Chapter 9: Failure
MODERATELY DUCTILE FAILURE

- Evolution to failure:
  - necking
  - void nucleation
  - void growth and linkage
  - shearing at surface
  - fracture

- Resulting fracture surfaces (steel)
  - particles serve as void nucleation sites.


“Cup and cone” ductile fracture
Ductile Fracture surface

From center of specimen

From shear edge of specimen
BRITTLE FRACTURE

- Intergranular (between grains)
  - 304 S. Steel (metal)

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

Initiation point
Brittle fracture surface

transgranular    intergranular

160 μm        4 mm
Failure MODE

Mode I
  tension

Mode II
  sliding

Mode III
  Tearing
FLAWS ARE STRESS CONCENTRATORS

• Stress distribution in front of a hole:

\[
\sigma_m = \sigma_0 \left[ 1 + 2 \left( \frac{a}{\rho_t} \right)^{1/2} \right]
\]

• Stress conc. factor: \( K_t = \frac{\sigma_{\text{max}}}{\sigma_0} \) OR \( K_t = 2 \left( \frac{a}{\rho_t} \right)^{1/2} \)

• Large \( K_t \) promotes failure:

NOT SO BAD

\( K_t=3 \)  BAD!

\( K_t>>3 \)
Example of commonly used shape

\[ K_t = \frac{\sigma_{\text{max}}}{\sigma_o} \]

- Avoid sharp 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.)
Based on data in Table B5, Callister 6e.

Composite reinforcement geometry is: \( f = \) fibers; \( sf = \) short fibers; \( w = \) whiskers; \( p = \) particles. Additional data as noted (vol. fraction of reinforcement):

2. (55 vol\%) Courtesy J. Cornie, MMC, Inc., Waltham, MA.
4. Courtesy CoorsTek, Golden, CO.
Crack growth condition: $K \geq K_c$

$Y\sigma\sqrt{\pi a}$

Largest, most stressed cracks grow first!

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

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

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

$$a_{\text{max}} < \frac{1}{\pi} \left( \frac{K_c}{Y\sigma_{\text{design}}} \right)^2$$
• **Increased loading rate...**
  --increases $\sigma_y$ and TS
  --decreases %EL

• **Why?** An increased rate gives less time for disl. to move past obstacles.

• **Impact loading:**
  --severe testing case
  --more brittle
  --smaller toughness

Adapted from Fig. 8.11(a) and (b), *Callister 6e*. (Fig. 8.11(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.)
• Increasing temperature...
  --increases %EL and $K_c$

• Ductile-to-brittle transition temperature (DBTT)...

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**TEMPERATURE**

![Graph showing the ductile-to-brittle transition temperature (DBTT) for different materials. The graph plots impact energy against temperature, with lines for low-strength (FCC and HCP) metals, low-strength steels (BCC), and high-strength materials, illustrating the change in behavior as temperature increases.]
Fatigue = failure under cyclic stress.

Stress varies with time.
--key parameters are $S$ and $\sigma_m$

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

Adapted from Fig. 8.16, *Callister 6e*. (Fig. 8.16 is from *Materials Science in Engineering, 4/E* by Carl A. Keyser, Pearson Education, Inc., Upper Saddle River, NJ.)
FATIGUE DESIGN PARAMETERS

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

- Sometimes, the fatigue limit is zero!

![Graph showing stress amplitude ($S$) vs. cycles to failure ($N$) for steel and Al.](image)
Fatigue Mechanism

Stable crack growth (stage II)

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

Striations – not visible to eye
Beachmarks – visible to eye
1. Impose a compressive surface stress (to suppress surface cracks from growing)

--Method 1: shot peening

2. Remove stress concentrators.

--Method 2: carburizing

Adapted from Fig. 8.22, Callister 6e.

Adapted from Fig. 8.23, Callister 6e.
• **Case Hardening:**
  --Diffuse carbon atoms into the host iron atoms at the surface.
  --Example of interstitial diffusion is a case hardened gear.

• **Result:** The "Case" is
  --hard to deform: C atoms "lock" planes from **shearing**.
  --hard to crack: C atoms put the surface in compression.
• Occurs at elevated temperature, $T > 0.4 \ T_{\text{melt}}$
• Deformation changes with time.

Adapted from Figs. 8.26 and 8.27, Callister 6e.
MEASURING ELEVATED T RESPONSE

- Elevated Temperature Tensile Test ($T > 0.4 \ T_{\text{melt}}$).
- Creep test

\[ \text{slope} = \dot{\varepsilon}_{\text{SS}} = \text{steady-state creep rate} \]

- Most of component life spent in secondary creep
- Strain rate is constant at a given $T$, $\sigma$
  --strain hardening is balanced by recovery

- Generally,
  \[
  \dot{\varepsilon}_{\text{SS}} \text{ceramics} < \dot{\varepsilon}_{\text{SS}} \text{metals} << \dot{\varepsilon}_{\text{SS}} \text{polymers}
  \]