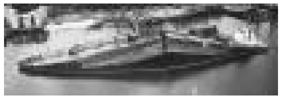
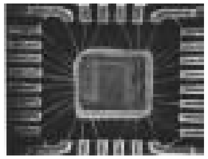
Chapter 8: Mechanical Failure

ISSUES TO ADDRESS...

1. How do flaws in a material initiate failure?
2. How is fracture resistance quantified; how do different material classes compare?
3. How do we estimate the stress to fracture?
4. How do loading rate, loading history, and temperature affect the failure stress?


ship-cyclic loading from waves
Callister Fig. 8.0


computer chip-cyclic thermal loading
Callister Fig. 23.22


hip implant-cyclic loading from walking
Callister Fig. 23.13

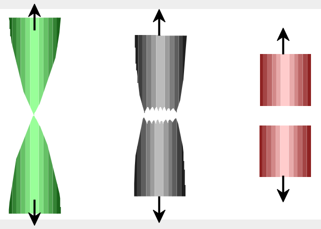
Ductile versus Brittle Fracture

- Classification:

Fracture behavior:	Very Ductile	Moderately Ductile	Brittle
%AR or %EL:	Large	Moderate	Brittle

VIMS:
Str-str diag.
necking

Fig. 8.1
Callister



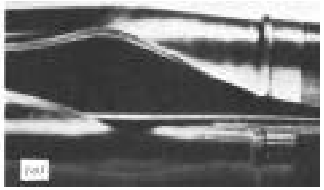
- Ductile fracture is desirable!

Ductile:
warning
before
fracture

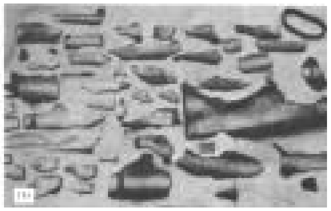
Brittle:
No
warning

Example: Failure of a Pipe

Ductile failure:
-one piece
-large
deformation



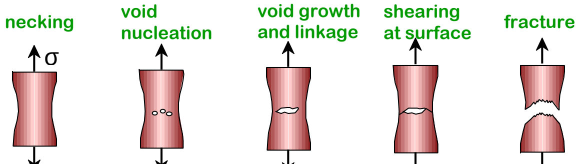
Brittle failure:
-many pieces
-small
deformation



Colangelo/Heiser Fig. 4.1

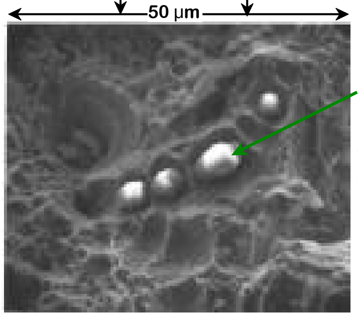
Moderately Ductile Fracture Surfaces

- Evolution to failure



Callister, Fig. 8.2

- Resulting fracture surface: (steel)



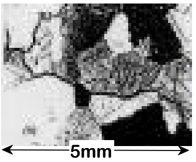
Particles (esp. larger ones) are often the source of void nucleation

Colangelo and Heiser Fig. 11.28

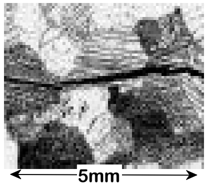
Brittle Fracture Surfaces

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

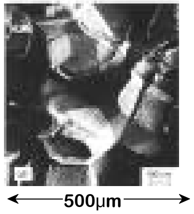
Iron
(metal)
ASM Handbook



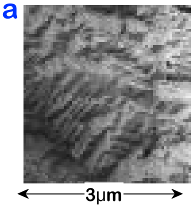
Iron
(metal)
ASM Handbook



Polypropylene
(polymer)
Hertzberg, Fig. 7.35(d)

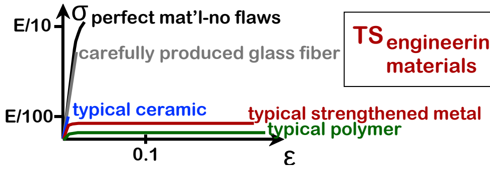


Alumina
(ceramic)
Frechette, Fig. 7-3



Ideal versus Real Materials

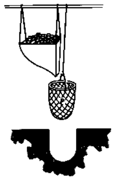
- Stress-strain behavior (Room T):



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

- DaVinci (500 years ago!) Observed...
  - -The longer the wire, the smaller the load to fail it.

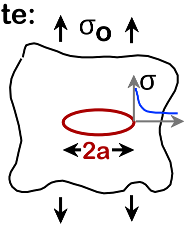
Reasons...
- -Flaws cause premature failure.
- -Larger samples are more flawed!



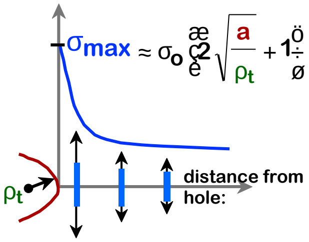
Hertzberg, Fig. 7.4

Flaws Produce Stress Concentrations!

- Elliptical hole in a plate:

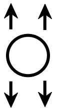


- Stress distrib. in front of hole:



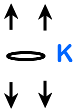
- Stress concentration factor: $K_t = \sigma_{max} / \sigma_o$
- Large K_t promotes failure

NOT SO BAD



$K_t=3$

BAD!



$K_t>>3$

Engineering Design

- Avoid sharp corners!

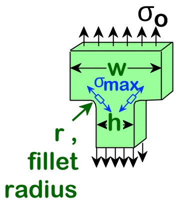
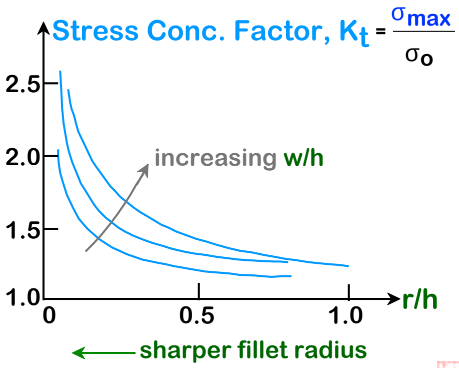
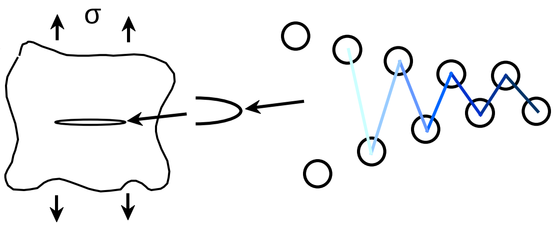


Fig. 8.8(c) Callister



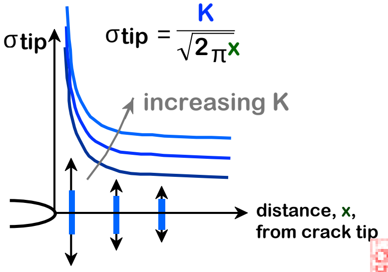
When does a crack propagate?

- ρ_t at a crack tip is very small!



- Result: the stress is very large
- Crack propagates when the tip stress is large enough to make:

$$\boxed{K = K_c}$$



$$\sigma_{tip} = \frac{K}{\sqrt{2\pi x}}$$

Effects of Geometry, Load, & Material

- Condition for crack propagation:

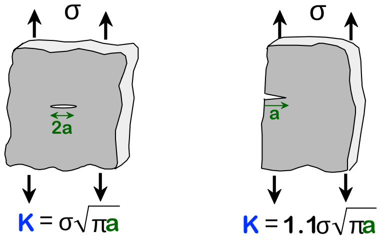
$$K \geq K_c$$

Stress Intensity Factor: depends on load, geometry

Fracture Toughness: depends on the material, temperature, rate of loading

- Values of K for some standard loads & geometries:

units of K:
MPa$\sqrt{m}$
or
ksi$\sqrt{in}$



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

Embedded crack

$K = 1.1\sigma\sqrt{\pi a}$

Edge crack

Fig. 8.11
Callister

Comparison: Fracture Toughness Values

$$K_c^{metals} > K_c^{composites} > K_c^{ceramics} \approx K_c^{polymers}$$

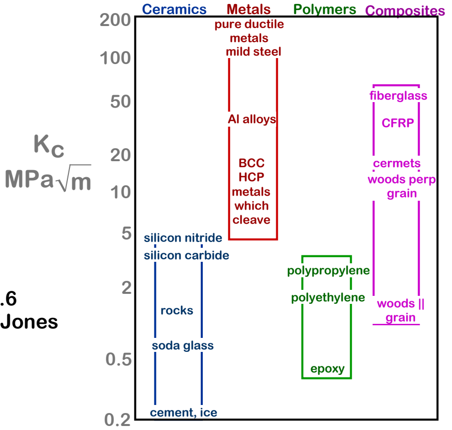


Fig. 13.6
Ashby/Jones

Design Against Crack Growth

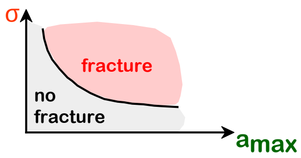
- Crack Growth Condition: $K = K_c$

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

$$Y = \begin{cases} 1.0 \text{(internal crack, length = 2a)} \\ 1.1 \text{(surface crack, depth = a)} \end{cases}$$

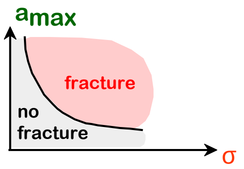
- The largest, most stressed cracks grow first!
- Result 1: Max. flaw size dictates design stress

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



- Result 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 $K_c = 26\text{MPa}\sqrt{m}$
- Two designs to consider...
- Design A
  -largest flaw: 9mm
  -failure stress = 112MPa
- Design B
  -same material as in A
  -largest flaw: 4mm
  -failure stress = ?

First: Recall that $\sigma_c = \frac{K_c}{Y\sqrt{\pi a_{max}}}$

Same for both designs (both designs use same material)

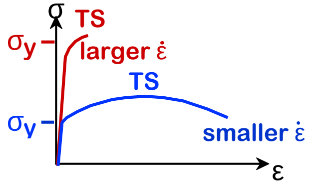
Same for both designs

Result: $\sigma_c\sqrt{a_{max}}$ = same value for both designs!

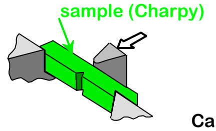
Answer: $\sigma_c^B = \sigma_c^A\sqrt{\frac{a_{max}^A}{a_{max}^B}}$ 9mm 4mm $\boxed{\sigma_c^B = 168\text{MPa}}$

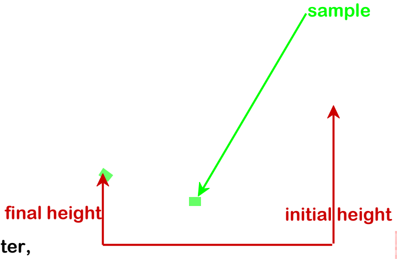
Reducing flaw size pays off!

Loading Rate



- Increased loading rate...
  -increases σ_y and TS
  -decreases %EL
- Reason?
  -Increased loading rate gives less time for dislocations to move past obstacles.
- Impact loading:
  -severe testing case
  -more brittle
  -smaller toughness



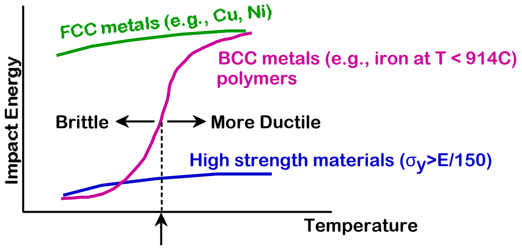


Callister, Fig. 8.16

Temperature

- Increasing temperature...
  -increases %EL and K_c
- Ductile-to-brittle transition temperature...

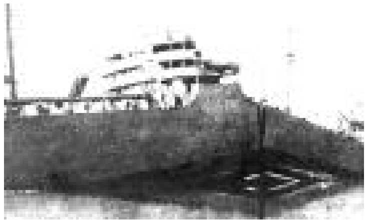
BNT, Fig. 6.21

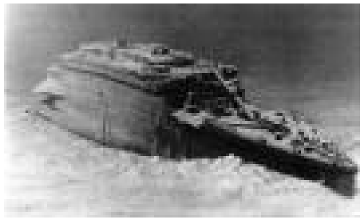


Ductile-to-brittle transition temperature

Design: Stay above Ductile-Brittle Transition Temperature

- WWII: Liberty Ships
- Pre WWII: The Titanic


Hertzberg, Fig. 7.1(a)


Hertzberg, Fig. 7.1(b)

Problem: Ductile-Brittle Transition Temp ~ Room Temperature

Fatigue

- Fatigue = Failure under cyclic stress

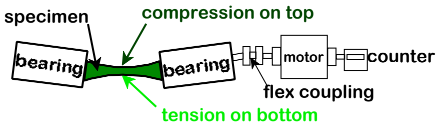
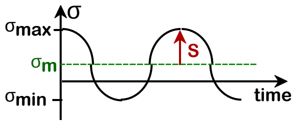


Fig. 8.21, Callister

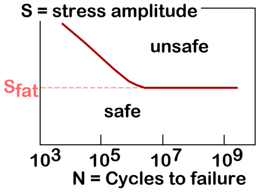
- Stress varies with time
- Key parameters:
  S and σ_m



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

Fatigue Design Parameters

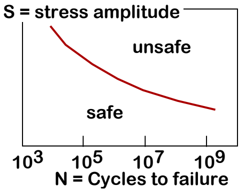
- Fatigue limit, S_{fat}:
  -No fatigue if $S < S_{fat}$.



case for steel (typ.)

Fig. 8.22(a), Callister

- Sometimes, the fatigue limit is zero!
  S_{fat} = 0!



case for Al (typ.)

Fig. 8.22(b), Callister

Fatigue Mechanism

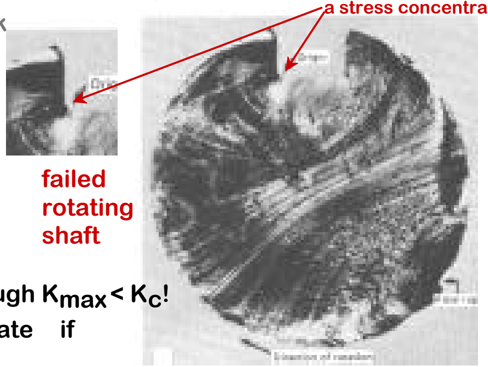
- Crack grows incrementally

increase in crack length per cycle

typ. 1 to 6

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

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



origin of fatigue crack: a stress concentration!

failed rotating shaft

- Key points:
  -failed even though $K_{max} < K_c$!
  -crack growth rate if
    $\Delta\sigma$
    a
    frequency of loading

Fig. 8.26, Callister

Improving Fatigue Life

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

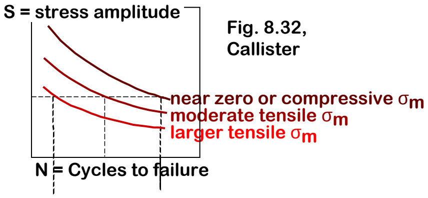
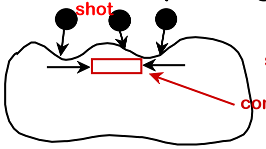


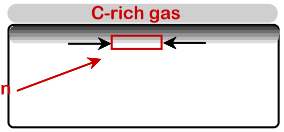
Fig. 8.32, Callister

- Ex. 1: shot peening



put surface into compression

- Ex. 2: carburizing



2. Remove stress concentrators

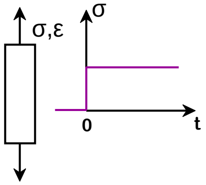
bad better

bad better

Fig. 8.33, Callister

Creep

- Requires elevated Temp: $T > 0.4T_{melt}$
- Deformation changes with time



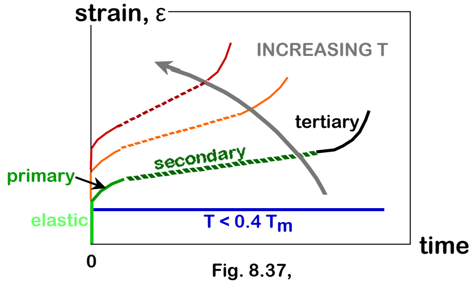


Fig. 8.37, Callister

Secondary Creep

- Most of component life spent here
- Strain rate is constant

  -strain hardening balanced by recovery

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

K_2: material constant
σ: applied tensile stress
n: stress exponent (material parameter)
Q_c: activation energy for creep (material parameter)
T: temperature

Eqn. 8.34, Callister

- Strain rate increases with...
  - -applied stress
  - -temperature

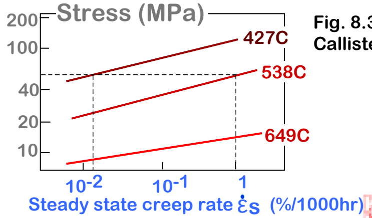


Fig. 8.39, Callister

Creep Failure

- Failure occurs along grain boundaries

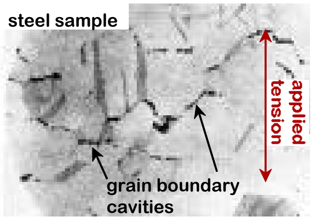


Fig. 4.32, Colangelo & Heiser

- Cavities link up

$$T\cdot(20+\log t_r) \approx L(\sigma)$$

T: Temp.
t_r: Time to failure
σ: Stress

- Example: S-590 Iron:

  T = 800°C, σ = 20ksi

$$T\cdot(20+\log t_r) \approx L(\sigma)$$

1073K

24×10^3 (K-log hr)

t_r=233hr

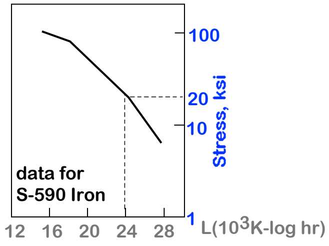


Fig. 8.40, Callister

SUMMARY

- Engineering materials:

  don't reach theoretical strength.
- Flaws:

  produce stress conc. that cause premature failure.
- Sharp corners:

  produce large stress conc. and premature failure.
- Failure:

  -for constant σ , $T < 0.4T_m$: $K > K_c$

  In general, K as:
  -σ
  -crack size

  K_c: larger for metals, smaller for ceramics, many polymers.
  In general, K_c as:
  -as σ_y
  -T
  -rate of loading

  -for cyclic σ:

  N_{fail} as Δσ

  -for higher T ($T > 0.4T_m$):

  t_{fail} as σ or T