

CHAPTER 8:

MECHANICAL FAILURE

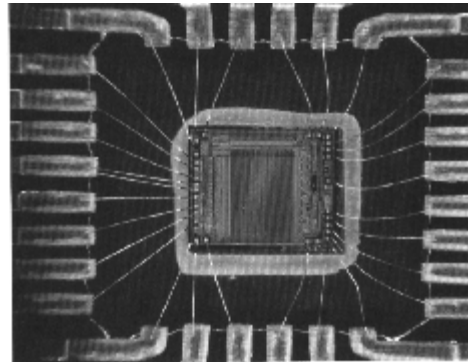
ISSUES TO ADDRESS...

- 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.)

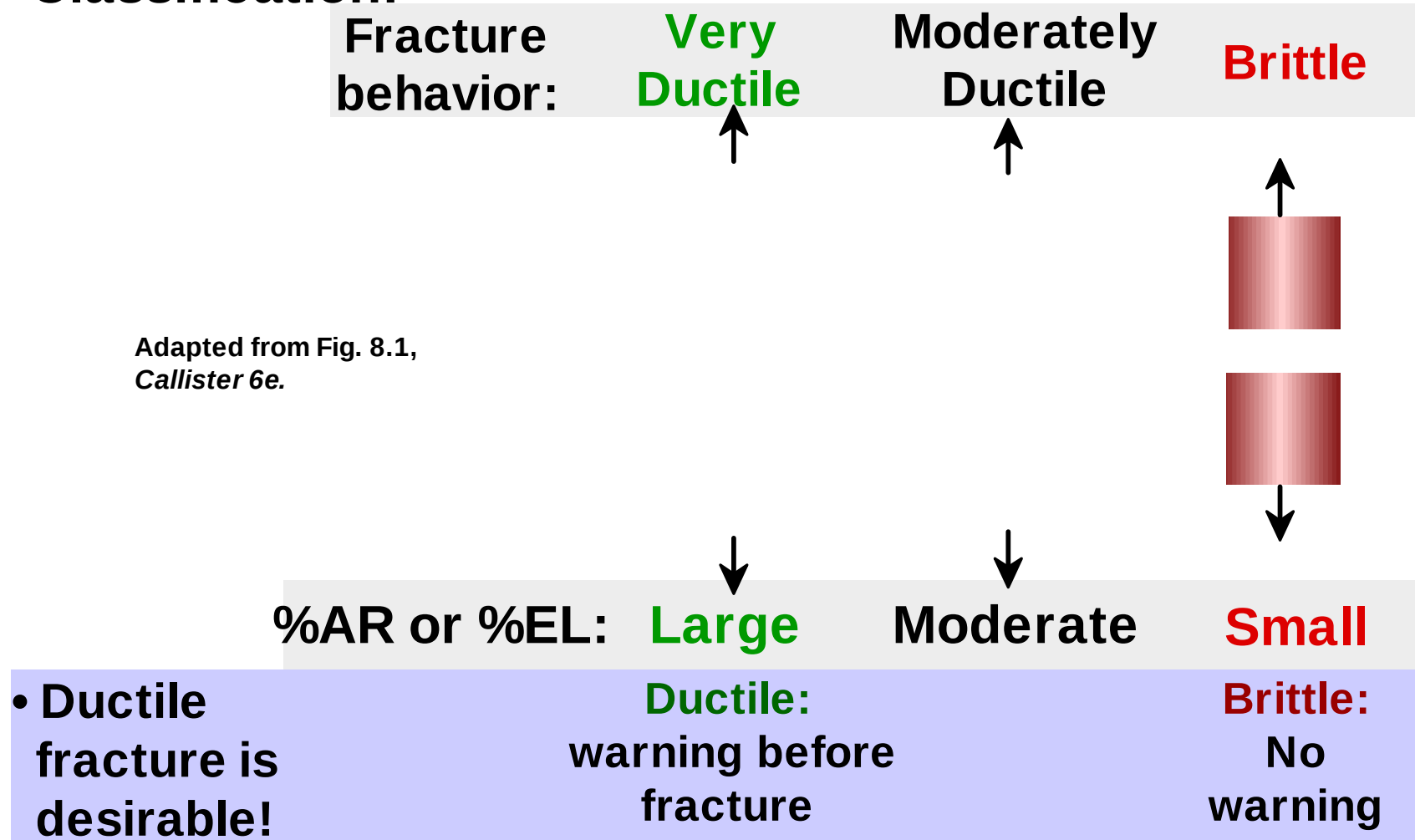


**Hip implant-cyclic
loading from walking.**

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

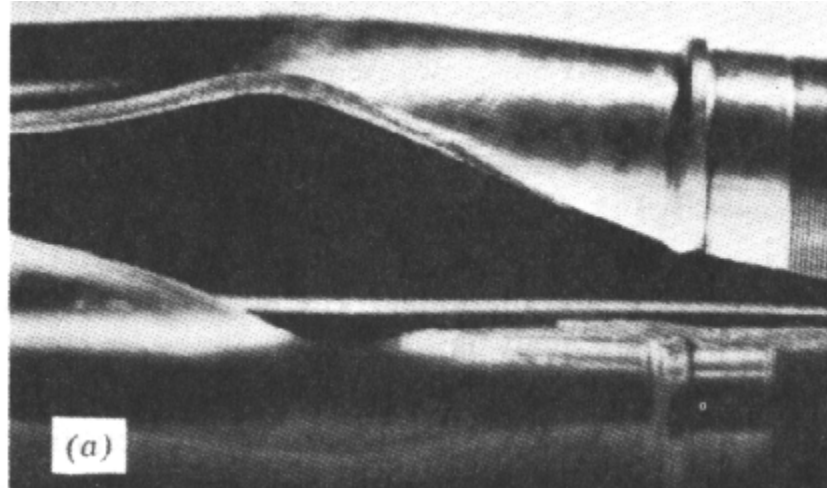
DUCTILE VS BRITTLE FAILURE

- Classification:

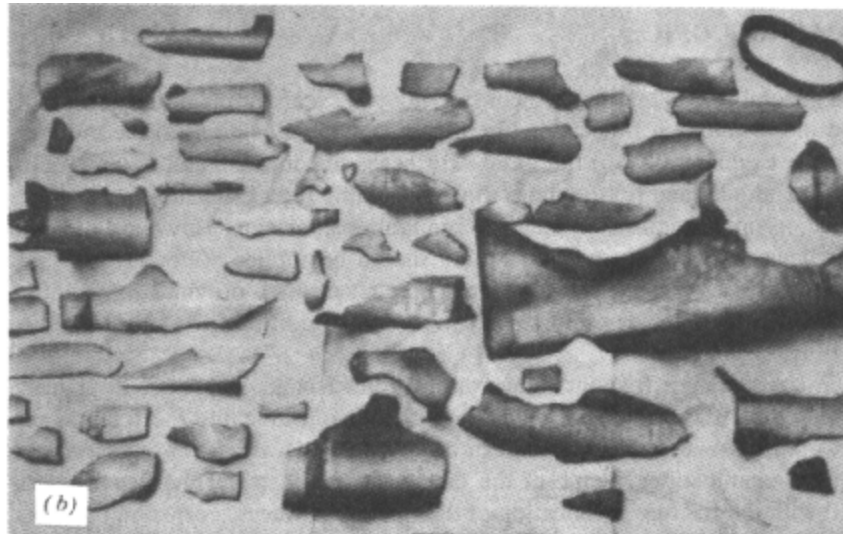


EX: FAILURE OF A PIPE

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



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

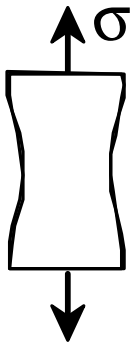


Figures from V.J. Colangelo and F.A. Heiser, *Analysis of Metallurgical Failures* (2nd ed.), Fig. 4.1(a) and (b), p. 66 John Wiley and Sons, Inc., 1987. Used with permission.

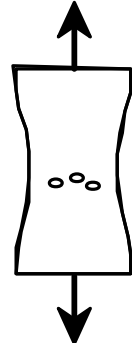
MODERATELY DUCTILE FAILURE

- Evolution to failure:

necking



void nucleation



void growth and linkage



shearing at surface

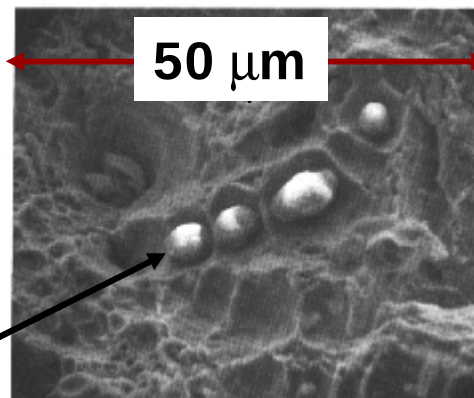


fracture

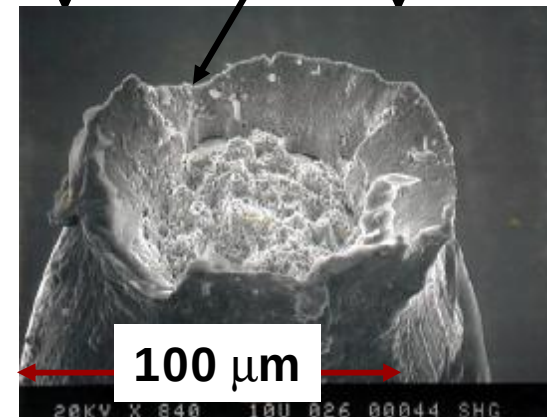


- Resulting fracture surfaces (steel)

particles serve as void nucleation sites.



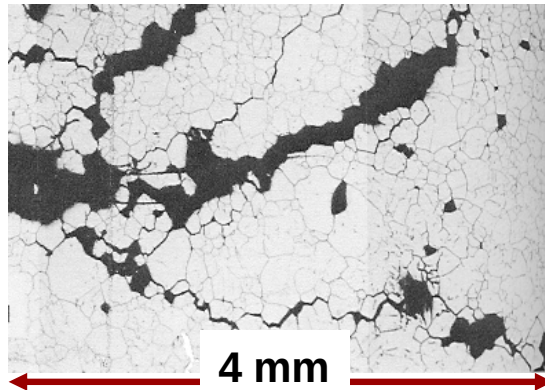
From V.J. Colangelo and F.A. Heiser, *Analysis of Metallurgical Failures* (2nd ed.), Fig. 11.28, p. 294, John Wiley and Sons, Inc., 1987. (Orig. source: P. Thornton, *J. Mater. Sci.*, Vol. 6, 1971, pp. 347-56.)



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)



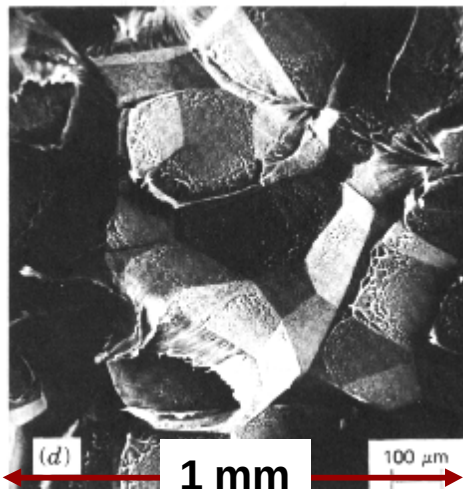
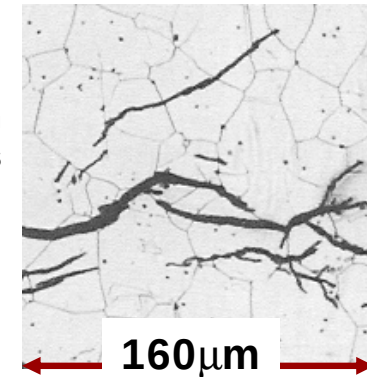
**304 S. Steel
(metal)**

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.)

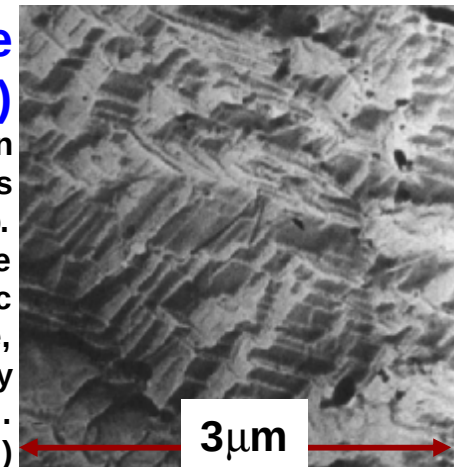


**Polypropylene
(polymer)**

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.

**Al Oxide
(ceramic)**

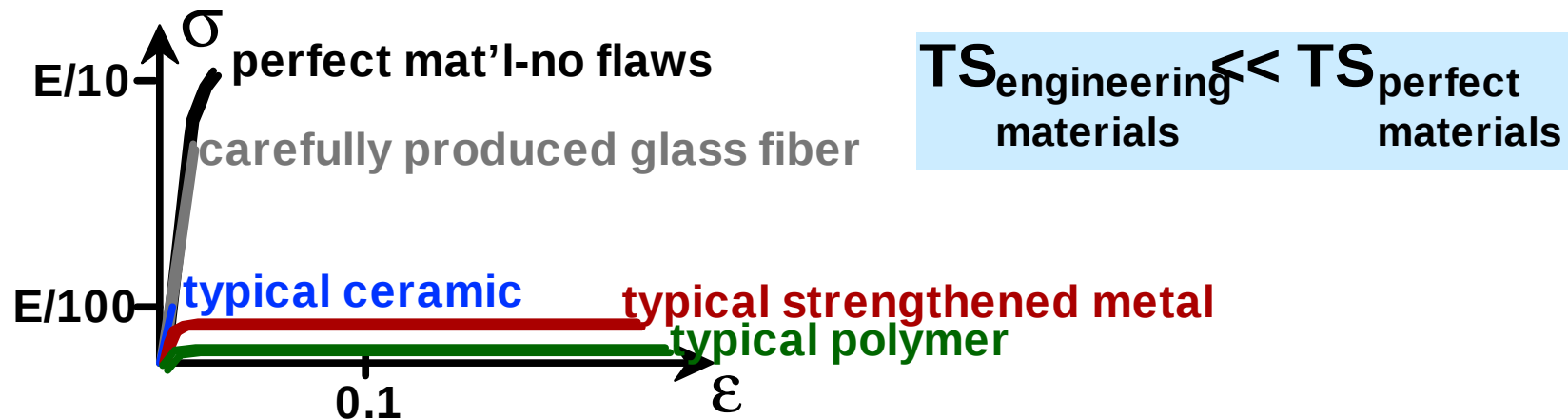
Reprinted w/ permission from "Failure Analysis of Brittle Materials", p. 78. Copyright 1990, The American Ceramic Society, Westerville, OH. (Micrograph by R.M. Gruver and H. Kirchner.)



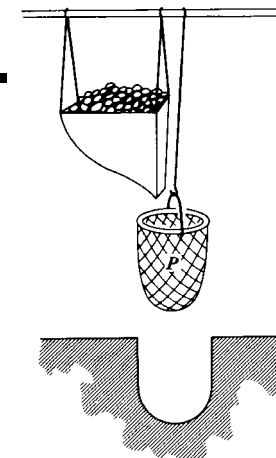
(Orig. source: K. Friedrich, *Fracture* 1977, Vol. 3, ICF4, Waterloo, CA, 1977, p. 1119.)

IDEAL VS REAL MATERIALS

- Stress-strain behavior (Room T):



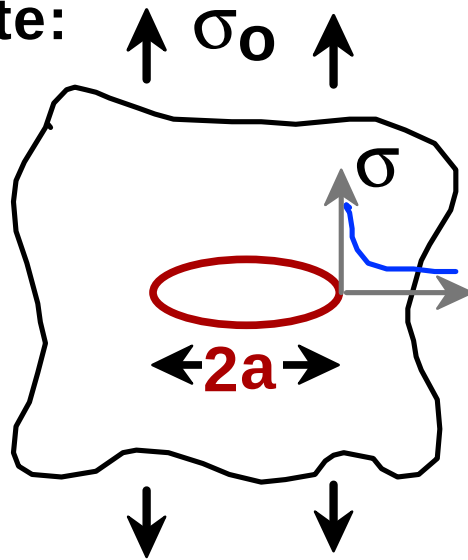
- DaVinci (500 yrs ago!) observed...
 - the longer the wire, the smaller the load to fail it.
- Reasons:
 - flaws cause premature failure.
 - Larger samples are more flawed!



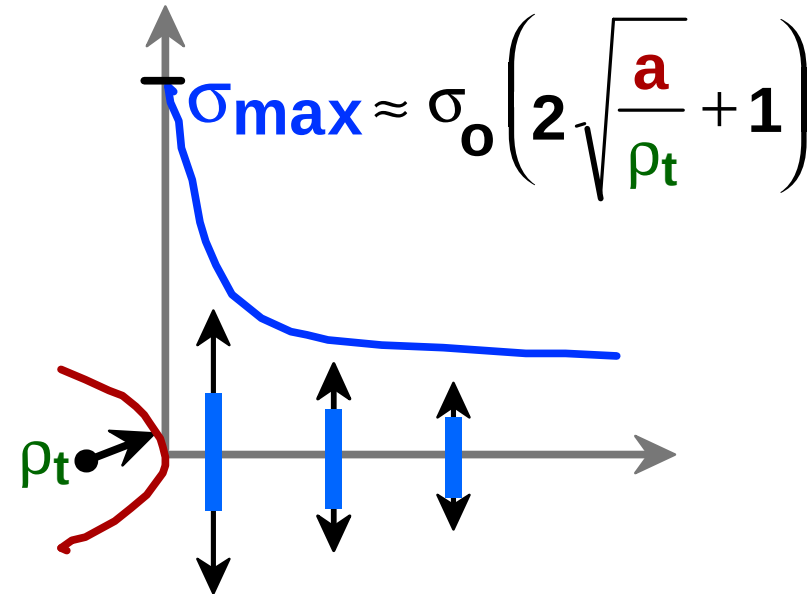
Reprinted w/
permission from
R.W. Hertzberg,
"Deformation and
Fracture Mechanics
of Engineering
Materials", (4th ed.)
Fig. 7.4. John Wiley
and Sons, Inc.,
1996.

FLAWS ARE STRESS CONCENTRATORS!

- Elliptical hole in a plate:

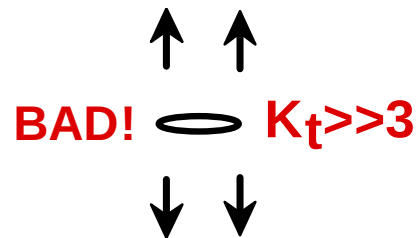
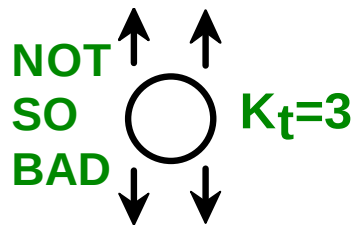


- Stress distrib. in front of a hole:



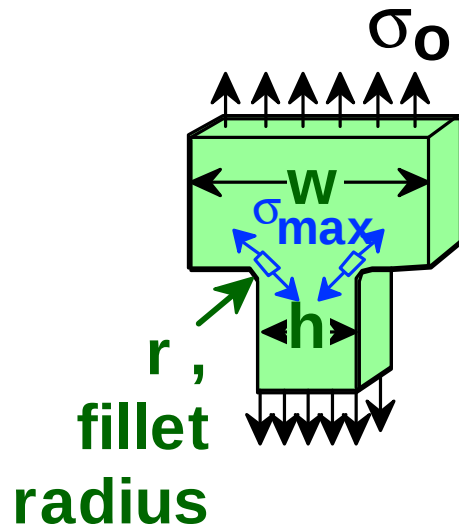
- Stress conc. factor: $K_t = \sigma_{max} / \sigma_o$

- Large K_t promotes failure:

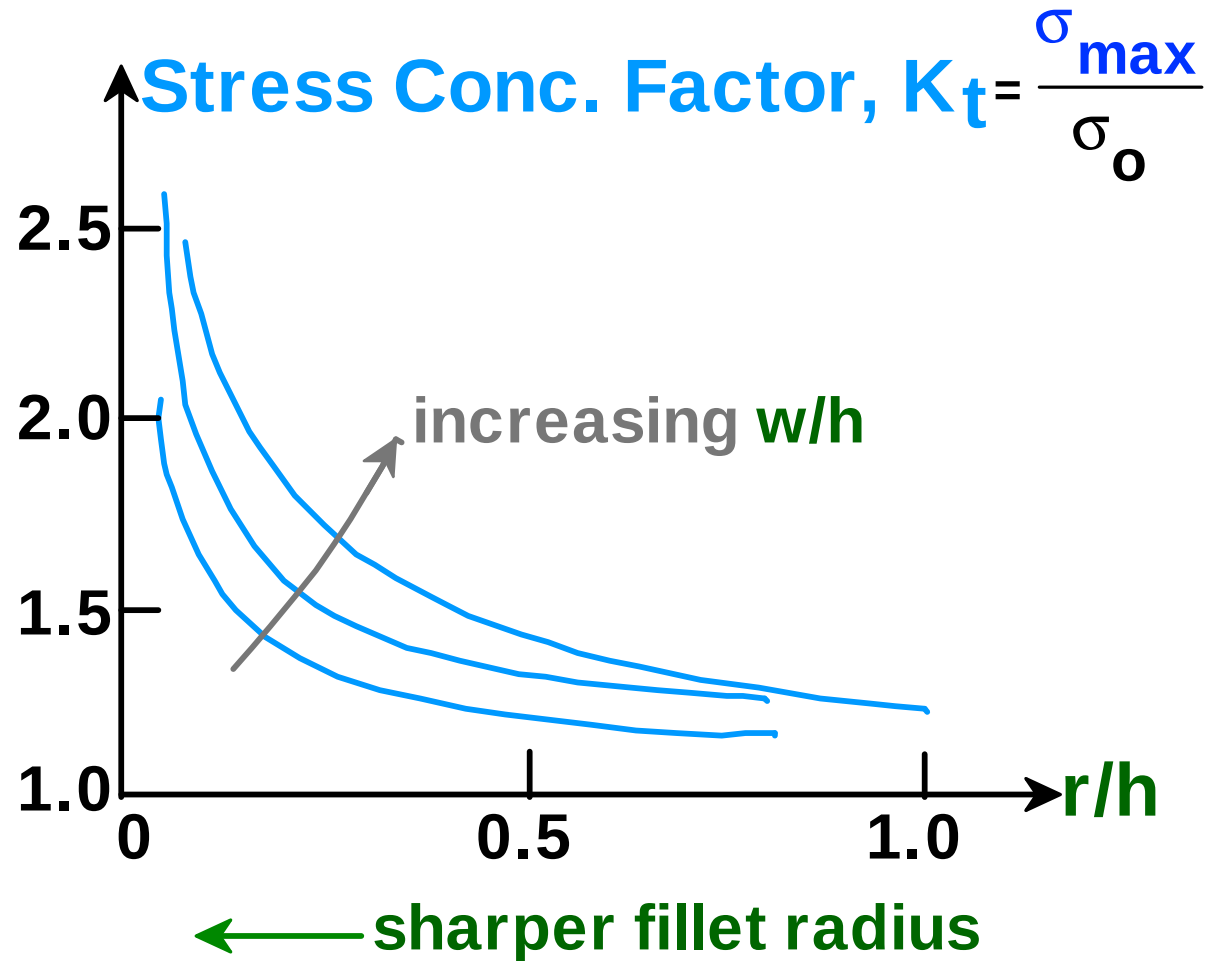


ENGINEERING FRACTURE DESIGN

- Avoid sharp corners!

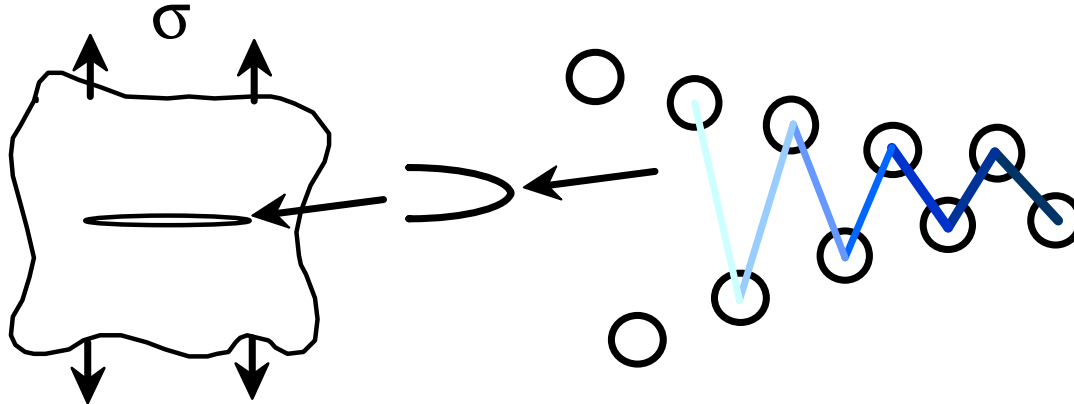


Adapted from Fig. 8.2W(c), *Callister 6e*.
(Fig. 8.2W(c) is from
G.H. Neugebauer, *Prod.*
Eng. (NY), Vol. 14, pp.
82-87 1943.)



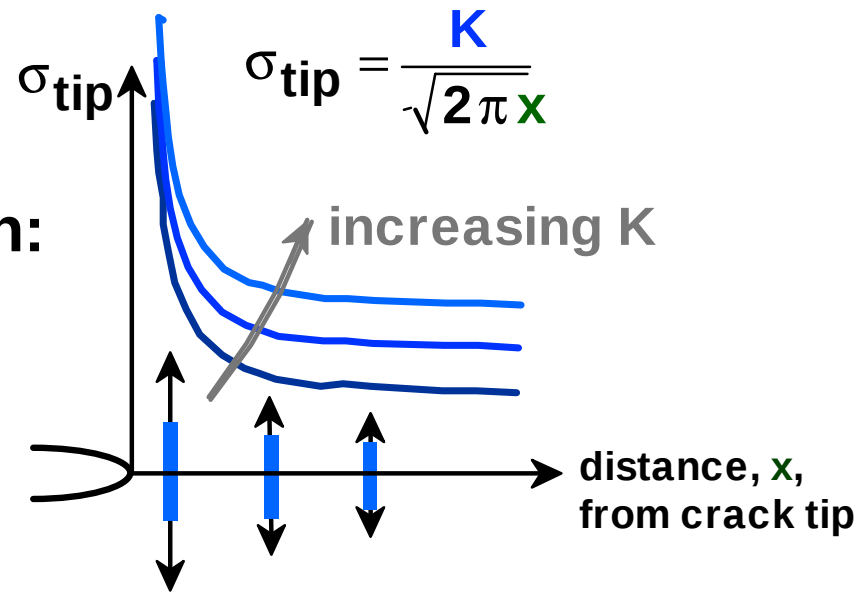
WHEN DOES A CRACK PROPAGATE?

- 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:

$$K \geq K_c$$



GEOMETRY, LOAD, & MATERIAL

- Condition for crack propagation:

Stress Intensity Factor:

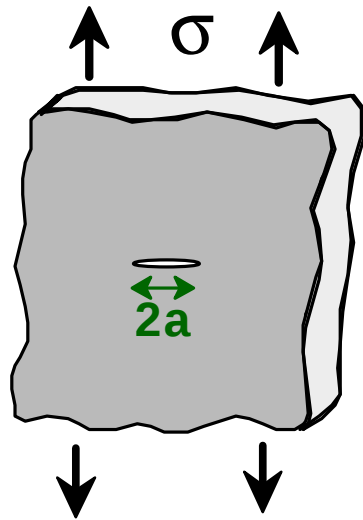
--Depends on load & geometry.

$$K \geq K_c$$

Fracture Toughness:

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

- Values of K for some standard loads & geometries:



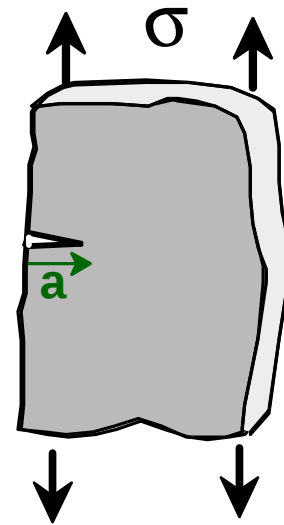
$$K = \sigma \sqrt{\pi a}$$

units of K :

$\text{MPa}\sqrt{\text{m}}$

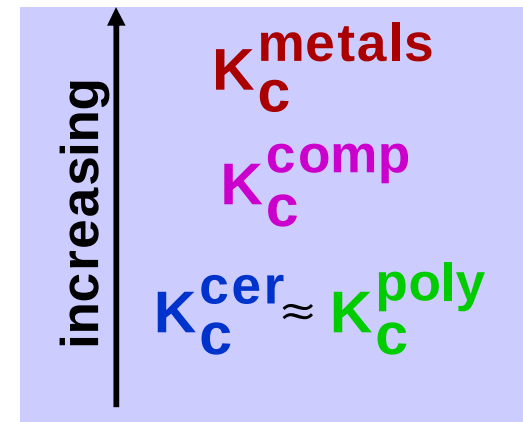
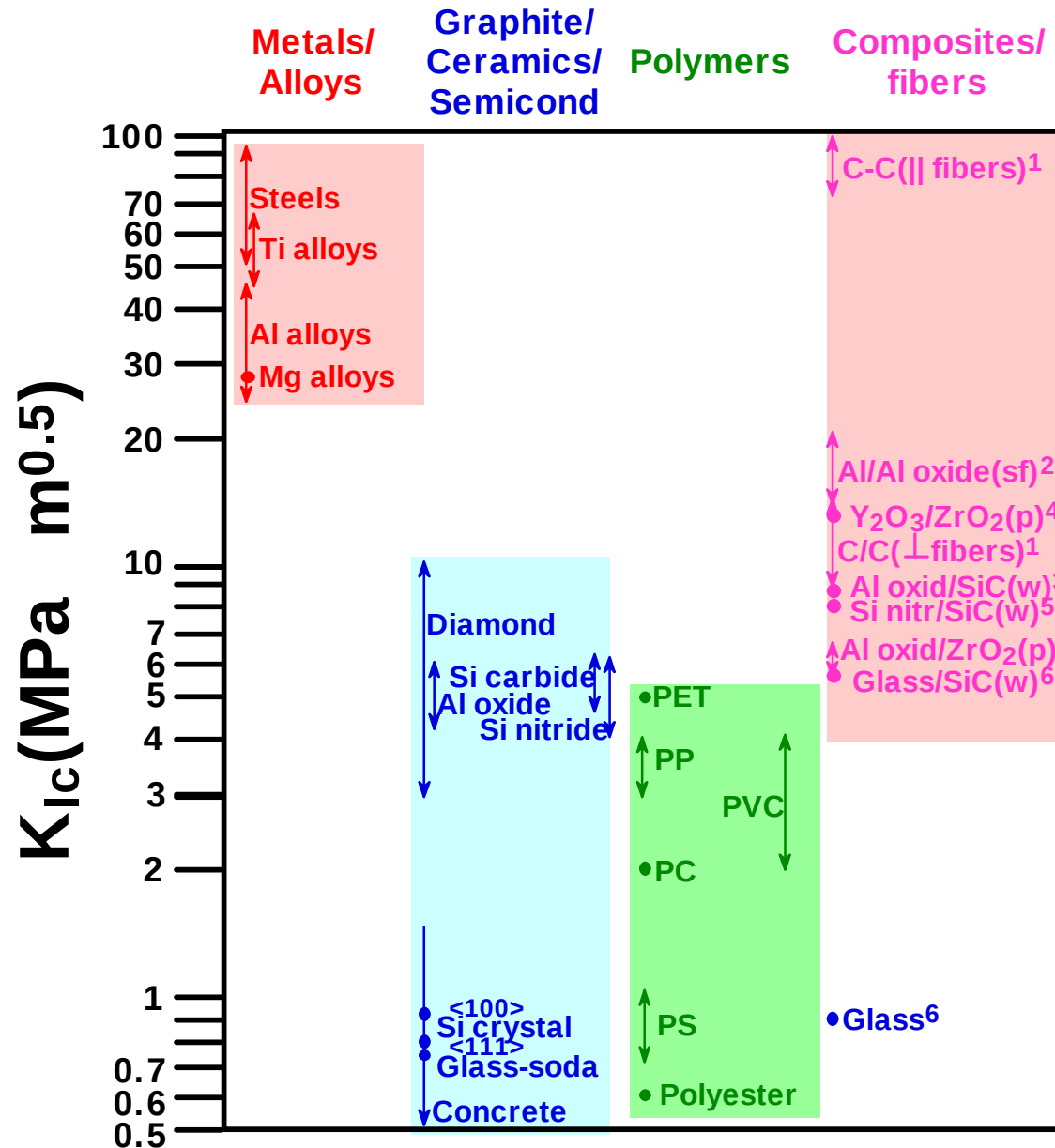
or $\text{ksi}\sqrt{\text{in}}$

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: $K \geq K_c$

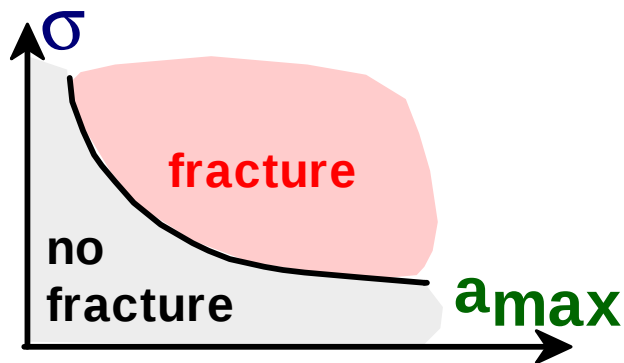
$$Y\sigma\sqrt{\pi a}$$

↗

- **Largest**, most **stressed** cracks grow first!

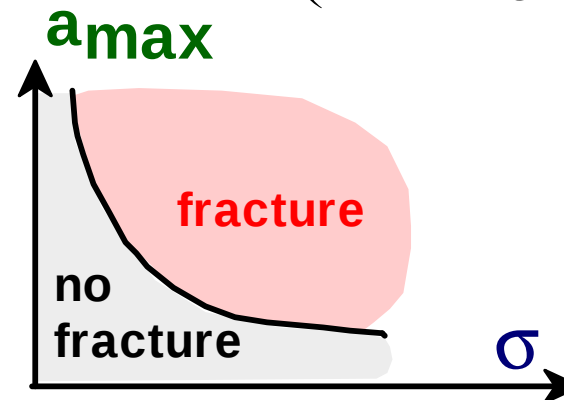
--Result 1: Max flaw size dictates design stress.

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



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

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



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

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

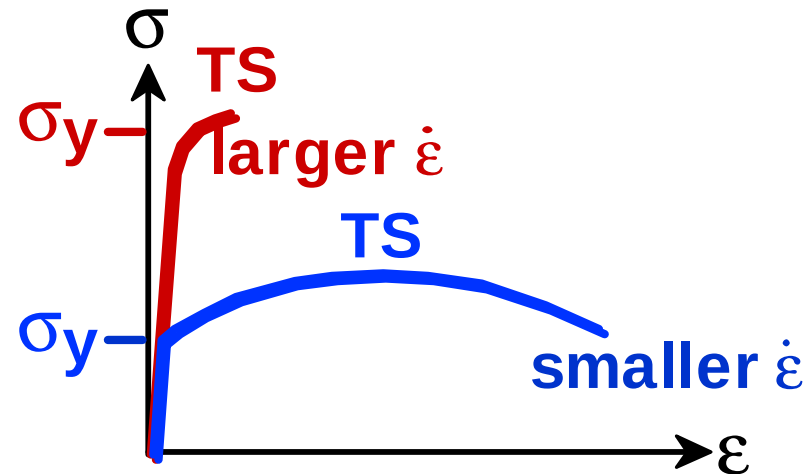
$$\left(\overset{112 \text{ MPa}}{\sigma_c} \sqrt{\overset{9 \text{ mm}}{a_{\max}}} \right)_A = \left(\sigma_c \sqrt{\overset{4 \text{ mm}}{a_{\max}}} \right)_B$$

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

- Reducing flaw size pays off!

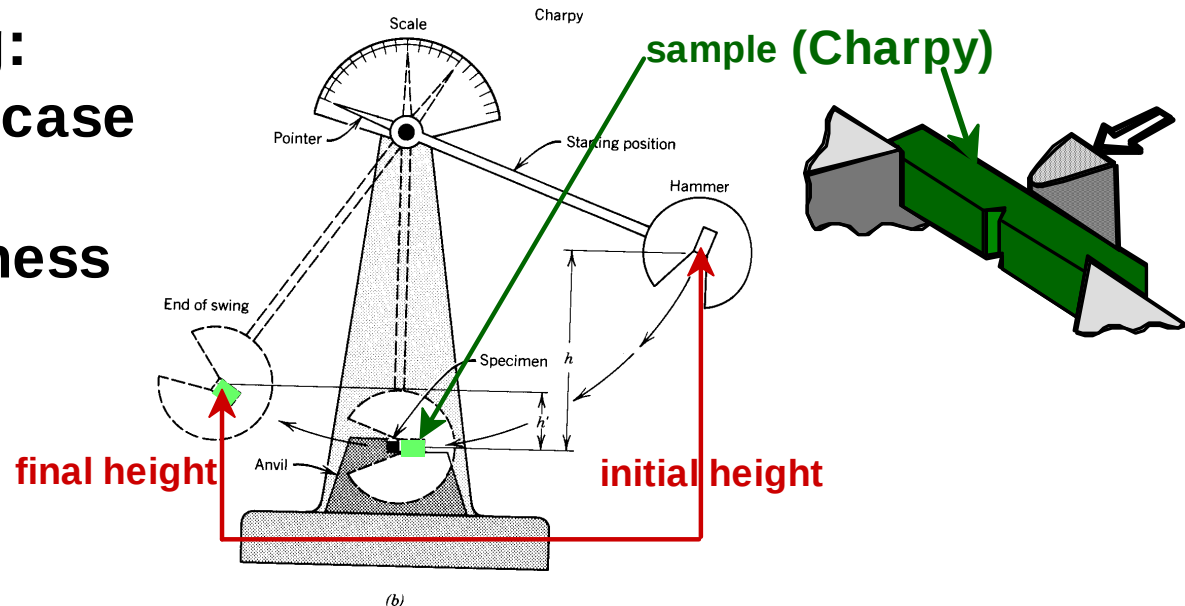
LOADING RATE

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



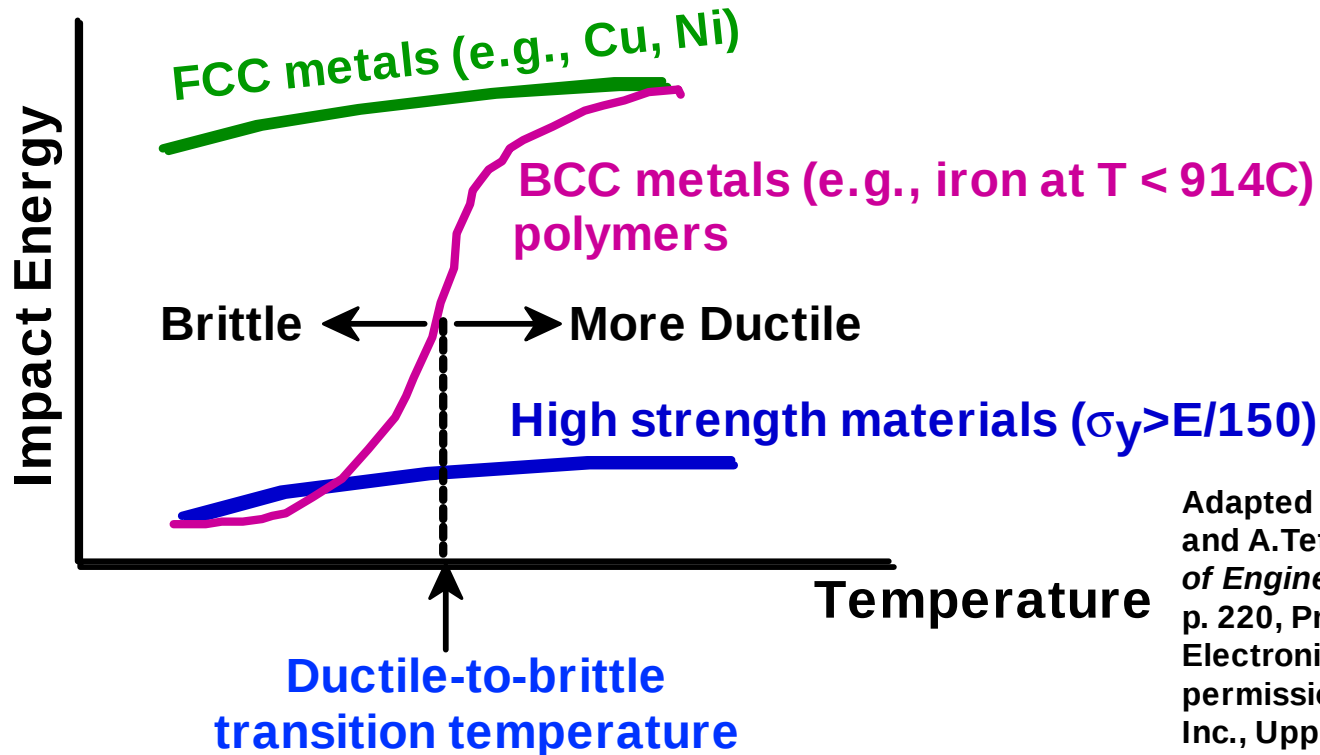
- Impact loading:
 - severe testing case
 - more brittle
 - smaller toughness

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.

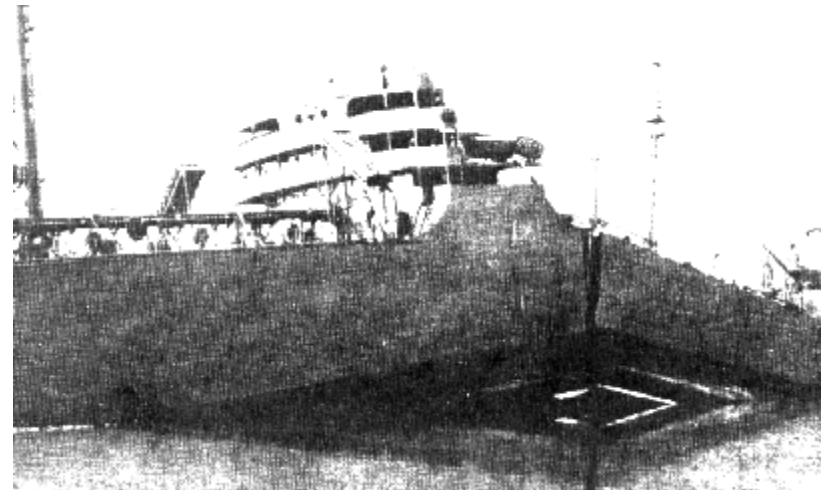
DESIGN STRATEGY: STAY ABOVE THE DBTT!

- 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

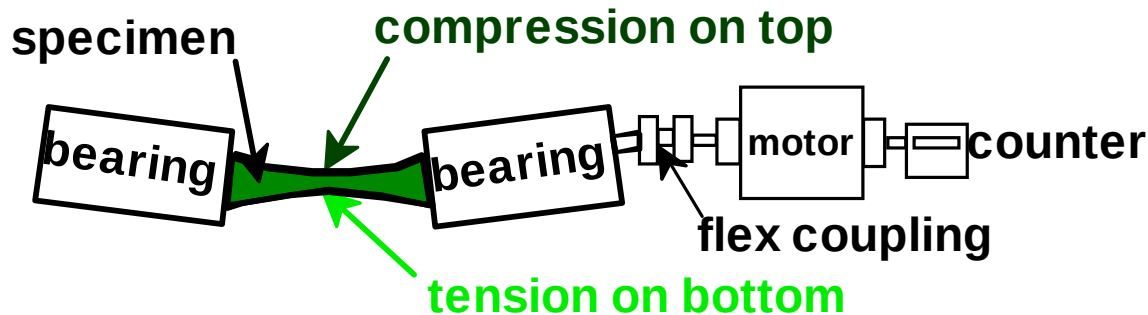


Reprinted w/ permission from R.W. Hertzberg, "Deformation and Fracture Mechanics of Engineering Materials", (4th ed.) Fig. 7.1(b), p. 262, John Wiley and Sons, Inc., 1996. (Orig. source: Earl R. Parker, "Behavior of Engineering Structures", Nat. Acad. Sci., Nat. Res. Council, John Wiley and Sons, Inc.,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

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

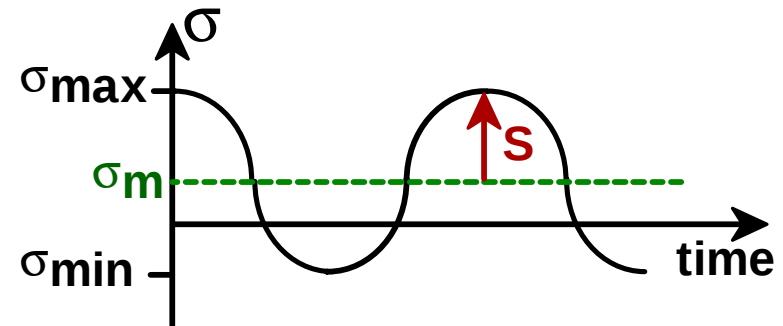
FATIGUE

- **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.)

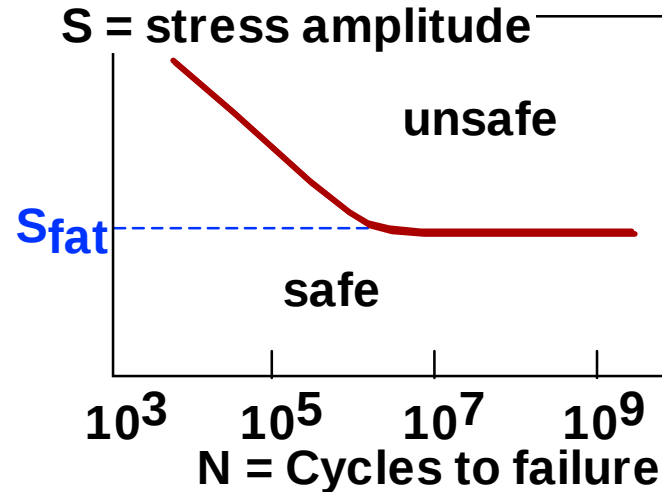
- Stress varies with time.
 - key parameters are **S** and σ_m



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

FATIGUE DESIGN PARAMETERS

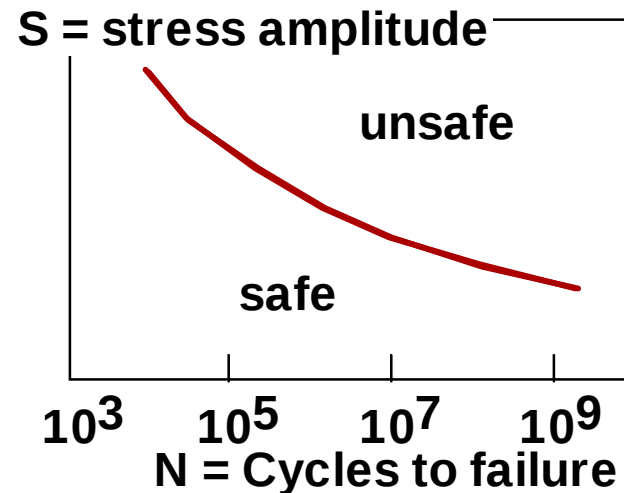
- **Fatigue limit, S_{fat} :**
--no fatigue if $S < S_{fat}$



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

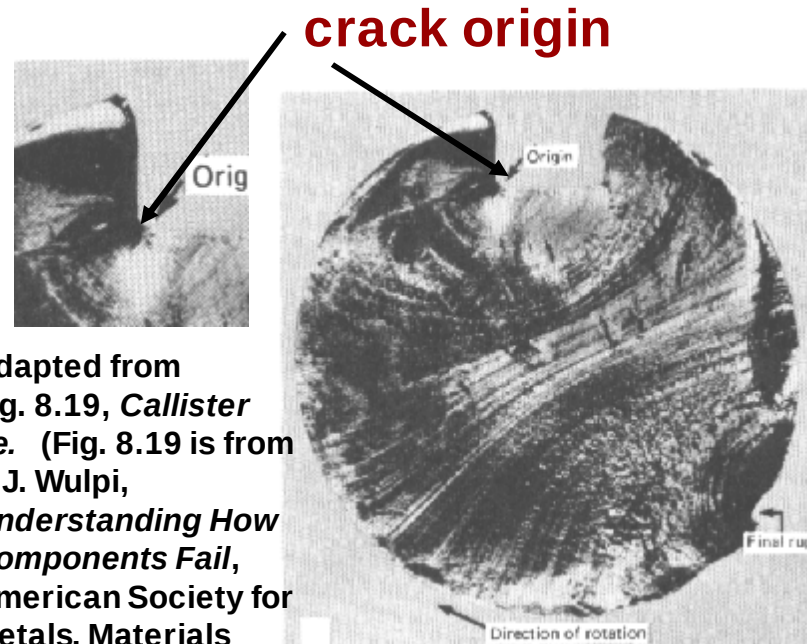
- Crack grows *incrementally*

$$\frac{da}{dN} = (\Delta K)^m \sim (\Delta \sigma) \sqrt{a}$$

typ. 1 to 6

increase in crack length per loading cycle

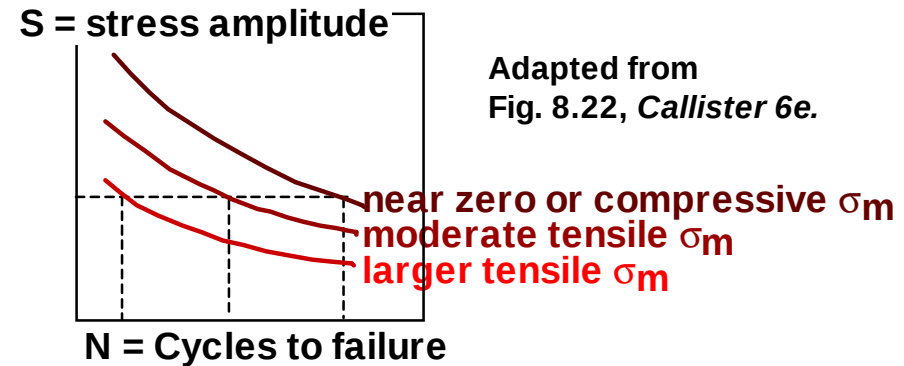
- Failed rotating shaft
 - crack grew even though $K_{max} < K_c$
 - crack grows faster if
 - $\Delta \sigma$ increases
 - crack gets longer
 - loading freq. increases.



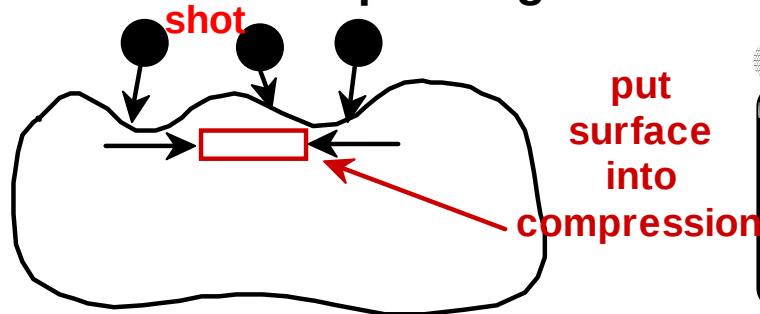
Adapted from
Fig. 8.19, Callister
6e. (Fig. 8.19 is from
D.J. Wulpi,
*Understanding How
Components Fail*,
American Society for
Metals, Materials
Park, OH, 1985.)

IMPROVING FATIGUE LIFE

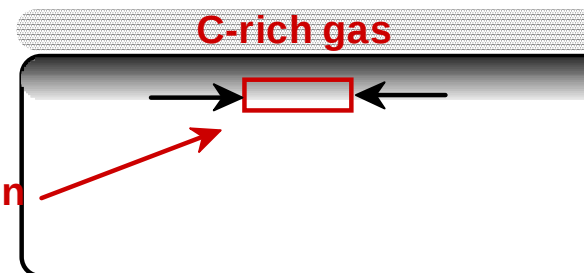
1. Impose a compressive surface stress
(to suppress surface cracks from growing)



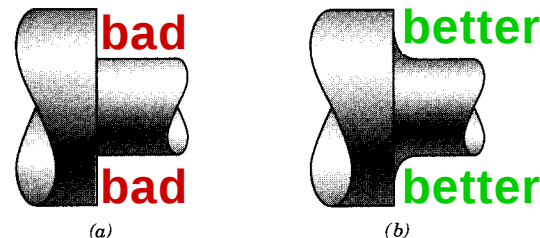
--Method 1: shot peening



--Method 2: carburizing



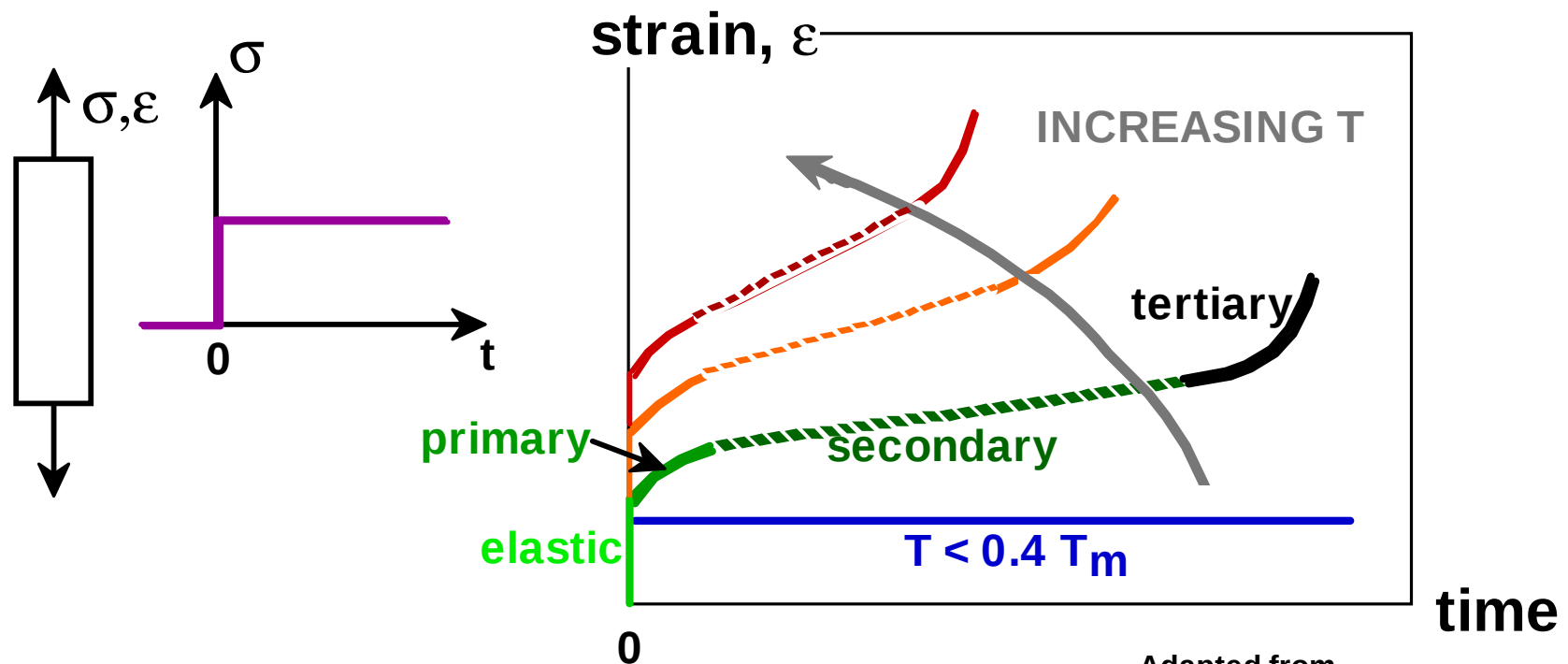
2. Remove stress concentrators.



Adapted from Fig. 8.23, Callister 6e.

CREEP

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



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

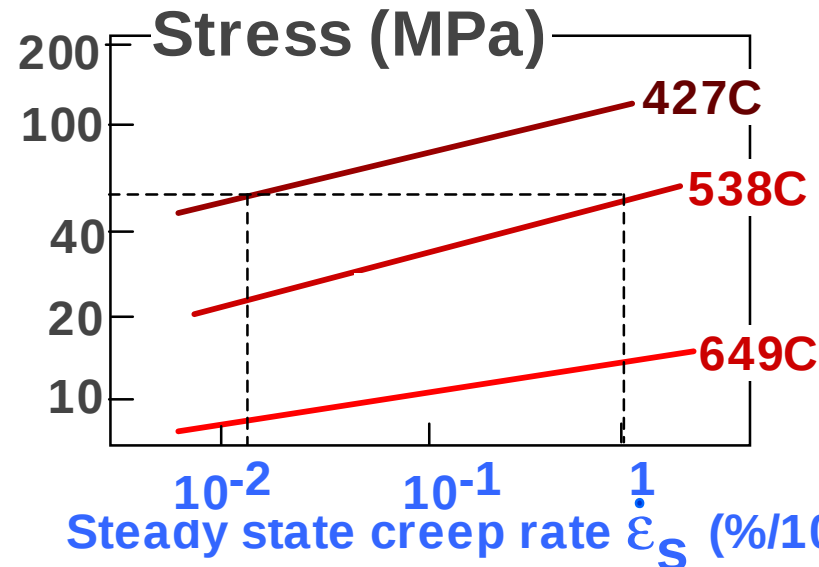
SECONDARY CREEP

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

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

strain rate $\rightarrow \dot{\epsilon}_S$
 material const. $\rightarrow K_2$
 applied stress $\rightarrow \sigma$
 stress exponent (material parameter) $\rightarrow n$
 activation energy for creep (material parameter) $\rightarrow Q_c$

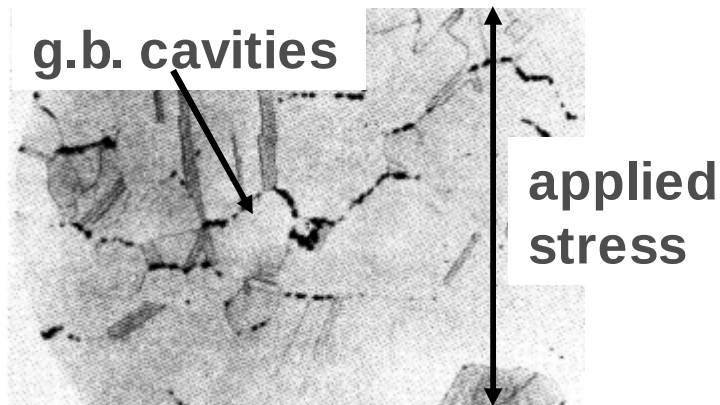
- Strain rate increases for larger T, σ



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.)

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

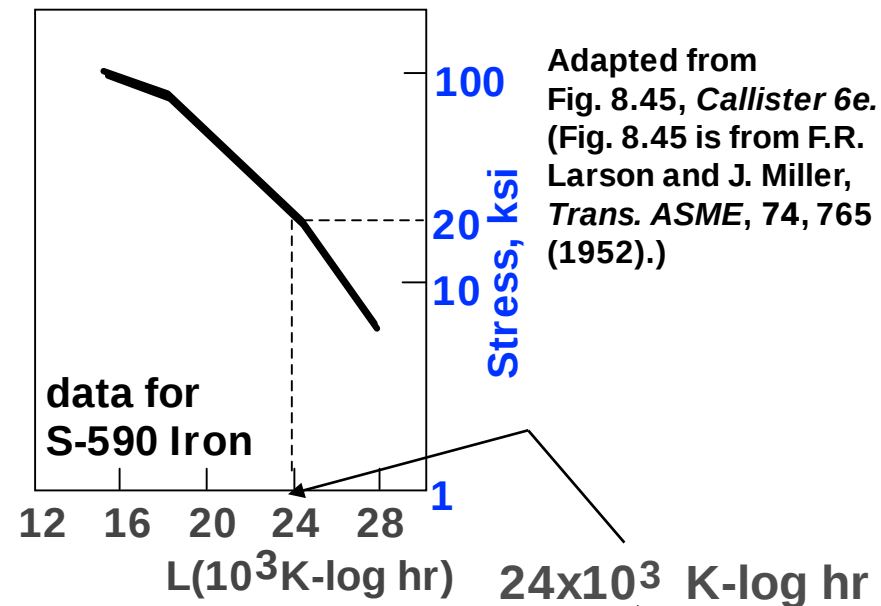
$$T(20 + \log t_r) = L$$

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: $t_r = 233\text{hr}$

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 $T < 0.4T_m$, 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.