Fracture and fatigue

Key point:
Preexisting surface flaws and preexisting internal cracks play a central role in the failure of materials.

ISSUES TO ADDRESS...

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

Fracture mechanisms

• Ductile fracture
  – Occurs with plastic deformation and with high energy absorption before fracture

• Brittle fracture
  – Little or no plastic deformation with low energy absorption
  – Catastrophic
An oil tanker that fractured in a brittle manner by crack propagation around its girth

**Ductile vs Brittle Failure**

- **Classification:**
  
  Fracture behavior
  
<table>
<thead>
<tr>
<th>%AR or %EL</th>
<th>Very Ductile</th>
<th>Moderately Ductile</th>
<th>Brittle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moderate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Small</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Ductile fracture is usually 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

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

- **Evolution to failure:**

  - necking
  - void nucleation
  - void growth and linkage
  - shearing at surface
  - fracture

- **Resulting fracture surfaces (steel)**

  - 50 mm particles serve as void nucleation sites.


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

Adapted from Fig. 8.3, Callister 7e.

- cup-and-cone fracture
- brittle fracture

Fractured aluminium alloy I, with a dimpled texture
Fractured aluminium alloy II, with a typical cleavage texture
Scanning electron micrographs (a) spherical dimples characteristic of ductile fracture, (b) parabolic-shaped dimples characteristic of ductile fracture.

Brittle Failure

Arrows indicate origin of crack
Transgranular fracture

Intergranular fracture

Brittle Failure

Principles of fracture mechanics

Flaws are Stress Concentrators or stress raisers

Results from crack propagation

- Griffith Crack

\[ S_m = 2S_o \left( \frac{a}{r_t} \right)^{1/2} = K_t S_o \]

where

- \(r_t\) = radius of curvature of the crack tip
- \(S_o\) = applied stress
- \(S_m\) = stress at crack tip

\(K_t\) : stress concentration factor
Concentration of Stress at Crack Tip

Adapted from Fig. 8.8(b), Callister 7e.

Engineering Fracture Design

- Avoid sharp corners!

\[ s_m = 2s_o \left( \frac{a}{r_f} \right)^{1/2} = K_t s_o \]

Stress Conc. Factor, \( K_t = \frac{s_{\text{max}}}{s_o} \)

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 propagate due to sharpness of crack tip

- A plastic material deforms at the tip, "blunting" the crack.

Energy balance on the crack

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

When Does a Crack Propagate?

- Critical stress for crack propagates in a brittle material

\[ \sigma_m > \sigma_c \quad \text{i.e.,} \quad \sigma_c = \left( \frac{2Eg_s}{pa} \right)^{1/2} \]

or \[ K_t > K_c \]

where

- \( E \) = modulus of elasticity
- \( g_s \) = specific surface energy
- \( a \) = one half length of internal crack
- \( K_c = \frac{s_c}{s_0} \)

- For ductile \( \Rightarrow \) replace \( g_s \) by \( g_s + g_p \),

where \( g_p \) is plastic deformation energy

Example problem 8.1, p217
Fracture toughness

Critical stress for crack propagation ($s_c$) and crack length ($a$)

$$K_C = Ys_c \left( \frac{P}{a} \right)^{1/2}$$

1. $Y$: geometry factor, on the order of 1
2. $s_c$: the overall applied stress at failure
3. $a$: the length of a surface crack (one-half the length of an internal crack)
4. Unit of $K_C$: MPa · m$^{1/2}$

$K_C$: fracture toughness

the critical ($c$) value of the stress intensity factor at a crack tip necessary to produce failure

The three modes of crack surface displacement

(a) **mode I**, opening or tensile mode
   plane strain fracture toughness

$$K_{IC} = Ys_c \left( \frac{P}{a} \right)^{1/2}$$

(b) **mode II**, sliding mode

(c) **mode III**, tearing mode
### Room-temperature mechanical properties for selected engineering materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Yield Strength</th>
<th>Fracture Toughness</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MPa</td>
<td>ksi</td>
</tr>
<tr>
<td><strong>Metals</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminum Alloy&lt;sup&gt;a&lt;/sup&gt;</td>
<td>495</td>
<td>72</td>
</tr>
<tr>
<td>(7075-T651)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminum Alloy&lt;sup&gt;a&lt;/sup&gt;</td>
<td>345</td>
<td>50</td>
</tr>
<tr>
<td>(2024-T3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Titanium Alloy&lt;sup&gt;b&lt;/sup&gt;</td>
<td>910</td>
<td>132</td>
</tr>
<tr>
<td>(Ti-6Al-4V)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alloy Steel&lt;sup&gt;c&lt;/sup&gt;</td>
<td>1640</td>
<td>238</td>
</tr>
<tr>
<td>(4340 tempered at 260°C)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alloy Steel&lt;sup&gt;c&lt;/sup&gt;</td>
<td>1420</td>
<td>206</td>
</tr>
<tr>
<td>(4340 tempered at 425°C)</td>
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<td></td>
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<tr>
<td><strong>Ceramics</strong></td>
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<td></td>
</tr>
<tr>
<td>Concrete</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Soda-Lime Glass</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Aluminum Oxide</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td><strong>Polymers</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polystyrene (PS)</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Poly(methyl methacrylate) (PMMA)</td>
<td>53.8–73.1</td>
<td>7.8–10.6</td>
</tr>
<tr>
<td>Polycarbonate (PC)</td>
<td>62.1</td>
<td>9.0</td>
</tr>
</tbody>
</table>


### Fracture Toughness

![Fracture Toughness Diagram](image)
Design Against Crack Growth

- Crack growth condition:
  \[ K \geq K_c = Y \sqrt{\pi a} \]

- **Largest, most stressed** cracks grow first!

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

\[
S_{\text{design}} < \frac{K_c}{Y \sqrt{\pi a_{\text{max}}}}
\]

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

\[
a_{\text{max}} < \frac{1}{Y} \left( \frac{K_c}{S_{\text{design}}} \right)^2
\]

Design Example: Aircraft Wing

- Material has \( K_c = 26 \text{ MPa} \cdot \text{m}^{0.5} \)
- 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
    - failure stress = ?

- Use...
  \[
  s_c = \frac{K_c}{Y \sqrt{\pi a_{\text{max}}}}
  \]

- Key point: \( Y \) and \( K_c \) are the same in both designs.

--Result:

\[
\frac{112 \text{ MPa} \sqrt{9 \text{ mm}}}{4 \text{ mm}} = \frac{4 \text{ mm}}{4 \text{ mm}}
\]

- Reducing flaw size pays off!

Answer: \((s_c)_B = 168 \text{ MPa}\)
**Loading Rate**

- Increased loading rate...
  - increases $s_y$ and $TS$
  - decreases $\%EL$

- Why? An increased rate gives less time for dislocations to move past obstacles.

**Impact fracture testing**

**Charpy test of impact energy**

1. A notched specimen – stress concentrating
2. Loading applied rapidly
3. Impact energy - the energy necessary to fracture the test specimen

The swinging pendulum
The initial height $h$
The final height $h'$
1040 carbon steel: Fe-0.4C-0.75 Mn

J: joule. 1 J = 1 N \cdot m

<table>
<thead>
<tr>
<th>Alloy Description</th>
<th>Impact energy [J ft-lb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. 1040 carbon steel</td>
<td>180 (133)</td>
</tr>
<tr>
<td>2. 8040 low alloy steel</td>
<td>25 (41)</td>
</tr>
<tr>
<td>3. 400 stainless steel</td>
<td>74 (75)</td>
</tr>
<tr>
<td>4. Ti-6Al-4V steel</td>
<td>56 (10)</td>
</tr>
<tr>
<td>5. Titanium superalloys (Ti60)</td>
<td>24 (25)</td>
</tr>
<tr>
<td>6. a. 316 stainless steel</td>
<td>91 (1)</td>
</tr>
<tr>
<td>7. b. 2024-T6 alloy aluminum</td>
<td>61 (40)</td>
</tr>
<tr>
<td>8. a. Al23Mg11 magnesium</td>
<td>41 (15)</td>
</tr>
<tr>
<td>9. b. AM60B1 magnesium</td>
<td>68 (60)</td>
</tr>
<tr>
<td>10. Aluminum bronze, 8% copper alloy</td>
<td>26 (7)</td>
</tr>
<tr>
<td>11. Monel 400 (nickel alloy)</td>
<td>200 (73)</td>
</tr>
<tr>
<td>12. Ti-50 alloy (lead alloy)</td>
<td>71 (150)</td>
</tr>
<tr>
<td>13. NO-1 Zr (refractory metal)</td>
<td>174 (128)</td>
</tr>
</tbody>
</table>

Cu: fcc, ductile

Mg alloy: hcp, relatively brittle

**Toughness obtained in a tensile test**

Toughness = \( \int s \cdot e \, ds \), the area under the \( s \cdot e \) curve

**Unit of toughness: N/m²**

Or (N/m²) \cdot (mm / mm) = N \cdot m / (mm)³

**Toughness:** the energy necessary to fracture per unit volume of material
Temperature dependence of the Charpy V-notch impact energy and shear fracture for an A283 steel.

Schematic curves for the three general types of impact energy-versus-temperature behavior
**Ductile-to-Brittle Transition Temperature (DBTT)**

1. in bcc alloys
2. an abrupt drop in ductility and toughness as the temperature is lowered

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**Plain-carbon steels with various carbon levels**

**Fe-Mn-0.05C alloys with various manganese levels**

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**Design Strategy: Stay Above The DBTT!**

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

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- **Problem: Used a type of steel with a DBTT ~ Room temp.**
Fatigue = failure under cyclic stress
- failure after N cycles
- load < T.S

Figure 8.8 Fatigue corresponds to the brittle fracture of an alloy after a total of N cycles to a stress below the tensile strength.

Fatigue-testing apparatus for making rotating-bending tests
• Stress varies with time.
  -- key parameters are $S$, $s_m$, and frequency

- $S =$ stress amplitude, $s_m =$ mean stress,
  \[ s_m = \frac{(s_{\text{max}} + s_{\text{min}})}{2} \]
  \[ S = \frac{(s_{\text{max}} - s_{\text{min}})}{2} \]
- Load ratio $R = \frac{s_{\text{min}}}{s_{\text{max}}}$

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

**Typical fatigue curve (S-N curve)**

FIG. 14.4.3

*S-N Curve (SAE 4140 Normalized Steel). S-N = cyclic stress versus number of cycles to failure. At the endurance limit, the number of cycles becomes indeterminately large.*

(Adapted from R. E. Peterson, ASTM Materials Research and Standards.)
Fatigue Design Parameters

- **Fatigue limit, \( S_{\text{fat}} \):**
  --no fatigue if \( S < S_{\text{fat}} \)

- **Sometimes, the fatigue limit is zero! (a material does not display a fatigue limit)**

\[ S = \text{stress amplitude} \]

\[ N = \text{Cycles to failure} \]

Adapted from Fig. 8.19b, Callister 7e.

Fatigue S-N probability of failure curves for a 7075-T6 Al alloy
Fatigue Mechanism

- Crack grows incrementally
  \[
  \frac{da}{dN} = \Delta K^{1/2} \quad \text{typ. 1 to 6}
  \]
  \[
  \sim D_s \sqrt{a}
  \]
  increase in crack length per loading cycle

- Failed rotating shaft
  --crack grew even though
  \[ K_{\text{max}} < K_c \]
  --crack grows faster as
  - \( D_s \) increases
  - crack gets longer
  - loading freq. increases.

Texture of the fatigue fracture surface – clamshell or beachmark texture

Intrusions and extrusions. SEM.
Transmission electron fractograph showing fatigue striations in aluminum

Each striation is thought to represent the advance distance of a crack front during a single load cycle, striation width depends on and increases with increasing stress range.

### Improving Fatigue Life

1. Decrease the mean stress level

2. Impose a compressive surface stress (to suppress surface cracks from growing)
   - **Method 1:** shot peening
     - Put surface into compression
   - **Method 2:** carburizing

3. Remove stress concentrators.
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,
  - decreased $T$,
  - increased rate of loading.
- for cyclic $s$:
  - cycles to fail decreases as $D_s$ increases.
- for higher $T$ ($T > 0.4T_m$):
  - time to fail decreases as $s$ or $T$ increases.

SUMMARY

Homework 8.6 and 8.12, p246