SMM 3622

Materials Technology

3.1 Fatigue

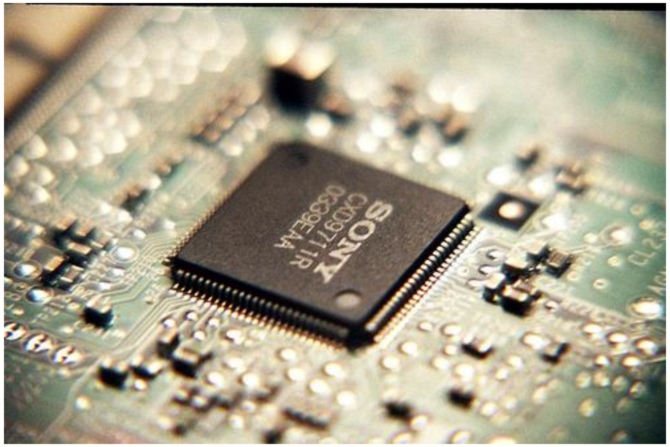
MECHANICAL FAILURE – FATIGUE

ISSUES TO ADDRESS...

- **What is fatigue?**
- **Types of fatigue loading?**
- **Empirical data**
- **Estimating endurance/Fatigue strength**
- **Strategies for analysis**

Fatigue failure of a windmill.

Hip implant-cyclic loading from walking.



Computer chip-cyclic thermal loading.

fatigue is a lack of energy and motivation

When fatigue is not relieved by enough sleep, good nutrition, or a low-stress environment, it should be evaluated by your doctor. Because fatigue is a common complaint, sometimes a potentially serious cause may be overlooked.

What is Fatigue?

Fatigue: the weakening or breakdown of a material subject to cyclic stress

Cyclic stress can be the result of fluctuations in loads, temperature, swelling, chemical environment, etc.

Cause Premature Failures

Design Philosophy

Total life – assumes device defect free.

- Life is based on initiation and propagation of flaws.

Defect tolerant – assumes all materials have initial flaws.

- Life is based on propagation.

Total Life Philosophy

- ❖Founded on the premise that the component is initially defect free.

- ❖Life of the device is based on the initiation of a flaw and the subsequent growth into a critical crack size.

- ❖Damage is accumulated until the device reaches a critical level of damage and failure then ensues.

- ❖Fatigue characterization is based on a stress-based or strain-based test

- ❖Unnotched specimens are subjected to a constant amplitude load cycle until failure occurs

WHAT IS FATIGUE?

- Fatigue failure is the phenomenon leading to fracture under repeated cyclic or fluctuating stresses (*mechanical or thermal*) that are less than the tensile strength of the material.

Fatigue fractures are progressive, and always start at a crack that grow under the action of cyclic stress. There are three stages in fatigue failure:

1. Crack initiation (short duration)
2. Crack propagation (most of the part life)
3. Final fracture (occurs due to unstable crack growth)

The initiation site is very small, extending only about two to five grains around the origin. The location of the initiation is at a stress concentration and may be difficult to distinguish from the succeeding stage of propagation, or crack growth. The crack initiation site is always parallel to the shear stress direction.

- Fatigue failures are common in moving parts such as shafts, connecting rods, gears, axles and springs in applications such aircraft and automotive.

- A bridge also undergoes cyclic loading in service according to the pattern of traffic flow and the force of the wind.

- It is estimated that 90% of all engineering failures are due to fatigue

- Fatigue failure appears brittle even in ductile materials

- Fatigue failure occurs due to cumulative actions of thousands or millions of load cycles, which result in initiation and then propagation of cracks.

- Fatigue failure usually occurs at stress concentrators and/ or surfaces

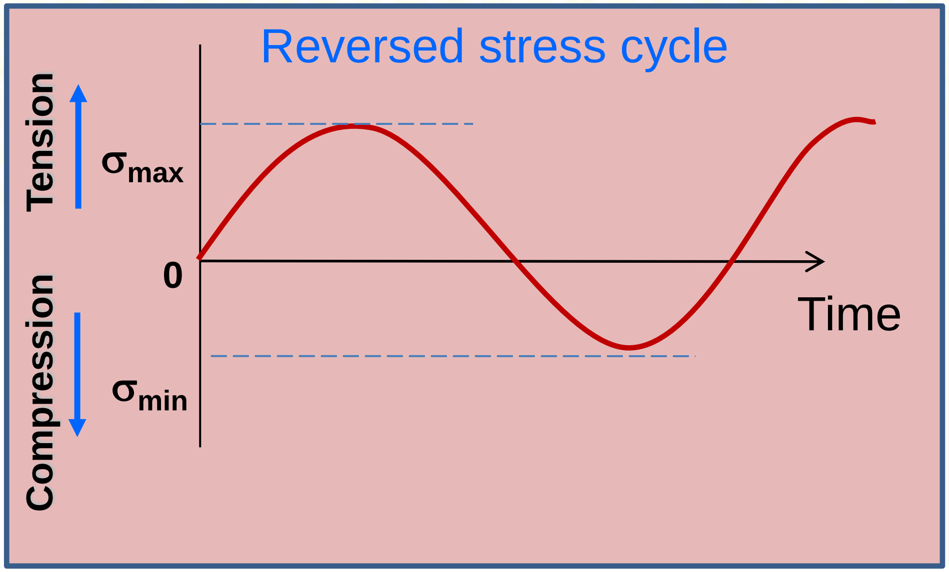
Examples of fatigue failures

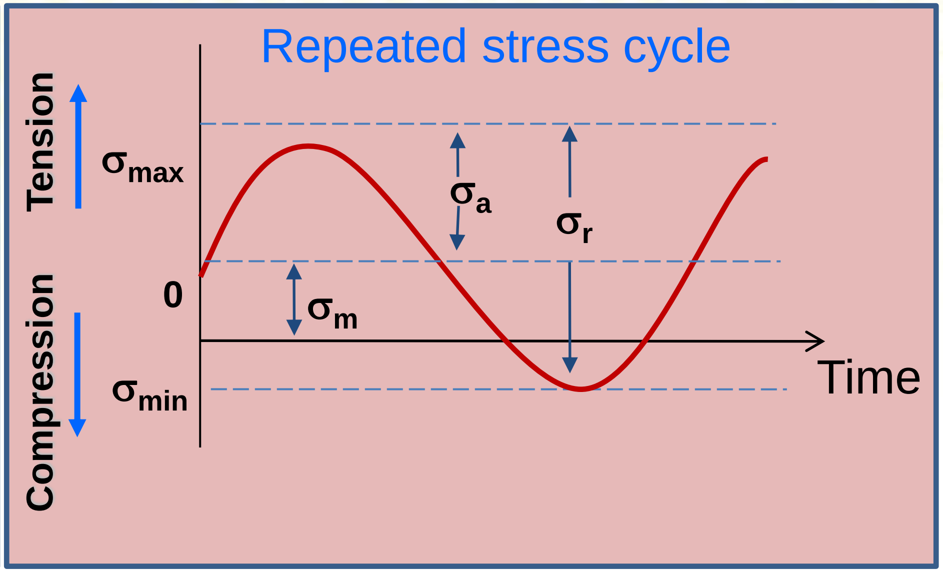
- De Havilland Comet (first commercial jet) G-ALYP/6003, January 1954
- Aloha Airlines Flight 243, April 1988
- Eschede train crash, Germany 1988

Applied Stress

- Tension – compression
- Flexural (bending)
- Torsional (twisting)

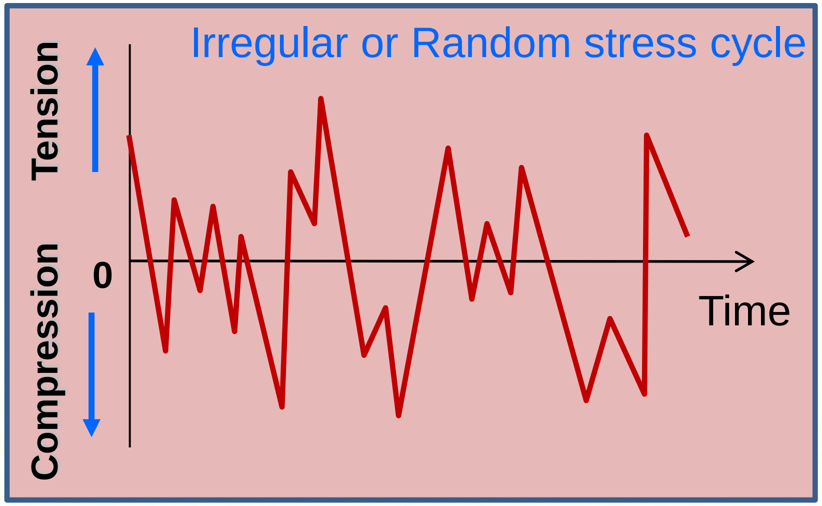
CYCLIC STRESSES


Reversed stress cycle


Repeated stress cycle

Regular, sinusoidal time dependence (mean stress = 0)

Max and min stress are asymmetrical relative to zero stress level


Irregular or Random stress cycle

Aircraft wing which is subjected to unpredictable overloads due to gusts (sudden strong wind)

Stress level vary randomly in amplitude and frequency

- A fatigue cycle is a single segment of the stress function that is periodically repeated.
- For example, in reversed stress cycle (Figure above) one cycle consists of *ZERO-TENSION-ZERO-COMPRESSION-ZERO*

- Other common fatigue terms include:

1. The stress range, σ_r:

$$\sigma_r = \sigma_{\max} - \sigma_{\min}$$

2. Stress amplitude, σ_a:

$$\sigma_a = \frac{\sigma_{\max} - \sigma_{\min}}{2}$$

3. Mean stress, σ_m:

$$\sigma_m = \frac{\sigma_{\max} + \sigma_{\min}}{2}$$

4. Stress ratio, R:

For reversed stresses, $\sigma_m = 0$

$$R = \sigma_{\min} / \sigma_{\max}$$

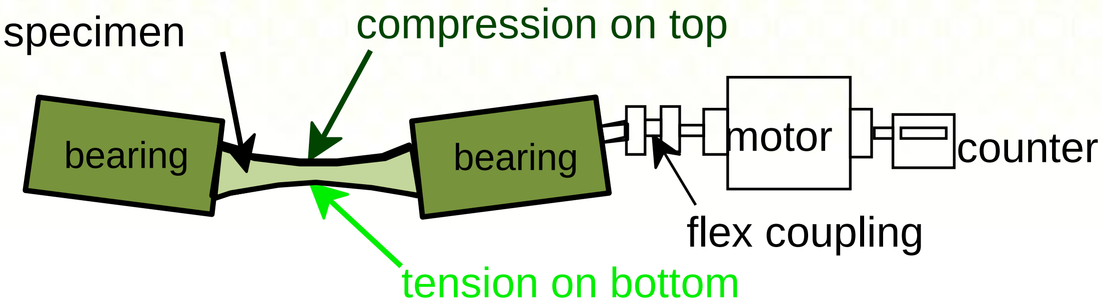
S-N CURVE

- Fatigue life of an engineering component is generally defined by the S-N curve, which shows the fatigue strength versus number of loading cycles.

- Two most common methods used to determine the fatigue properties are:
  1. Rotating (reversed)-bending test (used for reversed stress cycles). This type of test is the most widely used

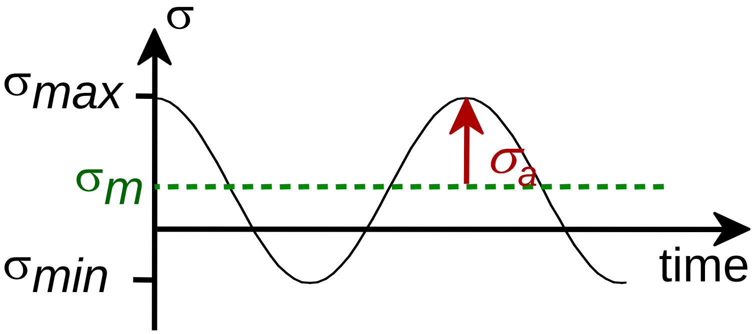
  2. Uniaxial tension test (used for repeated stress cycles)

- Fatigue = failure under cyclic stress.



Adapted from Fig. 8.18, *Callister 7e.* (Fig. 8.18 is from *Materials Science in Engineering*, 4/E by Carl. A. Keyser, Pearson Education, Inc., Upper Saddle River, NJ.)

- Stress varies with time.
  - -- key parameters are σ_a, σ_m, and frequency



- Key points: Fatigue...
  - --can cause part failure, even though $\sigma_{max} < \sigma_c$.
  - --causes ~ 90% of mechanical engineering failures.

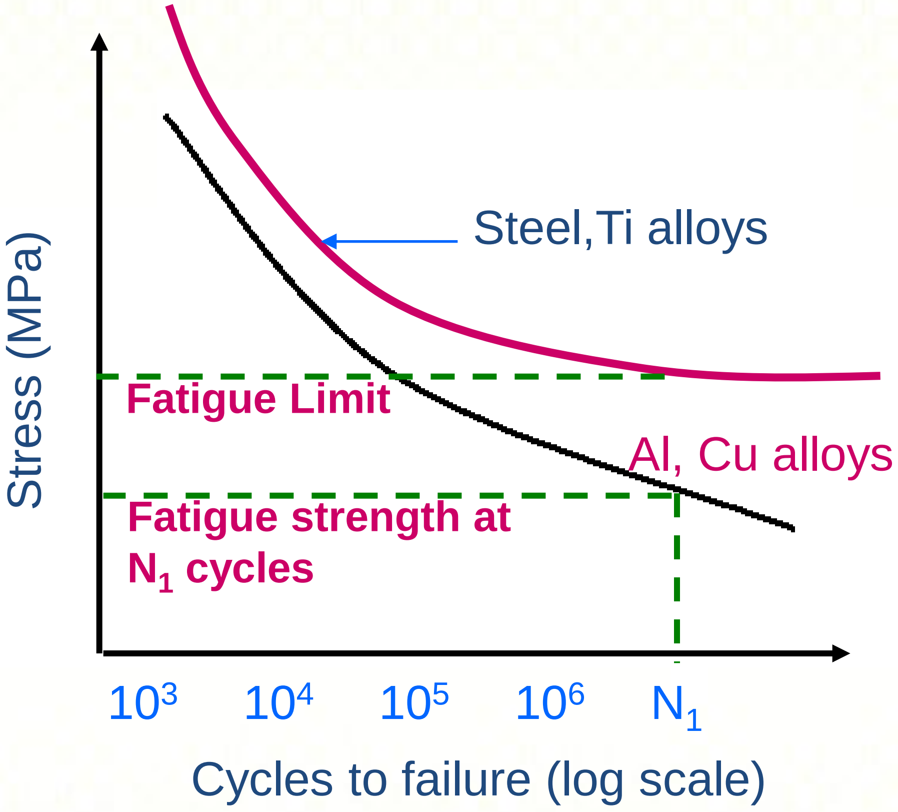
S – N CURVE

- Two regimes are defined in the S-N curve

1. Low Cycle Fatigue (LCF): failure occurs below 10^5 cycles, and associated with high stresses (σ_a)
2. High Cycle Fatigue (HCF): failure occurs above 10^5 cycles, and associated with low stresses (σ_a)

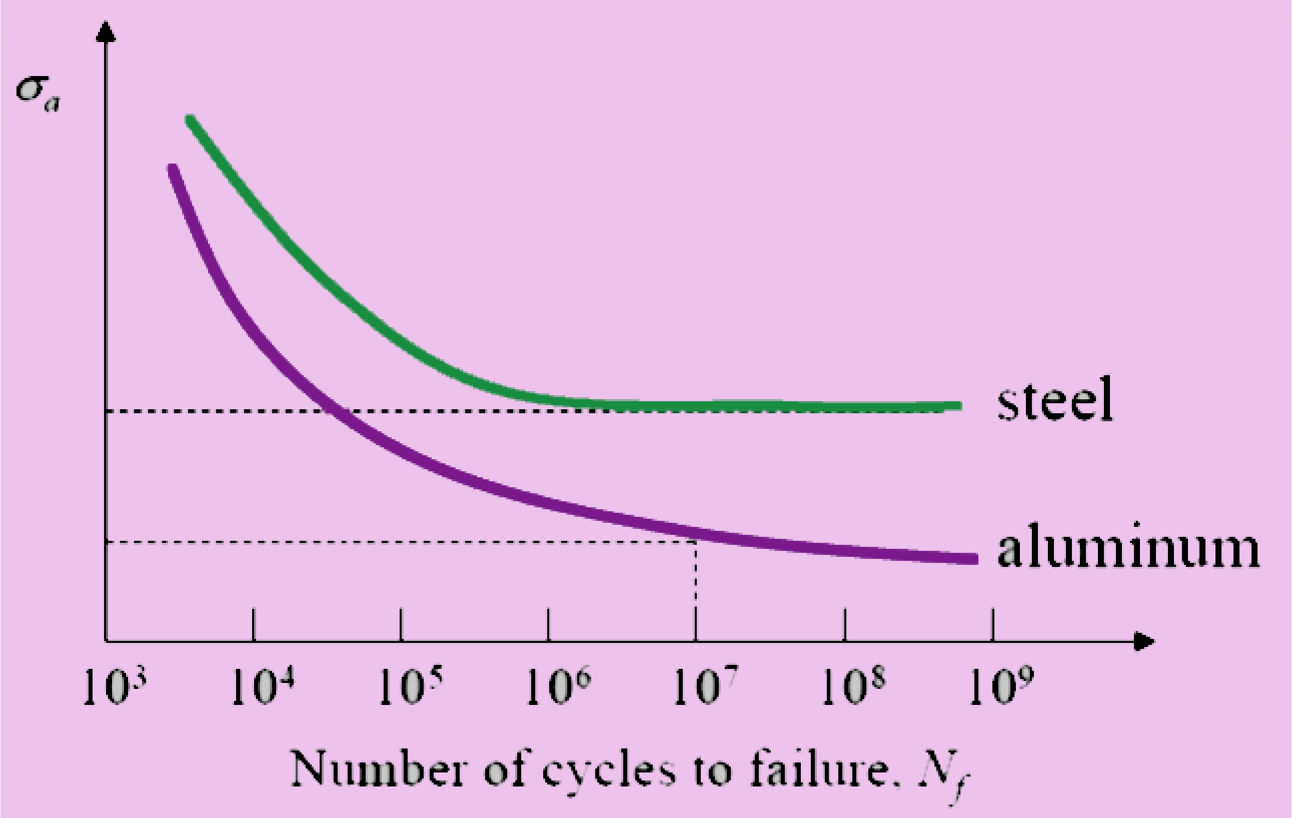
- The usual procedure for determining an S-N curve is to test the first specimen at a high stress where failure is expected in a low number of cycles. The test stress is then decreased for each succeeding specimen until one or two specimens do not fail. The highest stress at which no failure is obtained is taken as the fatigue limit

Typical S – N curve



- The higher, the magnitude of stress the smaller the number of cycles the material is capable of sustaining before failure.
- Some ferrous (iron base) and Ti alloys the S-N curve become horizontal at higher N values. This limit is called Fatigue limit (or endurance limit). Below this limit, no failure.
- Most of the steel, fatigue limit range between 35% - 60% of tensile strength.
- Most nonferrous alloy e.g. Al, Cu, Mg do not have fatigue limit. The fatigue response is specified as fatigue strength at certain N cycles.
- N_f is refer to the number of fatigue cycles to cause failure at certain stress level.

S-N curve



- Steel has a limit (fatigue strength, ~ 0.5σUTS), below which the fatigue life is infinite.
- Aluminium does not have a limit. Use the stress amplitude corresponding to a specified fatigue life (e.g., N = 10^7) as fatigue strength.

Endurance Limit

$S_{e'}$

A stress level below which a material can be cycled infinitely without failure.

Many materials have an endurance limit:
Low-strength carbon and alloy steels, some stainless steels, irons, molybdenum alloys, titanium alloys, and some polymers.

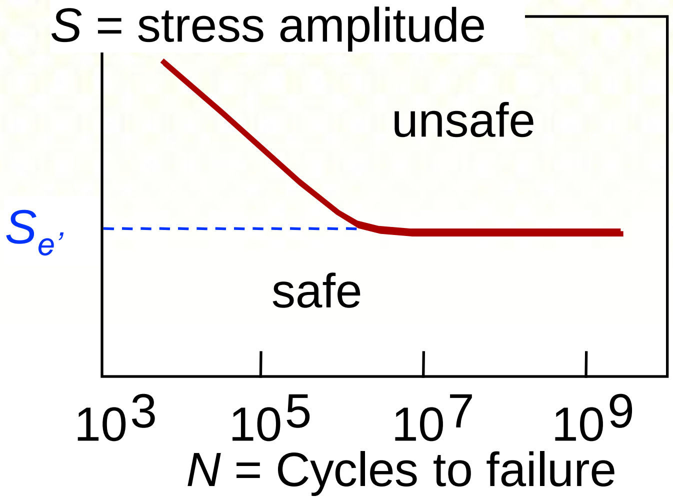
Many other materials do not have an endurance limit:
Aluminium, magnesium, copper, nickel alloys, some stainless steels, high-strength carbon and alloy steels.

$S_{f'}$

For these, we use FATIGUE STRENGTH defined for a certain number of cycles.

Fatigue Design Parameters

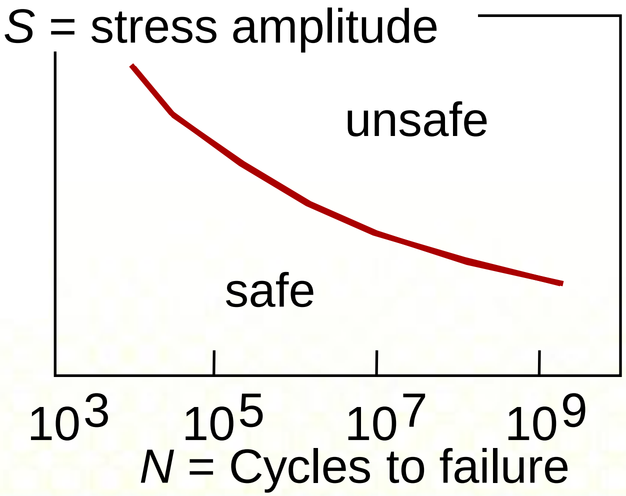
- Fatigue limit, $S_{e'}$:
  --no fatigue if $S < S_{e'}$



case for
steel (typ.)

Adapted from Fig. 8.19(a), *Callister 7e.*

- Sometimes, the fatigue limit is zero!
- Use Fatigue Strength or Fatigue Life.



case for
Al (typ.)

Adapted from Fig. 8.19(b), *Callister 7e.*

FATIGUE LIFE

- Fatigue life of a component is defined as the total number of stress cycles to cause failure, N_f,

- This fatigue life can be expressed as consisting of 3 stages:
  1. Crack initiation
  2. Crack propagation - Oscillating stress… crack grows
  3. Fast fracture - Sudden, brittle-like fracture

- This gives:

$$\boxed{N_f = N_i + N_p}$$

- N_i: number of cycles required to initiate a crack (depends on stress level, stress concentrations, imperfections, environment, etc…)
- N_p: number of cycles required to propagate a crack (depends on stress level, microstructure and environment)

FACTORS AFFECTING FATIGUE LIFE

– *Mechanical factors, Microstructural factors,* and *Environmental factors.*

1. Mechanical Factors
   - a. Mean stress
   - b. Stress concentration (notch sensitivity) (design factor)
   - c. Surface effects

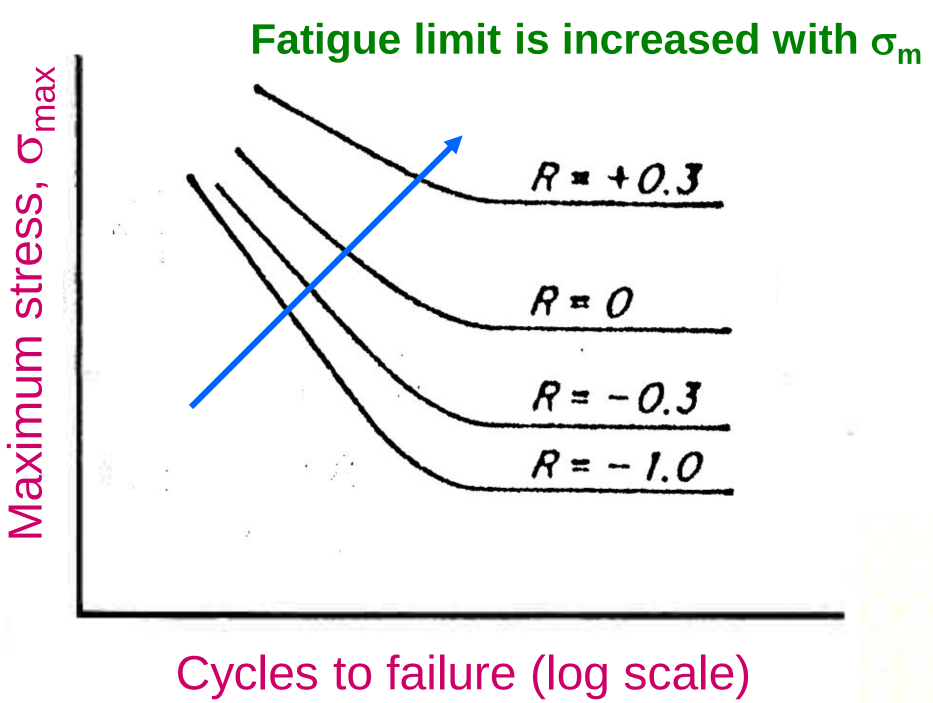
a. Mean stress

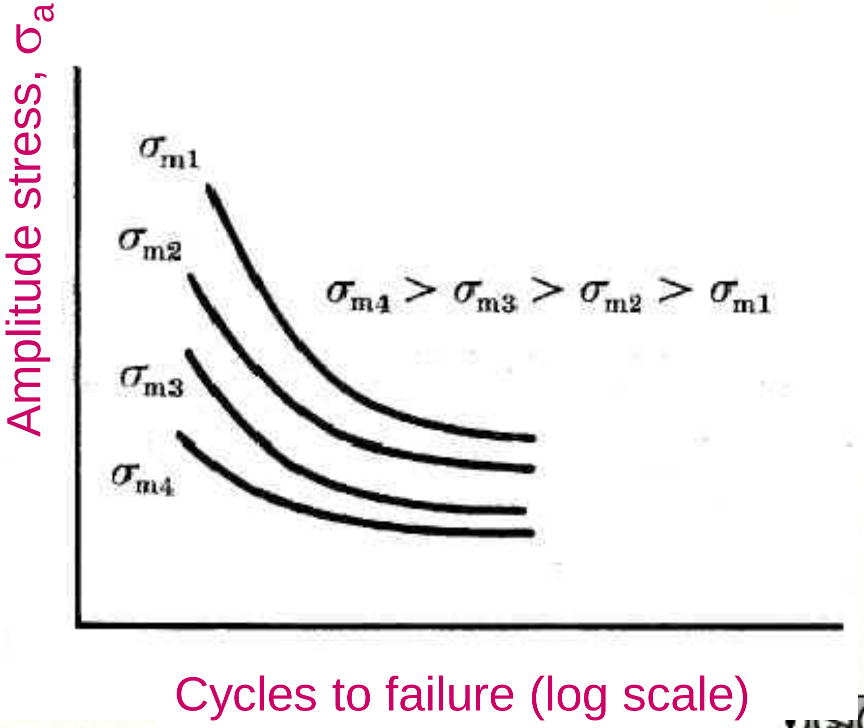
Much of the fatigue data have been determined for conditions of completely reversed stresses where $\sigma_m = 0$

However, in practice, conditions of where σ_m is $\neq 0$ exist

In this case the stress ratio, $R = \sigma_{min} / \sigma_{max}$ is described

- Increasing the mean stress, σ_m, leads to a decrease in fatigue life
- This is shown below in two different methods



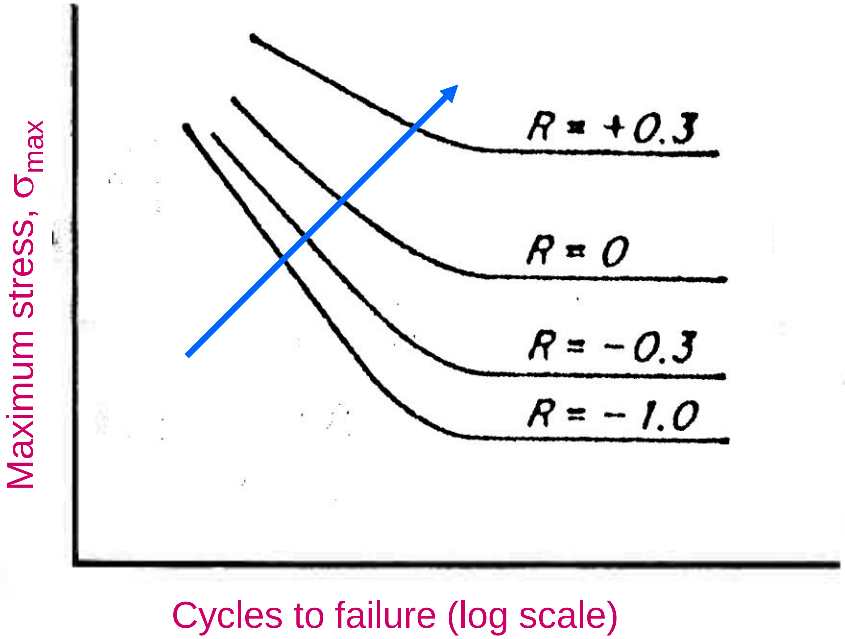


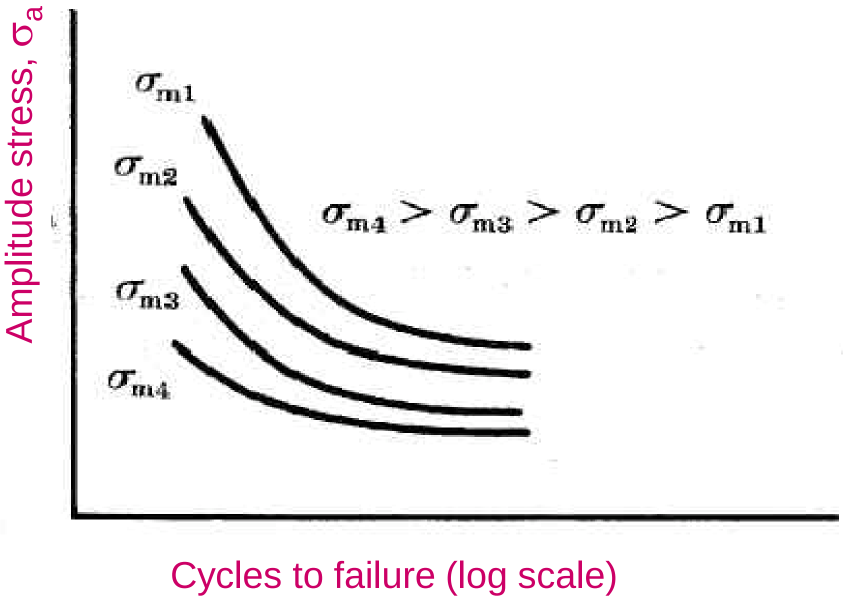
a. Mean stress

b. However, in practice, conditions of where σ_m is $\neq 0$ exist
In this case the stress ratio, R = $\sigma_{min} / \sigma_{max}$ is described

- Increasing the mean stress, σ_m, leads to a de ase in fatigue life

Fatigue limit is increased with σ_m





- Can achieved by applying a series of stress cycles with decreasing max stress and adjusting the min stress in each case .
- R become more positive equivalent to increasing the mean stress, thus the measured fatigue limit become greater

- The mean becomes more positive as the allowable alternating (amplitude) stress decreases.

b. Stress concentration (notch sensitivity)

- Fatigue strength is strongly reduced by the introduction of stress concentrators such as: Notches, holes, screw threaded regions or irregular geometries.

- Reducing stress concentrators will improve the fatigue life. This can be achieved through: careful design, prevention of accidental stress raisers during production and fabrication.

- The influence of notches (usually V-notch or circular notch) ,for example, is evaluated by comparing notched and unnotched S-N data for the same material

The notch sensitivity of a material is expressed by a notch sensitivity factor, q, as:

$$\boxed{q=\frac{K_f-1}{K_t-1}}$$

$$K_t=\frac{\sigma_{m(\max)}}{\sigma_{o(applied)}}=2\left(\frac{a}{\rho_t}\right)^{1/2}$$

K_t is the stress concentration factor for notch.
K_f is the fatigue notch factor which expresses the effectiveness of the notch in decreasing the fatigue limit.

A material which experiences no reduction in fatigue due to a notch (K_f = 1) has a factor q =0, while, material in which the notch has its full theoretical effect (K_f=K_t), q=1.

- K_f varies with:
  - Severity of the notch (size, how serious)
  - Type of the notch
  - Material
  - Type of loading and stress level.

- High values of "q" indicate a notch sensitivity material and means that a notched specimen has a low fatigue strength compared to that of an unnotched sample. (K_f>1).

- A material is said to be notch sensitive if there is a reduction in fatigue limit due to the presence of a notch. Hence, it has a high value of "q".

c. Surface effects

- Since fatigue cracks frequently start at or near the surface of the material, the surface condition is an important consideration in fatigue life. The surface conditions include: surface finish, surface properties and residual stresses.

- Removal of machining marks (small notches or groves produced by the machining tools) and other surface irregularities improves the fatigue properties.

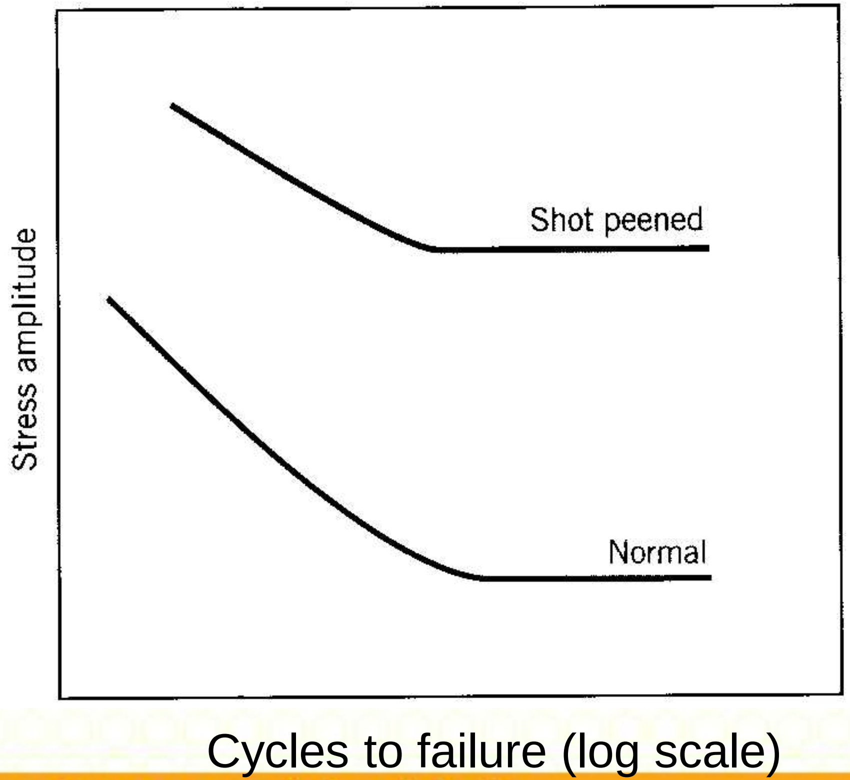
- Putting the surface layer under compression by surface treatment also improves the fatigue life.

- Tensile residual stresses can promote fatigue cracking and decrease the fatigue life. On the other hand, compressive residual stresses at the surface of a material offset the effect of applied tensile stress and the overall fatigue life is usually increased.

surface layer under compression by surface treatment

- E.g. shot peening process

Small and hard particles (shot) having diameters 0.1-1.0 mm are projected at high velocity onto the surface to be treated.



Schematic S-N fatigue curves for normal and shot-peened steel.

Other surface treatment:
Case hardening-carburizing or nitriding

2. Microstructural Factors

- A microstructure with small grain size usually has a good fatigue life. A small grain size contains very large number of grain boundaries, and this will impede or delay crack initiation (stage I crack growth).

- The presence of second phase particles in an engineering material, and although they increase the overall strength, decrease the fatigue life because they act as stress concentrators and hence accelerate the crack initiation

3. Environmental Factors

- Fatigue occurring in a corrosive environment is usually referred to as corrosion-fatigue.

- Corrosive attack by a liquid can produce pits that may act as notches, but when the corrosive attack is simultaneous with fatigue stressing, the effect will be greater.