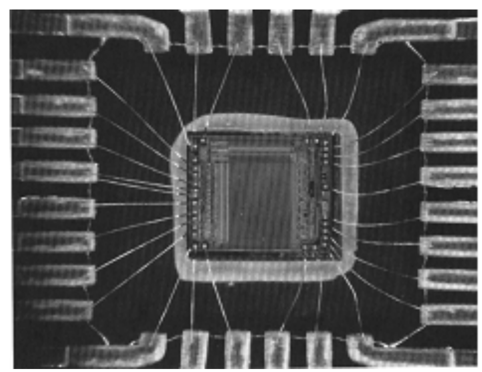
Chapter 8: Mechanical Failure

ISSUES TO ADDRESS...

- How do cracks that lead to failure form?
- How is fracture resistance quantified? How do the fracture resistances of the different material classes compare?
- How do we estimate the stress to fracture?
- How do loading rate, loading history, and temperature affect the failure behavior of materials?

Ship-cyclic loading from waves.

Adapted from chapter-opening photograph, Chapter 8, *Callister & Rethwisch 8e.* (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.

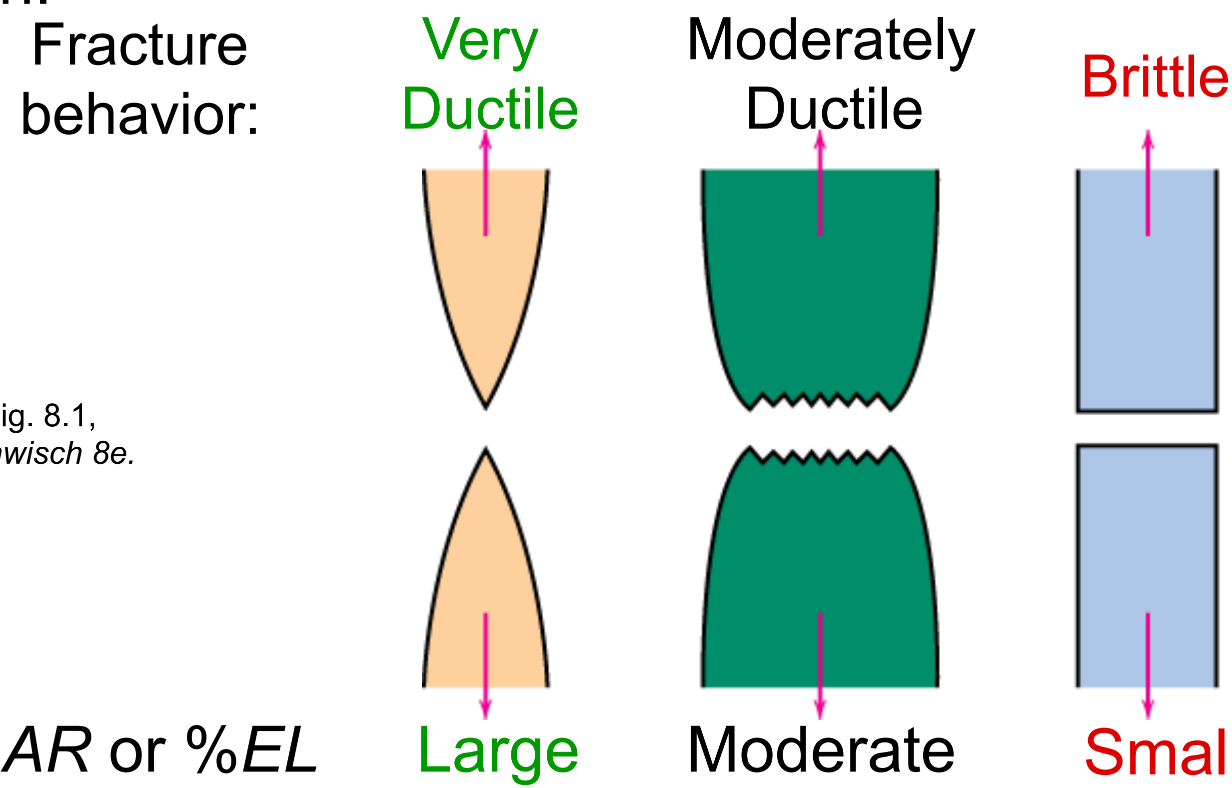
Adapted from Fig. 22.26(b), *Callister 7e.*

Fracture mechanisms

- Ductile fracture
  - Accompanied by significant plastic deformation
- Brittle fracture
  - Little or no plastic deformation
  - Catastrophic

Ductile vs Brittle Failure

- Classification:



Adapted from Fig. 8.1, *Callister & Rethwisch 8e.*

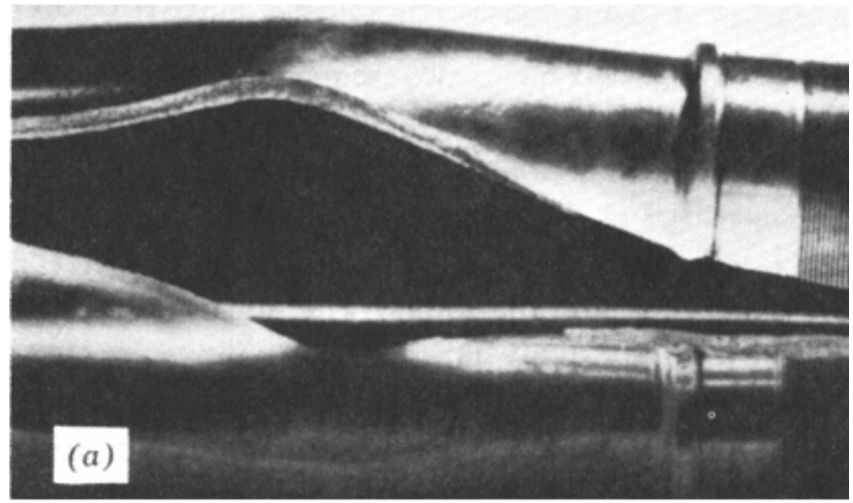
- Ductile fracture is usually more desirable than brittle fracture!

Ductile: Warning before fracture

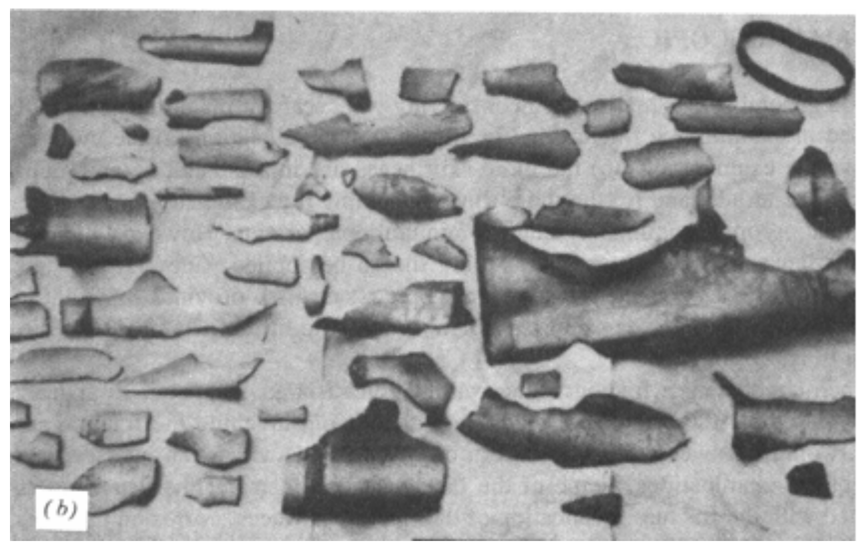
Brittle: No warning

Example: Pipe Failures

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



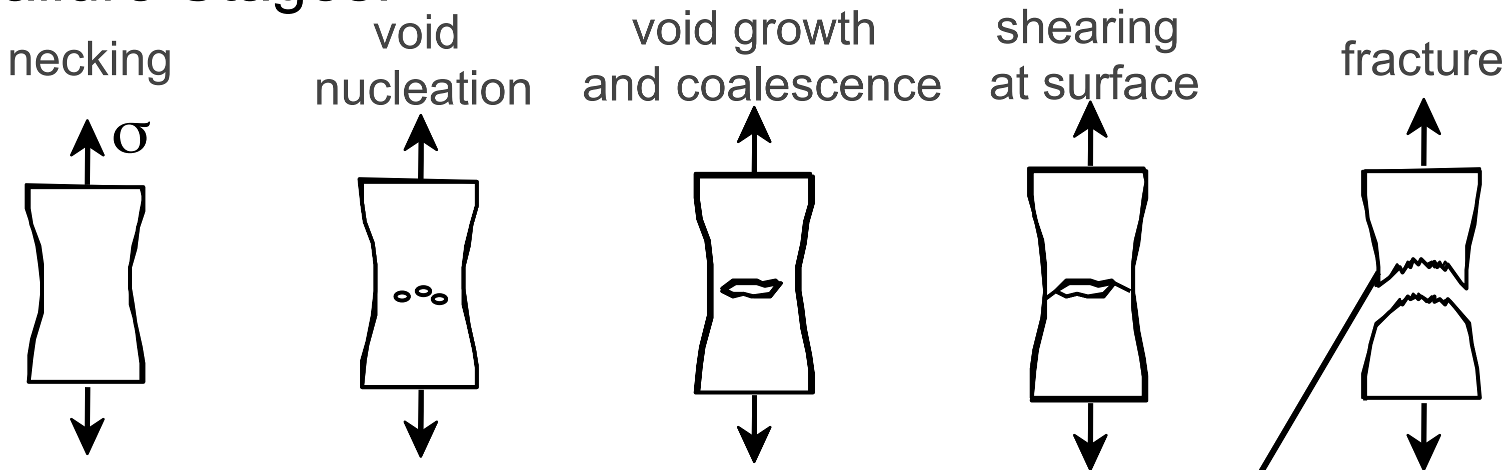
- **Brittle failure:**
  -- many pieces
  -- small deformations



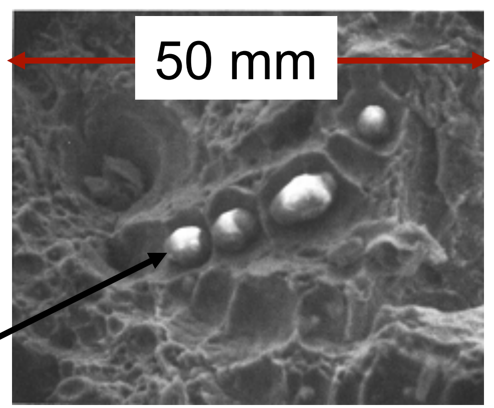
Figures from V.J. Colangelo and F.A. Heiser, *Analysis of Metallurgical Failures* (2nd ed.), Fig. 4.1(a) and (b), p. 66 John Wiley and Sons, Inc., 1987. Used with permission.

Moderately Ductile Failure

- Failure Stages:

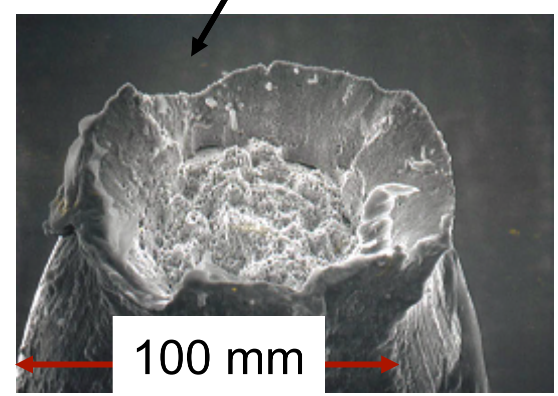


- Resulting fracture surfaces (steel)



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 in aluminum

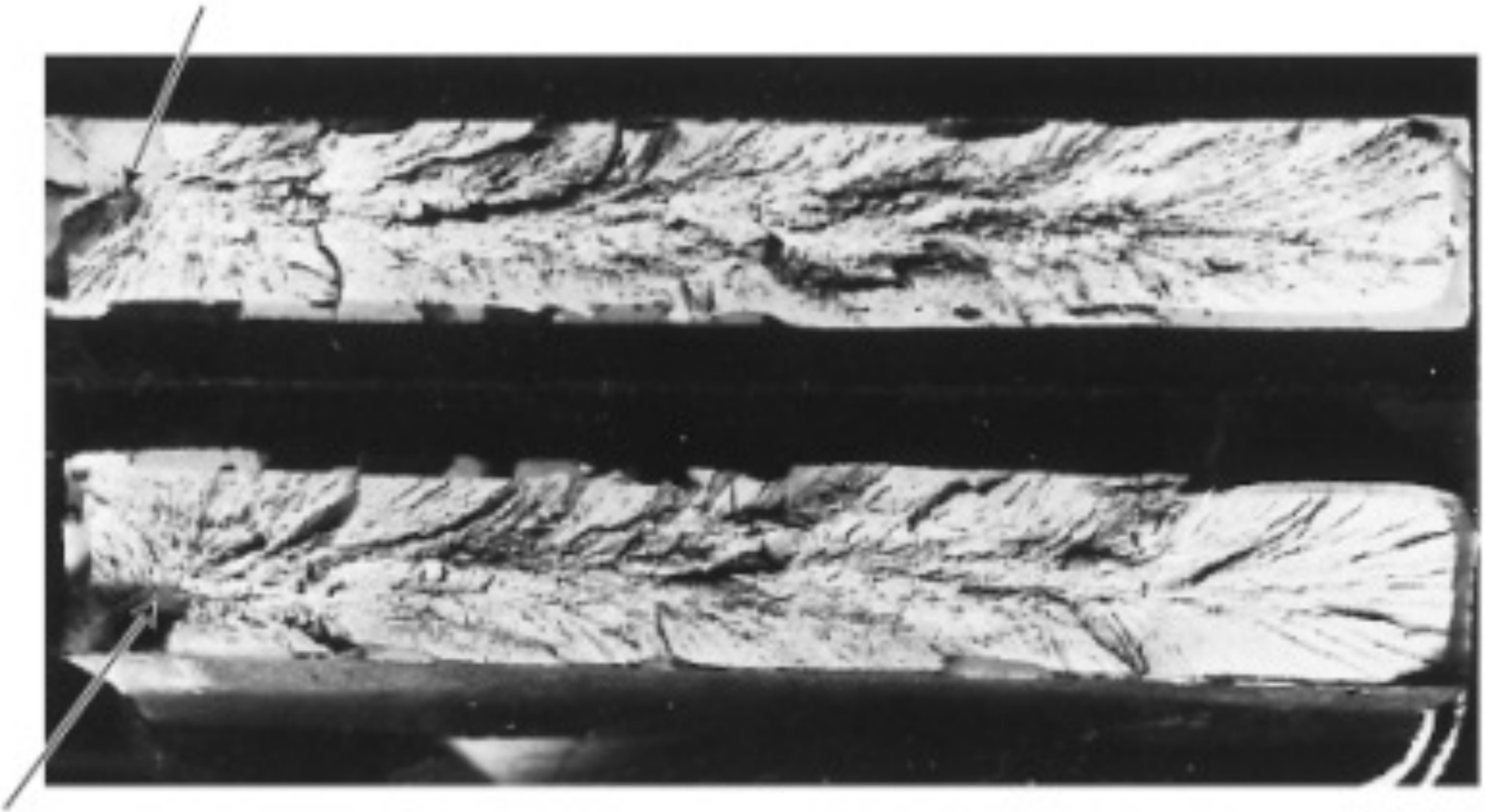
brittle fracture in a mild steel

Irregular and fibrous appearance as an indicative of plastic deformation

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

Brittle Failure

Arrows indicate point at which failure originated



Adapted from Fig. 8.5(a), *Callister & Rethwisch 8e.*

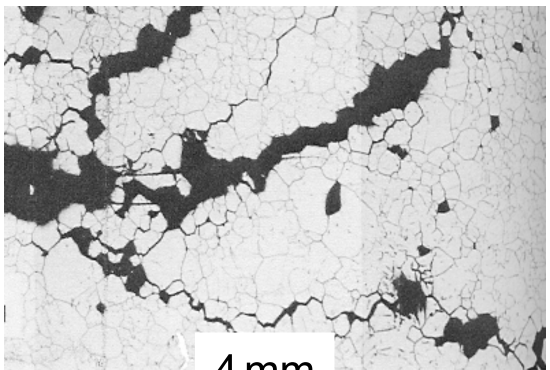
Brittle Fracture Surfaces

Successive and repeated breaking of atomic bonds along specific crystallographic planes, process is called cleavage.

• Intergranular
(between grains)

304 S. Steel (metal)

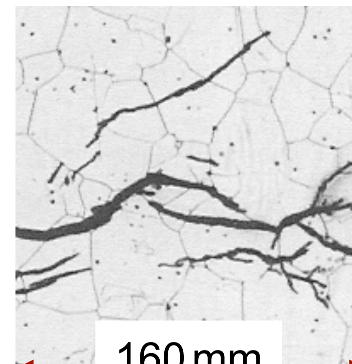
Reprinted w/permission from "Metals Handbook", 9th ed, Fig. 633, p. 650. Copyright 1985, ASM International, Materials Park, OH. (Micrograph by J.R. Keiser and A.R. Olsen, Oak Ridge National Lab.)

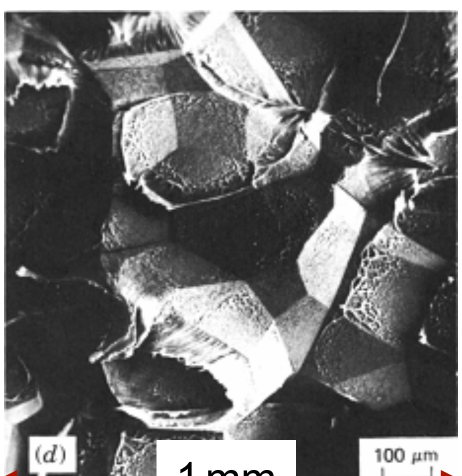


• Transgranular
(through grains)

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.)





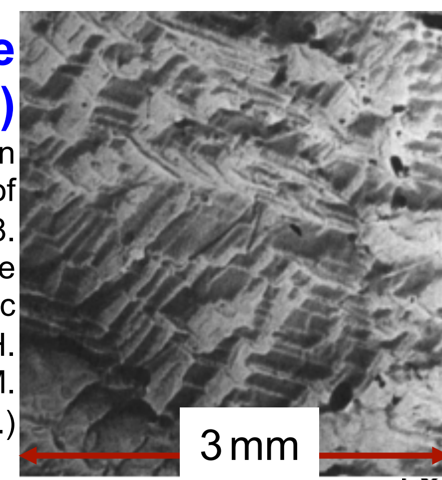
Polypropylene (polymer)

Reprinted w/ permission from R.W. Hertzberg, "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.)

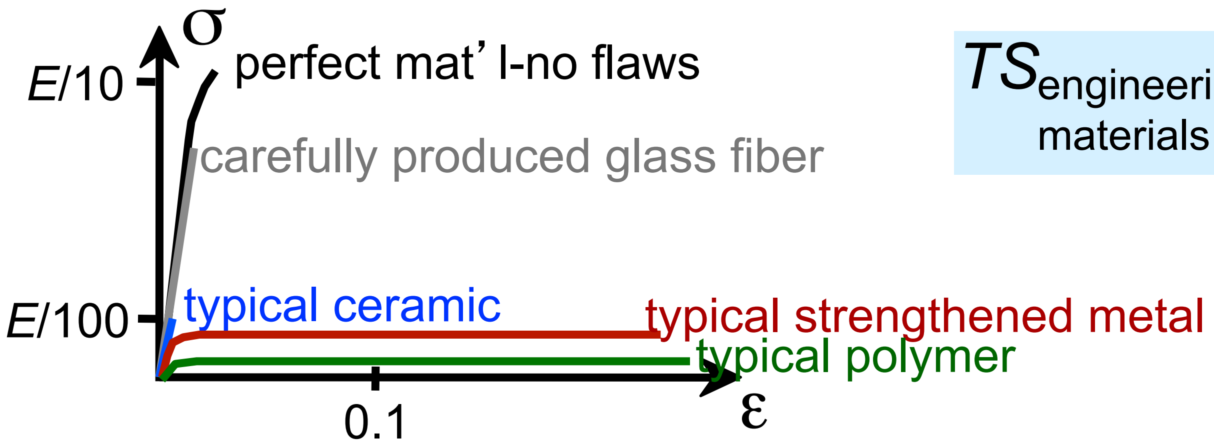
Al Oxide (ceramic)

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.)



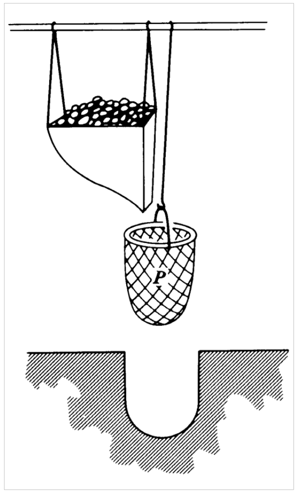
Ideal vs Real Materials

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



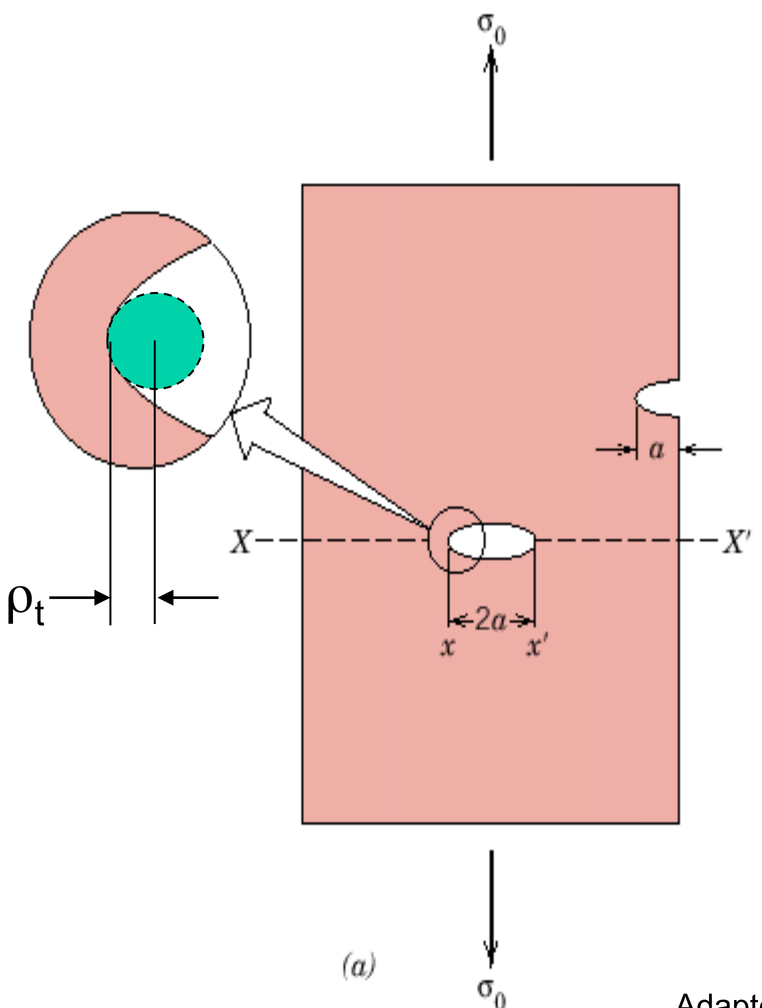
$TS_{\text{engineering materials}} << TS_{\text{perfect materials}}$

- DaVinci (500 yrs ago!) observed...
  -- the longer the wire, the smaller the load for failure.
- Reasons:
  -- flaws cause premature failure.
  -- larger samples contain longer 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!



- Griffith Crack

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

where

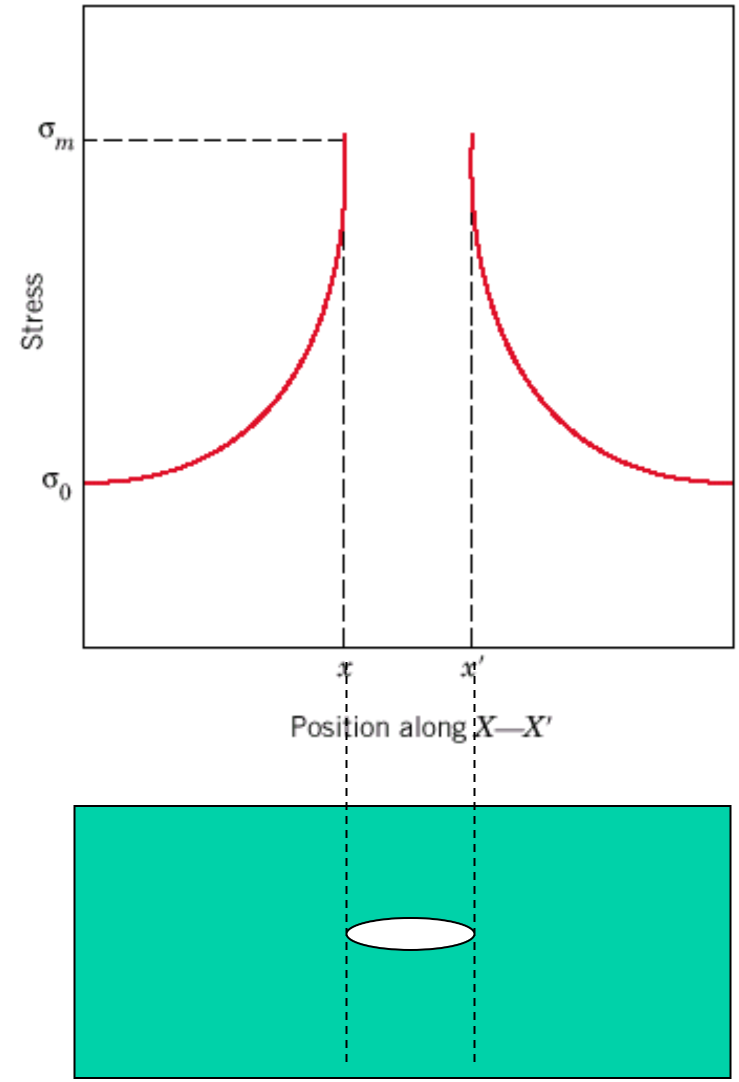
ρ_t = radius of curvature

σ_o = applied stress

σ_m = stress at crack tip

Adapted from Fig. 8.8(a), *Callister & Rethwisch 8e.*

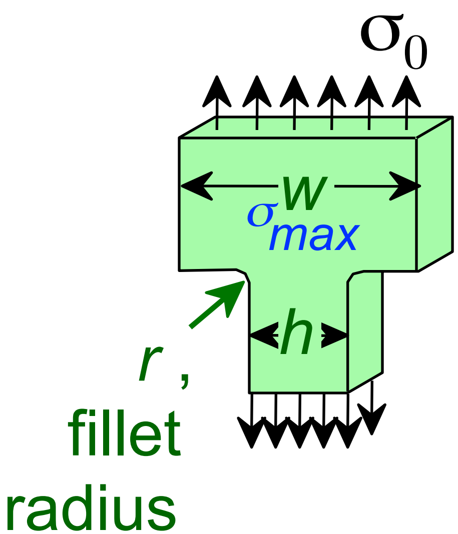
Concentration of Stress at Crack Tip



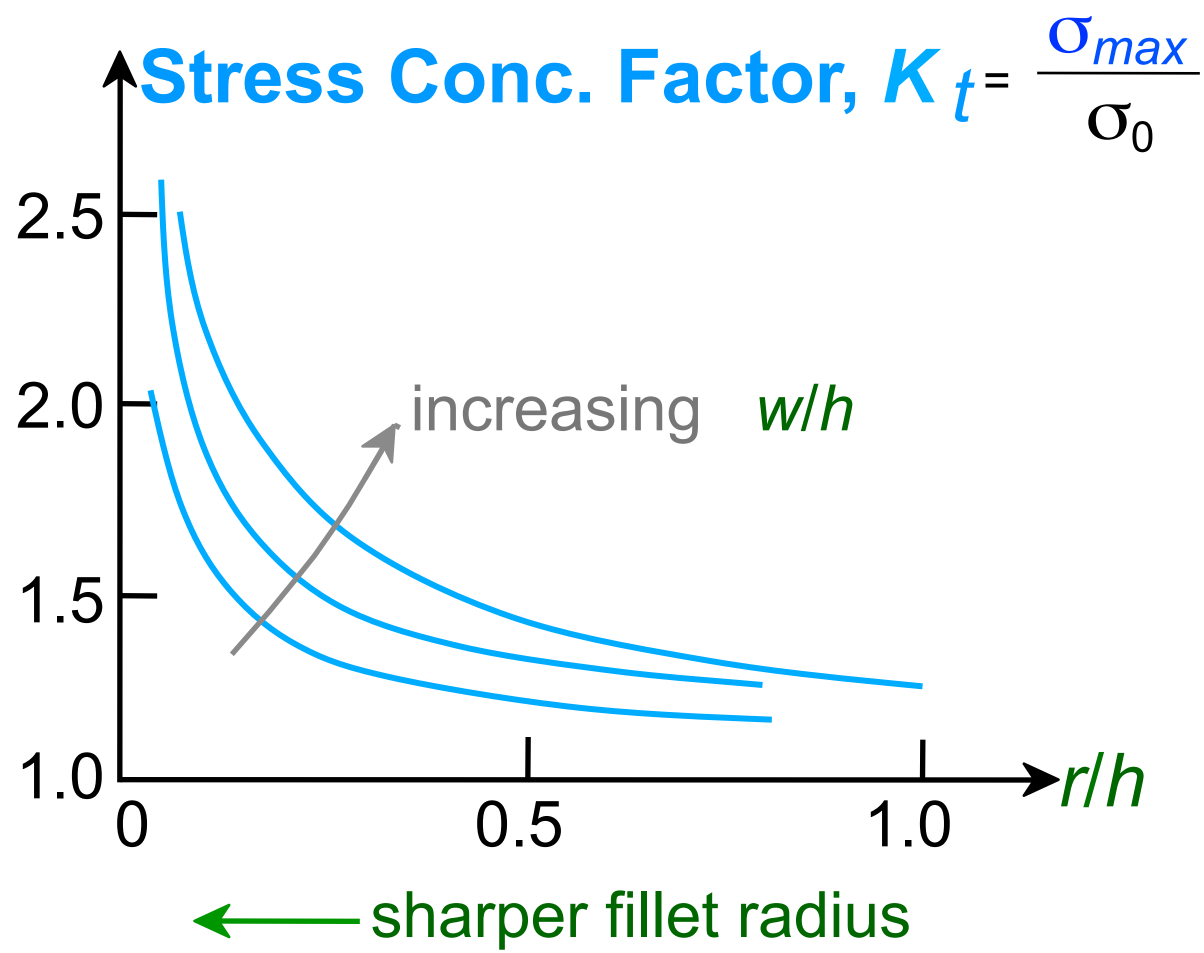
Adapted from Fig. 8.8(b), *Callister & Rethwisch 8e.*

Engineering Fracture Design

- **Avoid sharp corners!**



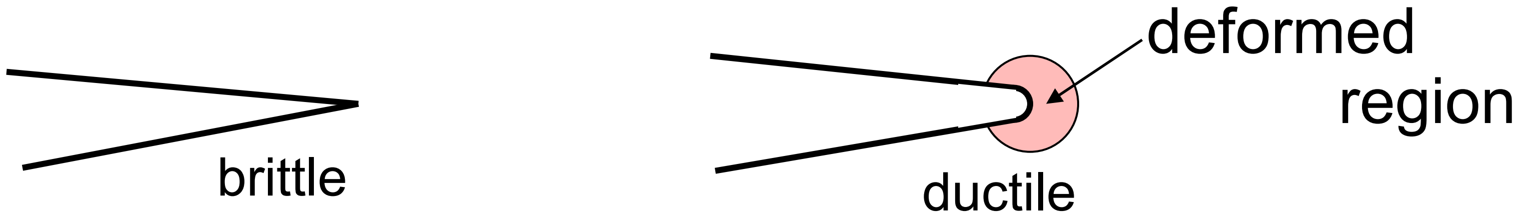
Adapted from Fig. 8.2W (c), *Callister 6e.*
(Fig. 8.2W(c) is from G.H. Neugebauer, *Prod. Eng.* (NY), Vol. 14, pp. 82-87 1943.)



Crack Propagation

Cracks having sharp tips propagate easier than cracks having blunt tips

- A plastic material deforms at a crack tip, which “blunts” 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

Criterion for Crack Propagation

Crack propagates if crack-tip stress (σ_m) exceeds a critical stress (σ_c)

i.e., $\sigma_m > \sigma_c$

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

where

- E = modulus of elasticity
- γ_s = specific surface energy
- a = one half length of internal crack

For ductile materials => replace γ_s with $\gamma_s + \gamma_p$ where γ_p is plastic deformation energy

Design Against Crack Growth

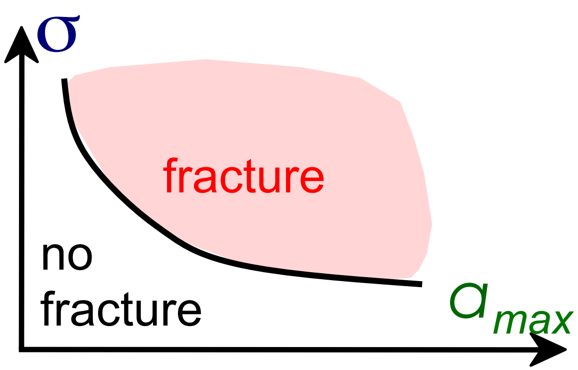
- Fracture toughness: materials' resistance to brittle fracture when a crack is present
- Crack growth condition:

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

- Largest, most highly stressed cracks grow first!

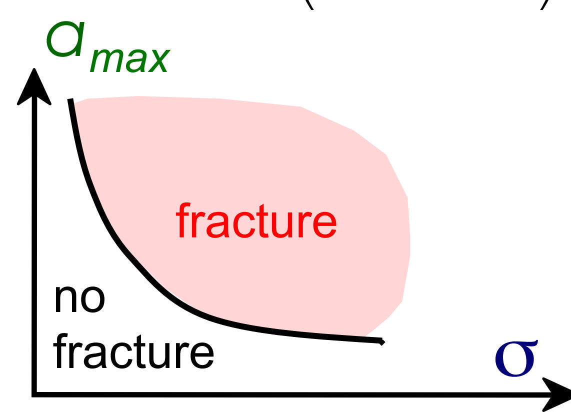
--Scenario 1: Max. flaw size dictates design stress.

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

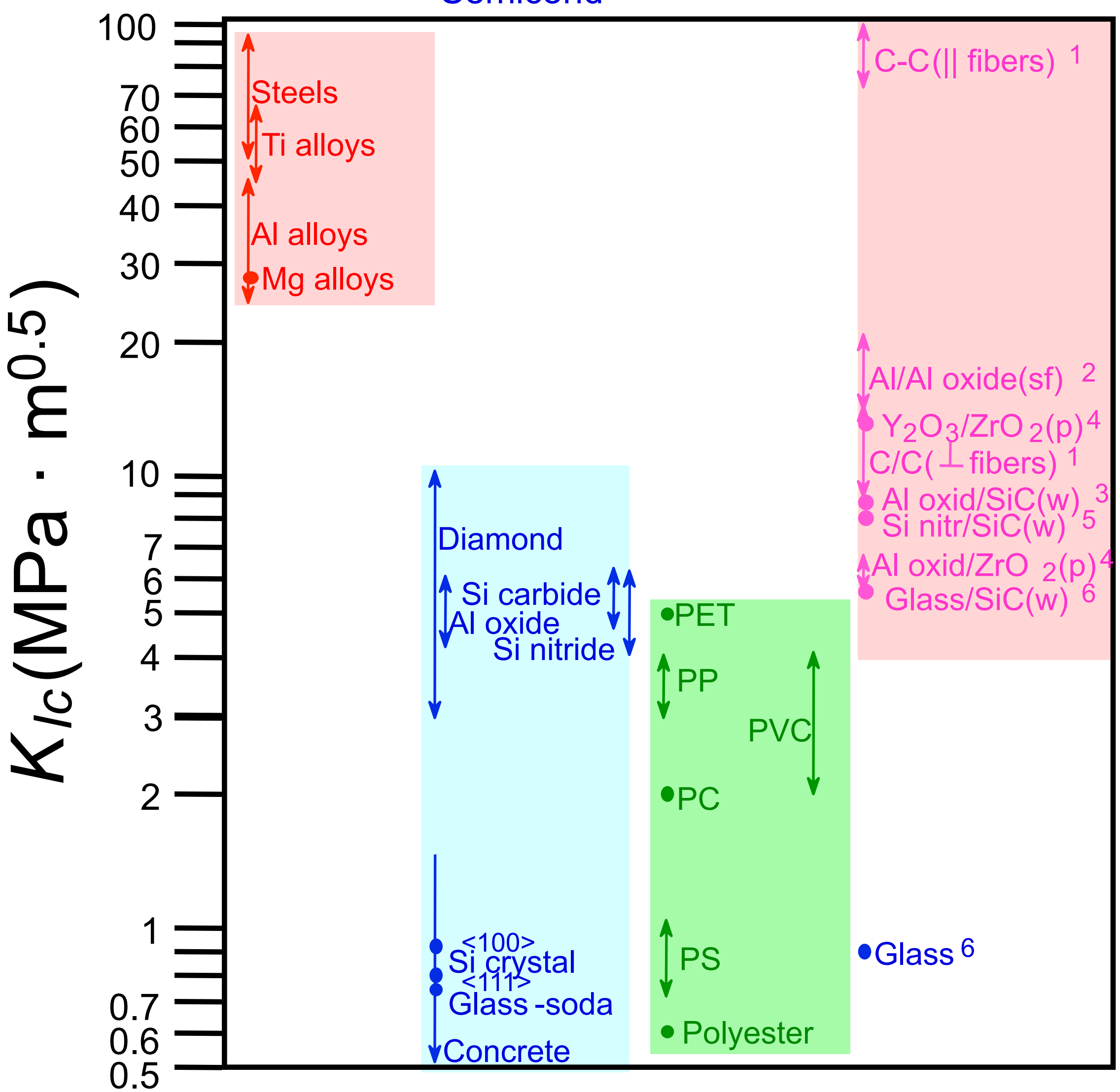


--Scenario 2: Design stress dictates max. flaw size.

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



Fracture Toughness Ranges



Based on data in Table B.5, *Callister & Rethwisch 8e.*

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 Example: Aircraft Wing

- Material has K_{Ic} = 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...

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

- Key point: Y and K_{Ic} are the same for both designs.

$$\frac{K_{Ic}}{Y\sqrt{\pi}} = \sigma\sqrt{a} = \text{constant}$$

--Result:

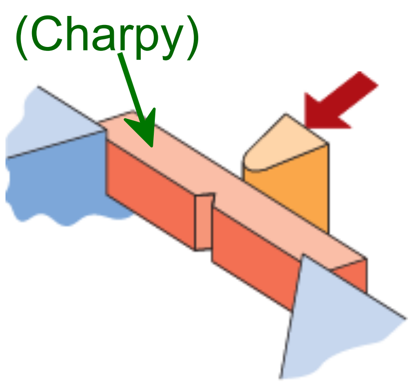
112 MPa **9 mm** **4 mm**

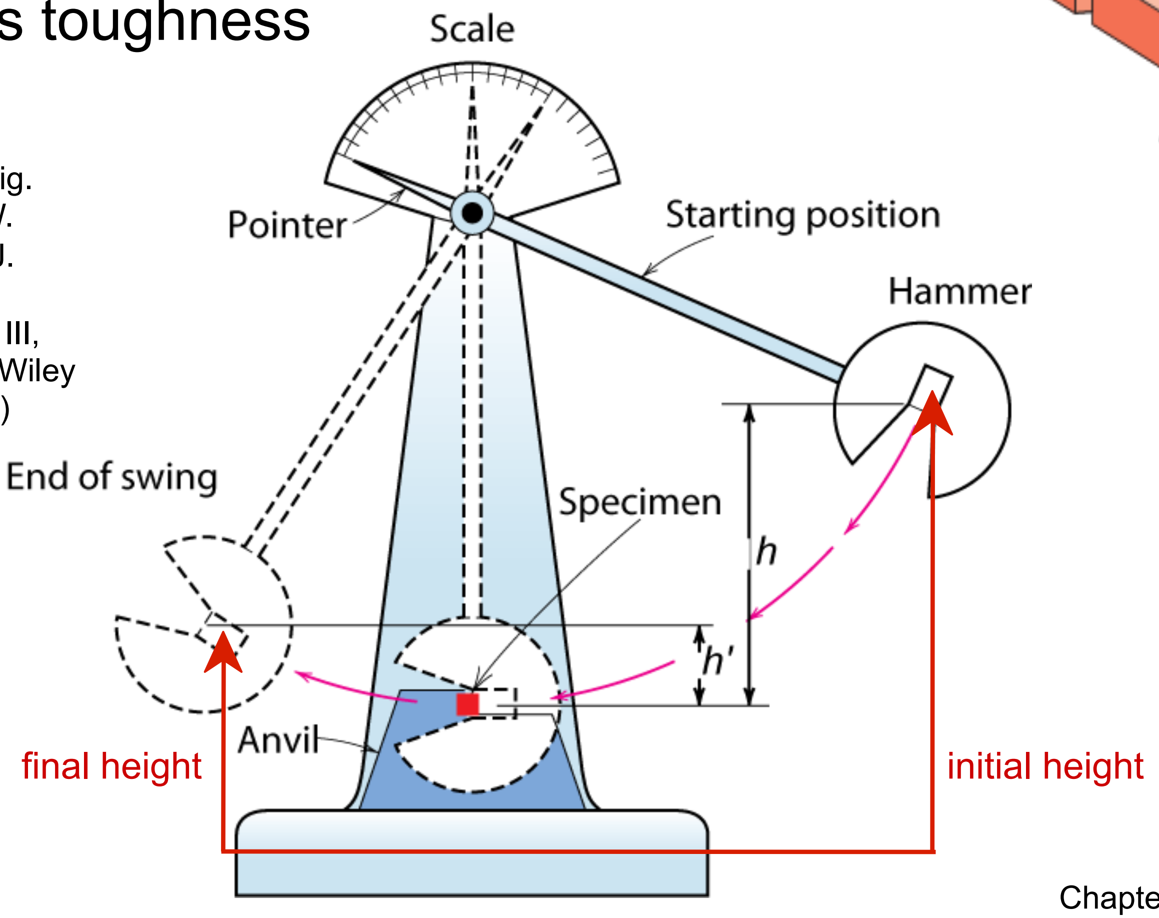
$$\left(\sigma_c\sqrt{a_{max}}\right)_A = \left(\sigma_c\sqrt{a_{max}}\right)_B$$

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

Impact Testing

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

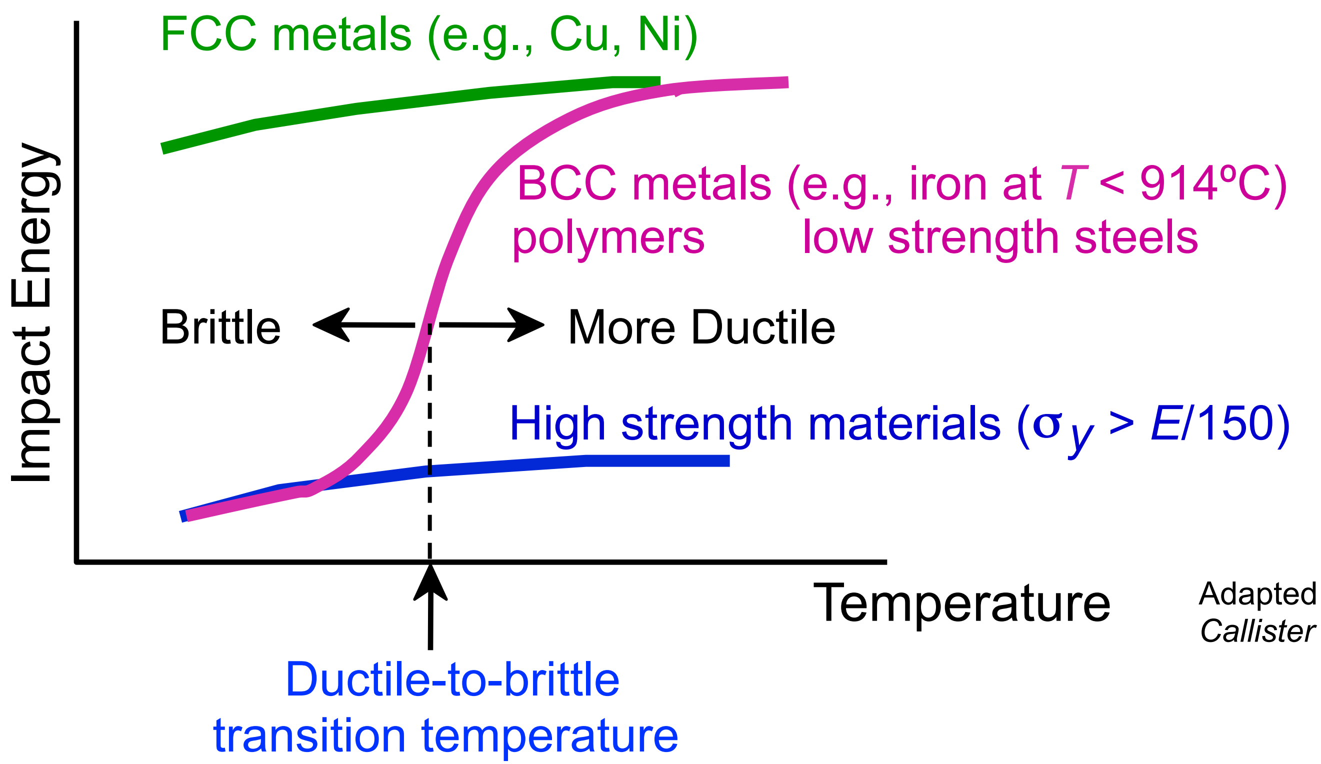




Adapted from Fig. 8.12(b), *Callister & Rethwisch 8e.* (Fig. 8.12(b) is adapted from H.W. Hayden, W.G. Moffatt, and J. Wulff, *The Structure and Properties of Materials*, Vol. III, *Mechanical Behavior*, John Wiley and Sons, Inc. (1965) p. 13.)

Influence of Temperature on Impact Energy

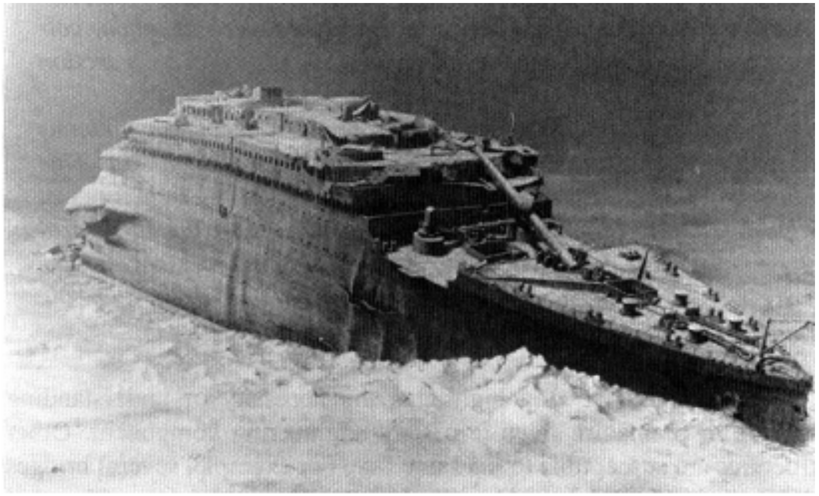
- **Ductile-to-Brittle Transition Temperature (DBTT)...**



Adapted from Fig. 8.15, *Callister & Rethwisch 8e.*

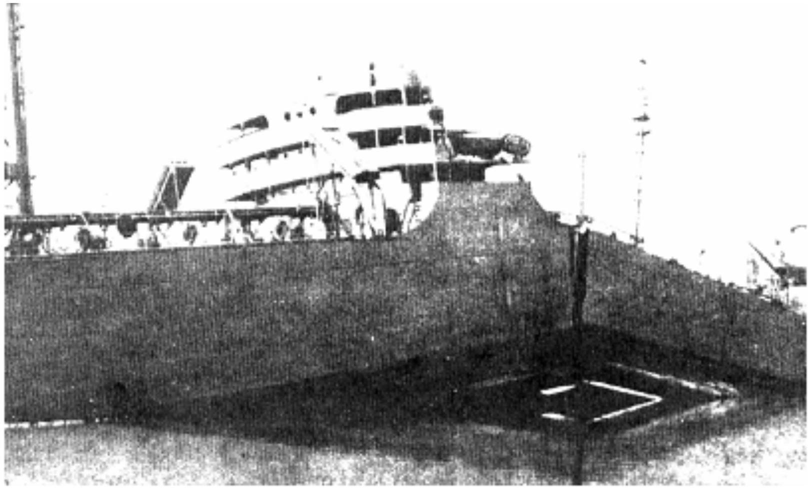
Design Strategy: Stay Above The DBTT!

- **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.)

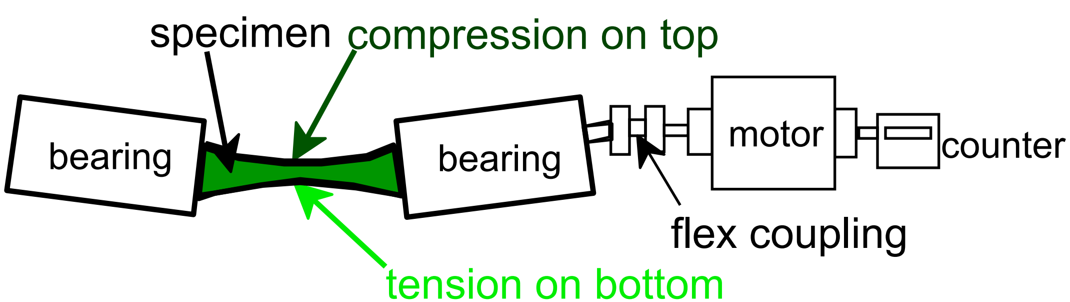
- Problem: Steels were used having DBTT's just below room temperature.

Q7. A structural component in the form of a wide plate is to be fabricated from a steel alloy that has a plane strain fracture toughness of 77.0 MPa m and a yield $\text{MPa}\sqrt{\text{m}}$ of 1400 MPa. The flaw size resolution limit of the flaw detection apparatus is 4.1 mm. If the design stress is one half of the yield strength and the value of *Y* is 1.0, determine whether or not a critical flaw for this plate is subject to detection.

The 1948 Northwest Airlines Flight 421 crash due to fatigue failure in a wing spar root
The 1957 "Mt. Pinatubo", presidential plane of Philippine President Ramon Magsaysay, crashed due to engine failure caused by metal fatigue.
The 1968 Los Angeles Airways Flight 417 lost one of its main rotor blades due to fatigue failure
The 1968 MacRobertson Miller Airlines Flight 1750 that lost a wing due to improper maintenance leading to fatigue failure
The 1977 Dan-Air Boeing 707 crash caused by fatigue failure resulting in the loss of the right horizontal stabilizer
The 1980 LOT Flight 7 that crashed due to fatigue in an engine turbine shaft resulting in engine disintegration leading to loss of control
The 1985 Japan Airlines Flight 123 crashed after the aircraft lost its vertical stabilizer due to faulty repairs on the rear bulkhead
The 1988 Aloha Airlines Flight 243 suffered an explosive decompression due to fatigue failure
The 1989 United Airlines Flight 232 lost its tail engine due to fatigue failure in a fan disk hub.
The 1992 El Al Flight 1862 lost both engines on its right-wing due to fatigue failure in the pylon mounting of the #3 Engine
The 1998 Eschede train disaster was caused by fatigue failure of a single composite wheel
The 2000 Hatfield rail crash was likely caused by rolling contact fatigue
The 2002 China Airlines Flight 611 had disintegrated in-flight due to fatigue failure
The 2005 Chalk's Ocean Airways Flight 101 lost its right wing due to fatigue failure brought about by inadequate maintenance practices

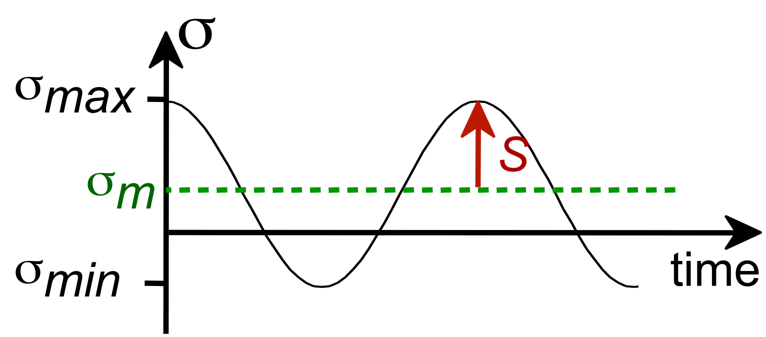
Fatigue

- Fatigue = failure under applied cyclic stress.



Adapted from Fig. 8.18, *Callister & Rethwisch 8e.* (Fig. 8.18 is from *Materials Science in Engineering*, 4/E by Carl. A. Keyser, Pearson Education, Inc., Upper Saddle River, NJ.)

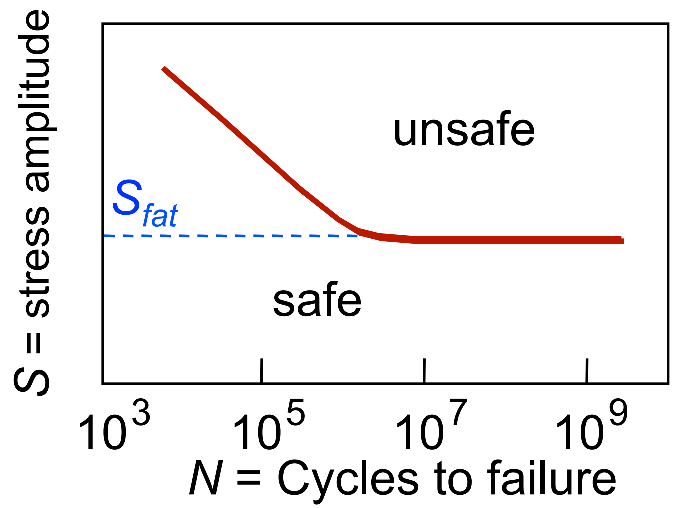
- Stress varies with time.
  -- key parameters are S, σ_m, and cycling frequency



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

Types of Fatigue Behavior

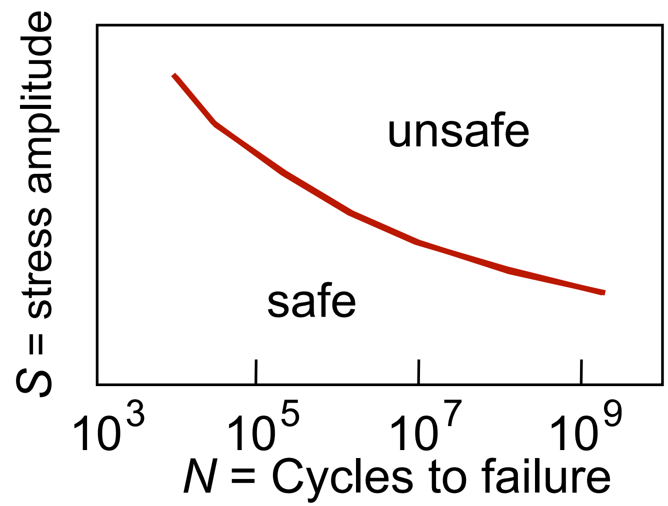
- Fatigue limit, S_{fat}:
  --no fatigue if $S < S_{fat}$



case for steel (typ.)

Adapted from Fig. 8.19(a), *Callister & Rethwisch 8e.*

- For some materials, there is no fatigue limit!



case for Al (typ.)

Adapted from Fig. 8.19 (b), *Callister & Rethwisch 8e.*

Rate of Fatigue Crack Growth

- Crack grows *incrementally*

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

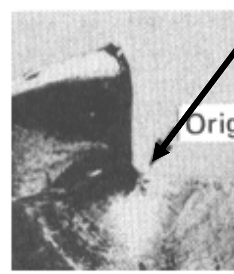
typ. 1 to 6

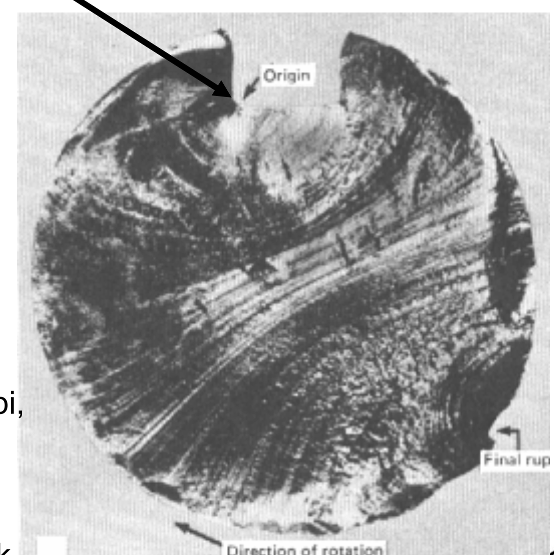
$$\sim (\Delta\sigma)\sqrt{a}$$

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

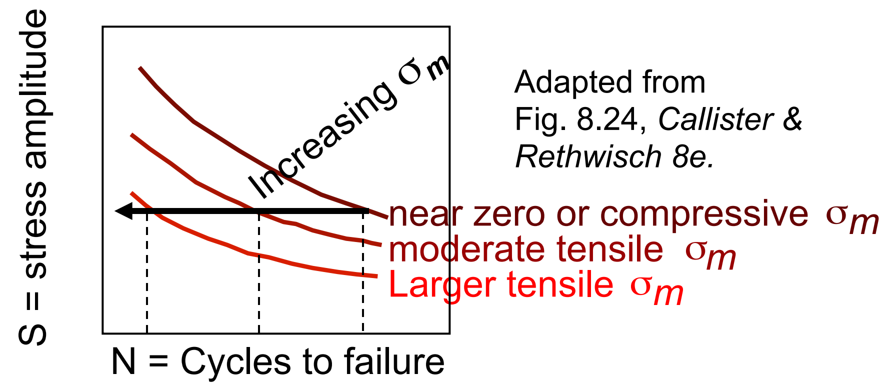




Adapted from Fig. 8.21, *Callister & Rethwisch 8e.* (Fig. 8.21 is from D.J. Wulpi, *Understanding How Components Fail*, American Society for Metals, Materials Park, OH, 1985.)

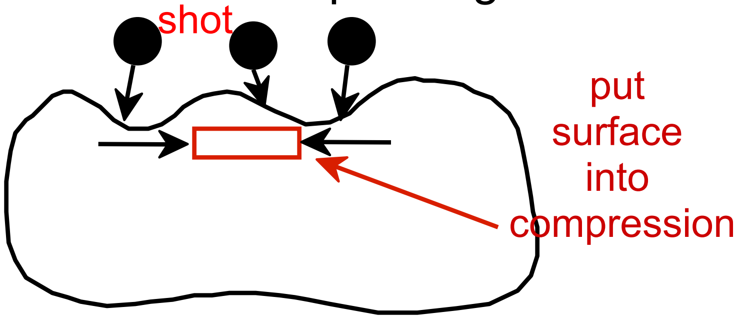
Improving Fatigue Life

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

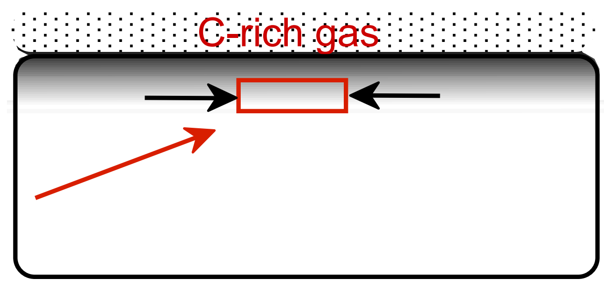


Adapted from Fig. 8.24, *Callister & Rethwisch 8e.*

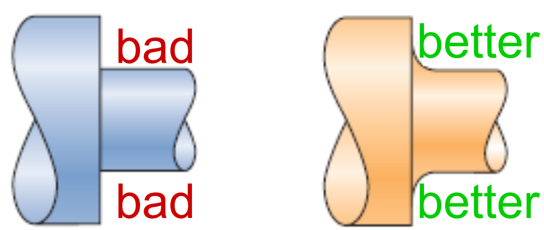
--Method 1: shot peening



--Method 2: carburizing



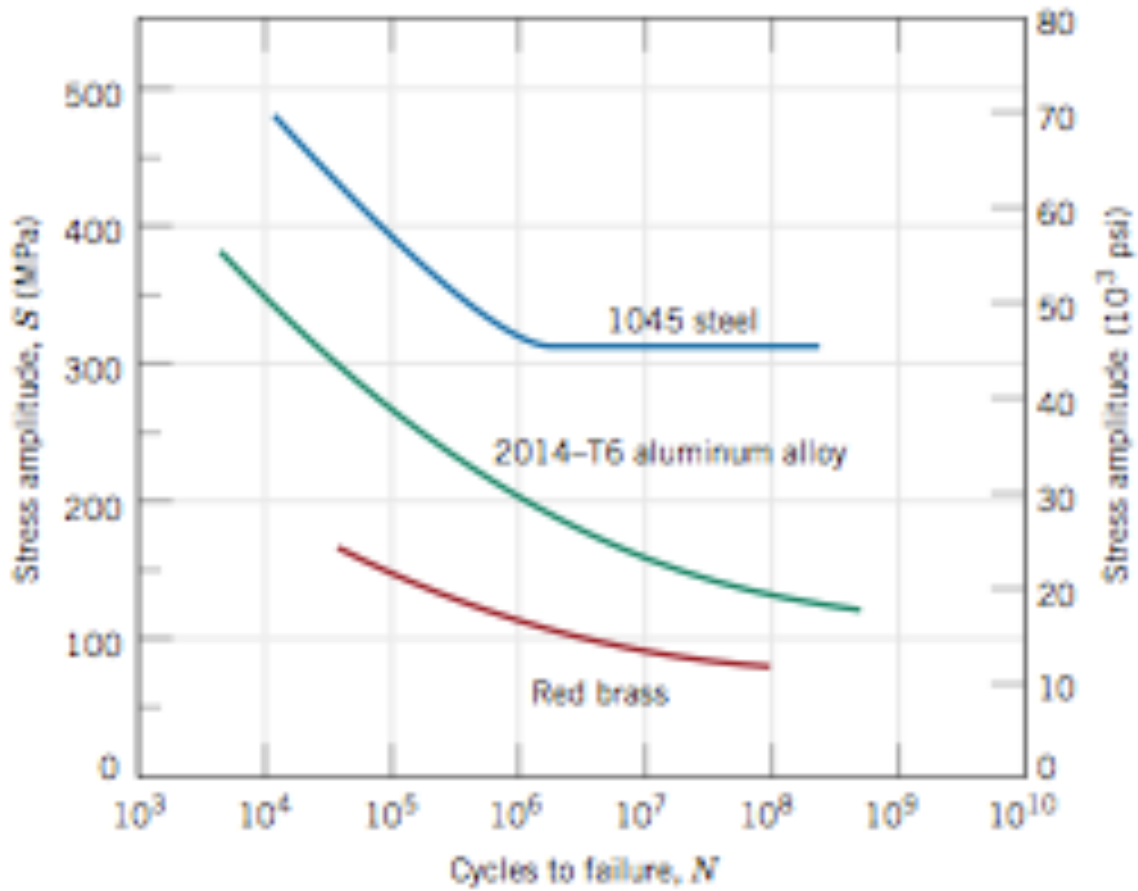
2. Remove stress concentrators.



Adapted from Fig. 8.25, *Callister & Rethwisch 8e.*

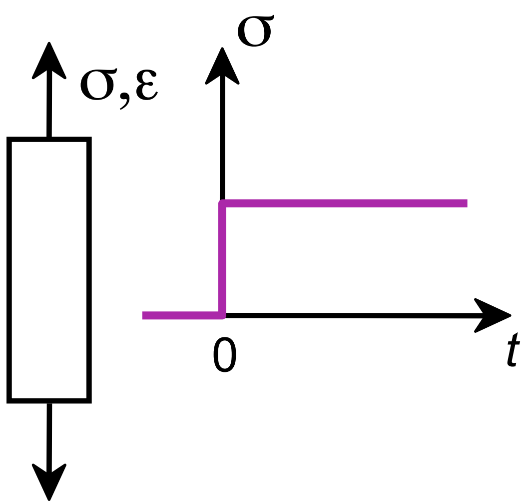
Question: A 12.5 mm diameter cylindrical rod fabricated from a 2014-T6 alloy (Figure 8.34) is subjected to a repeated tension–compression load cycling along its axis. Compute the maximum and minimum loads that will be applied to yield a fatigue life of 1.0×10^7 cycles.

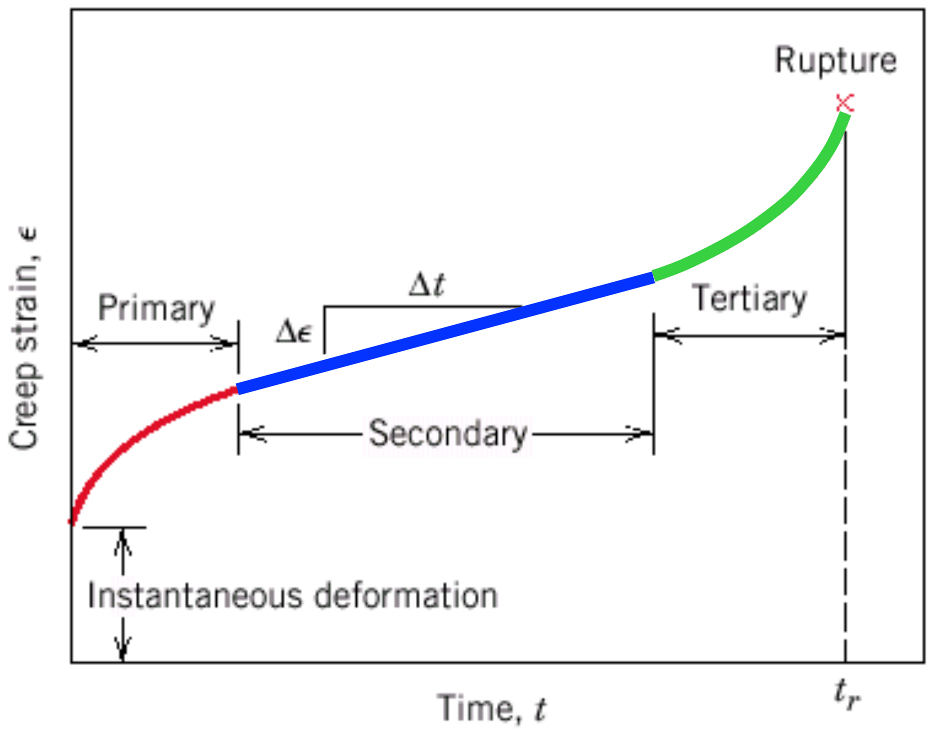
Assume that the stress plotted on the vertical axis is stress amplitude, and data were taken for a mean stress of 50 MPa.



Creep

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





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

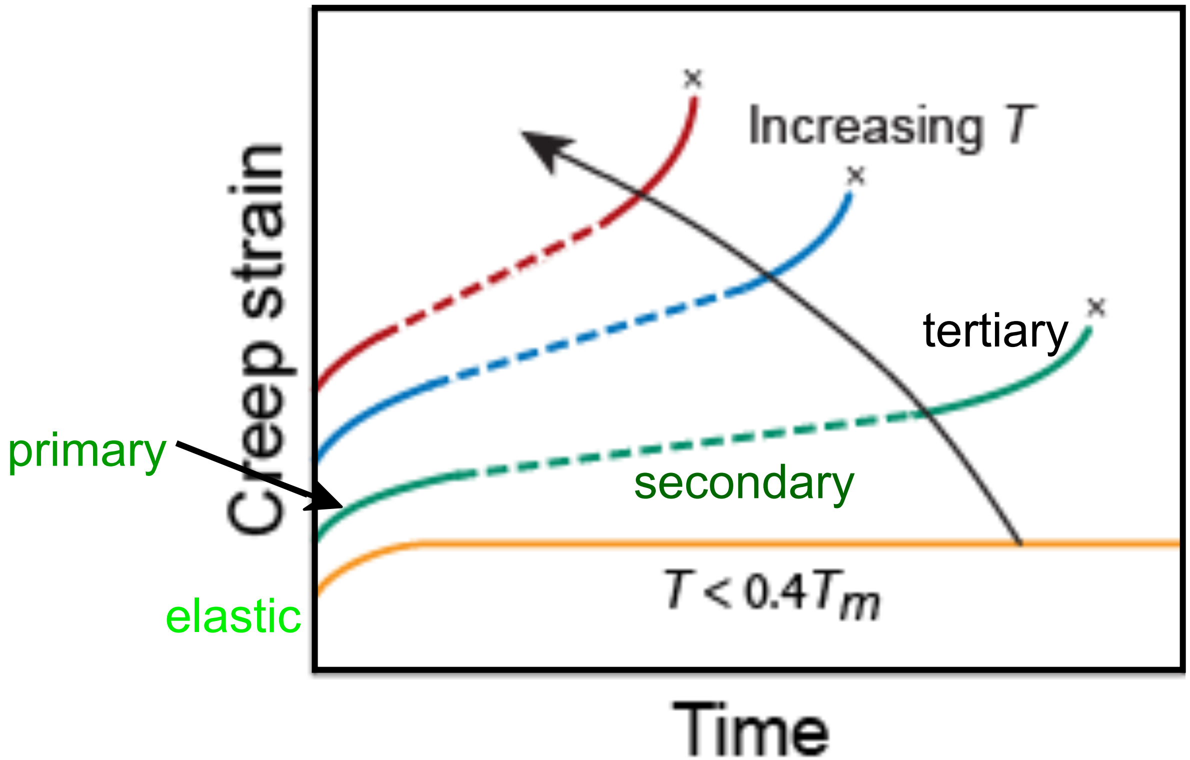
Secondary Creep: steady-state i.e., constant slope ($\Delta\varepsilon/\Delta t$).

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

Adapted from Fig. 8.28, *Callister & Rethwisch 8e.*

Creep: Temperature Dependence

- Occurs at elevated temperature, $T > 0.4\ T_m$ (in K)



Adapted from Fig. 8.29,
Callister & Rethwisch 8e.

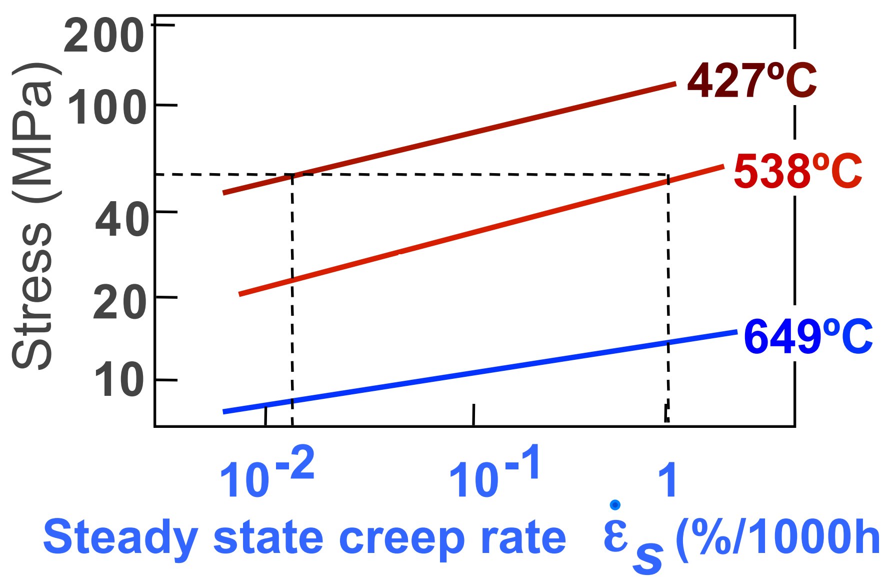
Secondary Creep

- 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

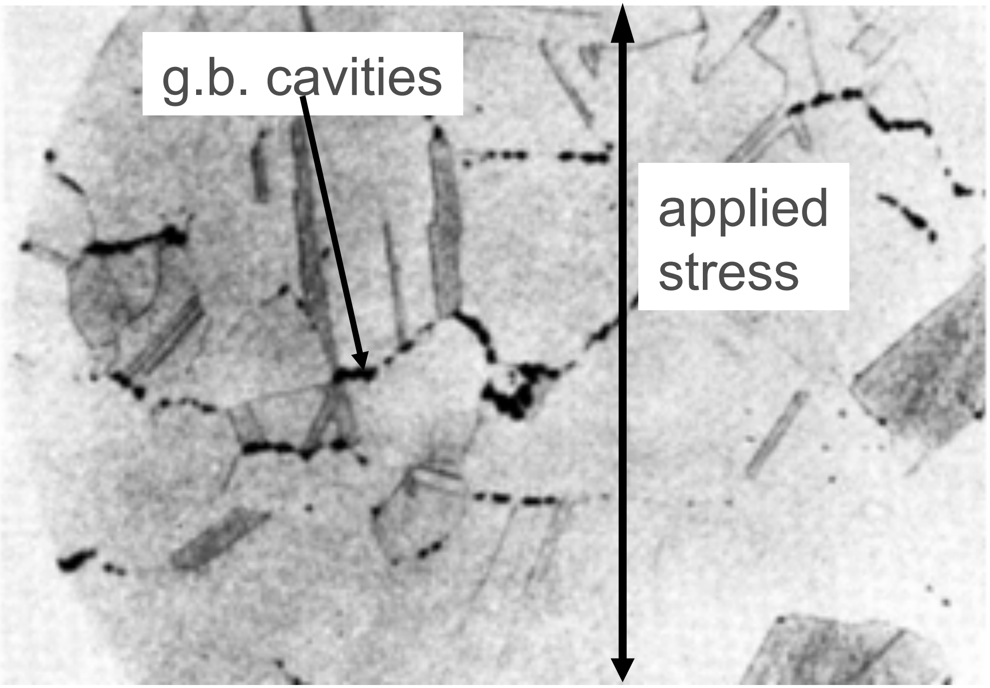
- Strain rate increases with increasing T, σ



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.

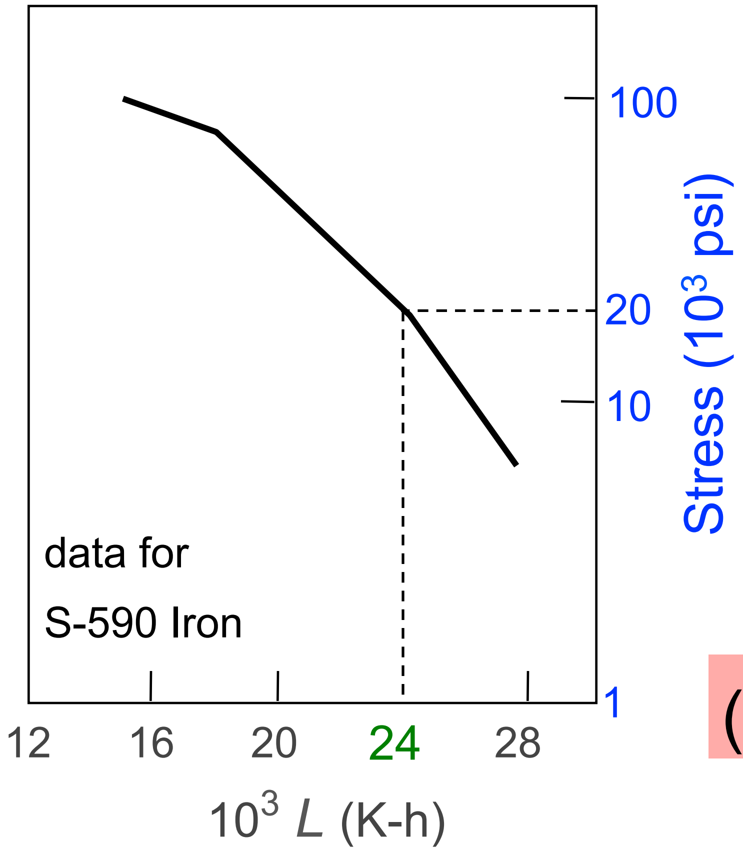


From V.J. Colangelo and F.A. Heiser, *Analysis of Metallurgical Failures* (2nd ed.), Fig. 4.32, p. 87, John Wiley and Sons, Inc., 1987. (Orig. source: Pergamon Press, Inc.)

Prediction of Creep Rupture Lifetime

- Estimate rupture time

S-590 Iron, T = 800ºC, σ = 20,000 psi



Adapted from Fig. 8.32, *Callister & Rethwisch 8e.* (Fig. 8.32 is from F.R. Larson and J. Miller, *Trans. ASME*, **74**, 765 (1952).)

Time to rupture, t_r

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

temperature

time to failure (rupture)

function of applied stress

$$(1073\,\mathrm{K})(20 + \log t_r) = 24\mathrm{x}10^3$$

Ans: t_r = 233 hr

Estimate the rupture time for S-590 Iron, T = 750ºC, σ = 20,000 psi

- **Solution:**

Time to rupture, t_r

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

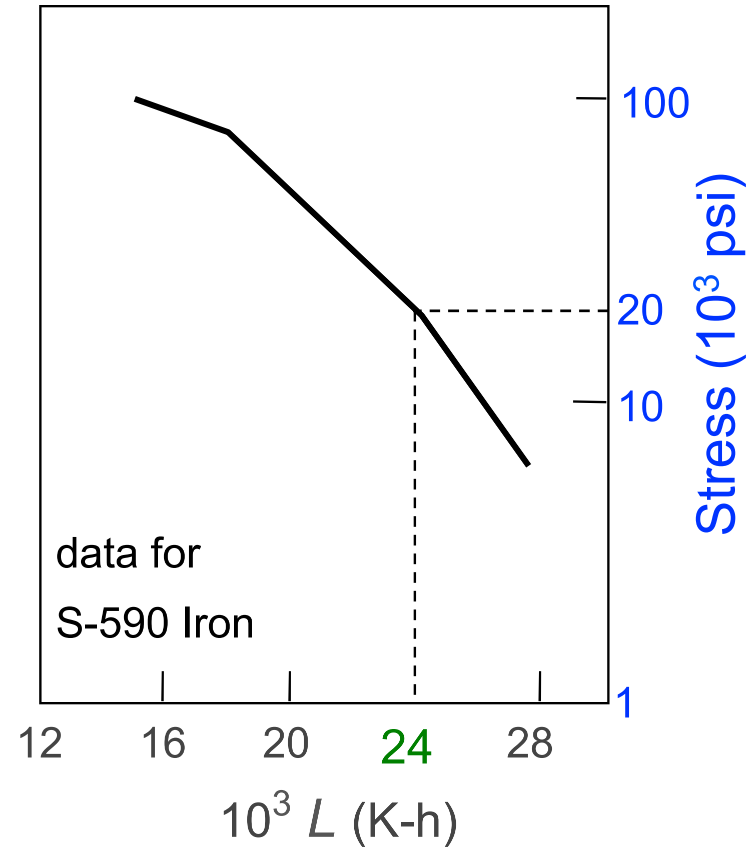
temperature

time to failure (rupture)

function of applied stress

$$(1023\ \text{K})(20 + \log t_r) = 24\text{x}10^3$$

Ans: t_r = 2890 hr



Adapted from Fig. 8.32, *Callister & Rethwisch 8e.* (Fig. 8.32 is from F.R. Larson and J. Miller, *Trans. ASME*, **74**, 765 (1952).)

SUMMARY

- Engineering materials not as strong as predicted by theory
- Flaws act as stress concentrators that cause failure at stresses lower than theoretical values.
- Sharp corners produce large stress concentrations and premature failure.
- Failure type depends on T and σ:

  -For simple fracture (noncyclic σ and $T < 0.4T_m$), failure stress decreases with:

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

  - For fatigue (cyclic σ):

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

  - For creep ($T > 0.4T_m$):

  - time to rupture decreases as σ or T increases.