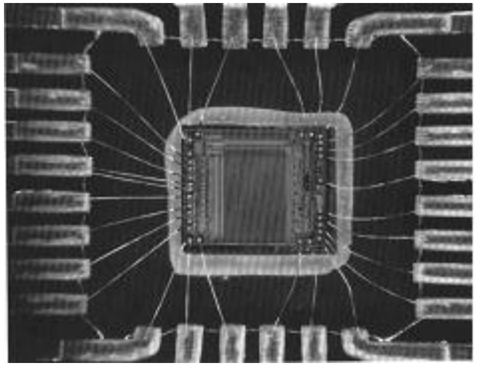
Chapter 8: Mechanical Failure

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.*

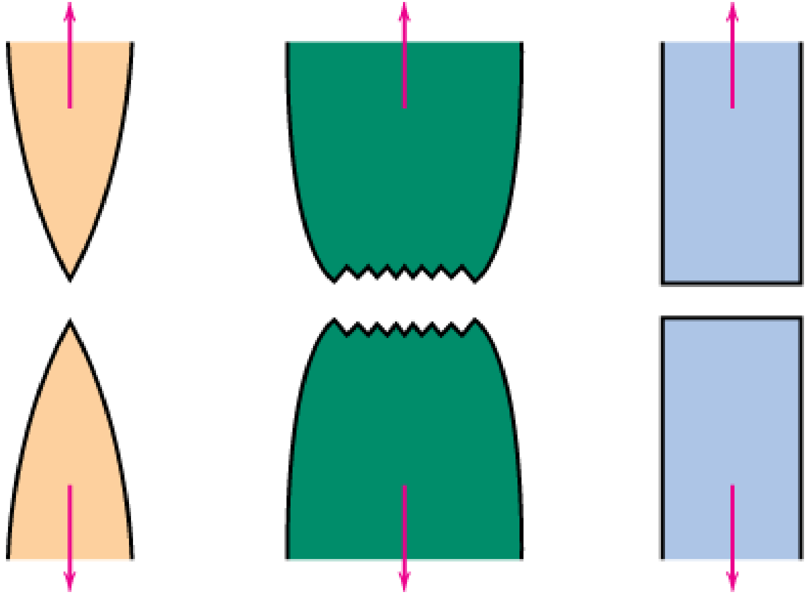
Fracture mechanisms

- 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



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

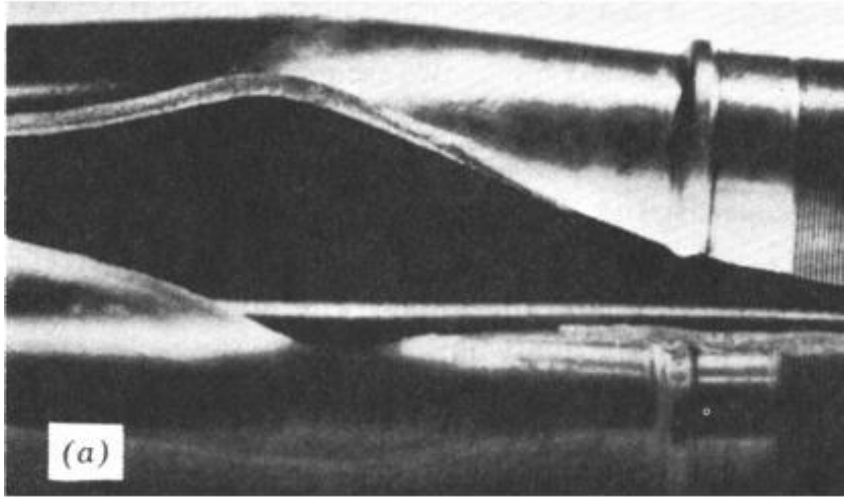
- Ductile fracture is usually desirable!

Ductile: warning before fracture

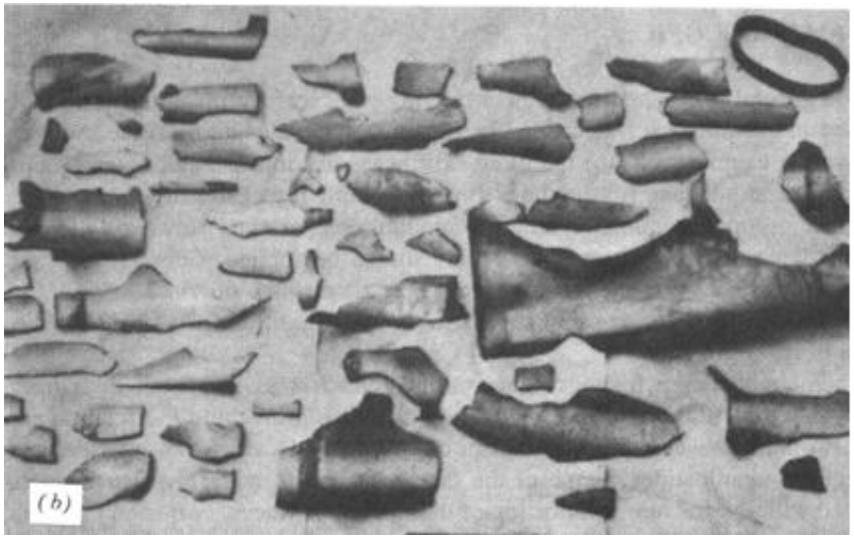
Brittle: No warning

Example: Failure of a Pipe

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



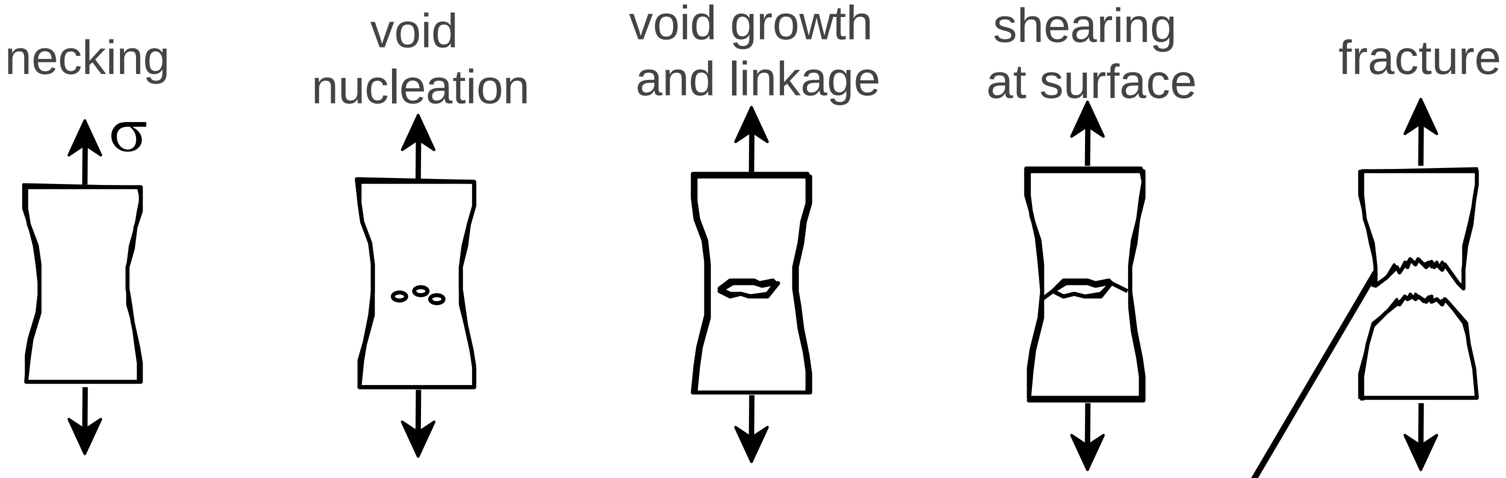
- **Brittle failure:**
  --many pieces
  --small deformation



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:



necking

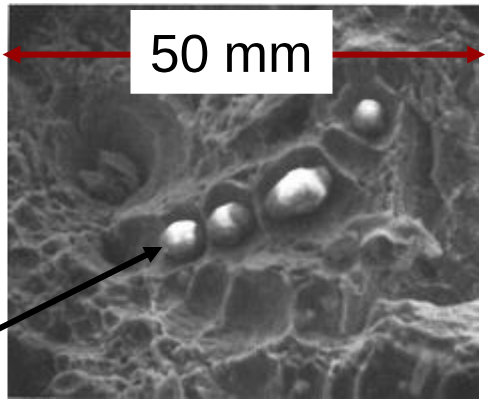
void nucleation

void growth and linkage

shearing at surface

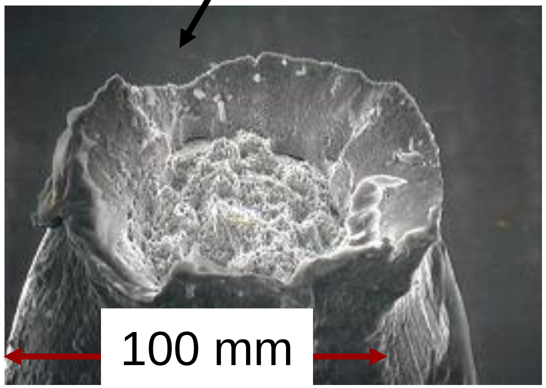
fracture

- 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.

Ductile vs. Brittle Failure

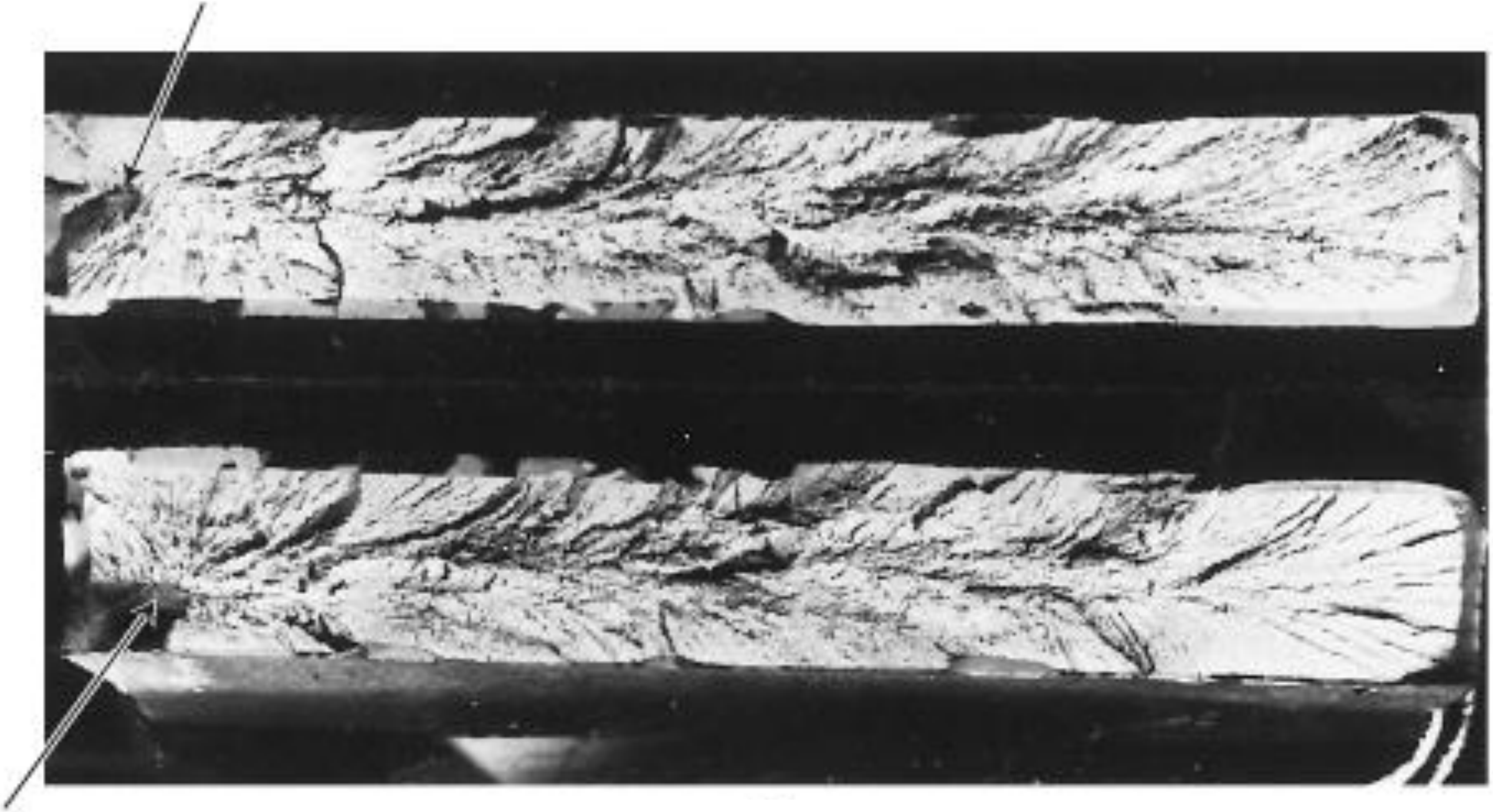
cup-and-cone fracture

brittle fracture

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

Brittle Failure

Arrows indicate pt at which failure originated

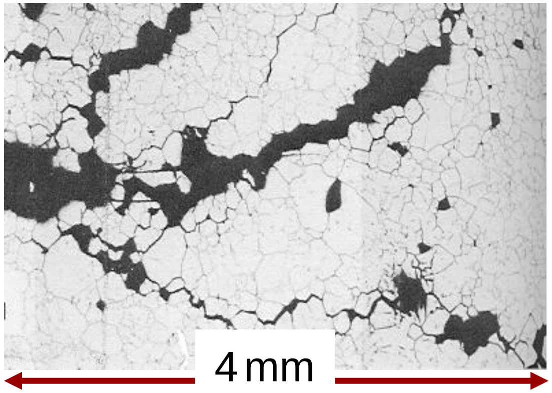


Adapted from Fig. 8.5(a), *Callister 7e.*

Brittle Fracture Surfaces

- Intergranular (between grains)

- Intragranular (within grains)

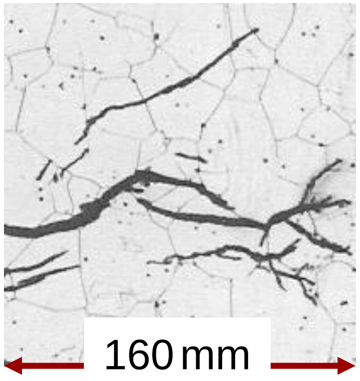


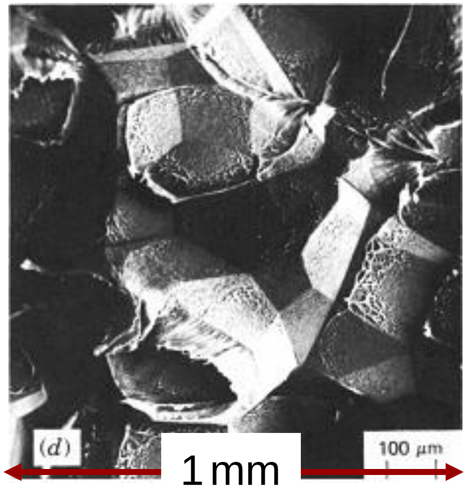
304 S. Steel (metal)

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.)





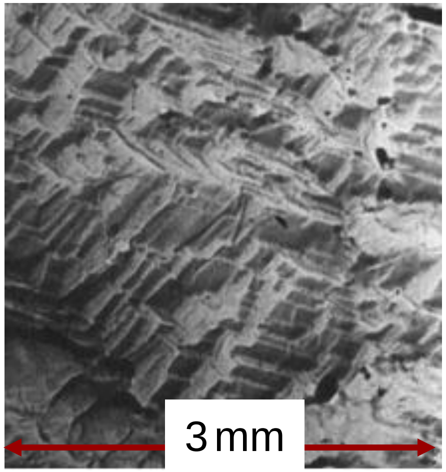
Polypropylene (polymer)

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.)

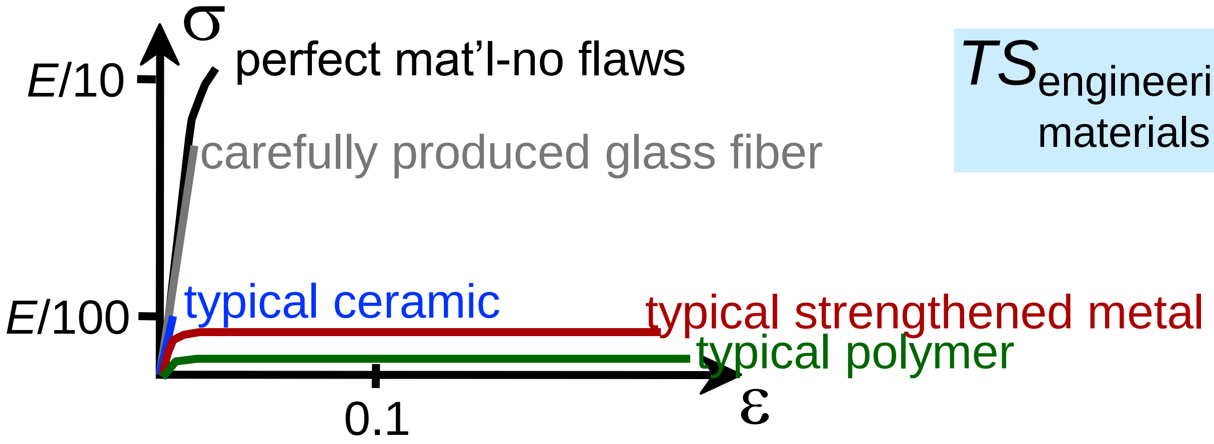
Al Oxide (ceramic)

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.)



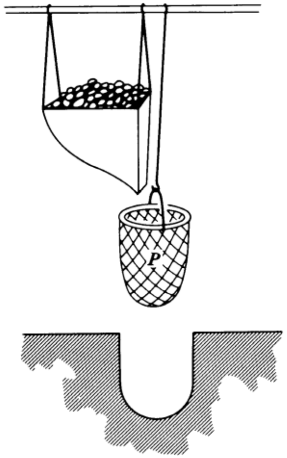
Ideal vs Real Materials

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



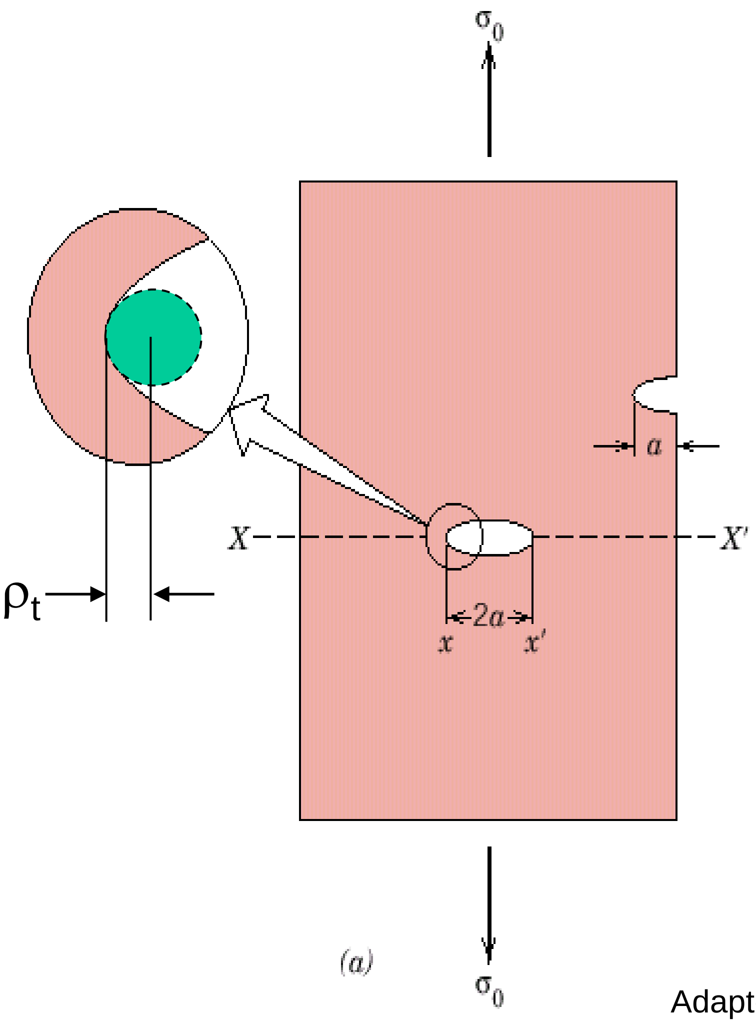
$TS_{\text{engineering materials}} \ll TS_{\text{perfect materials}}$

- 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/ 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!



Results from crack propagation

- Griffith Crack

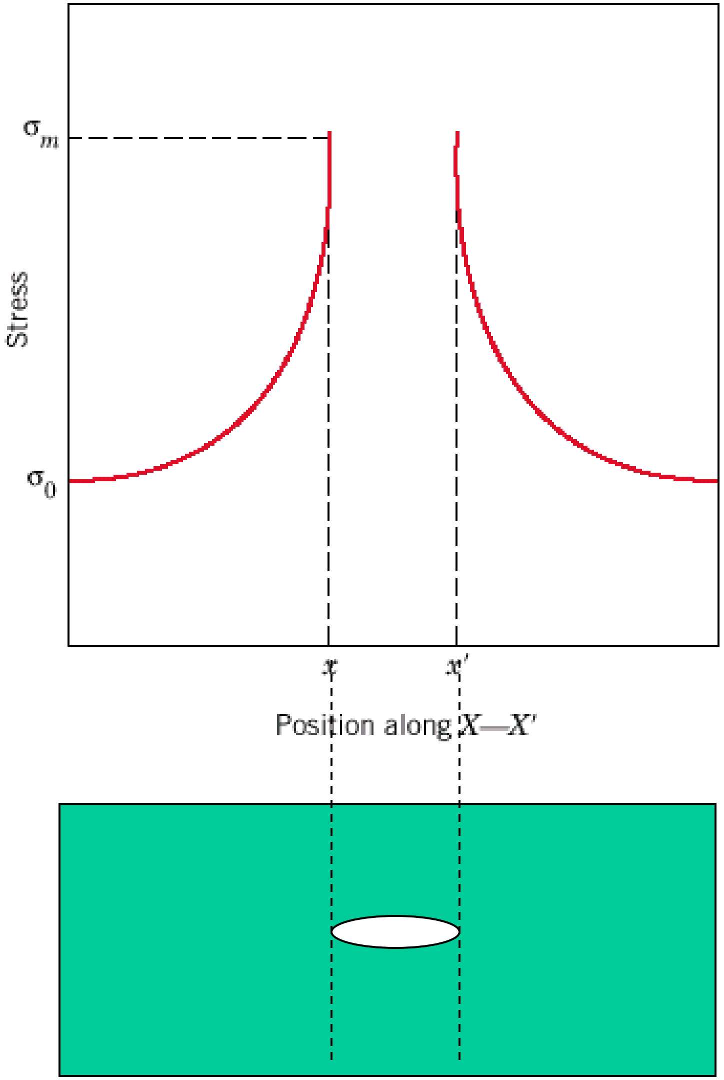
$$\sigma_m = 2\sigma_o\left(\frac{a}{\rho_t}\right)^{1/2} = K_t\sigma_o$$

where

ρ_t = radius of curvature
σ_o = applied stress
σ_m = stress at crack tip

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

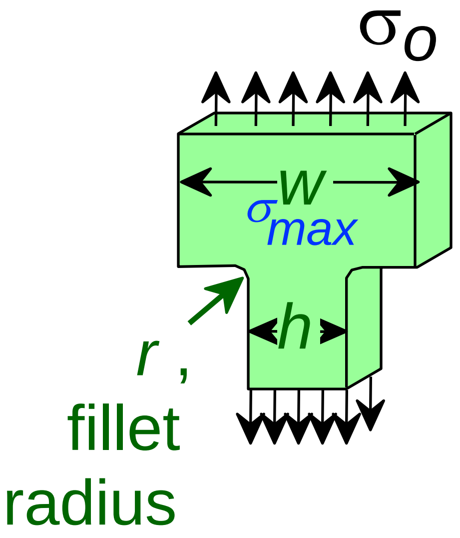
Concentration of Stress at Crack Tip

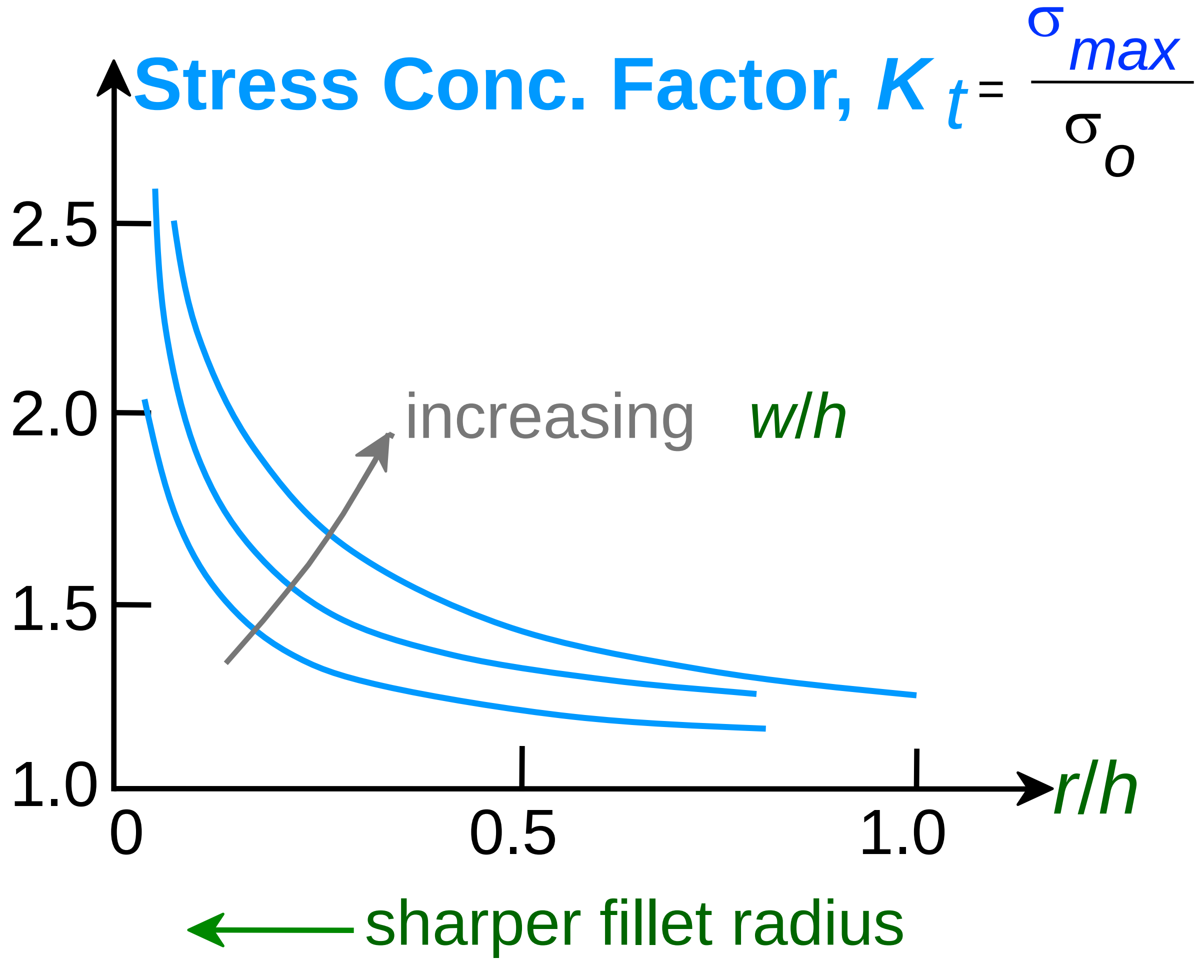


Adapted from Fig. 8.8(b), *Callister 7e.*

Engineering Fracture Design

- **Avoid sharp corners!**



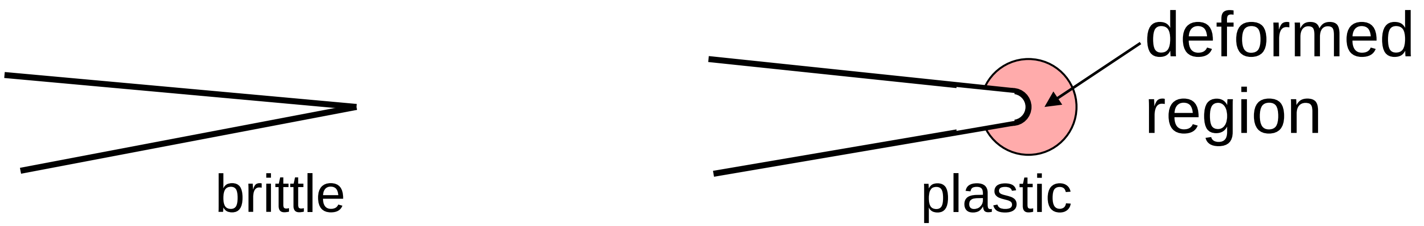


Adapted from Fig. 8.2W(c), *Callister 6e.* (Fig. 8.2W(c) is from G.H. Neugebauer, *Prod. Eng.* (NY), Vol. 14, pp. 82-87 1943.)

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 $K_t > K_c$

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

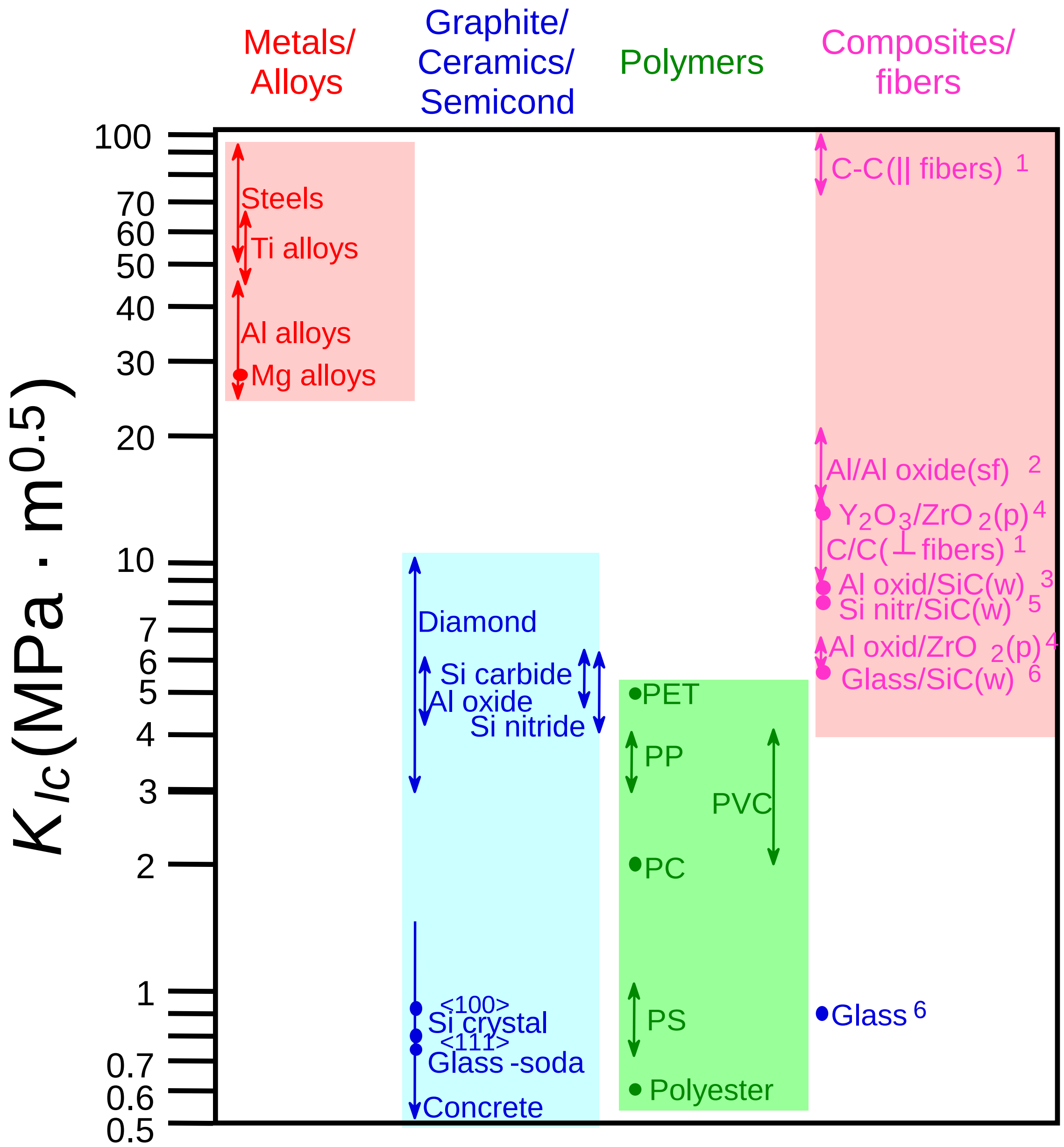
where

- 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

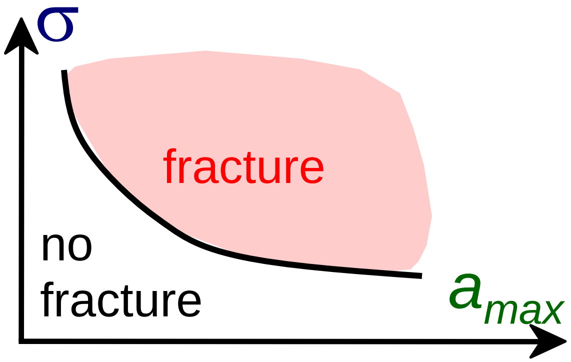
- Crack growth condition:

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

- Largest, most stressed cracks grow first!

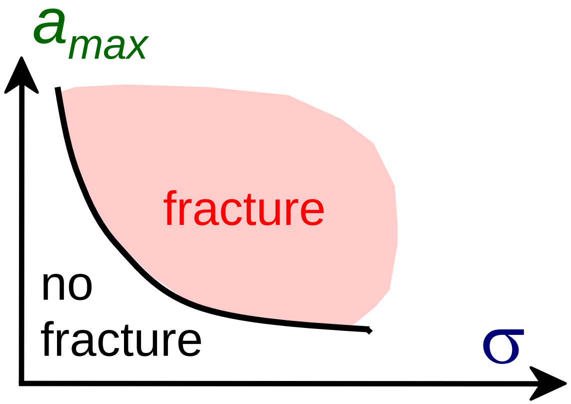
--Result 1: Max. flaw size dictates design stress.

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



--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:

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

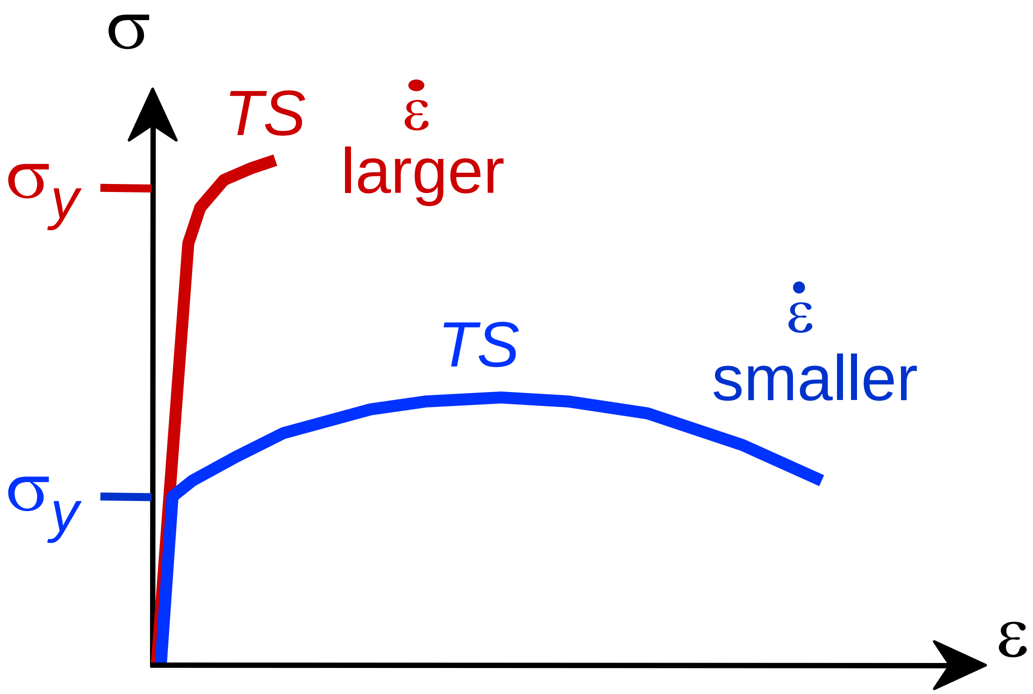
Answer: $(\sigma_c)_B = 168$ MPa

- Reducing flaw size pays off!

Loading Rate

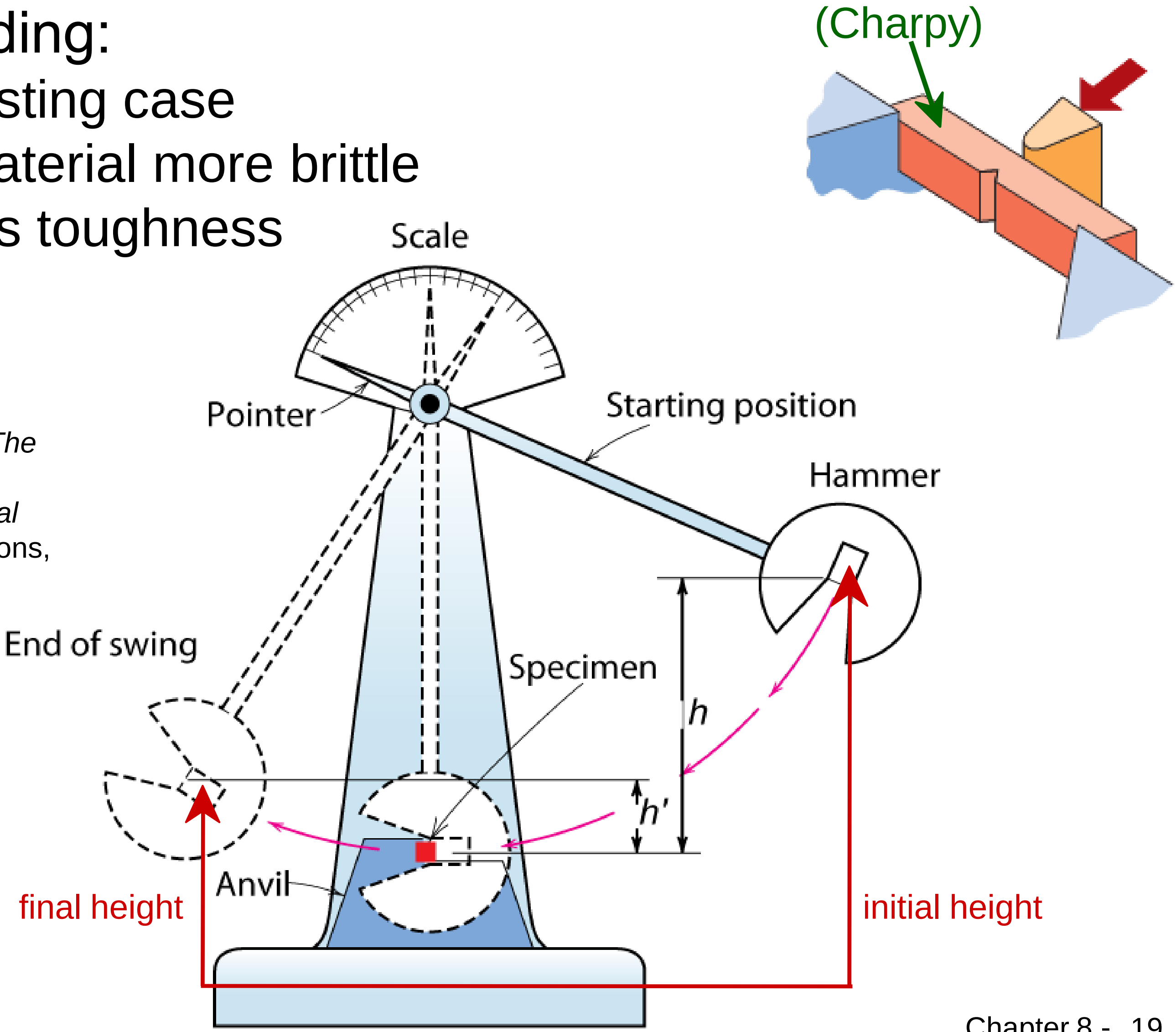
- Increased loading rate...
  -- increases σ_y and *TS*
  -- decreases %*EL*

- 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



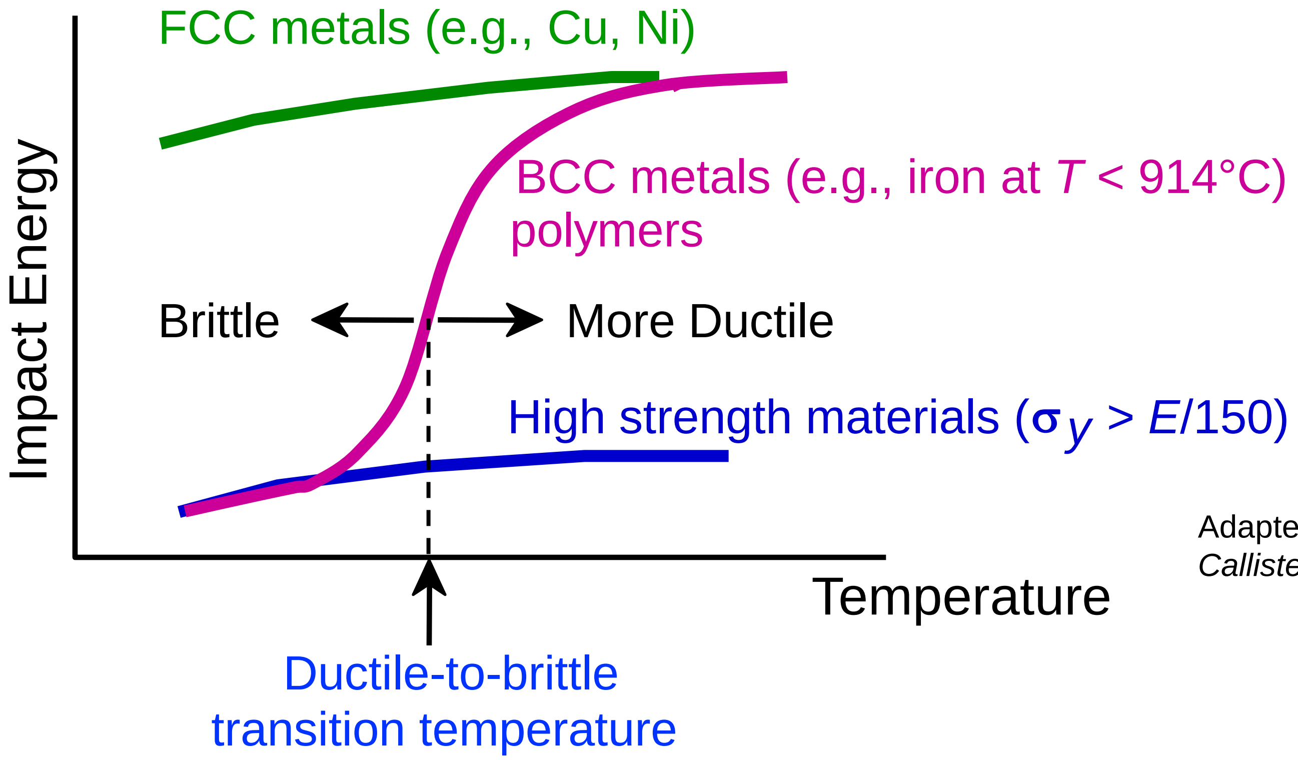
Adapted from Fig. 8.12(b), *Callister 7e.* (Fig. 8.12(b) is adapted from H.W. Hayden, W.G. Moffatt, and J. Wulff, *The Structure and Properties of Materials*, Vol. III, *Mechanical Behavior*, John Wiley and Sons, Inc. (1965) p. 13.)

Temperature

- **Increasing temperature...**

  --increases %*EL* and K_c

- **Ductile-to-Brittle Transition Temperature (DBTT)...**



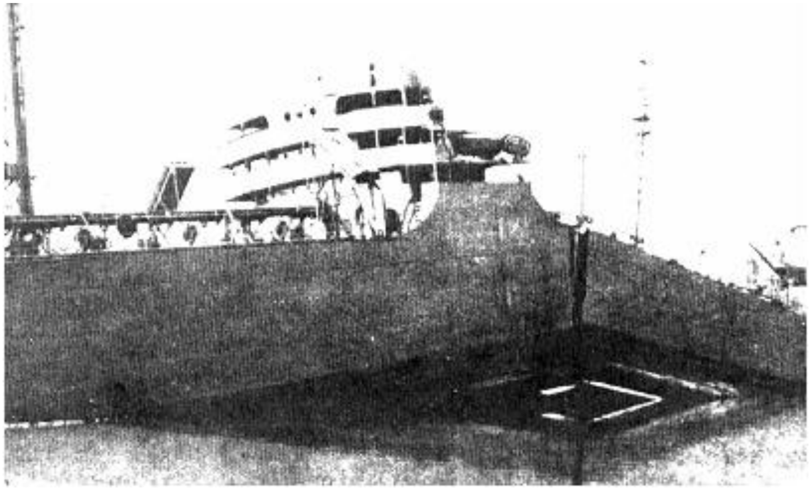
Adapted from Fig. 8.15, *Callister 7e.*

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**

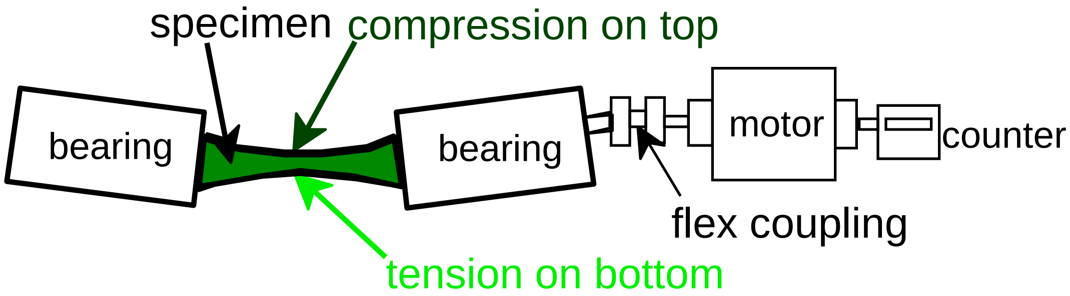


Reprinted w/ permission from R.W. Hertzberg, "Deformation and Fracture Mechanics of Engineering Materials", (4th ed.) Fig. 7.1(b), p. 262, John Wiley and Sons, Inc., 1996. (Orig. source: Earl R. Parker, "Behavior of Engineering Structures", Nat. Acad. Sci., Nat. Res. Council, John Wiley and Sons, Inc.,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

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

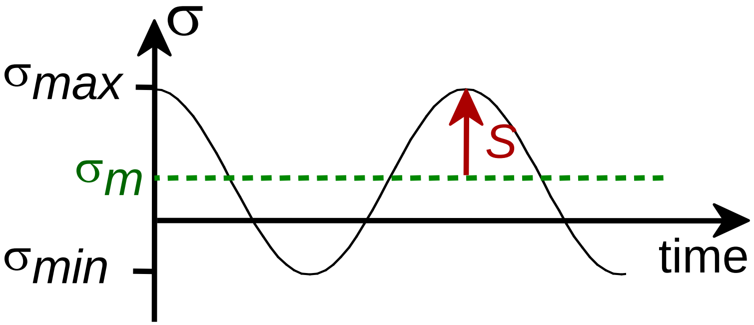
Fatigue

- 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

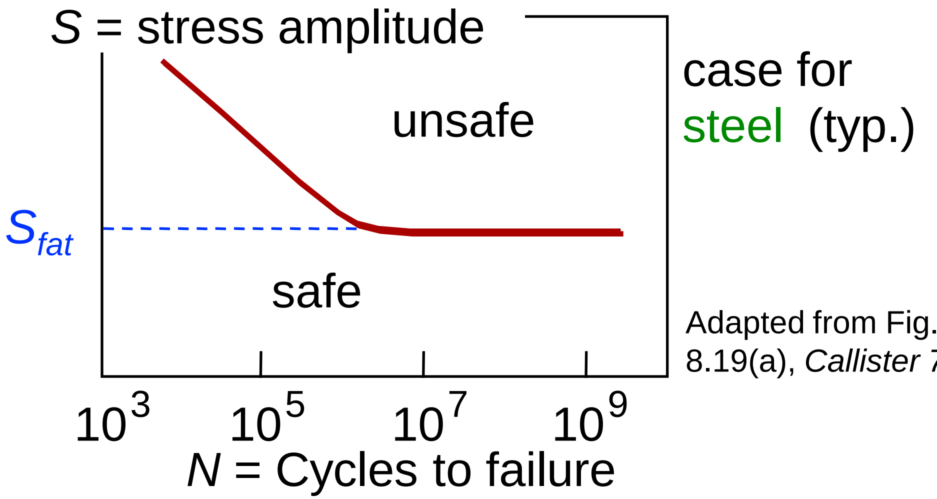


- Key points: Fatigue...
  - --can cause part failure, even though $\sigma_{max} < \sigma_c$.
  - --causes ~ 90% of mechanical engineering failures.

Fatigue Design Parameters

- Fatigue limit, S_{fat}:

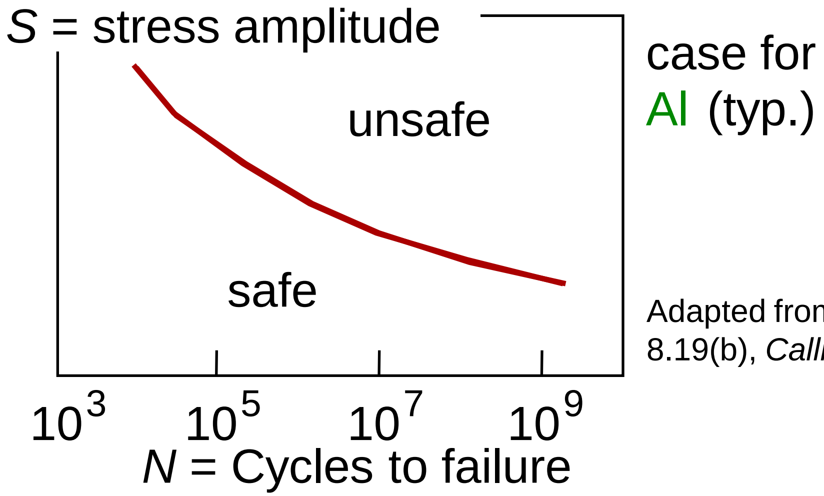
  --no fatigue if $S < S_{fat}$



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

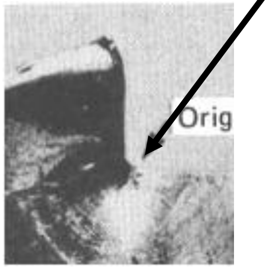
  --crack grew even though

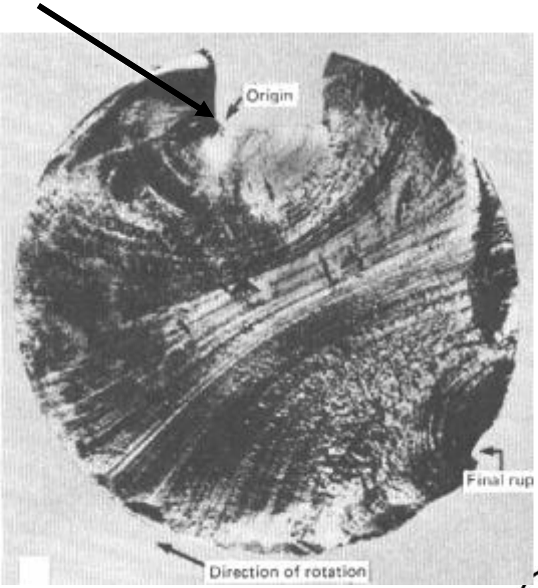
  $K_{max} < K_c$

  --crack grows faster as

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

crack origin

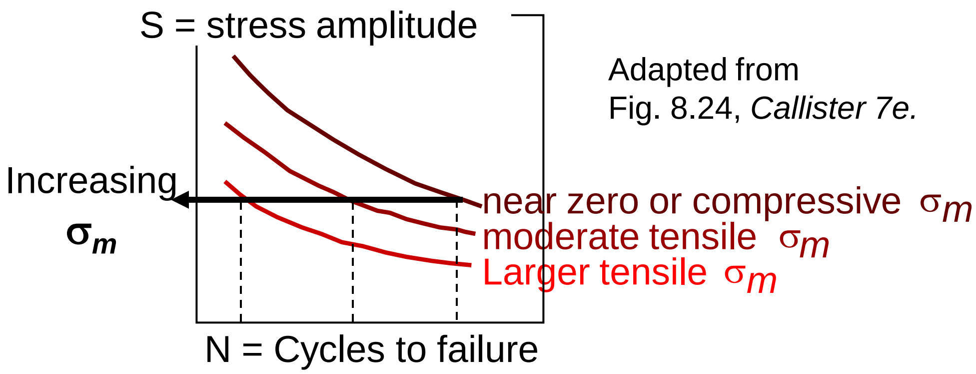




Adapted from Fig. 8.21, *Callister 7e.* (Fig. 8.21 is from D.J. Wulpi, *Understanding How Components Fail*, American Society for Metals, Materials Park, OH, 1985.)

Improving Fatigue Life

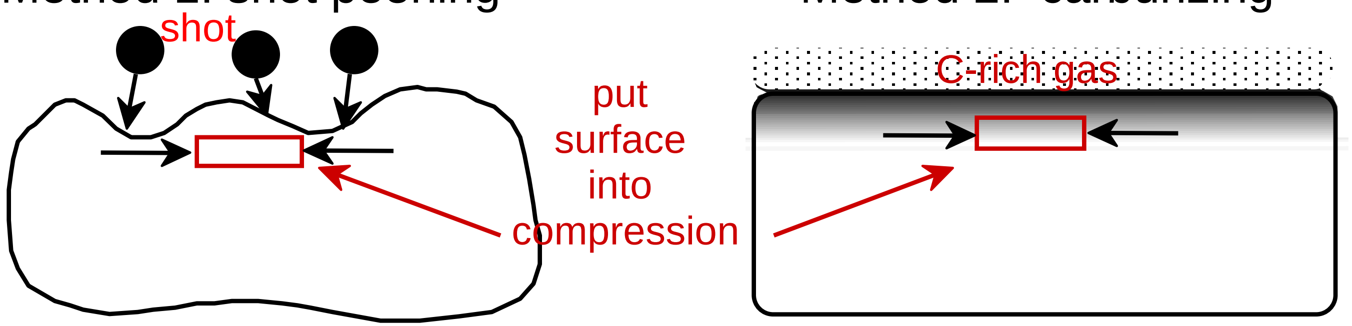
1. Impose a compressive surface stress (to suppress surface cracks from growing)



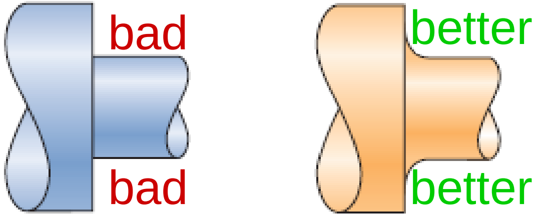
Adapted from Fig. 8.24, *Callister 7e.*

--Method 1: shot peening

--Method 2: carburizing



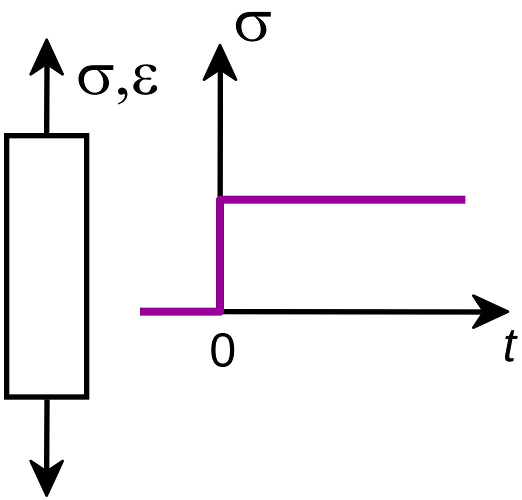
2. Remove stress concentrators.

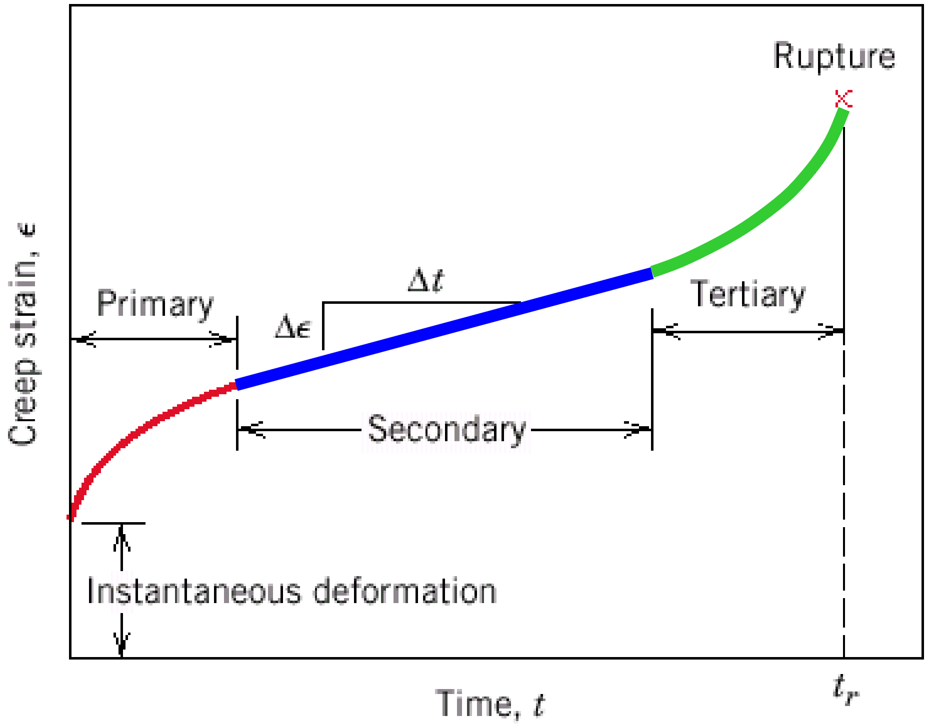


Adapted from Fig. 8.25, *Callister 7e.*

Creep

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





Adapted from
Fig. 8.28, *Callister 7e.*

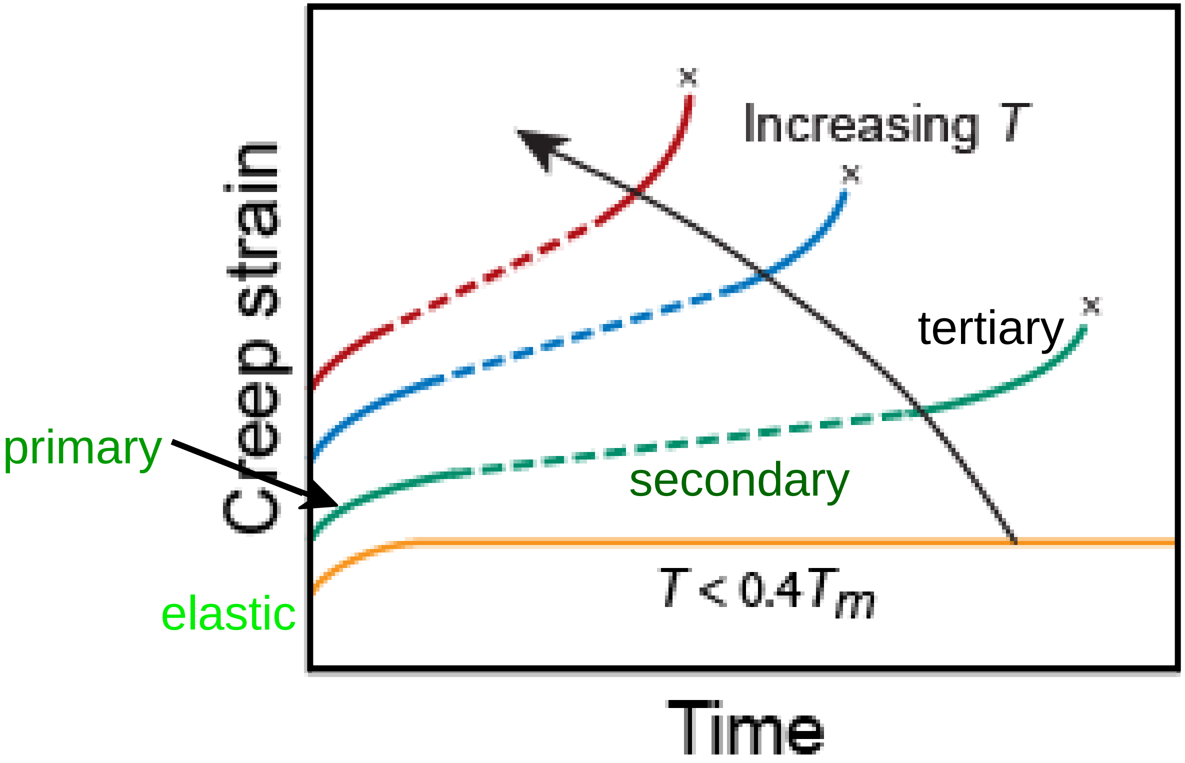
Primary Creep: slope (creep rate) decreases with time.

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

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

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

stress exponent (material parameter)

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

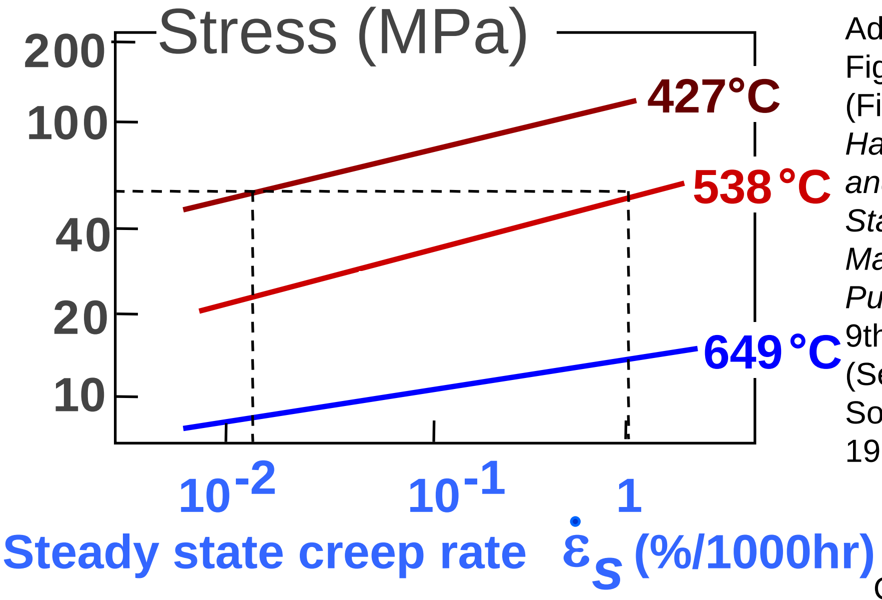
strain rate

material const.

applied stress

activation energy for creep (material parameter)

- Strain rate increases for higher *T*, σ

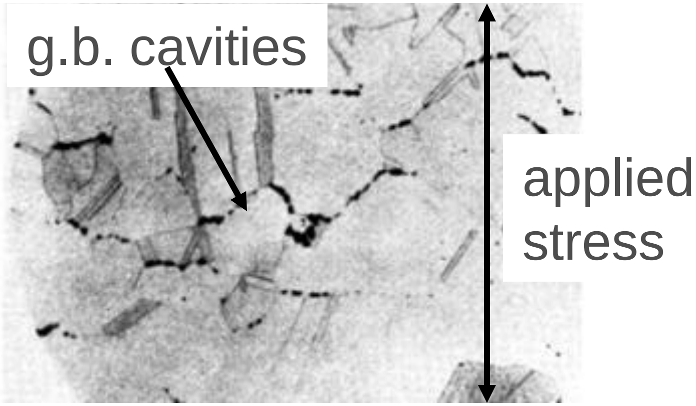


Adapted from Fig. 8.31, *Callister 7e.* (Fig. 8.31 is from *Metals Handbook: Properties and Selection: Stainless Steels, Tool Materials, and Special Purpose Metals*, Vol. 3, 9th ed., D. Benjamin (Senior Ed.), American Society for Metals, 1980, p. 131.)

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

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

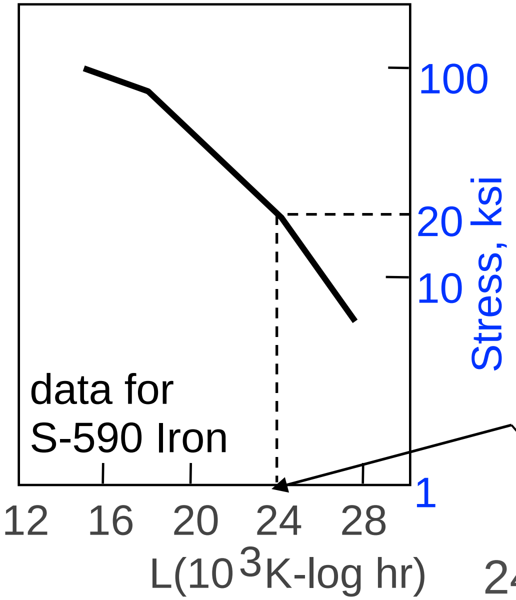
temperature

time to failure (rupture)

function of applied stress

- Estimate rupture time

S-590 Iron, T = 800°C, σ = 20 ksi



Adapted from Fig. 8.32, *Callister 7e.* (Fig. 8.32 is from F.R. Larson and J. Miller, *Trans. ASME*, **74**, 765 (1952).)

24×10^3 K-log hr

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

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 $T < 0.4T_m$, 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.

ANNOUNCEMENTS

Reading:

Core Problems:

Self-help Problems: