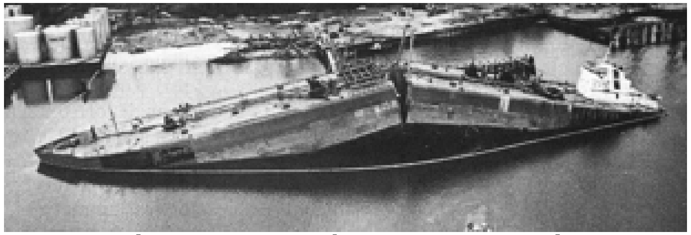
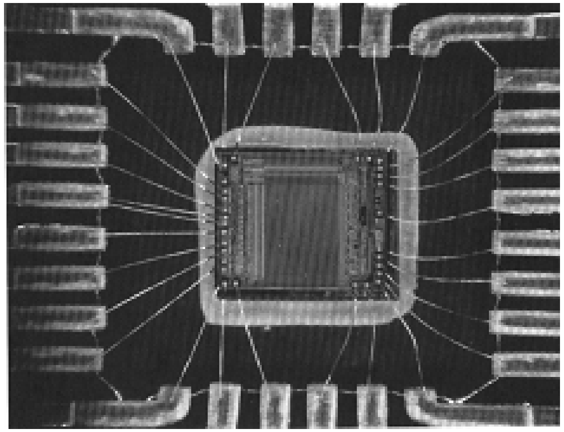
# Chapter 7: Fracture and Failure



Neal Boenzi/New York Times Pictures/Redux Pictures

**Ship-cyclic loading from waves.**

Chapter-opening photograph, Chapter 8, *Callister & Rethwisch 9e.*



**Computer chip-cyclic thermal loading.**

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

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

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

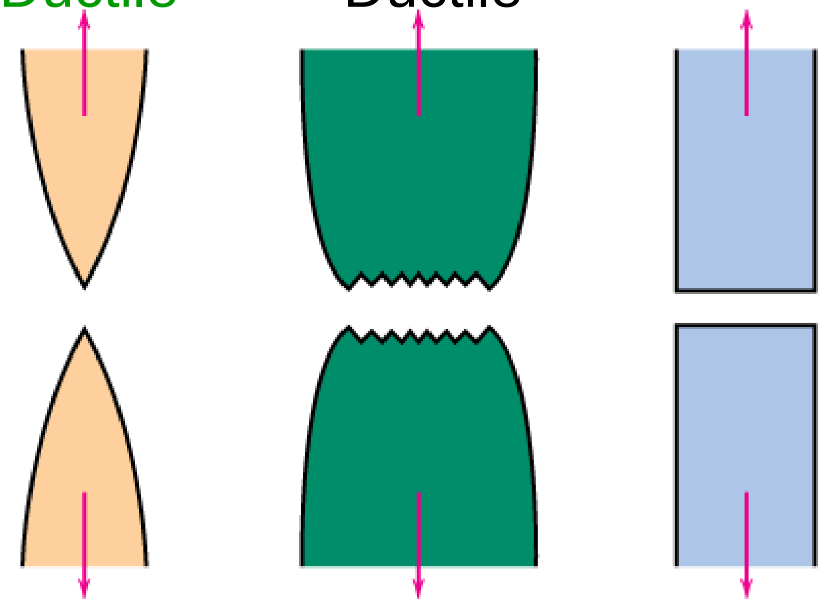
# Fracture mechanisms

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

# Ductile vs Brittle Failure

- Classification:

| Fracture behavior: | Very Ductile | Moderately Ductile | Brittle |
|---|---|---|---|



Adapted from Fig. 8.1, *Callister & Rethwisch 9e.*

| %*AR* or %*EL* | Large | Moderate | Small |
|---|---|---|---|

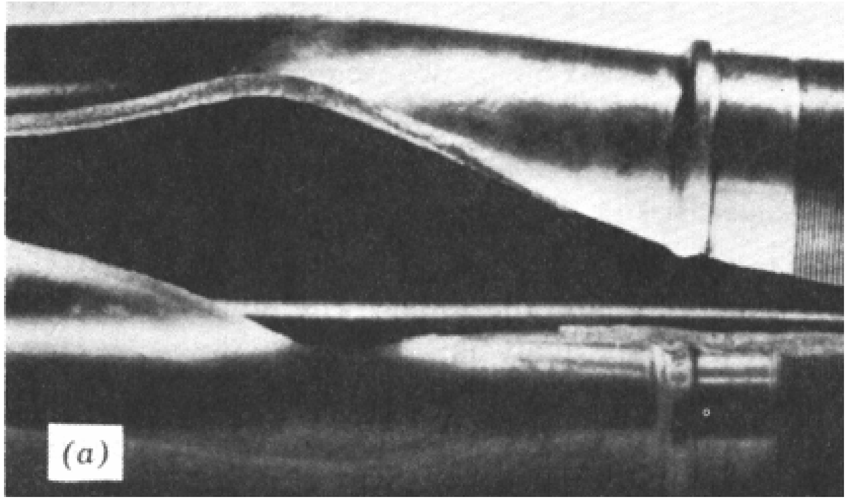
- Ductile fracture is usually more desirable than brittle fracture!

**Ductile:** Warning before fracture

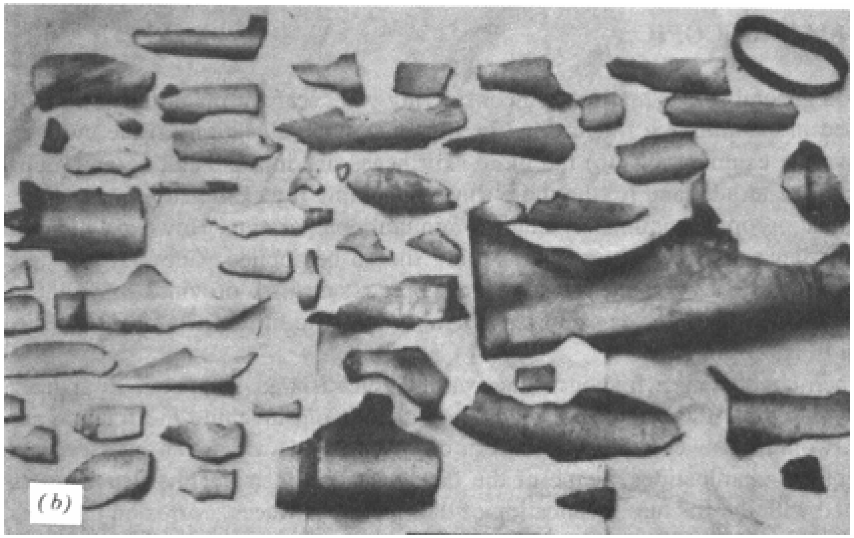
**Brittle:** No warning

# Example:  Pipe Failures

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



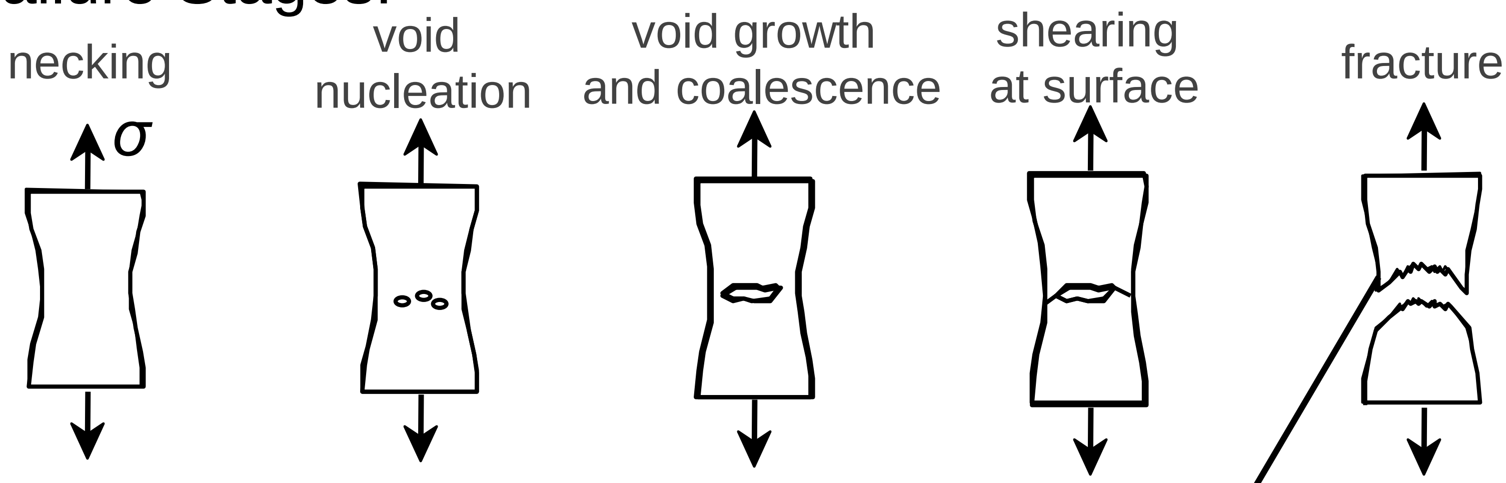

- **Brittle failure:**
  -- many pieces
  -- small deformations



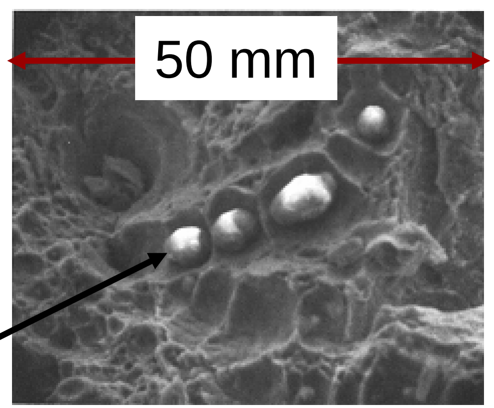

Figures from V.J. Colangelo and F.A. Heiser, *Analysis of Metallurgical Failures* (2nd ed.), Fig. 4.1(a) and (b), p. 66  John Wiley and Sons, Inc., 1987.  Used with permission.

# Moderately Ductile Failure

- Failure Stages:

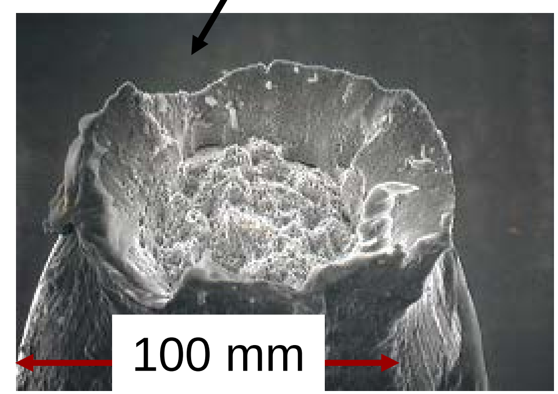



- Resulting fracture surfaces (steel)




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.

# Moderately Ductile vs. Brittle Failure

cup-and-cone fracture

brittle fracture

Fig. 8.3, *Callister & Rethwisch 9e.*

# Brittle Failure

Arrows indicate point at which failure originated

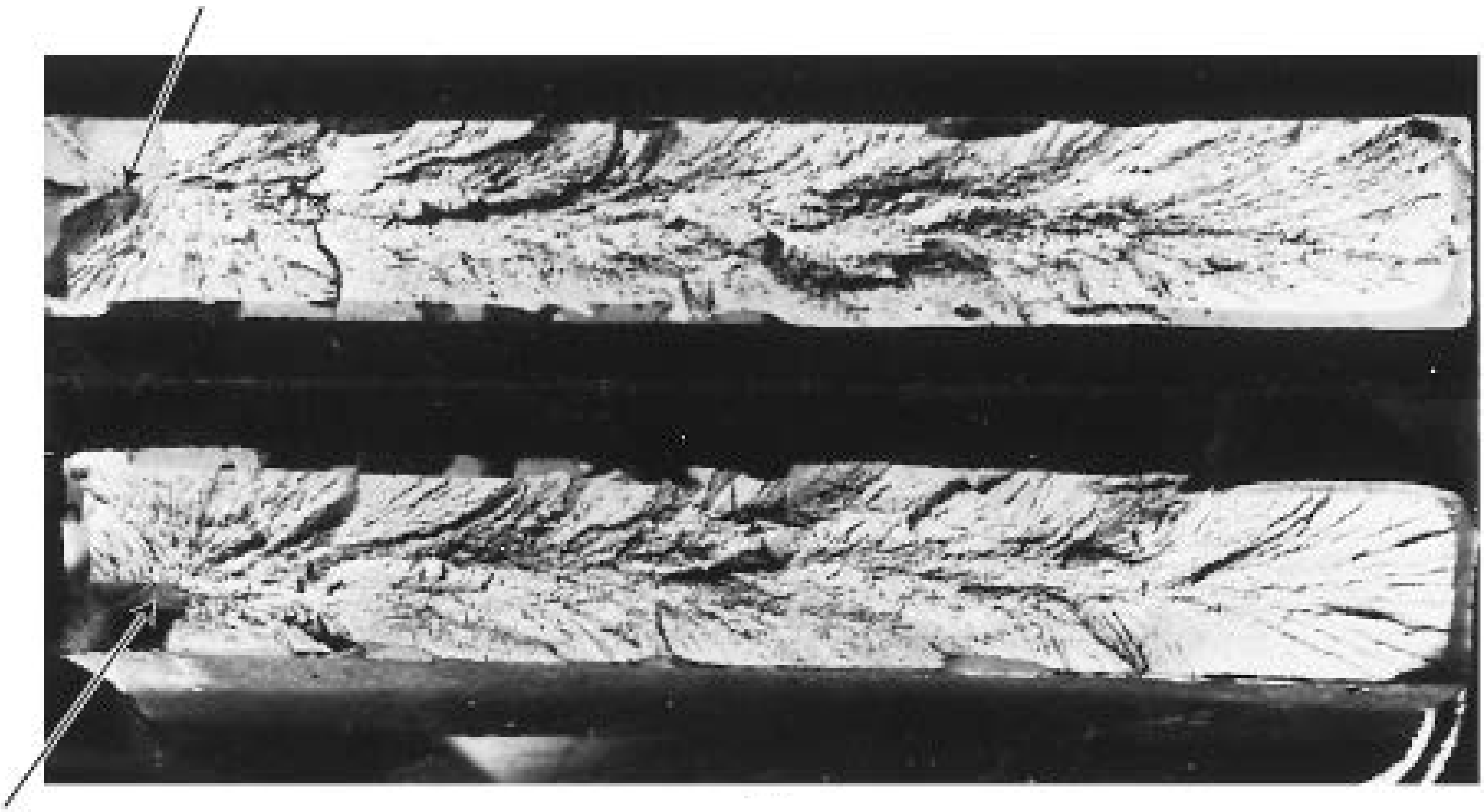
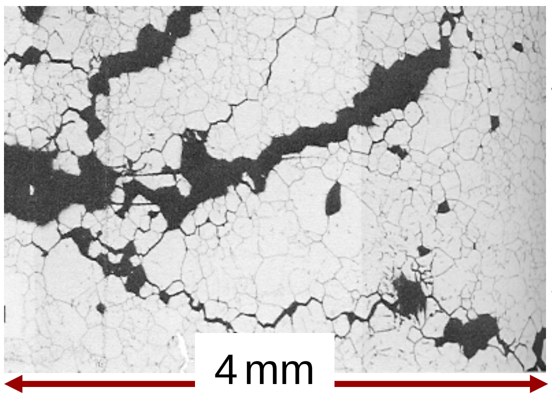


Fig. 8.5(a), *Callister & Rethwisch 9e.* [From R. W. Hertzberg, *Deformation and Fracture Mechanics of Engineering Materials*, 3rd edition. Copyright © 1989 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc. Photograph courtesy of Roger Slutter, Lehigh University.]

# Brittle Fracture Surfaces

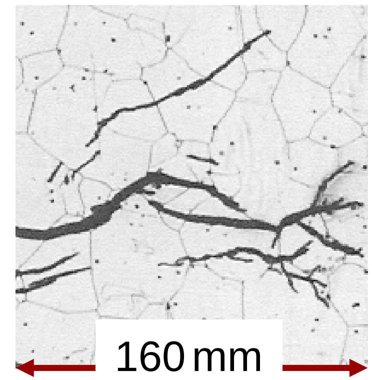
- Intergranular (between grains)

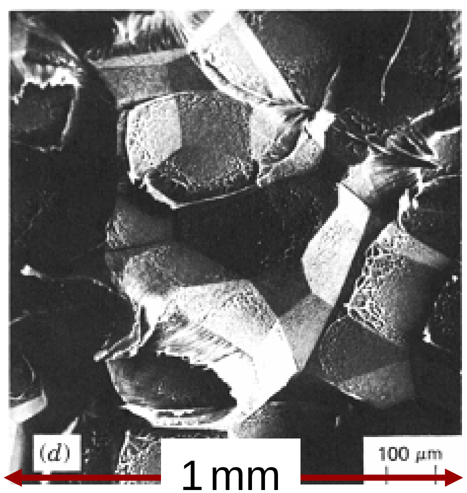



**304 S. Steel (metal)**
Reprinted w/permission from "Metals Handbook", 9th ed, Fig. 633, p. 650. Copyright 1985, ASM International, Materials Park, OH. (Micrograph by J.R. Keiser and A.R. Olsen, Oak Ridge National Lab.)

- 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.)

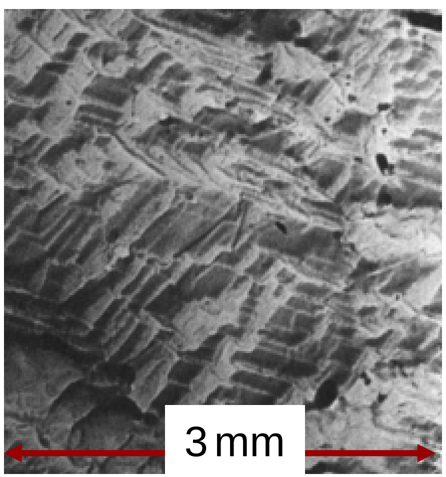



**Polypropylene (polymer)**
Reprinted w/ permission from R.W. Hertzberg, "Deformation and Fracture Mechanics of Engineering Materials", (4th ed.) Fig. 7.35(d), p. 303, John Wiley and Sons, Inc., 1996.

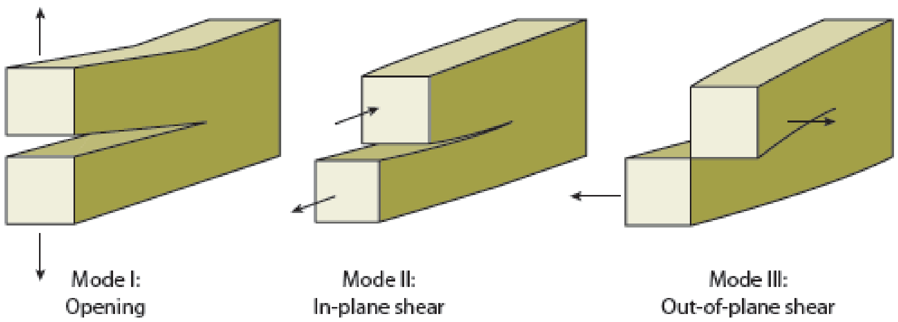
(Orig. source: K. Friedrick, *Fracture 1977*, Vol. 3, ICF4, Waterloo, CA, 1977, p. 1119.)

**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.)



# Fracture- Fracture of Brittle Materials: Ceramics, Metals, and Polymers

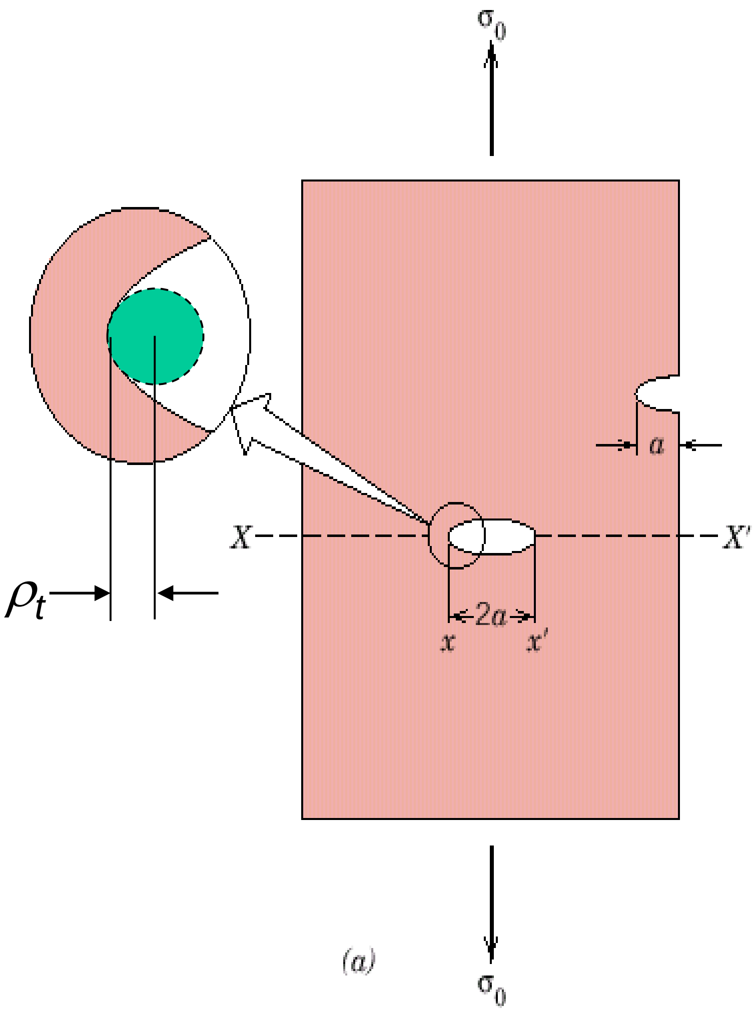
- **Ceramic materials and glass are brittle.**




There are three main modes of fracture:

- Left: Crack surface is perpendicular to applied tension.
- Center: Shear stress propagates crack parallel to direction of applied force.
- Right: Crack propagates perpendicular to direction of applied force.

# Flaws are Stress Concentrators!




- Griffith Crack

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

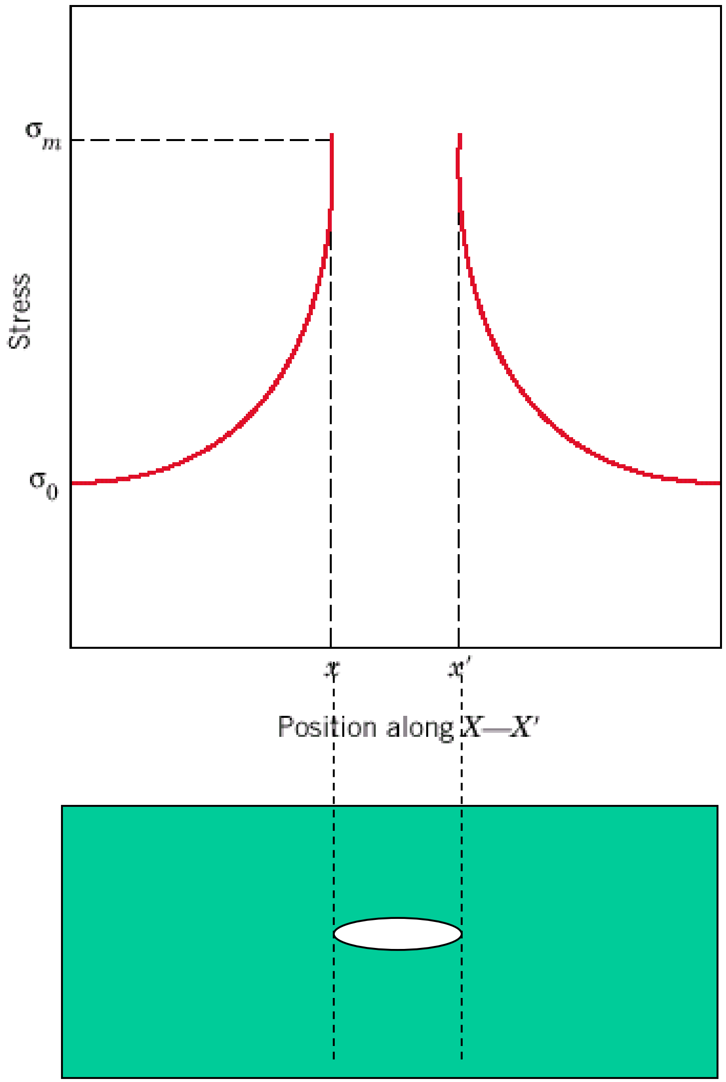
where

$\rho_t$ = radius of curvature

$\sigma_o$ = applied stress

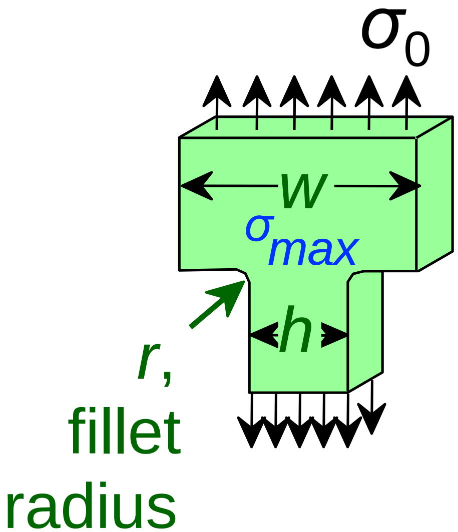
$\sigma_m$ = stress at crack tip

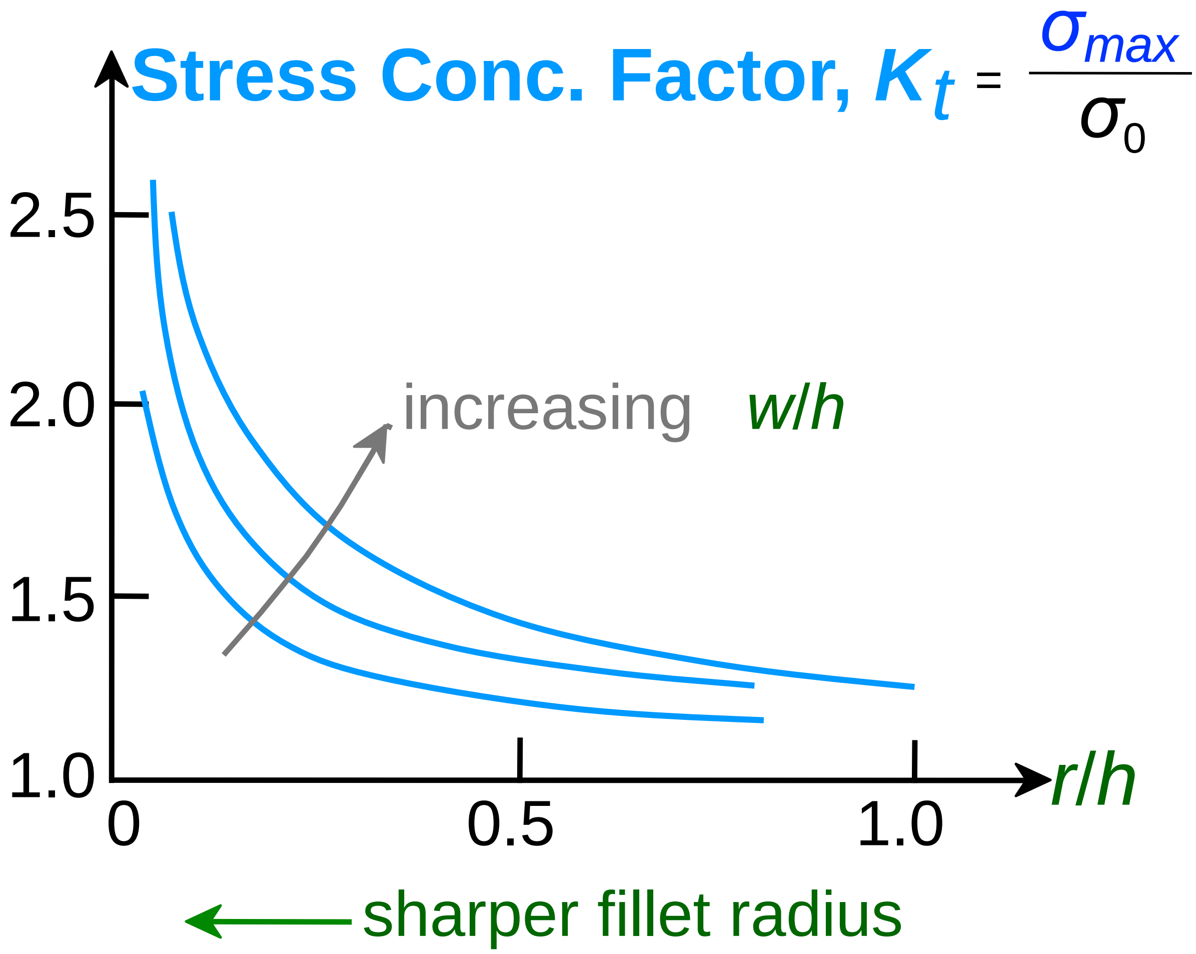
# Concentration of Stress at Crack Tip



# Engineering Fracture Design

- **Avoid sharp corners!**

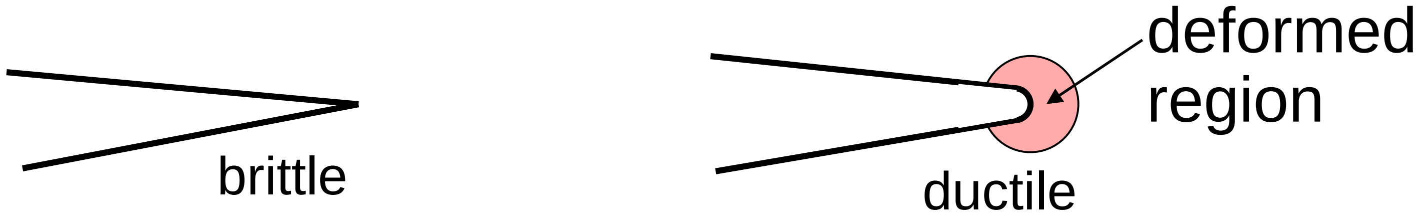


# Crack Propagation

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 ($\sigma_m$) exceeds a critical stress ($\sigma_c$)

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

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

where

- $E$ = modulus of elasticity
- $\gamma_s$ = specific surface energy, related to the creation of new surfaces (fractured surfaces)
- $a$ = one half length of internal crack

For ductile materials => replace $\gamma_s$ with $\gamma_s + \gamma_p$

where $\gamma_p$ is plastic deformation energy

# Fracture- Theory of Brittle Fracture

$$\sigma_f \sqrt{\pi a} = \sqrt{2E\gamma_s}$$

- The terms on the right-hand side of the equation are material constants.

- The Critical-stress intensity factor ($K_{Ic}$) is a material constant where Y is a geometric factor.

$$K_{IC} = Y\sigma_f \sqrt{\pi a} = Y\sqrt{2E\gamma_s}$$

For surface cracks: Y=1.1

For internal cracks: Y=1.0

# Design Against Crack Growth

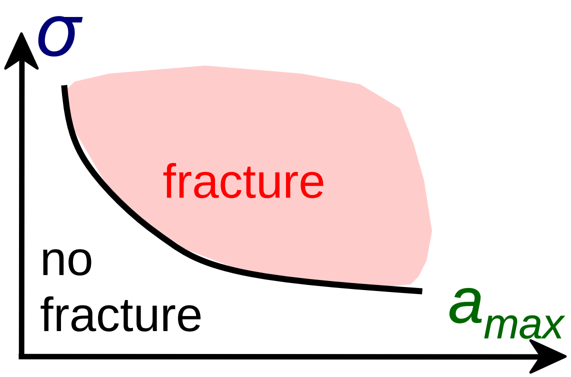
- Crack growth condition:

$$K \geq K_{IC} = Y\sigma\sqrt{\pi a} = Y\sqrt{2E\gamma_s}$$

- Largest, most highly stressed cracks grow first!

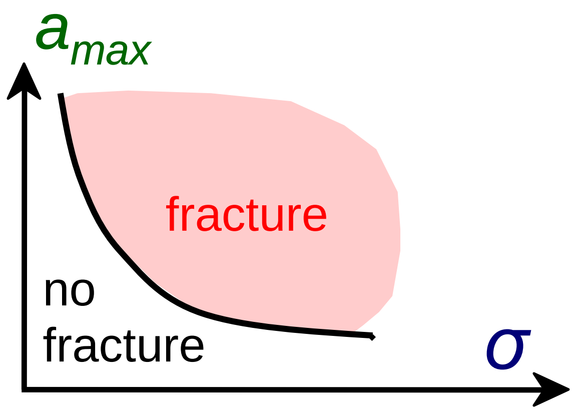
--Scenario 1: Max. flaw size dictates design stress.

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




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

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



# 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.

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

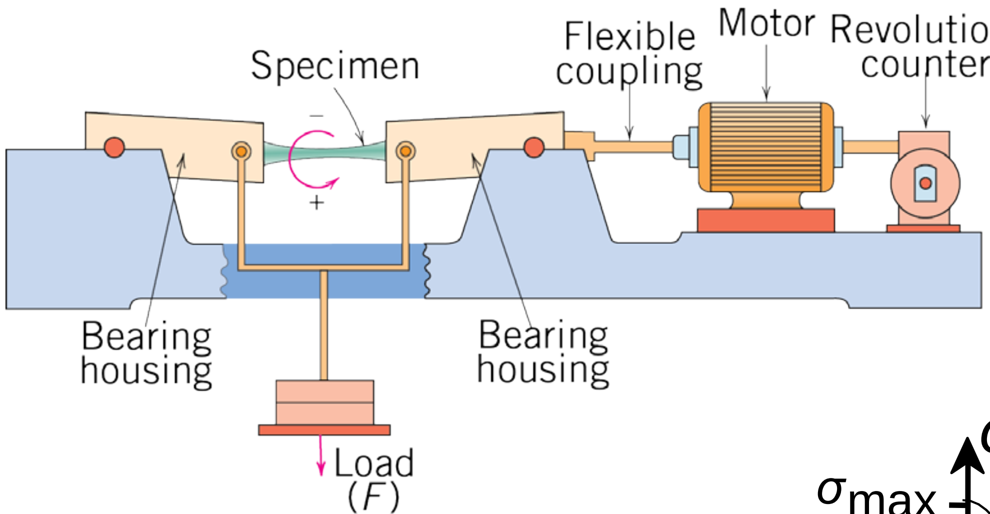
--Result:

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

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

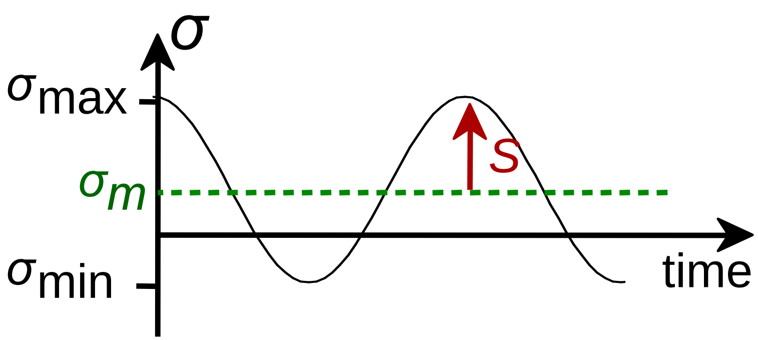
# Fatigue

- Fatigue = failure under applied cyclic stress.




Adapted from Fig. 8.18(a), *Callister & Rethwisch 9e.*

- Stress varies with time.
  -- key parameters are $S$, $\sigma_m$, and cycling frequency




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

# Fatigue Failure- Fatigue Tests of Smooth Metal and Polymer Specimens

- Fatigue Testing:
  - Multiple stress cycles are applied until failure occurs in a number of cycles ($N_f$).
  - A Fully-Reversed Stress is one in which stress goes from tension to an equal amount in compression.
    - The Mean Stress ($\sigma_m$) is zero for such a stress:

$$\sigma_m = \frac{\sigma_{\max} + \sigma_{\min}}{2}$$

    - The Stress Range ($\sigma_r$) is shown by:

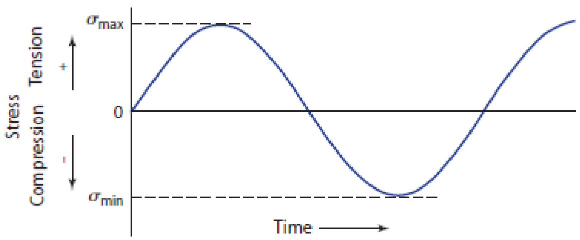
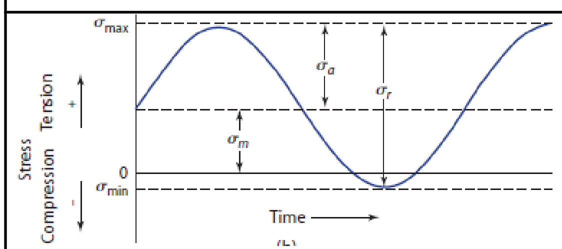
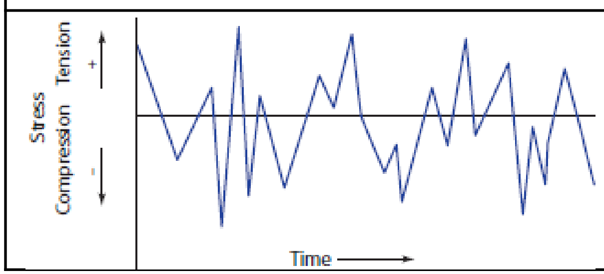
$$\sigma_r = \sigma_{\max} - \sigma_{\min}$$

# Fatigue Failure- Fatigue Tests of Smooth Metal and Polymer Specimens

- The Stress Amplitude ($\sigma_a$) is given as:

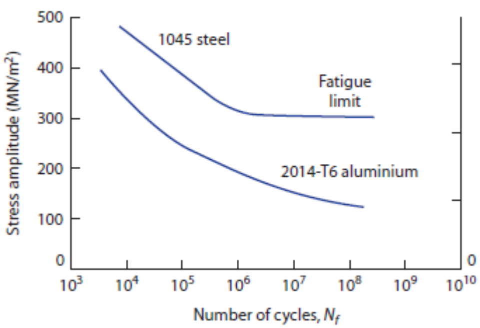
$$\sigma_a = \frac{\sigma_{\max} - \sigma_{\min}}{2} = \frac{\sigma_r}{2}$$

# Fatigue Failure- Fatigue Tests of Smooth Metal and Polymer Specimens

| Stress-Variations with Time | |
|---|---|
|  | A fully-reversed stress cycle where tensile stress is equal in magnitude to the compressive stress. |
|  | A stress cycle where magnitude of tensile stress is more than that of the compressive stress. |
|  | Random stresses are applied to a specimen. |

# Fatigue Failure- Fatigue Tests of Smooth Metal and Polymer Specimens

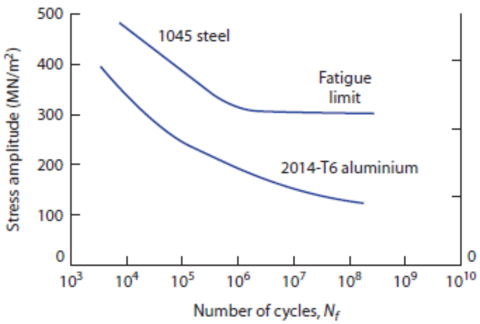
- The lifetime of a part that undergoes cyclic stresses depend on: The **Mean Stress** and the **Stress Range**.
- Fatigue Tests can be completed on **Tension-Compression, Torsion and Bending cyclic loading**.




Plot of the Average number of cycles to failure ($N_f$) vs. Stress amplitude ($\sigma_a$)

The plot on the left is called S-N plot for stress and number of cycles to failure.

- The stress cycle is a fully reversed stress cycle.




Plot of the Average number of cycles to failure ($N_f$) vs. Stress amplitude ($\sigma_a$)

As the stress amplitude increases, average number of cycles to failure decreases.

- Steep slope at high stress amplitudes.

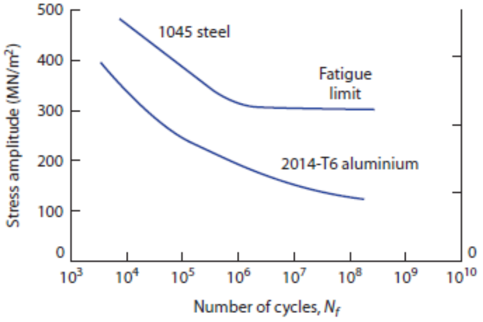
**Fatigue failure with high stress amplitude and low cycles to failure is Low Cycle Fatigue.**

At high stress amplitudes, there's both elastic and plastic deformation for each cycle.

If the stress-amplitude reduces, the average number of cycles to failure increases.

**Lower stresses lead to a large number of cycles to failure called High Cycle fatigue.**

Mainly elastic strain with a small amount of plastic strain.



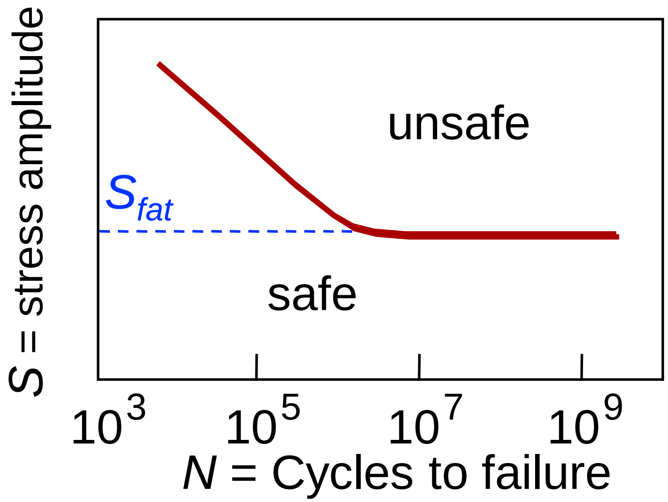

Plot of the Average number of cycles to failure ($N_f$) vs. Stress amplitude ($\sigma_a$)

**The Fatigue Endurance Limit is shown in the S-N curve when the plot becomes horizontal and approaches infinity.**

- For lower stresses, the number of cycles to failure is infinite.
- Steels with a sharp yield stress have an endurance limit.

# Types of Fatigue Behavior

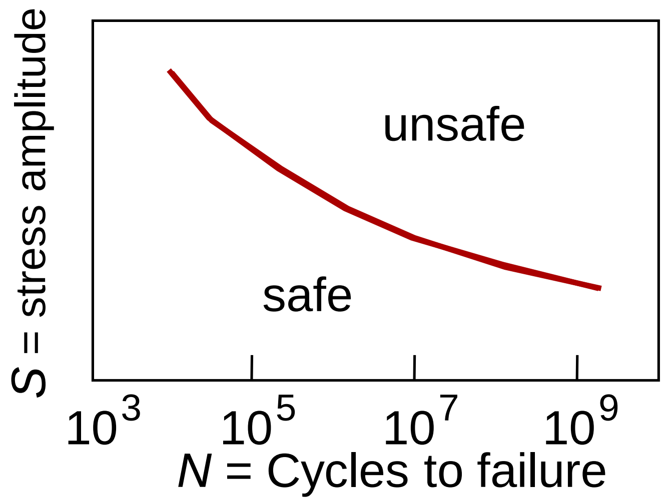
- Fatigue limit, $S_{fat}$:
  --no fatigue if $S < S_{fat}$




case for steel (typ.)

Adapted from Fig. 8.19(a), *Callister & Rethwisch 9e.*

- For some materials, there is no fatigue limit!




case for Al (typ.)

Adapted from Fig. 8.19(b), *Callister & Rethwisch 9e.*

# Rate of Fatigue Crack Growth

- Crack grows *incrementally*

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

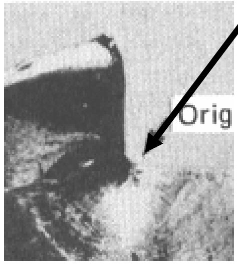
typ. 1 to 6

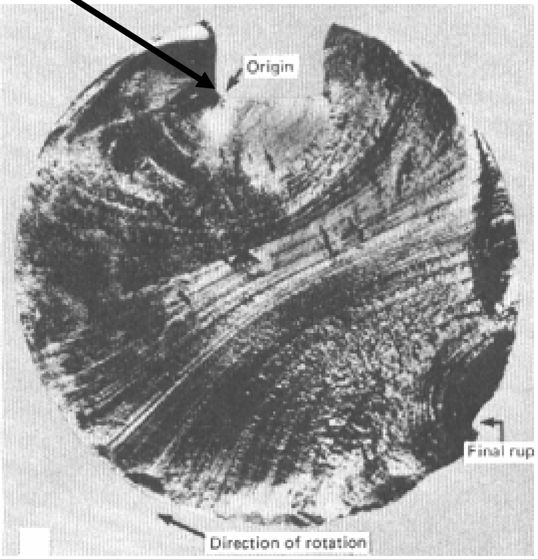
$$\sim (\Delta\sigma)\sqrt{a}$$

increase in crack length per loading cycle

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

crack origin



# Rate of Fatigue Crack Growth

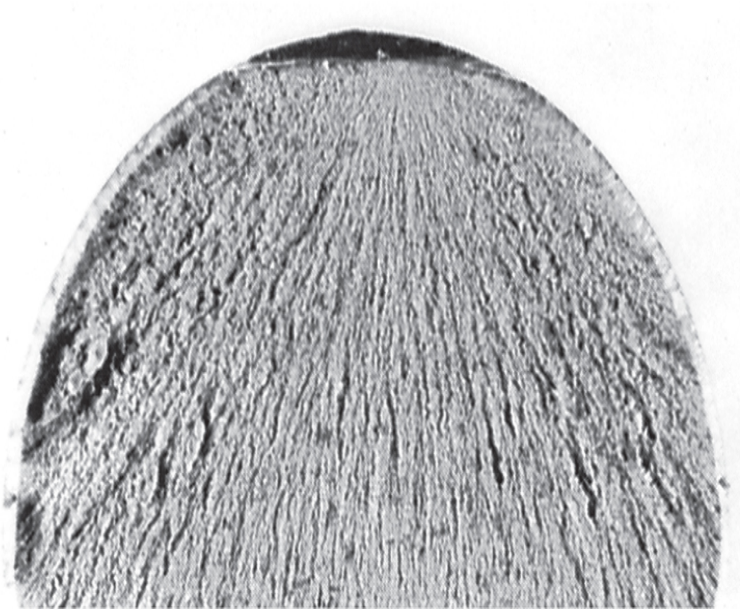
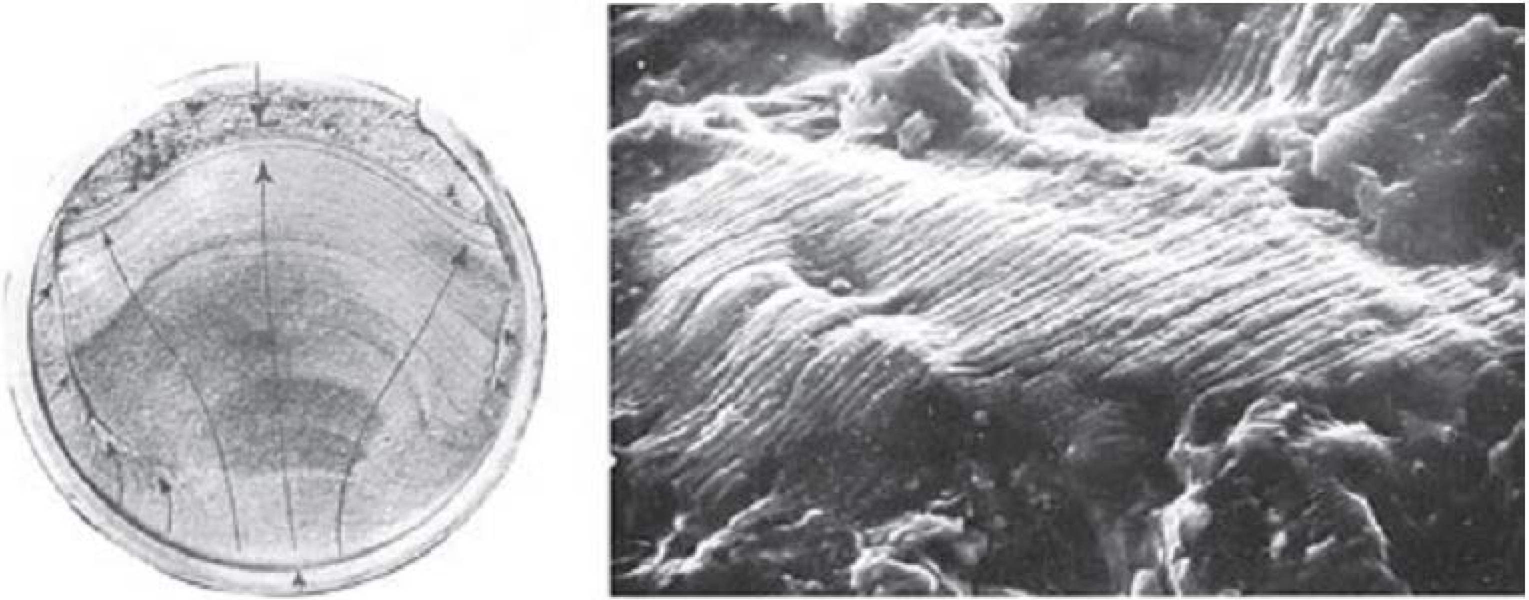


**Figure 7-9**
The Chevron pattern in a 1.25-cm-diameter quenched 4340 steel. The steel failed in a brittle manner by an impact blow. (*Reprinted courtesy of Don Askeland.*)

# Rate of Fatigue Crack Growth



(a) (b)

Figure 7-15 Fatigue fracture surface. (a) At low magnifications, the beach mark pattern indicates fatigue as the fracture mechanism. The arrows show the direction of growth of the crack front with the origin at the bottom of the photograph. (*C.C. Cottell, "Fatigue Failures, with Special Reference to Fracture Characteristics,"* Failure Analysis: The British Engine Technical Reports, *American Society of Metals, 1981, p. 318. Reprinted with permission of ASM International. All rights reserved. www.asminternational.org.*) (b) At very high magnifications, closely spaced striations formed during fatigue are observed (× 1000). (*Reprinted Courtesy of Don Askeland*)

# Rate of Fatigue Crack Growth

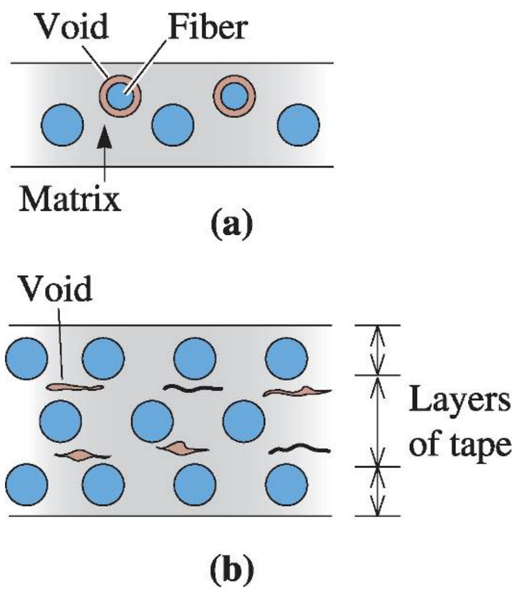
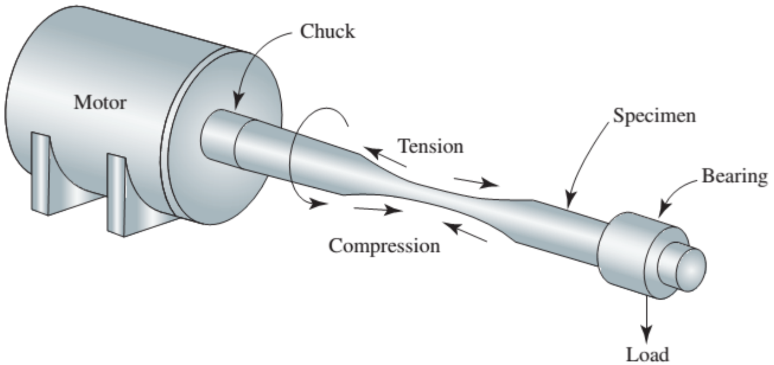



**Figure 7-12**
Fiber-reinforced composites can fail by several mechanisms. (a) Due to weak bonding between the matrix and fibers, voids can form, which then lead to fiber pull-out. (b) If the individual layers of the matrix are poorly bonded, the matrix may delaminate, creating voids.

# Fatigue Crack Growth

Lab fatigue experiment #6:

- the rotating cantilever beam fatigue test



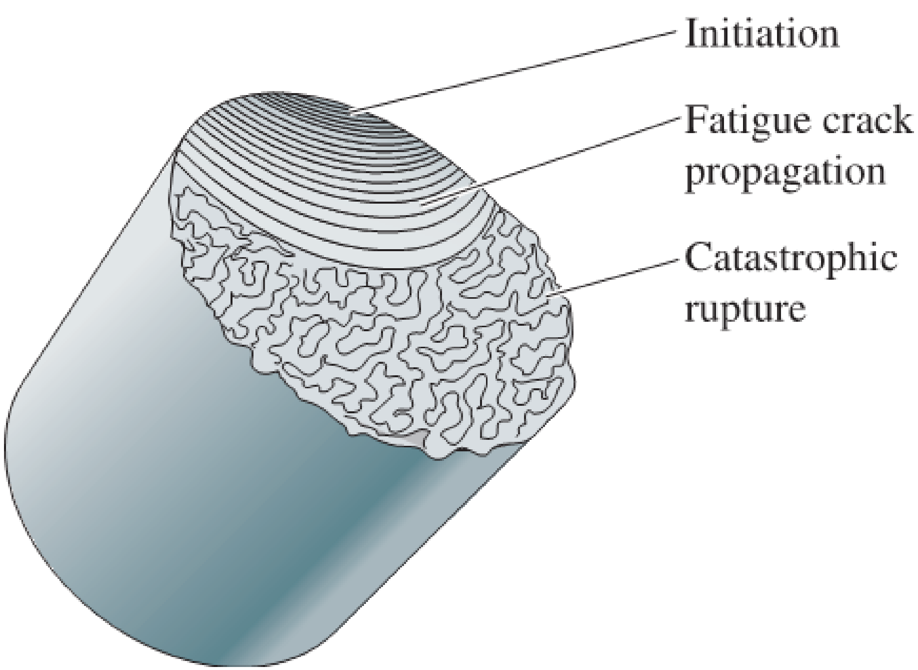
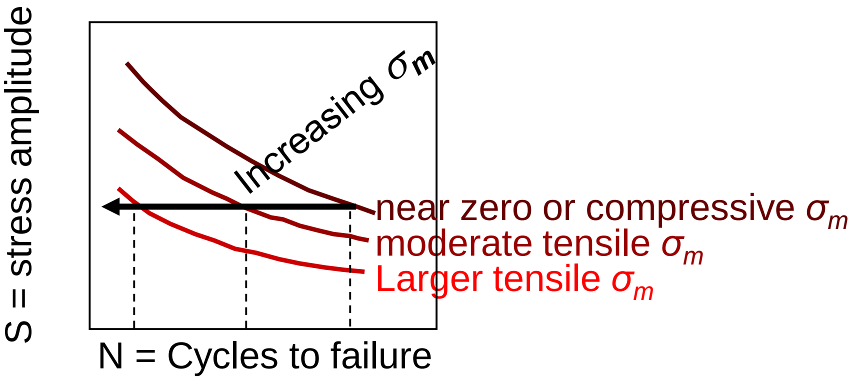




**Figure 7-16** Schematic representation of a fatigue fracture surface in a steel shaft, showing the initiation region, the propagation of the fatigue crack (with beach markings), and catastrophic rupture when the crack length exceeds a critical value at the applied stress.

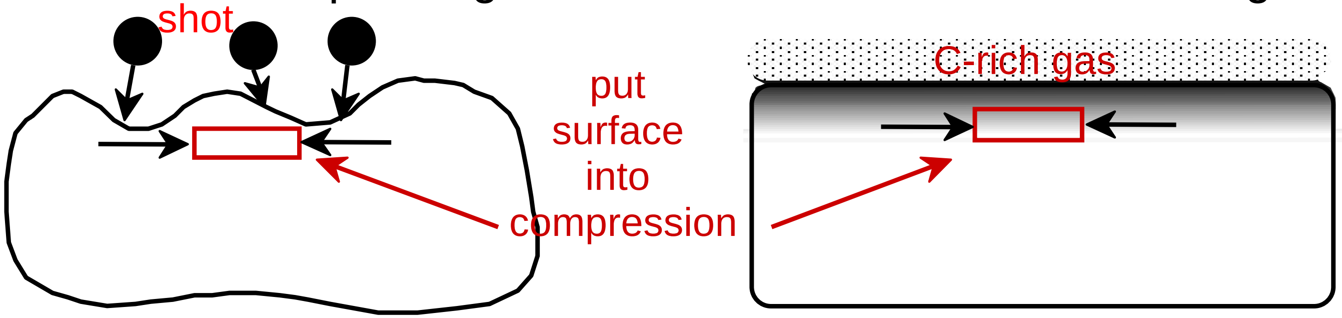
# Improving Fatigue Life

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




--Method 1: shot peening

--Method 2: carburizing




2. Remove stress concentrators.