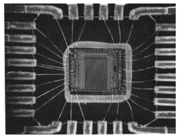
Chapter 9: Mechanical Failure

temperature, stress, cyclic and loading effect

Ship-cyclic loading from waves.

Chapter 9, *Callister & Rethwisch 3e.* (by Neil Boenzi, *The New York Times*.)



Computer chip-cyclic thermal loading.

Fig. 22.30(b), *Callister 7e.* (Fig. 22.30(b) is courtesy of National Semiconductor Corp.)

Hip implant-cyclic loading from walking.

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

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?

Chapter 9 Mechanical Failure: Fracture, Fatigue and Creep

Ship-cyclic loading - waves and cargo.

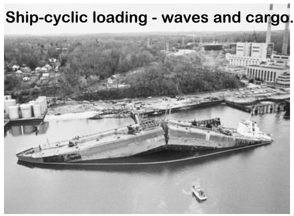


photo by Neal Noenzi (NYTimes)

It is important to understand the mechanisms for failure, especially to prevent in-service failures via design.

This can be accomplished via
Materials selection,
Processing (strengthening),
Design Safety (combination).

Objective: Understand how flaws in a material initiate failure.

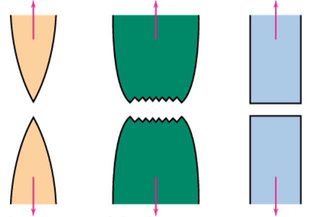
- Describe crack propagation for ductile and brittle materials.
- Explain why brittle materials are much less strong than possible theoretically.
- Define and use Fracture Toughness.
- Define fatigue and creep and specify conditions in which they are operative.
- What is steady-state creep and fatigue lifetime? Identify from a plot.

Fracture mechanisms

- Ductile fracture
  - – Accompanied by significant plastic deformation
- Brittle fracture
  - – Little or no plastic deformation
  - – Catastrophic
  - – Usually strain is < 5%.

Ductile vs Brittle Failure

- Classification:



Adapted from Fig. 9.1, *Callister & Rethwisch 3e.*

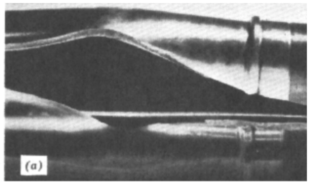
Fracture behavior:	Very Ductile	Moderately Ductile	Brittle
%*RA* or %*EL*	Large	Moderate	Small

- Ductile fracture is usually more desirable than brittle fracture!

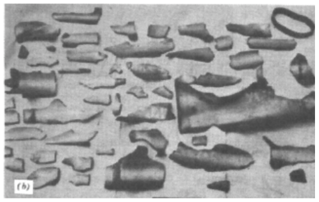
Ductile: Warning before fracture

Brittle: **No warning**

Example: Failure Of A Pipe



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



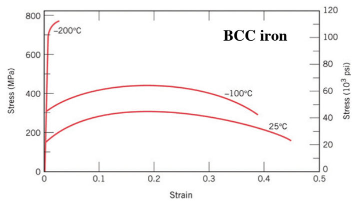
- **Brittle failure:**
  - --many pieces
  - --small deformation

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.

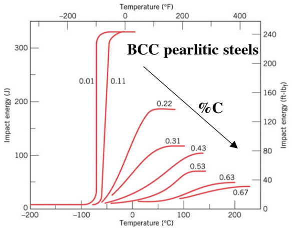
Stress-Strain Behavior versus Temperature

Ambient and operating T affects failure mode of materials.

Stress-strain curve



Charpy Impact Test



Shows Ductile to *Brittle* Transition with T reduction!
or increase in %C!

Energy to initiate crack propagation found via Charpy V-Notch (CVN) Test

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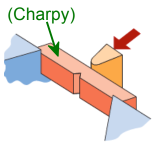
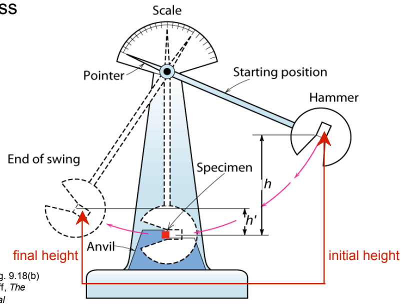
Charpy Impact Testing

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

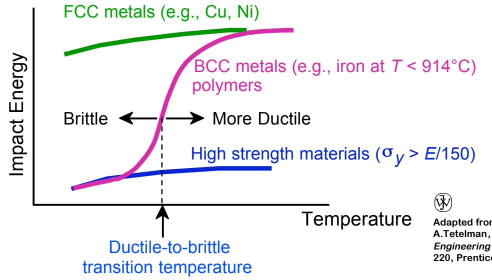




Adapted from Fig. 9.18(b), *Callister & Rethwisch 3e.* (Fig. 9.18(b) is adapted from H.W. Hayden, W.G. Moffatt, and J. Wulff, *The Structure and Properties of Materials*, Vol. III, *Mechanical Behavior*, John Wiley and Sons, Inc. (1965) p. 13.)

Charpy V-Notch Impact Data: Energy vs Temperature

Notched sample is hit and crack propagates.



Adapted from C. Barrett, W. Nix, and A.Tetelman, *The Principles of Engineering Materials*, Fig. 6-21, p. 220, Prentice-Hall, 1973.

- Increasing Temperature increases %EL and K_{Ic}.
- Temperature effect clear from these materials test.
- A238 Steel has more dramatic dependence around ocean T.

Design Strategy: Stay above the DBTT

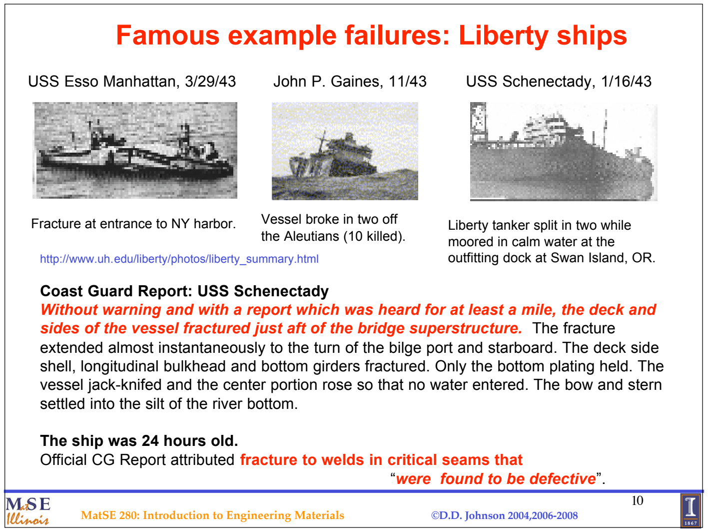
- **Pre-WWII: The Titanic**
- **WWII: Liberty ships**

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*.)

Fom R.W. Hertzberg, "Deformation and Fracture Mechanics of Engineering Materials", (4th ed.) Fig. 7.1(b), p. 262, John Wiley and Sons, Inc., 1996.

- **Problem: Used a steel with a DBTT ~ Room temp.**

For Liberty Ships it was in the process of steel that was issue for they made up to 1 ship every 3 days at one point!



Famous example failures: Liberty ships

USS Esso Manhattan, 3/29/43

Fracture at entrance to NY harbor.

John P. Gaines, 11/43

Vessel broke in two off the Aleutians (10 killed).

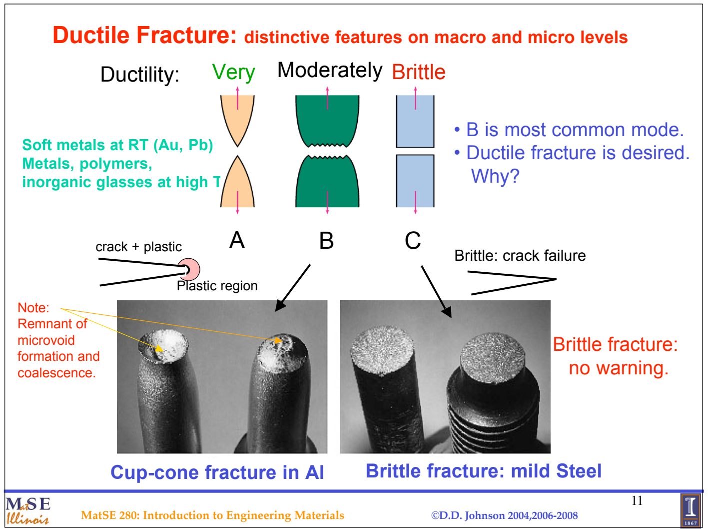
USS Schenectady, 1/16/43

Liberty tanker split in two while moored in calm water at the outfitting dock at Swan Island, OR.

http://www.uh.edu/liberty/photos/liberty_summary.html

Coast Guard Report: USS Schenectady
Without warning and with a report which was heard for at least a mile, the deck and sides of the vessel fractured just aft of the bridge superstructure. The fracture extended almost instantaneously to the turn of the bilge port and starboard. The deck side shell, longitudinal bulkhead and bottom girders fractured. Only the bottom plating held. The vessel jack-knifed and the center portion rose so that no water entered. The bow and stern settled into the silt of the river bottom.

The ship was 24 hours old.
Official CG Report attributed **fracture to welds in critical seams that "*were found to be defective*".**



Ductile Fracture: distinctive features on macro and micro levels

Soft metals at RT (Au, Pb)
Metals, polymers,
inorganic glasses at high T

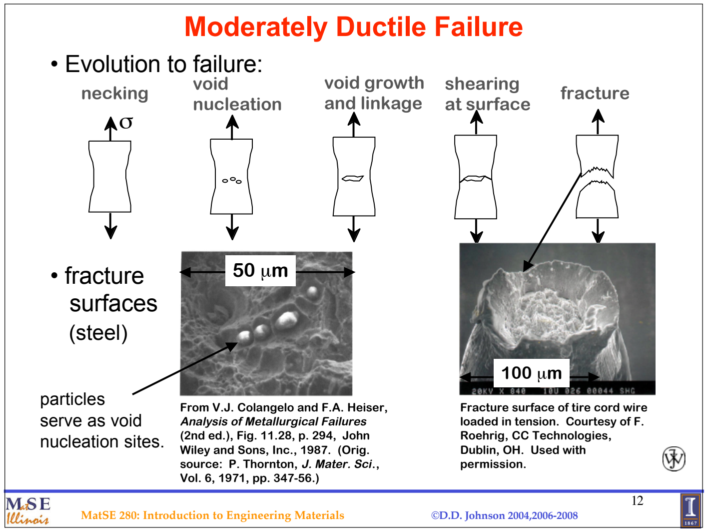
- B is most common mode.
- Ductile fracture is desired. Why?

Note: Remnant of microvoid formation and coalescence.

Brittle fracture: no warning.

Cup-cone fracture in Al

Brittle fracture: mild Steel



Moderately Ductile Failure

- Evolution to failure:

- fracture surfaces (steel)

particles serve as void nucleation sites.

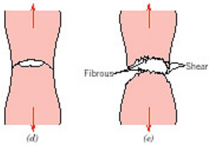
From V.J. Colangelo and F.A. Heiser, *Analysis of Metallurgical Failures* (2nd ed.), Fig. 11.28, p. 294, John Wiley and Sons, Inc., 1987. (Orig. source: P. Thornton, *J. Mater. Sci.*, Vol. 6, 1971, pp. 347-56.)

Fracture surface of tire cord wire loaded in tension. Courtesy of F. Roehrig, CC Technologies, Dublin, OH. Used with permission.

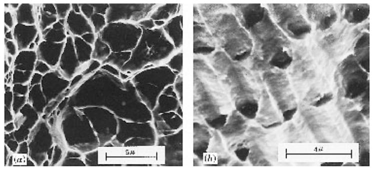
Fracture Surface under Tensile and Shear load

- Failure Evolution
  necking + void coalescence
  + cracks propagate

- Final shear fracture with fibrous pullout indicating plastic deformation



spherical dimples



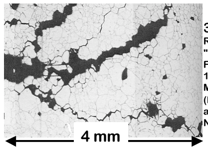
parabolic dimples

Tensile loading

Shear loading

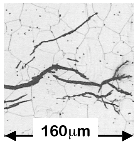
Brittle Fracture Surface

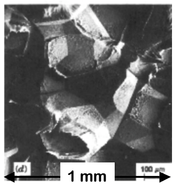
- **Intergranular (between grains)**
- **Intragranular (within grains)**



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.)

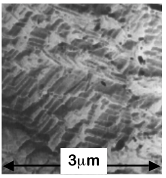
316 S. Steel (metal)
Reprinted w/ permission from "Metals Handbook", 9th ed, Fig. 650, p. 357. Copyright 1985, ASM International, Materials Park, OH. (Micrograph by D.R. Diercks, Argonne National Lab.)



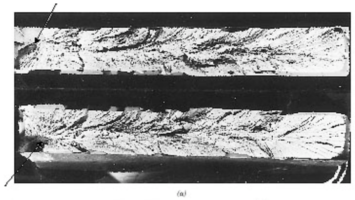


Polypropylene (polymer)
Reprinted w/ permission from R.W. Hertzberg, "Defor-mation and Fracture Mechanics of Engineering Materials", (4th ed.) Fig. 7.35(d), p. 303, John Wiley and Sons, Inc., 1996.

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.)

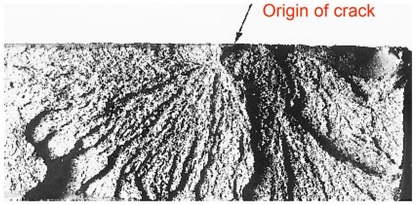


Brittle Fracture Surface



Chevron marks
From brittle fracture

Origin of crack

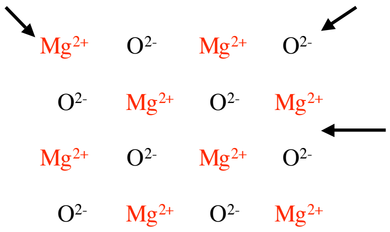


Fan-shaped ridges
coming from crack

Brittleness of Ceramics

- **Restricted slip planes** (reduced plasticity)
- **Stress concentrators** (voids, pores, cracks, oh, my!)

e.g, MgO What are possible slip paths?



Mg^{2+} O^{2-} Mg^{2+} O^{2-}

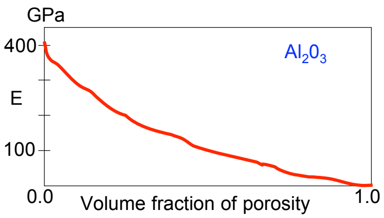
O^{2-} Mg^{2+} O^{2-} Mg^{2+}

Mg^{2+} O^{2-} Mg^{2+} O^{2-}

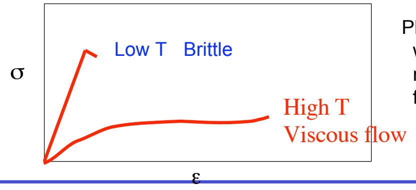
O^{2-} Mg^{2+} O^{2-} Mg^{2+}

What is restriction? Why is a metal different?

Porosity and Temperature Effects in Ceramics



Stiffness lost with porosity (voids).



Plasticity increased with temperature, more due to viscous flow less from slip.

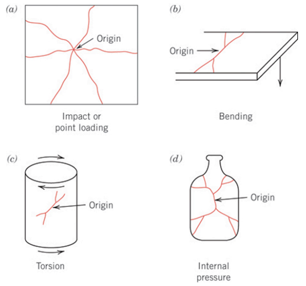
Nucleation and Propagation Of Cracks in Ceramics

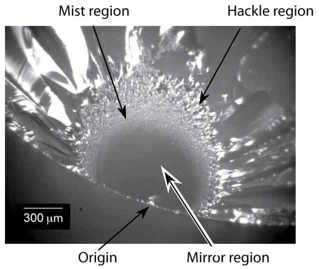
After reaching terminal velocity (~50%v_{sound}) crack bifurcates (branches) to relieve stress.

This permit retrace to origin of initial crack.

- Initial region (Mirror) is flat and smooth.
- branching least to Mist and Hackle regions.

Fracture surface Of a 6mm-diameter Fused Silica Rod





Adapted from Figs. 9.14 & 9.15, *Callister & Rethwisch 3e.*

Crazing during Fracture of Thermoplastic Polymers

- **Generally, polyermic materials have low fracture strengths compared to metals and ceramics.**
  - **Thermosets are brittle** (covalent bonds in network or crosslinks are severed).
  - **Thermoplastics have both ductile and brittle modes.**
    - ***Brittle fracture favored by reduced T, increased ε-rate, presence of shart notches, increased thickness, and change in chemical structure.***
    - ***Glassy thermoplastics become ductile near the "glass trans. temp.", and can "Craze" in the direction normal to applied stress.***

Craze: microvoids expand and form fibrilar bridges, then coalesce to form crack.

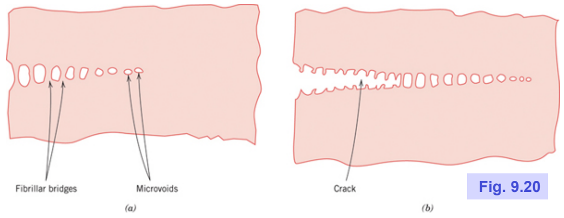
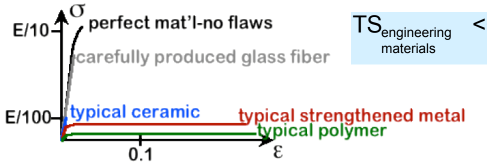


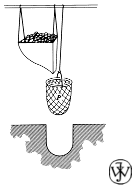
Fig. 9.20

Ideal versus Real Behavior

- Stress-strain behavior (Room T):

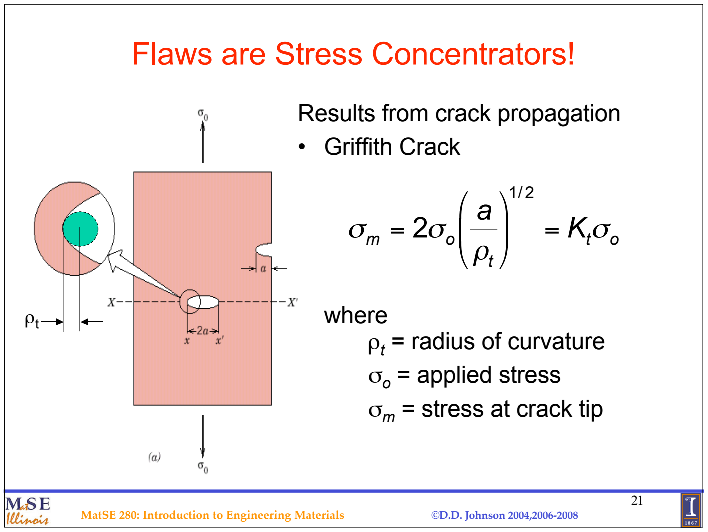


$TS_{\text{engineering materials}} << TS_{\text{perfect materials}}$



- DaVinci (500 yrs ago!) observed...
  --the longer the wire, the smaller the load to fail it.

- Reasons:
  --flaws cause premature failure.
  --Larger samples are more flawed!



Flaws are Stress Concentrators!

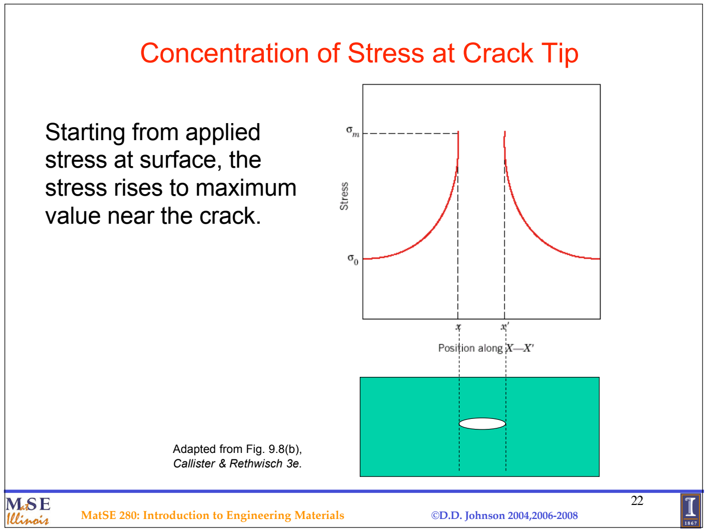
Results from crack propagation

- Griffith Crack

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

where

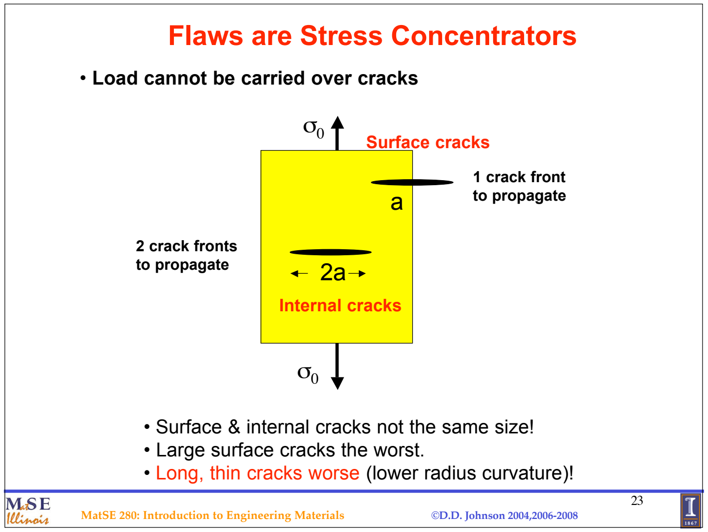
ρ_t = radius of curvature
σ_o = applied stress
σ_m = stress at crack tip



Concentration of Stress at Crack Tip

Starting from applied stress at surface, the stress rises to maximum value near the crack.

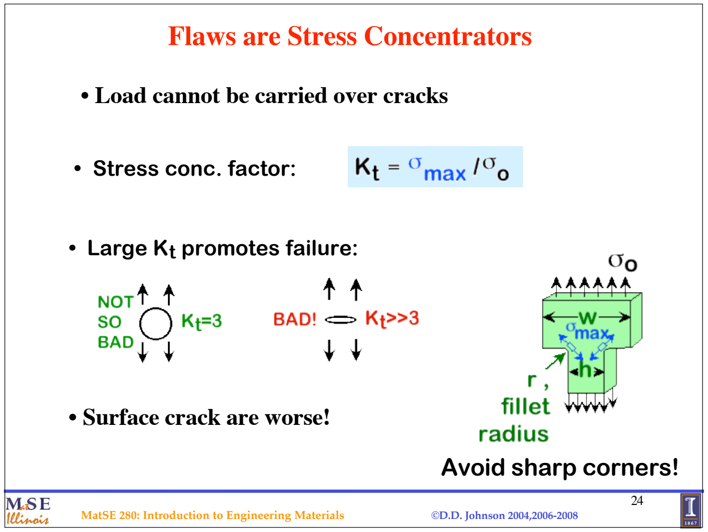
Adapted from Fig. 9.8(b), *Callister & Rethwisch 3e.*



Flaws are Stress Concentrators

- **Load cannot be carried over cracks**

- Surface & internal cracks not the same size!
- Large surface cracks the worst.
- Long, thin cracks worse (lower radius curvature)!



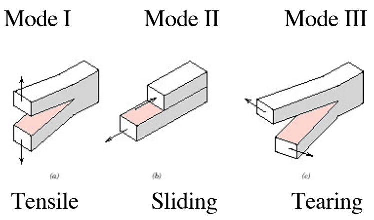
Flaws are Stress Concentrators

- **Load cannot be carried over cracks**
- **Stress conc. factor:** $K_t = \sigma_{max} / \sigma_o$
- **Large K_t promotes failure:**

- **Surface crack are worse!**

Avoid sharp corners!

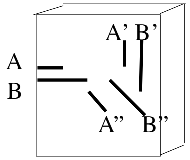
Modes of Fracture which Operate on Cracks



Mode I is most often encountered.

Griffith's Criteria for Fracture and Failure

A=A'=A" etc.



How could crack in Liberty Bell been stopped?

Crack sizes, orientations and distributions

It should be almost intuitive that the relative lengths of cracks will control which crack will propagate under stress, such can be said of the orientation and distribution also. Let us examine and example.

*If cracks each act independently, then, if A < B, ***failure will not occur from A***.

**Failure will not occur from A' and B'* because they are parallel to applied stress.

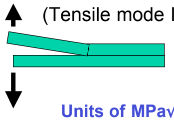
*Thus, ***B-type crack is failure mode***, as it has the highest stress concentration.

Theoretical cohesive strength is $\sigma = \sqrt{\frac{2E(\gamma_s + \gamma_P)}{\pi a}} = \sqrt{\frac{EG_c}{\pi a}}$

G_c = toughness = kJ/m^2 is the energy needed to generate a crack.

Fast-Fracture Condition

Griffith's Criteria
(Tensile mode I)



$$K = \sigma\sqrt{\pi a} = \sqrt{EG_c} = \text{constant!!}$$

$G_c \propto 2\gamma_s$
Surface energy

Units of MPa√m
"stress intensity factor"

Hard to measure
Internal flaws

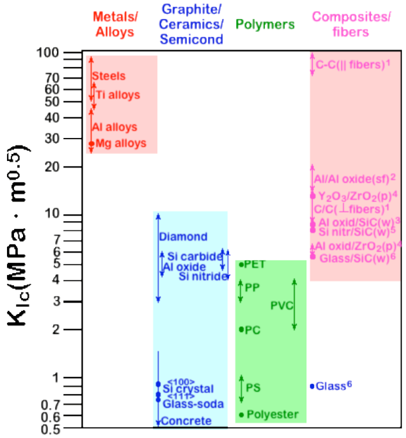
Measureable (fixed)
materials properties

- LHS of equation => ***fast fracture*** will occur when (in a material subjected to stress s) a crack reaches some critical size "a"; or, when a material constains cracks of size "a" is subjected to some critical stress s.

- Point is that the critical combination of stress and crack length at which fast fracture occurs is a *MATERIAL CONSTANT*!

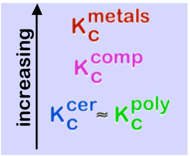
FAST Fracture will occur when $K \geq K_c = \sqrt{EG_c}$ = constant

Fracture Toughness, K_c

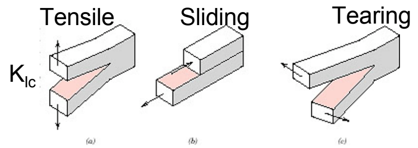


Fracture Toughness

Based on data in Table B5, *Callister 6e*.



Griffith’s Criteria is different for SLIDING and TEARING.



- TENSILE condition derived for an elliptical crack in thin plate.

$$K = \sigma\sqrt{\pi a} \;\Rightarrow\; K_{Ic} = \sqrt{EG_c} \text{ = constant}$$

- When $K = K_c$ fast fracture will occur:

$$K = K_{Ic} = \sigma\sqrt{\pi a}$$

Materials selection | **Design stress** | **Allowable flaw size or NDT flaw detection**

Griffith’s Criteria for TENSILE: more generally

- More generally, for K_{Ic} case:

Design stress

$$K = K_{Ic} = XY\sigma\sqrt{\pi c}$$

Materials selection

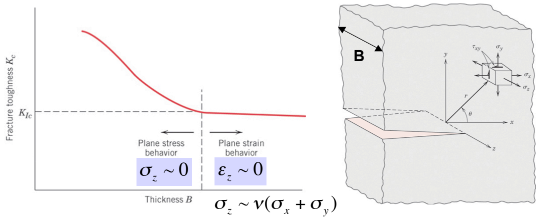
Geometric factor mostly 0.5 < Y < 2

Allowable interior or surface flaw size or NDT flaw detection
$c = 1/2\, a_{\text{interior}}$
or $c = a_{\text{surface}}$

Factor designating type of crack
X=1 for simple **interior** crack.
X=1.12 for simple **surface** crack.

- **Y is a geometric factor** reflecting **shape of crack** and **geometry of sample**.
  - Often Y is not known, but determined by K_c and s (e.g., HW)

Plane-Strain vs Plane-Stress State



$$\sigma_z \sim \nu(\sigma_x + \sigma_y)$$

- **Thinner plate:** *plane-stress state* as z-surface is free and stress cannot change appreciably over small distance.
- **Thicker plate:** *plane-strain state* as strain $\Delta l_z/l_z \sim 0$ and stress is established by the Poisson effect.
- **Experimentally, the plane-strain condition is found for** $B \geq 2.5\left(\dfrac{K_{Ic}}{\sigma_{ys}}\right)^2$
- **Plane-strain fracture toughness is** $K_{Ic} = XY\sigma\sqrt{\pi c}$

Importance of Fast Fracture: Example

(From Hertzberg, 4th Ed.)

- On 15 January 1919 on Commercial Street in Boston a huge tank of molasses (diameter: 27 m, height: 15 m) fractured catastrophically:

“Without an instant’s warning the top was blown into the air and the sides were burst apart. A city building nearby, where employees were at lunch, collapsed burying a number of victims and a firehouse was crushed in by a section of the tank, killing and injuring a number of firemen.”[1]

“On collapsing, a side of the tank was carried against one of the columns supporting the elevated structure [of the Boston Elevated Railway Co.] This column was completely sheared off…and forced back under the structure…. the track was pushed out of alignment and the superstructure dropped several feet … Twelve persons lost their lives either by drowning in molasses, smothering, or by wreckage. Forty more were injured. Many horses belonging to the paving department were drowned, and others had to be shot.”[2]

1. Scientific American **120** (1919) 99. 2. Engineering News-Record **82** (1919) 974.

Designing Against Crack Growth

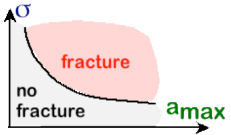
- Crack growth condition: $K \geq K_c$, with $K = XY\sigma\sqrt{\pi a}$
- Largest, most stressed cracks grow first!
  - Result 1: Max flaw size dictates design stress.
  - Result 2: Design stress dictates max. flaw size.

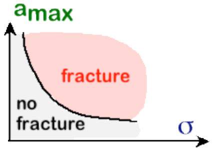
Interior crack X=1

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

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

NOTE: only K_{Ic}/σ is critical for design!





Design Example: Aircraft Wing

Material has K_C = 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
--What is failure stress?

- Use: $\sigma_c = \dfrac{K_c}{Y\sqrt{\pi a_{max}}}$
- Key point: Y and K_C are the same in both designs.

--Result:

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

Answer: $(\sigma_c)_B = 168 MPa$

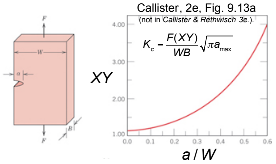
- Reducing flaw size pays off!

Design Example: Steel Plating

Material has K_c = 60 MPa-√m and YS = 1400 MPa

Steel plate has through-edge crack pictured.
Width **W = 40 mm** and thickness **B = 6 mm**.
Plane-strain K_c and YS given.

If the plate is to be loaded to **200 MPa**, would you expect failure to occur if ***a* = 16 mm**? **Why or why not?**


Callister, 2e, Fig. 9.13a (not in *Callister & Rethwisch 3e.*).

- **Two issues to consider...**
  1. Does condition of plane-strain hold? If so, use *fast-fracture criterion*.
  2. Use *fast-fracture criterion* for the correct plate and crack geometry!
- **Plane-strain?** Plane-strain observed if $B \geq 2.5\left(\frac{K_{Ic}}{\sigma_{ys}}\right)^2$

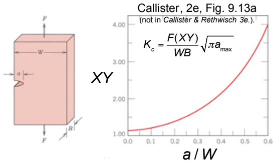
$$B \geq 2.5\left(\frac{K_{Ic}}{\sigma_{ys}}\right)^2 = 4.6\text{ mm, hence, } B = 6\text{ mm} > 4.6\text{ mm (Plane-strain holds!)}$$

- **We may use *fast-fracture criterion:*** $K = \sigma XY\sqrt{\pi a_{max}} > K_c$

Design Example: Steel Plating

Material has K_c = 60 MPa-√m and YS = 1400 MPa

If the plate (**W = 40 mm** and **B = 6 mm**) is to be loaded to **200 MPa**, would you expect failure to occur if ***a* = 16 mm**? **Why or why not?**


Callister, 2e, Fig. 9.13a (not in *Callister & Rethwisch 3e.*).

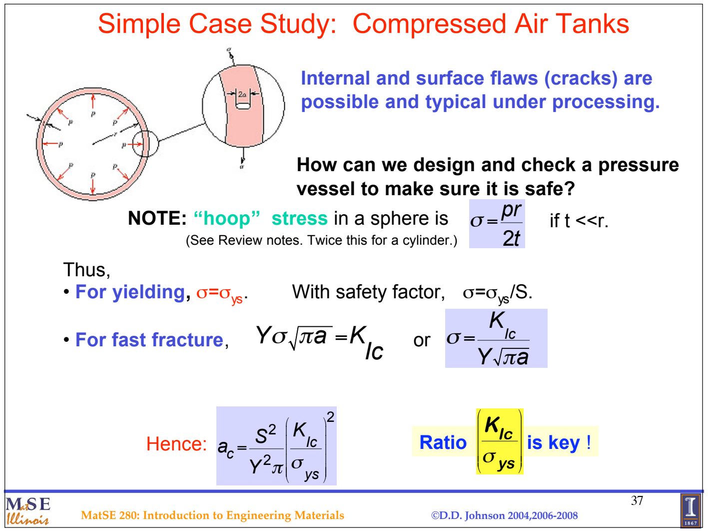
- **From *fast-fracture criterion:*** $K = \sigma XY\sqrt{\pi a_{max}} > K_c$

With $\frac{a}{W} = \frac{16\text{ mm}}{40\text{ mm}} = 0.4$ figure gives $XY = 2.12$

Thus, $K = (200\text{ MPa})(2.12)\sqrt{\pi(16\text{ mm})} = 95\text{ MPa}\sqrt{m} > K_{Ic}\ (60\text{ MPa}\sqrt{m})$

With K > K_{Ic}, we must expect fracture to occur by fast-fracture in the plate.

What would be the largest surface crack in plate to prevent failure by this mode?



Simple Case Study: Compressed Air Tanks

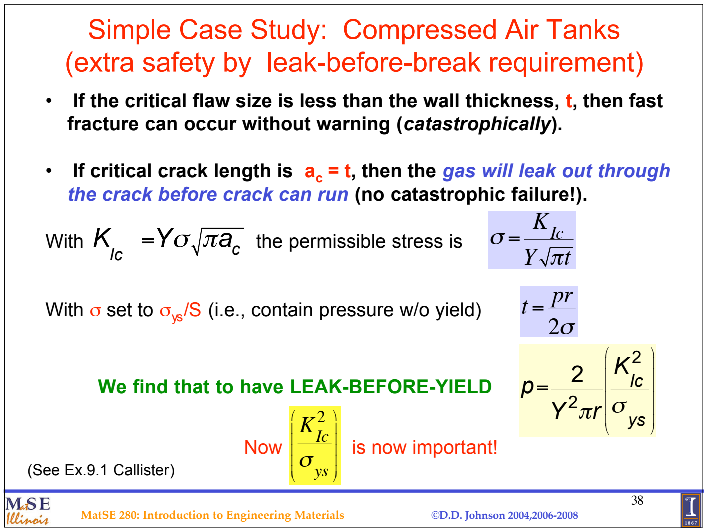
Internal and surface flaws (cracks) are possible and typical under processing.

How can we design and check a pressure vessel to make sure it is safe?

NOTE: "hoop" stress in a sphere is $\sigma = \frac{pr}{2t}$ if t <<r.
(See Review notes. Twice this for a cylinder.)

Thus,
- **For yielding**, $\sigma = \sigma_{ys}$. With safety factor, $\sigma = \sigma_{ys}/S$.
- **For fast fracture**, $Y\sigma\sqrt{\pi a} = K_{Ic}$ or $\sigma = \frac{K_{Ic}}{Y\sqrt{\pi a}}$

Hence: $a_c = \frac{S^2}{Y^2\pi}\left(\frac{K_{Ic}}{\sigma_{ys}}\right)^2$ **Ratio** $\left(\frac{K_{Ic}}{\sigma_{ys}}\right)$ **is key !**



Simple Case Study: Compressed Air Tanks
(extra safety by leak-before-break requirement)

- **If the critical flaw size is less than the wall thickness, t, then fast fracture can occur without warning (*catastrophically*).**
- **If critical crack length is $a_c = t$, then the *gas will leak out through the crack before crack can run* (no catastrophic failure!).**

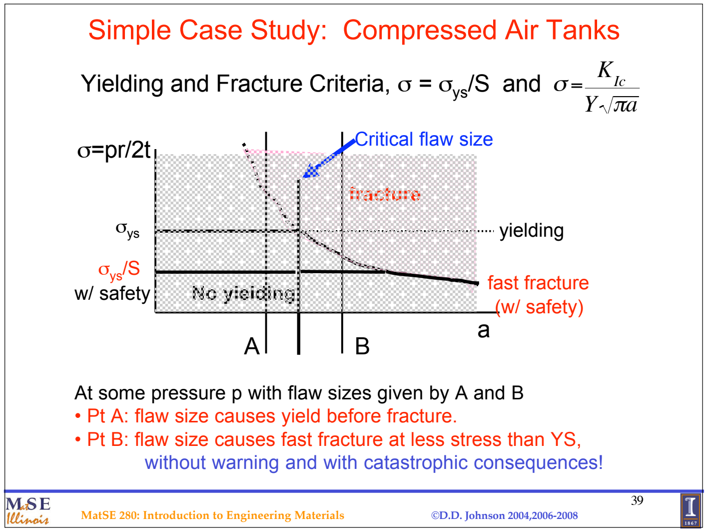
With $K_{Ic} = Y\sigma\sqrt{\pi a_c}$ the permissible stress is $\sigma = \frac{K_{Ic}}{Y\sqrt{\pi t}}$

With σ set to σ_{ys}/S (i.e., contain pressure w/o yield) $t = \frac{pr}{2\sigma}$

We find that to have LEAK-BEFORE-YIELD $p = \frac{2}{Y^2\pi r}\left(\frac{K_{Ic}^2}{\sigma_{ys}}\right)$

Now $\left(\frac{K_{Ic}^2}{\sigma_{ys}}\right)$ is now important!

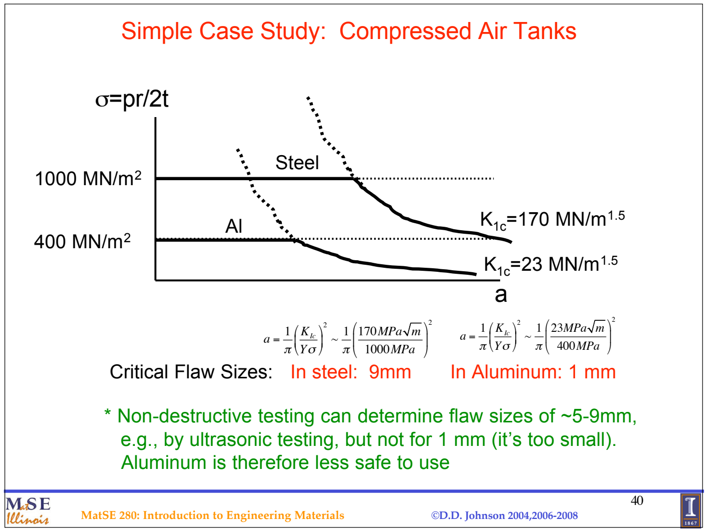
(See Ex.9.1 Callister)



Simple Case Study: Compressed Air Tanks

Yielding and Fracture Criteria, $\sigma = \sigma_{ys}/S$ and $\sigma = \frac{K_{Ic}}{Y\sqrt{\pi a}}$

At some pressure p with flaw sizes given by A and B
- Pt A: flaw size causes yield before fracture.
- Pt B: flaw size causes fast fracture at less stress than YS, without warning and with catastrophic consequences!

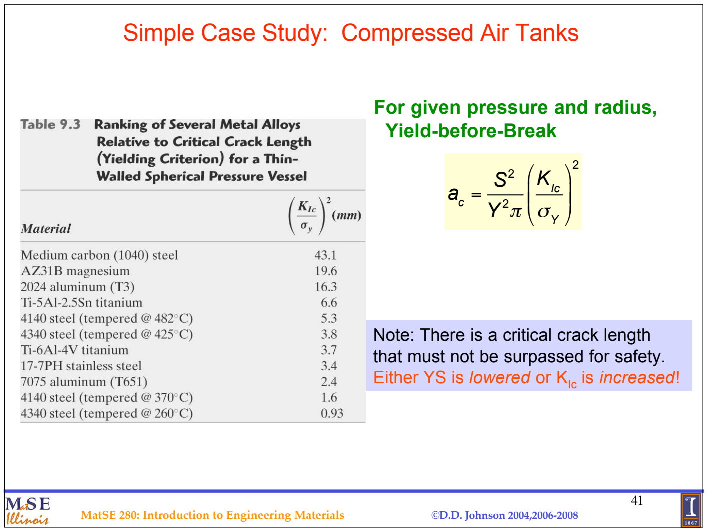


Simple Case Study: Compressed Air Tanks

$a = \frac{1}{\pi}\left(\frac{K_{Ic}}{Y\sigma}\right)^2 \sim \frac{1}{\pi}\left(\frac{170MPa\sqrt{m}}{1000MPa}\right)^2$ $a = \frac{1}{\pi}\left(\frac{K_{Ic}}{Y\sigma}\right)^2 \sim \frac{1}{\pi}\left(\frac{23MPa\sqrt{m}}{400MPa}\right)^2$

Critical Flaw Sizes: In steel: 9mm In Aluminum: 1 mm

* Non-destructive testing can determine flaw sizes of ~5-9mm, e.g., by ultrasonic testing, but not for 1 mm (it's too small). Aluminum is therefore less safe to use



Simple Case Study: Compressed Air Tanks

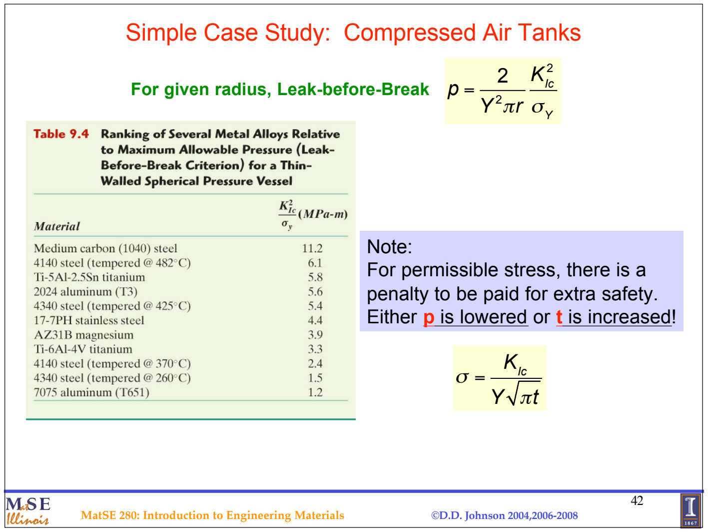
Table 9.3 Ranking of Several Metal Alloys Relative to Critical Crack Length (Yielding Criterion) for a Thin-Walled Spherical Pressure Vessel

Material	$\left(\frac{K_{Ic}}{\sigma_y}\right)^2$ *(mm)*
Medium carbon (1040) steel	43.1
AZ31B magnesium	19.6
2024 aluminum (T3)	16.3
Ti-5Al-2.5Sn titanium	6.6
4140 steel (tempered @ 482°C)	5.3
4340 steel (tempered @ 425°C)	3.8
Ti-6Al-4V titanium	3.7
17-7PH stainless steel	3.4
7075 aluminum (T651)	2.4
4140 steel (tempered @ 370°C)	1.6
4340 steel (tempered @ 260°C)	0.93

For given pressure and radius,
Yield-before-Break

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

Note: There is a critical crack length that must not be surpassed for safety. Either YS is *lowered* or K_{Ic} is *increased*!



Simple Case Study: Compressed Air Tanks

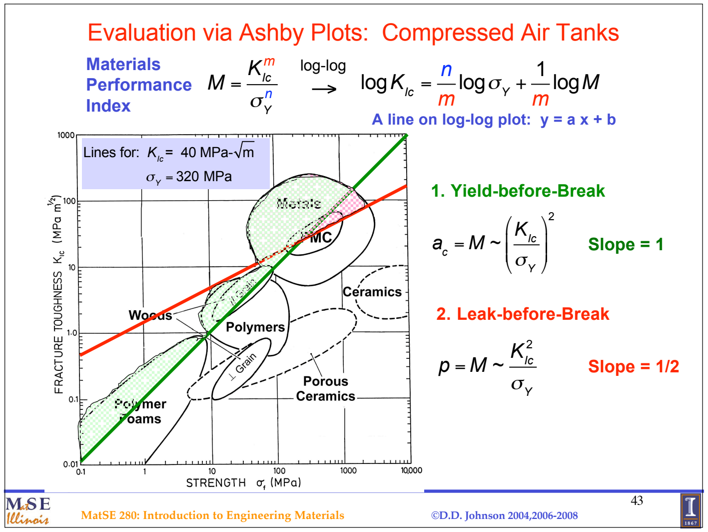
For given radius, Leak-before-Break $p = \frac{2}{Y^2\pi r}\frac{K_{Ic}^2}{\sigma_Y}$

Table 9.4 Ranking of Several Metal Alloys Relative to Maximum Allowable Pressure (Leak-Before-Break Criterion) for a Thin-Walled Spherical Pressure Vessel

Material	$\frac{K_{Ic}^2}{\sigma_y}$ *(MPa-m)*
Medium carbon (1040) steel	11.2
4140 steel (tempered @ 482°C)	6.1
Ti-5Al-2.5Sn titanium	5.8
2024 aluminum (T3)	5.6
4340 steel (tempered @ 425°C)	5.4
17-7PH stainless steel	4.4
AZ31B magnesium	3.9
Ti-6Al-4V titanium	3.3
4140 steel (tempered @ 370°C)	2.4
4340 steel (tempered @ 260°C)	1.5
7075 aluminum (T651)	1.2

Note:
For permissible stress, there is a penalty to be paid for extra safety.
Either p is lowered or t is increased!

$$\sigma = \frac{K_{Ic}}{Y\sqrt{\pi t}}$$



Evaluation via Ashby Plots: Compressed Air Tanks

Materials Performance Index $M = \frac{K_{Ic}^m}{\sigma_Y^n} \xrightarrow{\text{log-log}} \log K_{Ic} = \frac{n}{m}\log\sigma_Y + \frac{1}{m}\log M$

A line on log-log plot: y = a x + b

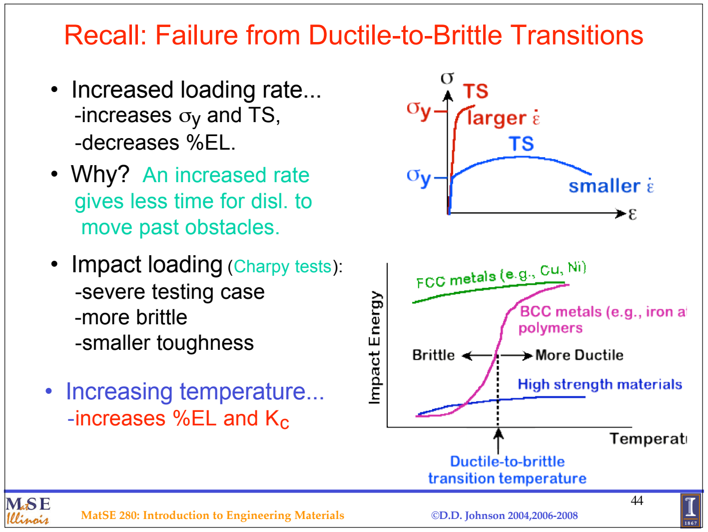
Lines for: K_{Ic} = 40 MPa-$\sqrt{m}$
σ_Y = 320 MPa

1. Yield-before-Break

$$a_c = M \sim \left(\frac{K_{Ic}}{\sigma_Y}\right)^2$$ **Slope = 1**

2. Leak-before-Break

$$p = M \sim \frac{K_{Ic}^2}{\sigma_Y}$$ **Slope = 1/2**

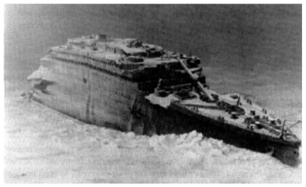


Recall: Failure from Ductile-to-Brittle Transitions

- Increased loading rate...
  -increases σ_y and TS,
  -decreases %EL.
- Why? An increased rate gives less time for disl. to move past obstacles.
- Impact loading (Charpy tests):
  -severe testing case
  -more brittle
  -smaller toughness
- Increasing temperature...
  -increases %EL and K_c

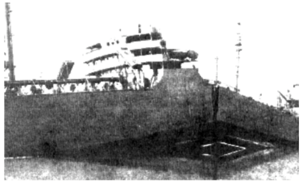
Design Strategy: Stay above the DBTT

- **Pre-WWII: The Titanic**



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**



Fom R.W. Hertzberg, "Deformation and Fracture Mechanics of Engineering Materials", (4th ed.) Fig. 7.1(b), p. 262, John Wiley and Sons, Inc., 1996.

- **Problem: Used a steel with a DBTT ~ Room temp.**

For Liberty Ships it was in the process of steel that was issue for they made up to 1 ship every 3 days at one point!

Chapter 9: Failure from Fatigue

As we have seen, Defects lead to failure due to

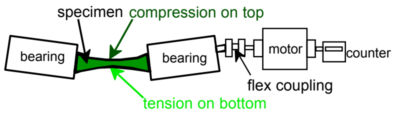
- Cracks (stress concentrators)
- Ductile-to-Brittle Transition Temperature

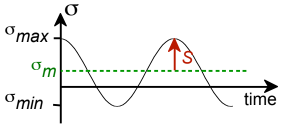
Another is Fatigue:

Failure from dynamic or fluctuating stresses from Lengthy period of repeated stress or strain cycles.

- What are the features of fatigue?
- How can we prevent it?

Fatigue: Failure from cyclic stress.





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

$$\sigma_r = \sigma_{\max} - \sigma_{\min} = 2\sigma_a = 2S$$ Range of stress and amplitude

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

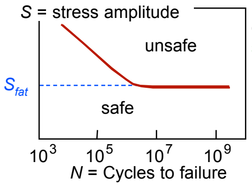
- Stress varies with time.
  - key parameters are S and σ_m

- Key points: Fatigue...
  - causes part failure, even though $\sigma_{max} < \sigma_c$.
  - causes ~90% of mechanical engineering failures.

Stress Amplitude (S) vs Number of Cycles (N): S-N Curves

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

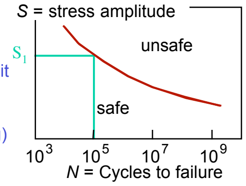
low-cycle fatigue, 10^4-10^5
high-cycle fatigue > 10^5



case for steel (typ.)

Adapted from Fig. 9.25(a,b), *Callister & Rethwisch 3e.*

- Fatigue limit can be zero!



case for Al (typ.)

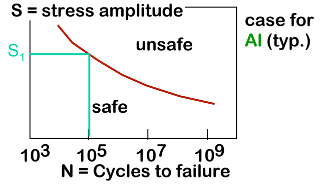
S-N behavior

- Fe- and Ti-based alloys, fatigue limit is 35-60% of TS.
- Non-ferrous alloys (e.g., Al, Cu, Mg) do not have fatigue limit!

Fatigue

S-N Curves

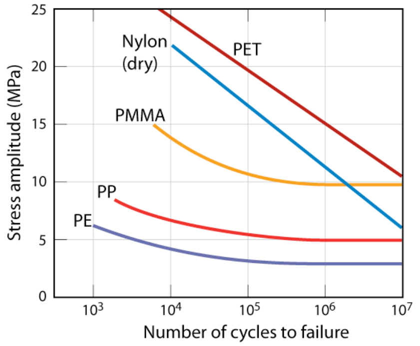
Failure



- Fatigue can occur under axial, flexoral, torsional stress/strain.
- Failure can occur:
  - at *stress less than YS or UTS for static load*.
  - *suddenly, without warning, and catastrophic!* (90% of metals)
- Fatigue failure is brittle in nature, even in normally ductile metals, due to initiation of crack propagation.
- Fatigue Life N_f (total cycles to failure) is sum of number to initiate cracks and number to propogate cracks: $N_f = N_i + N_p$.
  - Low-stress levels (high-cycle fatigue) $N_i >> N_p$.
  - High-stress levels (low-cycle fatigue) $N_i << N_p$.

Fatigue Behavior of Polymers

- Fatigue limit:
  - PMMA, PP, PE
- No fatigue limit:
  - PET, Nylon (dry)



Fatigue Mechanisms

- Crack grows *incrementally*

$$\frac{da}{dN} = (\Delta K)^m \qquad \Delta K \sim (\Delta\sigma)\sqrt{a}$$

typ. 1 to 6

increase in crack length per loading cycle

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

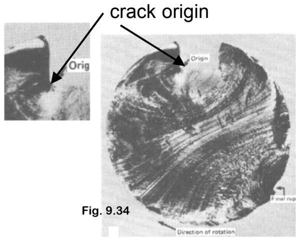


Fig. 9.34

Improving Fatigue Life

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

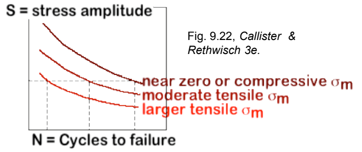
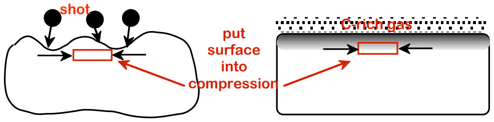


Fig. 9.22, *Callister & Rethwisch 3e.*

--Method 1: shot peening **--Method 2: carburizing**



2. Remove stress concentrators.

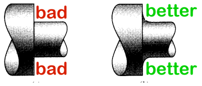
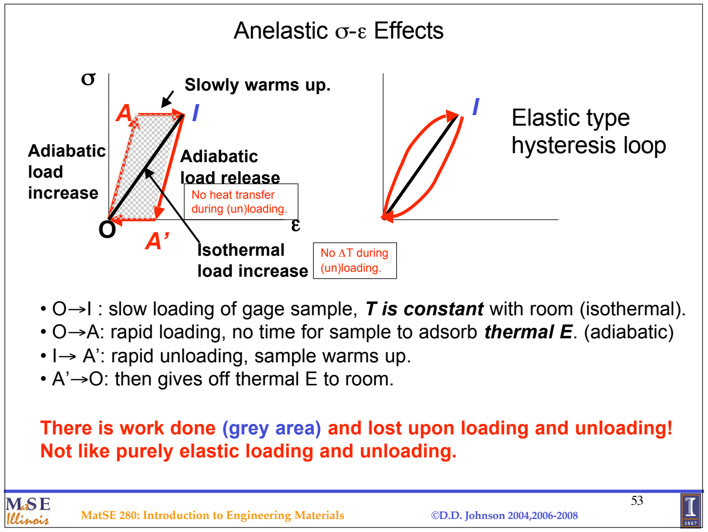


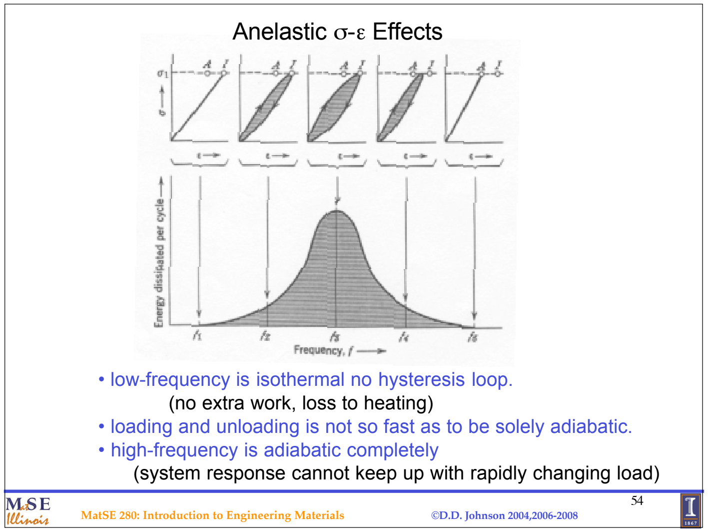
Fig. 9.23, *Callister & Rethwisch 3e.*



Anelastic σ-ε Effects

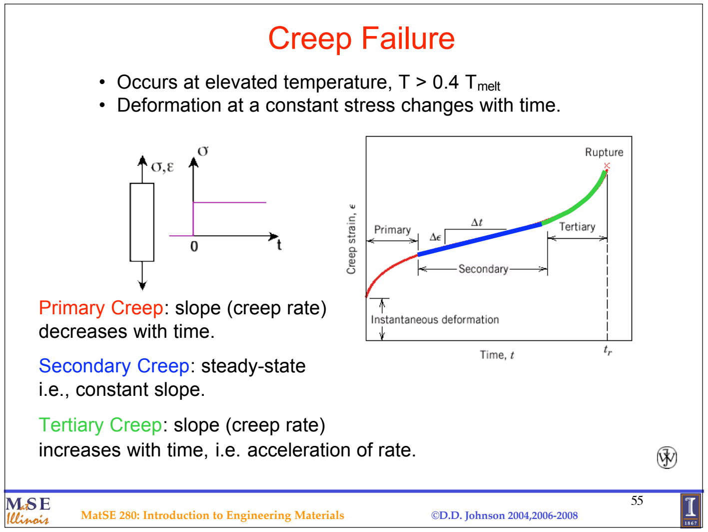
- O→I : slow loading of gage sample, ***T is constant*** with room (isothermal).
- O→A: rapid loading, no time for sample to adsorb ***thermal E***. (adiabatic)
- I→ A': rapid unloading, sample warms up.
- A'→O: then gives off thermal E to room.

There is work done (grey area) and lost upon loading and unloading! Not like purely elastic loading and unloading.



Anelastic σ-ε Effects

- low-frequency is isothermal no hysteresis loop.
  (no extra work, loss to heating)
- loading and unloading is not so fast as to be solely adiabatic.
- high-frequency is adiabatic completely
  (system response cannot keep up with rapidly changing load)



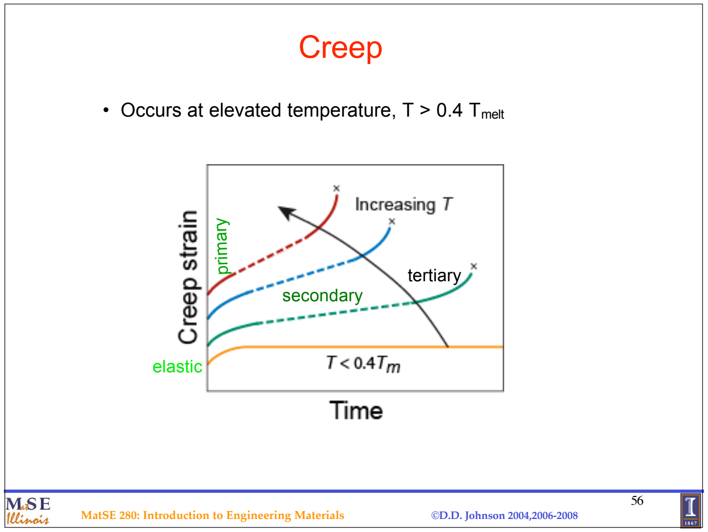
Creep Failure

- Occurs at elevated temperature, T > 0.4 T_{melt}
- Deformation at a constant stress changes with time.

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

Secondary Creep: steady-state i.e., constant slope.

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

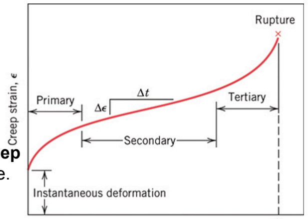


Creep

- Occurs at elevated temperature, T > 0.4 T_{melt}

Creep: deformation under elevated T and static stresses

Secondary creep
Steady-state creep rate dε/dt ~ constant
Competition between strain-hardening and recovery



Tertiary creep
accelerated creep rate
and failure!

Primary or transient creep
has decreasing creep rate.

Rupture time
caused by GB separation, cracks, voids, cavities, etc., including necking.

Secondary creep important
for long-life applications:
Nuclear power plant.

Short-life creep:
turbine blades, rocket nozzles.

Secondary Creep

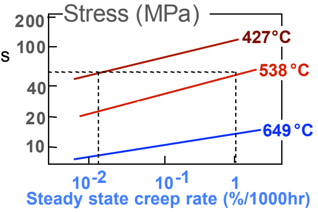
- Strain rate is constant at a given T, s
  -- strain hardening is balanced by recovery

stress exponent (material parameter)

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

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

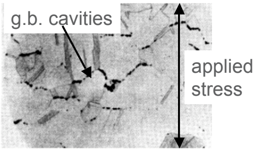
- Strain rate increases
  for higher T, s



Adapted from
Fig. 9.38, *Callister & Rethwisch 3e.*
(Fig. 9.38 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.)

Secondary Failure: Larson-Miller procedure

- Failure:
  along grain boundaries.



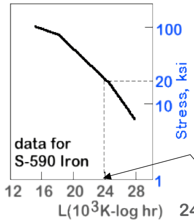
From V.J. Colangelo and F.A. Heiser, *Analysis of Metallurgical Failures* (2nd ed.), Fig. 4.32, p. 87, John Wiley and Sons, Inc., 1987. (Orig. source: Pergamon Press, Inc.)

- Time to rupture, t_r

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

temperature
function of
applied stress
time to failure (rupture)

- Estimate rupture time
  S 590 Iron, T = 800C, s = 20 ksi



Adapted from
Fig. 8.45, *Callister 6e.*

24x10^3 K-log hr

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

1073K

Ans: t_r = 233hr

Creep RECOVERY and Vacancy-assisted Climb

- Creep is an anelastic behavior of a material,
  i.e. the strain depends on temperature and time effects.

- Creep can be viewed as a manifestation of competitive work-hardening and recovery (or materials "softening") in Stage III response, where work-hardening involves dislocation glide.

- The main mechanism assumed to be important to the recover for the creep process is non-conservative climb.

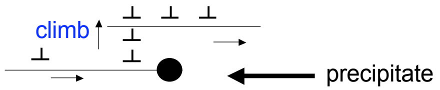
(a) How does climb help "soften" a material?
(b) Why is temperature important?

Major recover mechanism is non-conservative climb.

- Creep = Work-hardening + Recovery

(a) How does climb help "soften" a material?
Edge Dislocations will move out of one glide plane and into another via vacancy-assisted climb. By doing so, they can avoid "hard" obstacles (see diagram), rather than cut through them, making the system respond effectively "softer".

(b) Why is temperature important?
Climb requires mobile vacancies that can diffuse to the tensile side of the edge; hence, temperature is important as vacancies diffuse roughly when $T > 0.4\ T_{melting}$.



Summary

- Engineering materials don't reach theoretical strength.
- Flaws produce stress concentrations that cause premature failure.
- Sharp corners produce large stress concentrations and premature failure.
- Failure type depends on T and stress:
  - for noncyclic s and $T < 0.4T_m$, failure stress decreases with: increased maximum flaw size or rate of loading, or decreased T.
  - for cyclic σ: cycles to failure decreases as $\Delta\sigma$ increases.
  - for higher T ($T > 0.4T_m$): time to fail decreases as σ or T increases.