Chapter 10: Failure

How do Materials Break?

- **Ductile vs. brittle fracture**
- **Principles of fracture mechanics**
  - ✓ Stress concentration
- **Impact fracture testing**
- **Fatigue** (cyclic stresses)
  - ✓ Cyclic stresses, the S—N curve
  - ✓ Crack initiation and propagation
  - ✓ Factors that affect fatigue behavior
- **Creep** (time dependent deformation)
  - ✓ Stress and temperature effects
  - ✓ Alloys for high-temperature use

Fundamentals of Fracture

- Simple fracture is the separation of a body into two or more pieces in response to an imposed stress that is static (i.e. constant or slowly changing with time) and at a temperature that are low relative to the melting temperature of the material

- Fracture can also occur from fatigue and creep

- Fracture involve 2 steps
  - Crack formation
  - Propagation – in respond to an imposed stress

- Mode of failure is highly depend on the mechanism of crack propagation

- 2 types of fracture
  - Ductile fracture
  - Brittle fracture

Fracture mechanisms

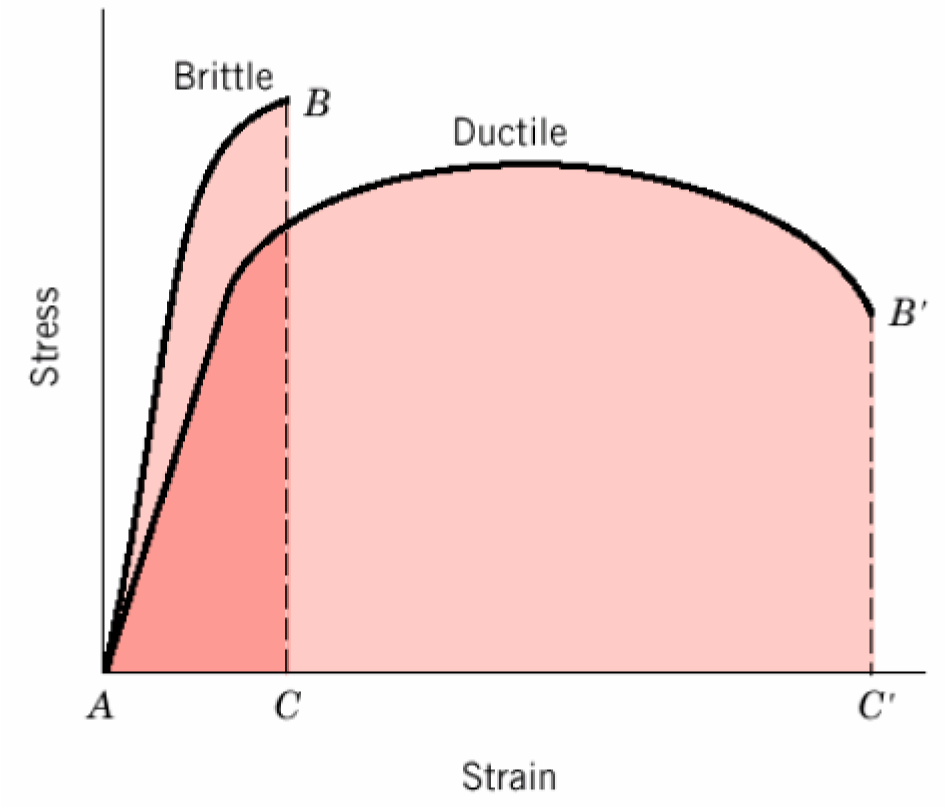
- Ductile fracture
  - Accompanied by significant plastic deformation

    (in the vicinity of an advancing crack.)
  - The process proceed slowly as the crack length extended (stable crack).
  - e.g., metal alloys

- Brittle fracture
  - Little or no plastic deformation
  - Crack spread extremely rapidly (unstable crack).
  - Once crack started it will continue spontaneously with an increase in magnitude of the applied stress.
  - Catastrophic
  - E.g. ceramics

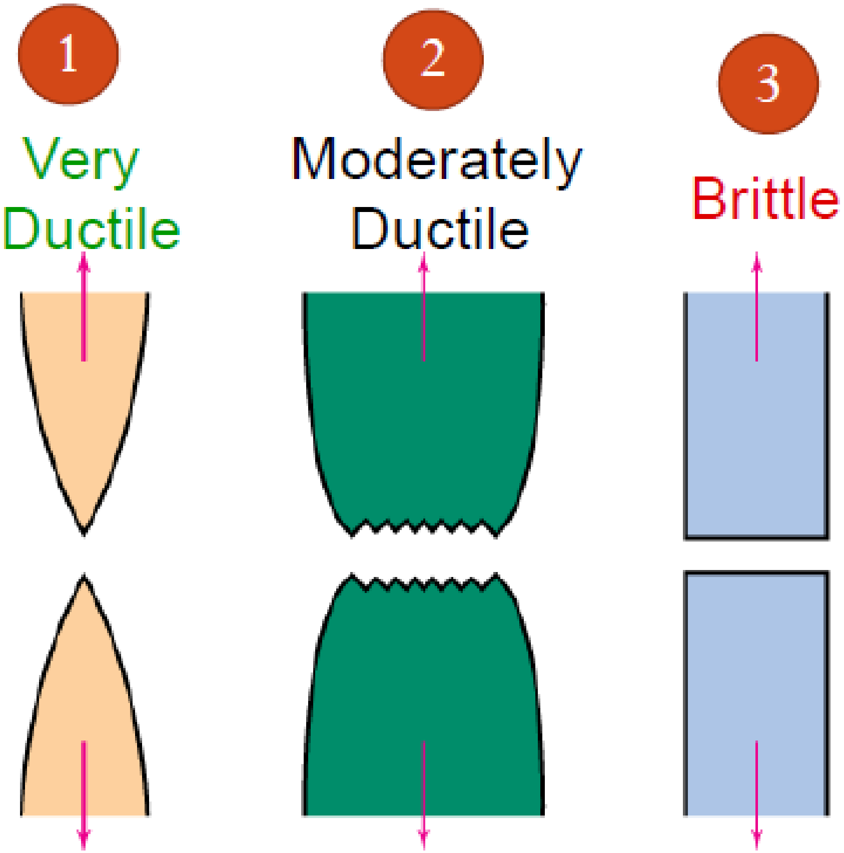
Brittle vs. Ductile Fracture

- **Ductile materials** - extensive plastic deformation and energy absorption ("toughness") before fracture
- **Brittle materials** - little plastic deformation and low energy absorption before fracture



Ductile vs Brittle Failure

- Classification:



	①	②	③
Fracture behavior:	Very Ductile	Moderately Ductile	Brittle
%*AR* or %*EL*	Large	Moderate	Small

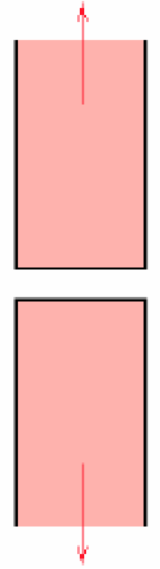
Adapted from Fig. 8.1, *Callister & Rethwisch 8e.*

- Ductile fracture is usually more desirable than brittle fracture!

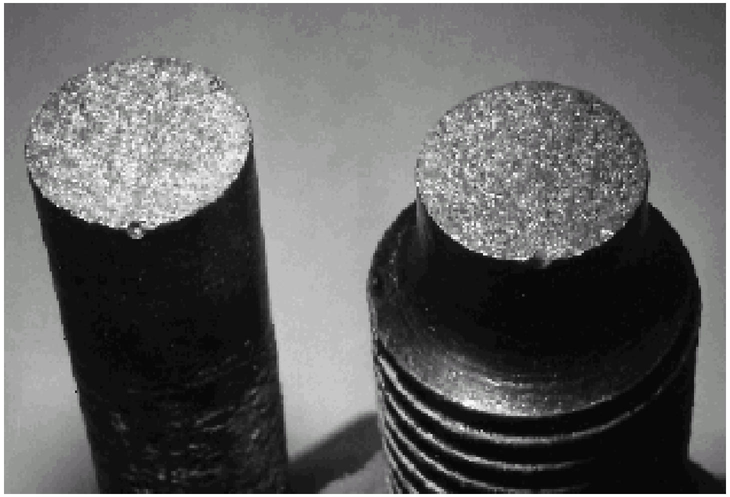
Ductile: Warning before fracture

Brittle: No warning

Brittle Fracture (Limited Dislocation Mobility)



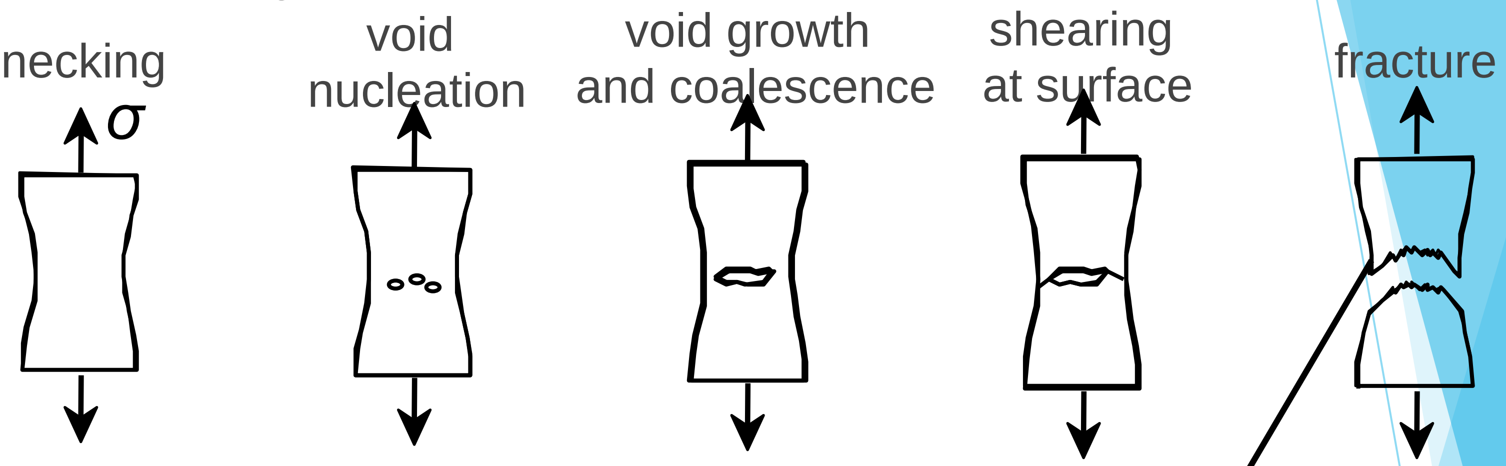
- No appreciable plastic deformation
- Crack propagation is very fast
- Crack propagates nearly perpendicular to the direction of the applied stress
- Crack often propagates by cleavage - breaking of atomic bonds along specific crystallographic planes (cleavage planes).



Brittle fracture in a mild steel

Moderately Ductile Failure

- Failure Stages:



necking σ

void nucleation

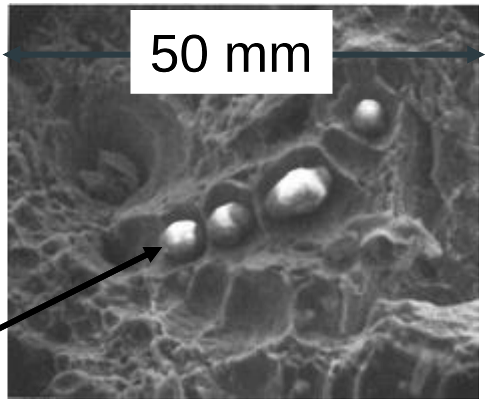
void growth and coalescence

shearing at surface

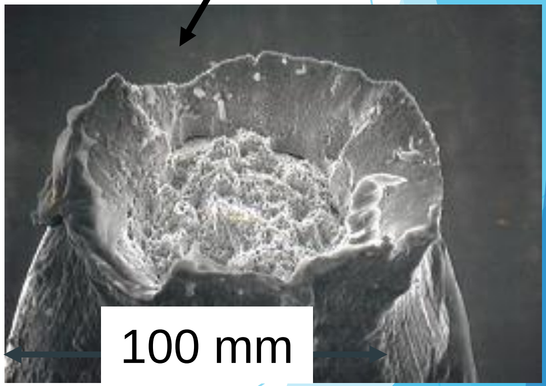
fracture

- 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.

Moderately Ductile vs. Brittle Failure

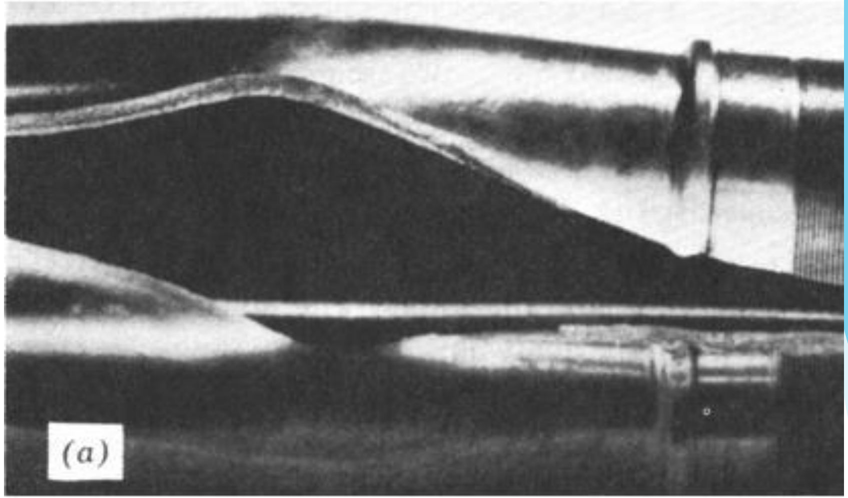
cup-and-cone fracture

brittle fracture

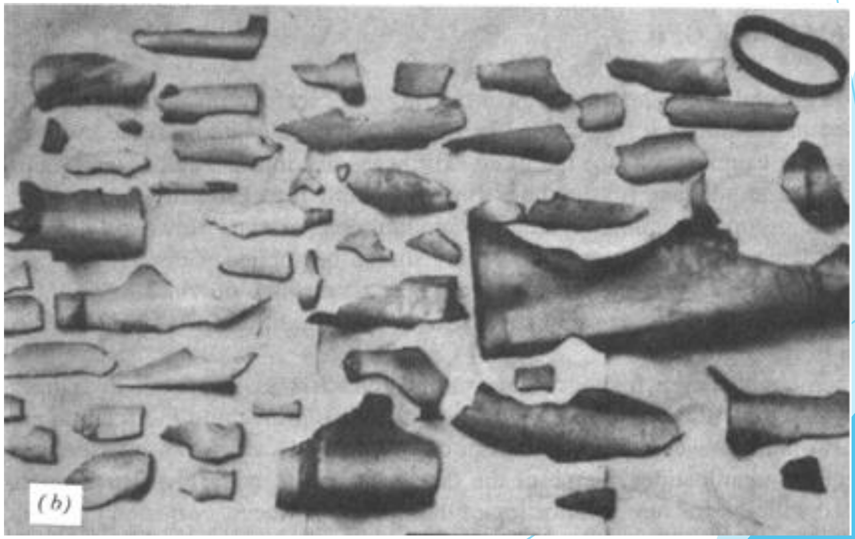
Fig. 10.3, *Callister & Rethwisch 9e.*

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.

Brittle Failure

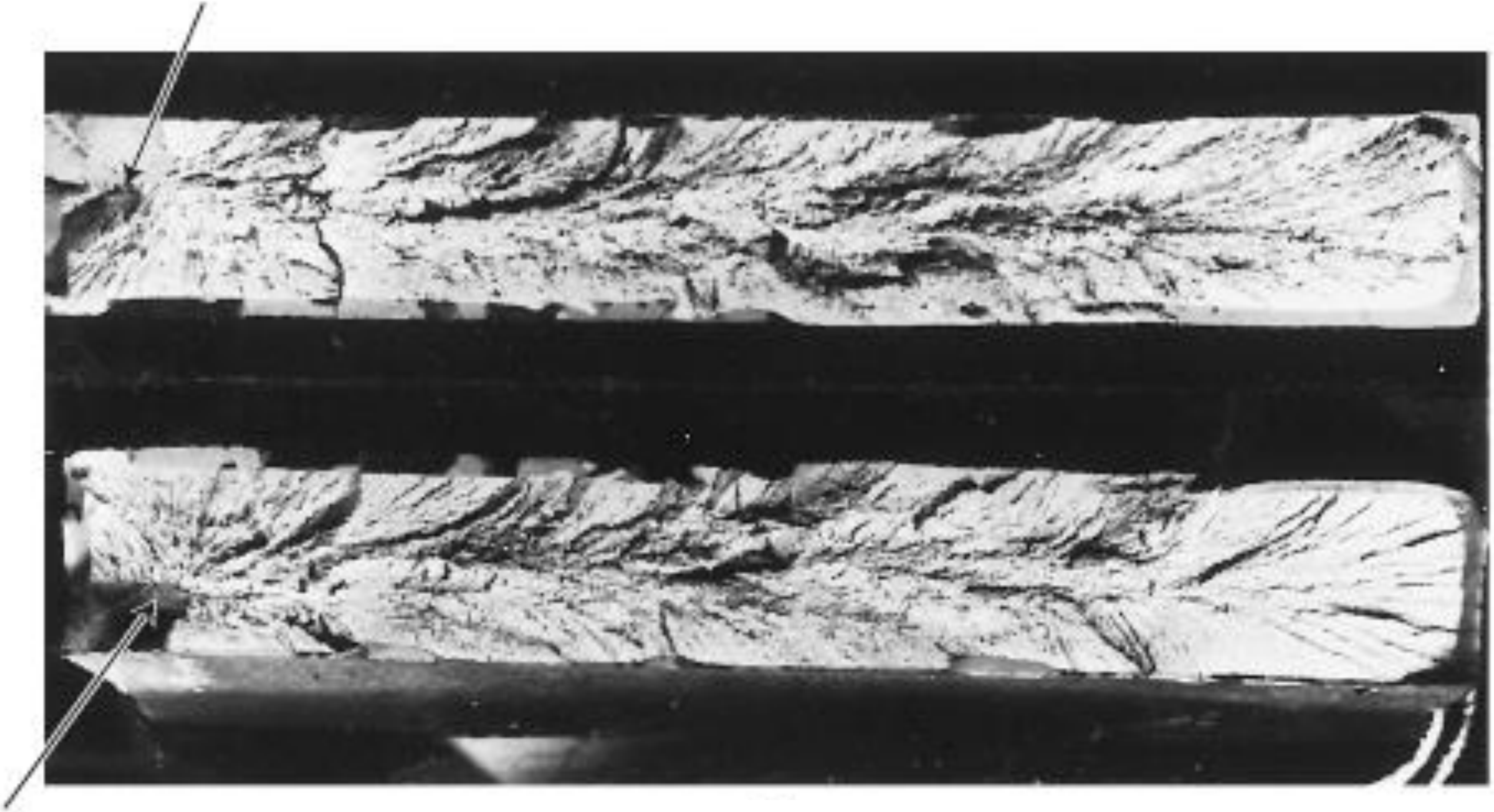
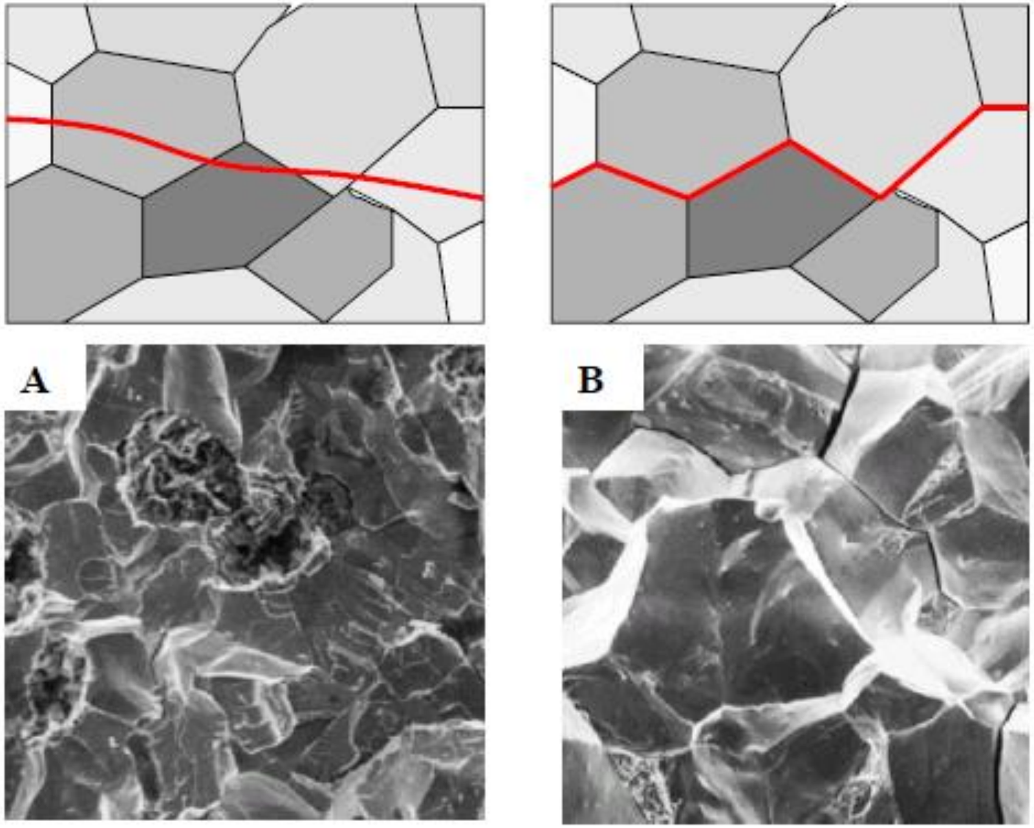


Fig. 10.5(a), *Callister & Rethwisch 9e.* [From R. W. Hertzberg, *Deformation and Fracture Mechanics of Engineering Materials*, 3rd edition. Copyright © 1989 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc. Photograph courtesy of Roger Slutter, Lehigh University.]

Brittle Fracture

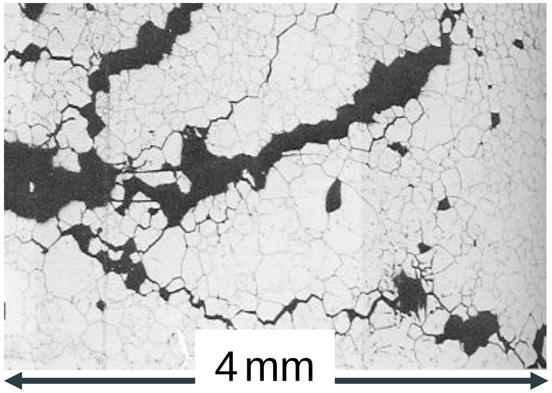
A. Transgranular fracture: Fracture cracks pass through grains. Fracture surface have faceted texture because of different orientation of cleavage planes in grains.

B. Intergranular fracture: Fracture crack propagation is along grain boundaries (grain boundaries are weakened or embrittled by impurities segregation etc.)



Brittle Fracture Surfaces

- Intergranular (between grains)



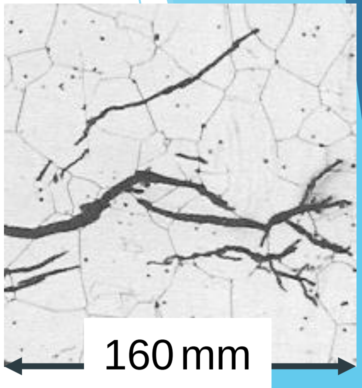
304 S. Steel (metal)

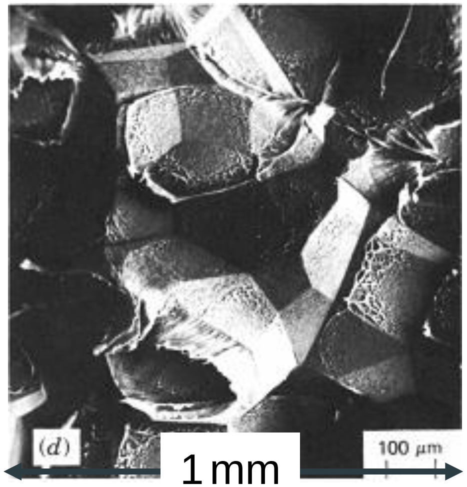
Reprinted w/permission from "Metals Handbook", 9th ed, Fig. 633, p. 650. Copyright 1985, ASM International, Materials Park, OH. (Micrograph by J.R. Keiser and A.R. Olsen, Oak Ridge National Lab.)

- 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.)





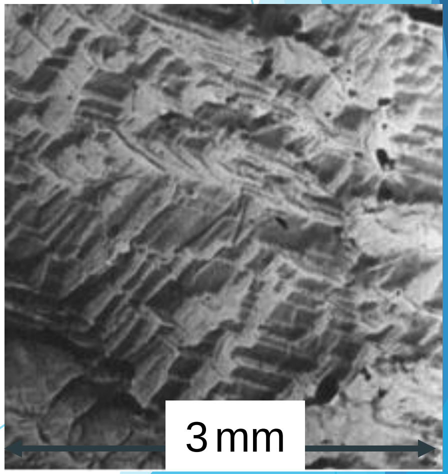
Polypropylene (polymer)

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.)



Flaws are Stress

Schematic of surface and internal crack

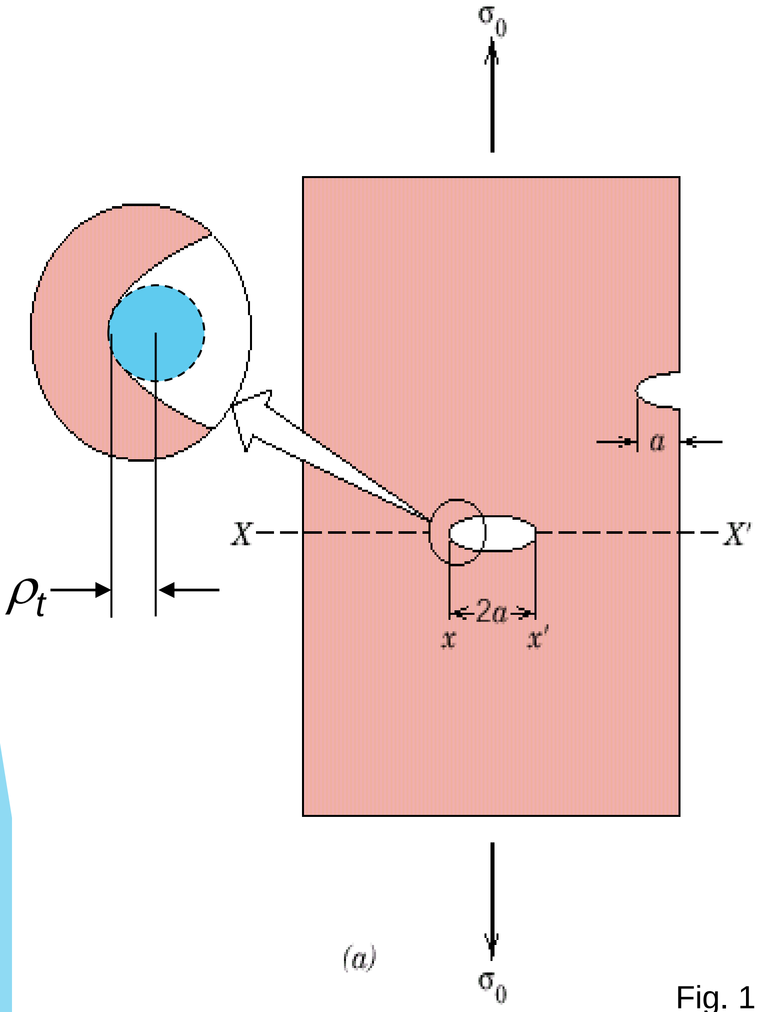


Fig. 10.8(a), *Callister & Rethwisch 9e.*

- 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

Stress Concentration

Fracture strength of a brittle solid is related to the cohesive forces between atoms. One can estimate that the theoretical cohesive strength of a brittle material should be ~ E/10. But experimental fracture strength is normally E/100 - E/10,000.

This much lower fracture strength is explained by the effect of **stress concentration** at microscopic flaws. The applied stress is amplified at the tips of micro-cracks, voids, notches, surface scratches, corners, etc. that are called **stress raisers.** The magnitude of this amplification depends on micro-crack orientations, geometry and dimensions.

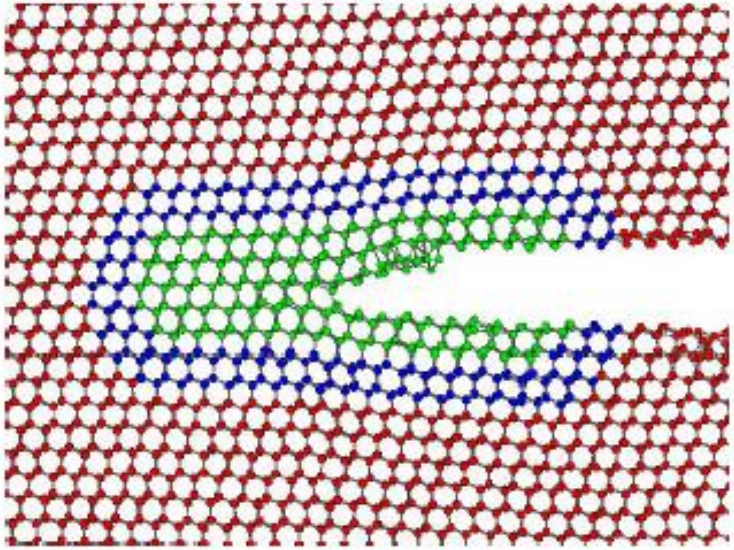
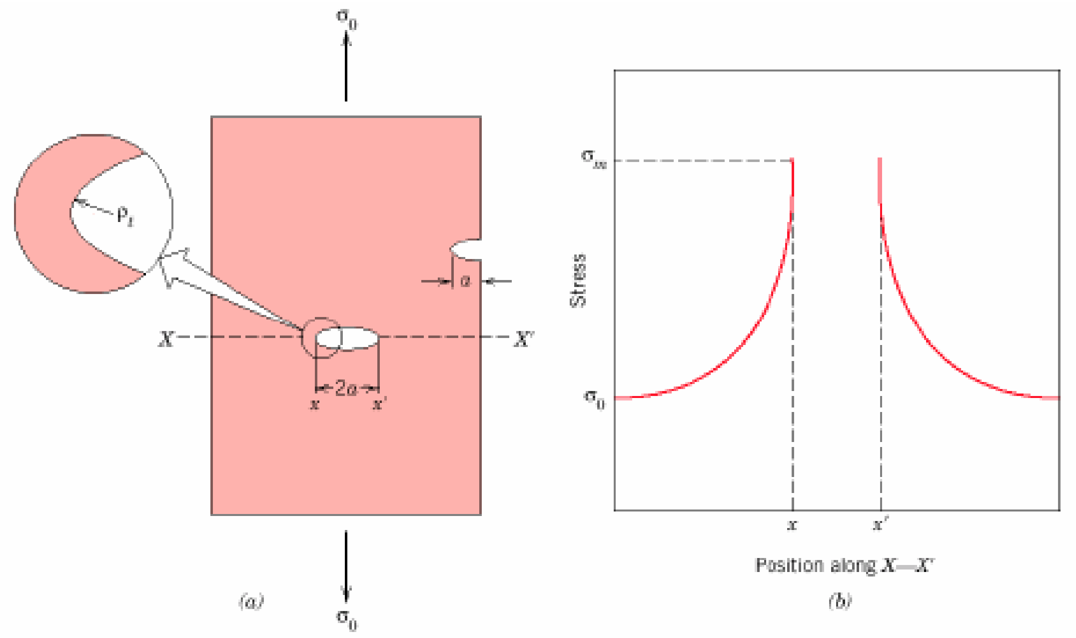


Figure by
N. Bernstein &
D. Hess, NRL

Stress Concentration



For a long crack oriented perpendicular to the applied stress the maximum stress near the crack tip is:

$$\sigma_m \approx 2\sigma_0 \left(\frac{a}{\rho_t}\right)^{1/2}$$

where $\boldsymbol{\sigma_0}$ is the applied external stress, **a** is the half-length of the crack, and $\boldsymbol{\rho_t}$ the radius of curvature of the crack tip. (note that **a** is half-length of the internal flaw, but the full length for a surface flaw).

The **stress concentration factor** is: $K_t = \frac{\sigma_m}{\sigma_0} \approx 2\left(\frac{a}{\rho_t}\right)^{1/2}$

Fracture Toughness

K_{IC} is used for estimation critical stress applied to a specimen with a given crack length:

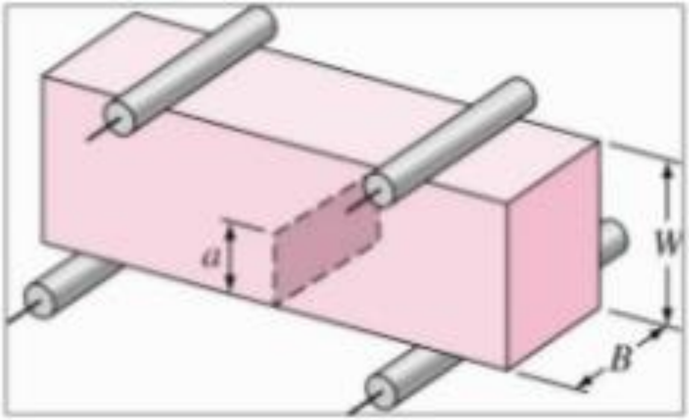
$$K_{1c} = Y\sigma_c\sqrt{\pi a}$$

K_{IC} – stress-intensity factor, measured in MPa*m½;
σ_C– the critical stress applied to the specimen;
a – the crack length for edge crack or half crack length for internal crack;
Y – geometry factor.

Toughness of ceramics

Example

A reaction-bonded silicon nitride has a strength of 300 MPa and a fracture toughness of 3.6 MPa.m$^{1/2}$, What is the largest-size internal crack that this material can support without fracturing? Given Y = 1



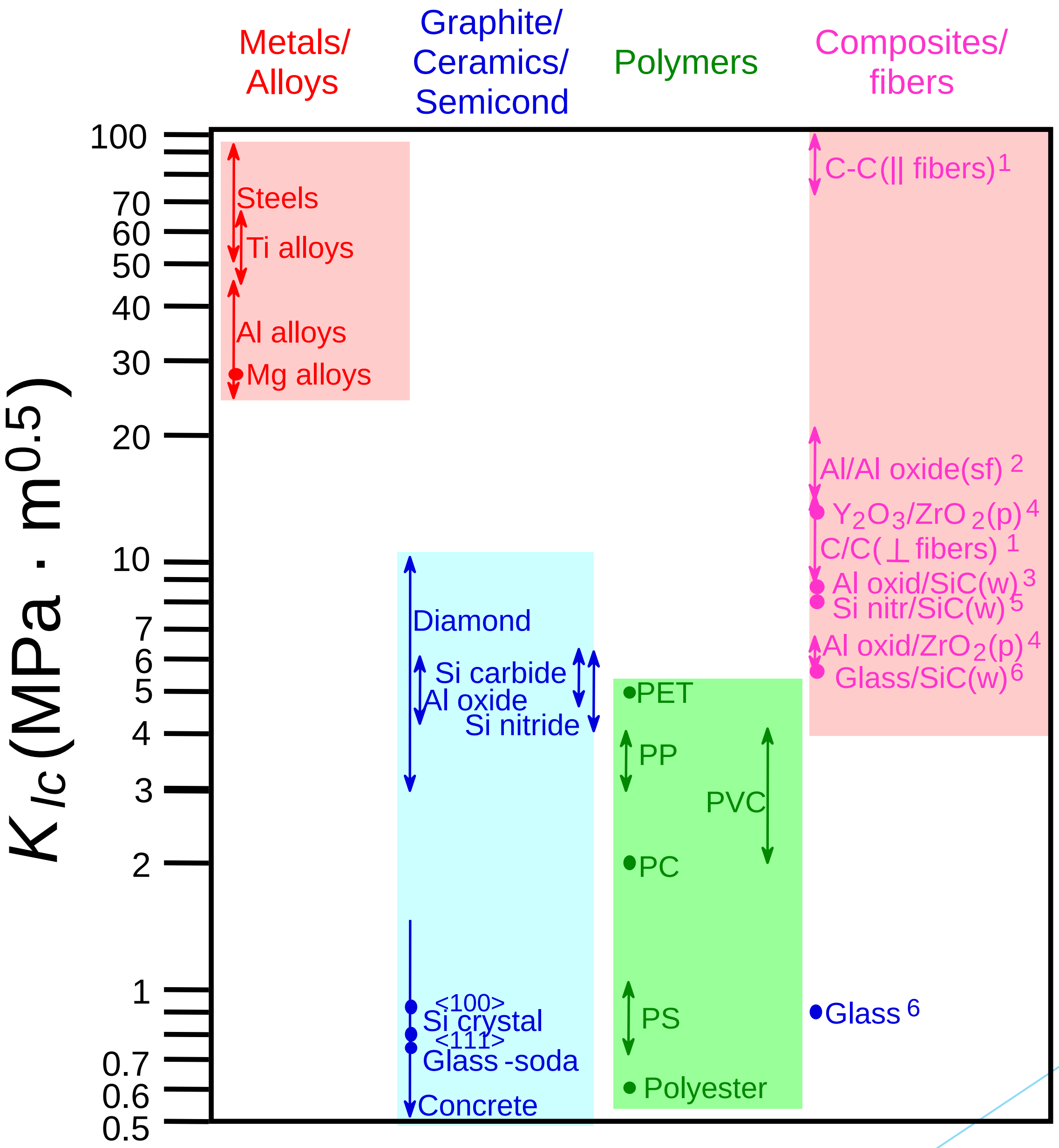
$$K_{IC} = Y\sigma_f\sqrt{\pi a}$$

$$a = \frac{K_{IC}^2}{\pi\sigma_f^2} = \frac{\left(3.6MPa.\sqrt{m}\right)^2}{\pi(300MPa)^2}$$

$$a = 4.58\times10^{-5}\,m = 45.8\,\mu m$$

Therefore the largest internal crack $2a = 91.6\ \mu m$

Fracture Toughness Ranges



Based on data in Table B.5,
Callister & Rethwisch 9e.

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.

Impact Testing

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

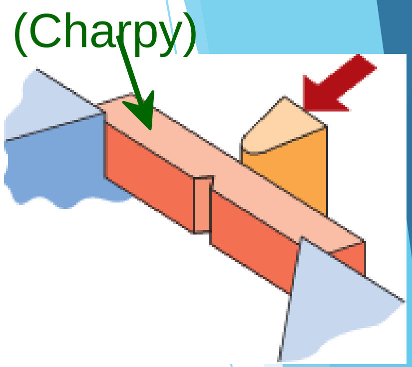
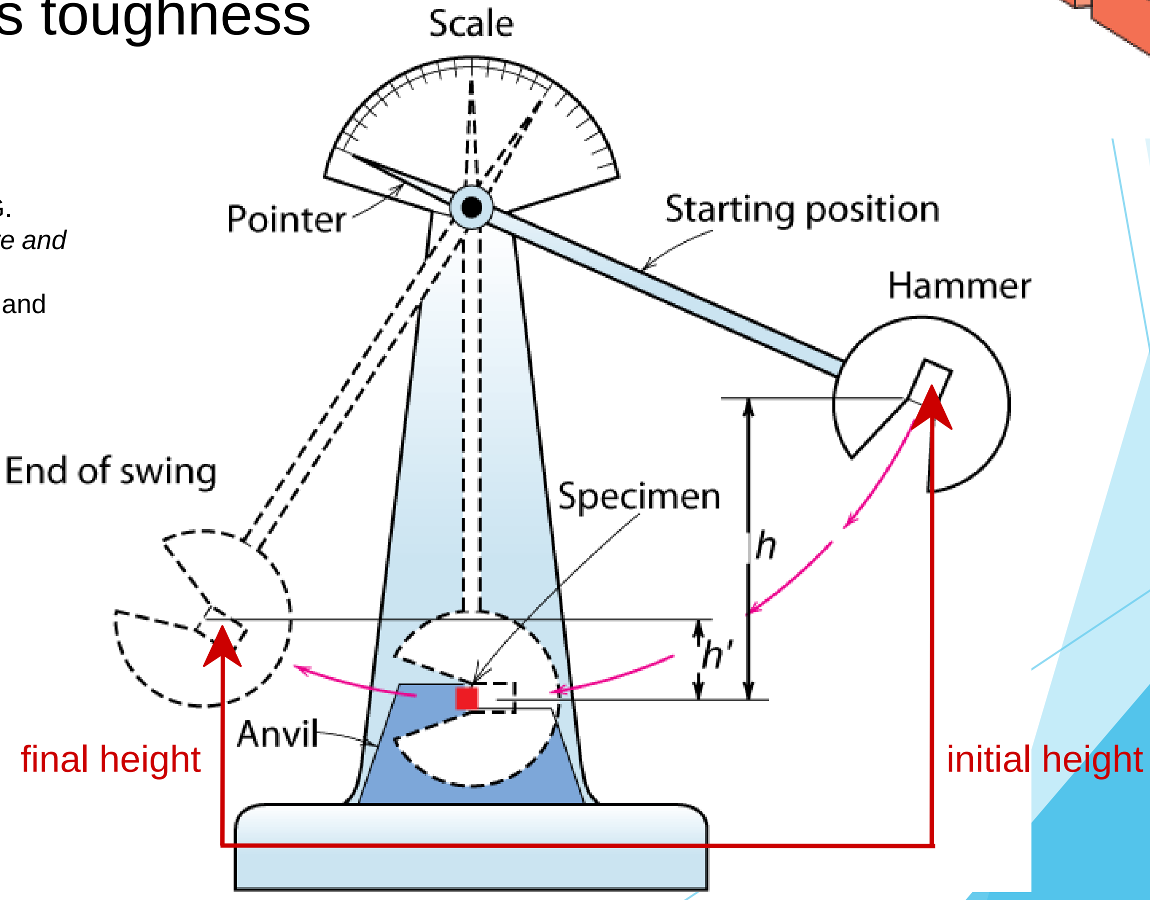


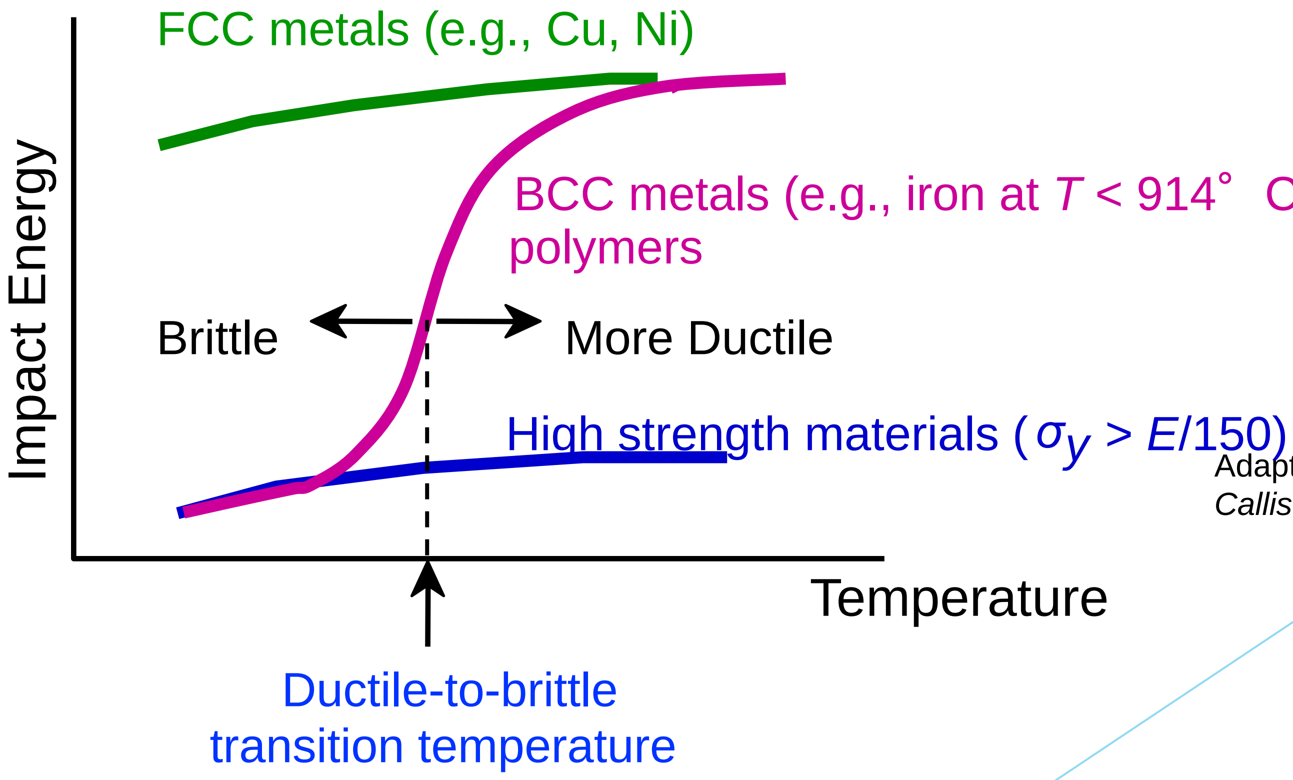
Fig. 10.12(b), *Callister & Rethwisch 9e.*
(Adapted from H.W. Hayden, W.G. Moffatt, and J. Wulff, *The Structure and Properties of Materials*, Vol. III, *Mechanical Behavior*, John Wiley and Sons, Inc. (1965) p. 13.)



Influence of Temperature on Impact Energy

Charpy tests - determine whether a material experiences a **ductile-to-brittle transition** with decreasing temperature and, if so, the range of temperatures over which it occurs.

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



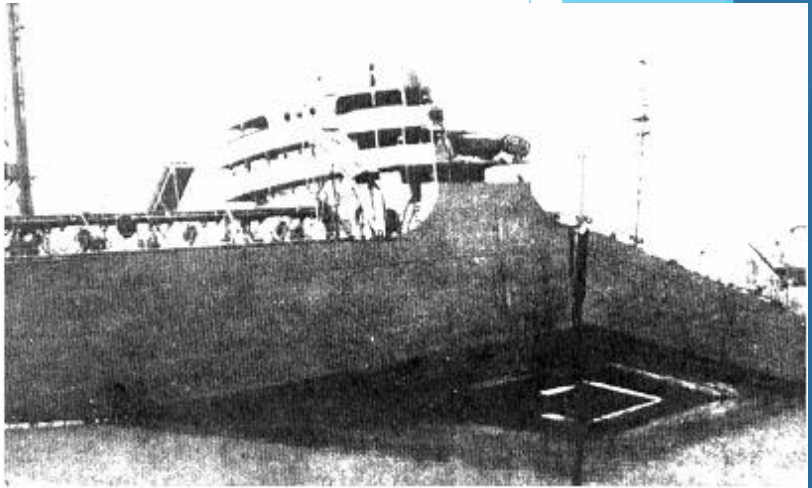
Adapted from Fig. 10.15, *Callister & Rethwisch 9e.*

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**



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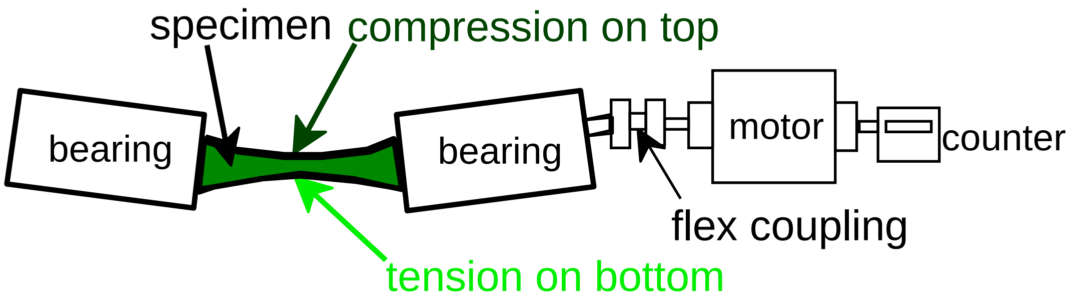
- Problem: Steels were used having DBTT's just below room temperature.

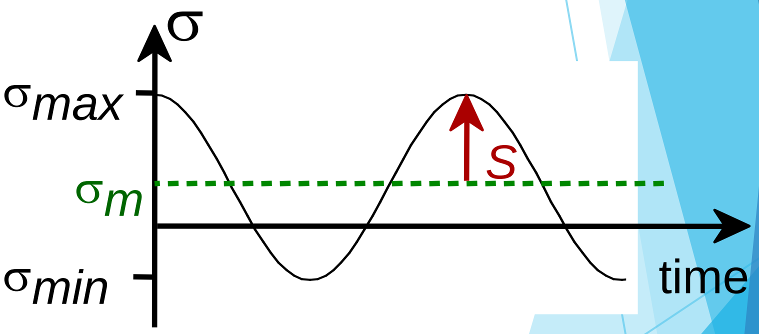
Fatigue

- **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.)

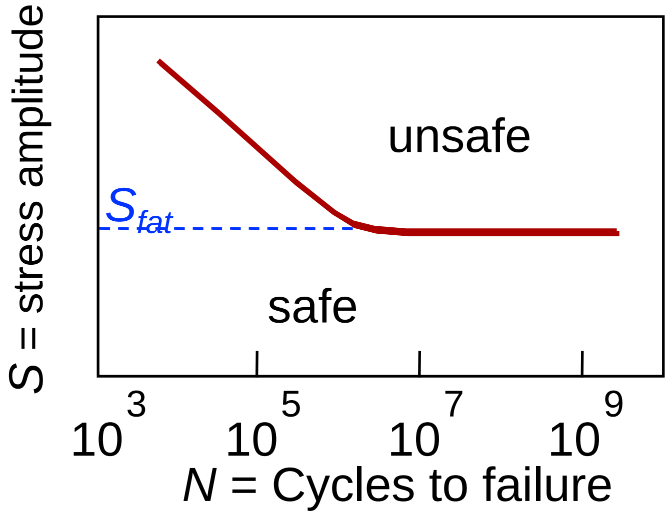
- Stress varies with time.
  -- key parameters are *S(stress amplitude)*, σ_m *(mean stress)*, and cycling frequency



- Key points: Fatigue...
  --can cause part failure, even though $\sigma_{max} < \sigma_y$ *(yield strength)*.
  --responsible for ~ 90% of mechanical engineering failures.
  --Catastrophic and insidious, occurring very suddenly and without warning.

Types of Fatigue Behavior

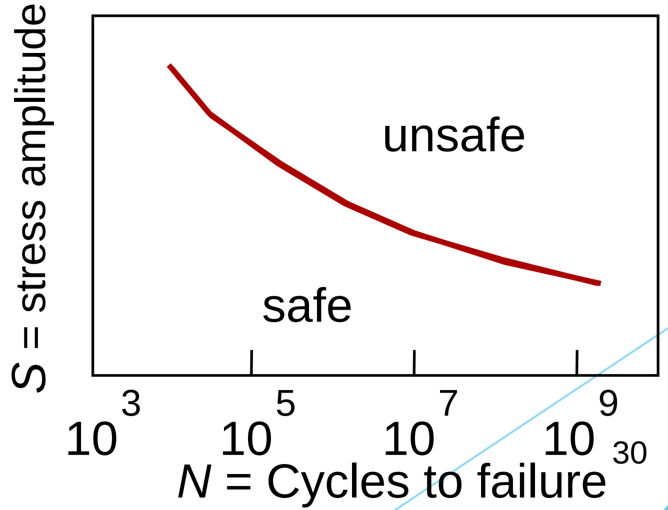
- Fatigue limit, S_{fat}:
  --no fatigue if $S < S_{fat}$



case for
steel (typ.)

Adapted from Fig. 10.19(a), *Callister & Rethwisch 9e.*

- For some materials, there is no fatigue limit!



case for
Al (typ.)

Adapted from Fig. 10.19(b), *Callister & Rethwisch 9e.*

Cyclic stresses (Fatigue)

mean stress σ_m

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

The *range of stress* σ_r is the difference between $\sigma_{\max}$ and $\sigma_{\min}$, namely,

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

Stress amplitude σ_a is one-half of this range of stress, or

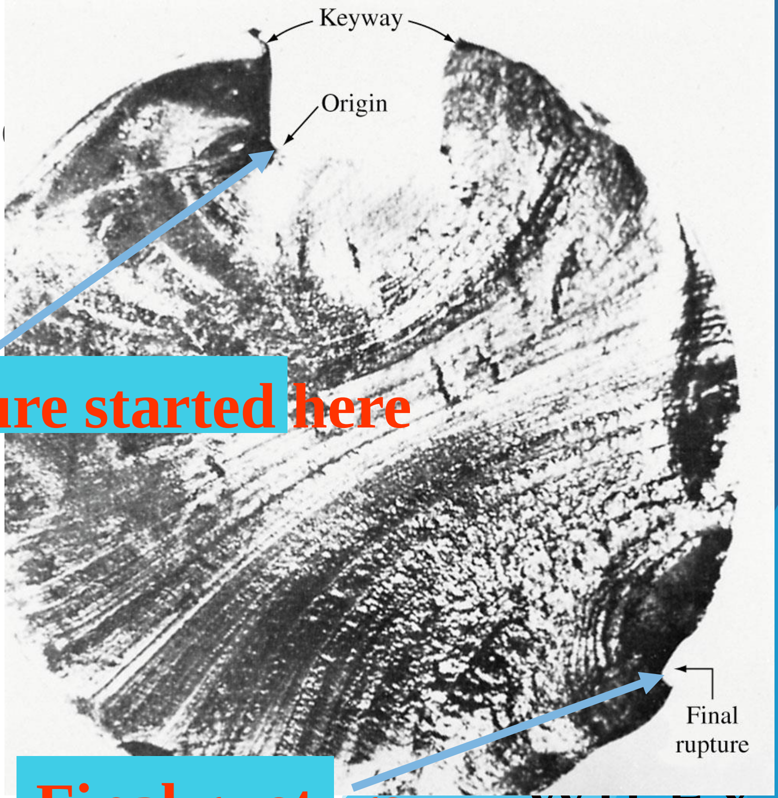
$$\sigma_a = \frac{\sigma_r}{2} = \frac{\sigma_{\max} - \sigma_{\min}}{2}$$

Finally, the *stress ratio* R is the ratio of minimum and maximum stress amplitudes:

$$R = \frac{\sigma_{\min}}{\sigma_{\max}}$$

Fatigue of Metals

- Metals often fail at much lower stress at cyclic loading compared to static loading.
- Crack nucleates at region of stress con and propagates due to cyclic loading.
- Failure occurs when cross sectional area of the metal too small to withstand applied load.



Fracture started here

Final rupture

Fatigue fractured surface of keyed shaft

Fatigue Crack Growth

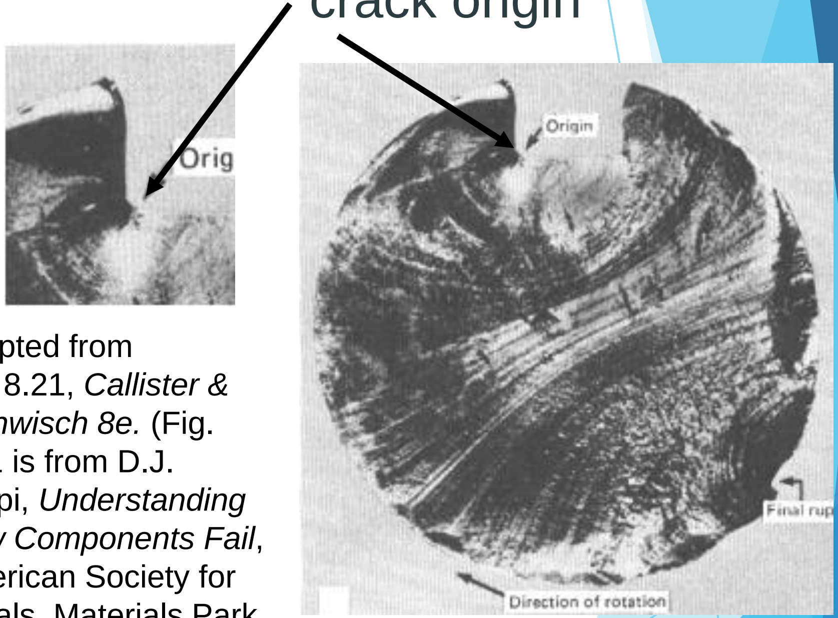
Fatigue failure process

i) Crack initiation

ii) Crack propagation

iii) Final failure

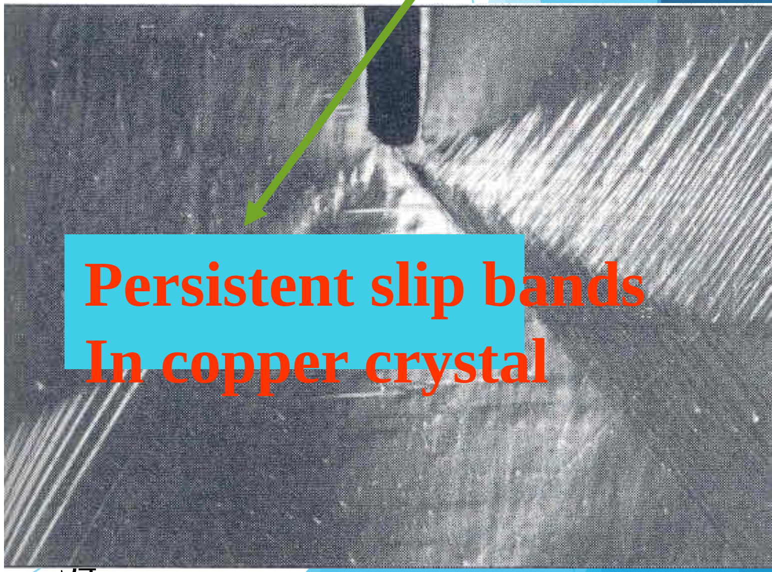
crack origin



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.)

Structural Changes in Fatigue Process

- Crack initiation first occurs.
- Reversed directions of crack initiation caused surface ridges and groves called *slipband* extrusion and intrusion.
- This is stage I and is very slow (10^{-10} m/cycle).
- Crack growth changes direction to be perpendicular to maximum tensile stress (rate microns/sec).
- Sample ruptures by ductile failure when remaining cross-sectional area is small to withstand the stress.



Persistent slip bands In copper crystal

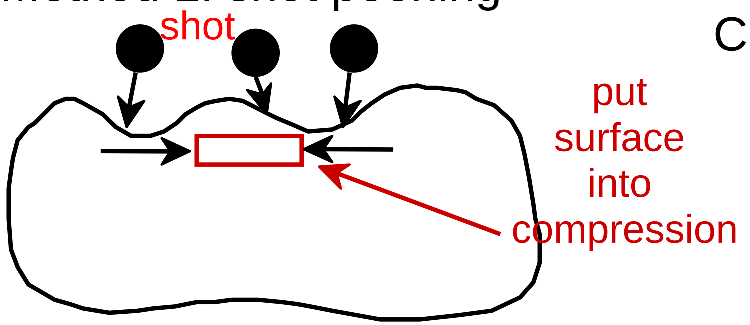
Factors Affecting Fatigue Strength

- Stress concentration: Fatigue strength is reduced by stress concentration.
- Surface roughness: Smoother surface increases the fatigue strength.
- Surface condition: Surface treatments like carburizing and nitriding increases fatigue life.
- Environment: Chemically reactive environment, which might result in corrosion, decreases fatigue life.

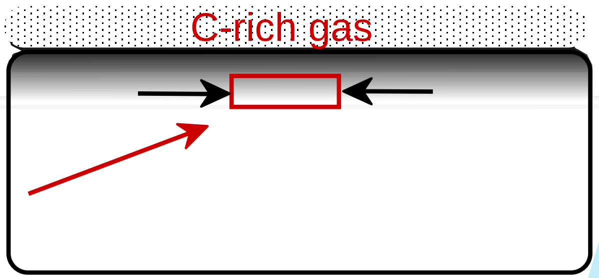
Improving Fatigue Life

1. Surface treatment – polishing ,impose compressive surface stresses (to suppress surface cracks from growing)

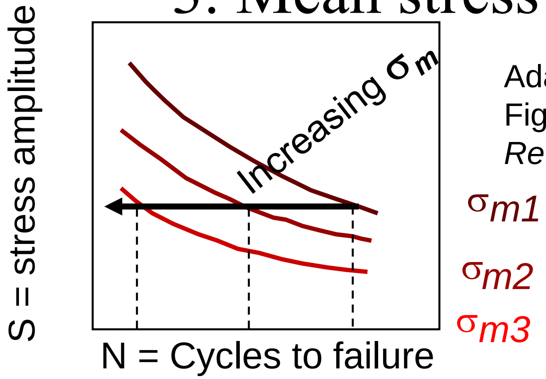
--Method 1: shot peening



Case hardening: carburizing at elevated temp

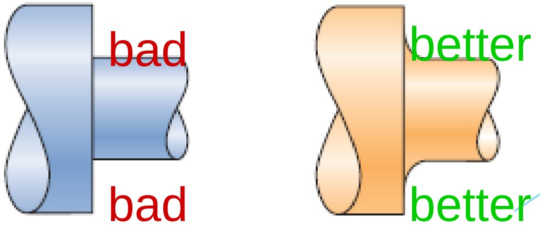


3. Mean stress -



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

2. Design factors- avoid notch or geometrical discontinuity, remove stress concentrators, eliminates sharp corners. large radii



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

Mean stress

- The dependence of fatigue life on stress amplitude is represented on the *S–N* plot.
- Such data are taken for a constant mean stress σ_m, often for the reversed cycle situation ($\sigma_m = 0$).
- Mean stress, however, also affects fatigue life; this influence may be represented by a series
- of *S–N* curves, each measured at a different σ_m
- increasing the mean stress level leads to a decrease in fatigue life.

Shot peening

- Residual compressive stresses are commonly introduced into ductile metals mechanically by localized plastic deformation within the outer surface region.
- Small, hard particles (shot) having dia within 0.1 -1.0 mm are projected at high velocities onto the surface to be treated.
- The resulting deformation induces compressive stresses to a depth of between one-quarter and one-half of the shot diameter.

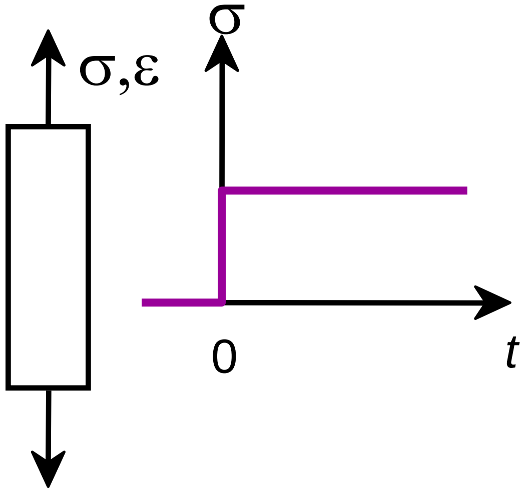
Case hardening

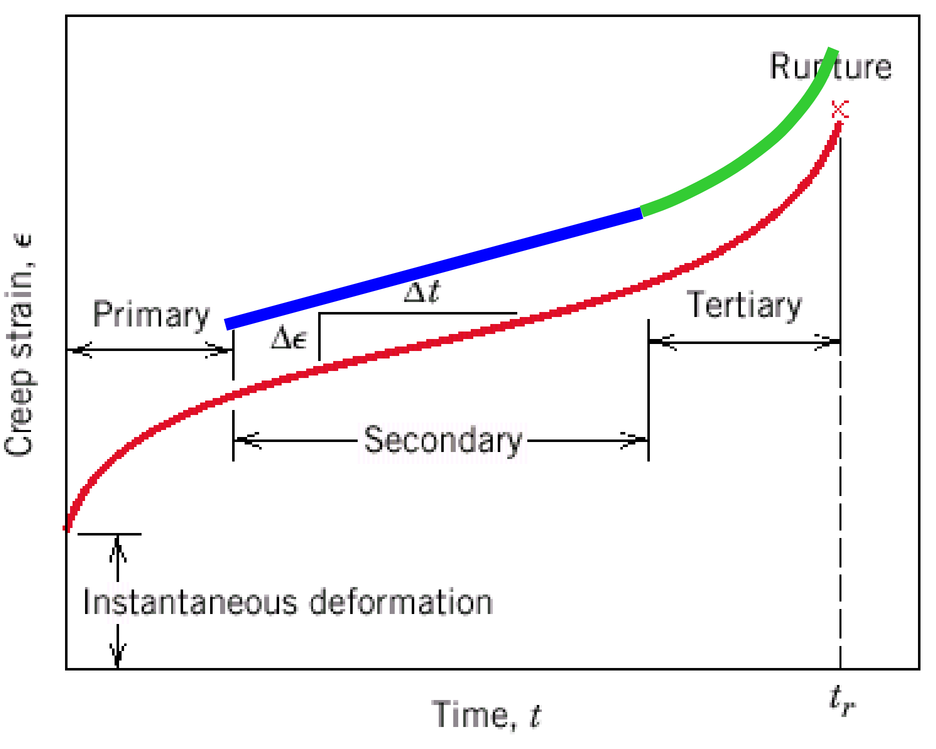
- Case hardening is a technique →both surface hardness and fatigue life are enhanced for steel alloys.
- accomplished by a carburizing or nitriding process by
- component is exposed to a carbonaceous / nitrogenous atmosphere at elevated temperature.

Creep

- Time dependent permanent deformation of materials when subjected to constant load or stress

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





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

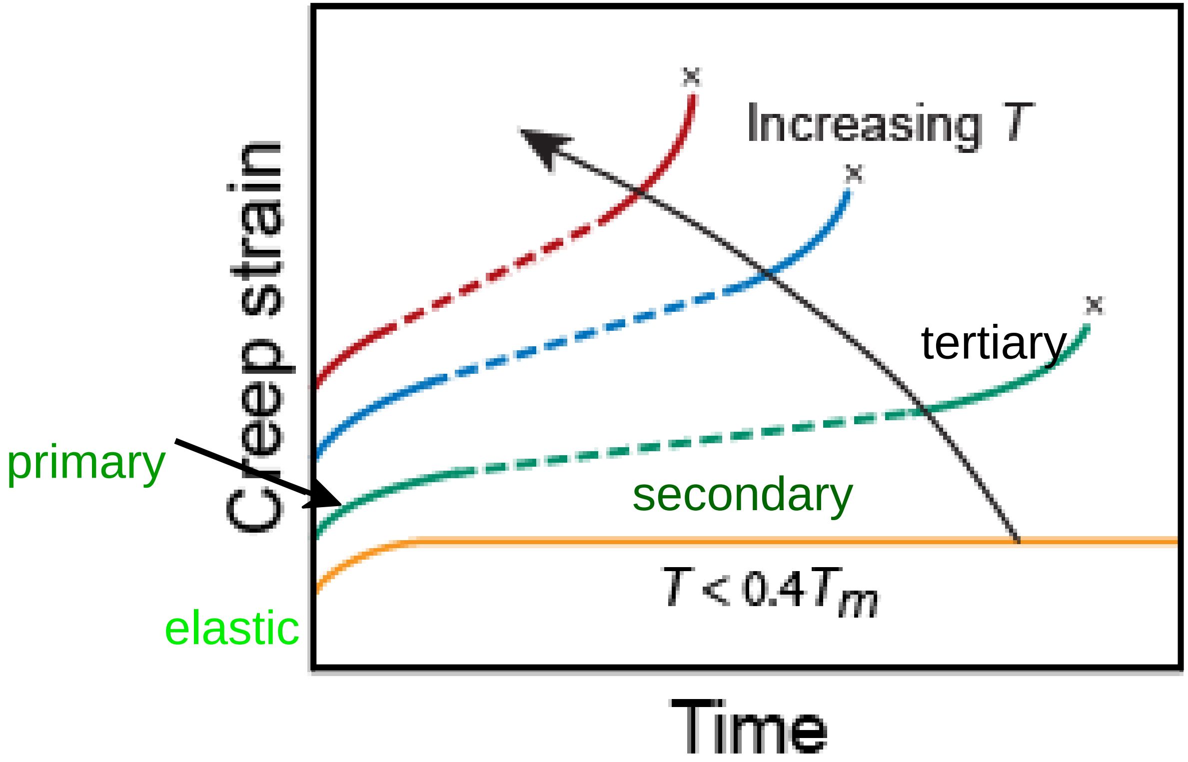
Secondary Creep: steady-state i.e., constant slope ($\Delta\varepsilon/\Delta t$).

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

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

Creep: Stress &Temperature Effects

- Occurs at elevated temperature, $T > 0.4\ T_m$ *or increasing stress*



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

1) Instantaneous strain increase
2) Steady state creep increase
3) Rapture lifetime is diminished

- Both T & level of applied stress influence creep characteristics
- At $T < 0.4T_m$, and after the initial deformation, the strain is virtually independent of time.
- With either increasing stress/temperature:
  - Instantaneous strain at the time of stress application increases
  - Steady-state creep rate increases
  - Rupture lifetime decreases.

Fatigue vs Creep

fatigue	Creep
component is subjected to cyclic loading	component experiences deformation with time as t is put into use.
crack propagation over time	permanent deformation over time.
Yield stress and ultimate stress of material are drastically reduced during fatigue.	Both T & level of applied stress influence creep characteristics
characterized by elongation of the crack	characterized by looking at the elongation of the sample.
Example It is difficult to break a wire by stretching but if we apply a cyclic load and bend unbend the wire a number of times it breaks easily	example to illustrate this is that electrical cables are taught(tight) when they are installed but after some time they experience sagging due to self weight

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.

ANNOUNCEMENTS

Reading:

Core Problems:

Self-help Problems: