Fatigue

Fatigue is the lowering of strength or the failure of a material due to repetitive stress, which may be above or below the yield strength.

Many engineering materials such as those used in cars, planes, turbine engines, machinery, shoes, etc are subjected constantly to repetitive stresses in the form of tension, compression, bending, vibration, thermal expansion and contraction or other stresses.

Fatigue

There are typically three stages to fatigue failure.

First, a small **crack is initiated or nucleates** at the surface and can include scratches, pits, sharp corners due to poor design or manufacture, inclusions, grain boundaries or dislocation concentrations.

Second, the **crack gradually propagates** as the load continues to cycle.

Third, a **sudden fracture** of the material occurs when the remaining cross-section of the material is too small to support the applied load.

Fatigue

At a local size scale the stress intensity, K_{IC} , exceeds the yield strength.

For fatigue to occur at least part of the stress in the material has to be tensile.

Fatigue is most common in metals and plastics, whereas ceramics fail catastrophically without fatigue because of their low fracture toughness.

Fatigue

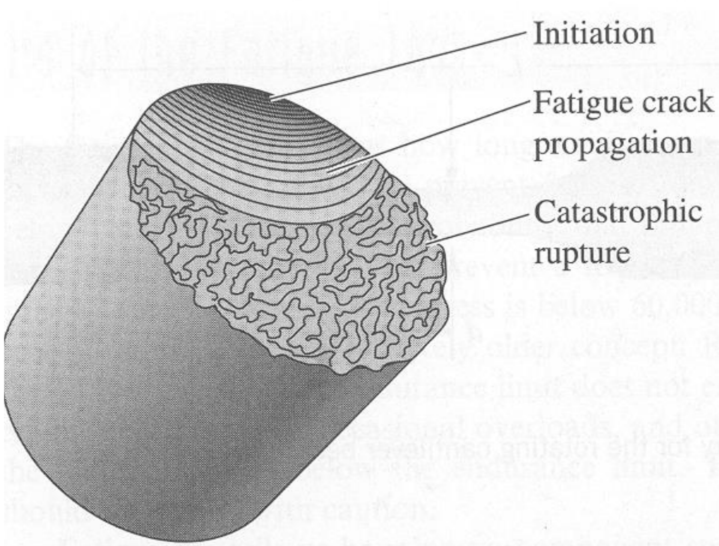
Fatigue failures are often easy to identify.

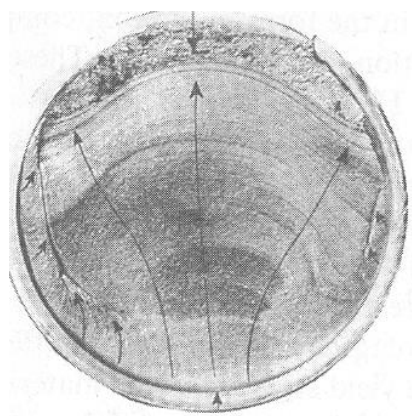
The fracture surface near the origin is usually smooth. The surface becomes rougher as the crack increases in size.

Microscopic and macroscopic examination reveal a beach mark pattern and striations.

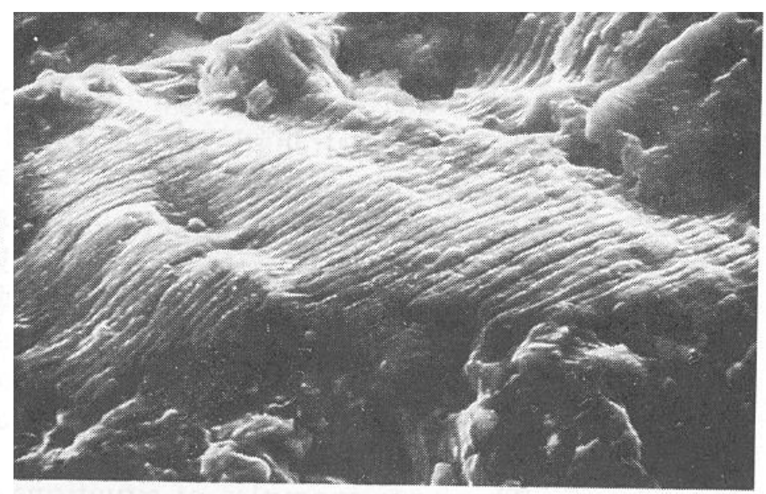
Beach mark patterns indicate that the load is changed during service or the load is intermittent.

Striations are on a much finer scale and show the position of the crack tip after each cycle.





(a)



(b)

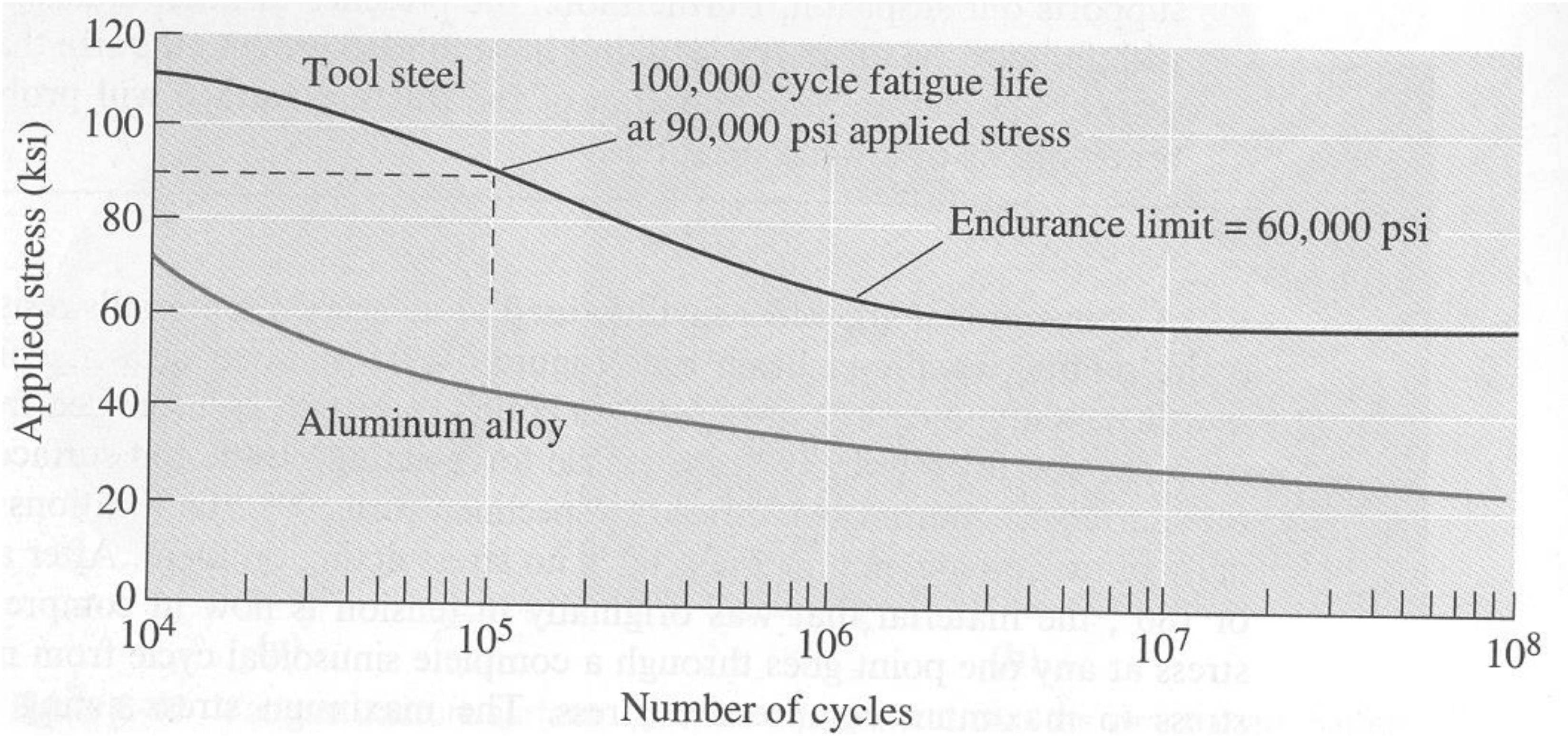
Fatigue

The most important fatigue data for engineering designs are the S-N curves, which is the Stress-Number of Cycles curves.

In a fatigue test, a specimen is subjected to a cyclic stress of a certain form and amplitude and the number of cycles to failure is determined.

The number of cycles, N, to failure is a function of the stress amplitude, S.

A plot of S versus N is called the S-N curve.



The S-N curves for a tool steel and an aluminum alloy showing the number of cycles to failure

Fatigue

Fatigue Limit:

- For some materials such as BCC steels and Ti alloys, the **S-N curves become horizontal** when the stress amplitude is decreased to a certain level.
- This stress level is called the **Fatigue Limit**, or **Endurance Limit**, which is typically ~**35-60% of the tensile strength** for steels.
- In some materials, including **steels**, the endurance limit is approximately half (50%) the tensile strength given by:

$$\text{Endurance ratio} = \frac{\text{endurance limit}}{\text{tensile strength}} \approx 0.5$$

Fatigue

Fatigue Strength:

For materials, which do not show a fatigue limit, i.e., the S-N curves do not become horizontal such as Al, Cu, and Mg (non-ferrous alloys), and some steels with a FCC structure,

- fatigue strength is specified as the stress level at which failure will occur for a specified number of cycles, where 10^7 cycles is often used.

Fatigue Failures

Types of stresses for fatigue tests include,

- **axial (tension – compression)**
- **flexural (bending)**
- **torsional (twisting)**

From these tests the following data is generated.

$$\text{Mean Stress, } \sigma_{\mathrm{m}} = \frac{\sigma_{\max} + \sigma_{\min}}{2}$$

$$\text{Stress Amplitude, } \sigma_{\mathrm{a}} = \frac{\sigma_{\max} - \sigma_{\min}}{2}$$

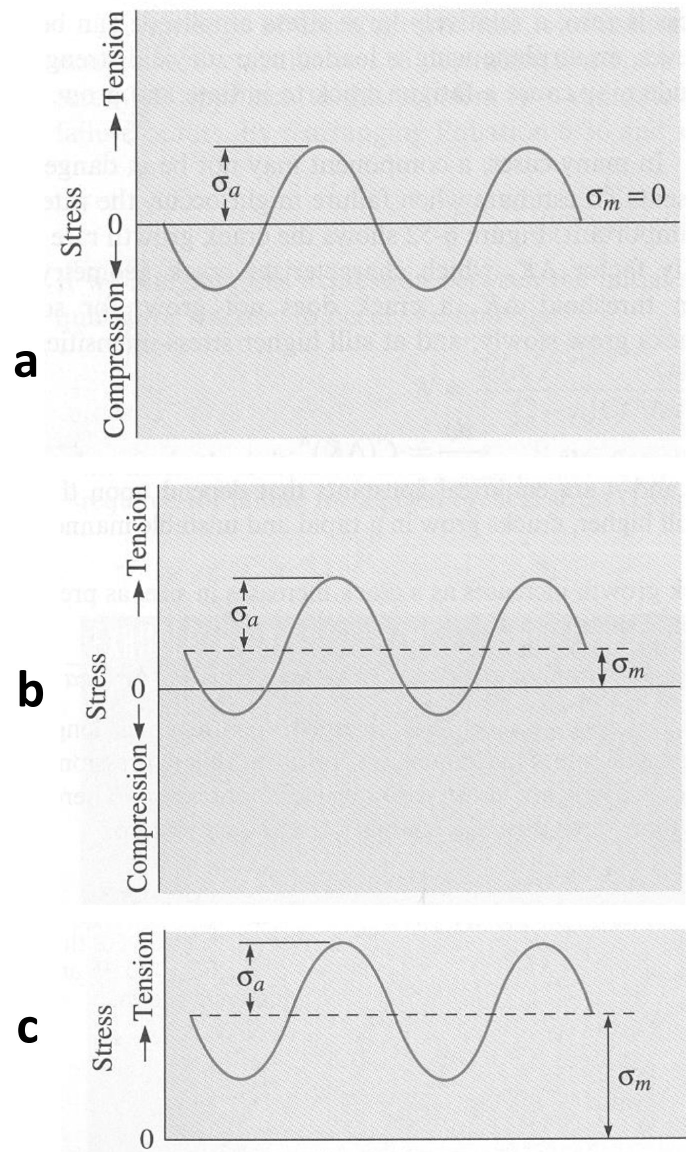
$$\text{Stress Range, } \sigma_{\mathrm{r}} = \sigma_{\max} - \sigma_{\min}$$

$$\text{Stress Ratio, } R = \frac{\sigma_{\min}}{\sigma_{\max}}$$

By convention, tensile stresses are positive and compression stresses are negative.

Fatigue Failures

Examples of stress cycles where a) shows the stress in compression and tension, b) shows there's greater tensile stress than compressive stress and in c) all of the stress is tensile.



Fatigue Failures

As the **mean stress, σ_m, increases**, the **stress amplitude, σ_a**, must decrease in order for the material to withstand the applied stress. This condition is summarized by the **Goodman relationship**:

$$\text{Stress Amplitude, } \sigma_a = \sigma_{fs}\left[1 - \left(\frac{\sigma_m}{\sigma_{TS}}\right)\right]$$

Where **σ_{fs} is the desired fatique strength for zero mean stress** and **σ_{TS} is the tensile strength** of the material.

Example, if an airplane wing is loaded near its yield strength, vibrations of even a small amplitude may cause a fatigue crack to initiate and grow. This is why aircraft have a routine inspection in order to detect the high-stress regions for cracks.

Fatigue Failures

Crack Growth Rate

To estimate whether a crack will grow, the **stress intensity factor** (ΔK), which characterizes the crack geometry and the stress amplitude can be used.

Below a threshold ΔK a crack doesn't grow.

For somewhat higher stress intensities, the cracks grow slowly.

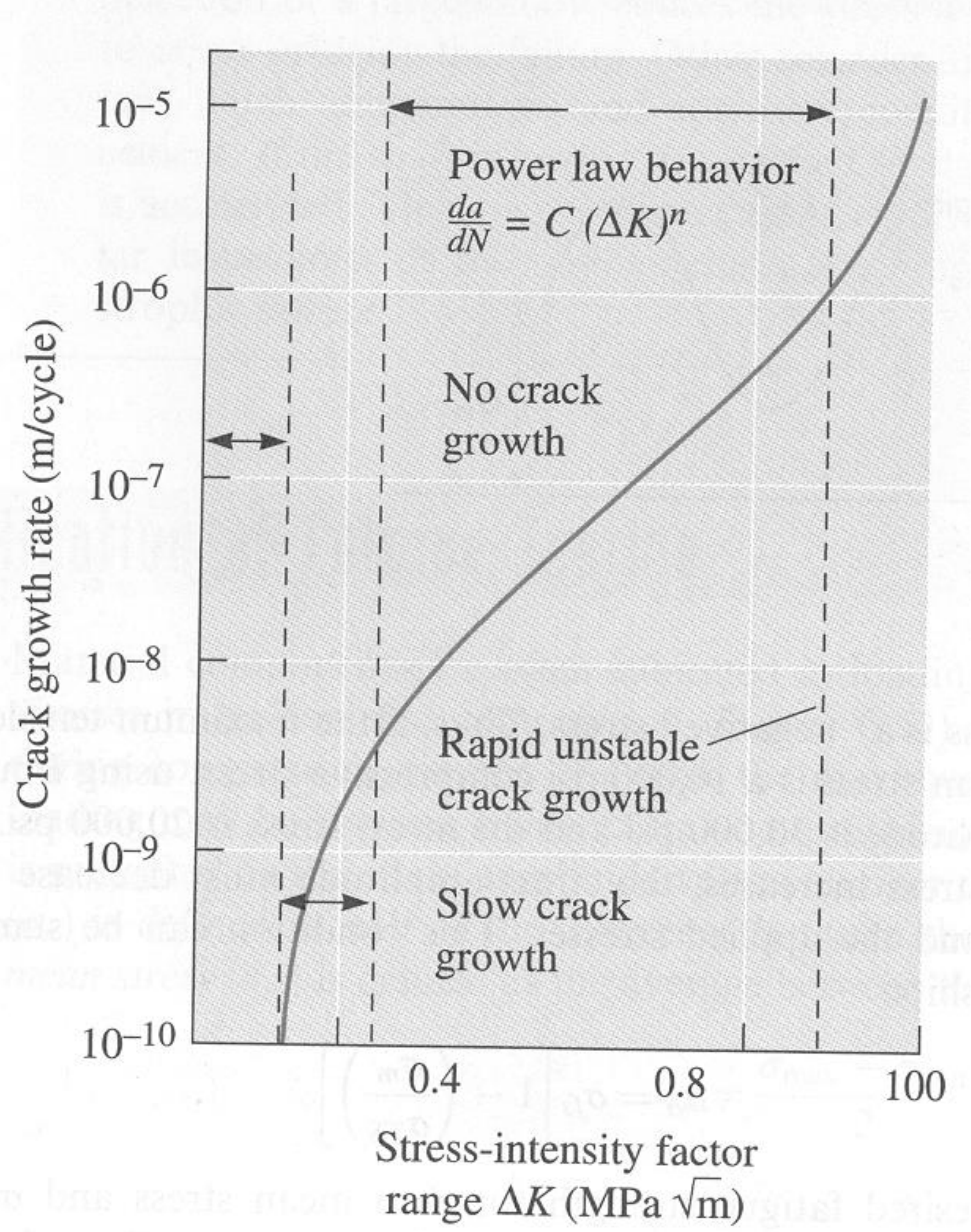
For still higher stress-intensities a crack grows at a rate given by:

$$\frac{da}{dN} = C(\Delta K)^n$$

Where C and n are empirical constants that depend on the material.

When ΔK is high, the cracks grow in a rapid and unstable manner until fracture occurs.

Fatigue Failures



Fatigue Failures

From the steady state crack growth relationship of

$$\frac{da}{dN} = C\left(\Delta K\right)^n$$

if we integrate between the initial size of a crack and the crack size required for fracture to occur, we find that the number of cycles to failure is given by

$$N = \frac{2\left[(a_c)^{(2-n)/2} - (a_i)^{(2-n)/2}\right]}{(2-n)Cf^n\Delta\sigma^n\pi^{n/2}}$$

where C and n are empirical constants that depend on the material.

Stress-Corrosion Failure

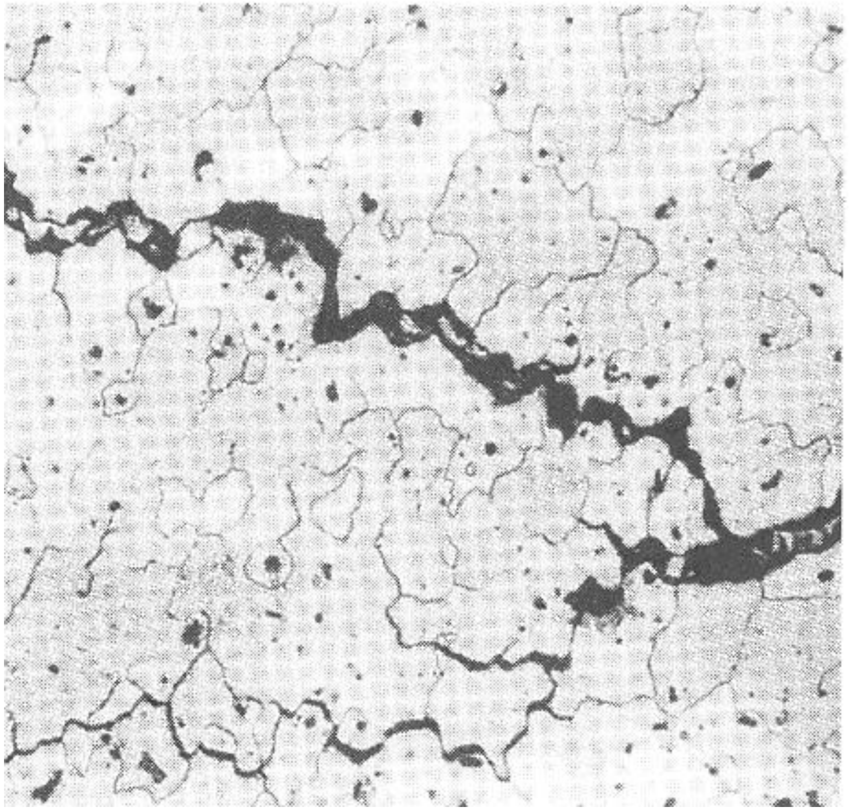
Stress corrosion happens when a material reacts with corrosive chemicals in its environment.

Two good examples,

- salt on the roads reacting with the steel in cars causing reduced lifetime of the car's components such as its frame and suspension system.
- salt in the ocean reacting with boats and their moorings where the corrosion reduces the life of the engine, which is cooled by the salt water, and the structural integrity of the boat is jeopardized if salt water sits in the hull or around the drive shaft.

Stress-Corrosion Failure

- Stress-corrosion will cause failure of materials below their yield strength because the corrosion will cause cracks to form, usually along grain boundaries.
- What material design model did we discuss that is a material property and accounts for the presence of cracks?
- Usually if there is a corrosion product on the surface where a crack is inside the material.
- The surface flaws themselves can be nucleation sites for crack growth.
- Usually materials are coated to reduce or prevent corrosion. The automotive industry has shown excellent results by applying metal coatings (Sn) and polymer coatings on the sheet steel used on the body of cars.



Intergranular cracks near a stress-corrosion fracture in a metal.

Note the many branches where the corrosion has eaten into the grain boundaries of the metal.

If you are offered materials to be used for structural purposes that have etch pits on the surface at a reduced price, think again, as the pits are surface cracks that could extend far into the material.

As a professional engineer, your career may be jeopardized by poor judgment that saved a little money in material costs but resulted in catastrophic failure during the service life of the material.