



IIT ROORKEE



NPTEL ONLINE
CERTIFICATION COURSE

Failure Analysis and Prevention

General Procedure of Failure Analysis: Application of fracture mechanics

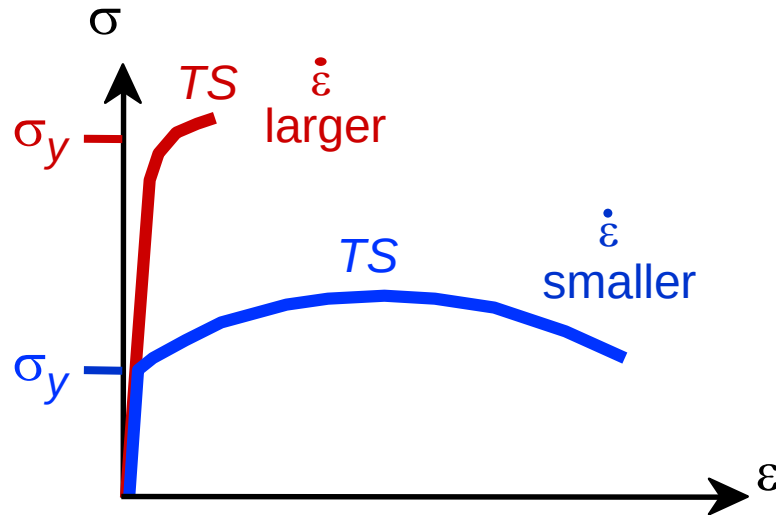
DHEERENDRA KUMAR DWIVEDI

MECHANICAL & INDUSTRIAL ENGINEERING DEPARTMENT



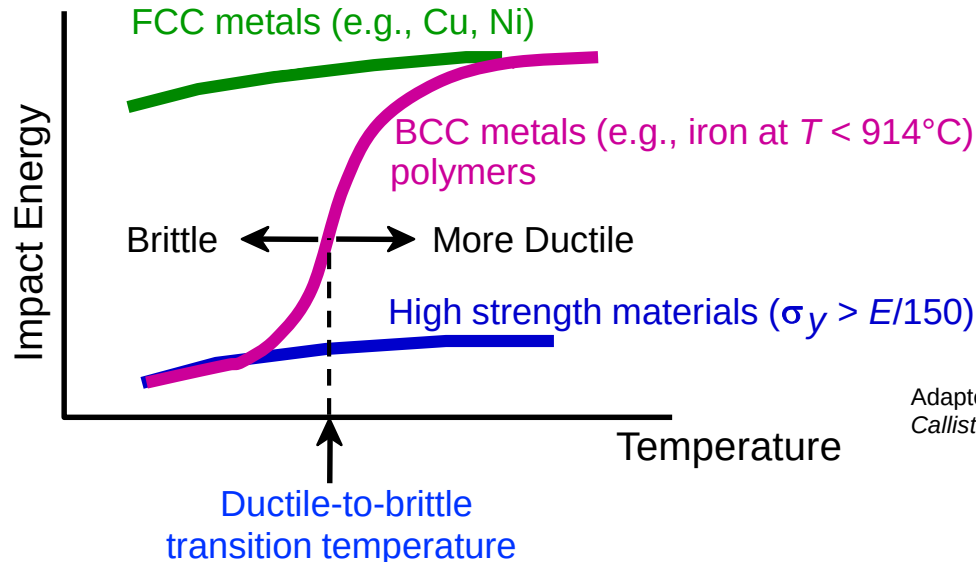
Considering Loading Rate Effect

- Increased loading rate...
 - increases σ_y and TS
 - decreases % EL



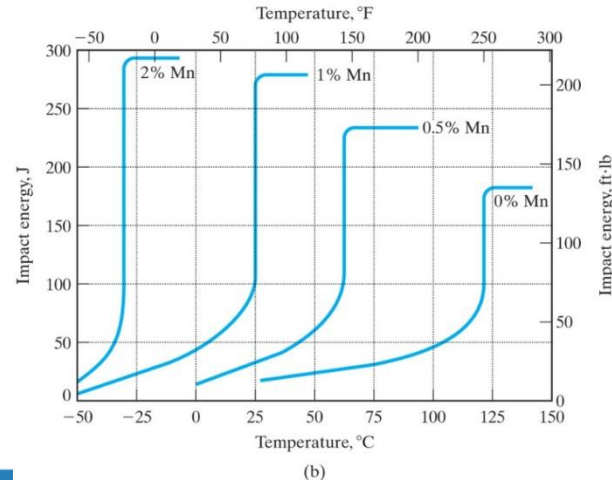
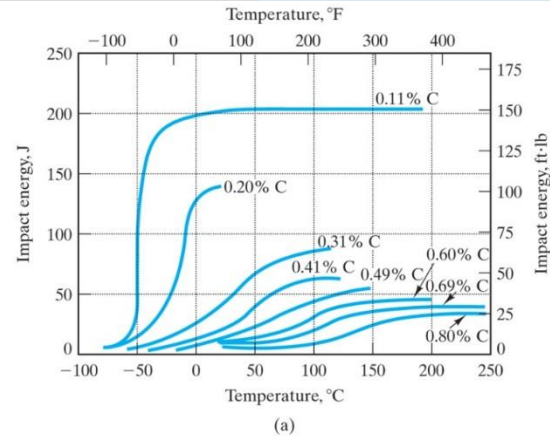
Considering Temperature Effects

- **Increasing temperature...**
--increases %*EL* and K_C
- **Ductile-to-Brittle Transition Temperature (DBTT)...**



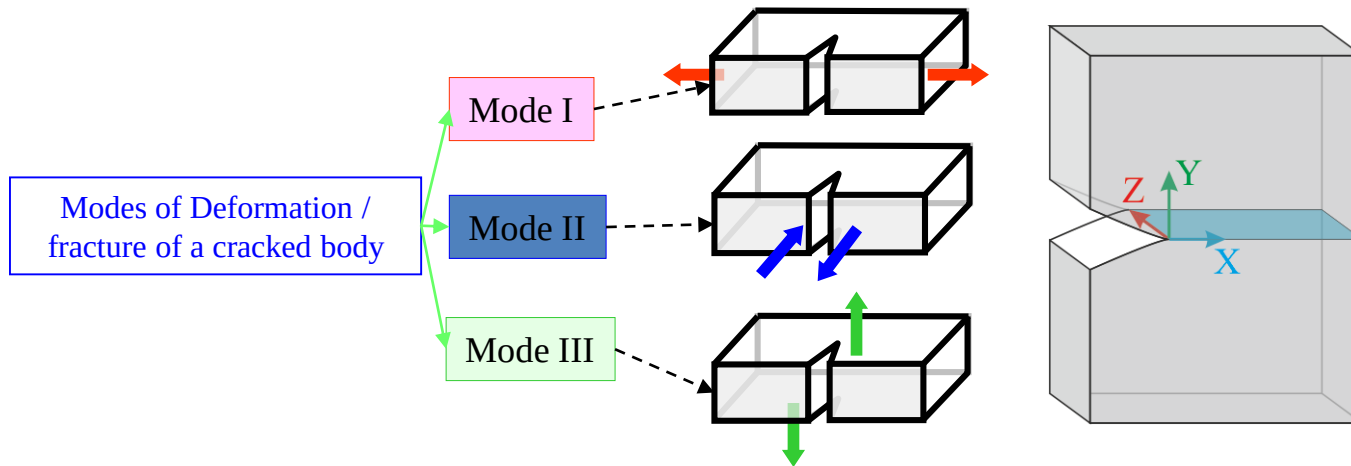
Adapted from Fig. 8.15,
Callister 7e.

DBTT(a) Charpy V-notch impact energy with temperature for plain-carbon steels with various carbon levels (in weight percent). (b) Charpy V-notch impact energy with temperature for Fe–Mn–0.05C alloys with various manganese levels (in weight percent).



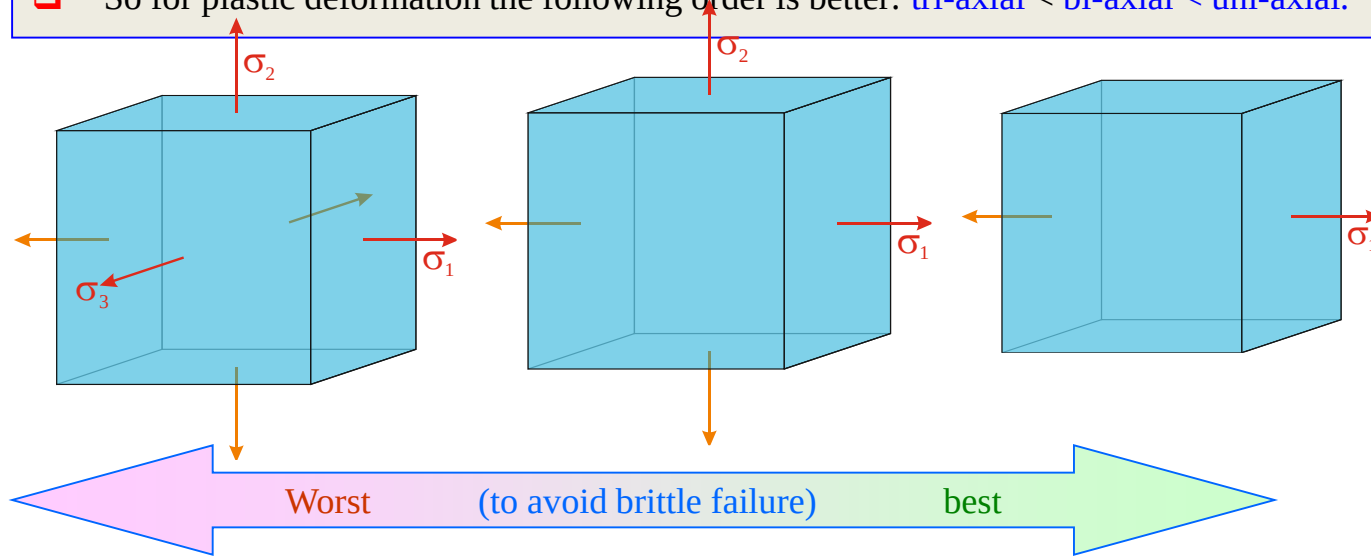
(From Metals Handbook, 9th ed., Vol. 1, American Society for Metals, Metals Park, OH, 1978.)

- ❑ Modes of loading
- Mode I: Opening mode
- Mode II: Sliding mode
- Mode III: Tearing mode

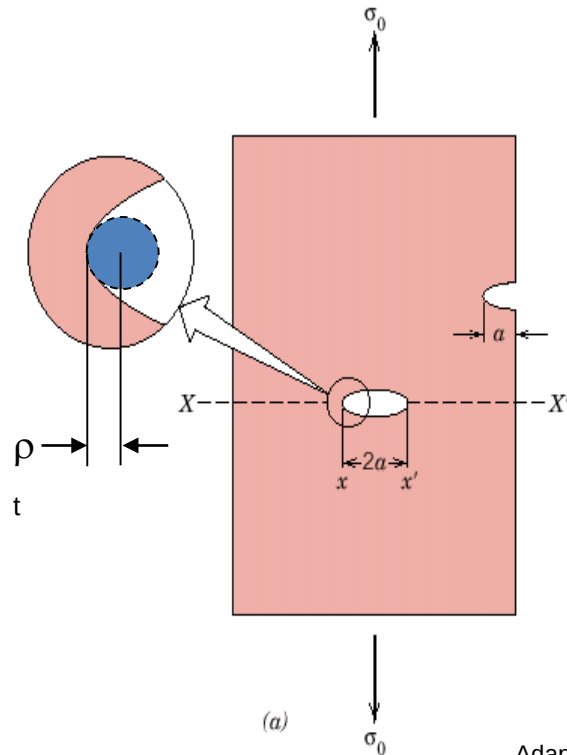


Important note: the loading specified and the geometry of the specimen illustrated for Mode II & III above do not give rise to pure Mode II and III deformation (other constraints or body shapes are required).

- ❑ By triaxial state of stress (SoS) means tensile stresses of *same sign* along 'y' and 'z' also.
- ❑ Triaxial SoS does not promote crack propagation, but suppresses plastic deformation
- ❑ Since plastic deformation is suppressed the crack tip remains sharp, thus promoting brittle fracture.
- ❑ So for plastic deformation the following order is better: *tri-axial* < *bi-axial* < *uni-axial*.



Flaws are Stress Concentrators!



Results from crack propagation

- Griffith Crack Model:

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

where

ρ_t = radius of curvature of
crack tip

σ_o = applied stress

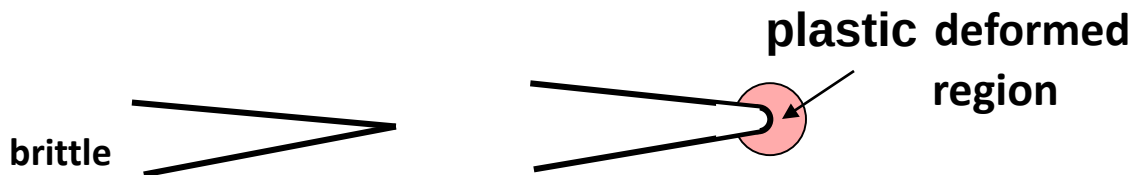
σ_m = stress at crack tip

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

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

When Does a Crack Propagate?

Crack propagates if applied stress is above **critical stress**

$$\begin{aligned} \text{i.e., } \sigma_m &> \sigma_c \\ \text{or } K_t &> K_c \end{aligned} \quad \sigma_c = \left(\frac{2E\gamma_s}{\pi a} \right)^{1/2}$$

where

- E = modulus of elasticity
- γ_s = specific surface energy
- a = one half length of internal crack
- $K_c = \sigma_c / \sigma_0$

For ductile materials $\Rightarrow$ replace γ_s by $\gamma_s + \gamma_p$
where γ_p is plastic deformation energy



TABLE 8.3**Typical Values of Fracture Toughness (K_{IC}) for Various Materials**

Material	K_{IC} (MPa $\sqrt{\text{m}}$)
Metal or alloy	
Mild steel	140
Medium-carbon steel	51
Rotor steels (A533; Discalloy)	204–214
Pressure-vessel steels (HY130)	170
High-strength steels (HSS)	50–154
Cast iron	6–20
Pure ductile metals (e.g., Cu, Ni, Ag, Al)	100–350
Be (brittle, hcp metal)	4
Aluminum alloys (high strength–low strength)	23–45
Titanium alloys (Ti–6Al–4V)	55–115



- Crack growth condition:

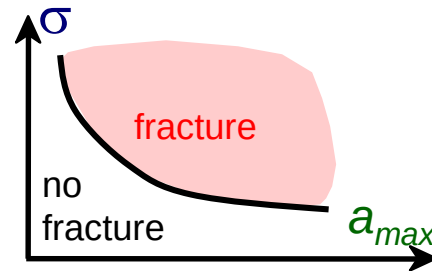
$$K \geq K_c = Y\sigma\sqrt{\pi a}$$

- Largest, most stressed cracks grow first!

Design Against Crack Growth

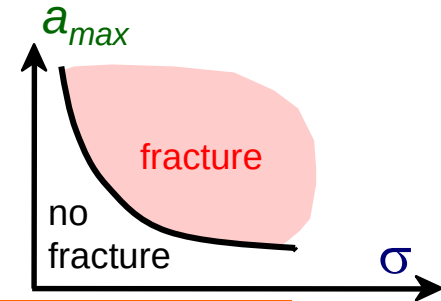
--Result 1: Max. flaw size dictates design stress!

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



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

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



Y is a material behavior shape factor

Design Example: Aircraft Wing

- Material has $K_c = 26 \text{ MPa-m}^{0.5}$
- Two designs to consider...

Design A

- largest flaw is 9 mm
- failure occurs at stress = 112 MPa

- Use...

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

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

$$\left(\overset{112 \text{ MPa}}{\sigma_c} \sqrt{\overset{9 \text{ mm}}{a_{\max}}} \right)_A = \left(\sigma_c \sqrt{a_{\max}} \right)_B$$

Design B

- use same material
- largest flaw is 4 mm
- failure stress = ?

Answer: $(\sigma_c)_B = 168 \text{ MPa}$

- Reducing flaw size pays off!



Example

- Steel subject to tensile stress of 1030 MPa, it has K_{1c} of 54.8 MPa $\sqrt{m}$
- If it has a 'largest surface crack' .5 mm (.0005 m) long will it grow and fracture?

What crack size *will* result in failure?

$$K_a = Y\sigma_a\sqrt{\pi a}$$

here

$$Y = 1$$

$$Y\sigma_a\sqrt{\pi a} = 1 * 1030 * \sqrt{3.141 * .0005} = 40.82$$

Since $K_a < K_{1c}$ the part won't fail!

$$K_{1c} = Y\sigma_c\sqrt{\pi a}$$

$$a = \left(\frac{K_{1c}}{Y\sigma_c} \right)^2 \frac{1}{\pi} = \left(\frac{54.8}{1 * 1030} \right)^2 \frac{1}{3.1416}$$

$$a = .0009m = .9mm$$



	Criterion	Comments	Fracture occurs if	Relevant formulae
Summary of Fracture Criteria	Inglis (σ_f) 1913	Involves crack tip radius (& crack length)	$\sigma \geq \sigma_f$	$\sigma_f = \sqrt{\frac{E\gamma\rho}{4a_0c}}$
	Griffith (σ_f) 1920	Involves crack length	$\sigma \geq \sigma_f$	$\sigma_f = \sqrt{\frac{2\gamma E}{\pi c^*}}$
	Irwin [K]	Concept of stress intensity factor.	$K_I \geq K_{IC}$ (in mode I)	$K_I = Y \left(\sigma_0 \sqrt{\pi c} \right)$
	Irvin [G]	Energy release rate based. Same as K based criterion for elastic bodies.	$G \geq G_C$	
	Wells (δ , CTOD) 1961	Involves crack (tip) opening displacement	$\delta \geq \delta_C$	$\delta = \beta \left(\frac{K_I^2}{E^* \sigma_y^*} \right)$
	Rice [J -integral] 1968	Generalized energy release rate concept. Applicable to non-linear elastic and elastic-plastic materials.	$J \geq J_C$ (crack initiation)	HRR fields.



Fracture Toughness* (K_{IC}) for some typical materials ^[1]

Material	K_{IC} [MPa $\sqrt{m}$]**
Cast Iron	33
Low carbon steel	77
Stainless steel	220
Al alloy 2024-T3	33
Al alloy 7075-T6	28
Ti-6Al-4V	55
Inconel 600 (Ni based alloy)	110

* We have already noted that fracture toughness is a microstructure sensitive property and hence to get 'true' value the microstructure has to be specified.

** Note the strange units for fracture toughness!

[1] Fracture Mechanics, C.T. Sun & Z.-H. Jin, Academic Press, Oxford (2012).



SCC conditions

Alloy	K_{IC} (MN/m ^{3/2})	SCC environment	K_{ISCC} (MN/m ^{3/2})
13Cr steel	60	3% NaCl	12
18Cr-8Ni	200	42% MgCl ₂	10
Cu-30Zn	200	NH ₄ OH, pH7	1
Al-3Mg-7Zn	25	Aqueous halides	5
Ti-6Al-1V	60	0.6M KCl	20

