BFF1113
Engineering Materials

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Course Guidelines:

1. Introduction to Engineering Materials
2. Bonding and Properties
3. Crystal Structures & Properties
4. Imperfection in Solids
5. Mechanical Properties of Materials
6. Physical Properties of Materials
7. **Failure & Fundamental of Fracture**
8. Metal Alloys
9. Phase Diagram
10. Phase Transformation – Heat Treatment
11. Processing and Application of Metals
12. Ceramic Materials
13. Polymer Materials
14. Composite Materials
15. Corrosion & Degradation of Materials
16. Environment and Sustainability

Failure & Fundamental of Fracture

1. **Fundamental of Fracture**
2. **Principle of fracture mechanics**
3. **Factors of Fracture**

Fundamental of Fracture

Ductile fracture
Brittle fracture

*Fundamental of Fractur*e

Fracture:

- Separation of body into 2 or more piece in response to stress.

- Influences the selection of a material for a application, the methods of manufacturing, and the service life of the component.

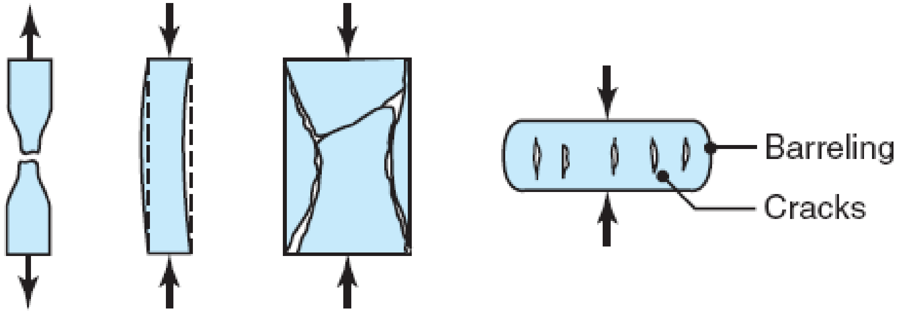
Two modes of fracture:

Ductile fracture:

- Occurs with plastic deformation
- High energy absorption

Brittle fracture

- Little or no plastic deformation
- Catastrophic
- Low energy absorption

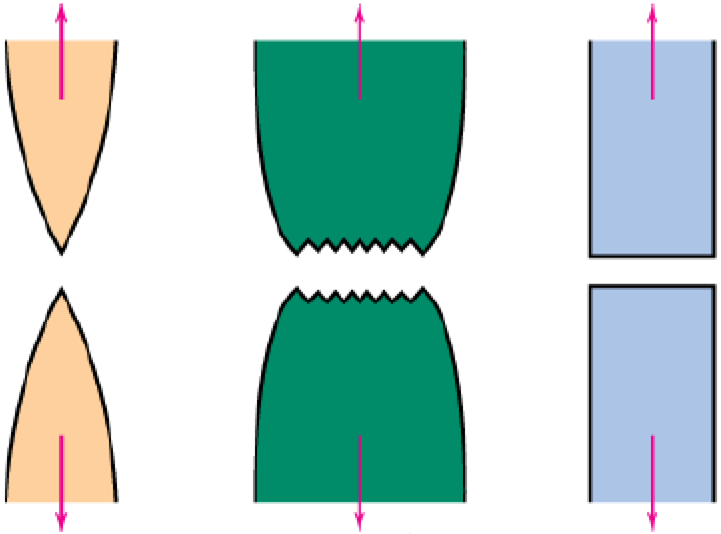


(a) (b) (c) (d)

Schematic illustration of types of failures in materials. (a) necking and fracture of ductile materials. (b) buckling of ductile material under compressive load. (c) fracture of brittle material in compression. (d) cracking on the barrel surface of ductile materials in compression.

Ductile vs Brittle Failure

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



Ductility are quantified by % elongation and % in reduction of area

Ductile: warning before fracture

Brittle: No warning

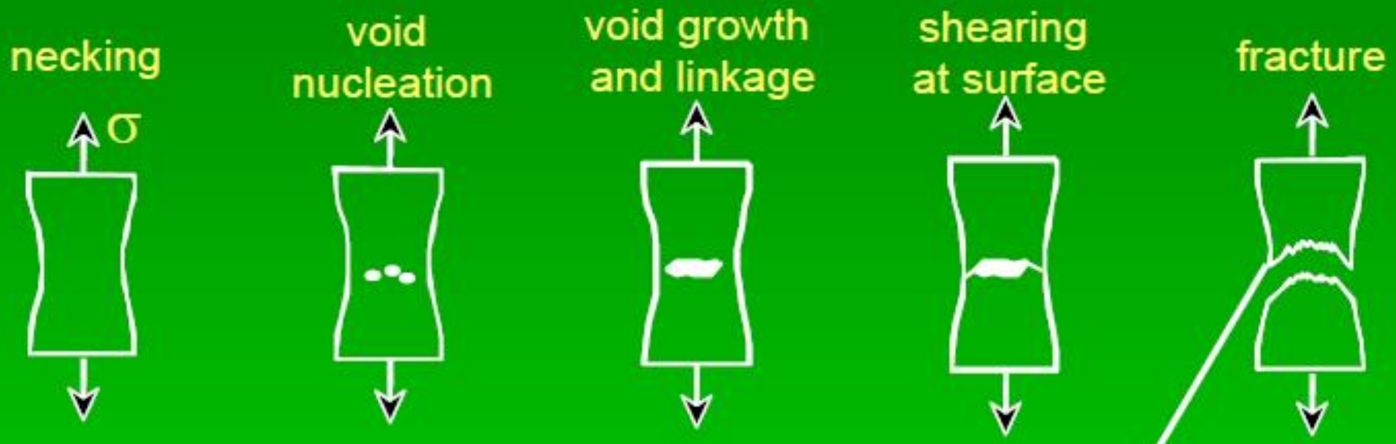
Ductile vs. Brittle Failure

cup-and-cone fracture

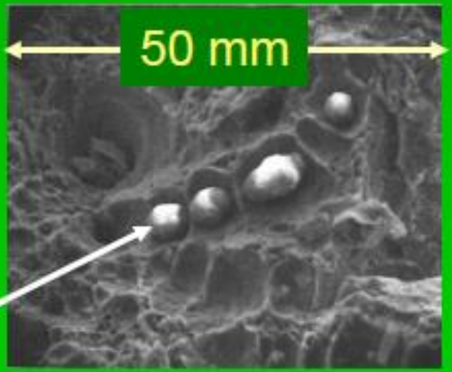
brittle fracture

Moderately Ductile Failure

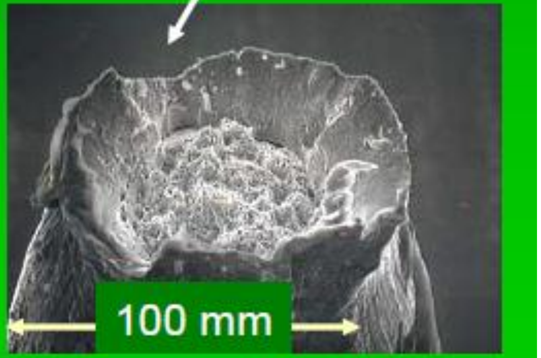
- 2 step in fracture: crack formation and crack propagation
  Evolution to failure:



- **Resulting fracture surfaces (steel)**

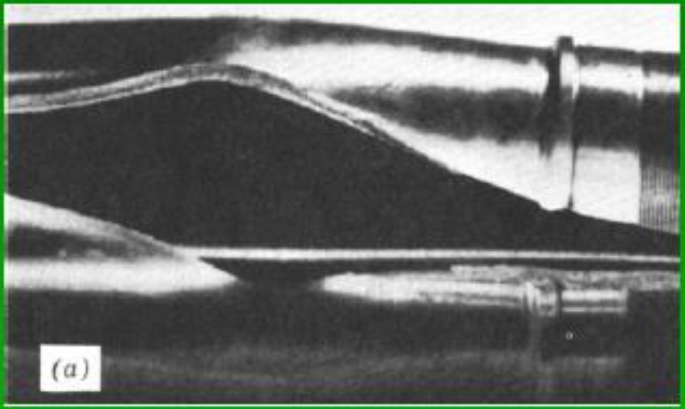


particles serve as void nucleation sites.

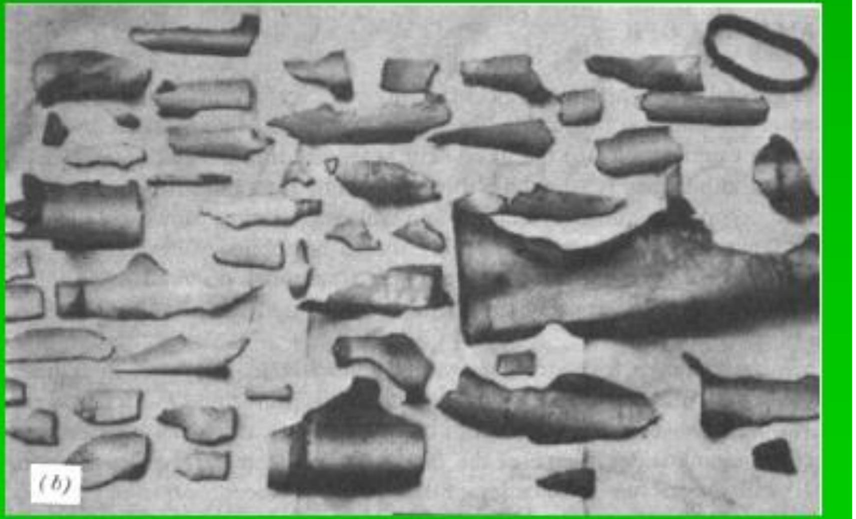


Fracture surface of tire cord wire loaded in tension. –irregular and fibrous appearance

Example: Failure of a Pipe

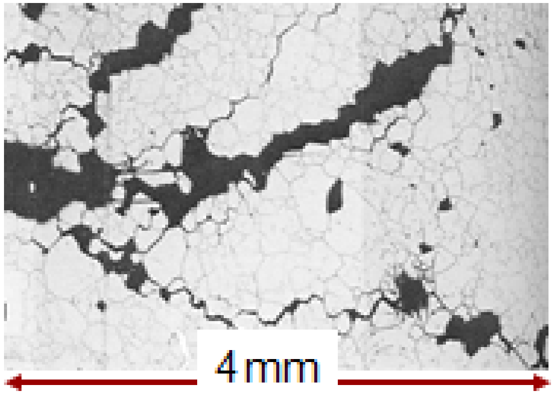


- **Ductile failure:**
  one piece
  large deformation



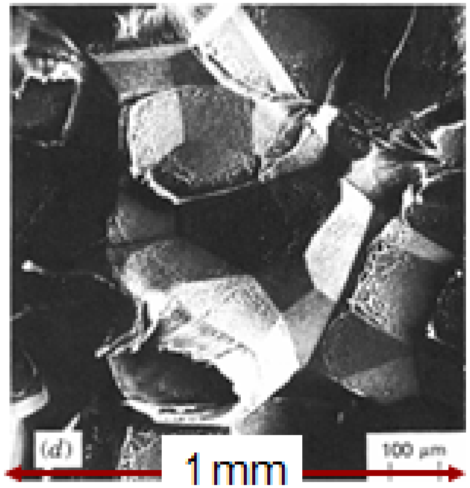
- **Brittle failure:**
  many pieces
  small deformation

- Intergranular (between 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.)



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.

(Orig. source: K. Friedrick, *Fracture 1977*, Vol. 3, ICF4, Waterloo, CA, 1977, p. 1119.)

- Transgranular (through grains)

316 S. Steel (metal)

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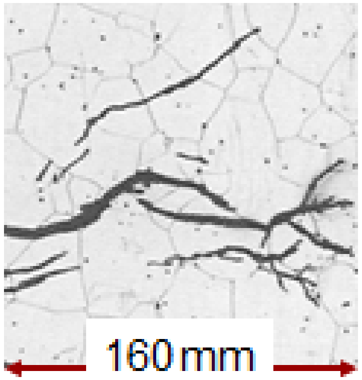

Al Oxide (ceramic)

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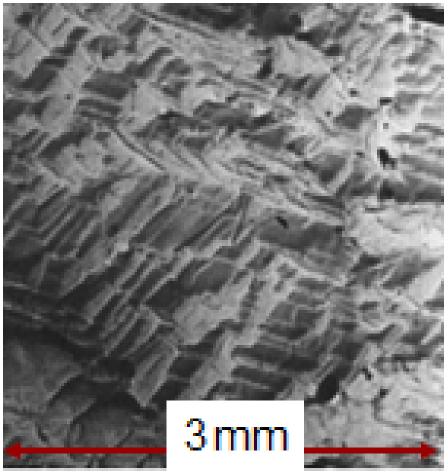
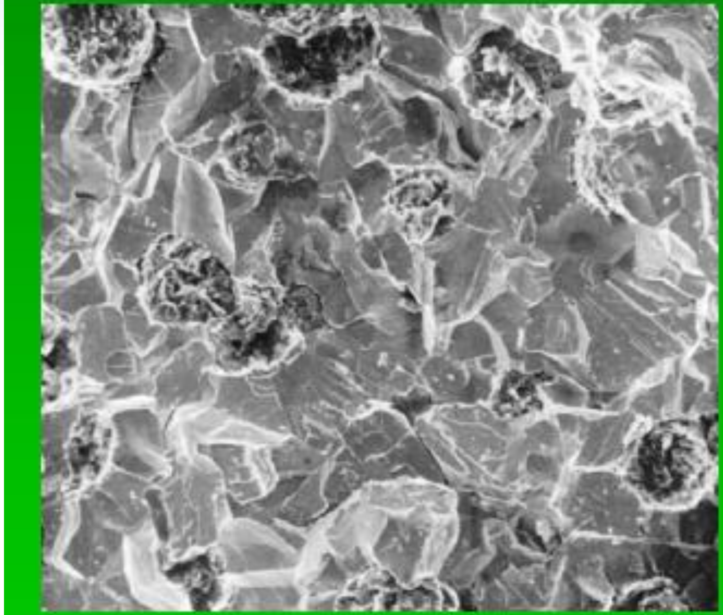
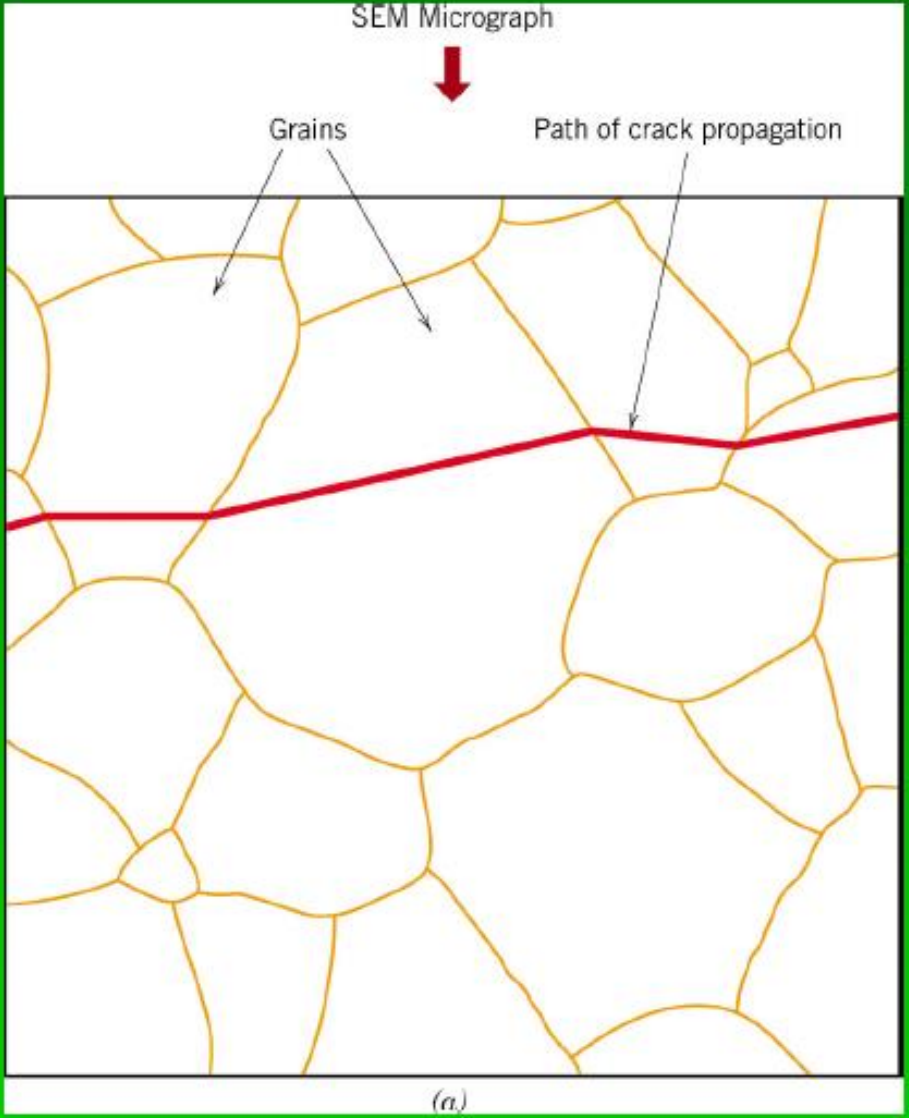


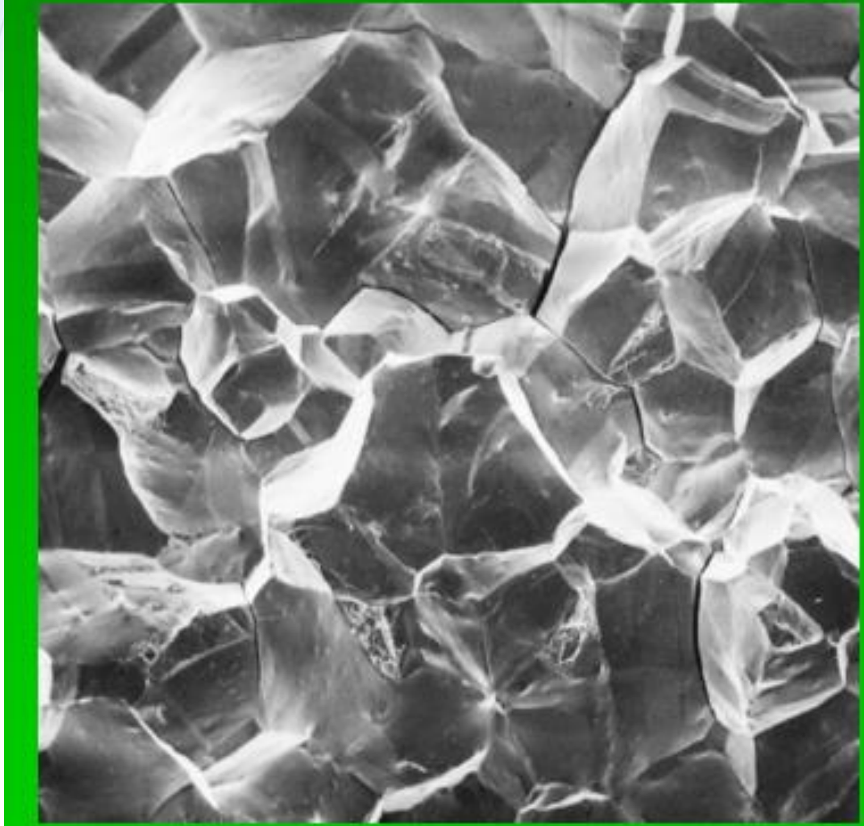
Intragranular-crack propagation through the interior of grain

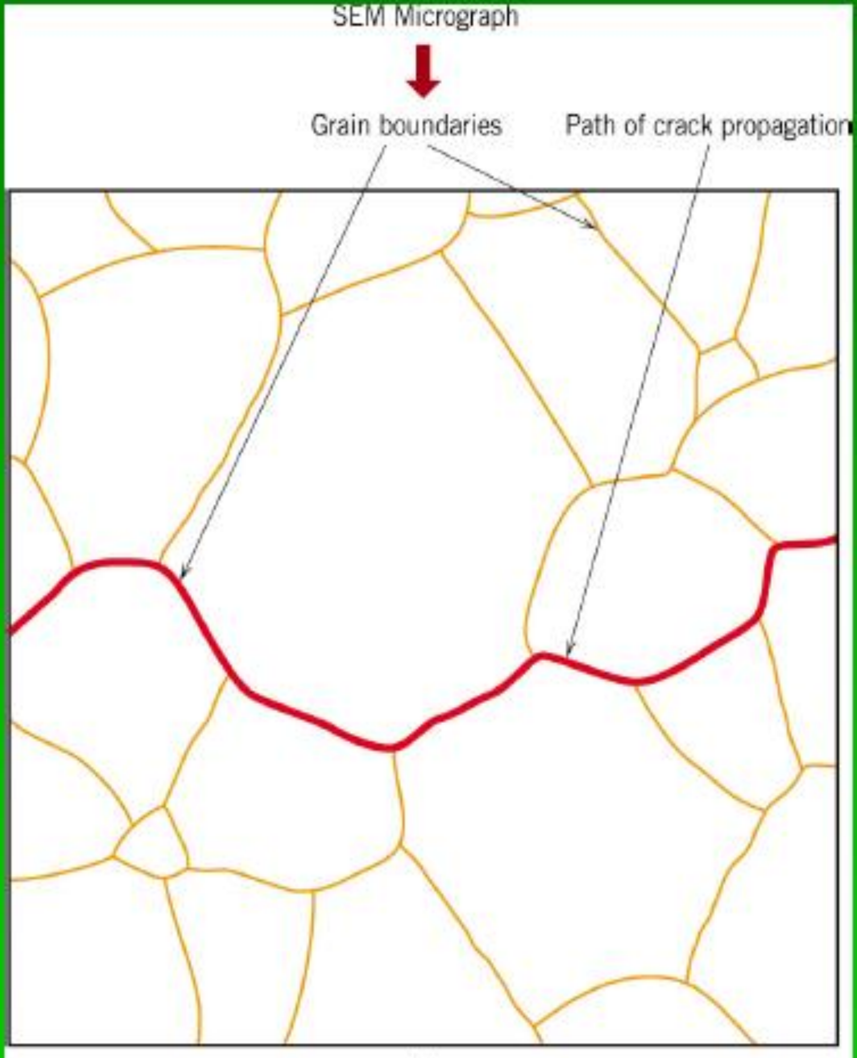
(transgranular)





Intergranular-crack propagation along the grain boundaries



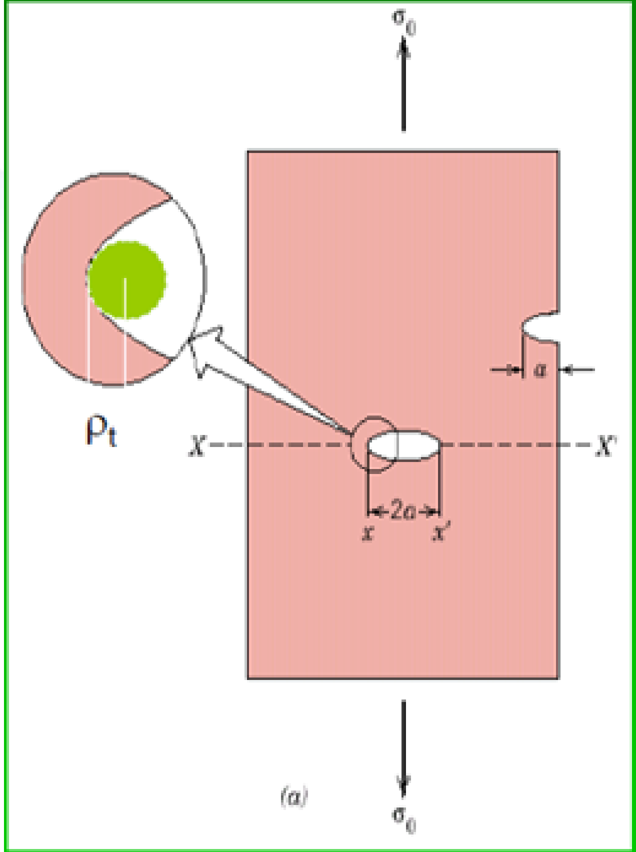


(a)

Principle of fracture mechanics

- Stress concentration
- Crack propagation
- Fracture toughness

STRESS CONCENTRATION POINT



Max stress occur at the crack tip

Can be calculated by

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

where

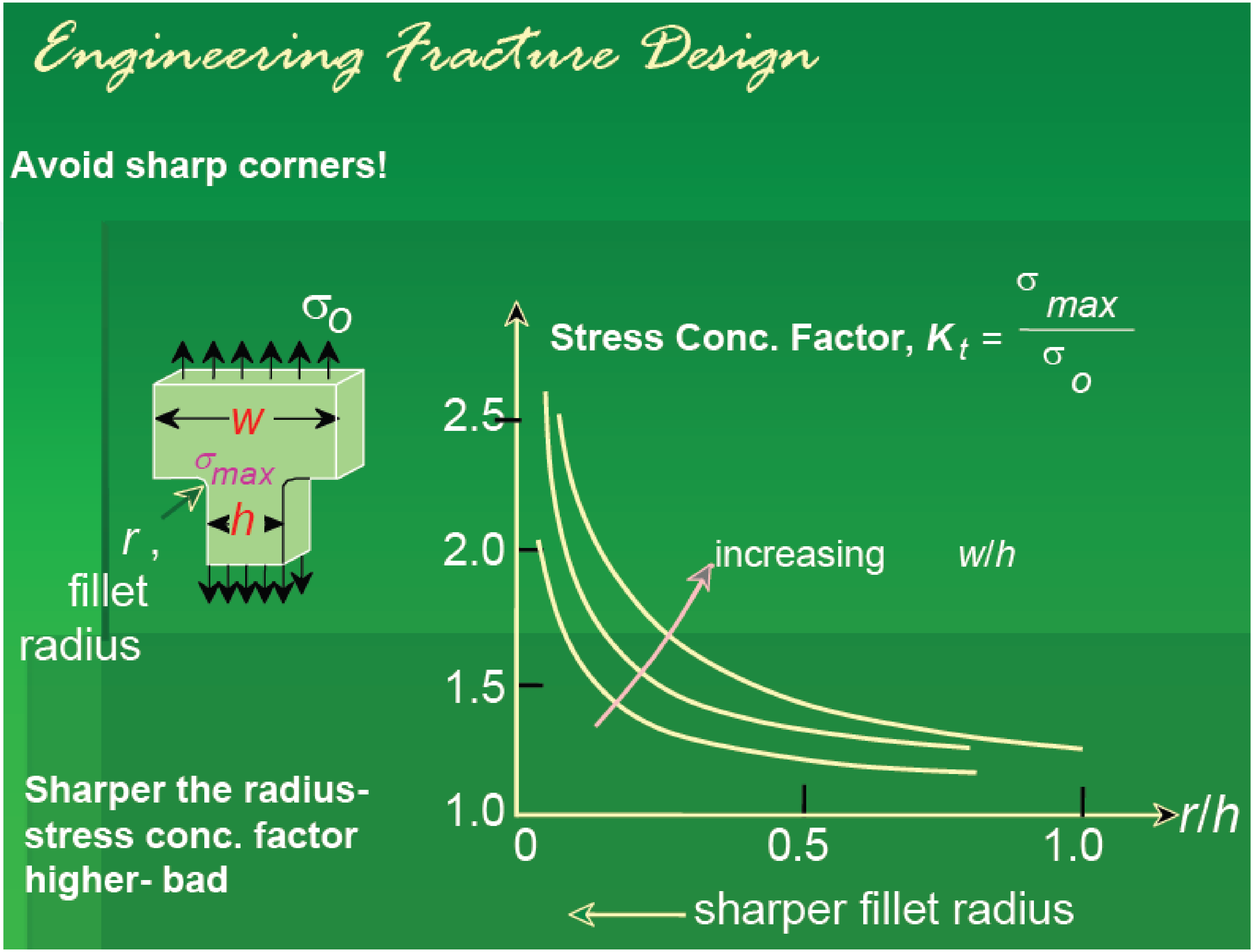
ρ_t = radius of curvature

σ_o = applied stress

σ_m = stress at crack tip

- Stress conc. factor: $K_t = \sigma_{max}/\sigma_o$ The ratio of max stress over applied stress

Stress concentration cont.



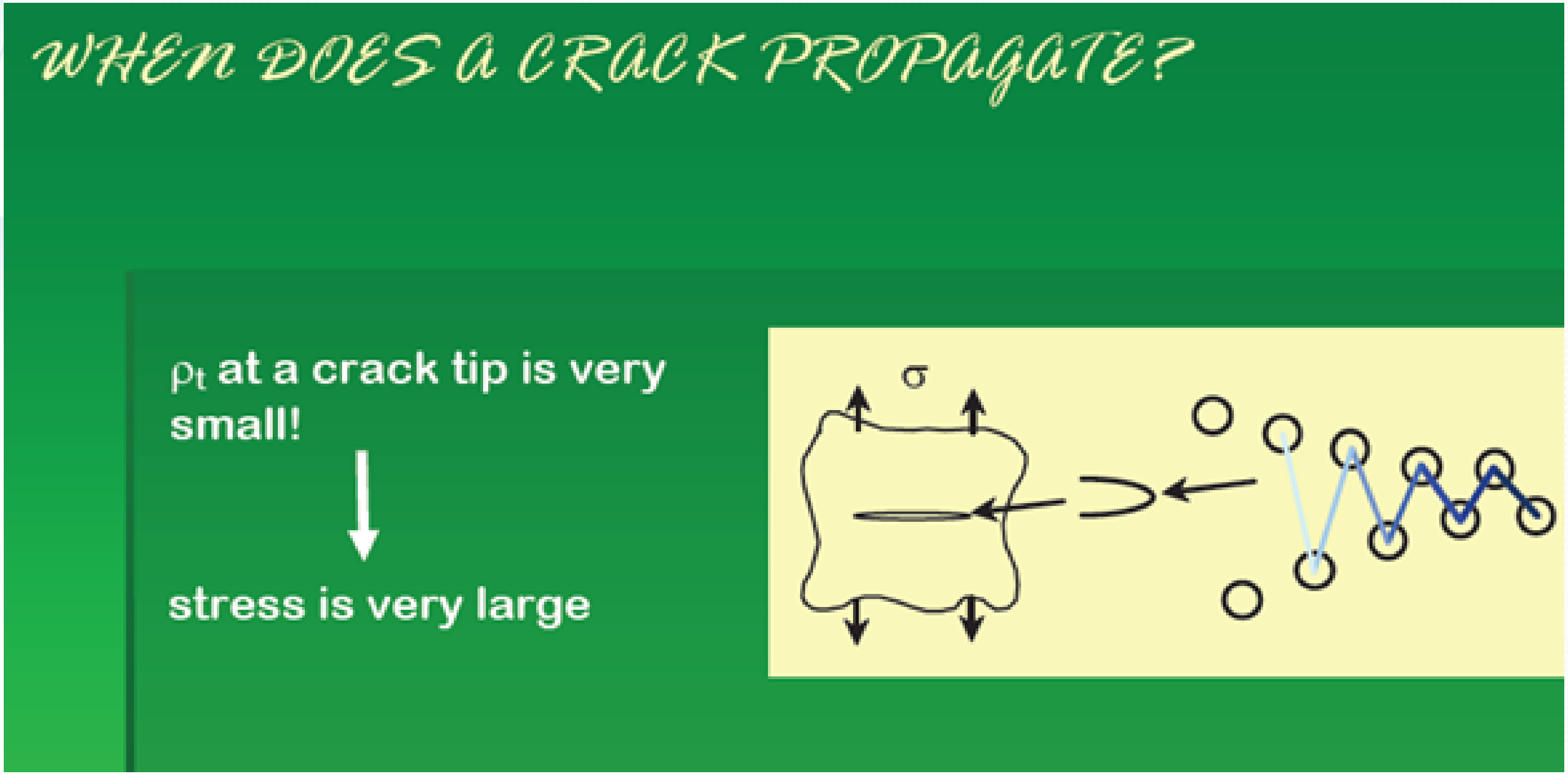
Engineering Fracture Design

Avoid sharp corners!

Stress Conc. Factor, $K_t = \frac{\sigma_{max}}{\sigma_o}$

Sharper the radius- stress conc. factor higher- bad

Crack propagation



WHEN DOES A CRACK PROPAGATE?

ρ_t at a crack tip is very small!

↓

stress is very large

- Large K_t promotes failure:

Crack propagation cont.

Criterion for Crack Propagation

Crack propagates if crack-tip stress (σ_m) exceeds a critical stress (σ_c)

i.e., $\sigma_m > \sigma_c$

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

where

- 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

EXAMPLE PROBLEM M.1

Maximum Flaw Length Computation

A relatively large plate of a glass is subjected to a tensile stress of 40 MPa. If the specific surface energy and modulus of elasticity for this glass are 0.3 J/m^2 and 69 GPa, respectively, determine the maximum length of a surface flaw that is possible without fracture.

Solution

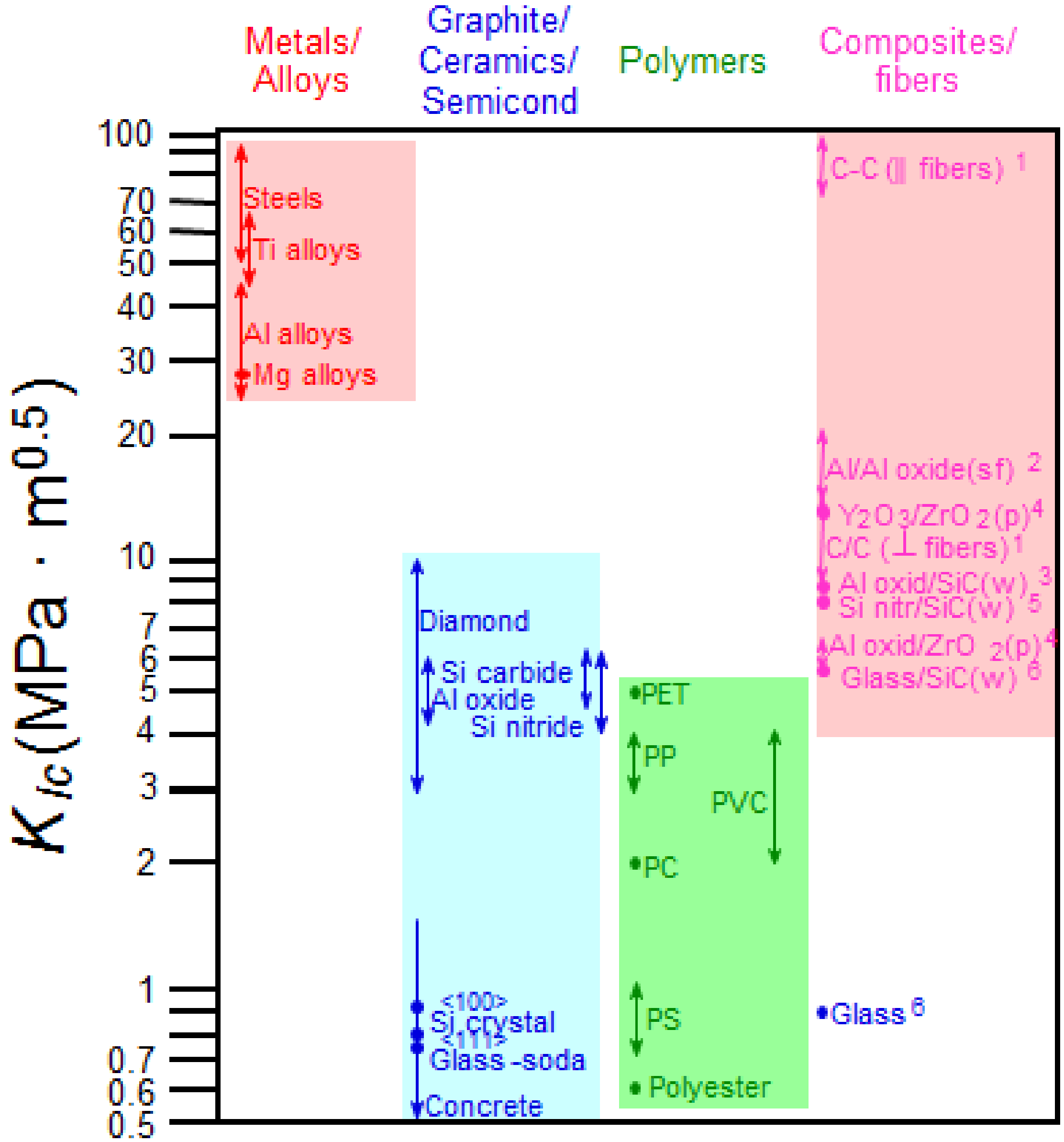
To solve this problem it is necessary to employ Equation M.3. Rearrangement of this expression such that a is the dependent variable, and realizing that $\sigma = 40$ MPa, $\gamma_s = 0.3$ J/m^2, and $E = 69$ GPa, lead to

$$a = \frac{2E\gamma_s}{\pi\sigma^2}$$

$$= \frac{(2)(69\times10^9\ \mathrm{N/m^2})(0.3\ \mathrm{N/m})}{\pi(40\times10^6\ \mathrm{N/m^2})^2}$$

$$= 8.2\times10^{-6}\ \mathrm{m} = 0.0082\ \mathrm{mm} = 8.2\ \mu\mathrm{m}$$

Fracture Toughness Ranges



Based on data in Table B.5, *Callister & Rethwisch 8e.*

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.

FRACTURE TOUGHNESS , *Kc*

a property that is a measure of a material's resistance to brittle fracture when a crack is present.

Design Against Crack Growth

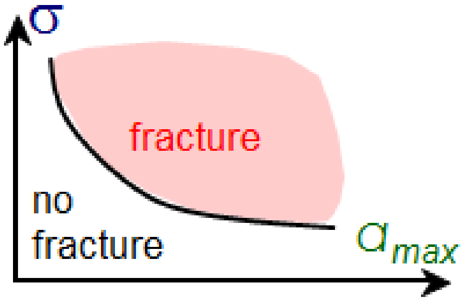
- Crack growth condition:

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

- Y is a dimensionless parameter / function that depends on both crack and specimen sizes, and geometries as well as the manner of load application.

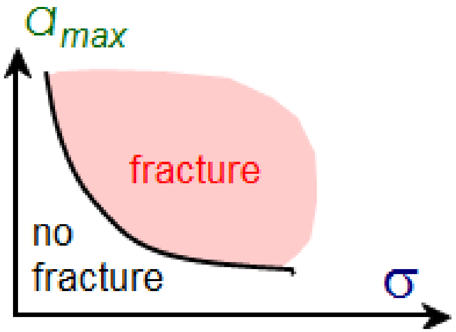
--Scenario 1: Max. flaw size dictates design stress.

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



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

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



GEOMETRY, LOAD, & MATERIAL

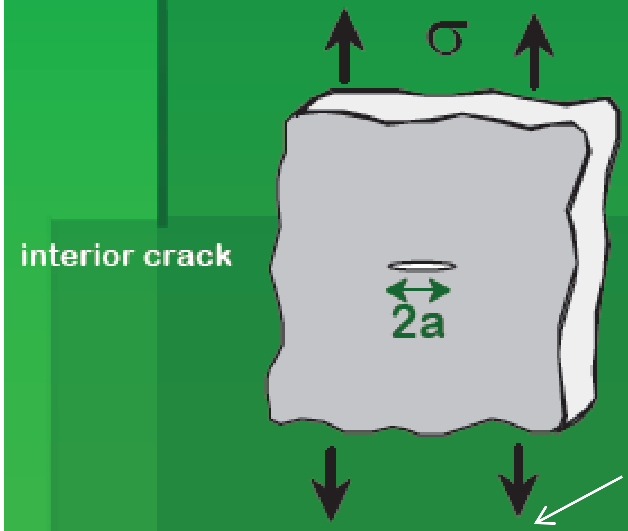
- Condition for crack propagation:

$$K \geq K_c$$

Stress Intensity Factor:
Depends on load & geometry.

Fracture Toughness:
Depends on the material, temperature, environment, & rate of loading.

- Values of K for some standard loads & geometries:



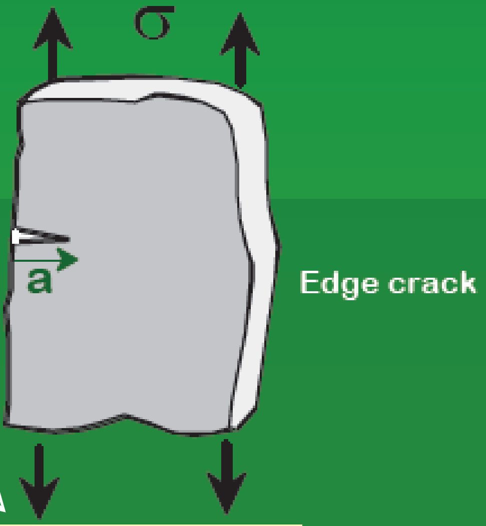
$K = \sigma\sqrt{\pi a}$

$Y = 1$

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

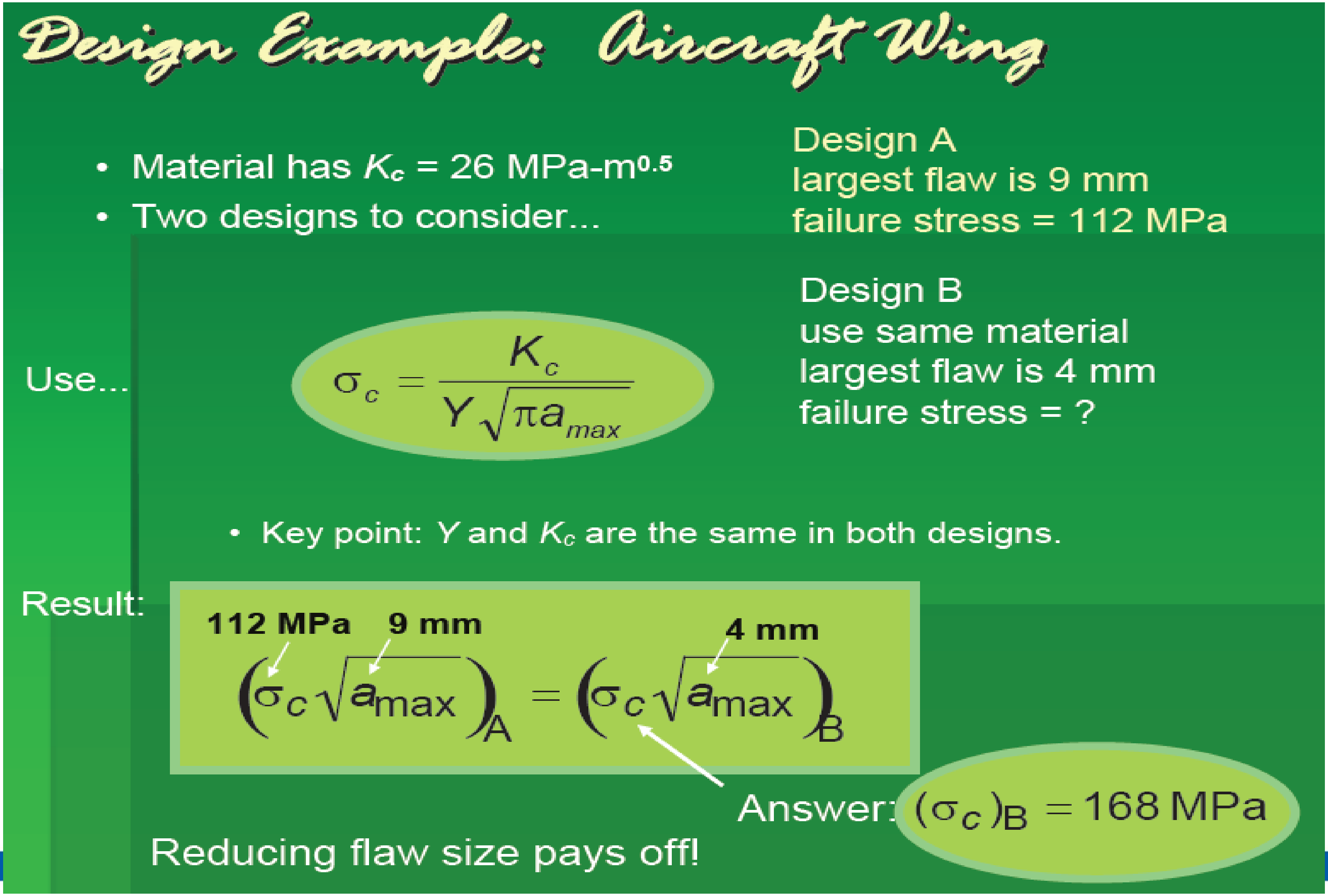
$Y = 1.1$

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



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

EXAMPLE:



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
failure stress = ?

Use...

$$\sigma_c = \frac{K_c}{Y\sqrt{\pi a_{max}}}$$

- 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

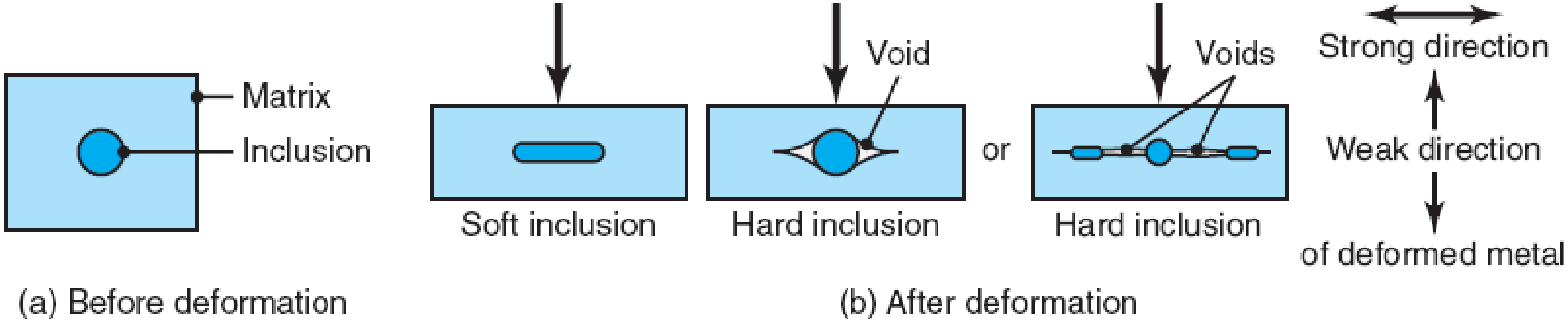
Reducing flaw size pays off!

Factors of Fracture

- Effects of inclusion
- Transition temperature

1.0: Effects of Inclusions

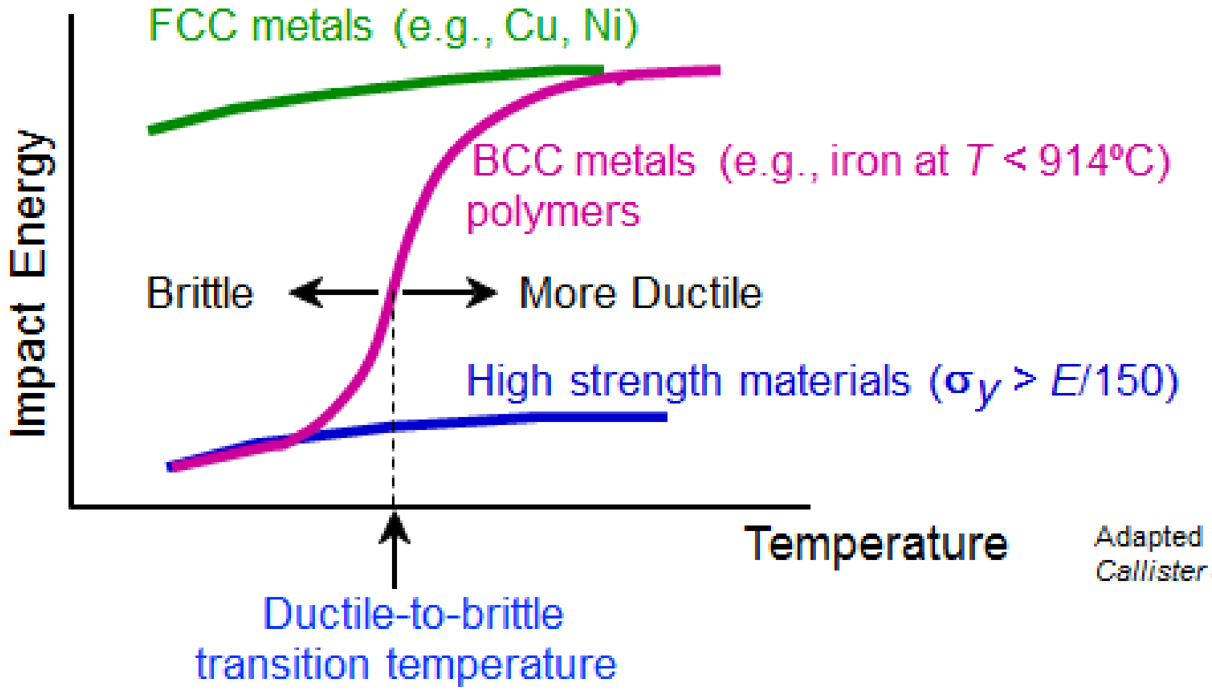
- *Inclusion of impurities* have an influence on ductile fracture and the workability of materials
- Consist of impurities of various kinds, ex: particles
- Voids and porosity can develop during processing of metals
- 2 factors affect void formation:
  1. Bond between an inclusion and the matrix
  2. Hardness of the inclusion



2.0: Transition Temperature

Influence of Temperature on Impact Energy

- **Ductile-to-Brittle Transition Temperature (DBTT)...**



Adapted from Fig. 8.15, *Callister & Rethwisch 8e.*

Design Strategy:
Stay Above The DBTT!

- **Pre-WWII: The Titanic**

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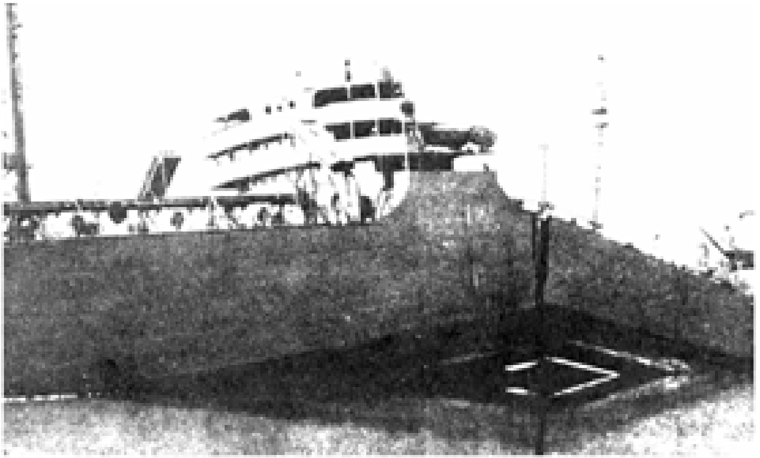
- **WWII: Liberty ships**



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- Problem: Steels were used having DBTT's just below room temperature.