Failure Mechanisms

Updated 20 October, 2011

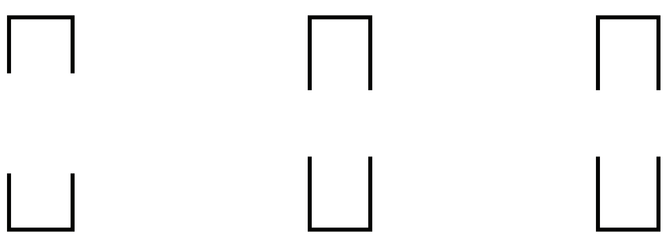
Failure in materials science encompasses any kind of unwanted deformation of a material due to a combination of ______ and ______ conditions. Failure analysis has enabled materials scientists and engineers to design and select materials with appropriate properties that allow them to be used safely.

Failure Mechanism	Fracture	Fatigue	Creep
Loading type			
Primary feature			

Fracture

The worst form of failure is complete fracture: the breaking apart of a body into two or more pieces. Theoretical calculations of the energy/stress required to cause fracture (i.e. break apart the material) are much higher than the actual energy required due to the presence of various-sized ______. This is quite analogous to why the theoretical energy/stress required to initiate plastic deformation is much higher than that for real materials due to the presence of dislocations. Again, no material is perfect, and there will almost always be cracks in a material: therefore, fracture almost always occurs at ______!

Say we load a material under a uniaxial tension test, like in Chapter 6 or 7. Generally, a material's structure will determine the type of fracture that occurs: fracture can either be ______ or ______.



Review pp. 236 – 241 (8th ed.) for very nice qualitative descriptions of simple fracture.

ductile | moderately ductile | brittle

Ductile materials only gradually undergo crack formation and propagation – but only after a large amount of applied strain energy goes into ______ of the material. This deformation (often in the form of necking) provides a warning before catastrophic failure occurs.

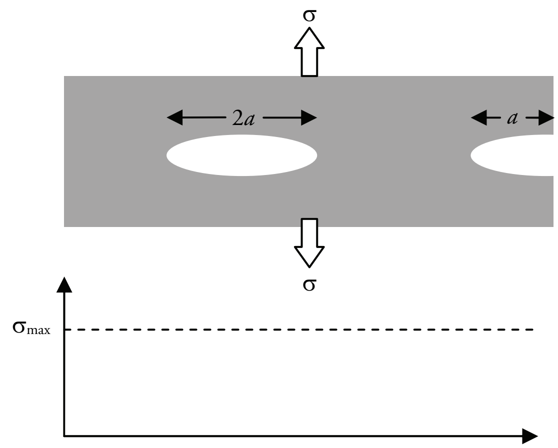
Brittle materials, on the other hand, fracture much more suddenly and violently. The catastrophic failure of brittle materials spurred an entire new field devoted to the quantitative study of crack propagation in brittle materials: fracture mechanics.

Introduction to Fracture Mechanics

Fracture almost always begins at cracks and other ______ such as sharp corners because of the amplification of local stresses around these regions. One can quantify the maximum stress near a crack in a material undergoing loading as

$$\sigma_{\max} = \sigma_0\left(1+\tfrac{2a}{b}\right) = \sigma_0\left(1+2\sqrt{\tfrac{a}{\rho_t}}\right)$$

a: half/full width of internal/surface crack
b: full height of crack
ρ_t: radius of curvature of crack tip = b^2/a



For long cracks where $a >> \rho_t$,

$$\sigma_{\max} \approx \text{______}$$

For a circle crack ($a = \rho_t$),

$$\sigma_{\max} = \text{______}$$

Clearly, both the applied stress and a crack's geometry affect the stresses inside a material. From fracture mechanics theory, a quantity called the stress intensity factor, K, can be calculated, which characterizes the severity of the crack situation due to its size, applied stress, and geometry:

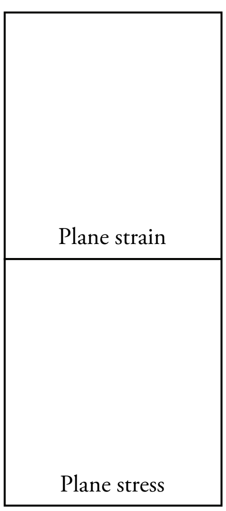
$$K = Y\sigma_{app}\sqrt{\pi a}$$

Y: geometrical constant (~1)
σ_{app}: applied stress
a: same as above

Do not use the book's explanation of fracture toughness (pp. 244-245). It gives wrong and misleading equations (8.4 and 8.5)!!

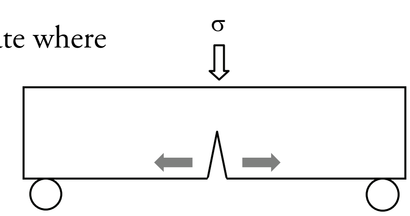
We can compare K to an experimentally determined material property called the ______, K_c. A material's fracture toughness is a measure of its resistance to ______ (i.e. brittle fracture). There are various industrial standards set by organizations like ASTM that set the loading and environmental conditions, and sample geometry when performing a measurement for K_c for a particular material.

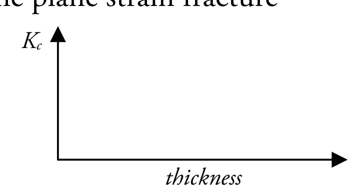
One important type of fracture toughness is plane strain fracture toughness, K_{Ic}.



Plane strain refers to a tensile loading state where strain near a crack exists only along the loading plane. This is only possible in relatively ______ materials, where contraction along the crack tip is ______ by the surrounding material. All the loading energy goes into ______ the crack. Measurements of K_{Ic} are performed by loading a pre-formed crack in a specimen with pure tensile stress (Mode I, bending). Bending loads are the most severe kind of loading, and will cause failure before Mode 2 or 3 loading.

Plane stress, on the other hand, refers to a tensile loading state where ______ exists only in the loading plane. This occurs in thin specimens, where there is not enough material present to prevent contraction along the crack tip; this, combined with the constraint that ______ must be stress-free, causes the stress along the crack tip to be zero. As a result, much of the loading energy in plane stress goes into causing ______ deformation (strain) around the crack and not into causing the crack to grow, thus causing the plane stress fracture toughness to be ______ than the plane strain fracture toughness, K_{Ic}.





Another, albeit qualitative, type of fracture test is the Charpy test, which measures the amount of energy (called impact energy) a crack absorbs upon impact with a hammer.

Ductile materials will become more brittle at lower temperatures, as can be evidenced by the decrease in impact energy for a colder material undergoing a Charpy test, as well as a change in the fracture surface.

Fracture Toughness Design

Comparing the stress intensity factor *(K)* to a materials' fracture toughness *(K_c* or K_{Ic} for plane strain) is analogous to comparing an applied stress *(σ_{app})* to a material's yield strength *(σ_y)*. For a given load, specimen geometry, and crack width, if $K = Y\sigma_{app}\sqrt{\pi a} \geq K_c$, brittle fracture (i.e. crack propagation) will occur.

However, we can also use the form of the equation for K to obtain the critical value of a parameter, by setting other parameters by materials selection of by applying an application constraint.

For example, if we select a material ($K \rightarrow K_{Ic}$) and set a maximum crack size a_{max}, we can calculate a critical stress

$\sigma_c =$ ____ ; if $\sigma_{app} \geq \sigma_c$, we have an undesirable situation.

If we set $K \rightarrow K_{Ic}$ and plan to use the material up to only a certain load σ_{design},

$a_c =$ ____ ; if $a \geq a_c$, we have an undesirable situation.

In practical situations, a_c is also limited by one's ability to detect cracks using non-destructive test methods (these NDTs have a limited spatial resolution).

Often, engineers will limit the load applied on a material to be only a fraction of the material's yield strength:

$$\sigma_{design} = \frac{1}{FS}\sigma_{yield}$$

The load we expect the material to experience

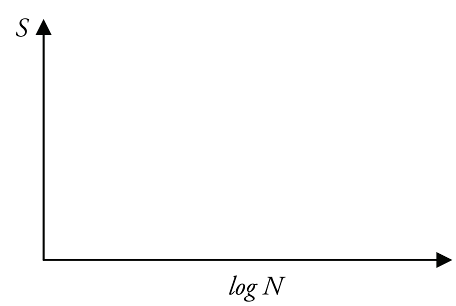
FS: factor of safety

Fatigue

Failure after a material is subjected to dynamic/fluctuating/ ____ loads below the tensile strength is called fatigue. Fatigue failure is normally ____, even for ductile materials, due to the usually high strain rates existent during cyclic loading.

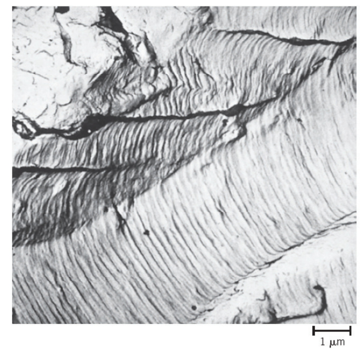
An experimentally obtained graphical relationship between the amplitude of an applied cyclic load versus the number of cycles a material can survive before failure is called an ____ plot (Stress applied – No. of load cycles). For high applied stresses, the number of cycles before failure is relatively ____. For low applied cyclic stresses, one of two behaviors is observed:

a) a material will be able to survive an indefinitely large number of loading cycles (the S-N graph plateaus to a flat line called the ____ limit); common for ferrous (BCC, steel) and HCP (Ti) materials
b) the fatigue strength *(S)* continues to ____ as the fatigue life *(N)* increases; common for non-ferrous (Al, Cu) materials

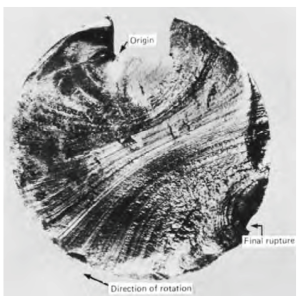


Fatigue test data will always have a scatter, or distribution of results, even for samples with identical processing and geometry, due to different distributions of ______ and ______ throughout a sample, and especially on its surface. Also, in reality, even if the applied load is less than the fatigue strength, a material can undergo failure due to unfavorable ______ conditions such as corrosion, structural degradation, or heat.

Fractography of Fatigue Fracture Surfaces



In fatigue failure, crack propagation will occur in ______ steps before complete fracture occurs. This results in microscopic ______ that can be seen in micrographs of fracture surfaces; the distance between each striation represents the distance that a crack advanced with each ______ cycle.



If we examine an entire fracture surface macroscopically, we will observe ______ patterns, which radiate out from the site of crack ______ (often at sharp corners). These patterns represent the amount of distance a crack moved with each ______ (i.e. a period of time during which the specimen underwent cyclic loading). Each beachmark contains thousands of striations.

How to Increase Fatigue Strength

Maximum stresses (and thus failure) often occur at ______; methods of increasing fatigue strength involve some kind of surface treatment.

- Polishing
- Case hardening
- Shot peening (for ductile materials only!)
- Cold rolling

Creep

Creep is the gradual deformation of a material when it is subject to ______ at an elevated ______. It is yet another example of a diffusion-governed process.

Atoms move along the paths where they have the highest ______ (i.e. highest diffusion coefficient):

D_0 (grain boundaries) > D_0 (dislocations) > D_0 (bulk)