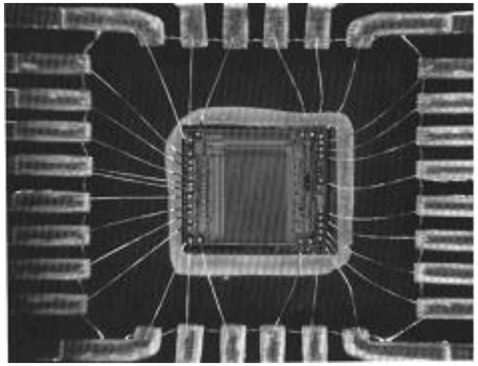
MECHANICAL FAILURE

Mechanical Failure

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?

Ship-cyclic loading from waves.



Computer chip-cyclic thermal loading.

Hip implant-cyclic loading from walking.

What is a Fracture?

- **Fracture is the separation of a body into two or more pieces in response to an imposed stress.**
- **The applied stress may be *tensile*, *compressive*, *shear*, or *torsional*.**
- **Stress can be caused by forces, temperature, etc.**
- **Any fracture process involves two steps—crack formation and propagation—in response to an imposed stress.**

Fracture Modes

- **Ductile fracture**
  - **Occurs with plastic deformation**
  - **Material absorbs energy before fracture**
  - **Crack is called stable crack: crack growth occurs with plastic deformation . Also, increasing stress is required for crack propagation.**

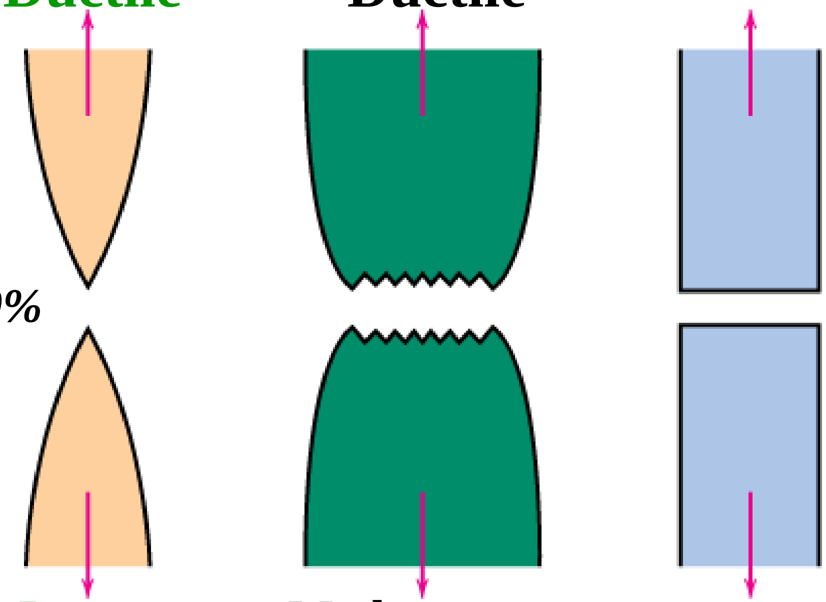
- **Brittle fracture**
  - **Little or no plastic deformation**
  - **Material absorb low energy before fracture**
  - **Crack is called unstable crack.**
  - **Catastrophic fracture (sudden)**

Ductile vs Brittle Failure

• **Classification:**

Fracture behavior: | **Very Ductile** | **Moderately Ductile** | **Brittle**

(%EL)=100%



Large | **Moderate** | **Small**

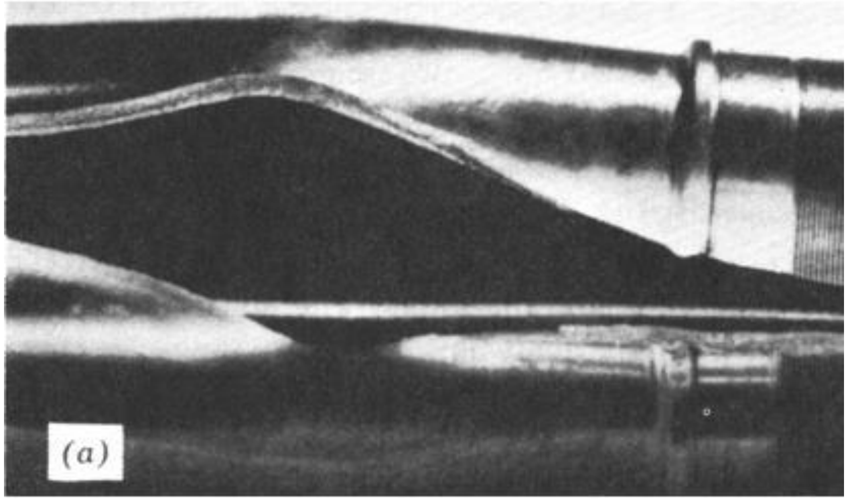
• **Ductile fracture is usually desirable!**

Ductile:
warning before fracture, as increasing force is required for crack growth

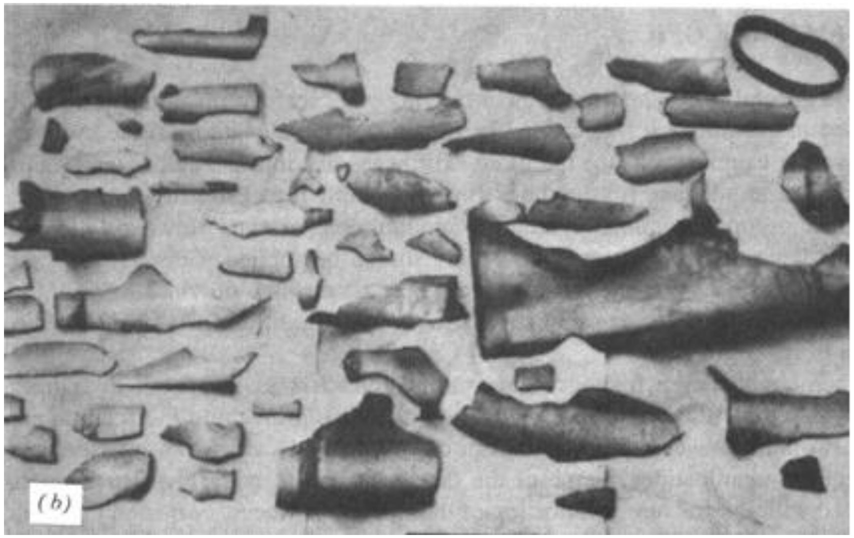
Brittle:
No warning

Example: Failure of a Pipe

- **Ductile failure:**
  - **--one/two piece(s)**
  - **--large deformation**

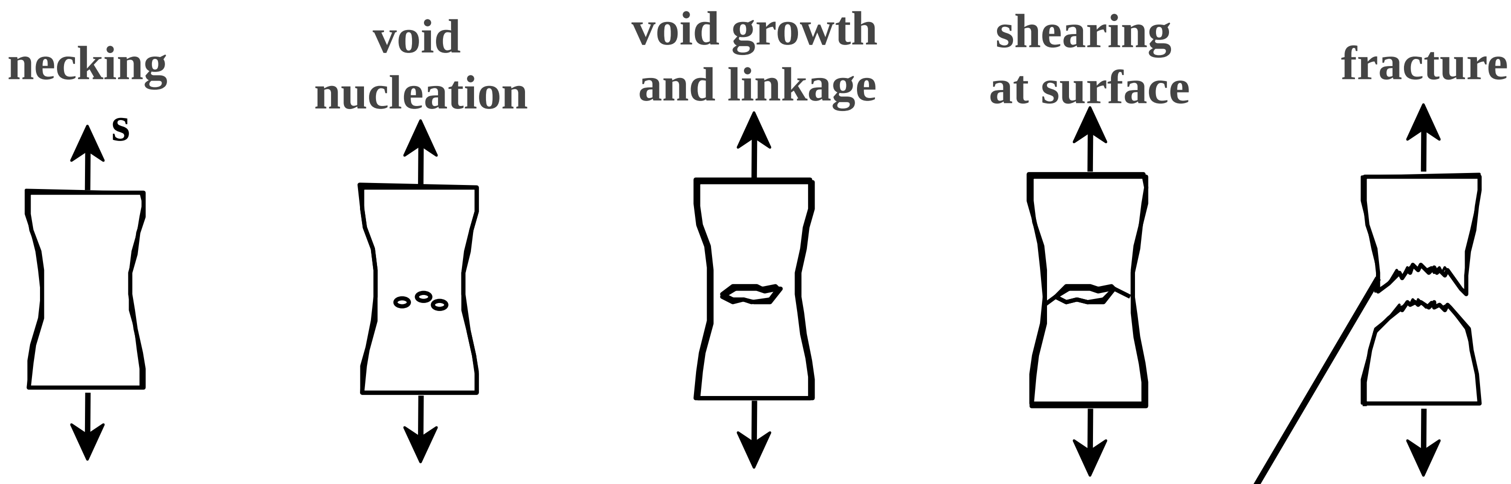


- **Brittle failure:**
  - **--many pieces**
  - **--small deformation**

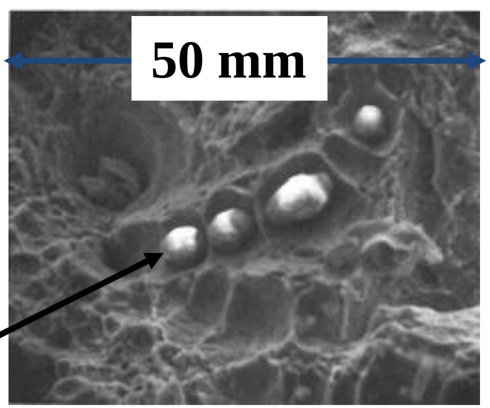


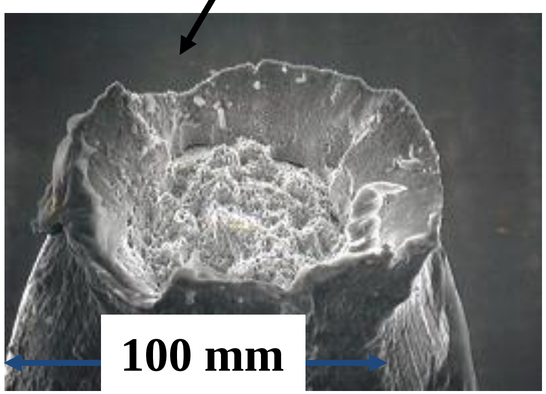
Moderately Ductile Failure- Cup & Cone Fracture

- **Evolution to failure:**



- **Resulting fracture surfaces (steel)**





particles serve as void nucleation sites.

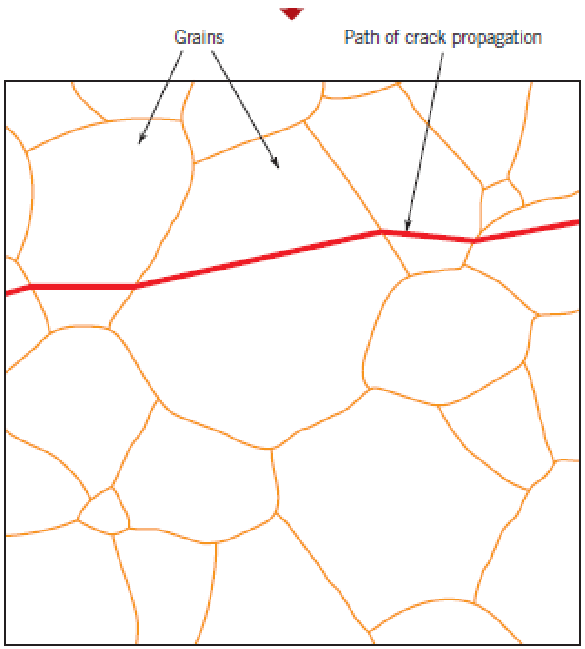
crack occurs perpendicular to tensile force applied

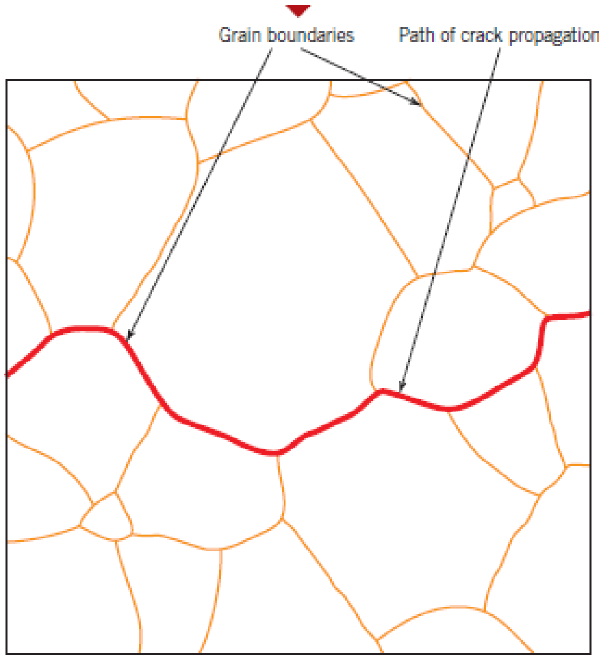
Ductile vs. Brittle Failure

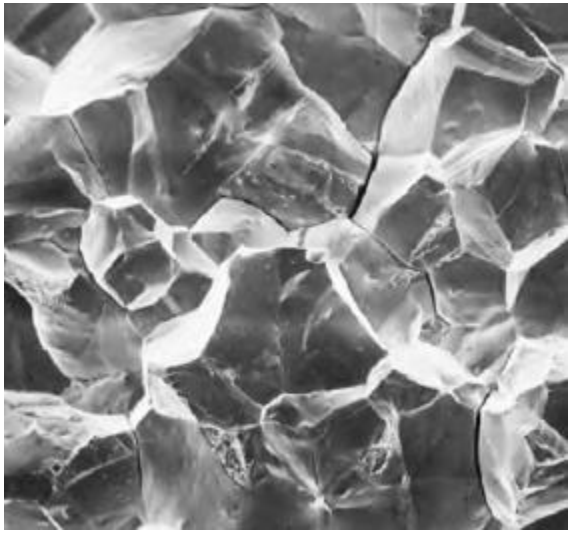
cup-and-cone fracture

brittle fracture

Transgranular vs Intergranular Fracture







Trans-granular Fracture

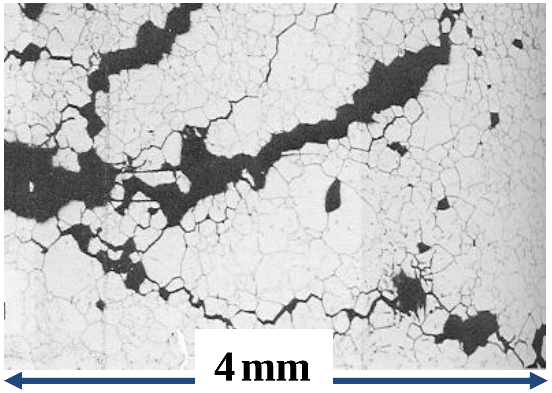
Intergranular Fracture

Brittle Fracture

Brittle Fracture Surfaces

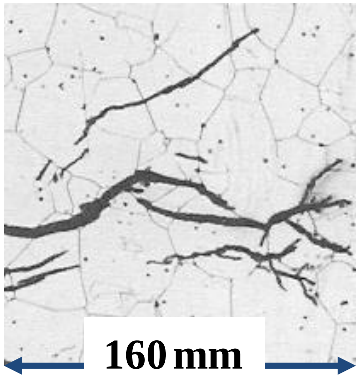
- **Intergranular (between grains)**

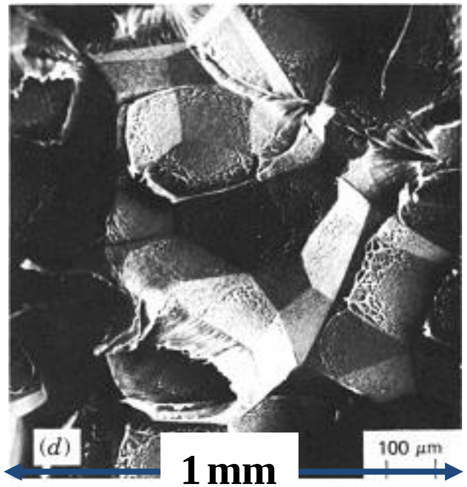
304 S. Steel (metal)



- **Transgranular (within grains)**

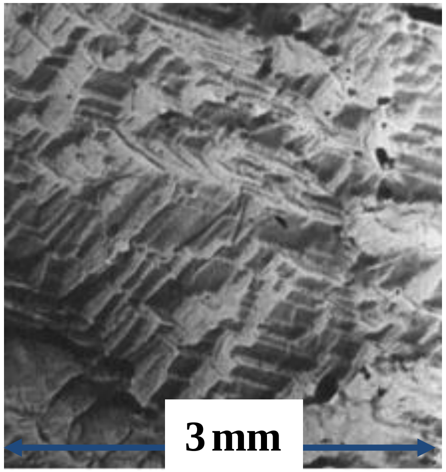
316 S. Steel (metal)





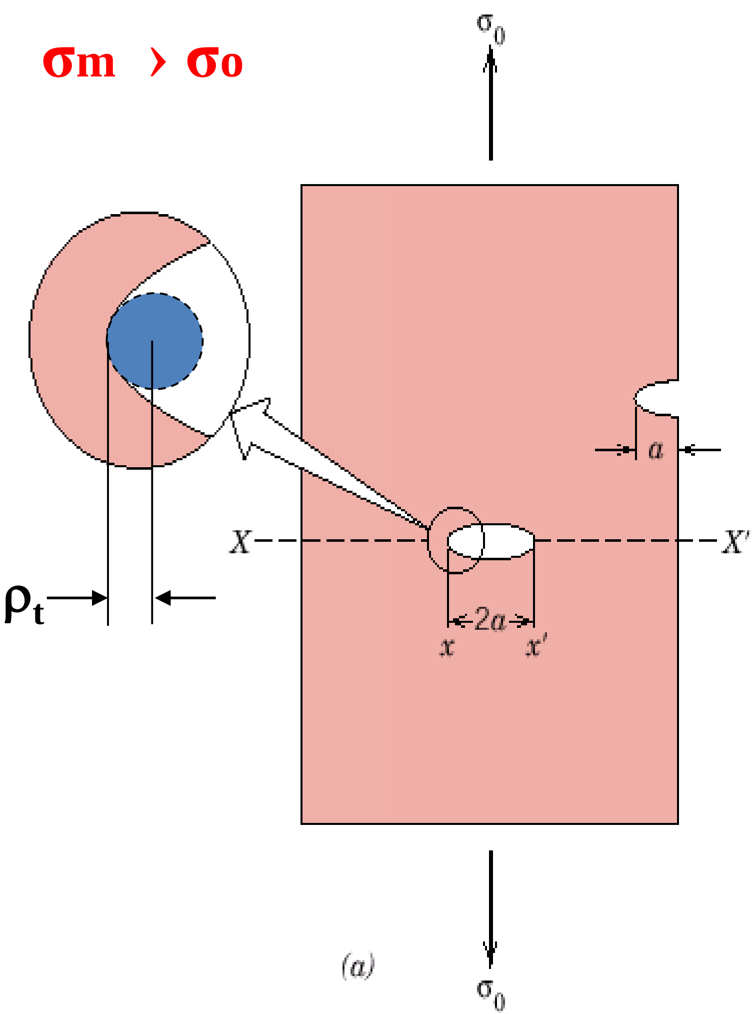
Polypropylene (polymer)

Al Oxide (ceramic)



Stress Concentration- Stress Raisers

$\sigma m \;\rangle\; \sigma o$



Theoretical fracture strength is higher than practical one; ***Why?***

Suppose an internal flaw (crack) already exits in a material and it is assumed to have a shape like a elliptical hole:

The maximum stress (σ_m) occurs at crack tip:

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

where

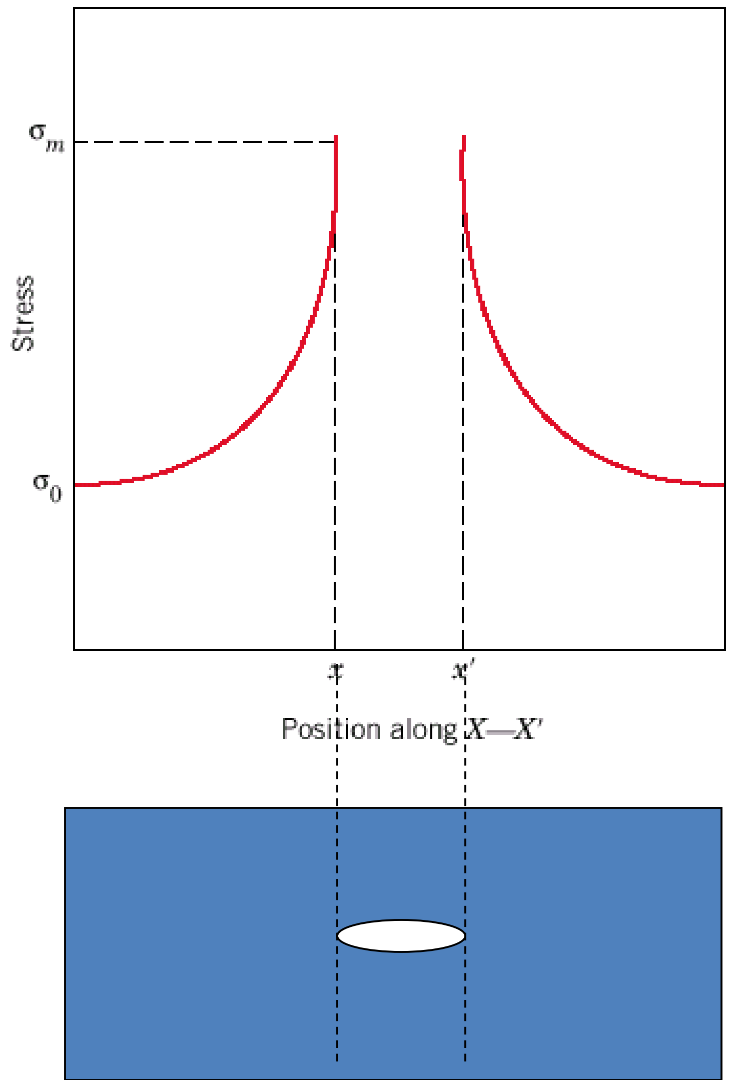
ρ_t = radius of curvature at crack tip

σ_o = applied stress

σ_m = stress at crack tip

K_t = Stress concentration factor

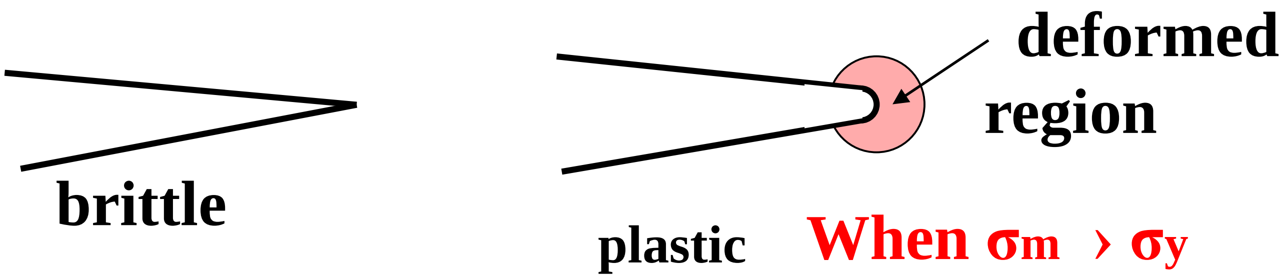
Concentration of Stress at Crack Tip



Crack Propagation

Cracks propagate due to sharpness of crack tip

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



When $\sigma_m > \sigma_y$

Effect of stress raiser is more significant in brittle materials than in ductile materials. When σ_m exceeds σ_y , plastic deformation of metal in the region of crack occurs thus blunting crack. However, in brittle material, it does not happen.

When Does a Crack Propagate?

Crack propagation in a brittle material occurs if

$\sigma_m > \sigma_c$

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

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

Where

- **σ_c= Critical stress to propagate crack**
- ***E* = modulus of elasticity**
- **γ_s = specific surface energy (J/m^2)**
- ***a* = one half length of internal crack**

For ductile => replace γ_s by $\gamma_s + \gamma_p$

where g_p is plastic deformation energy

Example – Brittle Fracture

- Given Glass Sheet with
  - Tensile Stress, σ = 40 Mpa
  - E = 69 GPa
  - γ = 0.3 J/m
- Find Maximum Length of a Surface Flaw
- Plan

- Set σ_c = 40Mpa
- Solve Griffith Eqn for Edge-Crack Length

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

- Solving

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

$$a = 8.2\times10^6\ \text{m} = 8.2\ \mu\text{m}$$

Fracture Toughness: Design Against Crack Growth

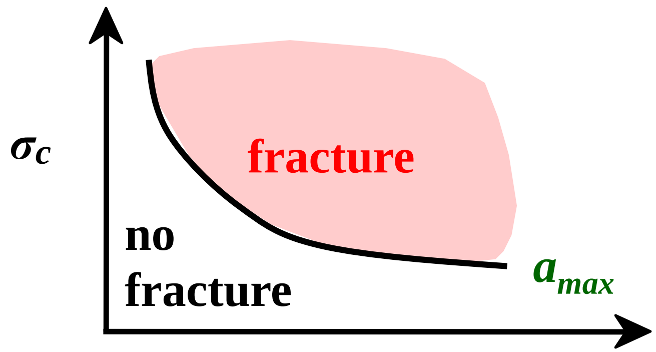
- Crack growth condition:

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

- Largest, most stressed cracks grow first!

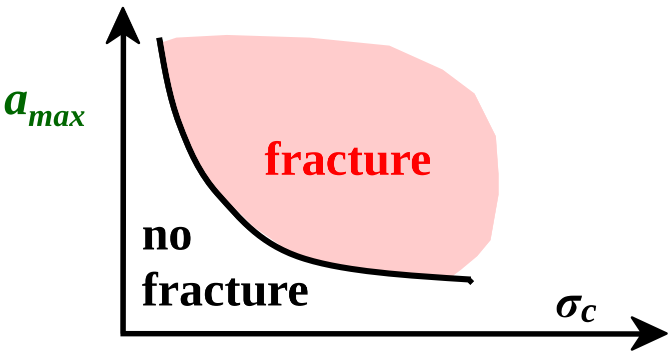
--Result 1: Max. flaw size dictates design stress (max allowable stress).

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



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

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



Design Example: Aircraft Wing

- Material has K_{Ic} = 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...

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

- Key point: Y and K_{Ic} are the same for both designs.

$$\frac{K_{Ic}}{Y\sqrt{\pi}} = \sigma\sqrt{a} = \text{constant}$$

--Result:

112 MPa, 9 mm, 4 mm

$$\left(\sigma_c\sqrt{a_{max}}\right)_A = \left(\sigma_c\sqrt{a_{max}}\right)_B$$

Answer: $(\sigma_c)_B = 168$ MPa

Design using fracture mechanics

$$\sigma_c \le \frac{K_{Ic}}{Y\sqrt{\pi a}} \qquad a_c = \frac{1}{\pi}\left(\frac{K_{Ic}}{\sigma Y}\right)^2$$

Example:

Compare the critical flaw sizes in the following metals subjected to tensile stress 1500MPa and $K = 1.12\,\sigma\sqrt{\pi a}$.

	K_{Ic} ($MPa.m^{1/2}$)	Critical flaw size (microns)
Al	250	7000
Steel	50	280
Zirconia(ZrO_2)	2	0.45
Toughened Zirconia	12	16

SOLUTION

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

Where Y = 1.12. Substitute values

8.14 A specimen of 4340 steel alloy with a plane strain fracture toughness of 54.8 MPa $\sqrt{m}$ (50 ksi$\sqrt{in.}$) is exposed to a stress of 1030 MPa (150,000 psi). Will this specimen experience fracture if it is known that the largest surface crack is 0.5 mm (0.02 in.) long? Why or why not? Assume that the parameter Y has a value of 1.0.

This problem asks us to determine whether or not the 4340 steel alloy specimen will fracture when exposed to a stress of 1030 MPa, given the values of K_{Ic}, Y, and the largest value of a in the material.

This requires that we solve for σ_c from Equation (8.7). Thus

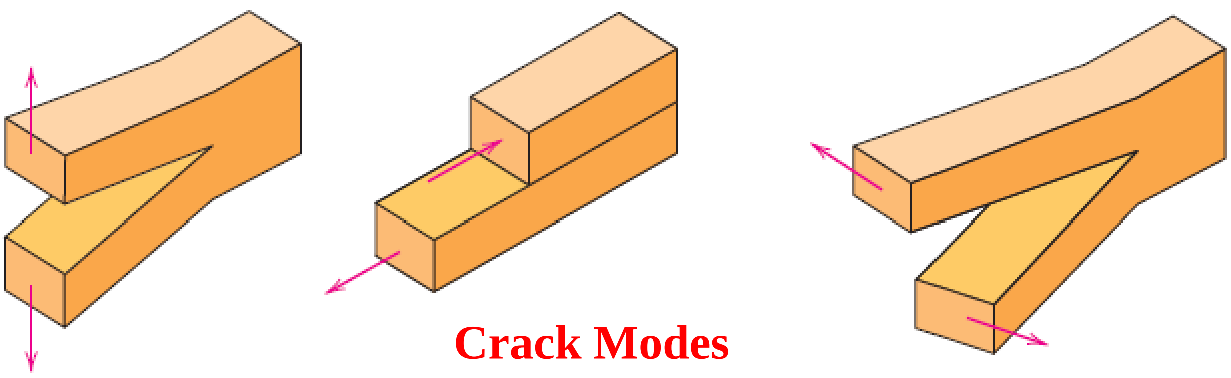
$$\sigma_c = \frac{K_{Ic}}{Y\sqrt{\pi a}} = \frac{54.8 \text{ MPa}\sqrt{m}}{(1)\sqrt{(\pi)\left(0.5 \times 10^{-3} \text{ m}\right)}} = 1380 \text{ MPa} \quad (199{,}500 \text{ psi})$$

Therefore, fracture will not occur because this specimen will tolerate a stress of 1380 MPa (199,500 psi) before fracture, which is greater than the applied stress of 1030 MPa (150,000 psi).

Fracture Toughness

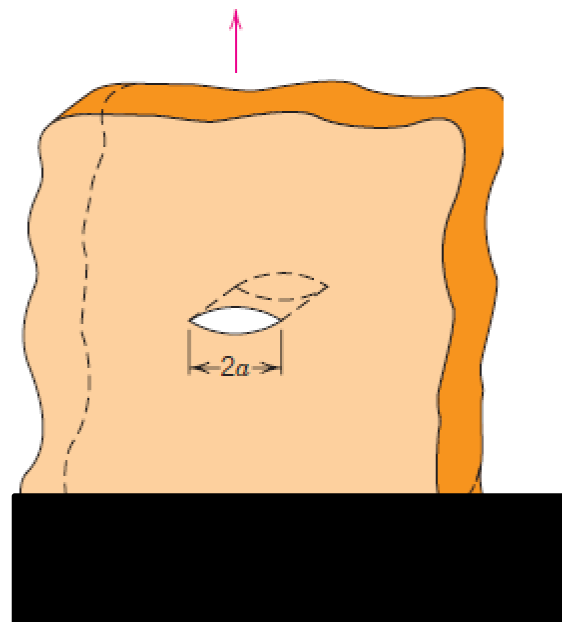
- For relatively thin specimens, the value of *K*c will depend on specimen thickness. However, when specimen thickness is much greater than the crack dimensions, *K*c becomes independent of thickness.
- The *K*c value for this thick-specimen situation is known as the plane strain fracture toughness K_{IC}

$$K_{Ic} = Y\sigma\sqrt{\pi a}$$



(a) (b) (c)

Crack Modes



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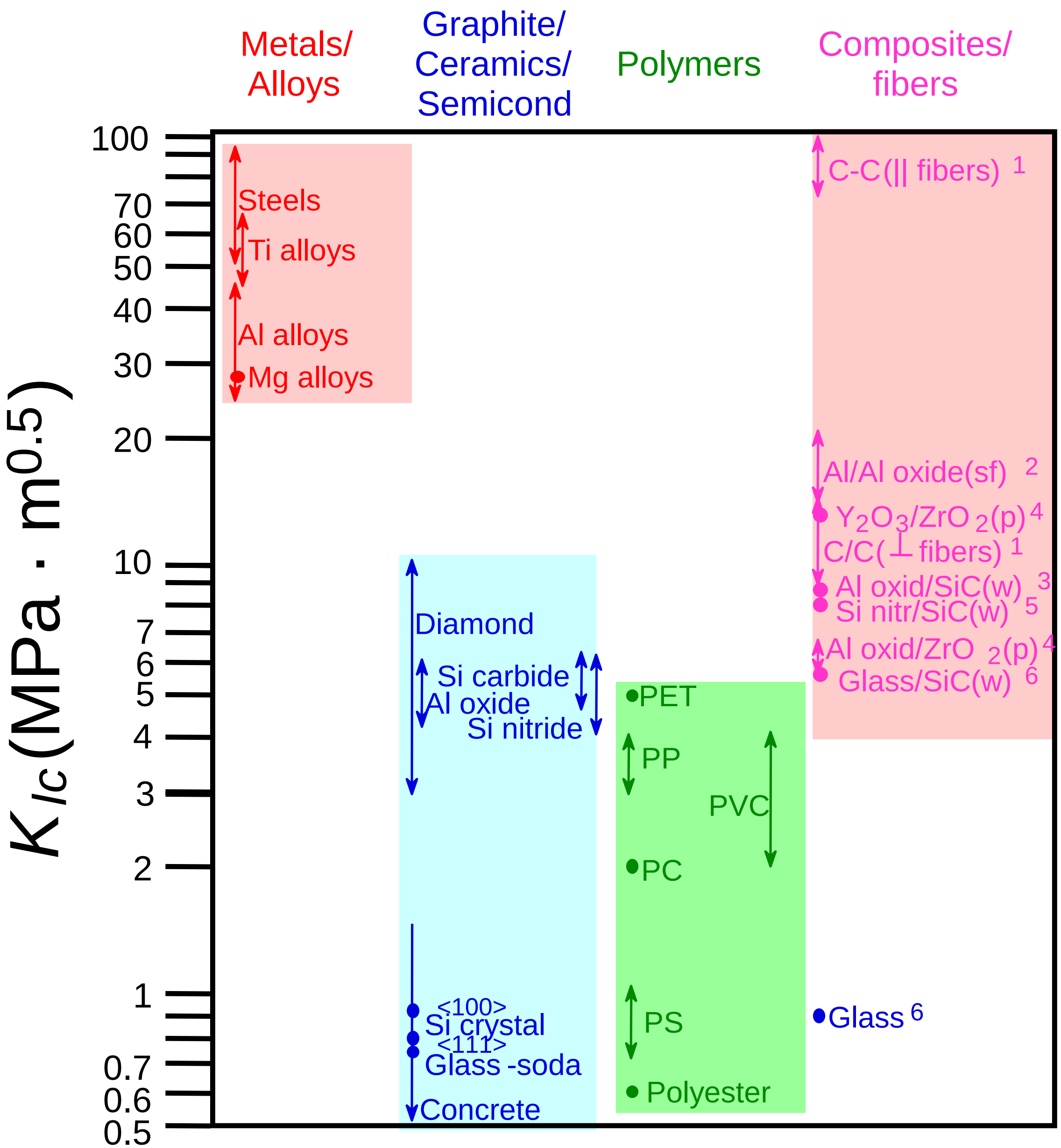
Fracture Toughness

- **Brittle materials do not undergo large plastic deformation, so they posses low K_{IC} than ductile ones.**
- **K_{IC} increases with increase in temp and with reduction in grain size if other elements are held constant**
- **K_{IC} reduces with increase in strain rate**

Fracture Toughness



$$K_{Ic} = Y\sigma\sqrt{\pi a}$$

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Design B
--use same material
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- **Use...**

$$\sigma_c = \frac{K_c}{Y\sqrt{\pi a}}$$

- **Key point: Y and K_c are the same in both designs.**
  --Result:

112 MPa 9 mm 4 mm

$$\left(\sigma_c\sqrt{a}\right)_A = \left(\sigma_c\sqrt{a}\right)_B$$

Answer: $(\sigma_c)_B = 168$ MPa

- **Reducing flaw size pays off!**