

# 1- Fracture

Fracture: Separation of a body into pieces due to stress, at temperatures below the melting point.

Steps in fracture:

1-Crack formation

2-Crack propagation

There are two modes of fracture depending on the ability of material to undergo plastic deformation before the fracture.

A-Ductile fracture mode

Ductile fracture  $\implies$  most metals (not too cold)

More of plastic deformation ahead of crack

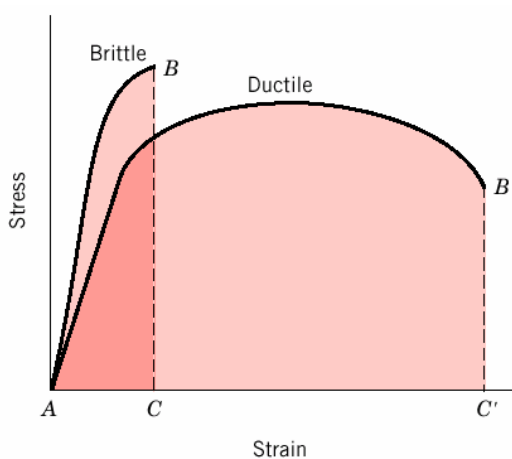
Crack is "unstable" Propagates rapidly without increase in applied stress.

**"Ductile fracture is preferred in most applications"**

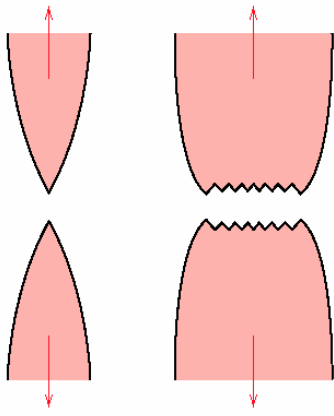
## Brittle vs. Ductile Fracture

Ductile materials  $\implies$  more plastic deformation and energy absorption (toughness) before fracture.

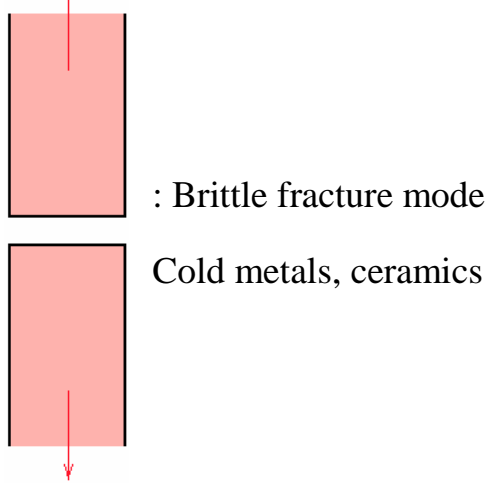
**Brittle fracture:**  $\implies$  little plastic deformation and low energy absorption



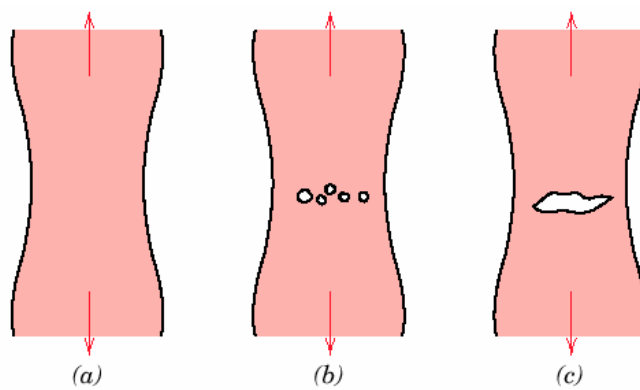
Ductile fracture mode:



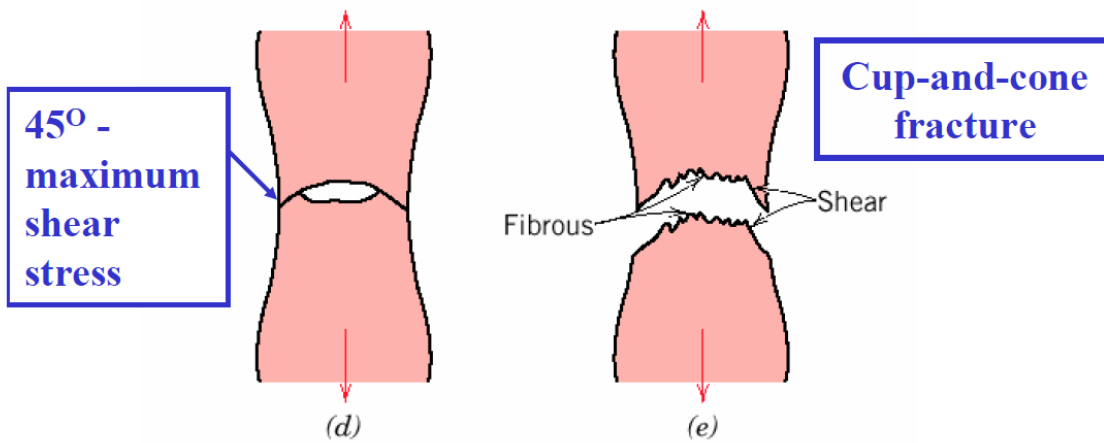
**Very ductile**, soft metals (e.g. Pb, Au) at room temperature, other metals, polymers, glasses at high temperature (Left side)  
**Moderately ductile fracture**, typical for ductile metals (Right Side)



Ductile fracture

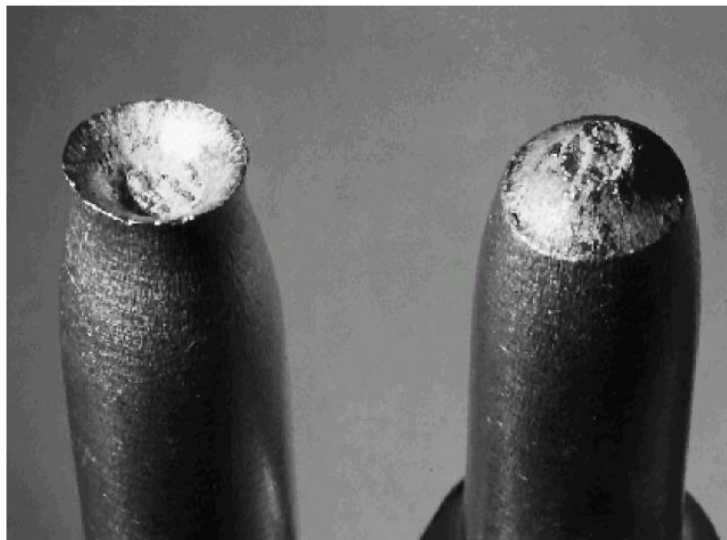


Crack grows 90° to applied stress



- (a) Necking**
- (b) Formation of microvoids**
- (c) Coalescence of microvoids to form a crack**
- (d) Crack propagation by shear deformation**
- (e) Fracture**

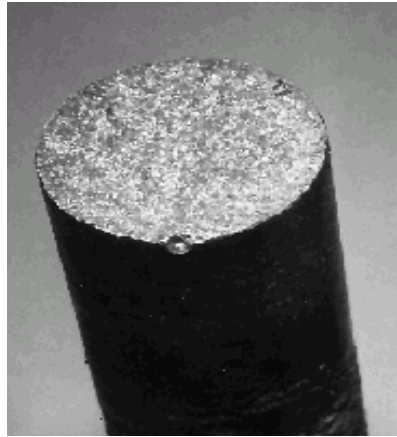
### Ductile Fracture



(Cup-and-cone fracture in Al)

## **Brittle Fracture**

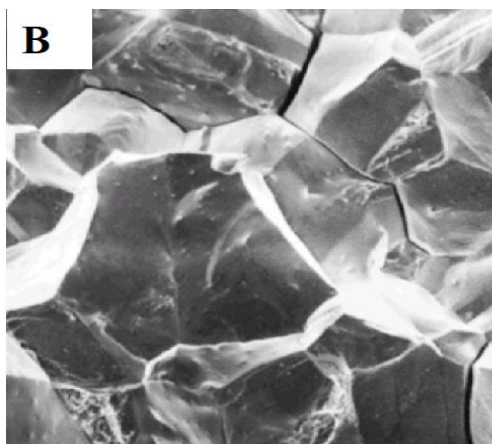
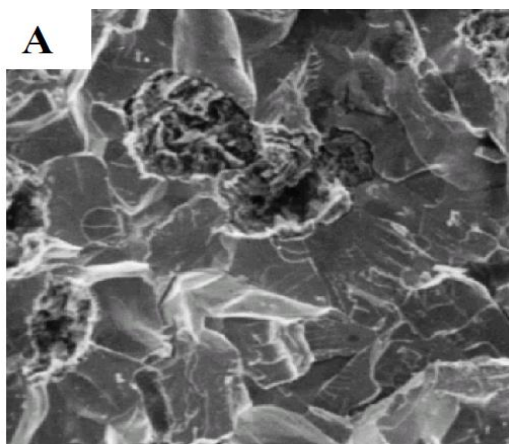
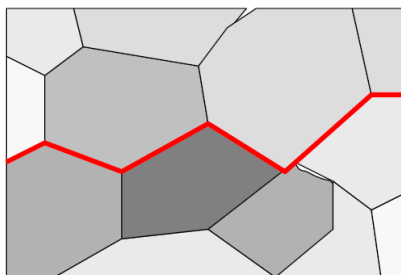
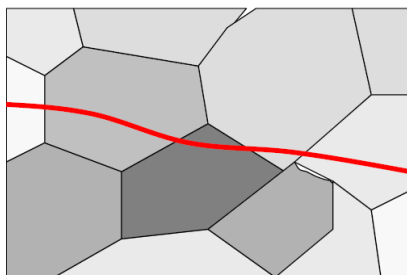
- No appreciable plastic deformation
- Crack propagation is very fast
- Crack propagates nearly perpendicular to the direction of the applied stress
- Crack often propagates by **cleavage** –breaking of atomic bonds along specific crystallographic planes (**cleavage planes**).



### **Brittle Fracture**

**A: Transgranular fracture:** Fracture cracks pass through grains. Fracture surface have faceted texture because of different orientation of cleavage planes in grains.

**B: Intergranular fracture:** Fracture crack propagation is along grain boundaries (grain boundaries are weakened or embrittled by impurities segregation etc.)



# Stress Concentration

Fracture strength of a brittle solid is related to the cohesive forces between atoms. One can estimate that the Theoretical cohesive strength of a brittle material should be  $\sim E/10$ . But experimental fracture strength is normally  $E/100 - E/10,000$ .

This much lower fracture strength is explained by the Effect of **stress concentration** at microscopic flaws. The Applied stress is amplified at the tips of micro-cracks, Voids, notches, surface scratches, corners, etc. that are Called **stress raisers**. The magnitude of this amplification Depends on micro-crack orientations, geometry and Dimensions.

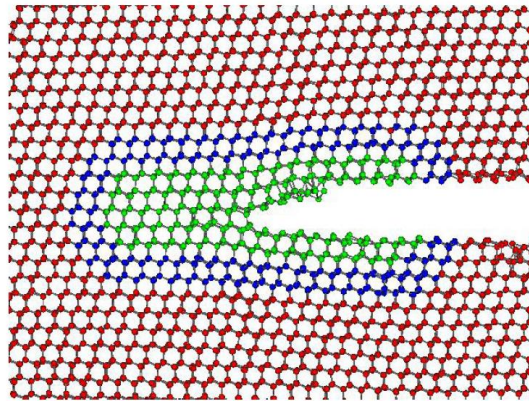
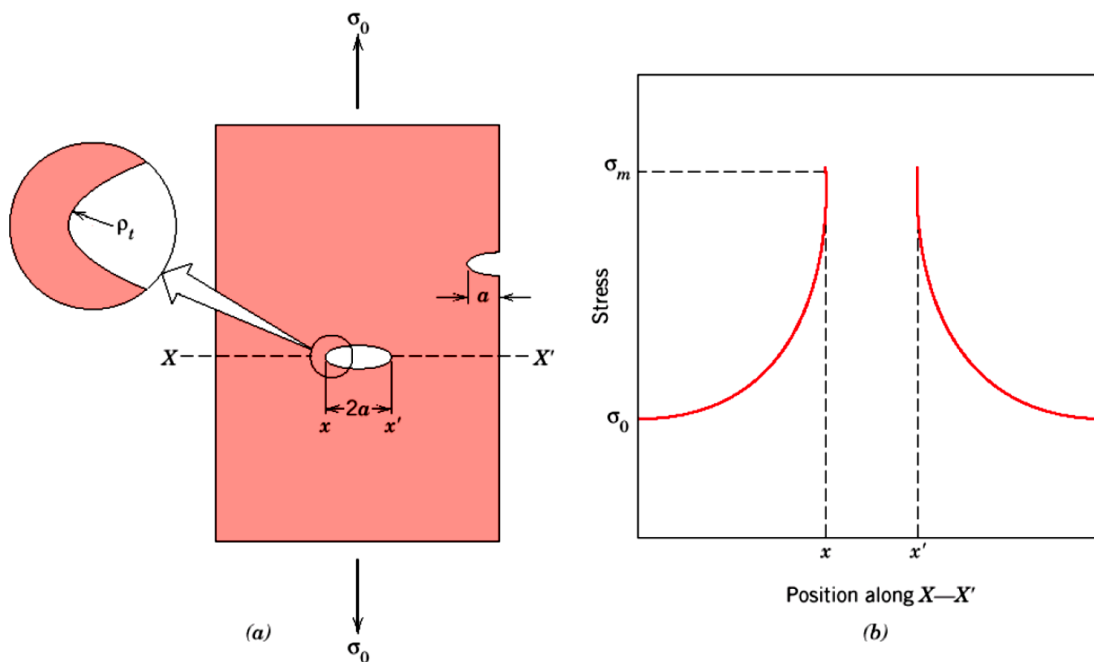


Figure by  
N. Bernstein &  
D. Hess, NRL



For a long crack oriented perpendicular to the applied stress the maximum stress near the crack tip is:

$$\sigma_m \approx 2\sigma_0 \left\{ \frac{a}{\rho_t} \right\}^{1/2}$$

Where  $\sigma_0$  is the applied external stress,  $a$  is the **half-length**

Of the crack, and  $\rho_t$  the radius of curvature of the crack tip. (Note that  $a$  is half-length of the internal flaw, but the full length for a surface flaw).

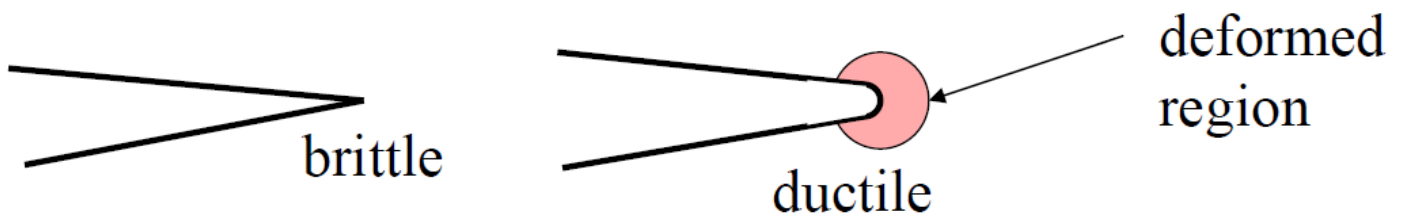
The **stress concentration factor** is:  $K_t = \frac{\sigma_m}{\sigma_0} \approx 2 \left\{ \frac{a}{\rho_t} \right\}^{1/2}$

## Crack propagation

Cracks with sharp tips propagate easier than cracks having blunt tips

$$\sigma_m \approx 2\sigma_0 \left\{ \frac{a}{\rho_t} \right\}^{1/2}$$

In ductile materials, plastic deformation at a crack tip “blunts” the crack.



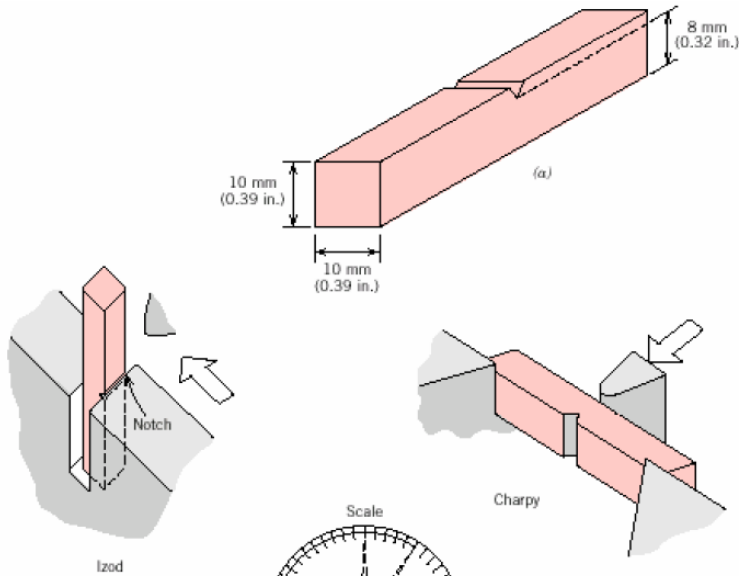
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## Impact Resistance Test

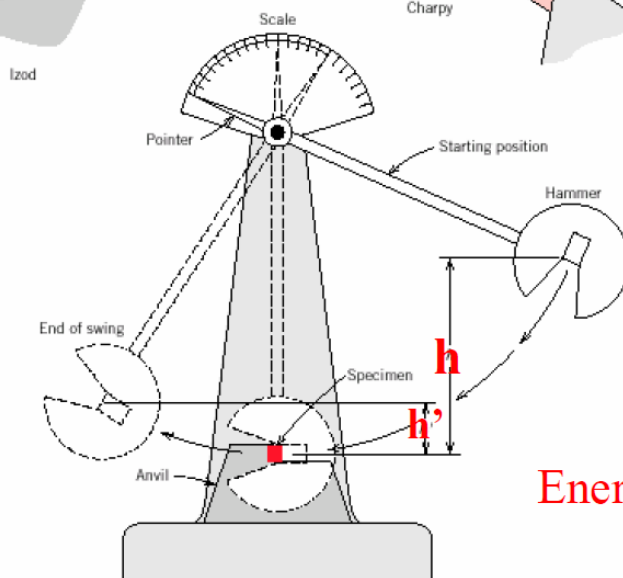
"testing fracture characteristics under high strain rates"

Two standard tests, the **Charpy** and **Izod**, measure the **impact energy** (the energy required to fracture a test piece under an impact load), also called the **notch toughness**.

**Izod**

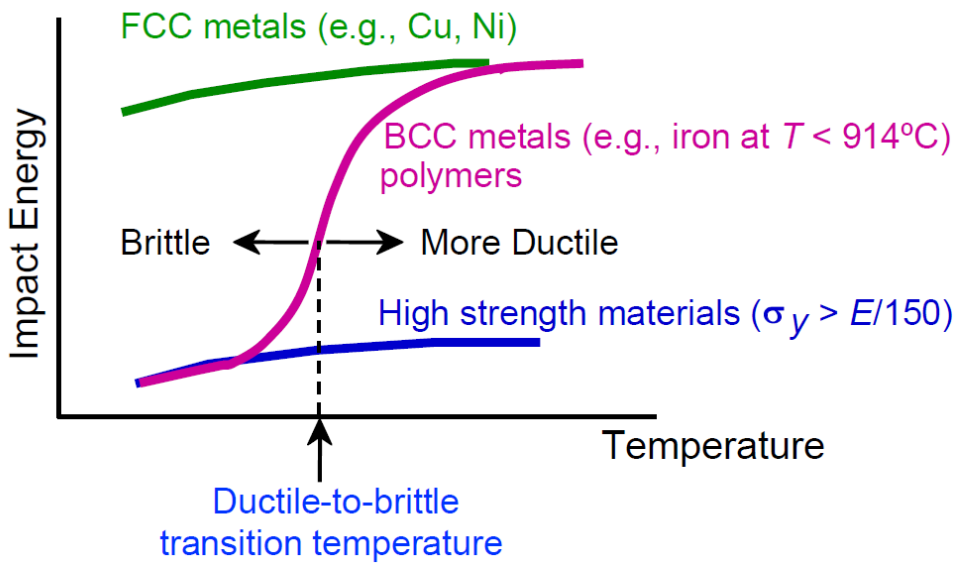


**Charpy**



## Ductile to Brittle Transition (DBTT)

As temperature decreases a ductile material can become brittle - [ductile-to-brittle transition](#)  
Alloying usually increases the ductile-to-brittle transition temperature. FCC metals remain ductile down to very low temperatures. For ceramics, this type of transition occurs at much higher temperatures than for metals. The ductile-to-brittle transition can be measured by impact testing: the impact energy needed for fracture drops suddenly over a relatively narrow temperature range – temperature of the ductile-to-brittle transition.



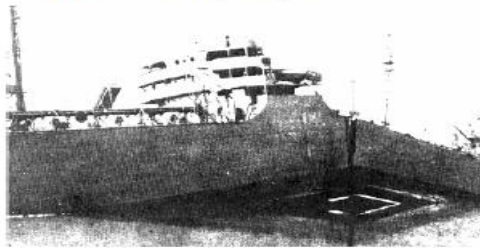
## Stay Above The DBTT!

- Pre-WWII: The Titanic



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- WWII: Liberty ships



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- **Problem:** Used a type of steel with a DBTT ~ Room temp.

## **Brittle fracture**

**Large grained materials with GB particles.**

**Low temperature**

**Triaxial state of stresses (notch effect)**

**High strain rate**

## **Ductile fracture**

**Fine grained material without GB particles.**

**High temperature**

**Absence of the notch**

**Low strain rate**

**Hydrostatic pressure (suppress crack initiation)**

## **Factors affecting modes of fracture**

**Metallurgical aspect, Temperature, State of stresses (notch effect), Strain rate, Loading condition.**

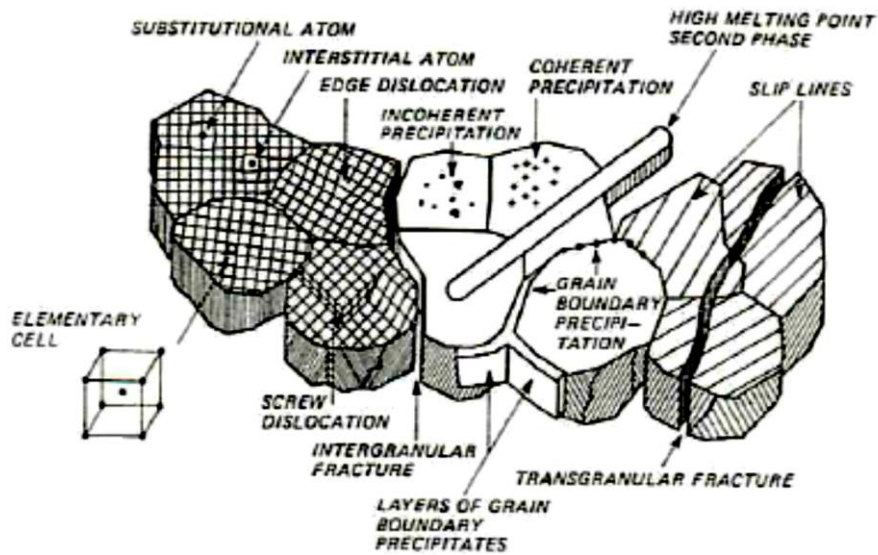
### **1-Metallurgical aspect of fracture**

- Microstructure in metallic materials are highly complex.
- Various microstructural features affect how the materials fracture.

*There are microstructural features that can play a role in determining the fracture path, the most important are;*

- (a) Second phase
- (b) Particles and precipitates
- (c) Grain size
- (d) Fibering and texturing

- High strength materials usually possess several microstructural features in order to optimize mechanical properties by influencing deformation behavior / fracture paths.



## 2-State of stresses (notch effect)

The difference in the state of stresses in the presence of a sharp crack or notch affects fracture in materials.

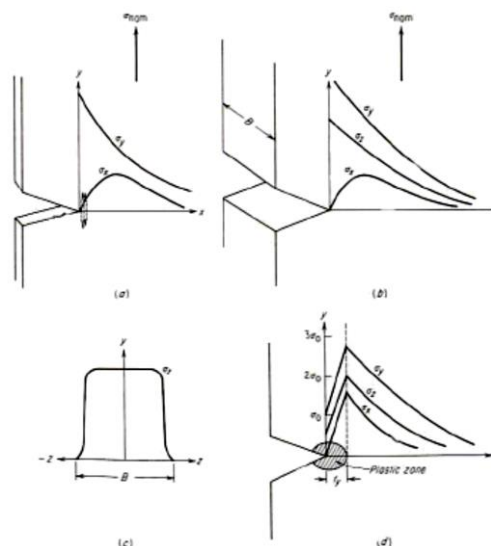
A notch or a sharp crack increases the tendency for brittle fracture in four important ways;

- 1) Producing high local stresses
- 2) Introducing a triaxial state of stresses
- 3) Producing high local strain hardening and cracking
- 4) Producing a local magnification to the strain rate.

Note: the notch also raises the plastic-constraint factor  $q$ , which does not exceed the value of 2.75

## Notch effect

- In a thin plate, stress in the  $z$  (thickness) direction is absence, the specimen is not constrained.
- In thicker plate,  $\sigma_y$  (in the tensile direction) is constrained due to the reaction of  $\sigma_z$  and  $\sigma_x$ , leading to triaxial state of stresses.
- Triaxial stresses limit plastic deformation ahead of the crack tip  $\rightarrow$  raising the general yield  $\rightarrow$  material prone to brittle fracture.



## Effects of combined stress and hydrostatic pressure on fracture

### Combined stress

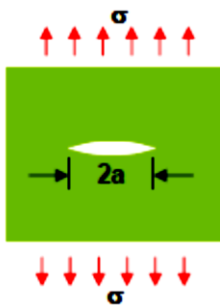
- Yielding under complex states of stress is difficult to predict.
- Available data on ductile metals, i.e., Al and Mg alloys and steel indicate that the maximum-shear stress criterion for fracture are in the best agreement.

### Hydrostatic pressure

- Hydrostatic pressure is triaxial compressive stress resist fracture and increase ductility.
- Hydrostatic pressure exerts no shear stress, it therefore does not influence crack initiation but affects crack propagation.

## Fracture Toughness

Griffith proposed that an existing crack will propagate when the released elastic strain energy is at least equal to the energy required to create the new crack surface.



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

- Irwin later modified the Griffith theory by replacing the term  $2\gamma_p$  with the potential strain energy release rate  $G$ , giving the expression as follows;

$$\sigma_f = \left( \frac{EG}{\pi a} \right)^{1/2}$$

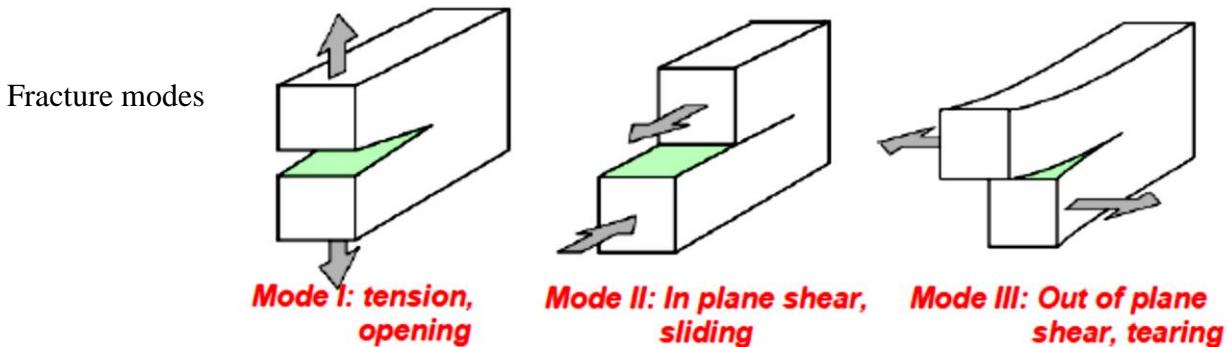
- Irwin showed that  $G$  is measurable and can be related to the stress intensity factor,  $K$ , obtained from the sharp crack fracture toughness test.
- The critical condition to which the crack propagates to cause global failure is when this  $G$  value exceeds the critical value,  $G_c$ .

## Stress intensity factor

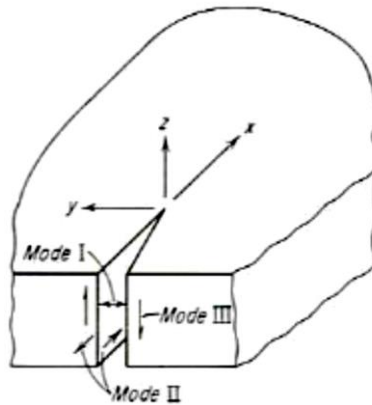
In mode I failure and plane-strain condition, the relationship between  $G_{IC}$  and  $K_{IC}$  can be shown by an expression as follows;

$$G_{IC} = \frac{K_{IC}^2 (1 - \nu^2)}{E}$$

Where  $K_{IC}$  is the critical stress intensity factor for mode I failure.



Crack deformation crack



**Note:**  $K$  value can be evaluated using standard experimental approaches, which is much more readily than values of  $G$ .

Stress intensity factor  $K_{IC}$  can be described as fracture toughness of materials (material resistance to crack propagation) under conditions of:

- 1) Brittle fracture
- 2) In the presence of a sharp crack
- 3) Under critical tensile loading

$$K_{IC} = \alpha \sigma_{app} \sqrt{\pi a_c}$$

Where

$K_{IC}$  is the critical stress intensity factor for plane strain condition in mode I failure.

$a_c$  is the critical crack length in an infinite plate  $\sigma_{app}$  is the applied stress  $\alpha$  is a parameter dependent on specimen and crack geometry.

## 2-Fatigue

"Failure under fluctuating / cyclic stresses"

\*Under fluctuating / cyclic stresses, failure can occur at loads considerably **lower than tensile or yield strengths of material** under a static load: **Fatigue** \*Estimated to causes 90% of all failures of metallic structures (bridges, aircraft, machine components, etc.)

\***Fatigue failure is brittle-like** (relatively little plastic deformation) - even in normally ductile materials. Thus sudden and catastrophic!

\*Applied stresses causing fatigue may be axial (tension or compression), flexural (bending) or torsional (twisting).

\*Fatigue failure proceeds in three distinct stages: crack initiation in the areas of stress concentration (near stress raisers), incremental crack propagation, final catastrophic failure.

### Examples of Fatigue Failure

\*Aircraft are particularly sensitive to fatigue.

\*Automobile parts such as axles, transmission parts, and suspension systems may fail by fatigue.

\*Turbine blades, bridges, and ships are other examples.

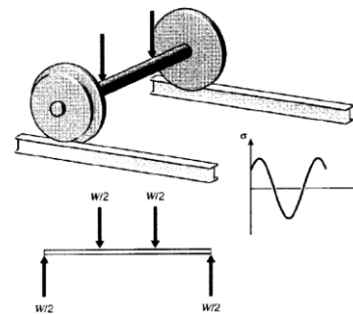


Figure 6.18: Fatigue in a railcar axle.

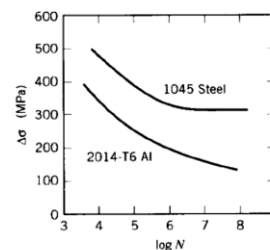
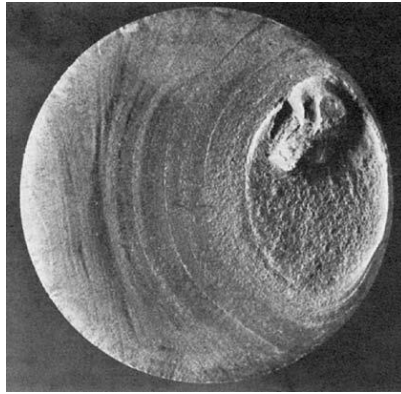
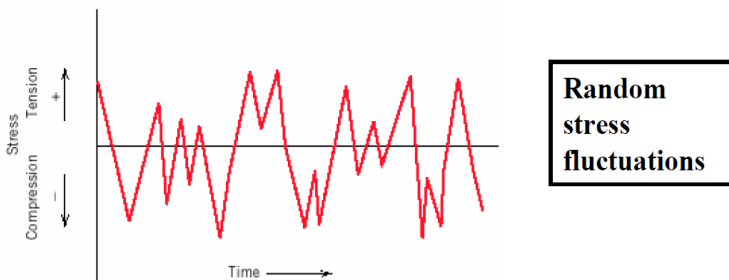
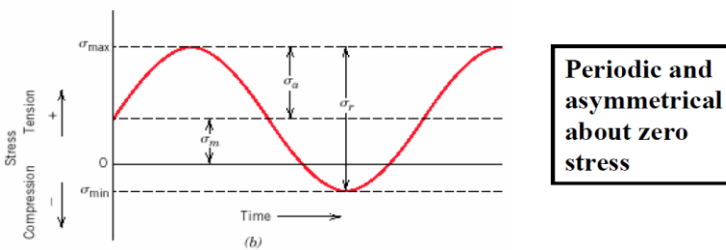
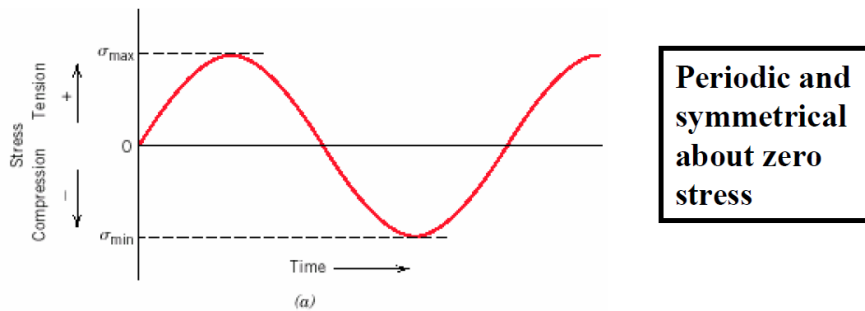


Figure 6.19:  $S - N$  curves for aluminum and low-carbon ste



Typical clamshell or beach markings on a fatigue fracture surface of a shaft. The fracture started at the left side of the bar and progressed to the right, where final failure occurred in a single cycle.

## Fatigue: Cyclic Stresses (I)



## Fatigue: Cyclic Stresses (II)

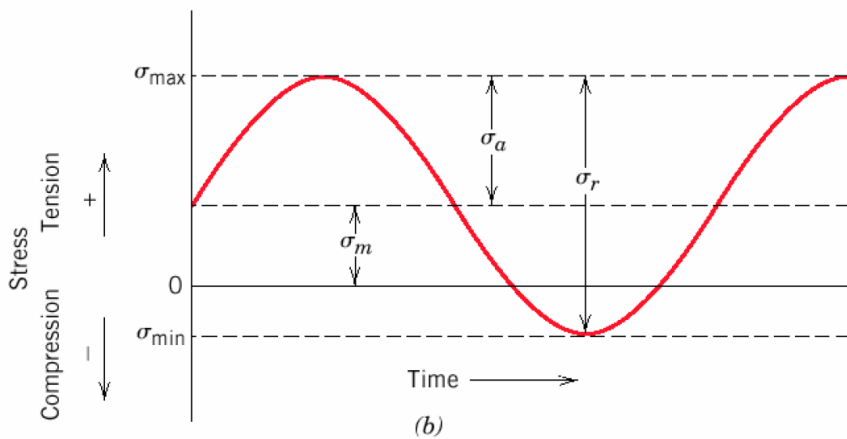
Cyclic stresses are characterized by maximum, minimum and mean stress, the range of stress, the stress amplitude, and the stress ratio.

Mean stress:  $\sigma_m = \{\sigma_{max} + \sigma_{min}\} / 2$

Range of stress:  $\sigma_r = \{\sigma_{max} - \sigma_{min}\}$

Stress amplitude:  $\sigma_a = \sigma_r / 2 = \{\sigma_{max} - \sigma_{min}\} / 2$

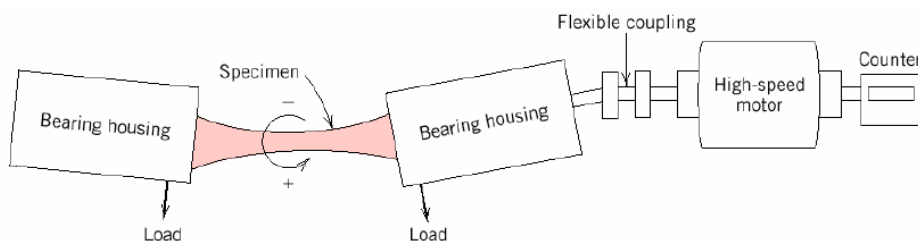
Stress ratio:  $R = \sigma_{min} / \sigma_{max}$



"Remember the convention that tensile stresses are positive, compressive stresses are negative"

## Fatigue: S - N curves (I) (Stress- Number of cycles to failure)

Fatigue properties of a material (S-N curves) are tested in rotating-bending tests in fatigue testing apparatus:

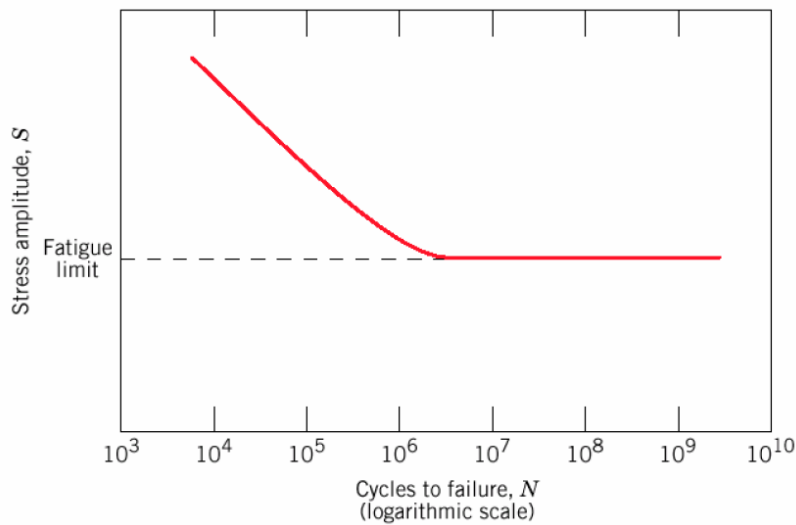


Result is commonly plotted as  $S$  (stress) vs.  $N$  (number of cycles to failure)

**Low cycle fatigue:** high loads, plastic and elastic deformation

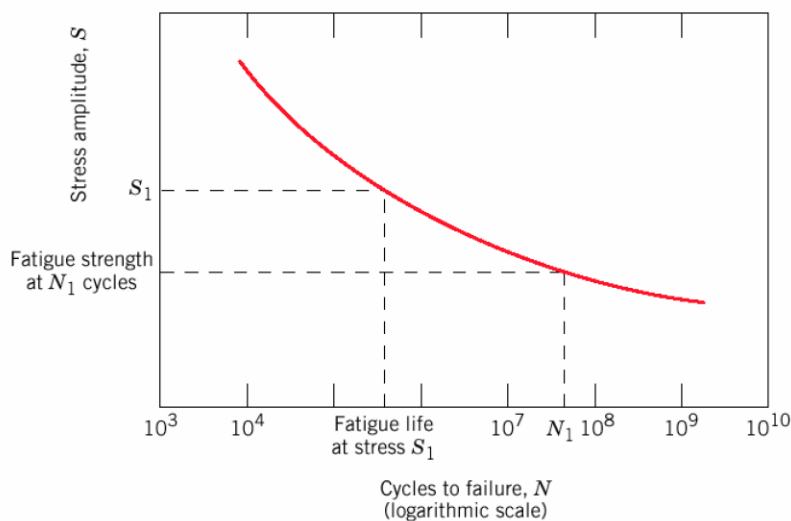
**High cycle fatigue:** low loads, elastic deformation ( $N > 10^5$ ).

### Fatigue: S—N curves (II) Fatigue



**Fatigue limit** (endurance limit) occurs for some materials (e.g. some Fe and Ti alloys). In this case, the S—N curve becomes horizontal at large  $N$ . The fatigue limit is a maximum stress amplitude below which the material never fails, no matter how large the number of cycles is.

### Fatigue: S—N curves (III)



In most alloys,  $S$  decreases continuously with  $N$ . In this cases the fatigue properties are described by:

**Fatigue strength:** stress at which fracture occurs after a specified number of cycles (e.g.  $10^7$ )

**Fatigue life:** Number of cycles to fail at a specified stress level

## Fatigue: Crack initiation and propagation (I)

Three stages of fatigue failure:

1. crack initiation in the areas of stress concentration (near stress raisers)
  2. incremental crack propagation
  3. final rapid crack propagation after crack reaches critical size
- The total number of cycles to failure is the sum of cycles at the first and the second stages:

$$N_f = N_i + N_p$$

$N_f$  : Number of cycles to failure

$N_i$  : Number of cycles for crack initiation

$N_p$  : Number of cycles for crack propagation

High cycle fatigue (low loads):  $N_i$  is relatively high. With increasing stress level,  $N_i$  decreases and  $N_p$  dominates

## Fatigue: Crack initiation and propagation (II)

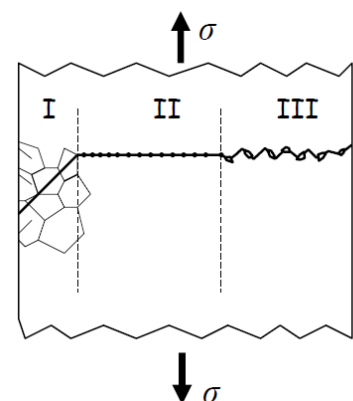
\*-Crack initiation at the sites of stress concentration (microcracks, scratches, indents, interior corners, dislocation slip steps, etc.). Quality of surface is important. \*-Crack propagation

**Stage I:** initial slow propagation along crystal planes with high resolved shear stress. Involves just a few grains, and has flat fracture surface

**Stage II:** faster propagation perpendicular to the applied stress. Crack grows by repetitive blunting and sharpening process at crack tip. Rough fracture surface. (Stable crack growth)

**Stage III:** Unstable crack growth or failure

\*Crack eventually reaches critical dimension and propagates very rapidly

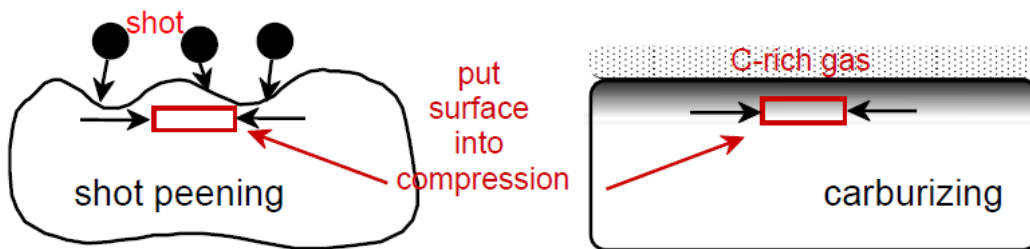


## Factors that affect fatigue life

Magnitude of stress (mean, amplitude...)      Quality of the surface (scratches, sharp transitions).

### Solutions:

- Polishing (removes machining flaws etc.)
- Introducing compressive stresses (compensate for applied tensile stresses) into thin surface layer by “Shot peening”
- Peening”- firing small shot into surface to be treated. High-tech solution - ion implantation, laser peening.
- Case Hardening - create C- or N- rich outer layer in steels by atomic diffusion from the surface. Makes harder outer layer and also introduces compressive stresses
- Optimizing geometry - avoid internal corners, notches etc.



## Factors that affect fatigue life: environmental effects

**Thermal Fatigue:** Thermal cycling causes expansion and contraction, hence thermal stress, if component is restrained.

### Solutions:

- eliminate restraint by design
- use materials with low thermal expansion coefficients

**Corrosion fatigue:** Chemical reactions induce pits which act as stress raisers. Corrosion also enhances crack propagation.

### Solutions:

- decrease corrosiveness of medium, if possible.
- add protective surface coating.
- add residual compressive stresses.

## Crack propagation

In the laboratory, crack growth rates may be determined during testing either optically with a microscope or by measuring the electrical resistance. It has been found that the crack growth rate depends on the range of the stress intensity factor,  $\Delta K$ ,

$$\begin{aligned}\Delta K &= K_{max} - K_{min} = \sigma_{max} f \sqrt{(\pi a)} - \sigma_{min} f \sqrt{(\pi a)} \\ &= (\sigma_{max} - \sigma_{min}) f \sqrt{(\pi a)}\end{aligned}$$

Or more simply

$$\Delta K = f \Delta \sigma \sqrt{(\pi a)}$$

Where  $\Delta \sigma = (\sigma_{max} - \sigma_{min})$

Figure below shows schematically the variation of  $da/dN$  with  $\Delta K$ . Below a threshold,  $\Delta K_{th}$ , cracks do not grow. There are three regimes of crack growth. One is a region where  $da/dN$  increases rapidly with  $\Delta K$ . Then there is a large region where  $\log(da/dN)$  is proportional to  $\log(\Delta K)$ , and finally at large values of  $\Delta K_I$  the crack growth rate accelerates more rapidly. Failure occurs when  $K_I = K_{IC}$ . In viewing this figure one should remember that  $\Delta K_I$  increases with growth of the crack, so that under constant load, a crack will progress up the curve to the right. In stage II,

$$\frac{da}{dN} = C(\Delta K_I)^m \text{ -----(1)}$$

where  $\frac{da}{dN}$  is crack growth rate, C is a material-dependent constant that increases with increasing stress ratio, R (i.e., mean stress). The exponent, m, is also material-dependent and is usually in the range from 2 to 7

Note that the crack length at any stage can be found by substituting  $(\Delta K_I)^m = [f \Delta \sigma \sqrt{(\pi a)}]^m$  into Equation (1) and rearranging:

$$\frac{da}{a^{\frac{m}{2}}} = C(f \Delta \sigma \sqrt{\pi})^m dN$$

Integration, neglecting the dependence of f on a, gives

$$a^{(1-\frac{m}{2})} - a_0^{(1-\frac{m}{2})} = \left(1 - \frac{m}{2}\right) C(f \Delta \sigma \sqrt{\pi})^m N$$

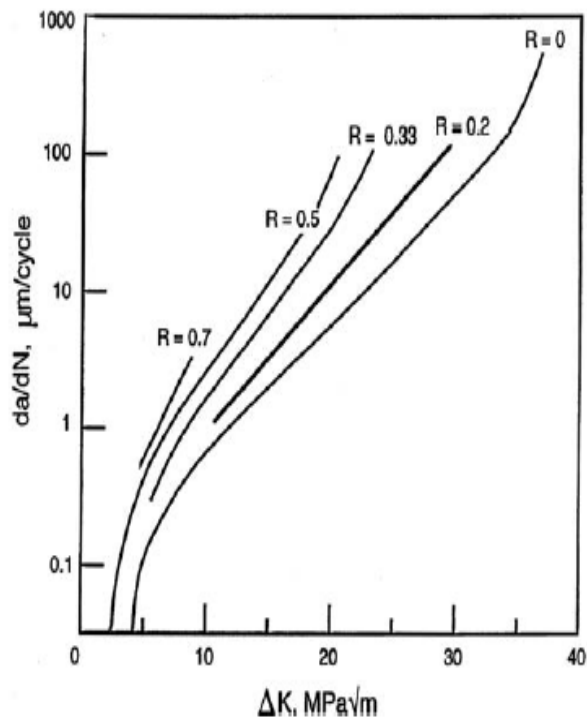
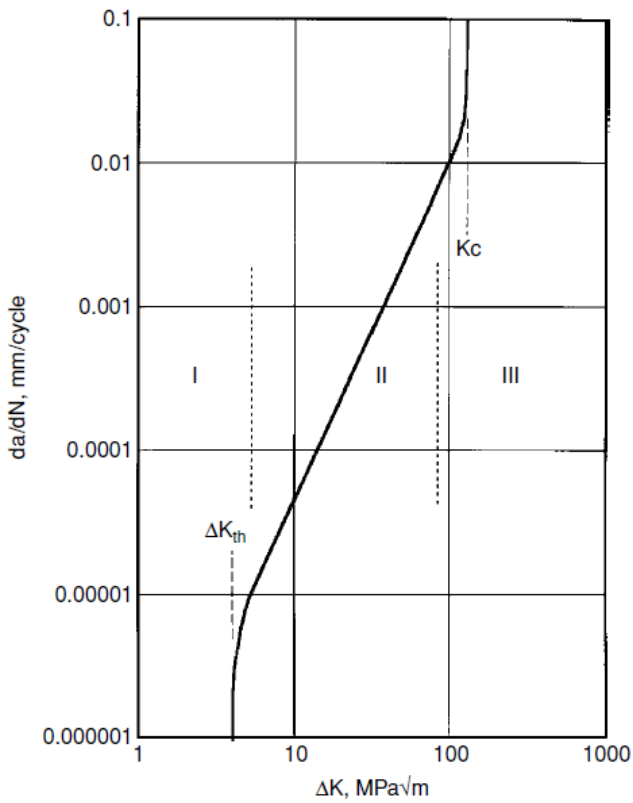
The number of cycles to reach a crack size a is then

$$N = [a^{(1-m/2)} - a_0^{(1-m/2)}] / \left[(1 - m/2)C(f \Delta \sigma \sqrt{\pi})^m\right].$$

**Figure** ↓

A schematic plot of the dependence of crack growth rate,  $da/dN$ , on the stress intensity factor,  $\Delta K_I$ . Because  $\Delta K_I$  increases with crack length, a, crack growth will progress up the curve. Below the threshold stress, cracks do not grow. In general there are three regions: An initial period (region I), a linear region (II) in which the rate of crack growth is given by Equations (above), and a final region (III) of acceleration to failure. The slope of the linear

region on the log-log plot equals  $m$ .



**Figure 17.21.** Crack growth rate in aluminum alloy 7076-T6 as a function of  $\Delta K$  for several levels of  $R$ . Note that  $da/dN$  increases with  $R$ . Data from C. A. Martin, NASA TN D5390, 1969.

Consider crack growth in 7076-T6 aluminum.

1. Determine the crack growth rate,  $da/dN$ , if  $\Delta\sigma = 200MPa$  and the crack is initially 1 mm in length. Assume  $R=0$  and  $f=1$ .

2. Calculate the number of cycles needed for the crack to grow from 0.01 to 10 mm  
if  $\Delta\sigma = 200$  MPa,  $m=4.05$ ,  $C=6.2 \times 10^{-11}$

Solution:

$$1- \quad \Delta K = f \Delta\sigma \sqrt{\pi a} = 200 \text{ MPa} \sqrt{0.001\pi} = 11.2 \text{ MPa} \sqrt{m}$$

From figure above

$$\frac{da}{dN} \approx 10^{-3} \text{ mm}$$

2-Using Equation above with  $m=4.05$  and  $C=6.2 \times 10^{-11}$  from

$$N = \frac{(10^{-2})^{-1.025} - (10^{-5})^{-1.025}}{[(-1.025)(6.2 \times 10^{-8})] \times (200\sqrt{\pi})^{4.05}}$$

$$= 99 \text{ cycles}$$