Aalto University
School of Engineering

COE-C2004 - Materials Science and Engineering

Prof. Junhe Lian
Wenqi Liu (Primary teaching Assistant)
Rongfei Juan (Teaching Assistant)

Hints:

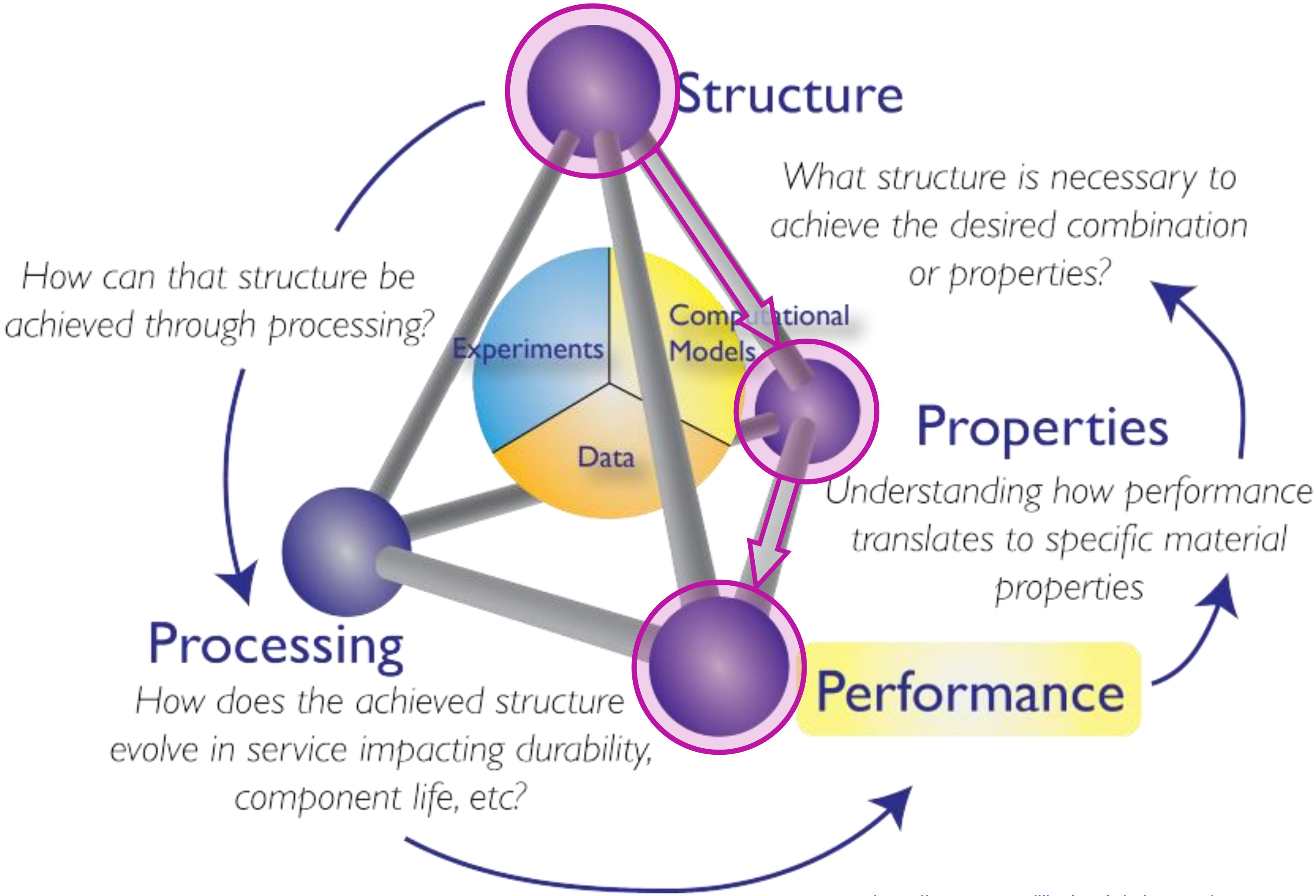
- Get learning materials from MyCourses.
- Get some coffee. Let’s watch a “movie”.
- Active participation is very much appreciated.

Ice Age

What have you learnt?

- Failure could be a catastrophe.
- Failure starts from “small” and runs “large”.
- “small” = crack; “large” = fracture
- We need a “Scrat” => Loading.
- We need an “Acorn” => Crack trigger.
- We also need time from crack to fracture => “running” rate
- …
- When failure happens, forget your belongs.

Previously



https://gems.matse.illinois.edu/educators/

Chapter 5: Failure

ISSUES TO ADDRESS...

- What is **failure** are what the different **types** of failure?
- What are the typical **characteristics** of each type of failure?
- What is the **mechanism** associated with each failure type?
- What parameter is used to quantify a material's **resistance to failure?**
- Under what **conditions/situation** does each type occur?
- What measures may be taken to **reduce the likelihood** of each failure type?

Failure

Fracture of pressure vessel

Failure: Material or component stops complying with the service requirement.

Failure types

The Titanic

Reprinted w/ permission 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*.)

- Failure
  - Fracture
    - Cleavage fracture
    - Ductile fracture
  - Corrosion
  - Creep
  - Fatigue

Rusted Gears

https://phys.org/news/2018-10-unmasking-corrosion-thin-metals.html

Creep in Turbine Blade

https://www.researchgate.net/publication/259911455_Development_of_Non-Destructive_Small_Specimen_Creep_Testing_Techniques/figures?lo=1

https://airwaysmag.com/airlines/32-years-aloha-flight-243-accident/

Aloha Airlines Flight 243

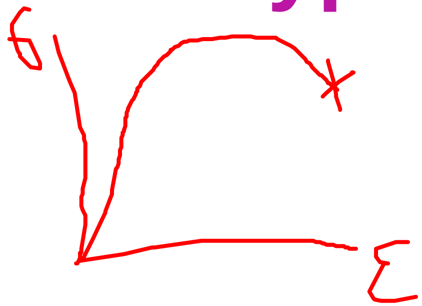
Fracture

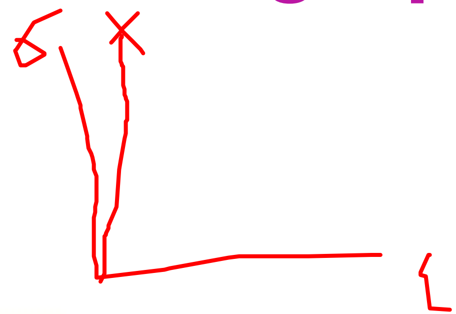
Fracture

- **Fracture** – the separation of a body into two or more pieces in response to a load. => The final exhibition of failure
- Fracture starts from **crack initiation** and accompanied by **crack propagation**.

https://www.youtube.com/watch?v=vCTNioSW730 Ice Age 1

Fracture Types – Surface Photographs





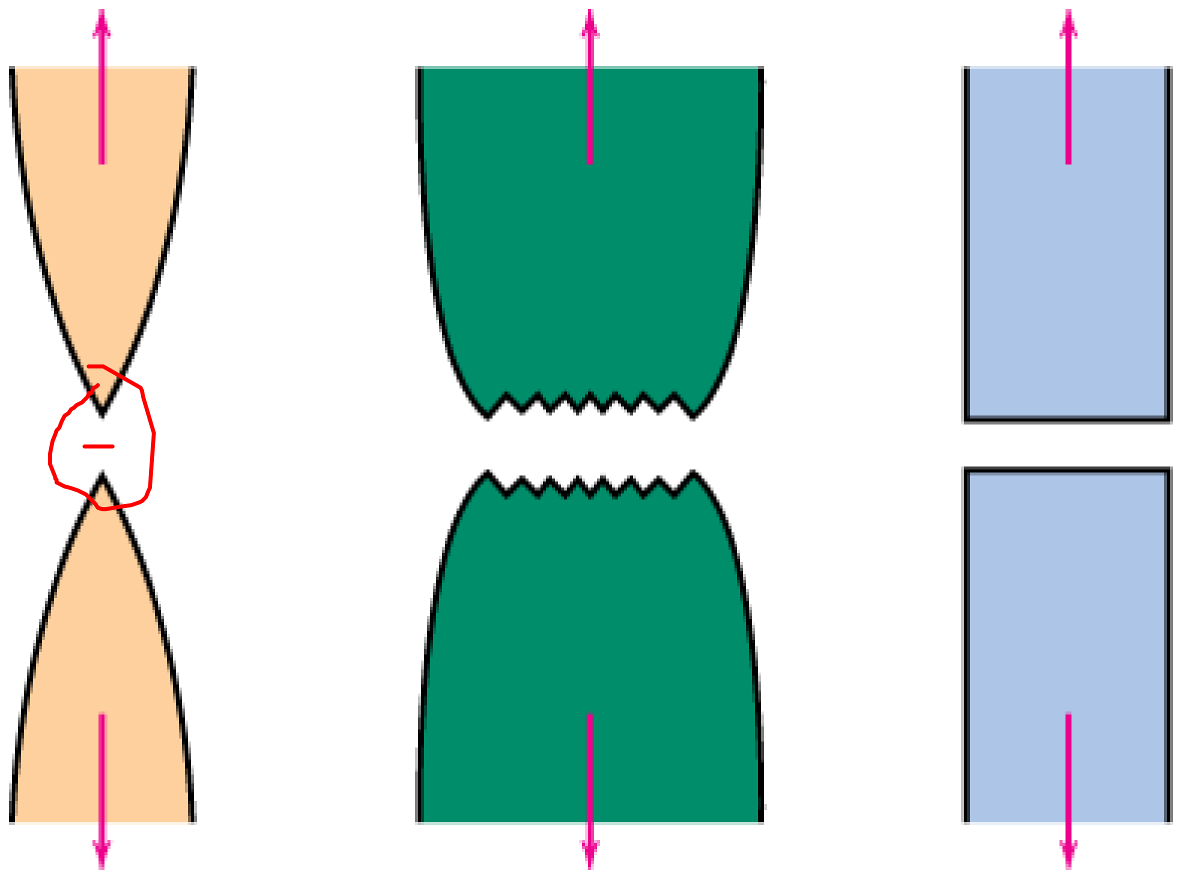
cup-and-cone fracture
- moderately ductile

brittle fracture
- totally brittle
- flat surfaces

Fig. 8.3, *Callister & Rethwisch 10e.*

Fracture Profiles

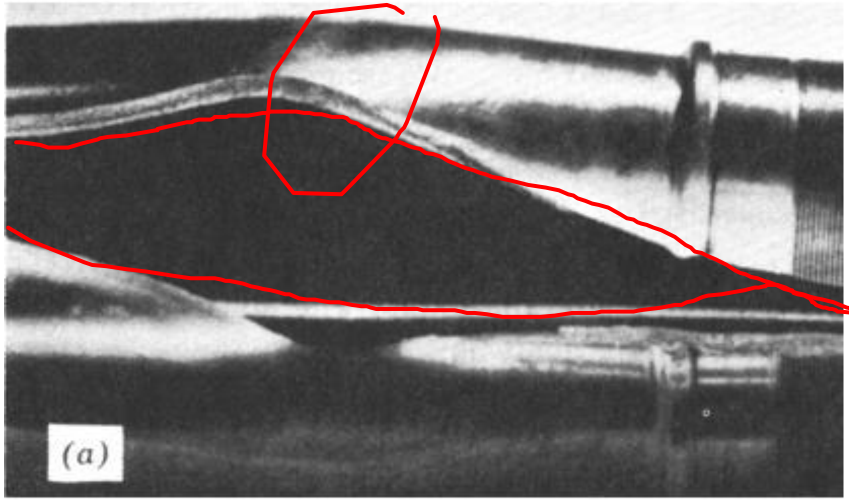
Very Ductile | Moderately Ductile | Brittle



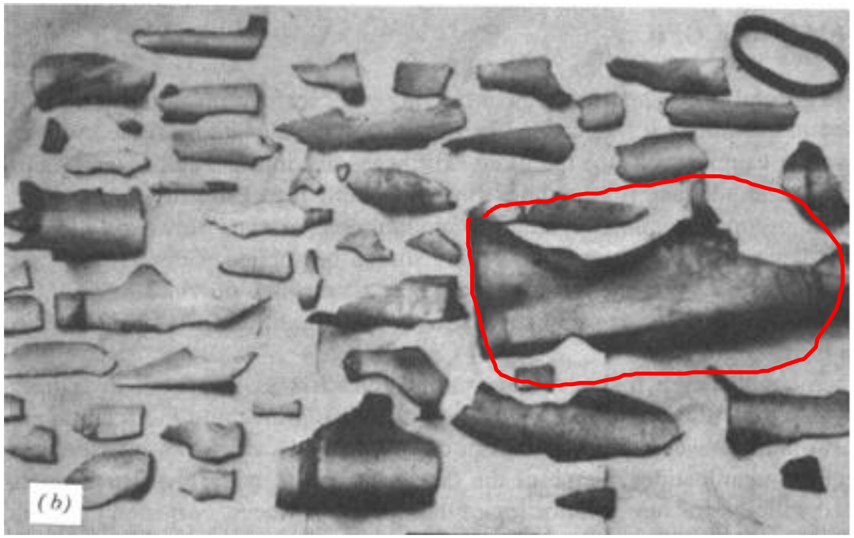
Adapted from Fig. 8.1, *Callister & Rethwisch 10e.*

Examples of Ductile and Brittle Fracture of Pipes

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



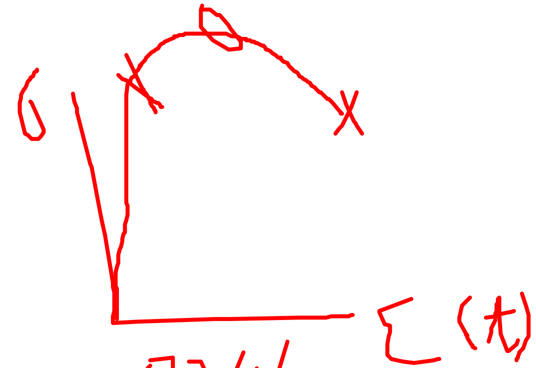
- **Brittle fracture:**
  -- many pieces
  -- small deformations

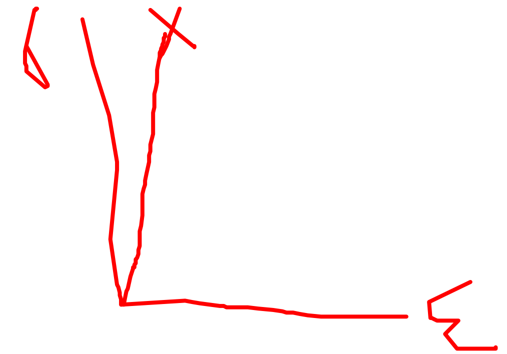


Figures from V.J. Colangelo and F.A. Heiser, *Analysis of Metallurgical Failures* (2nd ed.), Fig. 4.1(a) and (b), p. 66 John Wiley and Sons, Inc., 1987. Used with permission.

Fracture types

- Two general types of fracture
  - Ductile
    - Accompanied by significant plastic deformation
    - Slow crack propagation
    - Fails with warning
  - Brittle
    - Little or no plastic deformation
    - Rapid crack propagation
    - Fails without warning
- Ductile fracture generally more desirable than brittle fracture

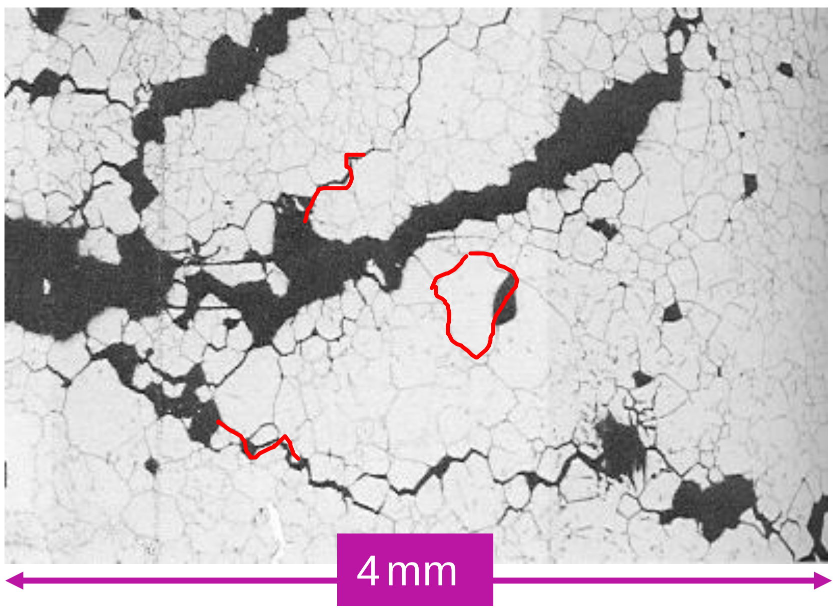




Brittle Fracture

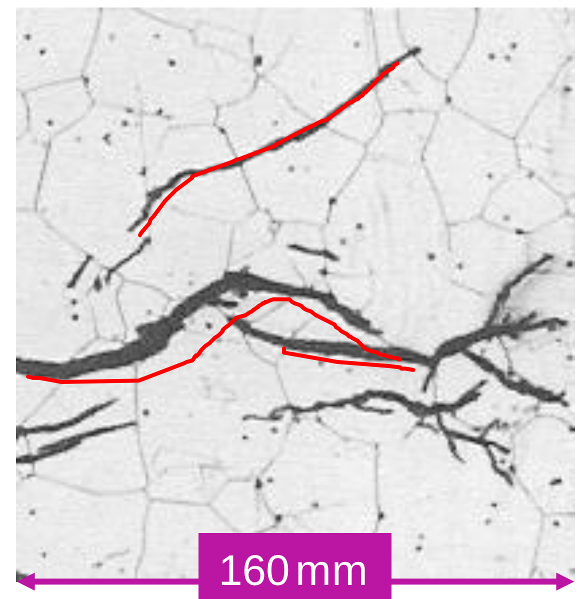
Photographs of Brittle Fracture Surfaces

- Intergranular crack propagation (between grains)
- Transgranular crack propagation (through 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.)

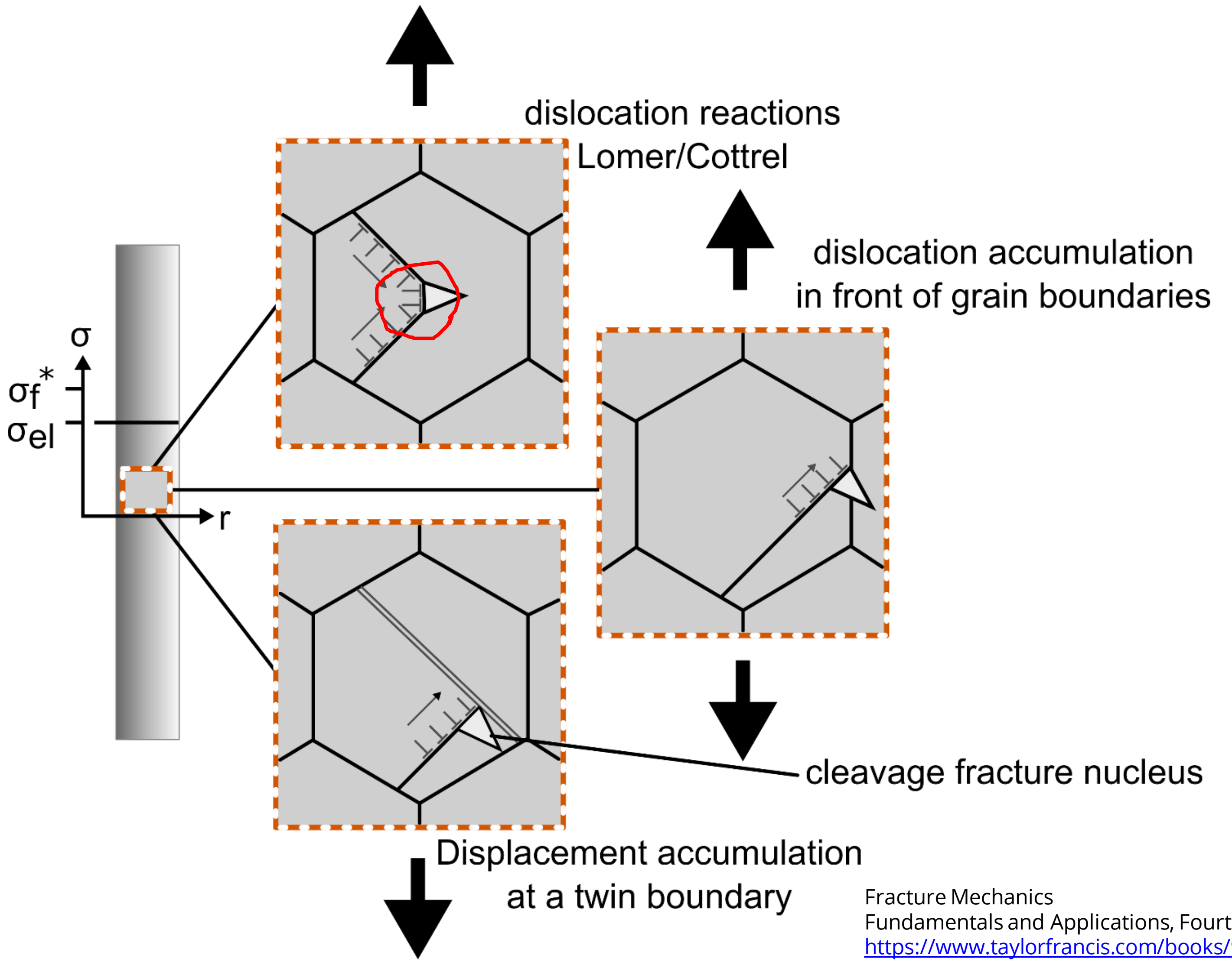


316 S. Steel (metal)

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.)

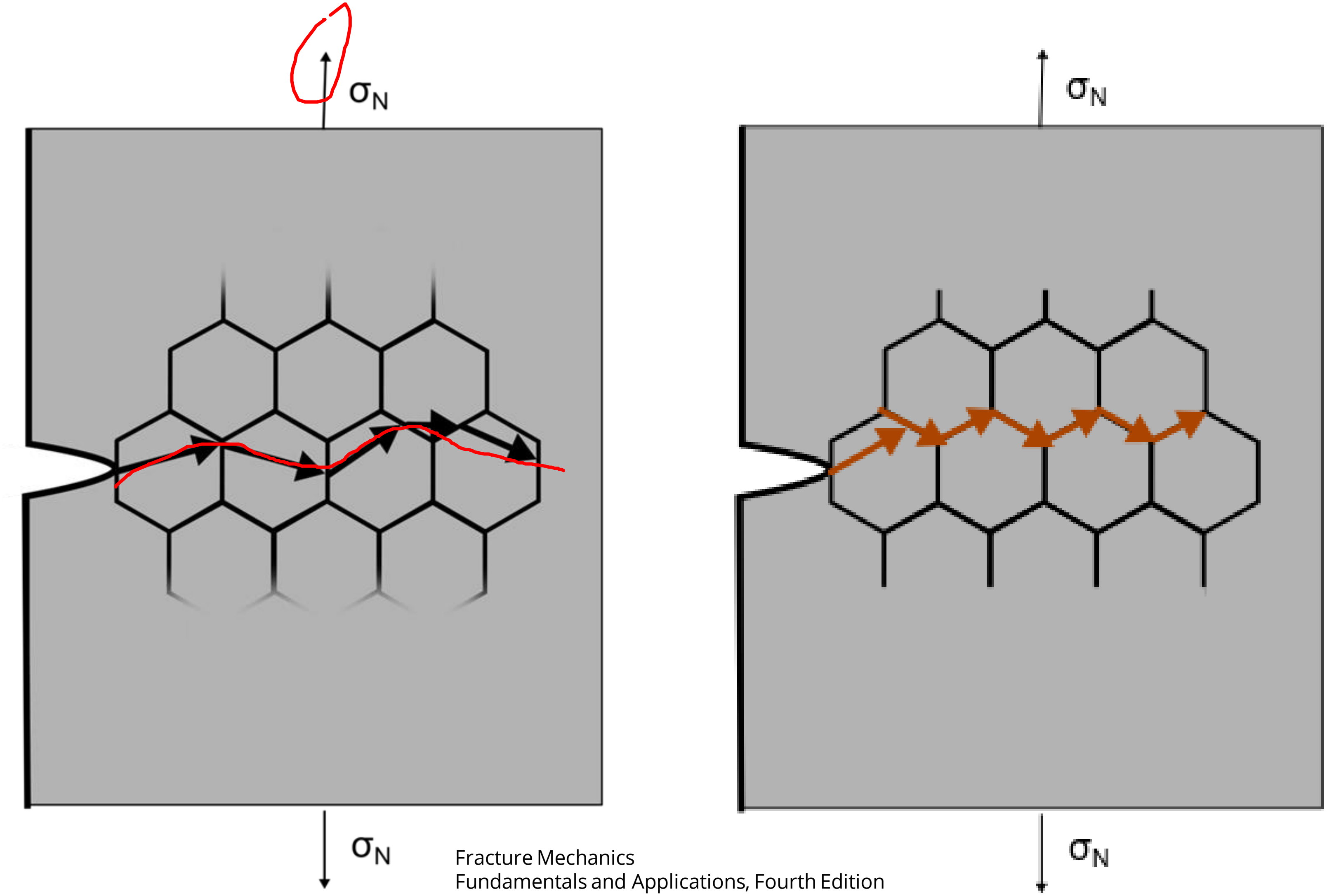
Break
back at 11:15

Brittle Fracture Mechanism



Fracture Mechanics
Fundamentals and Applications, Fourth Edition
https://www.taylorfrancis.com/books/9781315370293

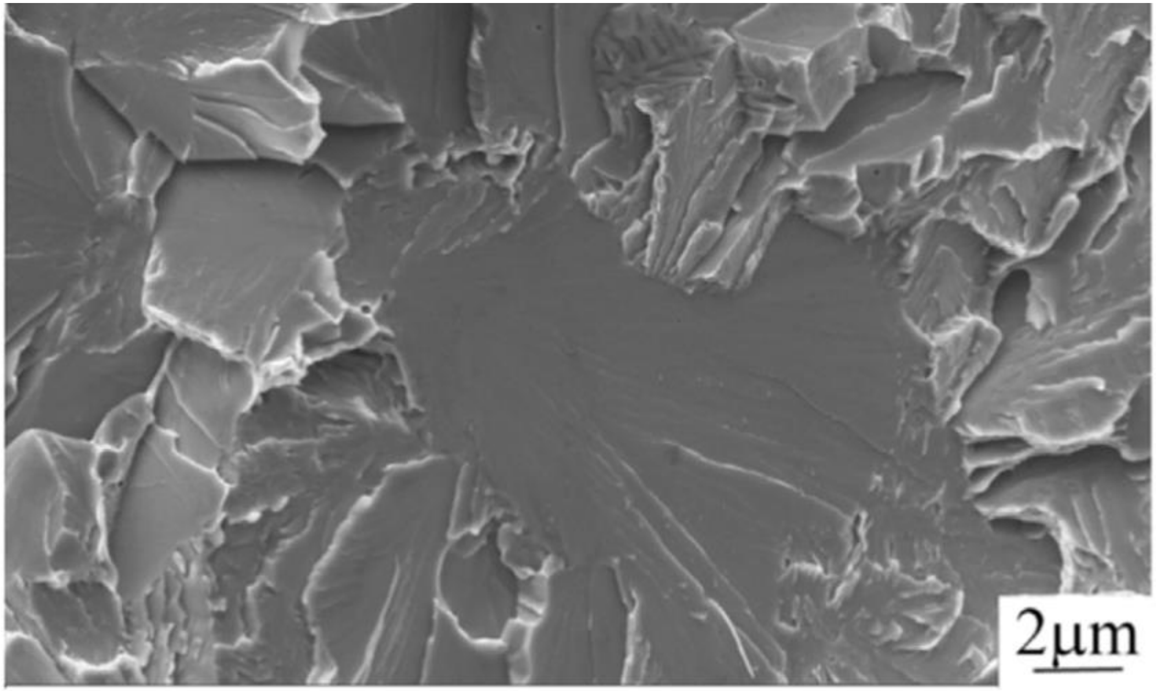
Brittle Fracture Mechanism



Fracture Mechanics
Fundamentals and Applications, Fourth Edition
https://www.taylorfrancis.com/books/9781315370293

Brittle Fracture Mechanism

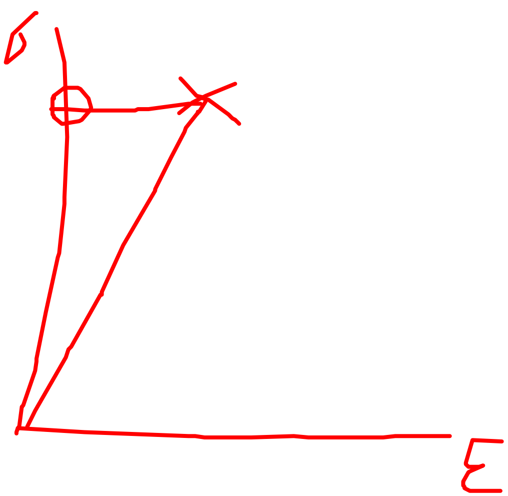
- Dislocation accumulation at grain boundaries, precipitates or inclusion -> local very high stress concentration.
- Crack propagates orthogonal to the highest principal normal stress via transgranular or intergranular path.

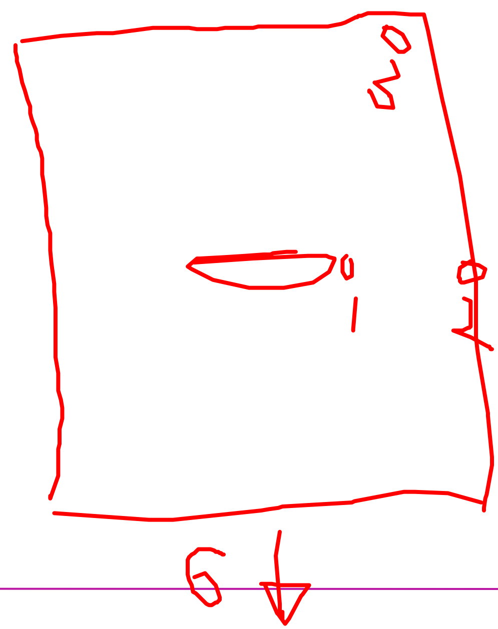


https://www.sciencedirect.com/science/article/pii/S0921509317300515?via%3Dihub

Quantifying Brittle Fracture – Fracture Mechanics

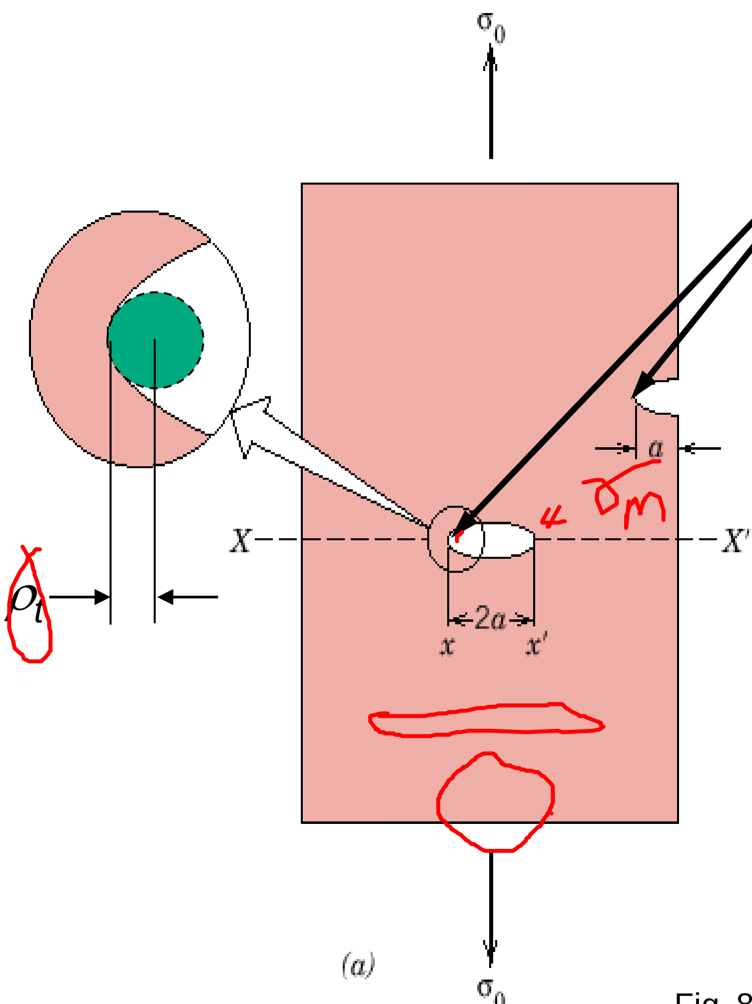
- Fracture occurs as result of crack propagation.
- Crack initiation triggers (microscopic flaws, cracks) always exist in materials.
- Magnitude of applied tensile stress amplified at the tips of these cracks.





Fracture Mechanics

Flaws are Stress Concentrators!



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

where

ρ_t = radius of curvature

σ_o = applied stress

σ_m = stress at crack tip

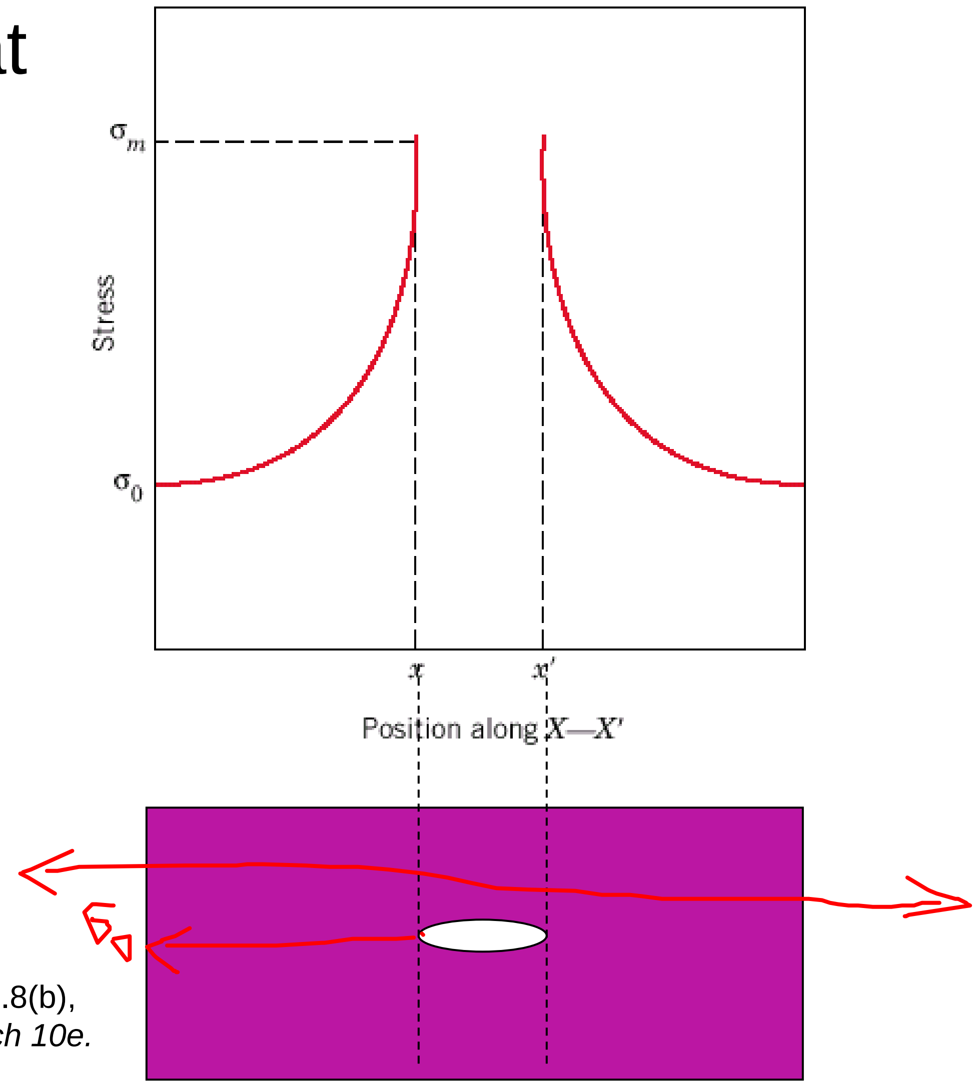
Fig. 8.8(a), *Callister & Rethwisch 10e.*

Fracture Mechanics (cont.)

Stress Concentration at Crack Tip

K_t = stress concentration factor

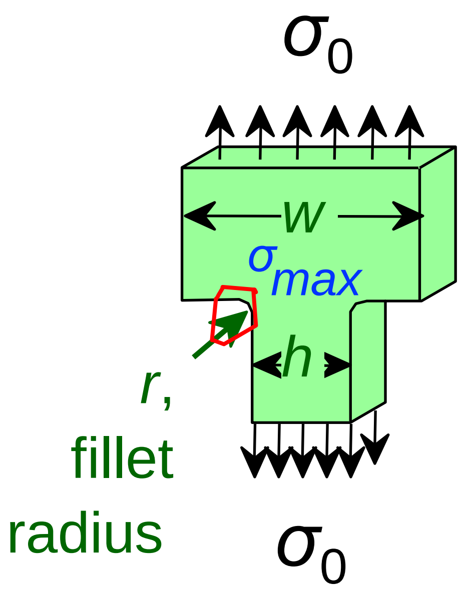
$$K_t = \frac{s_m}{s_o}$$



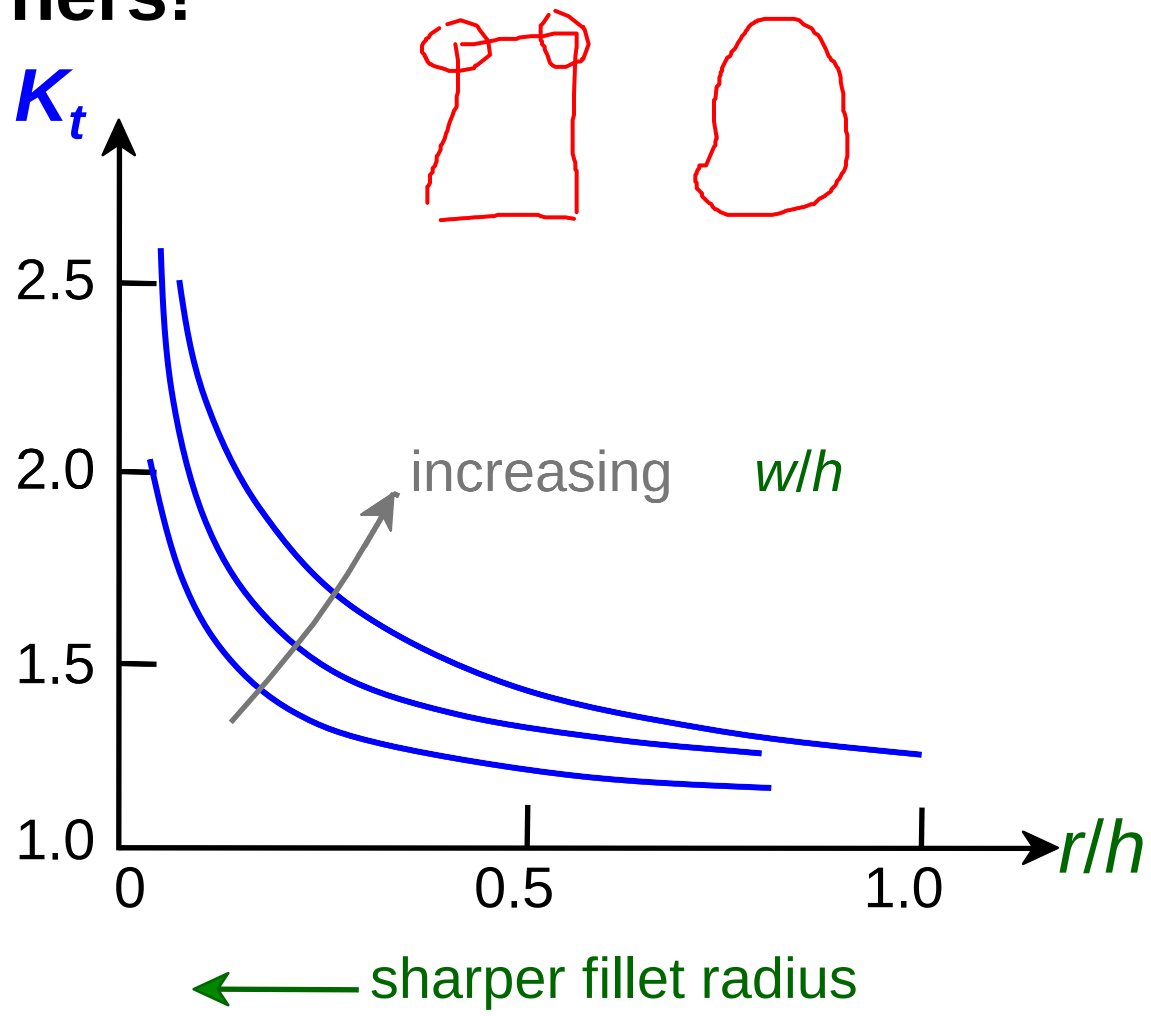
Adapted from Fig. 8.8(b), *Callister & Rethwisch 10e.*

Fracture Mechanics (cont.)

Avoid sharp corners!



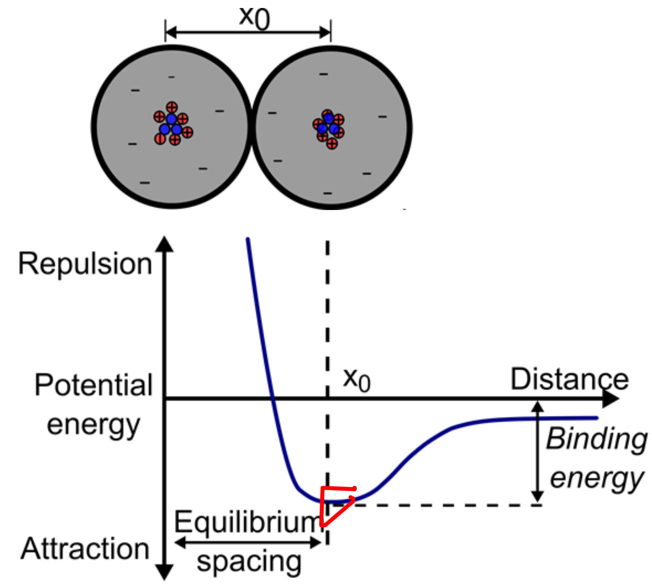
Adapted from Fig. 8.2W(c), *Callister 6e.*
(Fig. 8.2W(c) is from G.H. Neugebauer, *Prod. Eng.* (NY), Vol. 14, pp. 82-87 1943.)



Criterion for Crack Propagation

Critical stress for crack propagation (σ_c) of brittle materials

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



where

- σ_c = crack-tip stress
- E = modulus of elasticity
- γ_s = specific surface energy
- a = one half length of internal crack

- Materials have numerous cracks with different lengths and orientations
- Crack propagation (and fracture) occurs when $\sigma_m > \sigma_c$ for crack with lowest σ_c
- Largest, most highly stressed cracks grow first!

Fracture Toughness

- A measure of material's resistance to brittle fracture when a crack is present
- Defined as

$$K_C = Y\sigma_C\sqrt{\pi a}$$

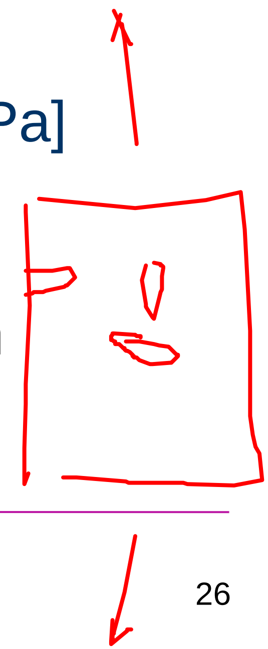
$$\sigma_c = \left(\frac{2E\gamma_s}{\pi a}\right)^{1/2}$$

K_c = fracture toughness [MPa $\sqrt{\text{m}}$]

Y = dimensionless parameter

σ_c = critical stress for crack propagation [MPa]

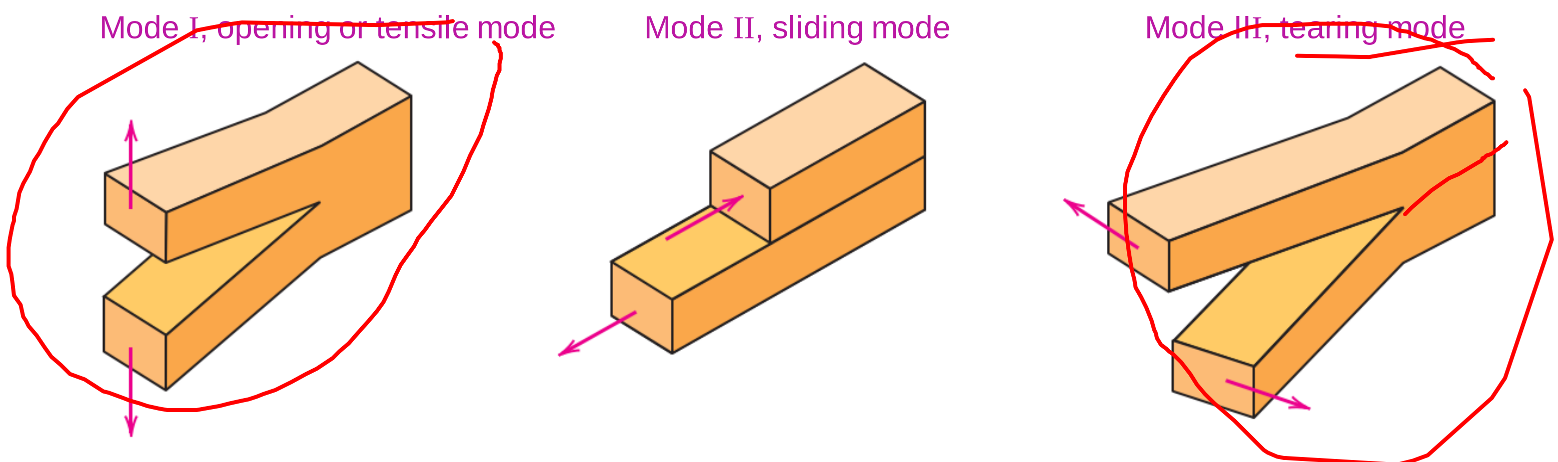
a = crack length [m]



➢ For planar specimens with cracks much shorter than specimen width, $Y \approx 1$

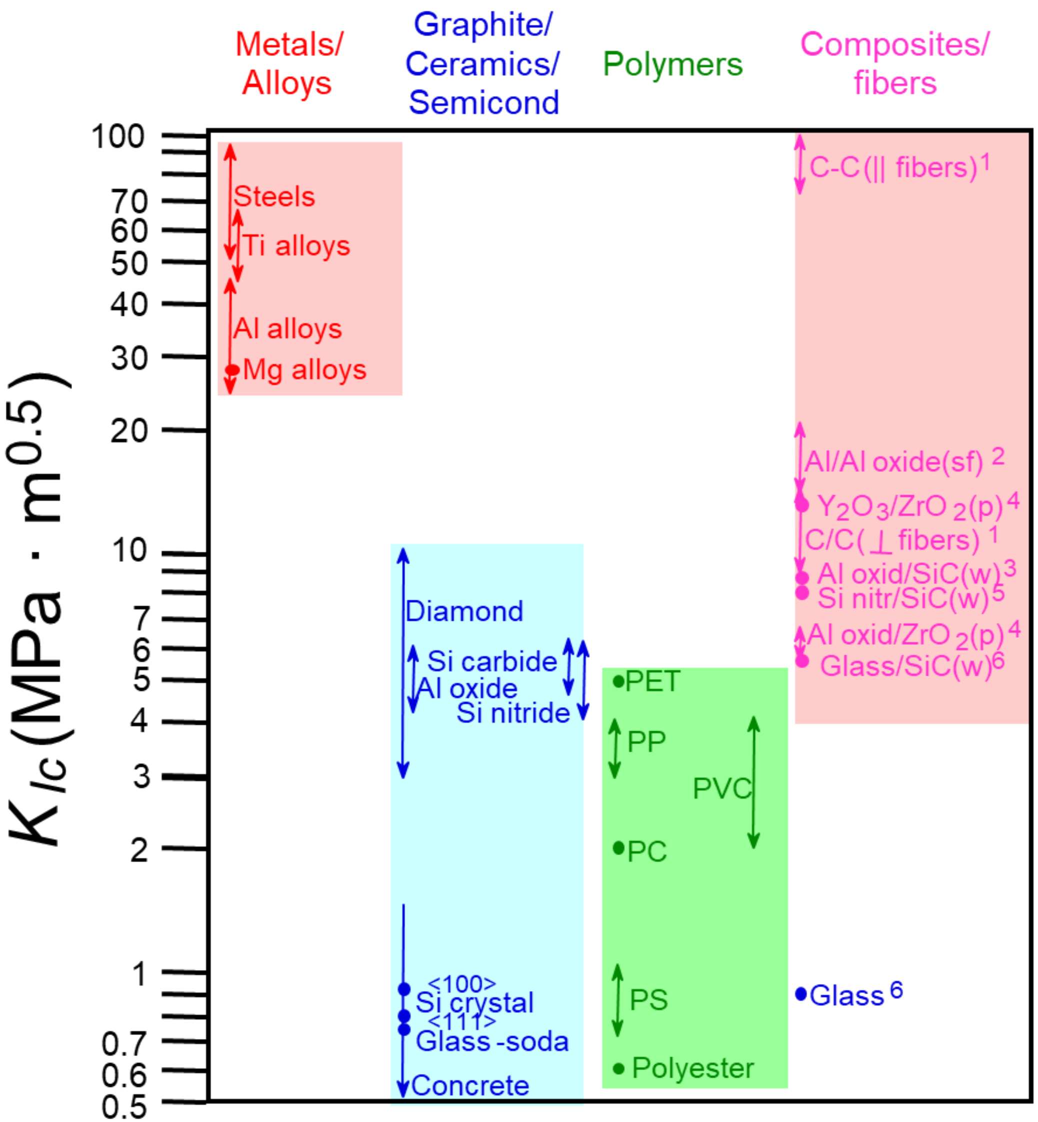
Plane Strain Fracture Toughness

- For specimen thickness much greater than crack dimension, K_C independent of thickness
  - Condition of plane strain exists
  - Leads to plane strain fracture toughness, K_{ic}, where I indicates mode I crack displacement



- Values of K_{ic} relatively high for ductile materials and low for brittle ones

Fracture Toughness Ranges



Based on data in Table B.5, *Callister & Rethwisch 10e.*

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.

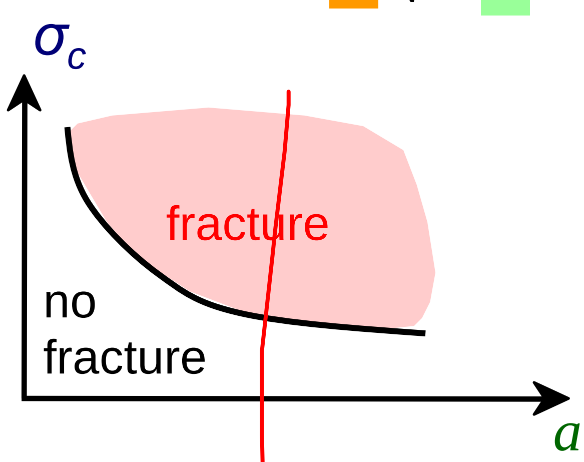
Design Against Fracture

- Crack growth condition:

$$K_{Ic} < Y\sigma_c\sqrt{\pi a}$$

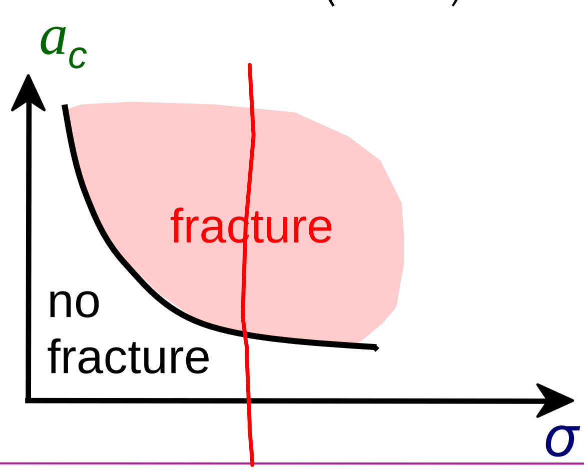
--Scenario 1: K_{Ic} and flaw size a specified - dictates max. design (critical) stress.

$$\sigma_c = \frac{K_{Ic}}{Y\sqrt{\pi a}}$$



--Scenario 2: K_{ic} and stress level specified - dictates max. allowable flaw size.

$$a_c = \frac{1}{\pi}\left(\frac{K_{Ic}}{Y\sigma}\right)^2$$



Summary

- **Failure** and four common **types of failure**
- **Fracture** – one type of failure
  - Occurs by **crack propagation**
  - **Ductile** fracture: plastic deformation – slow crack propagation
  - **Brittle** fracture: no plastic deformation – fast crack propagation
  - Fracture surfaces – different for ductile and brittle
- Quantification of brittle fracture
  - Small cracks or flaws exist in all materials
  - Applied tensile stress amplified at tips of flaws
  - **Fracture toughness** – measurement of material's resistance to fracture

Questions?