

Chapter 8: Mechanical Failure

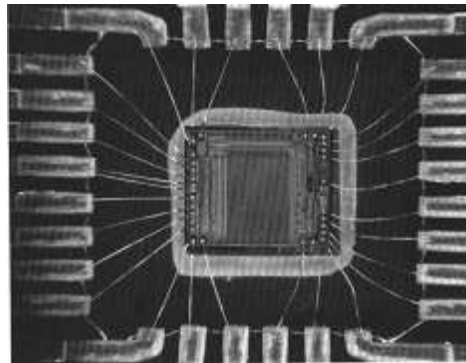
ISSUES TO ADDRESS...

- 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 chapter-opening photograph, Chapter 8, *Callister 7e.* (by Neil Boenzi, *The New York Times.*)



**Computer chip-cyclic
thermal loading.**

Adapted from Fig. 22.30(b), *Callister 7e.* (Fig. 22.30(b) is courtesy of National Semiconductor Corporation.)



**Hip implant-cyclic
loading from walking.**

Adapted from Fig. 22.26(b), *Callister 7e.*



Fracture mechanisms

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



Ductile vs Brittle Failure

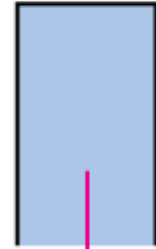
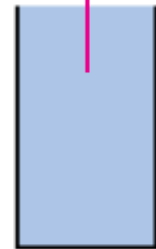
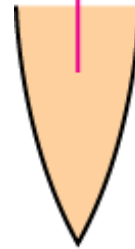
- Classification:

Fracture
behavior:

Very
Ductile

Moderately
Ductile

Brittle



%AR or %EL

Large

Moderate

Small

- Ductile fracture is usually desirable!

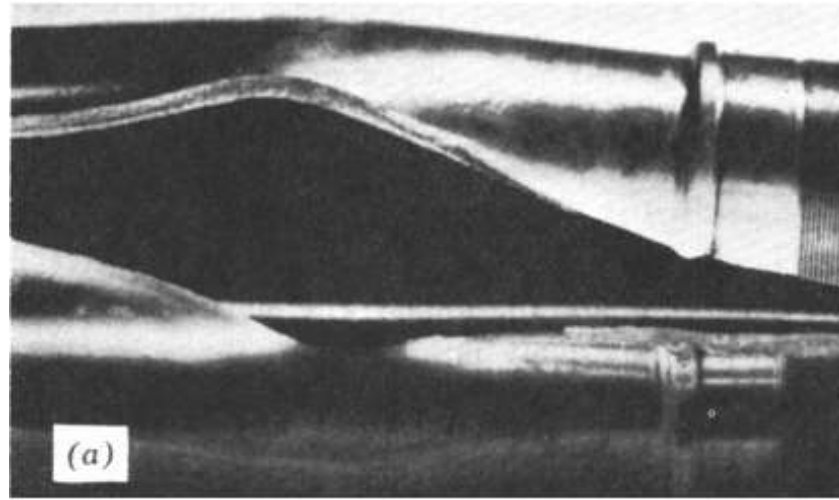
Ductile:
warning before
fracture

Brittle:
No
warning

Adapted from Fig. 8.1,
Callister 7e.

Example: Failure of a Pipe

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



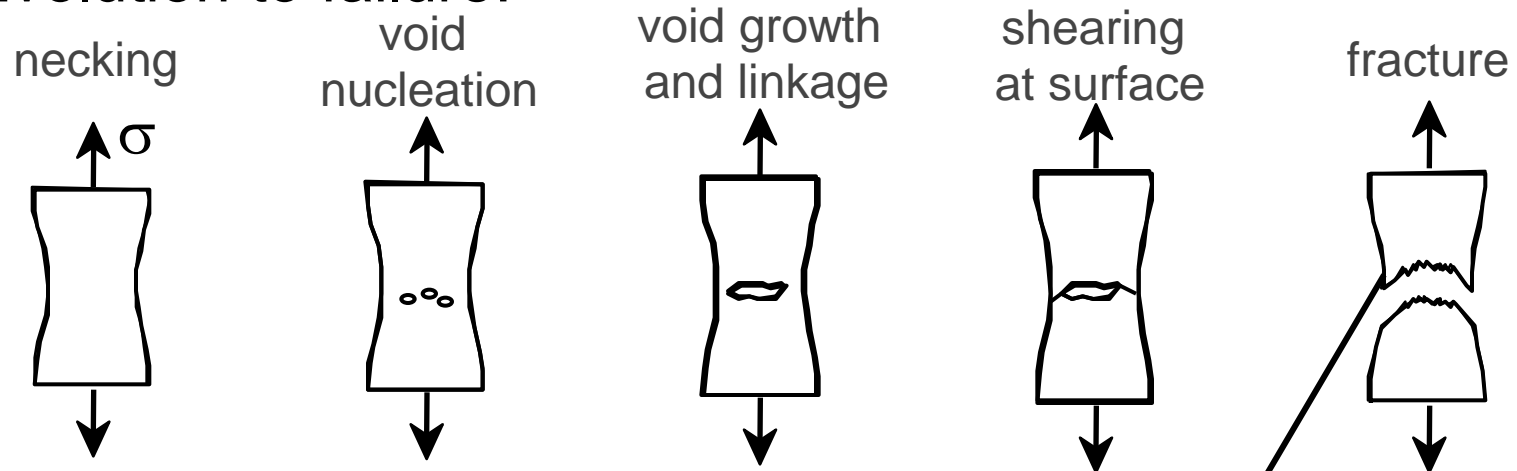
- **Brittle failure:**
 - many pieces
 - small deformation



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.

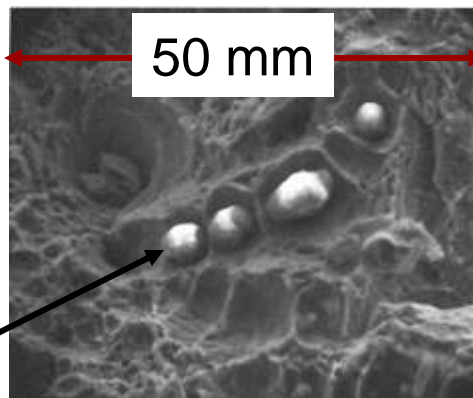
Moderately Ductile Failure

- Evolution to failure:

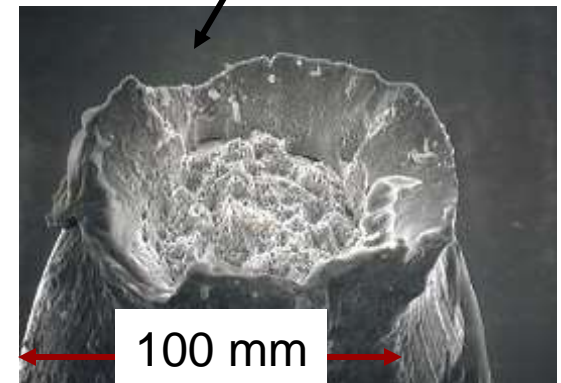


- Resulting fracture surfaces (steel)

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

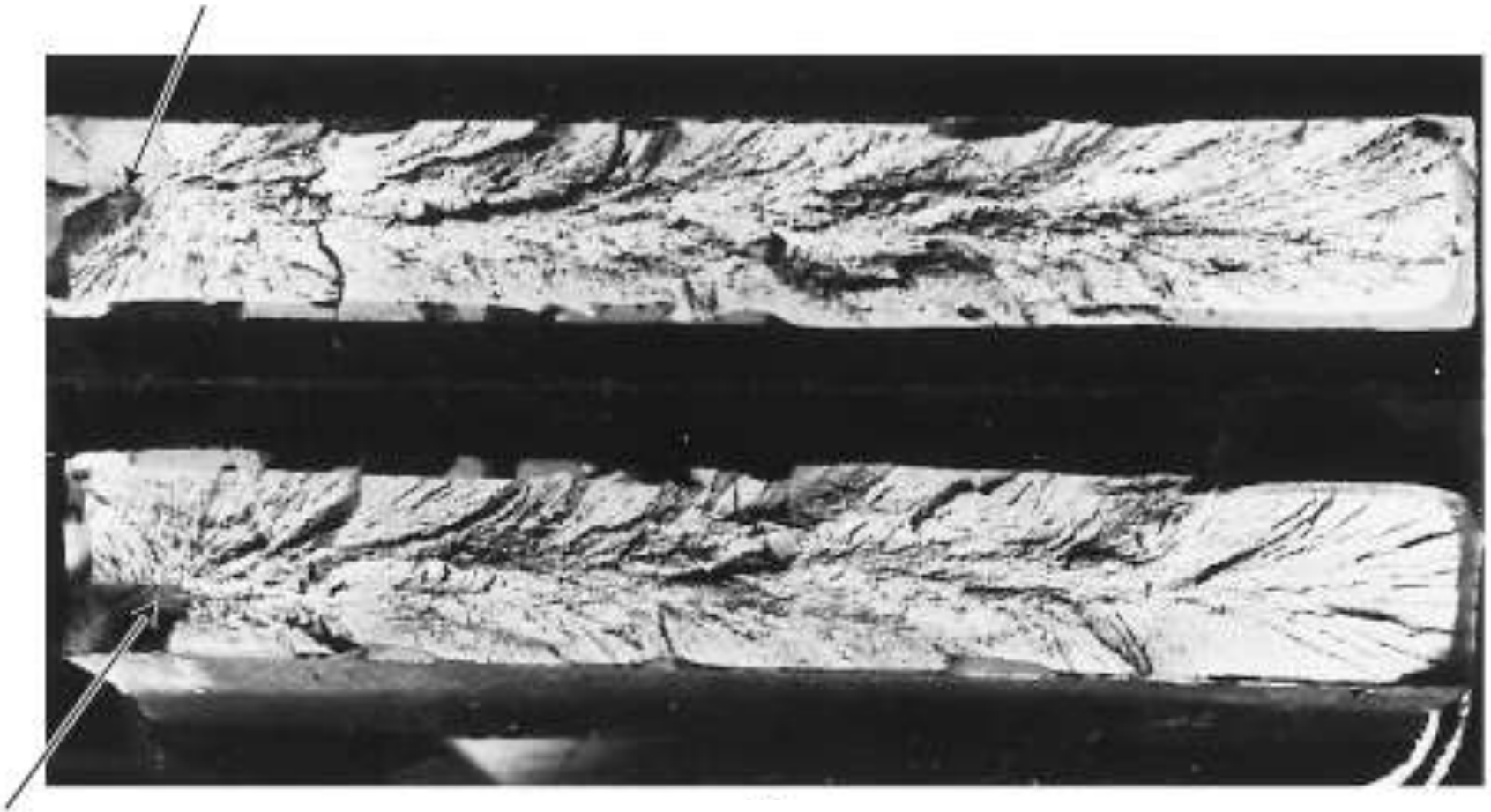


brittle fracture

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

Brittle Failure

Arrows indicate pt at which failure originated

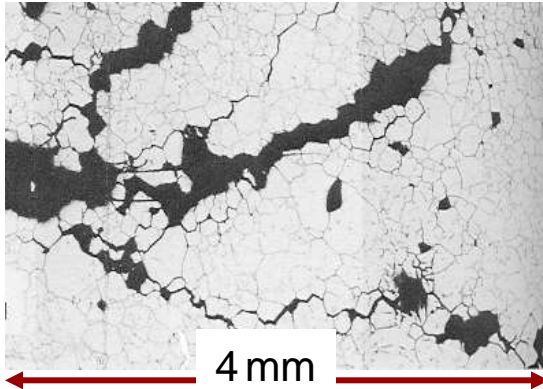


Adapted from Fig. 8.5(a), *Callister 7e*.



Brittle Fracture Surfaces

- Intergranular
(between grains)



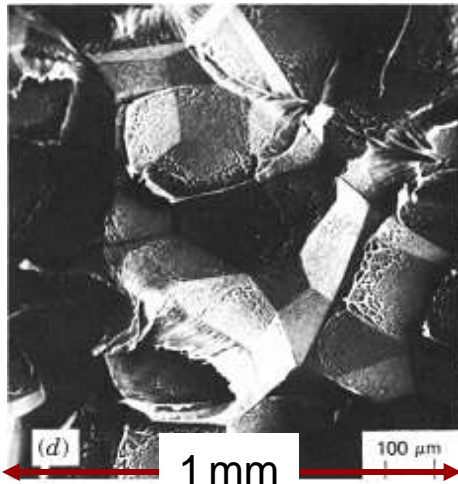
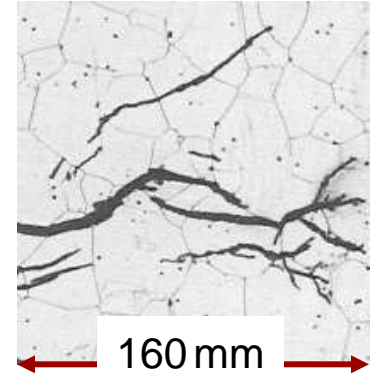
304 S. Steel (metal)

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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.
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Park, OH. (Micrograph by
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National Lab.)

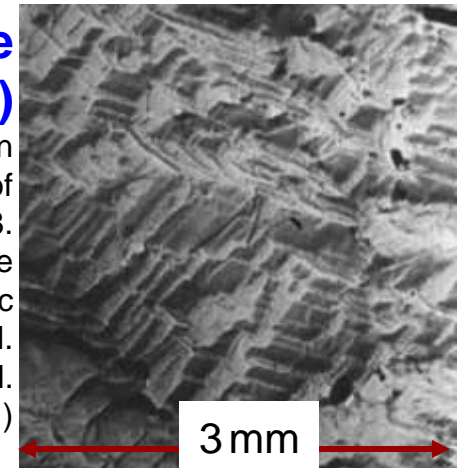


Polypropylene (polymer)

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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.

Al Oxide (ceramic)

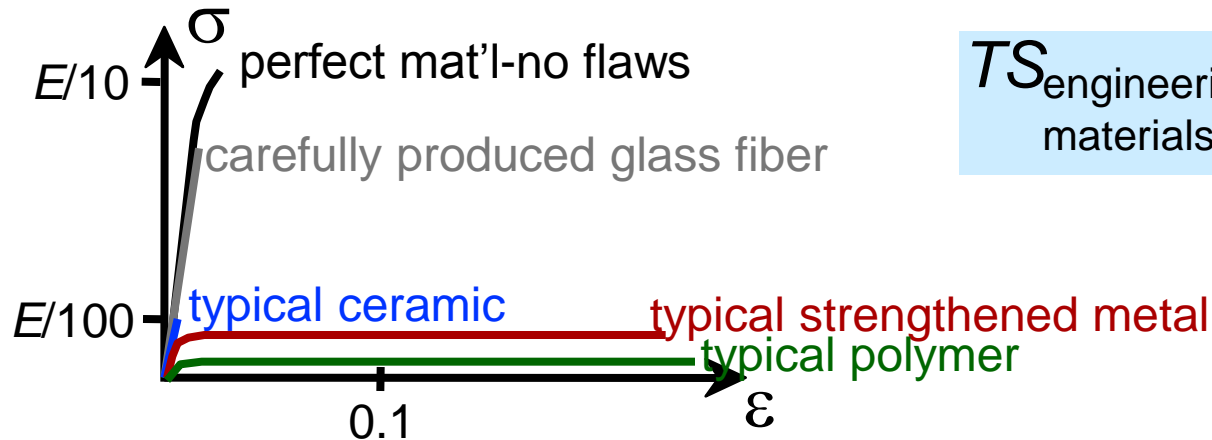
Reprinted w/ permission
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Brittle Materials", p. 78.
Copyright 1990, The
American Ceramic
Society, Westerville, OH.
(Micrograph by R.M.
Gruver and H. Kirchner.)



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

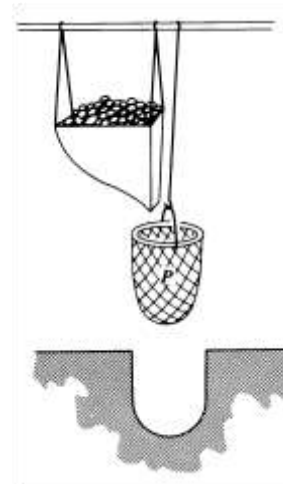
Ideal vs Real Materials

- 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!



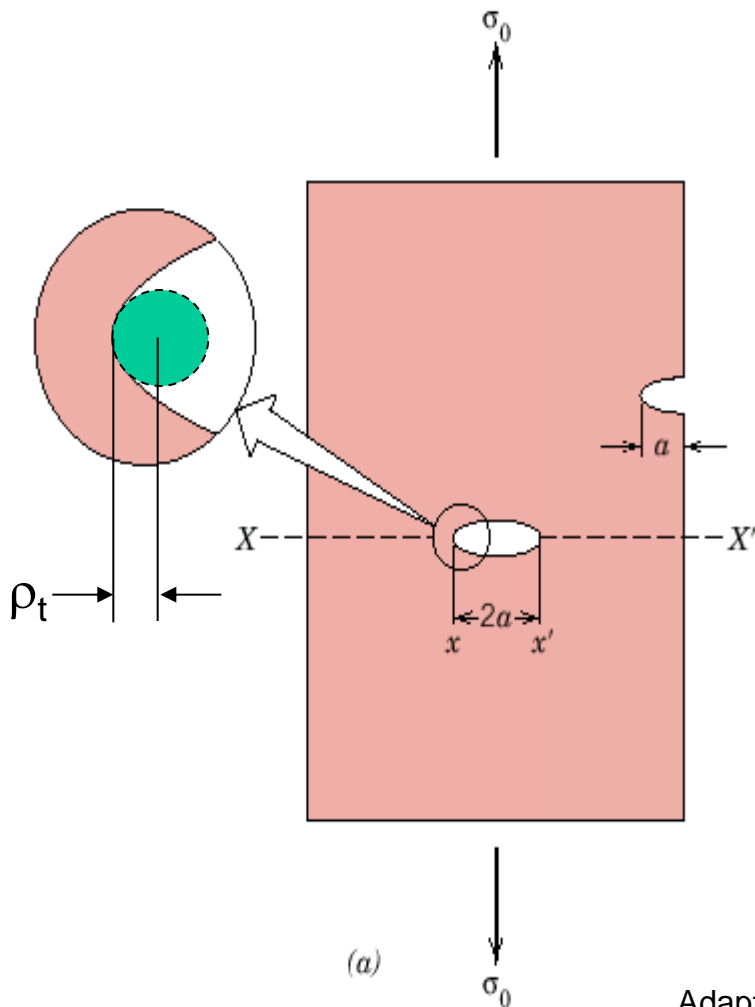
Reprinted w/
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Hertzberg,
"Deformation and
Fracture Mechanics
of Engineering
Materials", (4th ed.)
Fig. 7.4. John Wiley
and Sons, Inc., 1996.



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

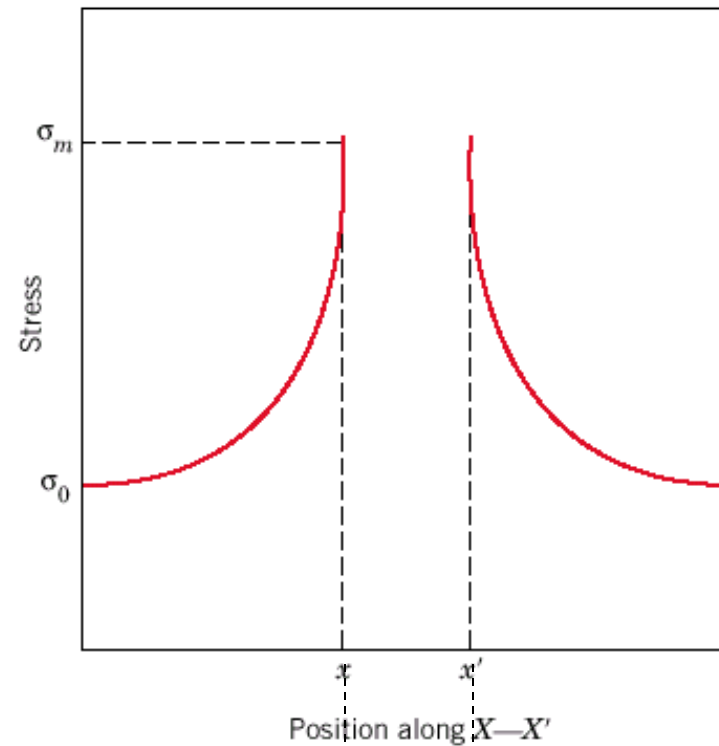
ρ_t = radius of curvature

σ_o = applied stress

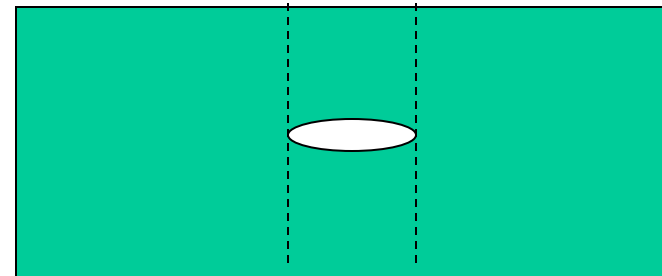
σ_m = stress at crack tip

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

Concentration of Stress at Crack Tip

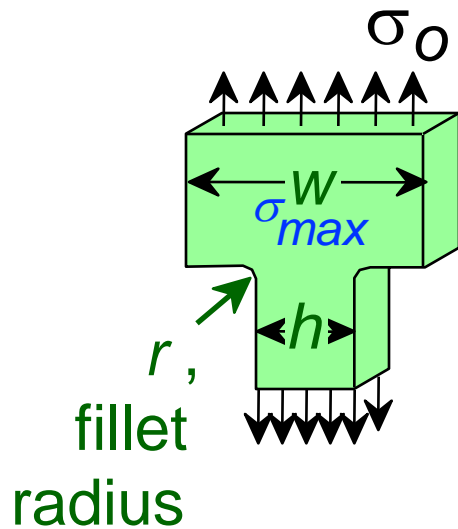


Adapted from Fig. 8.8(b), *Callister 7e*.

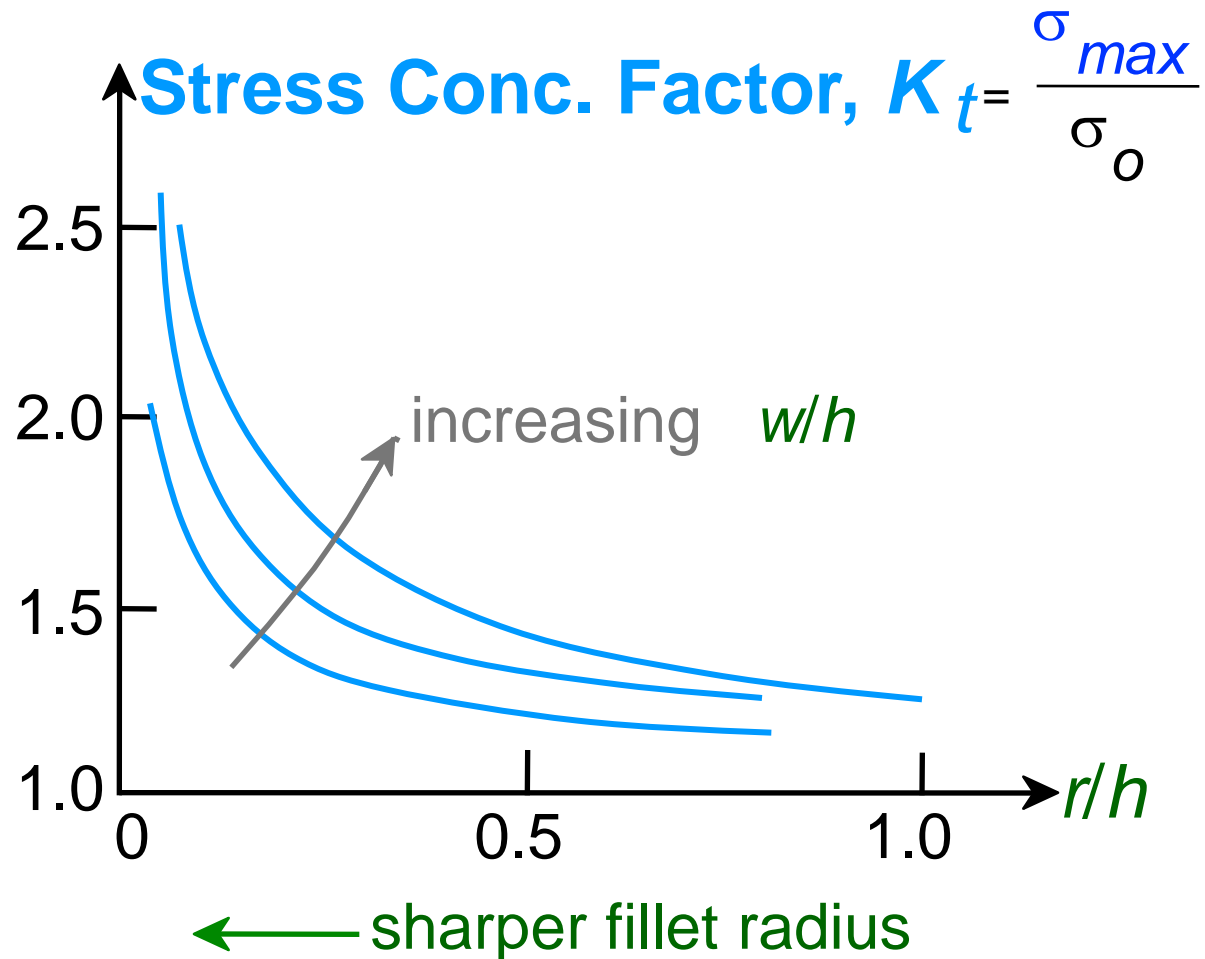


Engineering Fracture Design

- Avoid sharp corners!



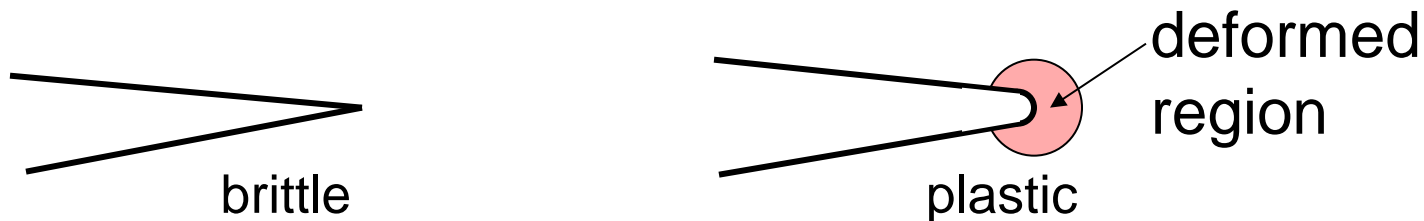
Adapted from Fig. 8.2W(c), Callister 6e.
(Fig. 8.2W(c) is from G.H. Neugebauer, *Prod. Eng.* (NY), Vol. 14, pp. 82-87 1943.)



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

$$\begin{aligned} \text{i.e., } \sigma_m &> \sigma_c \\ \text{or } K_t &> K_c \end{aligned} \quad \sigma_c = \left(\frac{2E\gamma_s}{\pi a} \right)^{1/2}$$

where

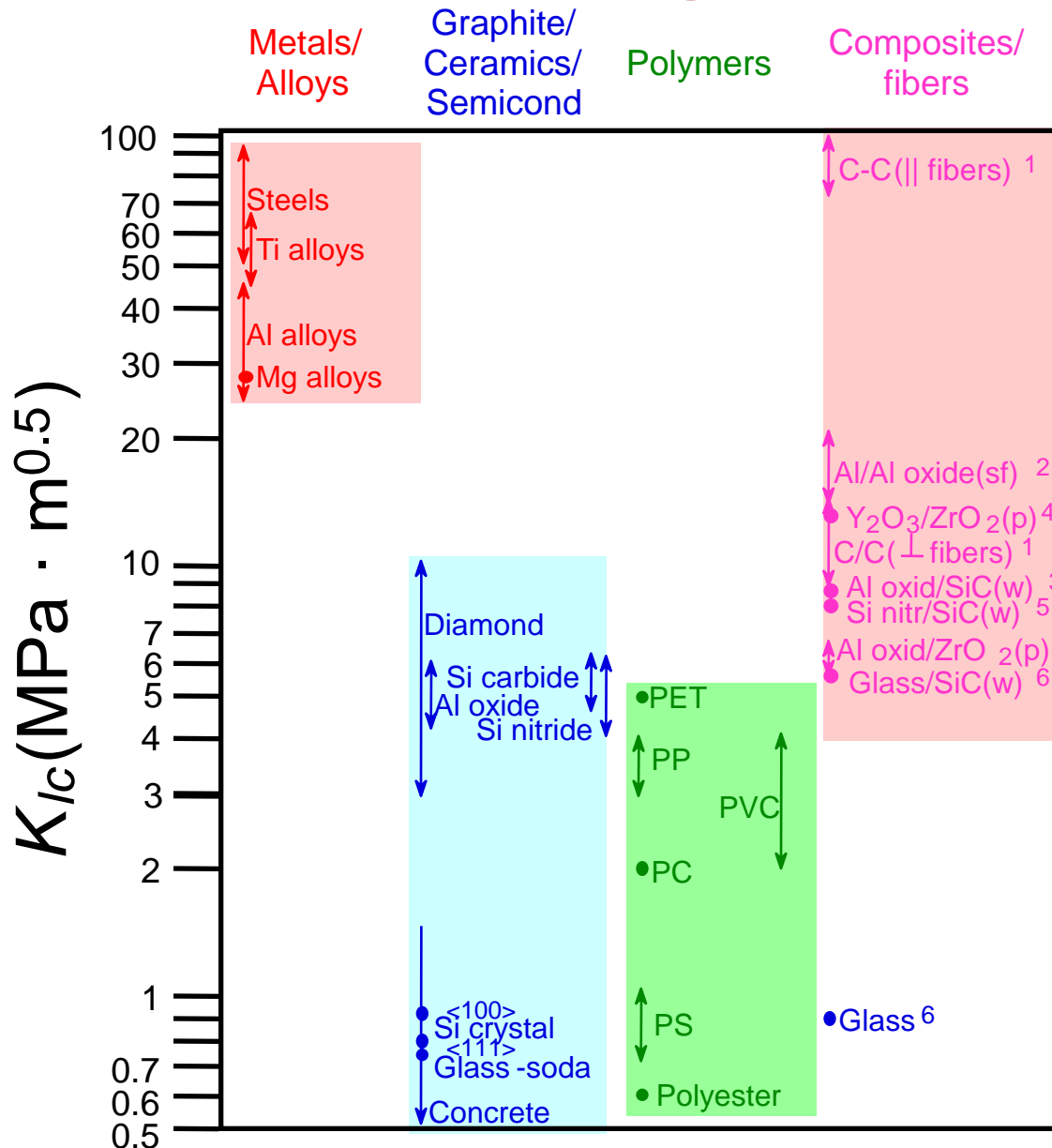
- E = modulus of elasticity
- γ_s = specific surface energy
- a = one half length of internal crack
- $K_c = \sigma_c / \sigma_0$

For ductile \Rightarrow 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

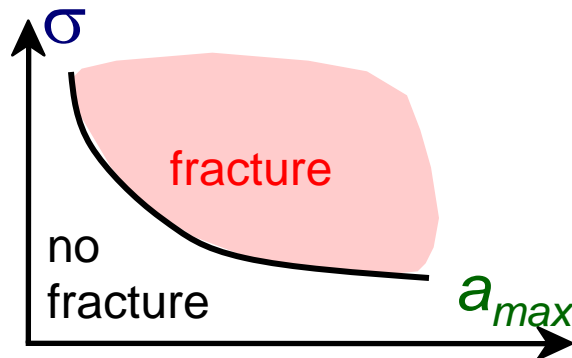
- Crack growth condition:

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

- Largest, most stressed cracks grow first!

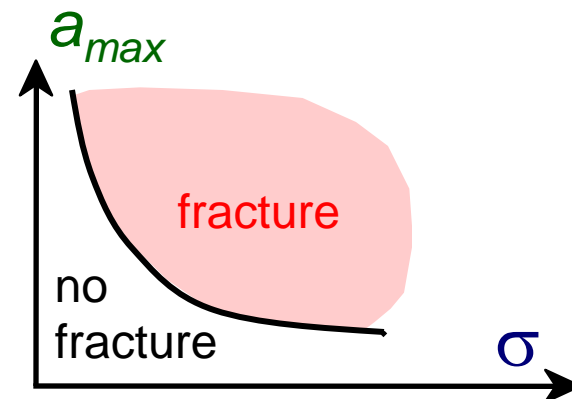
--Result 1: Max. flaw size dictates design stress.

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



--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 $K_c = 26 \text{ MPa-m}^{0.5}$
- 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...

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

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

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

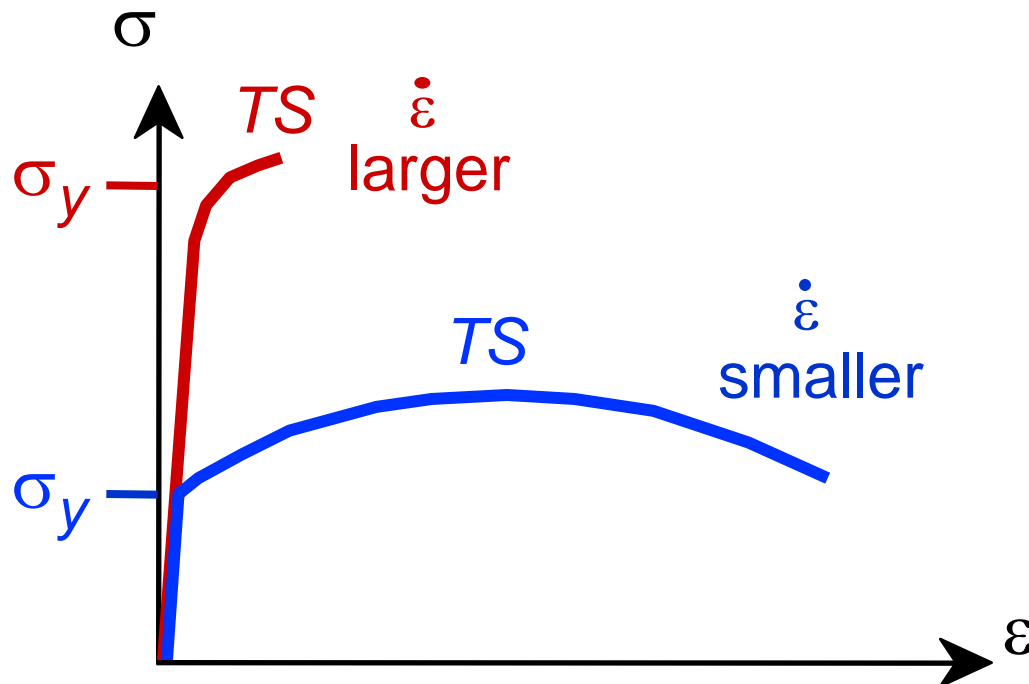
Answer: $(\sigma_c)_B = 168 \text{ MPa}$

- Reducing flaw size pays off!



Loading Rate

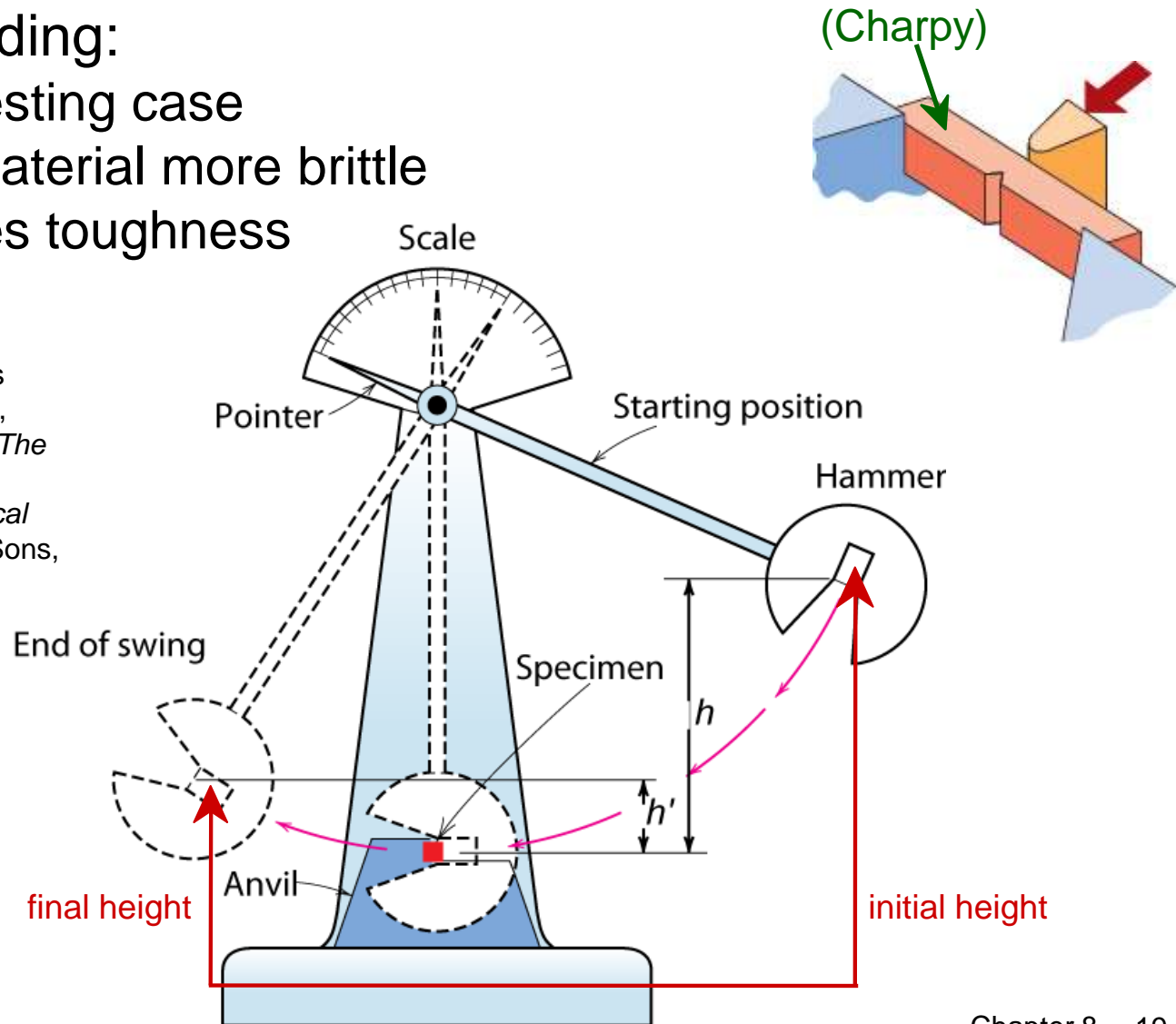
- Increased loading rate...
 - increases σ_y and TS
 - decreases % EL
- Why? An increased rate gives less time for dislocations to move past obstacles.



Impact Testing

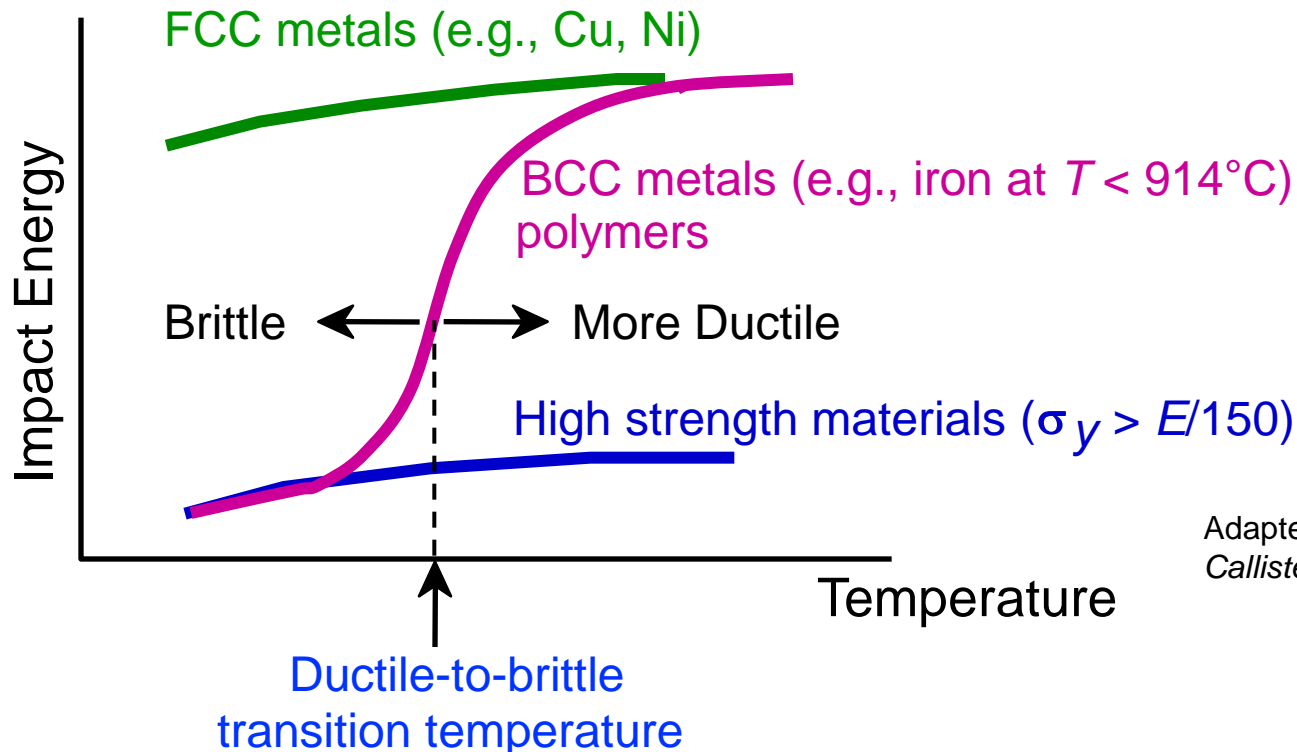
- Impact loading:
 - severe testing case
 - makes material more brittle
 - decreases toughness

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.



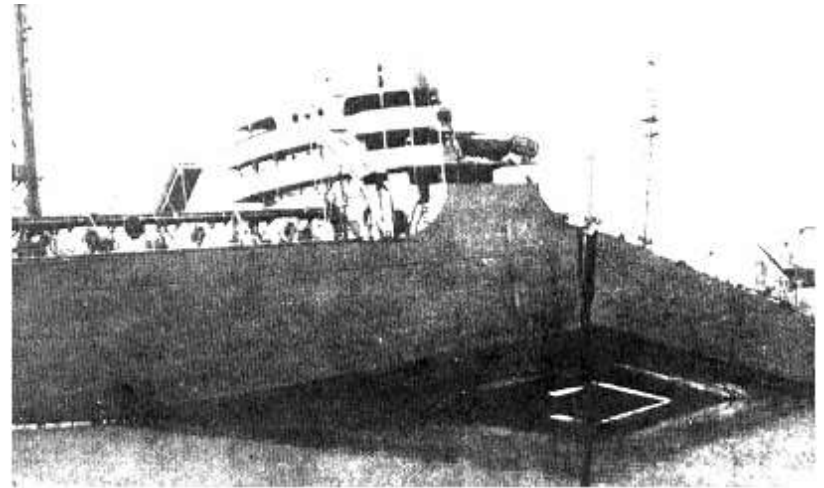
Design Strategy: Stay Above The DBTT!

- Pre-WWII: The Titanic



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



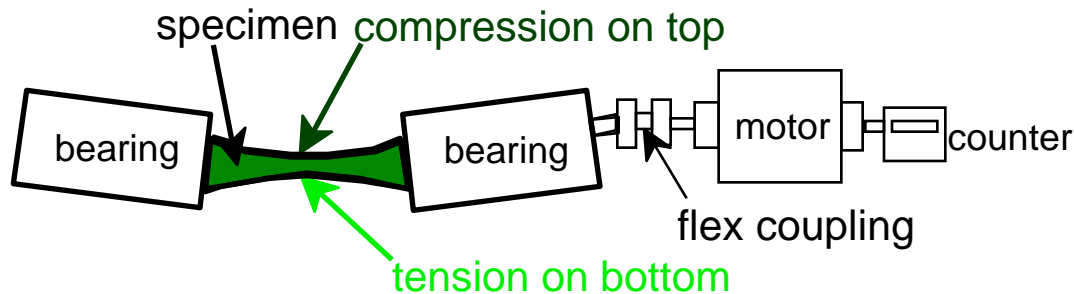
Reprinted w/ permission from R.W. Hertzberg, "Deformation and Fracture Mechanics of Engineering Materials", (4th ed.) Fig. 7.1(b), p. 262, John Wiley and Sons, Inc., 1996. (Orig. source: Earl R. Parker, "Behavior of Engineering Structures", Nat. Acad. Sci., Nat. Res. Council, John Wiley and Sons, Inc.,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

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



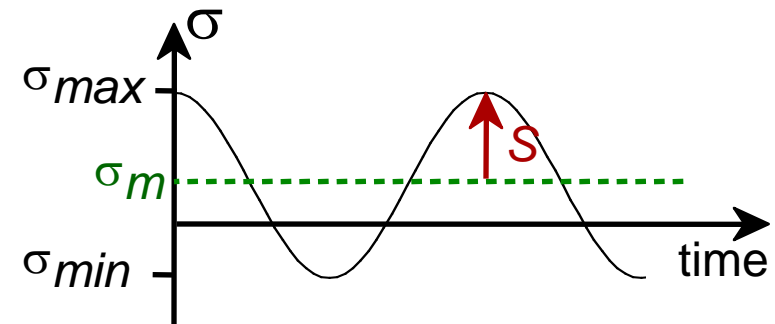
Fatigue

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



Adapted from Fig. 8.18, Callister 7e. (Fig. 8.18 is from *Materials Science in Engineering*, 4/E by Carl. A. Keyser, Pearson Education, Inc., Upper Saddle River, NJ.)

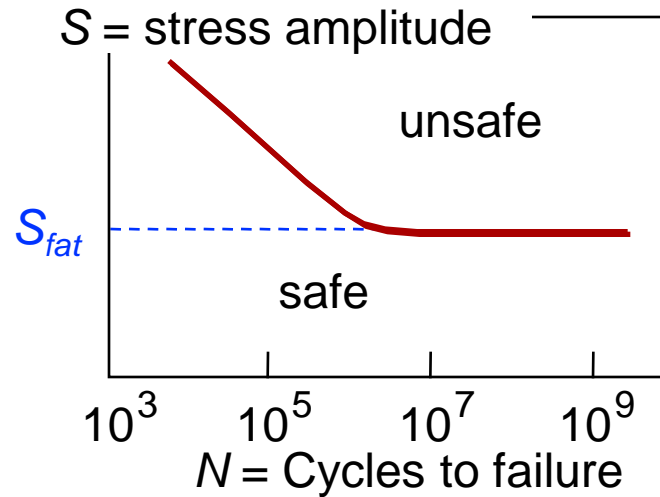
- Stress varies with time.
 - key parameters are S , σ_m , and frequency



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

Fatigue Design Parameters

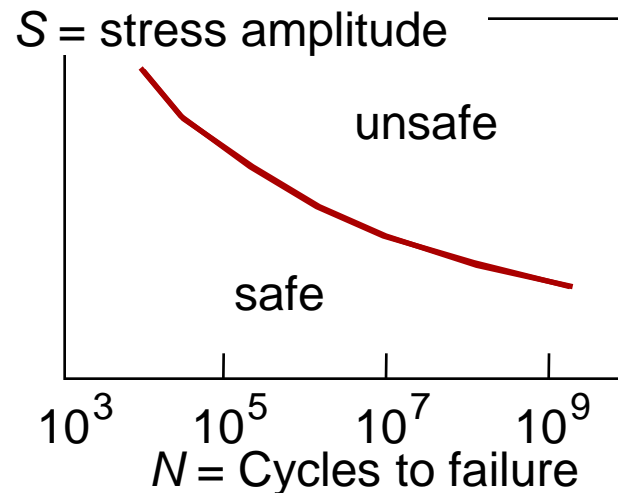
- **Fatigue limit, S_{fat} :**
--no fatigue if $S < S_{fat}$



case for
steel (typ.)

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

- Sometimes, the
fatigue limit is zero!



case for
Al (typ.)

Adapted from Fig.
8.19(b), Callister 7e.



Fatigue Mechanism

- Crack grows *incrementally*

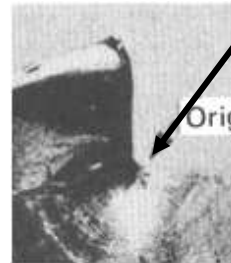
$$\frac{da}{dN} = (\Delta K)^m$$

typ. 1 to 6

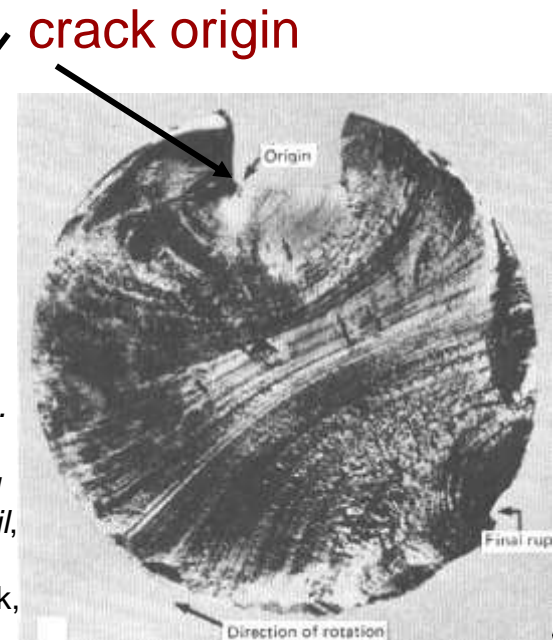
$$\sim (\Delta\sigma)\sqrt{a}$$

increase in crack length per loading cycle

- Failed rotating shaft
 - crack grew even though
$$K_{max} < K_C$$
 - crack grows faster as
 - $\Delta\sigma$ increases
 - crack gets longer
 - loading freq. increases.

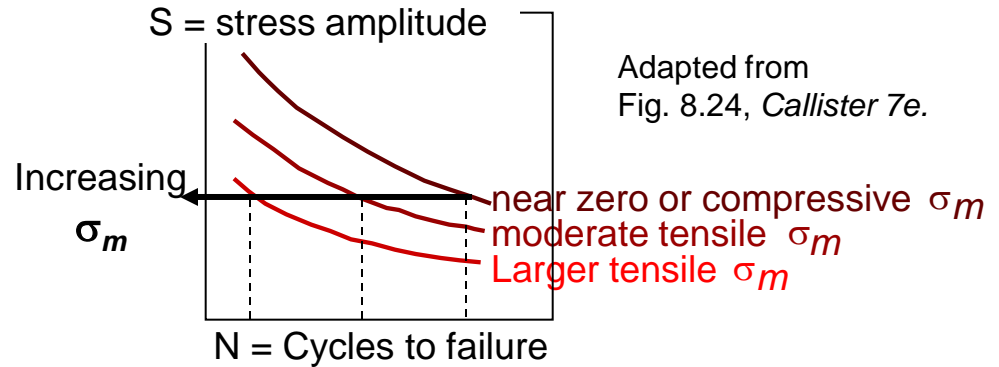


Adapted from
Fig. 8.21, *Callister 7e*.
(Fig. 8.21 is from D.J.
Wulpi, *Understanding
How Components Fail*,
American Society for
Metals, Materials Park,
OH, 1985.)

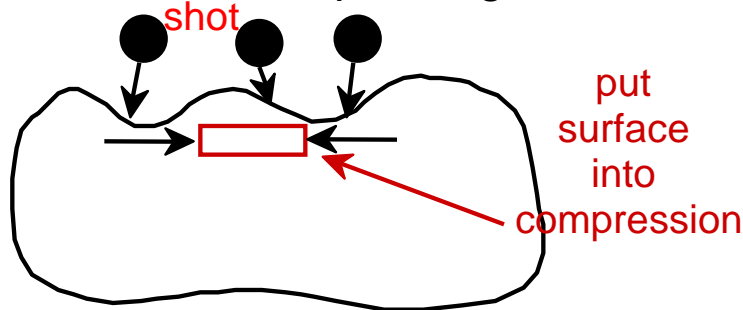


Improving Fatigue Life

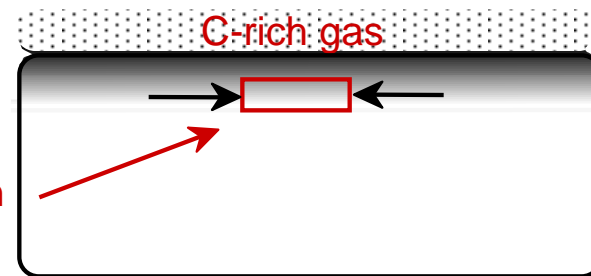
1. Impose a compressive surface stress
(to suppress surface cracks from growing)



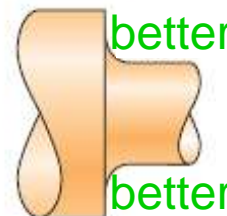
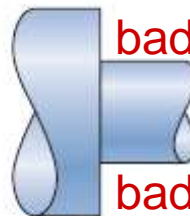
--Method 1: shot peening



--Method 2: carburizing



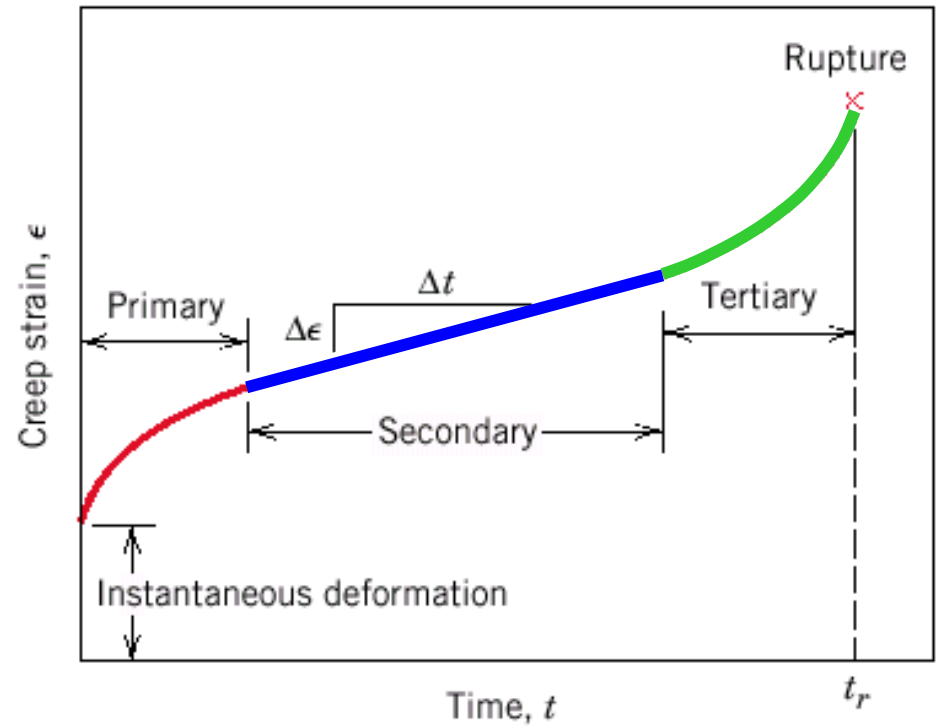
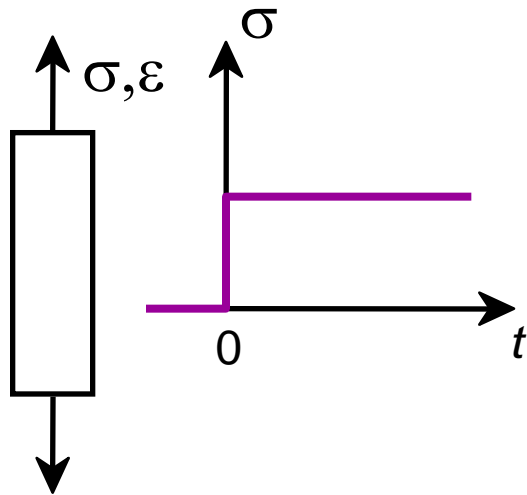
2. Remove stress concentrators.



Adapted from Fig. 8.25, Callister 7e.

Creep

Sample deformation at a constant stress (σ) vs. time



Primary Creep: slope (creep rate) decreases with time.

Secondary Creep: steady-state i.e., constant slope.

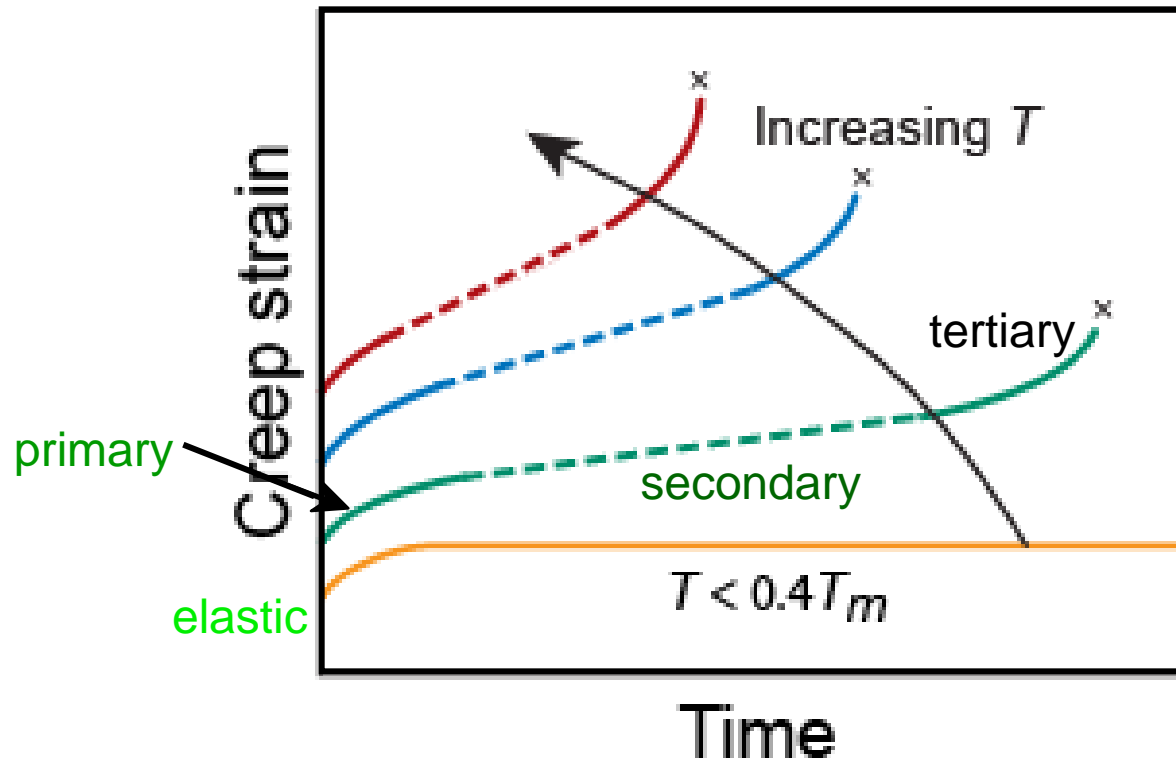
Tertiary Creep: slope (creep rate) increases with time, i.e. acceleration of rate.

Adapted from
Fig. 8.28, Callister 7e.



Creep

- Occurs at elevated temperature, $T > 0.4 T_m$



Adapted from Figs. 8.29,
Callister 7e.



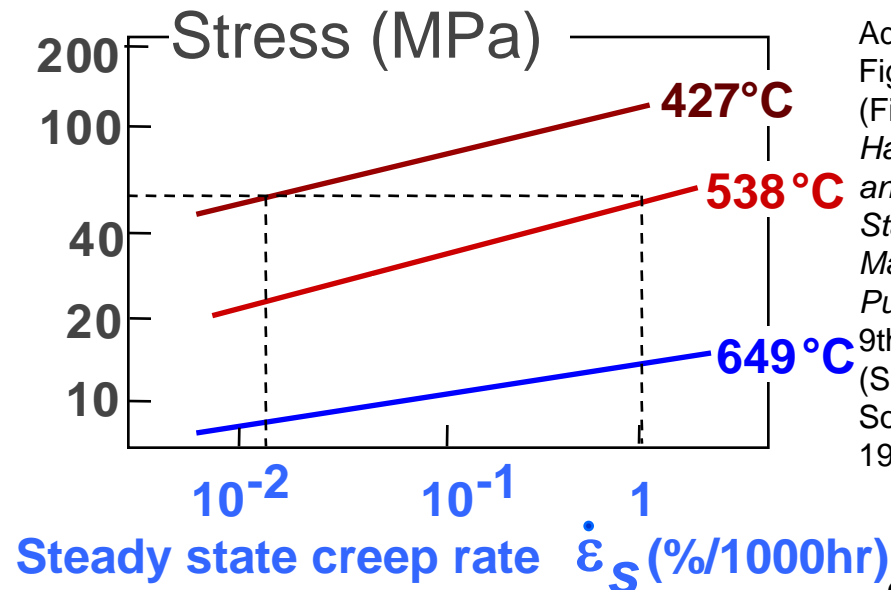
Secondary Creep

- Strain rate is constant at a given T , σ
 - strain hardening is balanced by recovery

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

strain rate $\dot{\epsilon}_s$ (blue box)
 material const. K_2 (black box)
 stress exponent (material parameter) n (green box)
 applied stress σ (black box)
 activation energy for creep (material parameter) Q_c (red box)

- Strain rate increases for higher T , σ

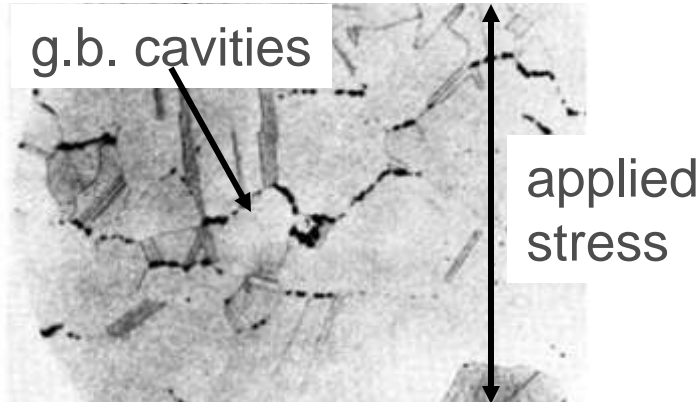


Adapted from Fig. 8.31, *Callister 7e*. (Fig. 8.31 is from *Metals Handbook: Properties and Selection: Stainless Steels, Tool Materials, and Special Purpose Metals*, Vol. 3, 9th ed., D. Benjamin (Senior Ed.), American Society for Metals, 1980, p. 131.)



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

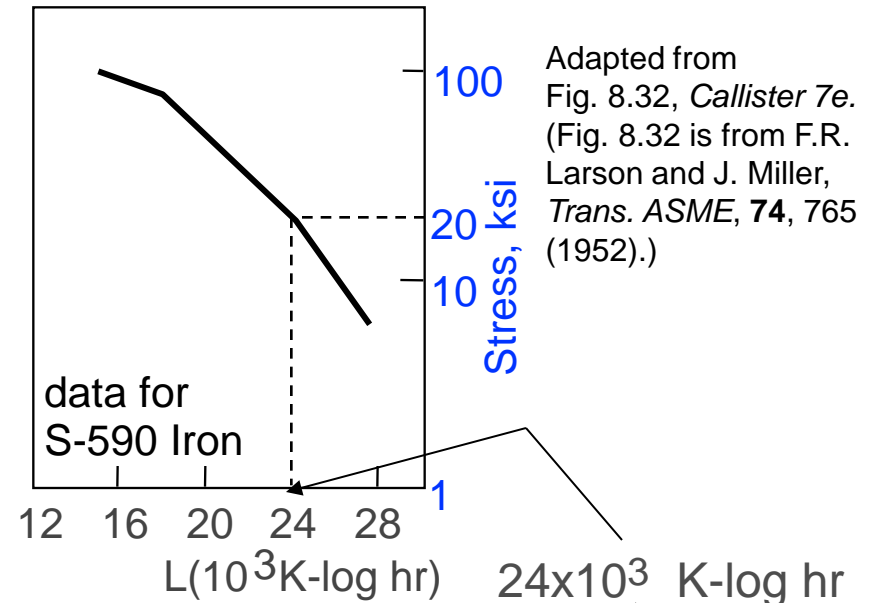
$$T(20 + \log t_r) = L$$

temperature

time to failure (rupture)

function of
applied stress

- Estimate rupture time
S-590 Iron, $T = 800^\circ\text{C}$, $\sigma = 20$ ksi



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

1073K

Ans: $t_r = 233$ hr

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 $T < 0.4 T_m$, 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 ($T > 0.4 T_m$):
 - time to fail decreases as σ or T increases.



ANNOUNCEMENTS

Reading:

Core Problems:

Self-help Problems:

