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 ⟹ most metals (not too cold)

More of plastic deformation ahead of crack

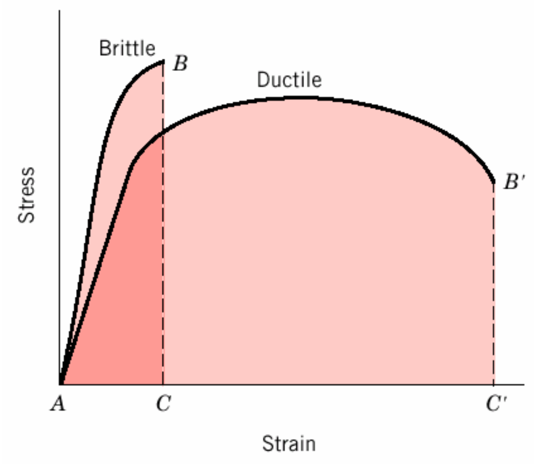
Crack is "unstable" Propagates rapidly without increase in applied stress.

"Ductile fracture is preferred in most applications"

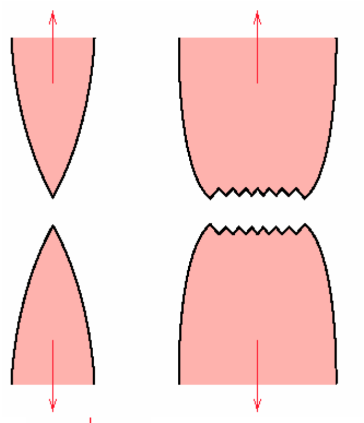
Brittle vs. Ductile Fracture

Ductile materials ⟹more plastic deformation and energy absorption (toughness) before fracture.

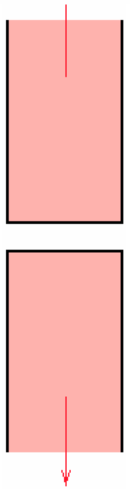
Brittle fracture:⟹little plastic deformation and low energy absorption



Ductile fracture mode:



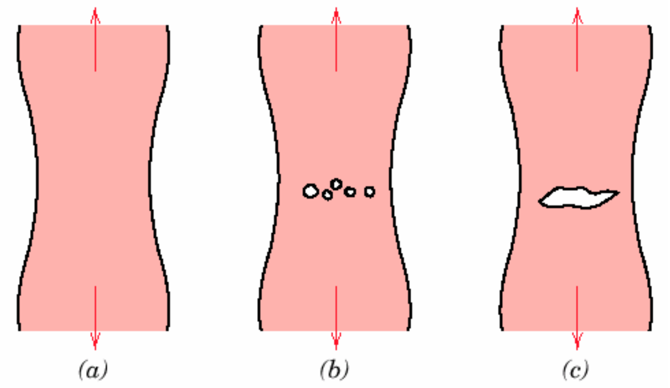
Very ductile, soft metals (e.g. Pb, Au) at room temperature, other metals, polymers, glasses at high temperature (Left side)
Moderately ductile fracture, typical for ductile metals (Right Side)



: Brittle fracture mode

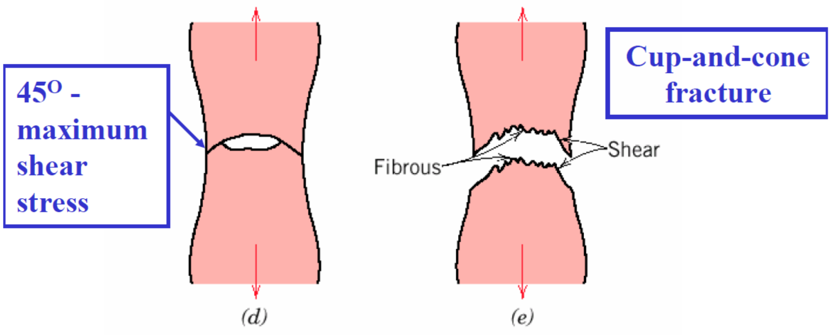
Cold metals, ceramics

Ductile fracture



(a) (b) (c)

Crack grows 90° to applied stress



(a) Necking

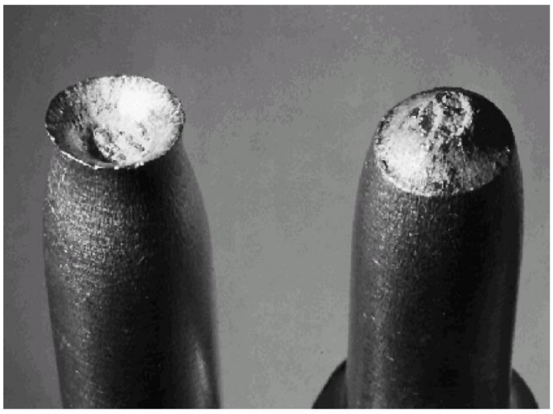
(b) Formation of microvoids

(c) Coalescence of microvoids to form a crack

(d) Crack propagation by shear deformation

(e) Fracture

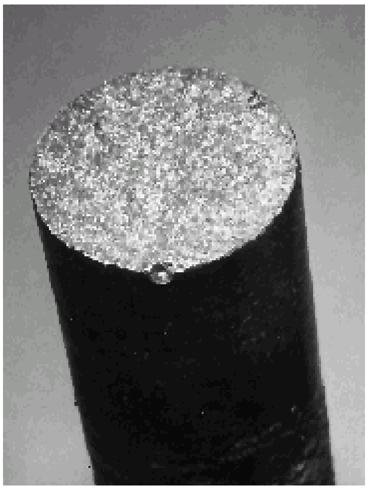
Ductile Fracture



(Cup-and-cone fracture in Al)

Brittle Fracture

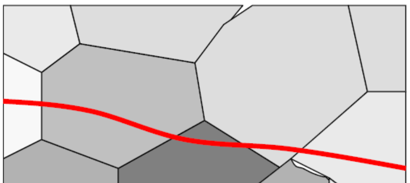
-No appreciable plastic deformation
-Crack propagation is very fast
-Crack propagates nearly perpendicular to the
Direction of the applied stress
- Crack often propagates by cleavage –breaking of atomic bonds along specific
Crystallographic planes (cleavage planes).

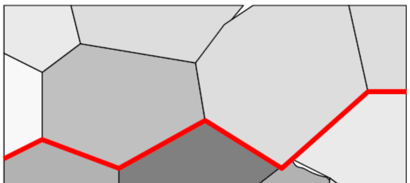


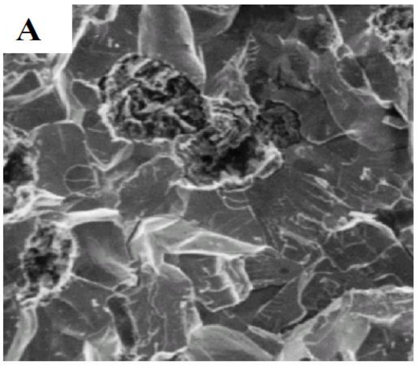
Brittle Fracture

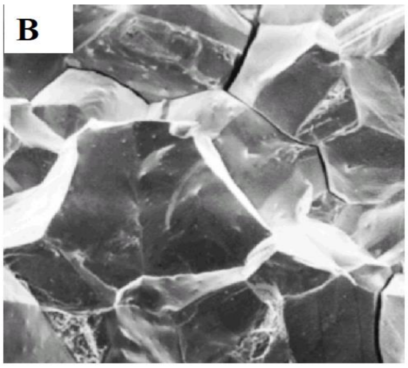
A: Transgranular fracture: Fracture cracks pass through grains. Fracture surface have faceted texture because of different orientation of cleavage planes in grains.

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
~ 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.

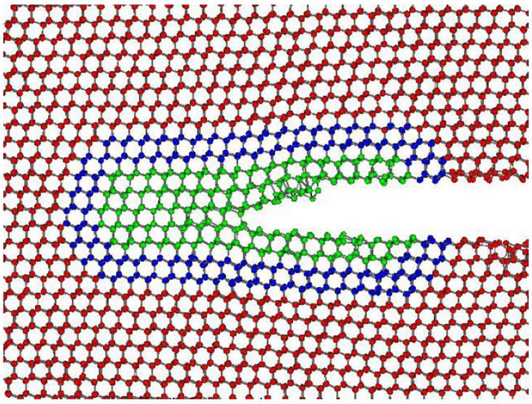
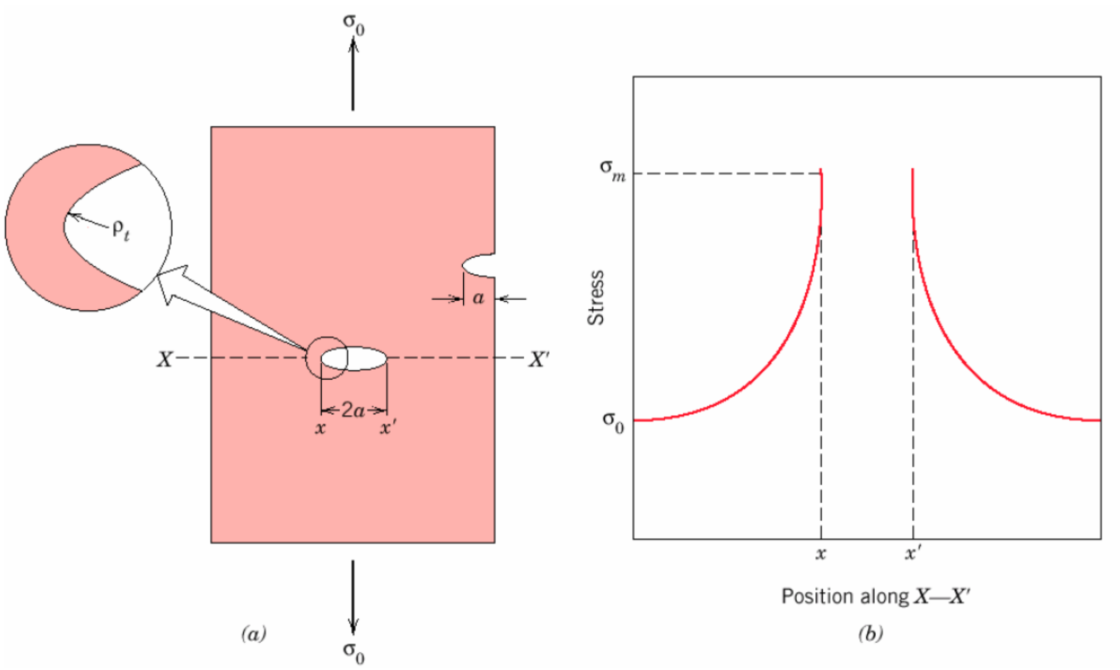


Figure by
N. Bernstein &
D. Hess, NRL



(a) (b)

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 σ_0 is the applied external stress, a is the half-length Of the crack, and ρ_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).

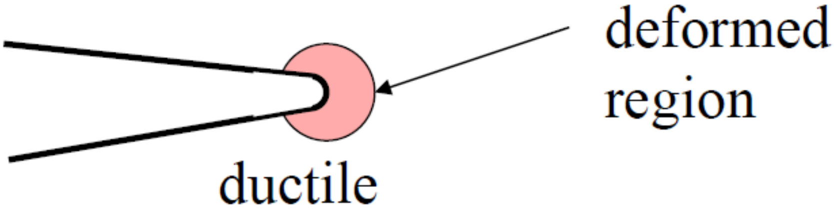
The **stress concentration factor** is: $K_t = \frac{\sigma_m}{\sigma_0} \approx 2\left\{\frac{a}{\rho_t}\right\}^{1/2}$

Crack propagation

Cracks with sharp tips propagate easier than cracks having blunt tips

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

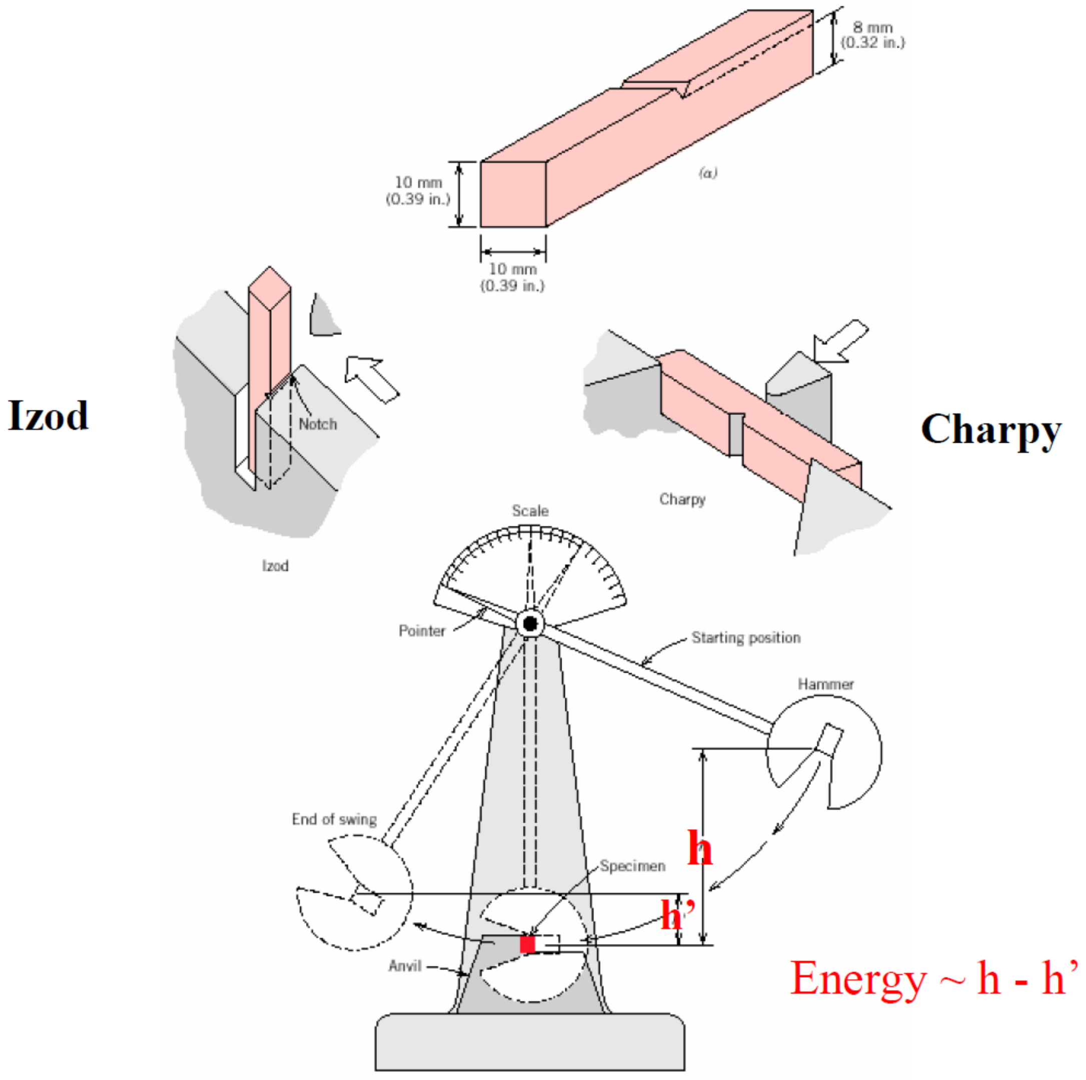
In ductile materials, plastic deformation at a crack tip “blunts” the crack.



2- Impact Resistance Test

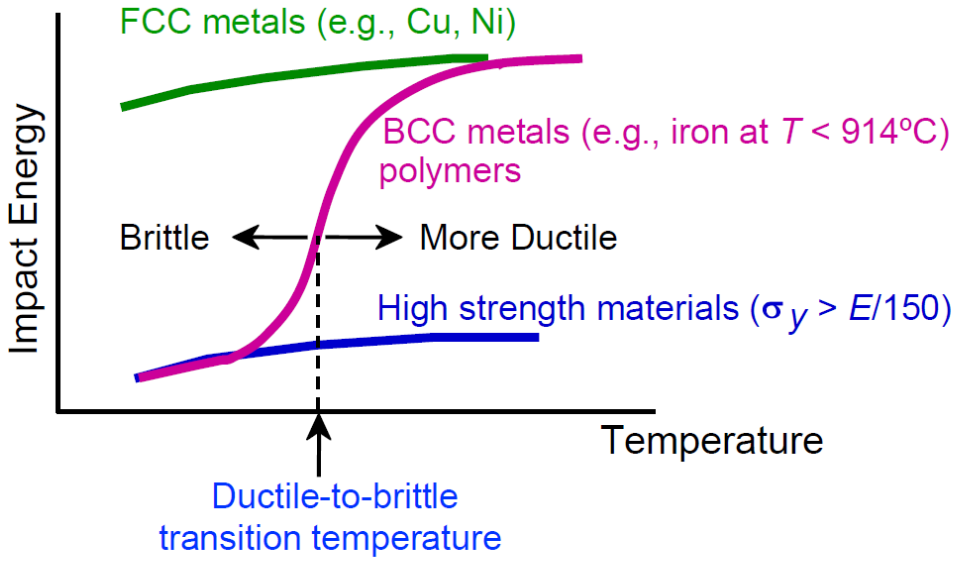
"testing fracture characteristics under high strain rates"

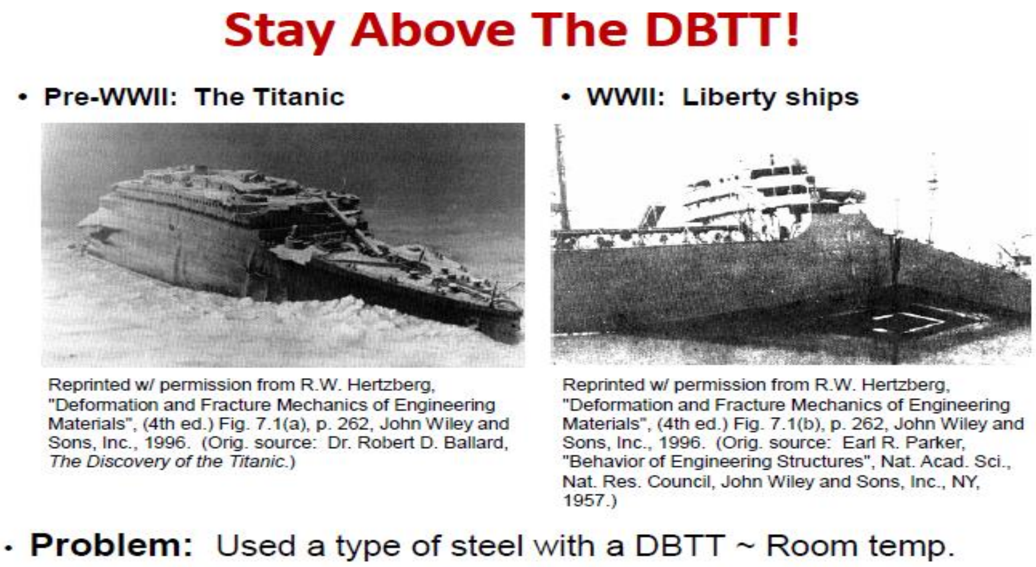
Two standard tests, the **Charpy** and **Izod,** measure the **impact energy** (the energy required to fracture a test piece under an impact load), also called the notch toughness.



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**
- **WWII: Liberty ships**

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.*)

Reprinted w/ permission from R.W. Hertzberg, "Deformation and Fracture Mechanics of Engineering Materials", (4th ed.) Fig. 7.1(b), p. 262, John Wiley and Sons, Inc., 1996. (Orig. source: Earl R. Parker, "Behavior of Engineering Structures", Nat. Acad. Sci., Nat. Res. Council, John Wiley and Sons, Inc., NY, 1957.)

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

3-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), flextural (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 Failur

*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.

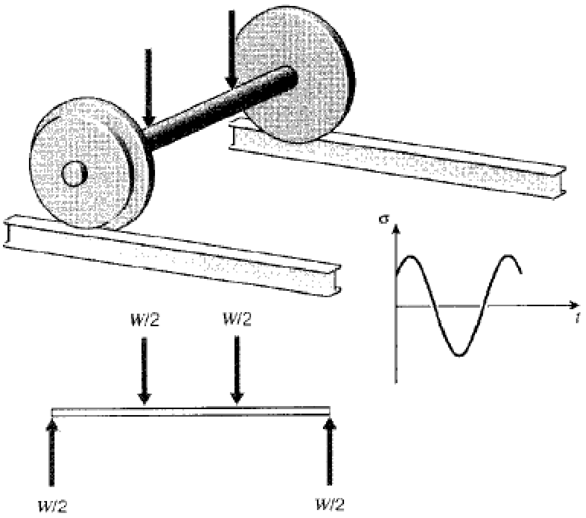


Figure 6.18: Fatigue in a railcar axle.

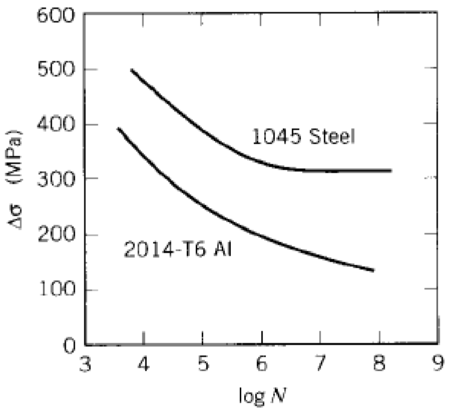
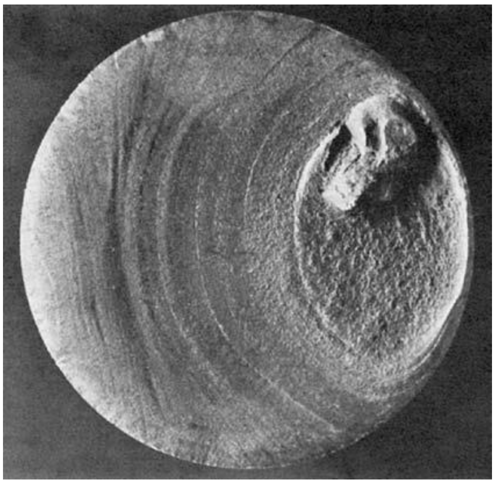
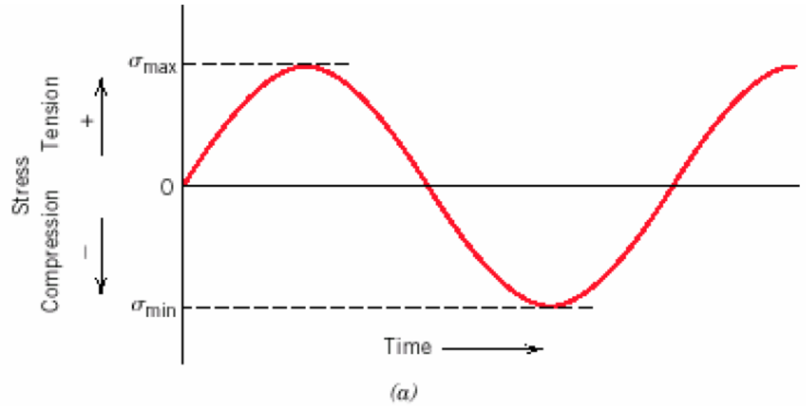


Figure 6.19: $S - N$ curves for aluminum and low-carbon ste

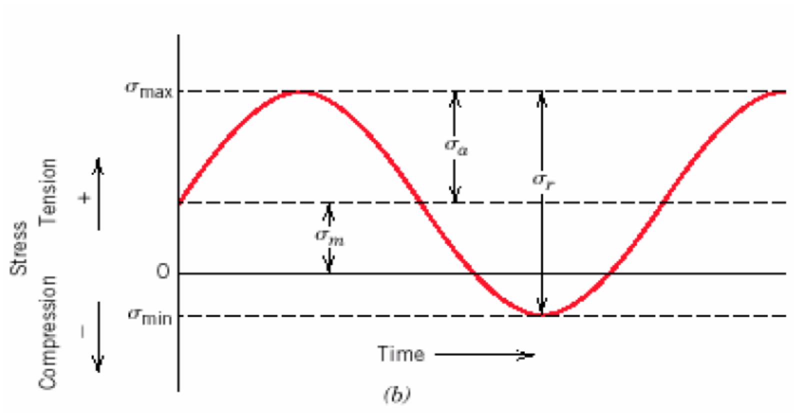


Typical clamshell or beach markings on a fatigue fracture surface of a shaft. The fracture started at the left side of the bar and progressed to the right, where final failure occurred in a single cycle. Courtesy of W. H. Durrant.

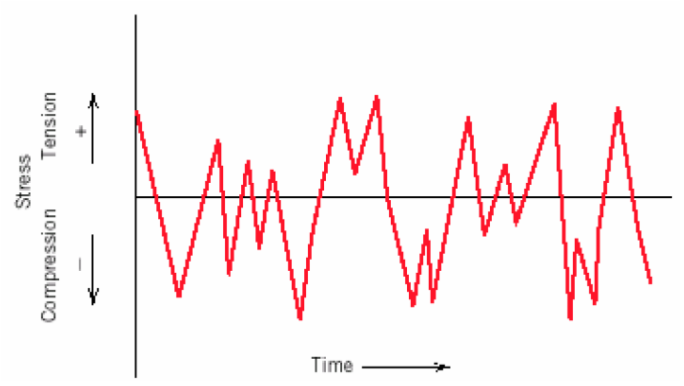
Fatigue: Cyclic Stresses (I)



Periodic and symmetrical about zero stress



Periodic and asymmetrical about zero stress



Random stress fluctuations

Fatigue: Cyclic Stresses (II)

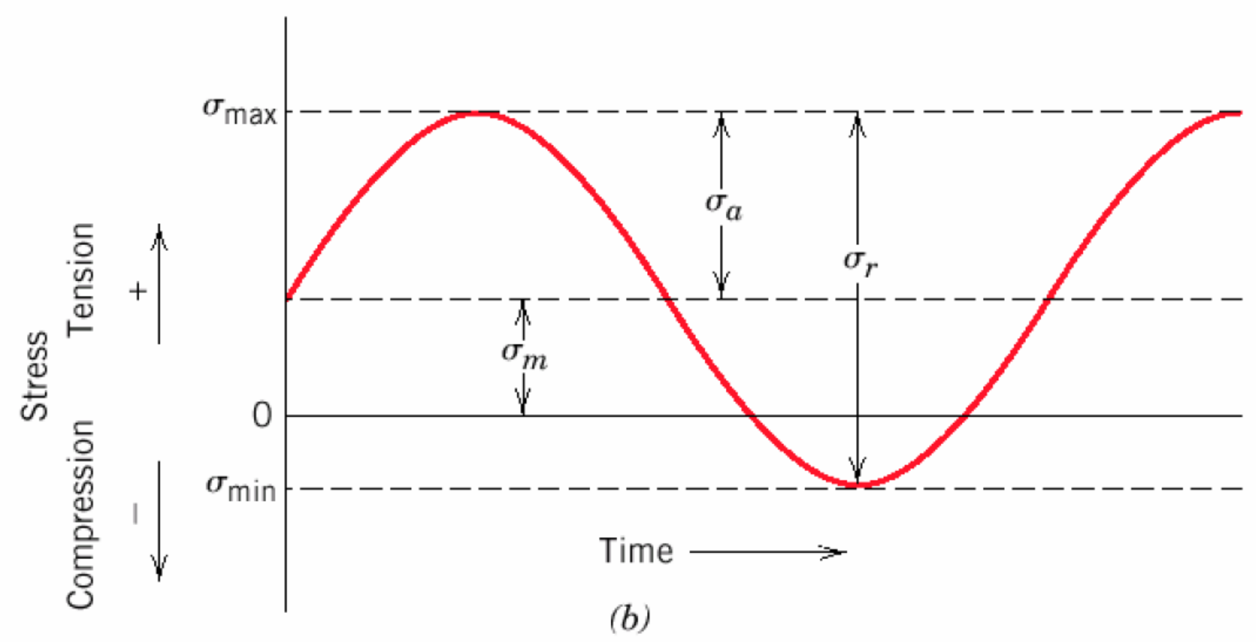
Cyclic stresses are characterized by maximum, minimum and mean stress, the range of stress, the stress amplitude, and the stress ratio.

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

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

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

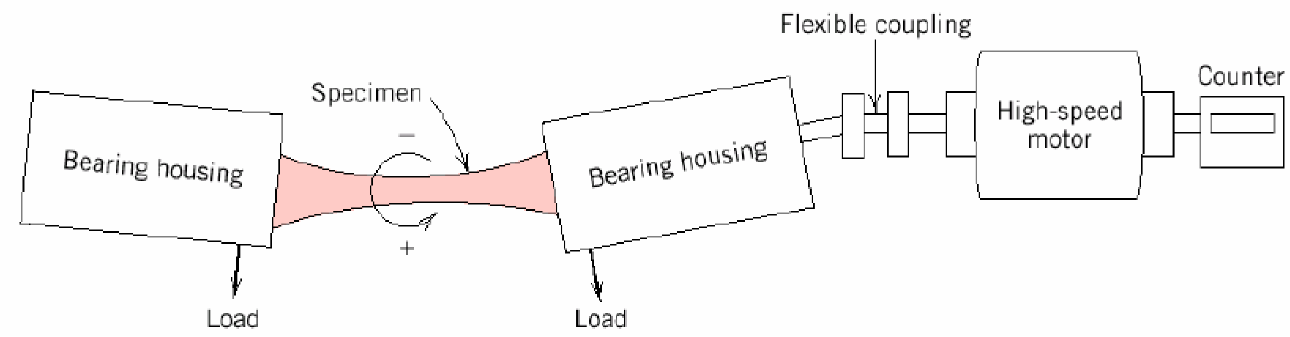
Stress ratio: $\mathbf{R} = \boldsymbol{\sigma_{min}/\sigma_{max}}$



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

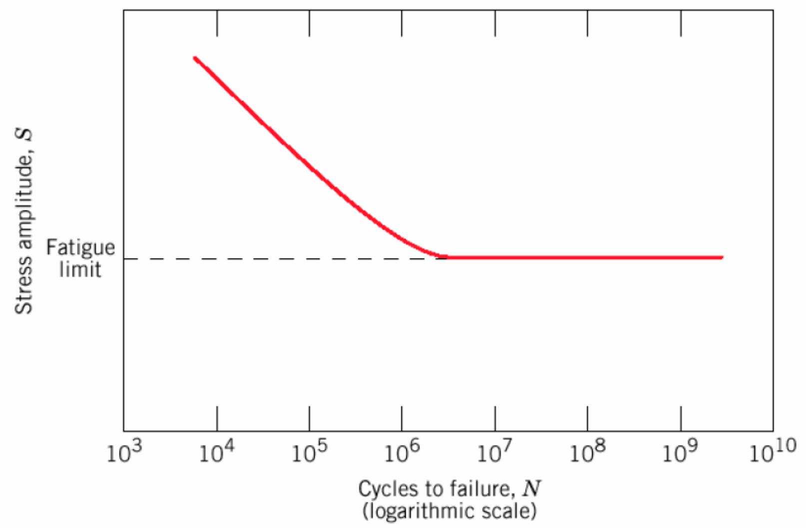
Fatigue: S - N curves (I) (stress - number of cycles to failure)

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



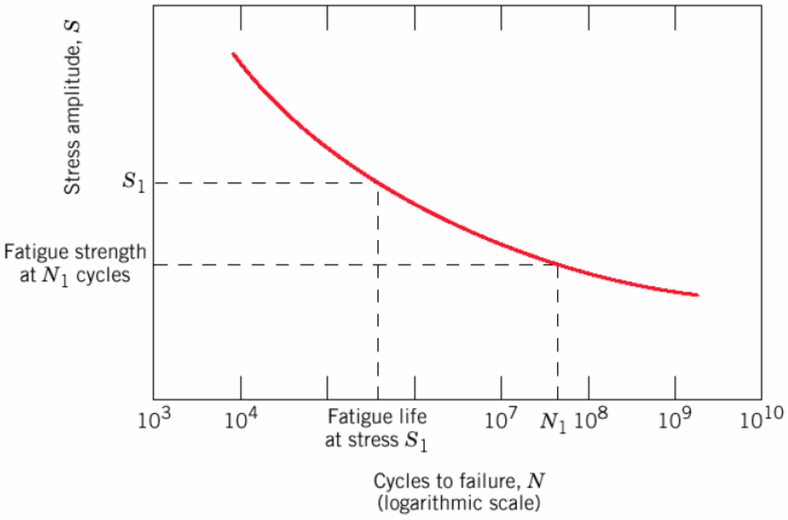
High cycle fatigue: low loads, elastic deformation (N >10^5).

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. 107)

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)

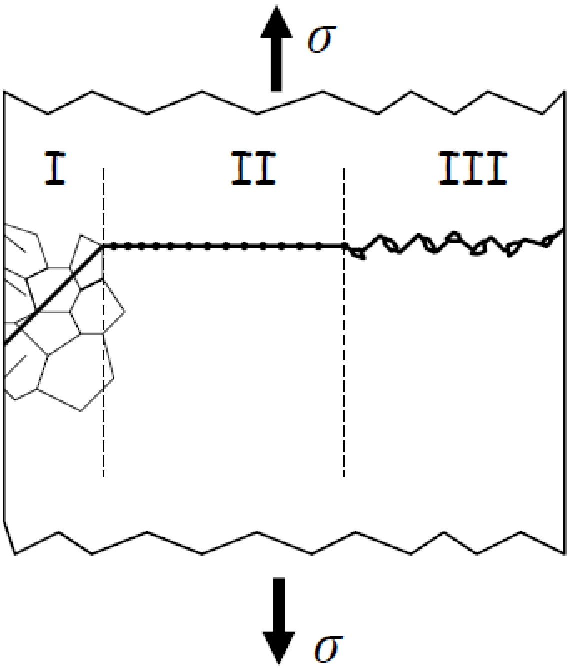
*-Crack initiation at the sites of stress concentration (microcracks, scratches, indents, interior corners, dislocation slip steps, etc.). Quality of surface is important.
*-Crack propagation

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

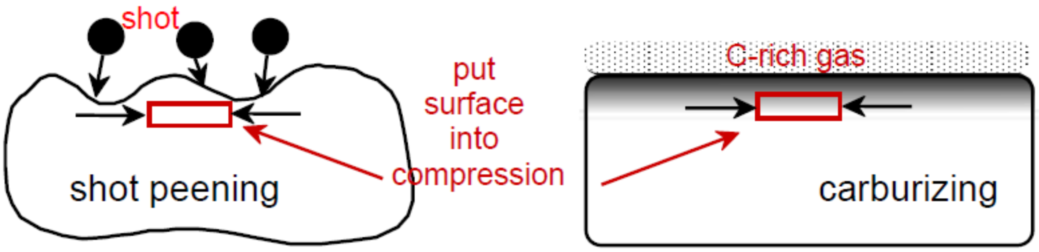


Factors that affect fatigue life

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"- 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, ΔK,

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

$$=(\sigma_{max} - \sigma_{\mathrm{min}}) f\sqrt{(\pi a)}$$

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/dNwith_ΔK. Below a threshold, ΔK_{th}, cracks do not grow. There are three regimes of crack growth. One is a region where da/dN increases rapidly with ΔK. Then there is a large region where $\log(da/dN)$ is proportional to $\log(\Delta K)$, and finally at large values of ΔK_I the crack growth rate accelerates more rapidly. Failure occurs when $K_I = K_{IC}$. In viewing this figure one should remember that ΔK_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,

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

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

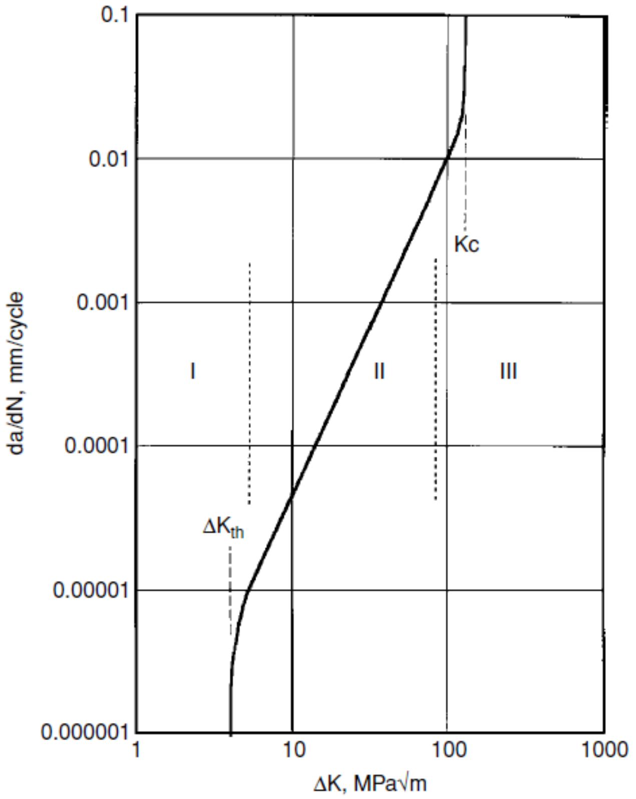
$$a^{\left(1-\frac{m}{2}\right)} - a_{\circ}^{\left(1-\frac{m}{2}\right)} = \left(1-\frac{m}{2}\right) C\left(f\Delta\sigma\sqrt{\pi}\right)^{m} N$$

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

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

Figure

A schematic plot of the dependence of crack growth rate, da/dN, on the stress intensity factor, ΔK_I. Because ΔK_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 Equation (17.19), and a final region (III) of acceleration to failure. The slope of the linear region on the log–log plot equals m.



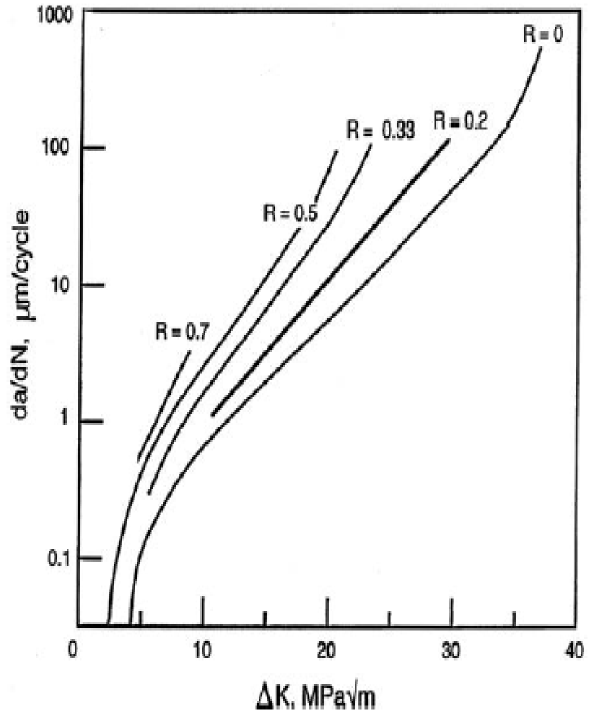


Figure 17.21. Crack growth rate in aluminum alloy 7076-T6 as a function of ΔK for several levels of R. Note that da/dN increases with R. Data from C. A. Martin, NASA TN D5390, 1969.

Example

Consider crack growth in 7076-T6 aluminum.

1. Determine the crack growth rate, d*a*/d*N*, 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=6.2×10^{-11}

Solution:

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

From figure above

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

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

$$N=[(10^{-2})^{-1.025} - (10^{-5})^{-1.025}]/\left[[(-1.0250)(6.2 \times 10^{-8})] \times (200\sqrt{\pi})^{4.05}\right]$$

=99 cycles