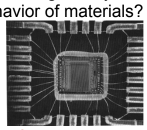
Chapter 8: Mechanical Failure

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.*

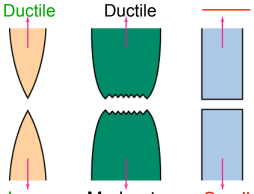
Fracture mechanisms

- Ductile fracture
  - Accompanied by significant _________ deformation
- Brittle fracture
  - Little or no ____________________
  - ____________

Ductile vs Brittle Failure

- Classification:

Fracture behavior: Ductile | Ductile | ______



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

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

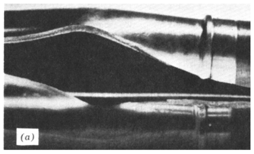
- Ductile fracture is usually more desirable than brittle fracture!

Ductile: Warning before fracture

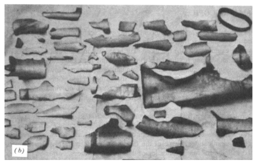
Brittle: No warning

Example: Pipe Failures

- __________ failure:
  -- one piece
  -- large deformation



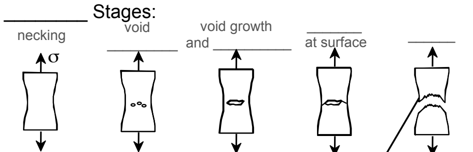
- __________ failure:
  -- many pieces
  -- small deformations



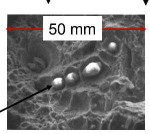
Figures from V.J. Colangelo and F.A. Heiser, *Analysis of Metallurgical Failures* (2nd ed.), Fig. 4.1(a) and (b), p. 66 John Wiley and Sons, Inc., 1987. Used with permission.

Moderately Ductile Failure

- ________ Stages:

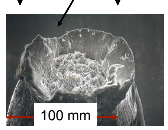


- Resulting ______ surfaces (steel)



______ 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

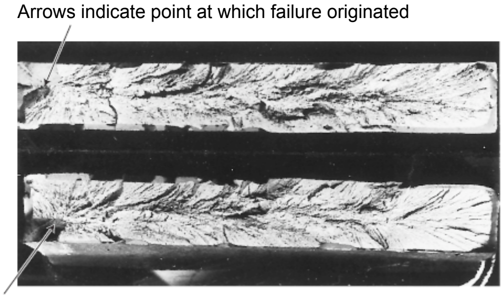
cup-and-cone fracture

brittle fracture

Adapted from Fig. 8.3, *Callister & Rethwisch 8e.*

Brittle Failure

Arrows indicate point at which failure originated

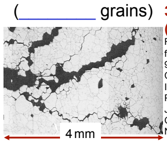


Adapted from Fig. 8.5(a), *Callister & Rethwisch 8e.*

Brittle Fracture Surfaces

- Intergranular (________ grains)

304 S. Steel (_______)

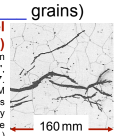


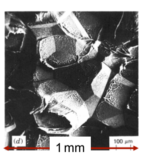
Reprinted w/permission from "Metals Handbook", 9th ed, Fig. 633, p. 650. Copyright 1985, ASM International, Materials Park, OH. (Micrograph by J.R. Keiser and A.R. Olsen, Oak Ridge National Lab.)

- Transgranular (______ grains)

316 S. Steel (_______)

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.)





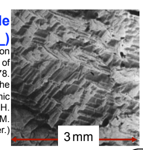
Polypropylene (__________)

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.)

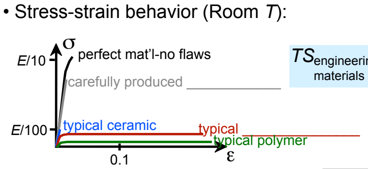
Al Oxide (________)

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.)



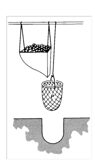
Ideal vs Real Materials

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



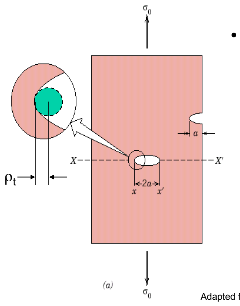
$TS_{\text{engineering materials}} << TS_{\text{perfect materials}}$

- 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!

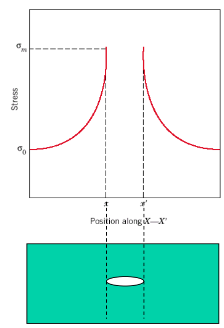


- Griffith Crack

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.*

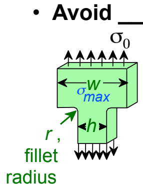
Concentration of Stress at Crack Tip



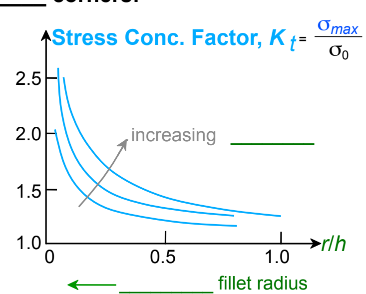
Adapted from Fig. 8.8(b), *Callister & Rethwisch 8e.*

Engineering Fracture Design

- **Avoid ______ corners!**



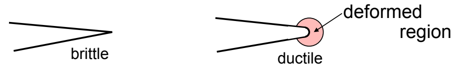
Adapted from Fig. 8.2W(c), *Callister 6e.* (Fig. 8.2W(c) is from G.H. Neugebauer, *Prod. Eng.* (NY), Vol. 14, pp. 82-87 1943.)



Crack Propagation

Cracks having sharp tips _________ easier than cracks having ________ tips

- A __________ material deforms at a crack tip, which "blunts" the crack.



Energy balance on the crack

- Elastic _______ energy-
  - energy stored in material as it is elastically deformed
  - this energy is released when the crack propagates
  - creation of new surfaces requires energy

Chapter 8 - 13

Criterion for Crack Propagation

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

i.e., $\sigma_m > \sigma_c$ $\qquad$ $\sigma_c = \left(\dfrac{2E\gamma_s}{\pi a}\right)^{1/2}$

where

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

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

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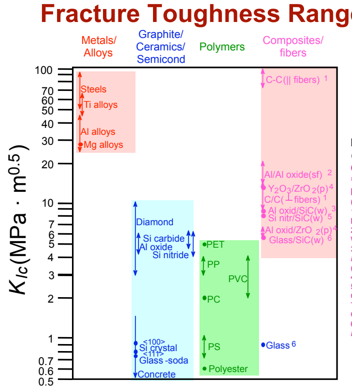
Fracture Toughness Ranges



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.

Chapter 8 - 15

Design Against Crack Growth

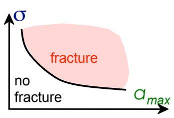
- Crack ________ condition:

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

- ___________, most highly __________ cracks grow first!

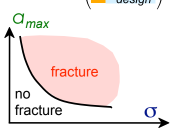
--Scenario 1: Max. flaw size dictates design stress.

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



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

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



Design Example: Aircraft Wing

- Material has K_{Ic} = ______________
- Two designs to consider...

Design A
--largest flaw is 9 mm
--failure stress = __________

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.

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

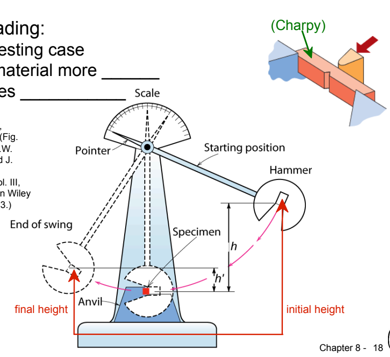
--Result: ______ 9 mm, 4 mm

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

Answer: $(\sigma_c)_B$ = ______MPa

________ Testing

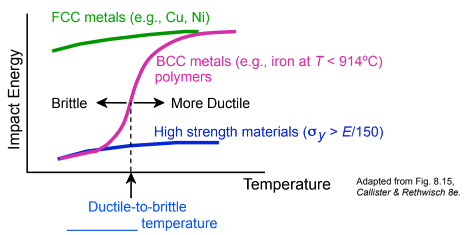
- Impact loading:
  - -- severe testing case
  - -- makes material more ______
  - -- decreases ___________



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 _____________ on Impact Energy

- **Ductile-to-Brittle __________Temperature (DBTT)...**



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

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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**

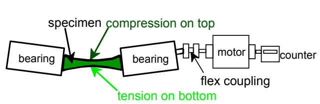
Reprinted w/ permission from R.W. Hertzberg, "Deformation and Fracture Mechanics of Engineering Materials", (4th ed.) Fig. 7.1(b), p. 262, John Wiley and Sons, Inc., 1996. (Orig. source: Earl R. Parker, "Behavior of Engineering Structures", Nat. Acad. Sci., Nat. Res. Council, John Wiley and Sons, Inc.,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

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

Chapter 8 - 20

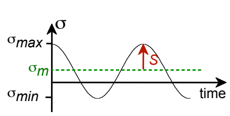
Fatigue

- ________ = failure under applied _______ 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 _________ are S, σ_m, and cycling ___________

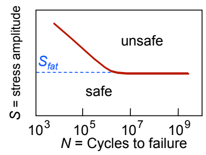


- Key points: ___________...
  --can cause part failure, even though $\sigma_{max} < \sigma_y$.
  --responsible for ~ 90% of mechanical engineering failures.

Chapter 8 - 21

Types of Fatigue Behavior

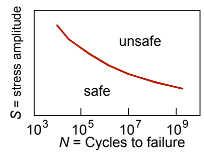
- Fatigue limit, S_{fat}:
  --no ______ if $S < S_{fat}$



case for ______(typ.)

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

- For some materials, there is no _______ limit!



case for __(typ.)

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

Rate of Fatigue Crack Growth

- Crack grows *incrementally*

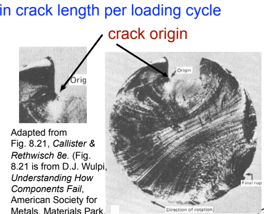
$$\frac{da}{dN} = (\Delta K)^m$$

m: typ. 1 to 6

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

da/dN: increase in crack length per loading cycle

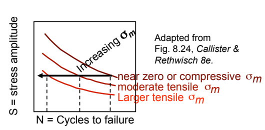
- Failed _______ shaft
  -- crack grew even though $K_{max} < K_c$
  -- crack grows _______ as
  - $\Delta\sigma$ ________
  - crack gets ________
  - loading freq. increases.



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.)

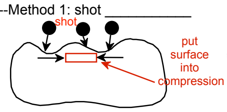
Improving Fatigue Life

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

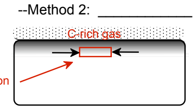


Adapted from Fig. 8.24, *Callister & Rethwisch 8e.*

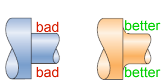
--Method 1: shot __________



--Method 2: __________



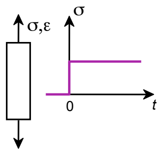
2. Remove ________ concentrators.

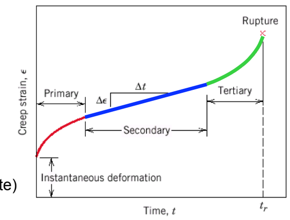


Adapted from Fig. 8.25, *Callister & Rethwisch 8e.*

Creep

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





Primary Creep: _____ (creep rate) ____________ with time.

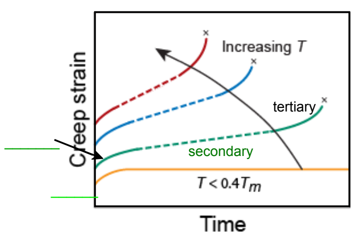
Secondary Creep: steady-state i.e., ________ slope (Δε/Δt).

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

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

Creep: Temperature Dependence

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



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

Secondary Creep

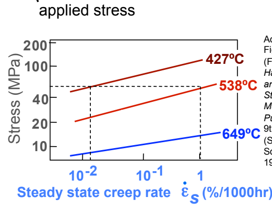
- Strain rate is constant at a given T, σ
  -- strain __________ is balanced by ___________

stress exponent (________ parameter)

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

strain rate; material const.; applied stress; ________ energy for creep (material parameter)

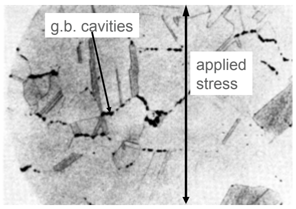
- Strain rate ______________ with increasing T, σ



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.



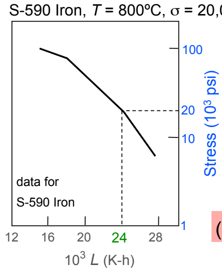
From V.J. Colangelo and F.A. Heiser, *Analysis of Metallurgical Failures* (2nd ed.), Fig. 4.32, p. 87, John Wiley and Sons, Inc., 1987. (Orig. source: Pergamon Press, Inc.)

Chapter 8 - 28

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 __________, t_r

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

temperature; time to failure (rupture); function of ______ stress

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

Ans: t_r = _________

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

- **Solution:**

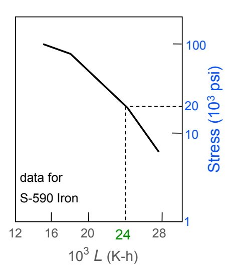
Time to rupture, t_r

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

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).)

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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.