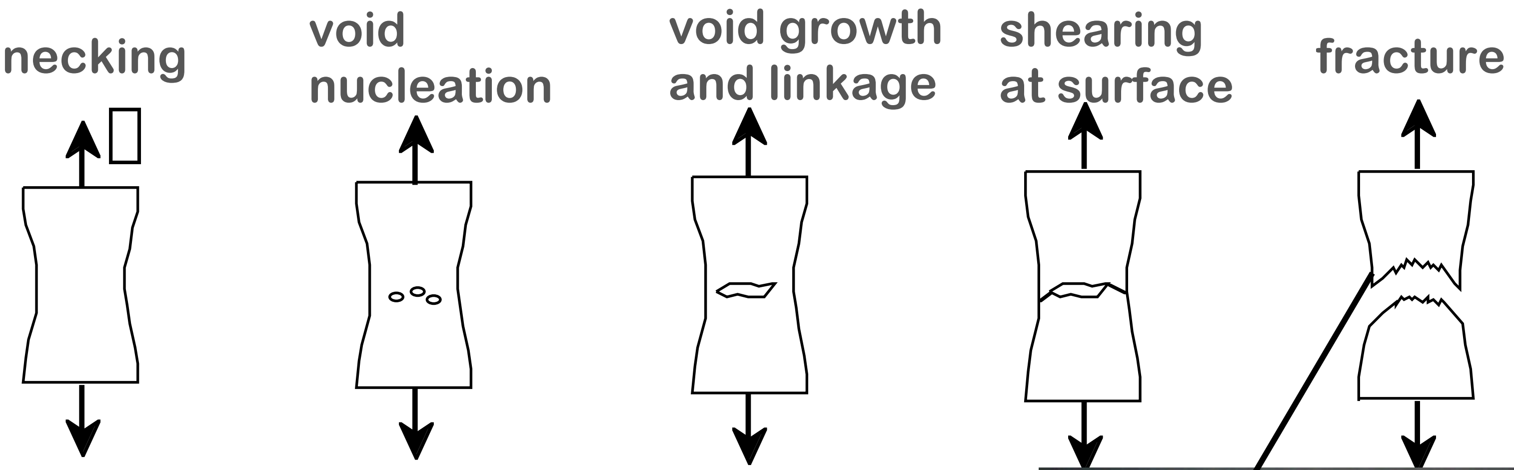
- **Brittle** failure:
  --many pieces
  --small deformation



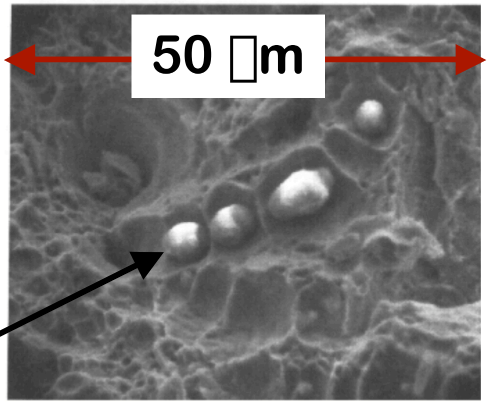
Figures from V.J. Colangelo and F.A. Heiser, *Analysis of Metallurgical Failures* (2nd ed.), Fig. 4.1(a) and (b), p. 66 John Wiley and Sons, Inc., 1987. Used with permission.

MODERATELY DUCTILE FAILURE

- **Evolution to failure:**

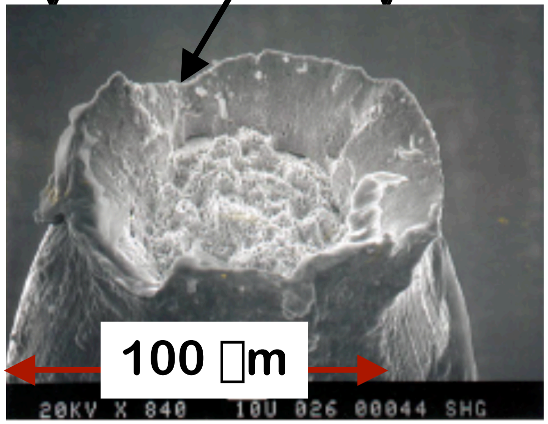


- **Resulting fracture surfaces (steel)**



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.)



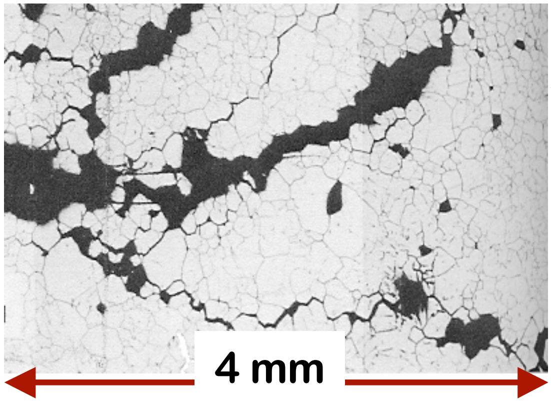
Fracture surface of tire cord wire loaded in tension. Courtesy of F. Roehrig, CC Technologies, Dublin, OH. Used with permission.

BRITTLE FRACTURE SURFACES

- **Intergranular** (between **grains**)

304 S. Steel (metal)

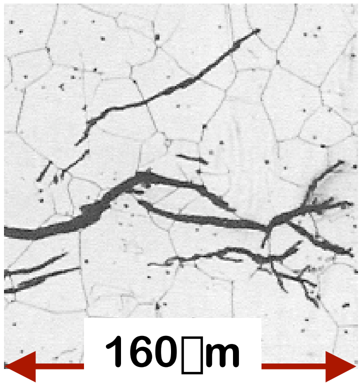
Reprinted w/permission from "Metals Handbook", 9th ed, Fig. 633, p. 650. Copyright 1985, ASM International, Materials Park, OH. (Micrograph by J.R. Keiser and A.R. Olsen, Oak Ridge National Lab.)



- **Intragranular** (within **grains**)

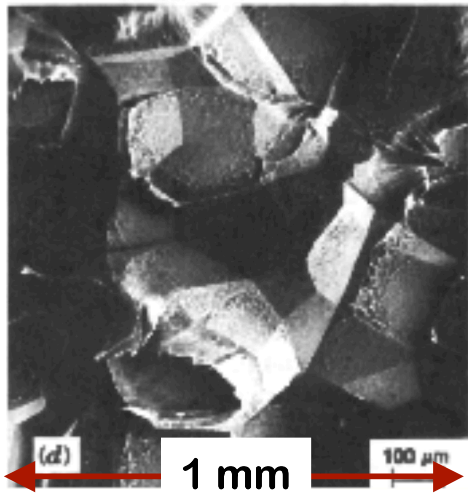
316 S. Steel (metal)

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.)



Polypropylene (polymer)

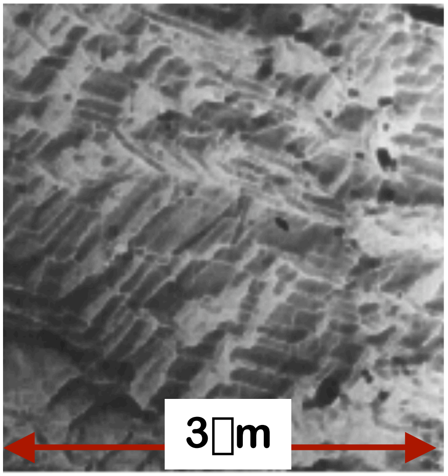
Reprinted w/ permission from R.W. Hertzberg, "Deformation and Fracture Mechanics of Engineering Materials", (4th ed.) Fig. 7.35(d), p. 303, John Wiley and Sons, Inc., 1996.



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

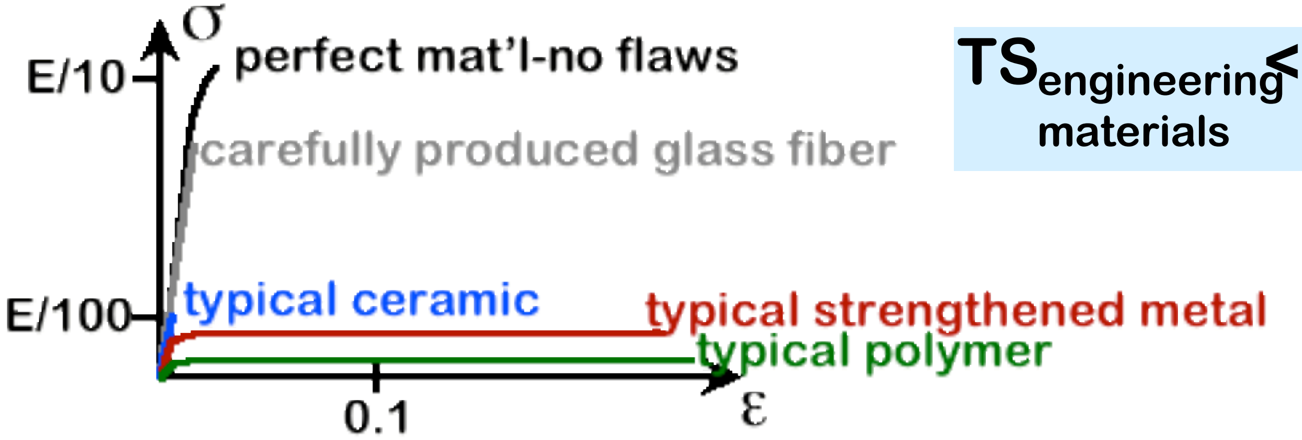
Al Oxide (ceramic)

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):



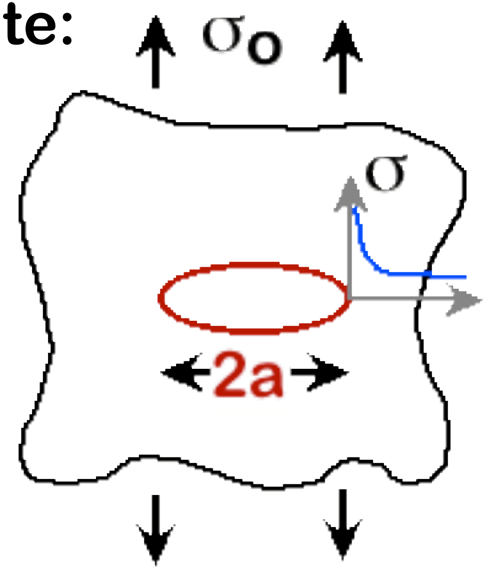
$TS_{\text{engineering materials}} << TS_{\text{perfect materials}}$

- 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!

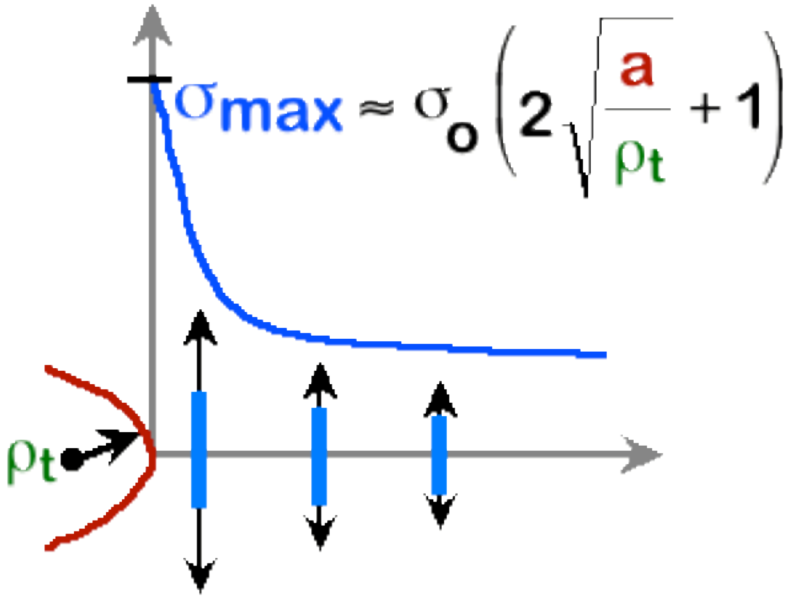
Reprinted w/ permission from R.W. Hertzberg, "Deformation and Fracture Mechanics of Engineering Materials", (4th ed.) Fig. 7.4. John Wiley and Sons, Inc., 1996.

FLAWS ARE STRESS CONCENTRATORS!

- Elliptical hole in a plate:



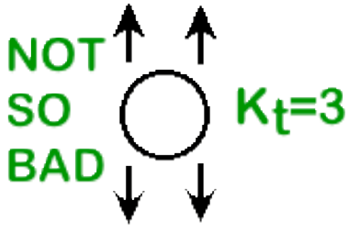
- Stress distrib. in front of a hole:

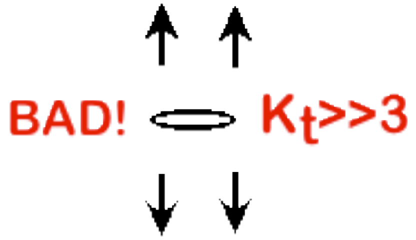


$$\sigma_{max} \approx \sigma_o \left(2\sqrt{\frac{a}{\rho_t}} + 1 \right)$$

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

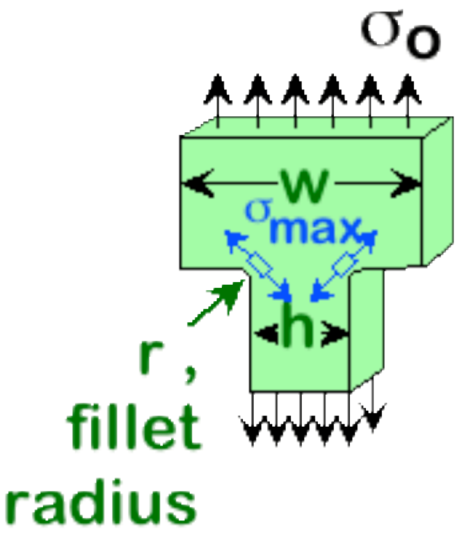
- Large K_t promotes failure:

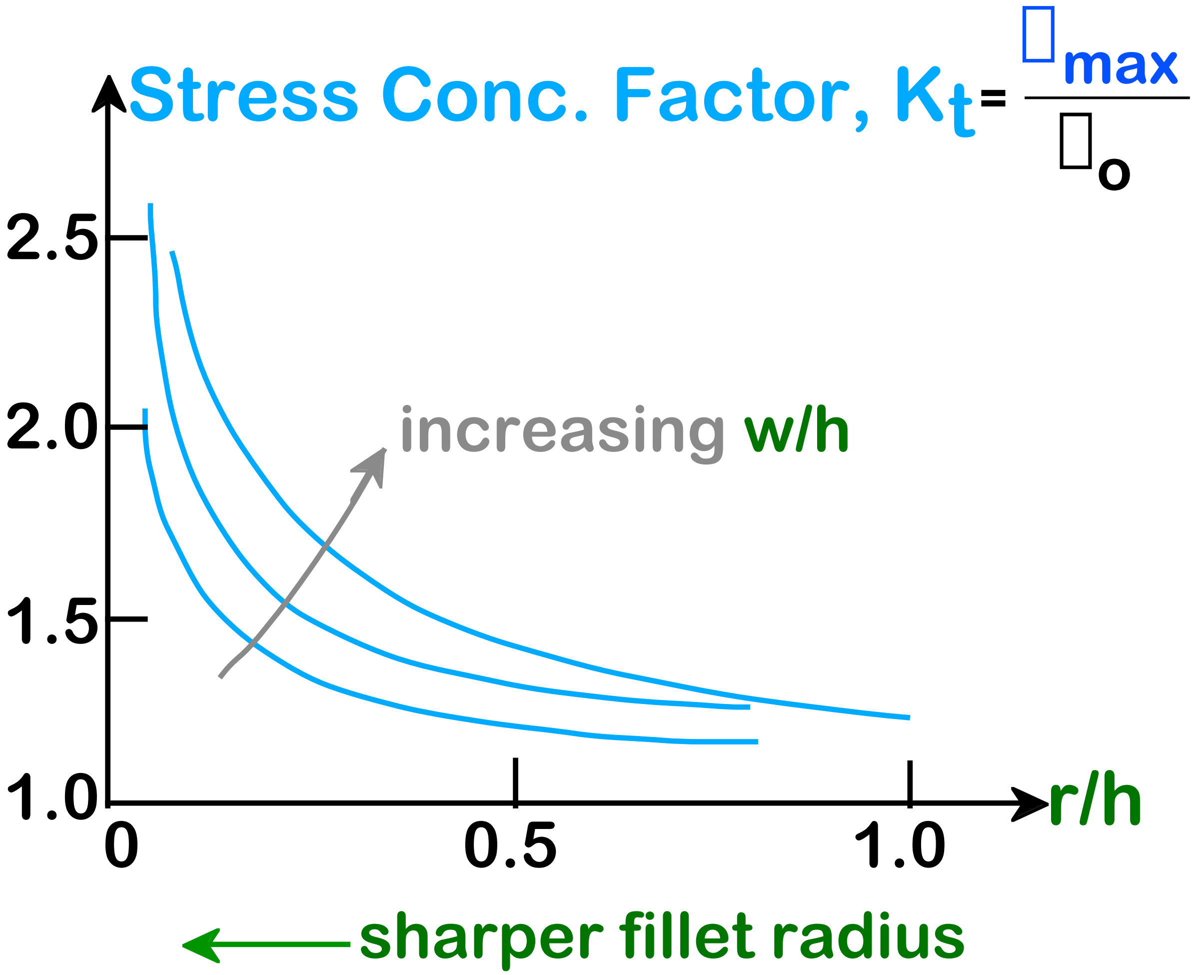




ENGINEERING FRACTURE DESIGN

- Avoid sharp corners!

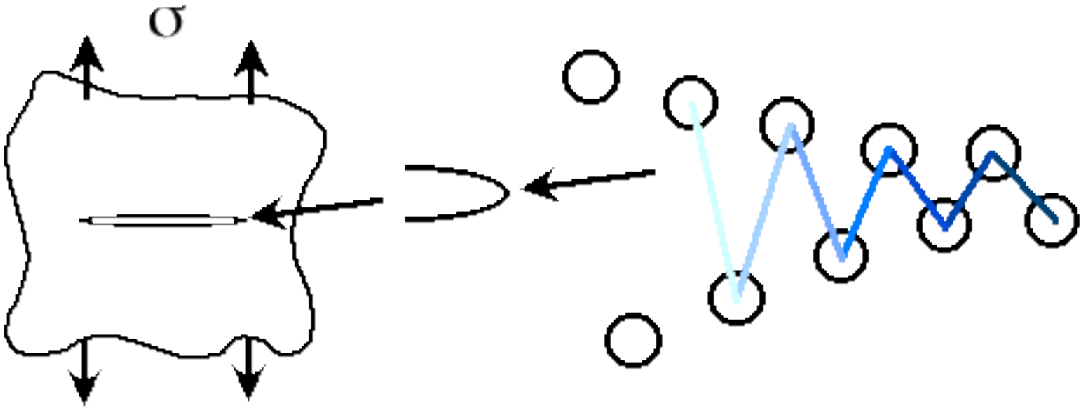




Adapted from Fig. 8.2W(c), *Callister 6e.* (Fig. 8.2W(c) is from G.H. Neugebauer, *Prod. Eng.* (NY), Vol. 14, pp. 82-87 1943.)

WHEN DOES A CRACK PROPAGATE?

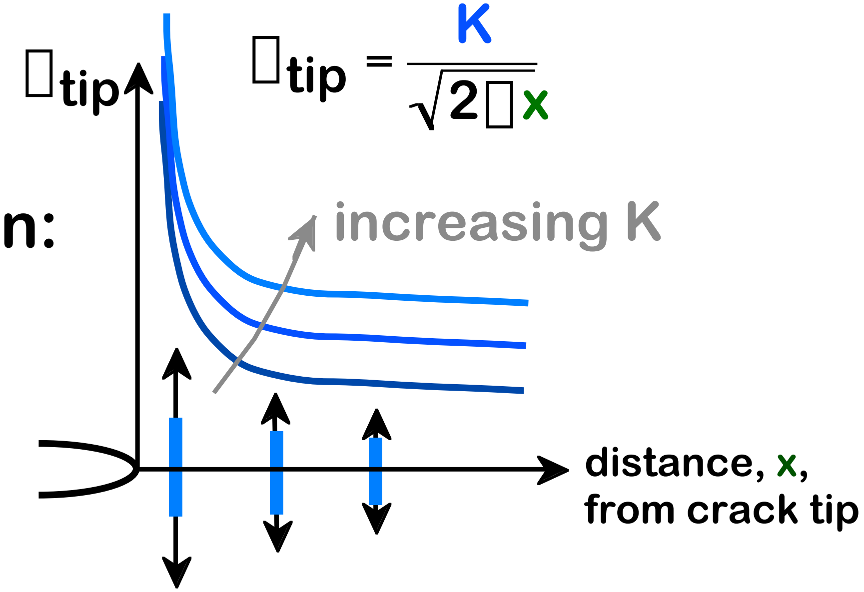
- ρ_t at a crack tip is very small!



- Result: crack tip stress is very large.

- Crack propagates when: the tip stress is large enough to make:

$$K \geq K_c$$



$$\sigma_{tip} = \frac{K}{\sqrt{2\pi x}}$$

GEOMETRY, LOAD, & MATERIAL

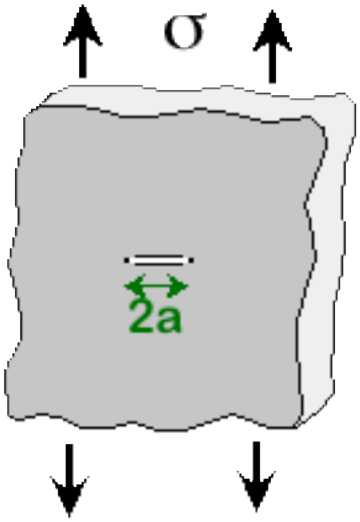
- Condition for crack propagation:

$$K \geq K_c$$

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

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

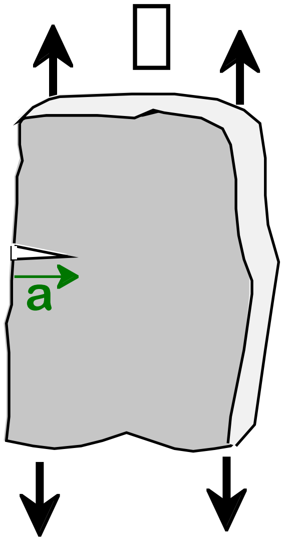
- Values of K for some standard loads & geometries:



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

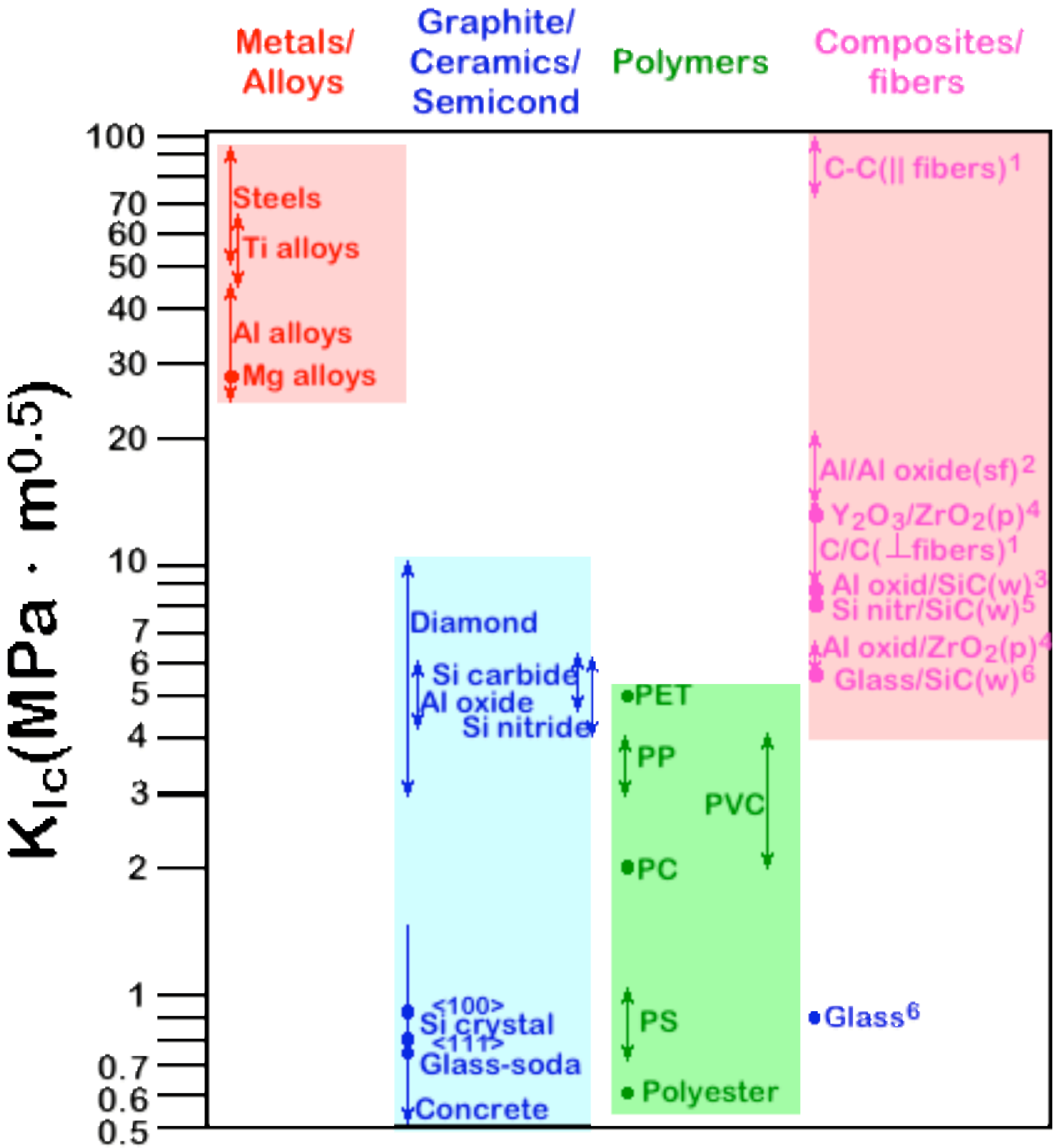
units of K :
$MPa\sqrt{m}$
or $ksi\sqrt{in}$

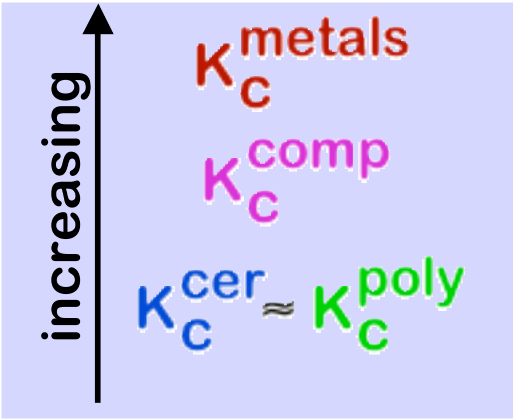
Adapted from Fig. 8.8, *Callister 6e.*



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

FRACTURE TOUGHNESS





increasing

K_c^{metals}

K_c^{comp}

$K_c^{cer} \approx K_c^{poly}$

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: $K \geq K_c$

$$Y\sigma\sqrt{\pi a} \rightarrow K$$

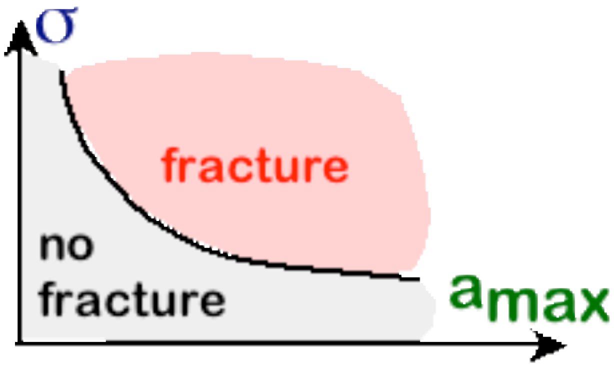
- Largest, most stressed cracks grow first!

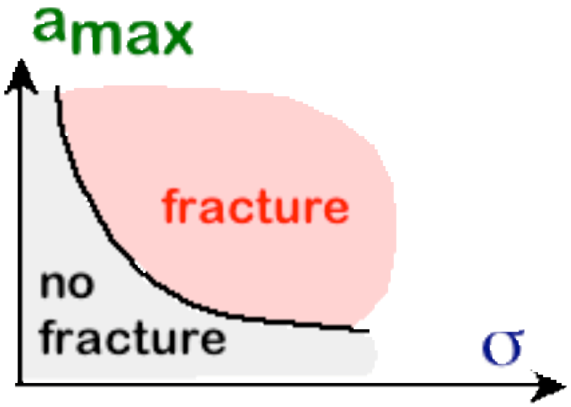
--Result 1: Max flaw size dictates design stress.

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

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

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





DESIGN EX: AIRCRAFT WING

- Material has $K_c = 26 \text{ MPa-m}^{0.5}$
- 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... $\sigma_c = \dfrac{K_c}{Y\sqrt{\pi a_{max}}}$
- Key point: Y and K_c are the same in both designs.

--Result:

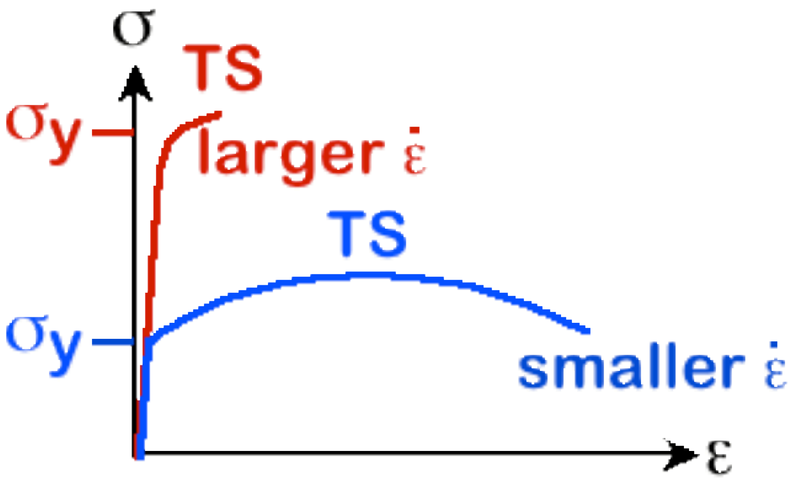
$$\left(\overset{112\text{ MPa}}{\sigma_c}\sqrt{\overset{9\text{ mm}}{a_{max}}}\right)_A = \left(\sigma_c\sqrt{\overset{4\text{ mm}}{a_{max}}}\right)_B$$

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

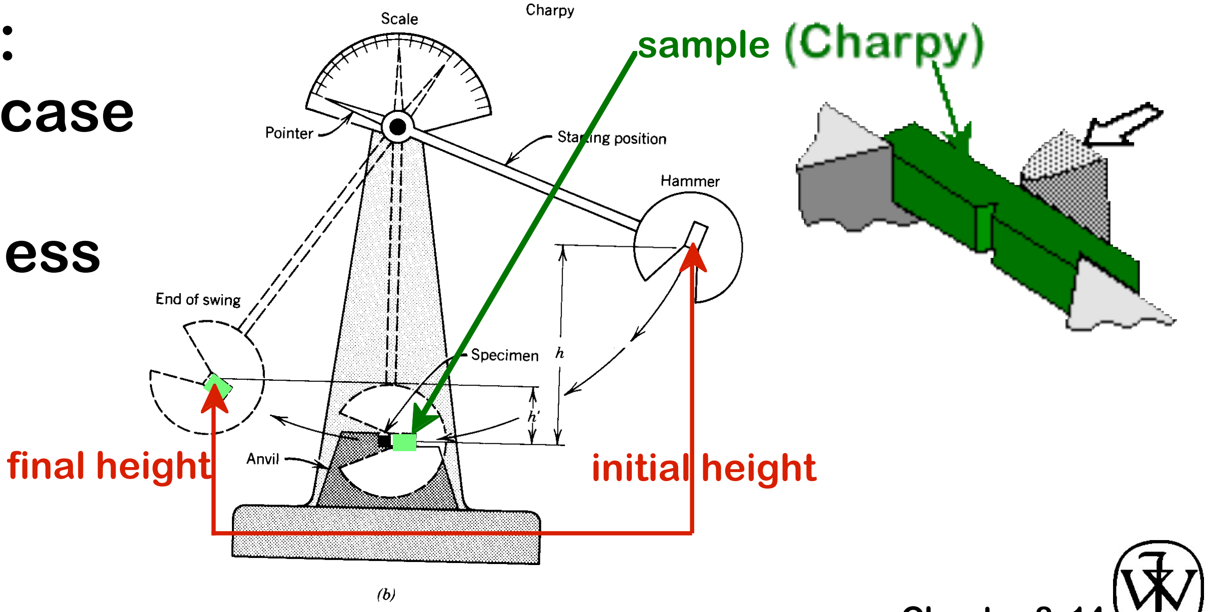
- Reducing flaw size pays off!

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.



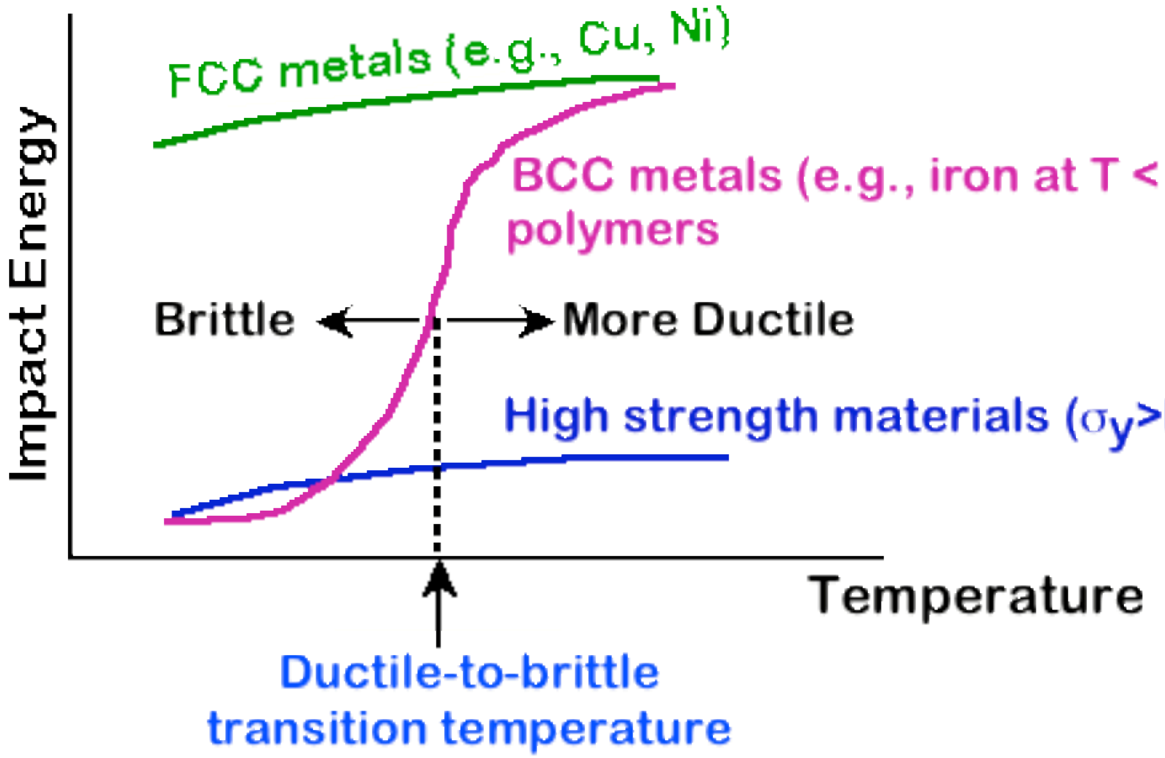
- Impact loading:
  - --severe testing case
  - --more brittle
  - --smaller toughness



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

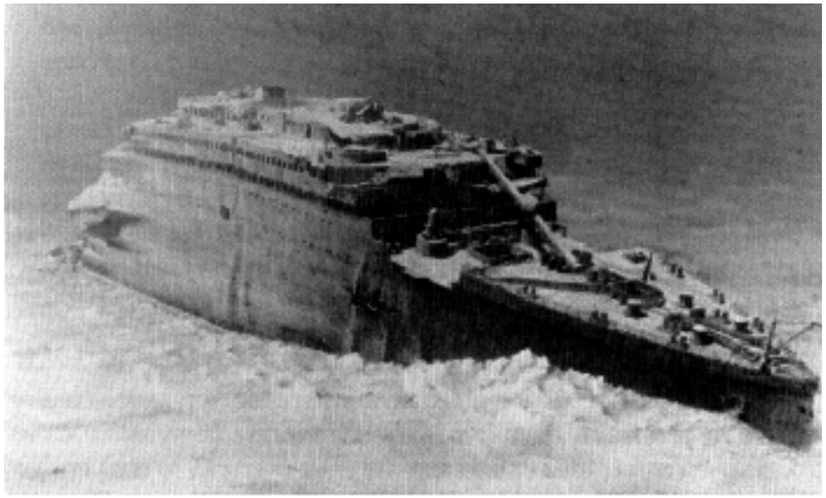
- Increasing temperature...
  --increases %EL and K_c
- Ductile-to-brittle transition temperature (DBTT)...



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.

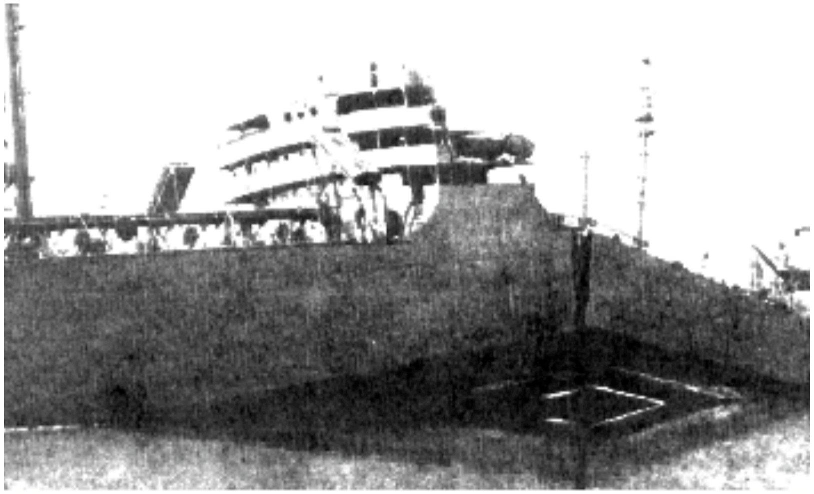
DESIGN STRATEGY:
STAY ABOVE THE DBTT!

- 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

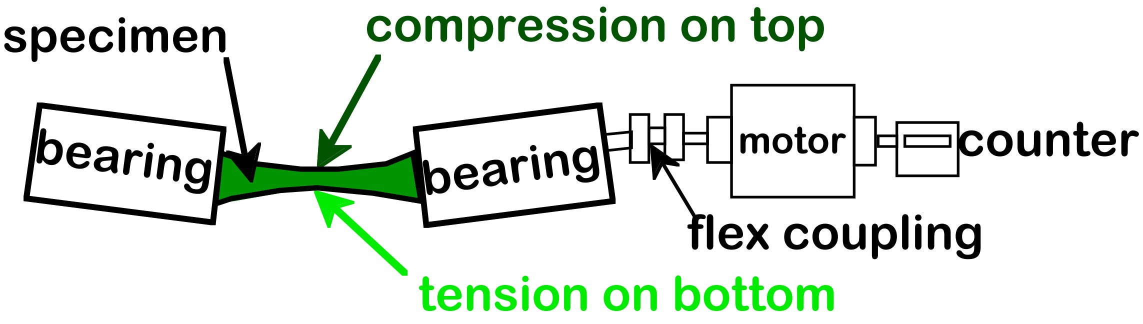


Reprinted w/ permission from R.W. Hertzberg, "Deformation and Fracture Mechanics of Engineering Materials", (4th ed.) Fig. 7.1(b), p. 262, John Wiley and Sons, Inc., 1996. (Orig. source: Earl R. Parker, "Behavior of Engineering Structures", Nat. Acad. Sci., Nat. Res. Council, John Wiley and Sons, Inc.,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

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

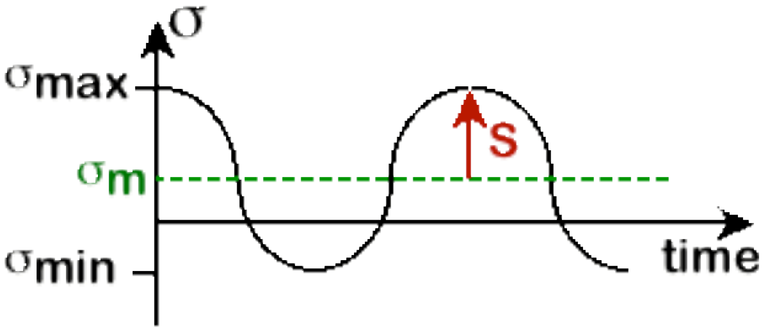
FATIGUE

- **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.)

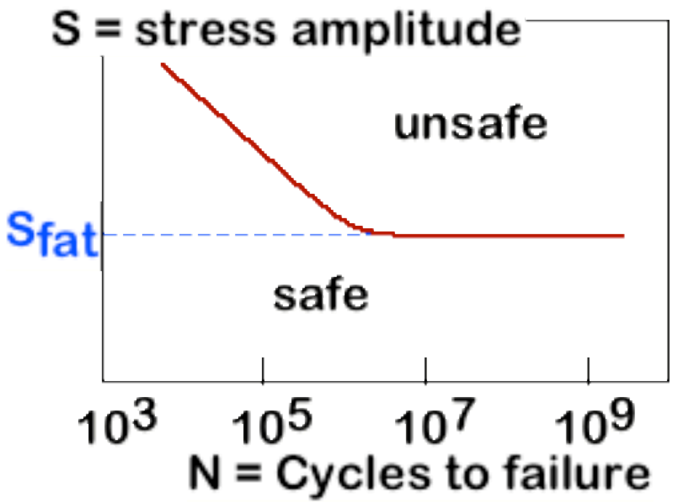
- Stress varies with time.
  --key parameters are S and σ_m



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

FATIGUE DESIGN PARAMETERS

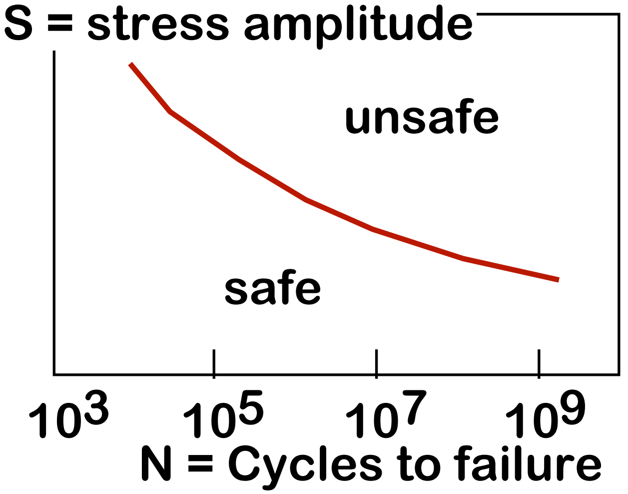
- **Fatigue limit, S_{fat}:**
  --no fatigue if $S < S_{fat}$



case for steel (typ.)

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

- Sometimes, the fatigue limit is zero!



case for Al (typ.)

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

FATIGUE MECHANISM

- Crack grows *incrementally*

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

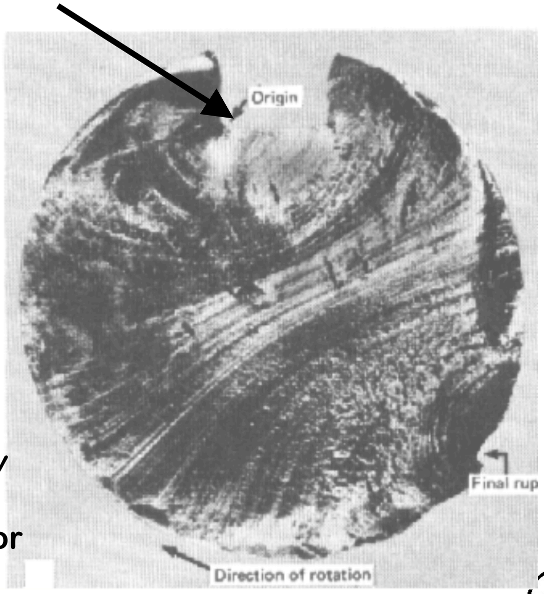
typ. 1 to 6

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

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.

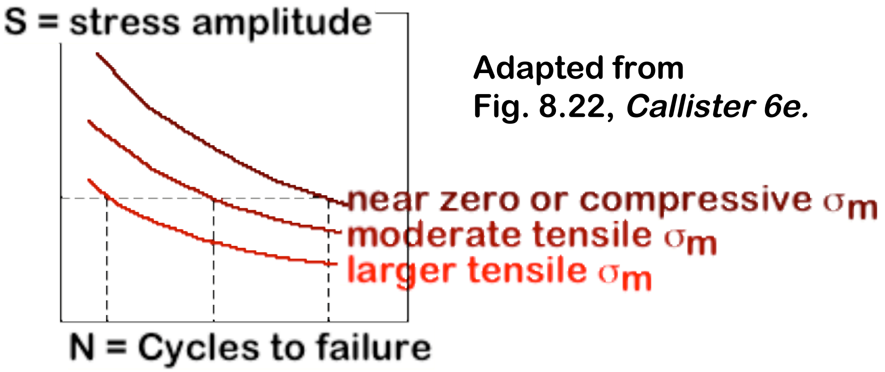
crack origin



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.)

IMPROVING FATIGUE LIFE

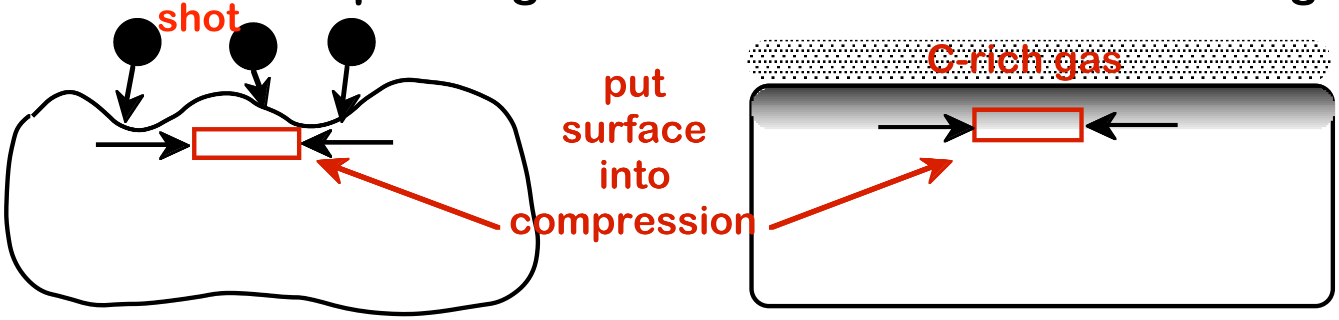
1. Impose a compressive surface stress
   (to suppress surface cracks from growing)



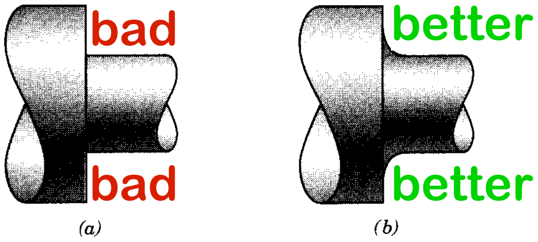
Adapted from
Fig. 8.22, *Callister 6e.*

--Method 1: shot peening

--Method 2: carburizing



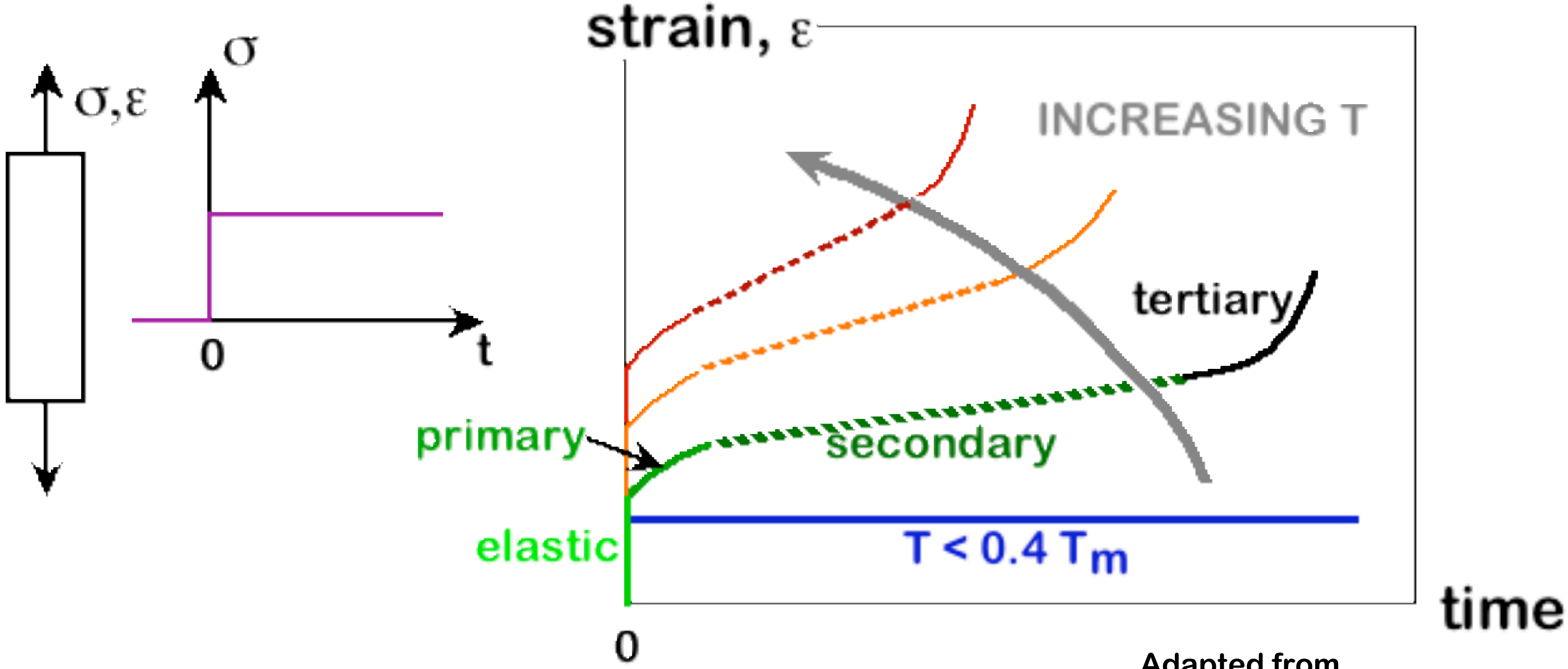
2. Remove stress concentrators.



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

stress exponent (material parameter)

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

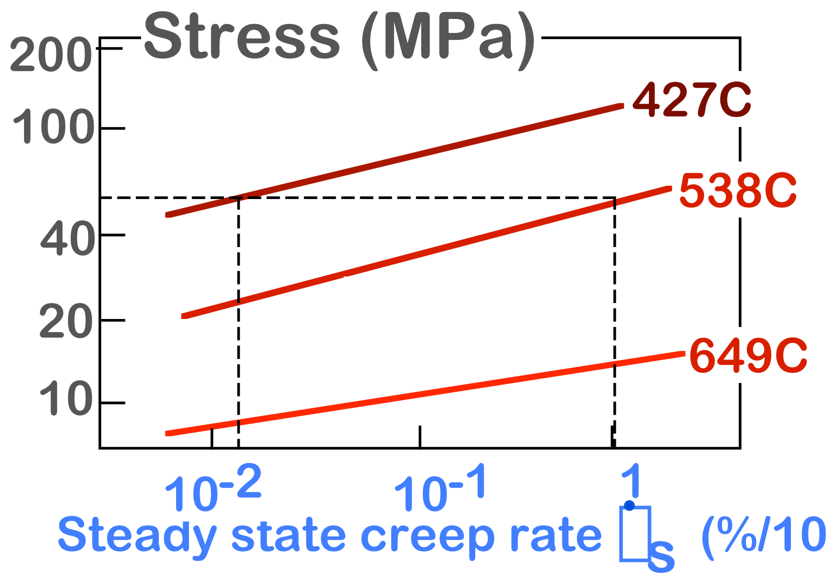
strain rate

material const.

applied stress

activation energy for creep (material parameter)

- Strain rate increases for larger T, σ

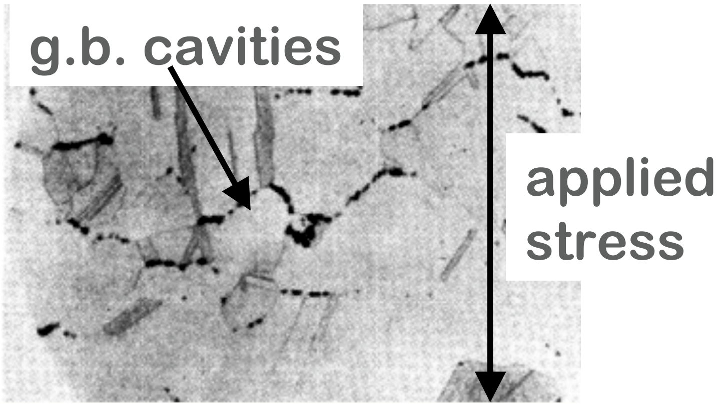


Adapted from Fig. 8.29, *Callister 6e.* (Fig. 8.29 is from *Metals Handbook: Properties and Selection: Stainless Steels, Tool Materials, and Special Purpose Metals*, Vol. 3, 9th ed., D. Benjamin (Senior Ed.), American Society for Metals, 1980, p. 131.)

CREEP FAILURE

- **Failure:**

along grain boundaries.



From V.J. Colangelo and F.A. Heiser, *Analysis of Metallurgical Failures* (2nd ed.), Fig. 4.32, p. 87, John Wiley and Sons, Inc., 1987. (Orig. source: Pergamon Press, Inc.)

- **Time to rupture, t_r**

$$T(20+\log t_r)=L$$

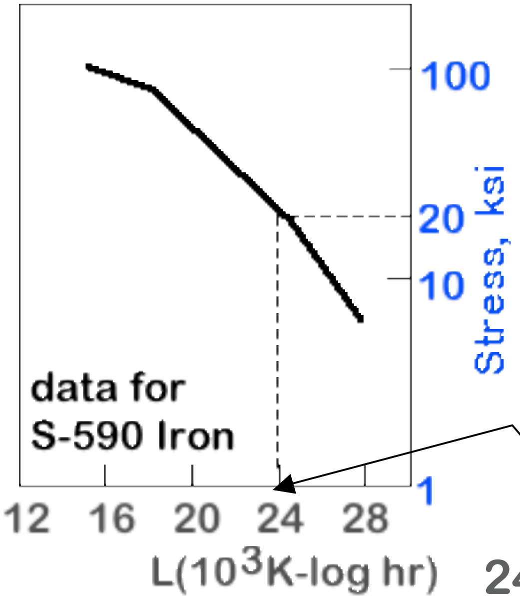
temperature

time to failure (rupture)

function of applied stress

- **Estimate rupture time**

S 590 Iron, T = 800C, □ = 20 ksi



Adapted from Fig. 8.45, *Callister 6e.* (Fig. 8.45 is from F.R. Larson and J. Miller, *Trans. ASME*, **74**, 765 (1952).)

$24\text{x}10^3$ K-log hr

$$T(20+\log t_r)=L$$

1073K

Ans: t_r = 233hr

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 □ and $T < 0.4T_m$, failure stress decreases with:

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

-for cyclic □:

cycles to fail decreases as □□ increases.

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

time to fail decreases as □ or T increases.

ANNOUNCEMENTS

Reading:

Core Problems:

Self-help Problems: