Chemical Engineering 378

Science of Materials Engineering

Lecture 16

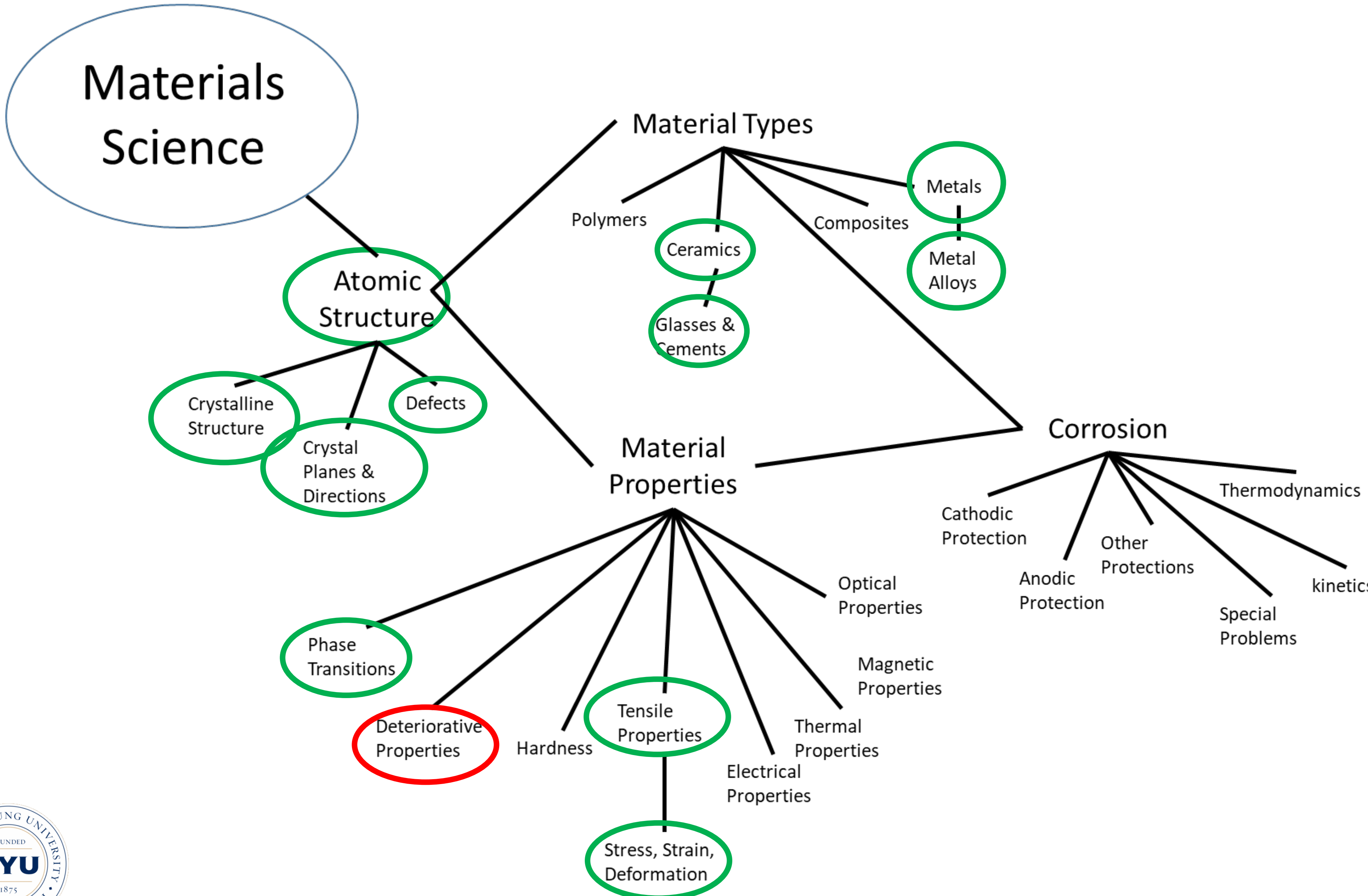
Creep, Fatigue

Spiritual Thought

"I speak next of the present-day challenge to the words of the Lord recorded in Genesis: "Be fruitful, and multiply, and replenish the earth" All my life I have heard the argument that the earth is over-populated… Few voices in the developed nations cry out in the wilderness against this coined phrase "sustainable growth." …The earth is capable of producing food for a population of at least eighty billion, eight times the ten billion expected to inhabit the earth by the year 2050. One study estimates that with improved scientific methods the earth could feed as many ***as one thousand billion people*** ("Ten Billion for Dinner Please," U.S. News & World Report, 12 September 1994, pp. 57–60). Those who argue for sustainable growth lack vision and faith. The Lord said, "For the earth is full, and there is enough and to spare" (D&C 104:17). That settles the issue for me. It should settle the issue for all of us. The Lord has spoken.

-Elder James E. Faust

Materials Roadmap



OEP 5

https://www.youtube.com/watch?v=q23jpbSu3dQ

Captain America

Group work okay, Due 10/18/23 at beginning of class

(Don't be afraid to "Google" for reasonable assumptions; just provide references!)

Hell hath no fury…

I don’t even think I need to finish that quote… in fact, after watching this clip with no context, my wife said “So what did he do to make her so mad?” Anyway, this clip provides us with most of the information we have on vibranium, the most commonly referenced supermetal in the universe. Lucky for you as material scientists, you have most of what you need to define the characteristics of vibranium. Please define, characterize, and quantify the thermophysical and tensile/compressive properties of vibranium. Be careful to use first the information provided in this scene, and then make APPROPRIATE assumptions and computations for the rest.

Criterion for Crack Propagation

Critical stress for crack propagation (σ_c) of brittle materials

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

where

- σ_c = critical crack-tip stress
- 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

- materials have numerous cracks with different lengths and orientations
- crack propagation (and fracture) occurs when $\sigma_m > \sigma_c$ for crack with lowest σ_c
- Largest, most highly stressed cracks grow first!

Fracture Toughness

- Measure of material's resistance to brittle fracture when a crack is present
- Defined as

$$K_C = Y\sigma_C\sqrt{\pi a}$$

K_c = fracture toughness [MPa $\sqrt{\text{m}}$]

Y = dimensionless parameter

σ_c = critical stress for crack propagation [MPa]

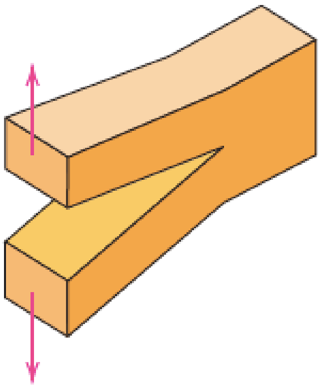
a = crack length [m]

- For planar specimens with cracks much shorter than specimen width, $Y \approx 1$

Plane Strain Fracture Toughness

- For specimen thickness much greater than crack dimension, K_C independent of thickness
  - Condition of plane strain exists
  - Leads to plane strain fracture toughness, K_{Ic}, where I indicates mode I crack displacement

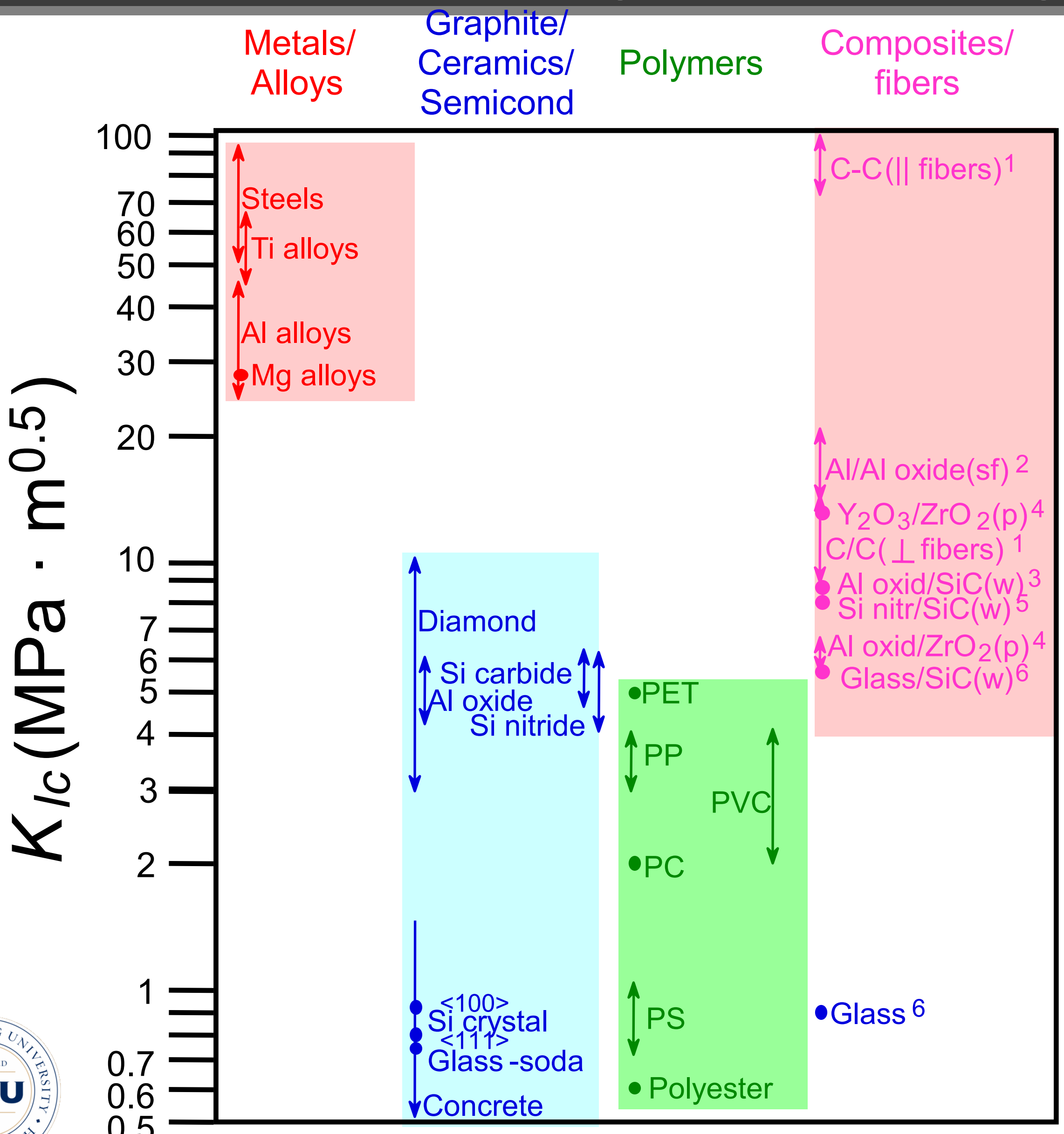
Mode I : Pulling
Mode II: Sliding
Mode III: Tearing



Mode I, opening or tensile mode of crack surface displacement

- values of K_{ic} relatively high for ductile materials and low for brittle ones

Fracture Toughness Ranges



Based on data in Table B.5, *Callister & Rethwisch 10e.*

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.

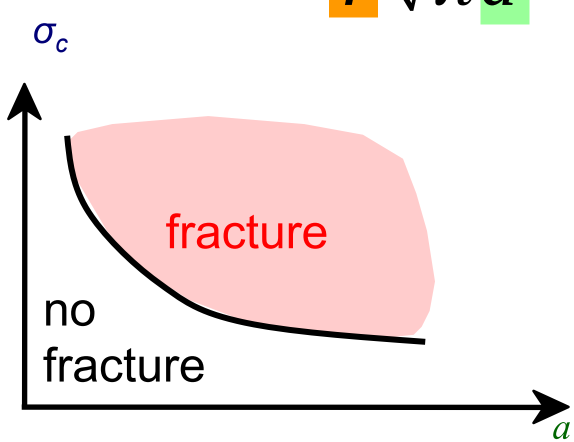
Design Against Fracture

- Crack growth condition:

$$K_{Ic} < Y\sigma_c\sqrt{\pi a}$$

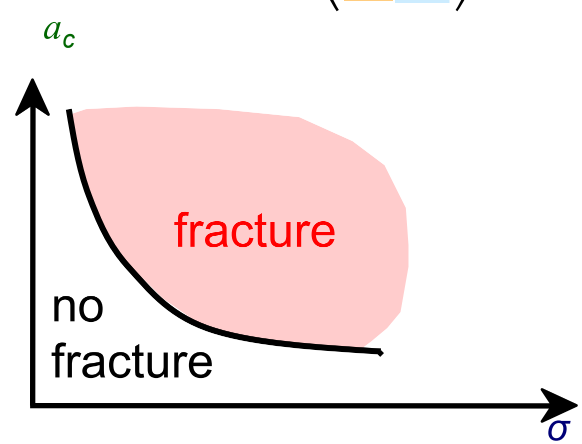
--Scenario 1: K_{Ic} and flaw size a specified - dictates max. design (critical) stress.

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



--Scenario 2: K_{ic} and stress level specified - dictates max. allowable flaw size.

$$a_c = \frac{1}{\pi}\left(\frac{K_{Ic}}{Y\sigma}\right)^2$$



Design Example: Aircraft Wing

An aircraft component is made from a material has K_{Ic} = 26 MPa-m$^{0.5}$ It has been determined that fracture results at a stress of 112 MPa when the maximum (critical) internal crack length is 9.0 mm. For this same component and alloy, compute the stress level at which fracture will occur for a critical internal crack length of 4.0 mm.

BRIGHAM YOUNG UNIVERSITY FOUNDED BYU 1875 PROVO, UTAH

Design Example: Aircraft Wing (cont.)

Solution: Given that fracture occurs for same component using same alloy the parameter *Y* will be the same for both situations. Solving for *Y* for the conditions under which fracture occurred using Equation 8.5.

$$Y = \frac{K_{Ic}}{\sigma_c\sqrt{\pi a}} = \frac{26\ \text{MPa-m}^{0.5}}{(112\ \text{MPa})\sqrt{\pi(9.0\ \text{mm})\left(\dfrac{1\ \text{m}}{1000\ \text{mm}}\right)}} = 1.38$$

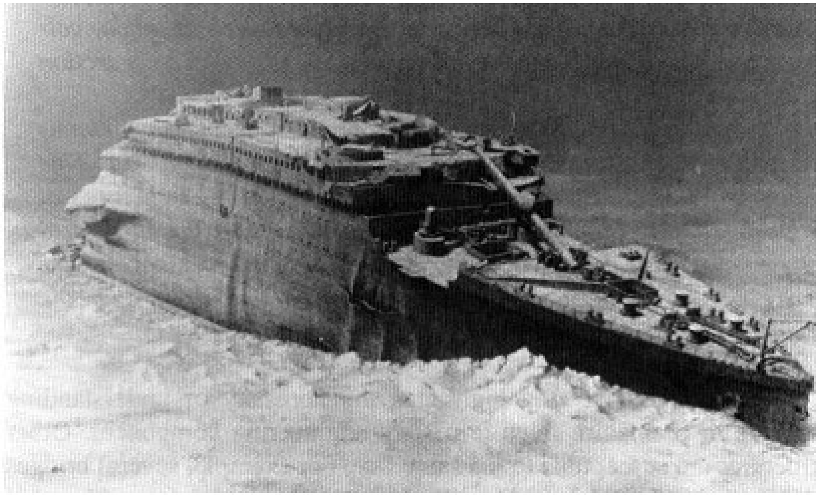
Now we will solve for σ_c using Equation 8.6 as

$$\sigma_c = \frac{K_{Ic}}{Y\sqrt{\pi a}} = \frac{26\ \text{MPa-m}^{0.5}}{(1.38)\sqrt{\pi(4.0\ \text{mm})\left(\dfrac{1\ \text{m}}{1000\ \text{mm}}\right)}}$$

Answer: $\sigma_c = 168\ \text{MPa}$

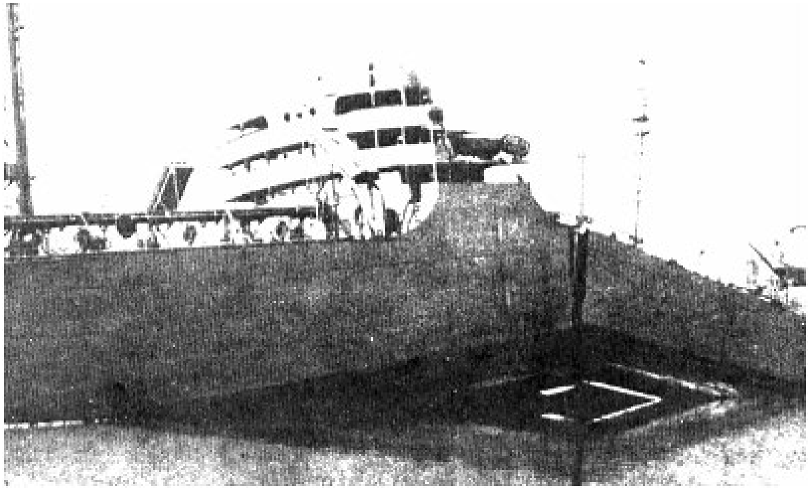
Brittle Fracture of Ductile Materials

- **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.)

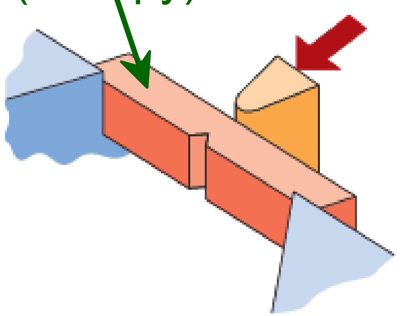
- Ships failed in a brittle manner though constructed of steel that, from tension tests, is normally ductile

Testing Ductile Materials for Brittle Failure

Impact Test

- Test conditions promoting brittle fracture:
  - -- High strain rate
  - -- Deformation at low temperatures
  - -- Presence of a notch

(Charpy)



Impact energy computed from difference between initial height *h* and final height *h*'

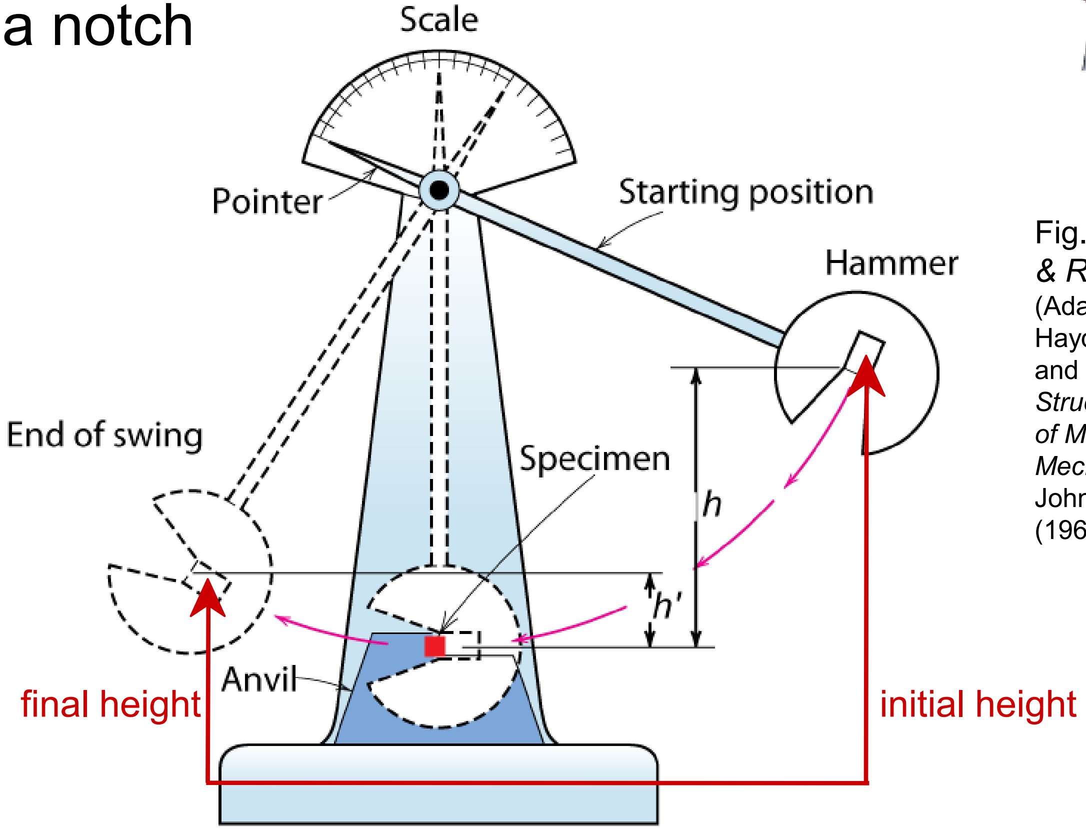
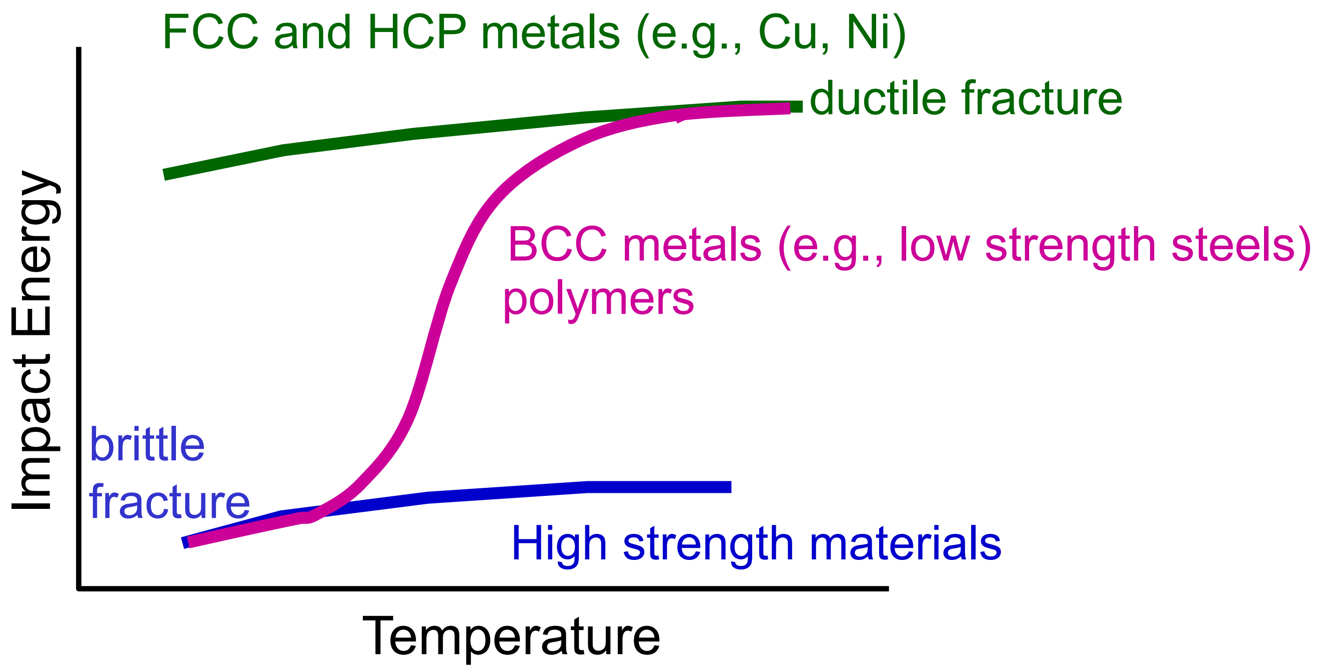


Fig. 8.13(b), *Callister & Rethwisch 10e.* (Adapted from H.W. Hayden, W.G. Moffatt, and J. Wulff, *The Structure and Properties of Materials*, Vol. III, *Mechanical Behavior*, John Wiley and Sons, Inc. (1965) p. 13.)

Influence of *T* on Impact Energy

- When impact tests conducted as function of temperature—three kinds of behavior observed for metals
- Some BCC metals exhibit Ductile-to-Brittle Transition Temperature (DBTT)

Adapted from Fig. 8.16, *Callister & Rethwisch 10e.*



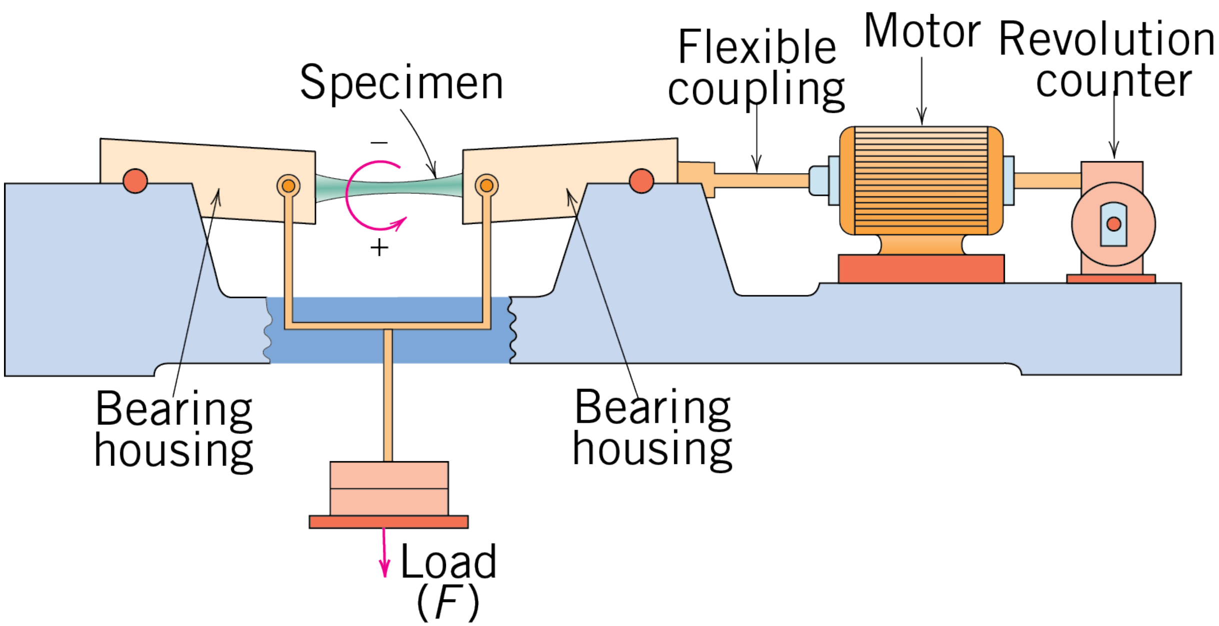
Metals having DBTT should only be used at temperatures where ductile.

Fatigue Failure

- Fatigue = failure under lengthy period of repeated stress or strain cycling
- Stress varies with time.
  -- key parameters are S, σ_m, and cycling frequency
- Key points: Fatigue...
  --can cause part failure, even though applied stress $\sigma_{max} < \sigma_y$.
  --responsible for ~ 90% of mechanical engineering failures.

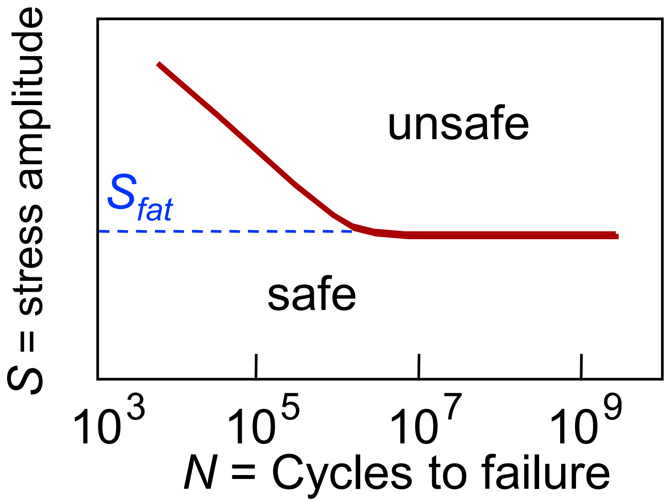
Schematic diagram of an apparatus for performing rotating-bending fatigue tests

Adapted from Fig. 8.19(a), *Callister & Rethwisch 10e.*



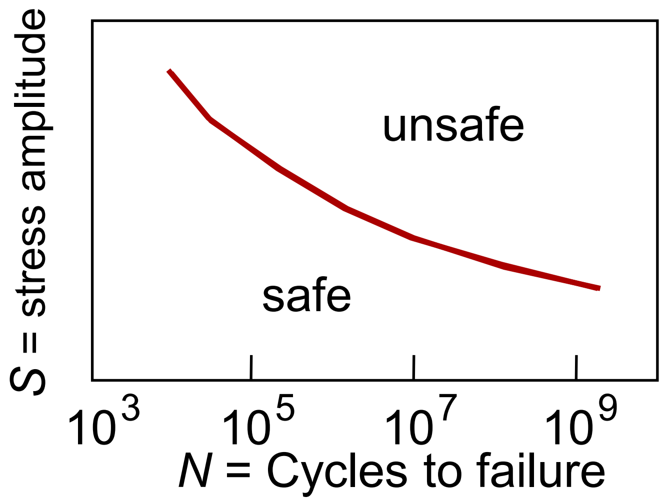
Types of Fatigue Behavior

- Fatigue data plotted as stress amplitude S vs. log of number N of cycles to failure.
- Two types of fatigue behavior observed
  - Fatigue limit, S_{fat}: no fatigue if $S < S_{fat}$
  - For some materials, there is no fatigue limit!
- Fatigue Life N_f = total number of stress cycles to cause fatigue failure at specified stress amplitude



case for steel (typ.)

Adapted from Fig. 8.20(a), *Callister & Rethwisch 10e.*

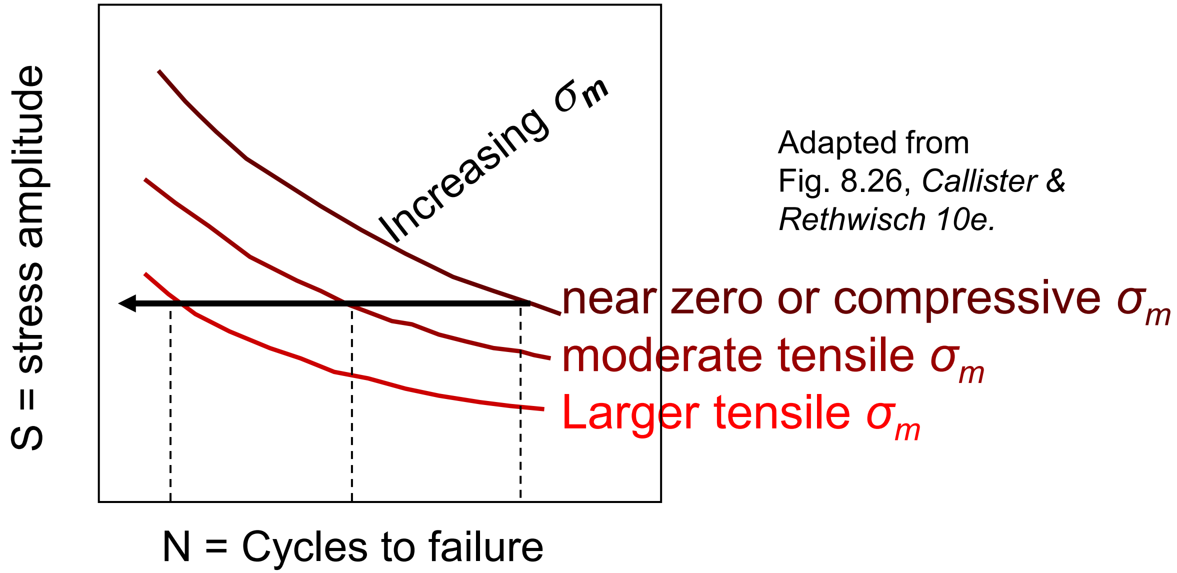


case for Al (typ.)

Adapted from Fig. 8.20(b), *Callister & Rethwisch 10e.*

Improving Fatigue Life

- Three general techniques to improve fatigue life
  1. Reducing magnitude of mean stress
  2. Surface treatments
  3. Design changes



Adapted from Fig. 8.26, *Callister & Rethwisch 10e.*

Decreasing mean stress increases fatigue life

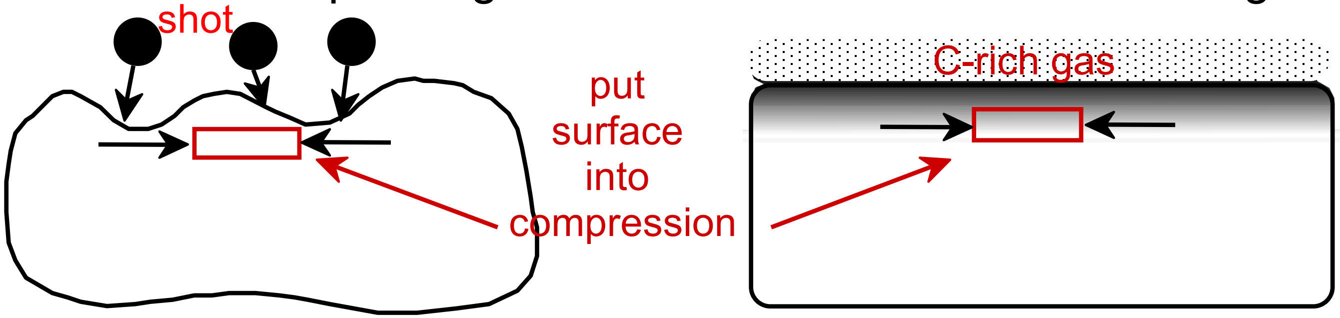
Improving Fatigue Life

- Three general techniques to improve fatigue life
  1. Reducing magnitude of mean stress
  2. Surface treatments
  3. Design changes

Imposing compressive surface stresses increases surface hardness – suppresses surface cracks from growing

--Method 1: shot peening

--Method 2: carburizing



surface compressive stress due to plastic deformation of outer surface layer

surface compressive stress due to carbon atoms diffusing into outer surface layer

Improving Fatigue Life

- Three general techniques to improve fatigue life
  1. Reducing magnitude of mean stress
  2. Surface treatments
  3. Design changes

Remove stress concentrators

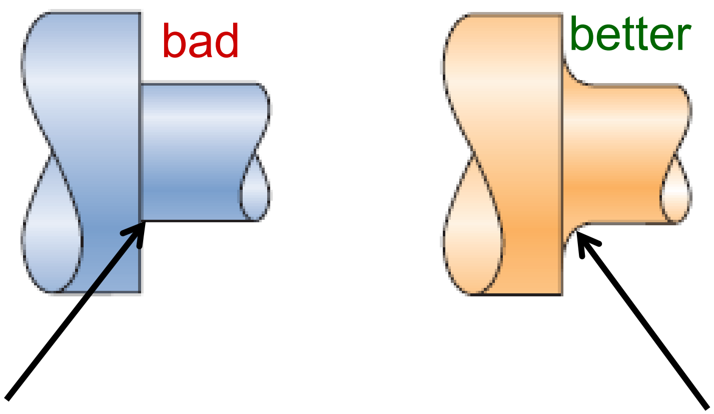


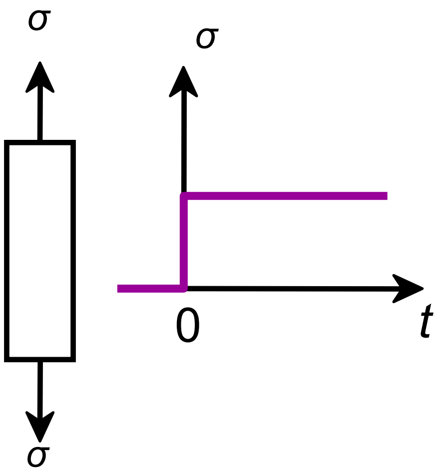
Fig. 8.27, *Callister & Rethwisch 10e.*

sharp corner – point of stress concentration

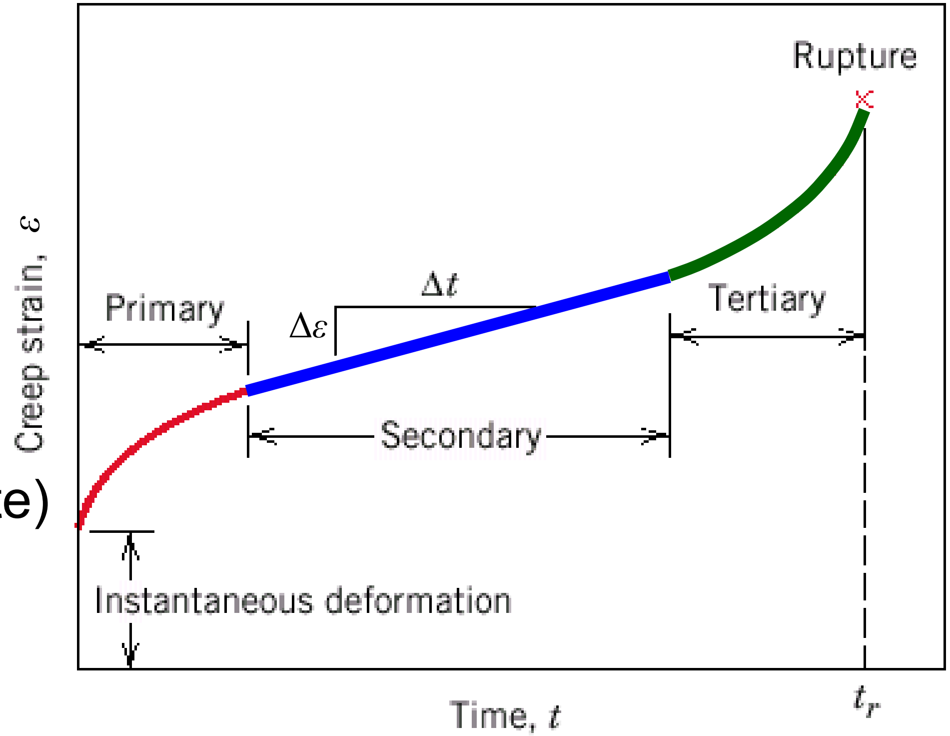
rounding corner reduces stress concentration

Creep

Measure deformation (strain) vs. time at constant stress



Occurs at elevated temperature for most metals, $T > 0.4\ T_m$ (in K)

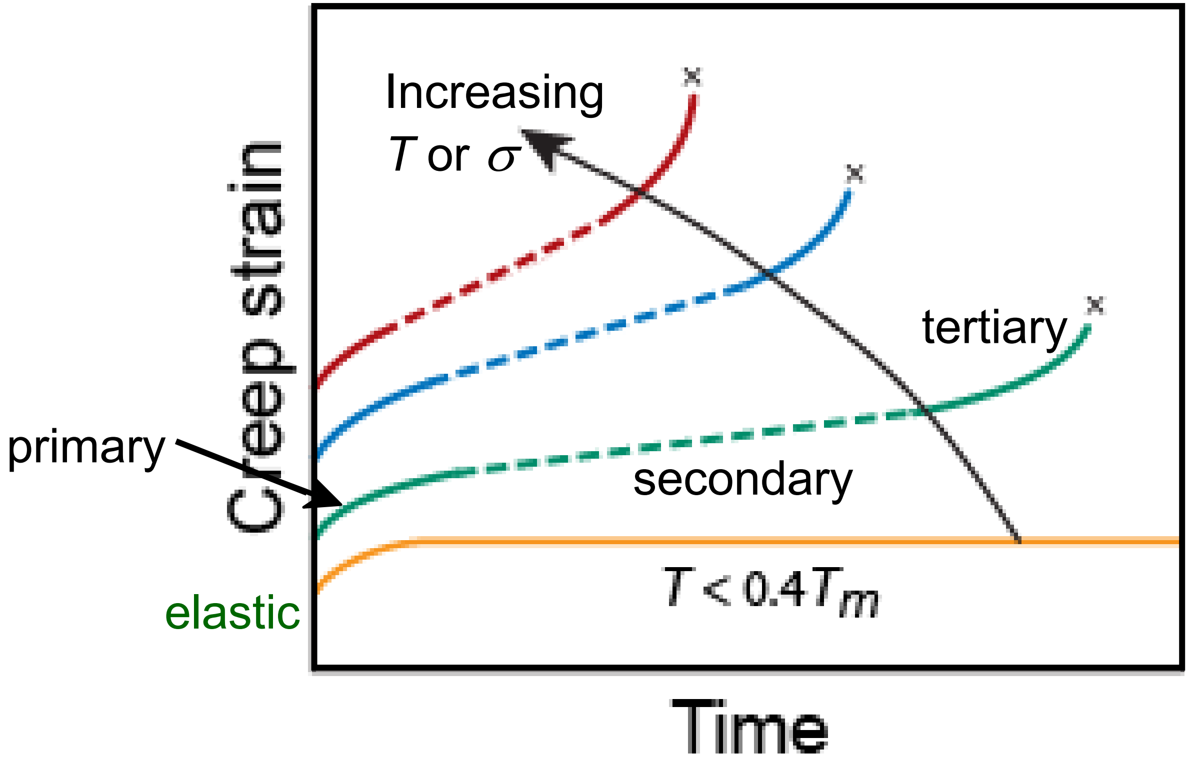


Adapted from Fig. 8.30, *Callister & Rethwisch 10e.*

Stages of Creep

- 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.

Creep: Temperature Dependence



Figs. 8.31, *Callister & Rethwisch 10e.*

- Steady-state creep rate ($\dot{\varepsilon}_s$) increases with increasing T and σ
- Rupture lifetime (t_r) decreases with increasing T and σ

Steady-State Creep Rate

- $\dot{\varepsilon}_s$ constant for constant T, σ
  - -- strain hardening is balanced by recovery
  - -- dependence of steady-state creep rate on T, σ

stress exponent (material parameter)

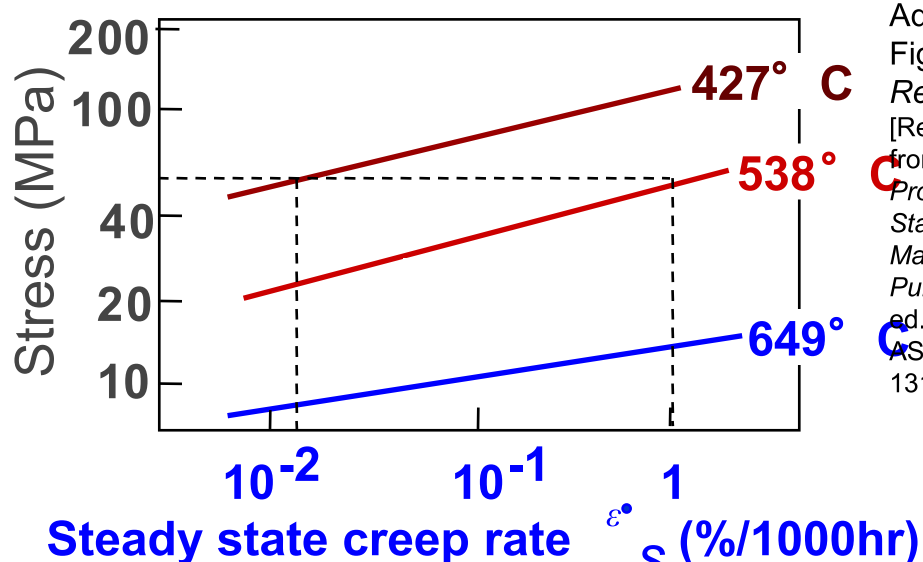
$$\dot{\varepsilon}_s = K_2 \sigma^n \exp\left(-\frac{Q_c}{RT}\right)$$

activation energy for creep (material parameter)

material const.

applied stress

- Steady-state creep rate increases with increasing T, σ



Adapted from Fig. 8.31, *Callister & Rethwisch 7e.* [Reprinted with permission from *Metals Handbook: Properties and Selection: Stainless Steels, Tool Materials, and Special Purpose Metals*, Vol. 3, 9th ed., D. Benjamin (Senior Ed.), ASM International, 1980, p. 131.]

Prediction of Creep Rupture Lifetime

Time to rupture, t_r

- Creep data for prolonged time (e.g., years) impractical to collect in lab
- Extrapolate from data collected for shorter time at higher T using Larson-Miller parameter, m, defined as

constant (normally ≈ 20)

$$T(C + \log t_r) = m$$

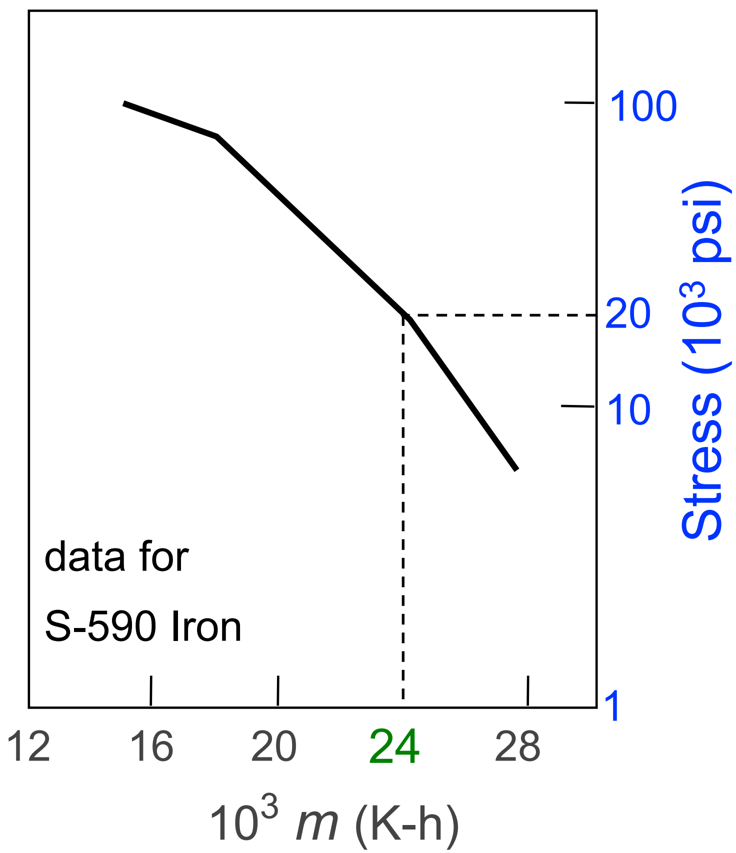
temperature

function of
applied stress

time to failure (rupture)

Prediction of Creep Rupture Lifetime (cont.)

- Plot of log stress vs. Larson-Miller parameter



Adapted from Fig. 8.34, *Callister & Rethwisch 10e.* (From F.R. Larson and J. Miller, *Trans. ASME*, **74**, 765 (1952). Reprinted by permission of ASME)

- Example: Estimate the rupture time t_r for S-590 Iron at T = 800° C and σ= 20,000 psi

$$T = 800 + 273 = 1073\text{ K}$$

$$T(C + \log t_r) = m$$

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

Ans: t_r = 233 hr

Summary

- What: Crack Propagation
  - Why:
  - How:
  - Key points: ductile vs. brittle, mechanisms
- What: Fatigue
  - Why:
  - How:
  - Key points: three ways to protect, improve lifetime (cycles)
- What: Creep
  - Why:
  - How:
  - Key points: mechanism, improvement, prediction, three regions
- Know computations!