Chapter 4: Fatigue Failure

Introduction to Fatigue in Metals

- Prior to the nineteenth century, engineering design was based primarily on static loading.

- Slow speeds, light loads, and large factors of safety.

Introduction to Fatigue in Metals

- With the development of engines capable of higher speeds, and materials capable of higher loads, parts began to be subject to significantly higher cycles at high stress.
- Stresses well below the yield strength, *BUT* increase in sudden ultimate fractures.
- The most distinguishing feature of the failures was a large number of cycles.

This led to the notion that the part had simply become "tired" from repeated cycling, hence the origin of the term fatigue failure.

Introduction to Fatigue in Metals

- Testing proved that the material properties had *NOT* changed. (Despite failure looking like brittle fracture)
- Fatigue failure is due to a crack initiating and growing when subjected to many repeated cycles.
- August Wöhler is credited with deliberately studying and articulating some of the basic principles of fatigue failure.

Examples of Fatigue Failures

- Versailles railroad axle (1842)
- Liberty ships (1943)
- multiple de Havilland Comet crashes (1954)
- Kielland oil platform collapse (1980)
- Aloha B737 accident (1988)
- DC10 Sioux City accident (1989)
- MD-88 Pensacola engine failure (1996)
- Eschede railway accident (1998)
- GE CF6 engine failure (2016)
- Denver Colorado Boeing 777 turbine blade break (2021)

Crack Nucleation and Propagation

Fatigue failure is due to crack nucleation and propagation.

A fatigue crack will initiate at a location that experiences repeated applications of locally high stress (and thus high strain).

The locally high stress is often at a discontinuity.

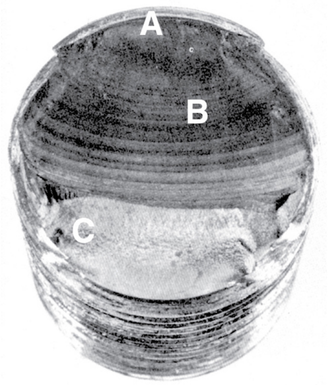
- Geometric changes, e.g. keyways, holes
- Manufacturing imperfections, e.g. stamp marks, scratches
- Composition of the material, e.g. from rolling, forging, casting, heat treatment, inclusions, voids

Stages of Fatigue Failure

Stage I - Initiation of micro-crack due to cyclic plastic deformation

Stage II – Progresses to macro-crack that repeatedly opens and closes, creating bands called beach marks

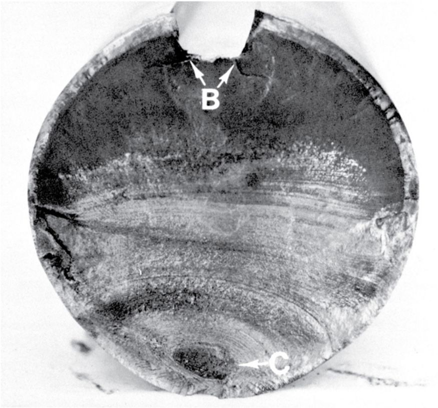
Stage III – Crack has propagated far enough that remaining material is insufficient to carry the load, and fails by simple ultimate failure



Fatigue failure of a bolt due to repeated bending

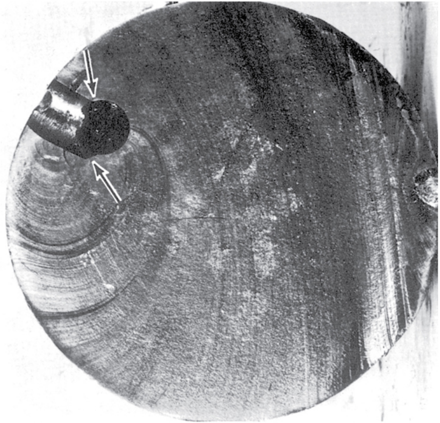
Fatigue Fracture Examples

- AISI 4320 drive shaft
- B: crack initiation at stress concentration in keyway
- C: Final brittle failure



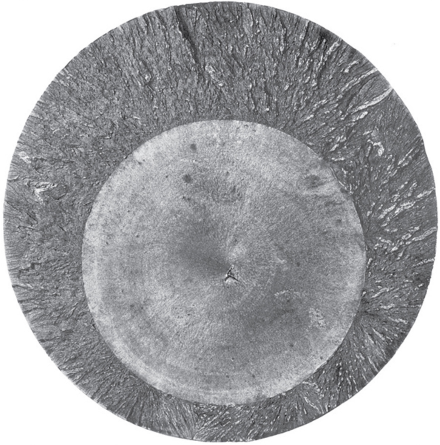
Fatigue Fracture Examples

- Fatigue failure initiating at grease hole
- Sharp corners (at arrows) provided stress concentrations

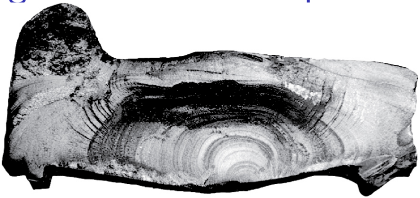


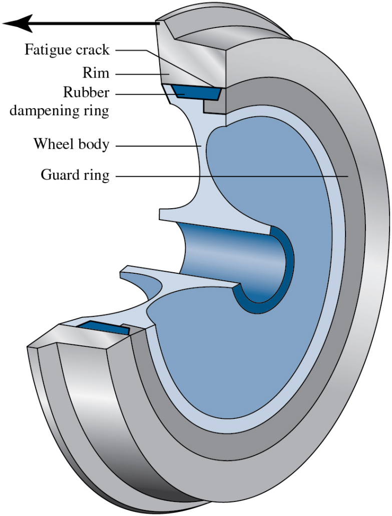
Fatigue Fracture Examples

- Fatigue failure of a 200-mm diameter piston rod of an alloy steel steam hammer
- Loaded axially
- Crack initiated at a forging flake internal to the part
- Internal crack grew outward symmetrically



Fatigue Fracture Examples



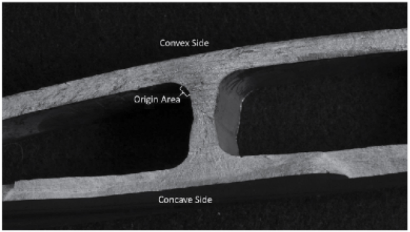


- Fatigue failure of wheel rim of the Eschede railway accident (1998)
- The crack origin is near the bottom center in the detail view, with beach marks emanating from it, showing approximately 80

Fatigue Fracture Examples

Fatigue failure of turbine blade from a Pratt & Whitney engine on a Boeing 777 which failed shortly after takeoff from Denver, C O in 2021.

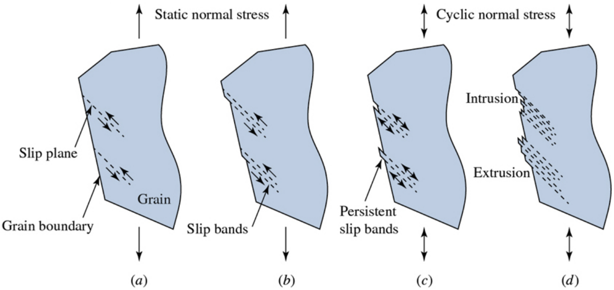
(a)



(b)

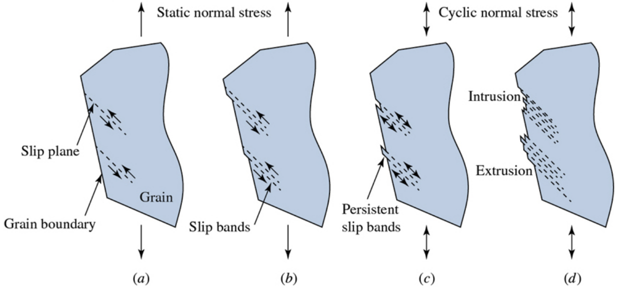
Crack Nucleation

- Crack nucleation occurs in the presence of localized plastic strain.
- Plastic strain involves breaking of a limited number of atomic bonds, forming slip planes, in which atoms in crystal planes slip past one another.
- The slip planes prefer movement within a grain of the material in a direction requiring the least energy.
- The preferential orientation is usually along the plane of maximum shear stress, at 45° to the loading direction. (Fig. a)



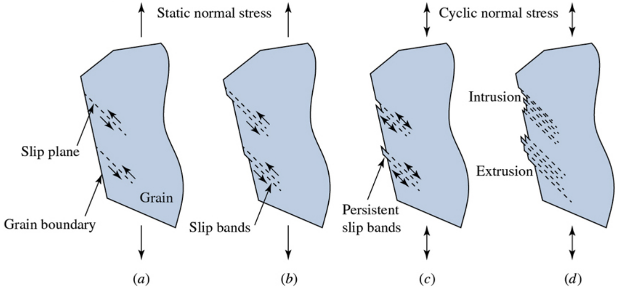
Crack Nucleation

- Slip planes tend to be parallel to one another, and bunch together to form slip bands. (Fig. b)
- When the slip bands reach the edge of a grain, and especially at the surface of the material, they extrude very slightly, and are called persistent slip bands. (Fig. c)



Crack Nucleation

- Continued cyclic loading of sufficient level eventually causes further sliding of the persistent slip bands.
- Extrusions and intrusions are formed at the grain boundaries, on the order of 1 to 10 microns. (Fig. d)
- These tiny steps in the surface act as stress concentrations, which locally accelerates the process, tending to nucleate a microcrack.



Crack Nucleation

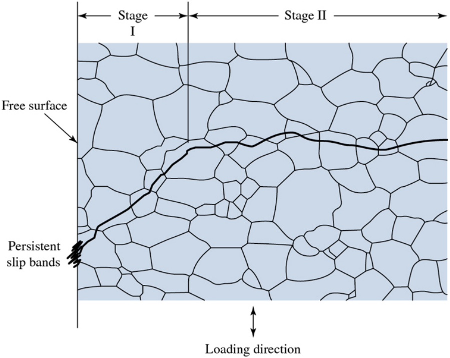
Microcrack nucleation is much more likely at the free surface of a part, where

- Stresses are often highest
- Stress concentrations often exist
- Surface roughness exists
- Oxidation and corrosion accelerate the process
- There is less resistance to plastic deformation

Crack Propagation

Stage I crack growth (shear mode)

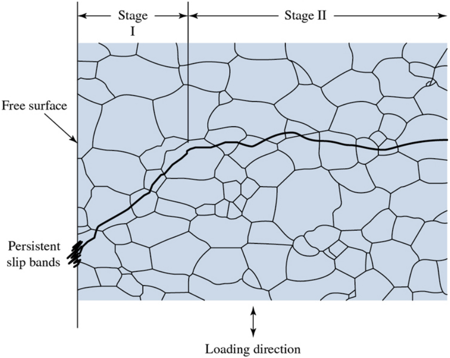
- Continued cycling progressively breaks bonds between slip planes across a single grain.
- The growth rate is very slow, on the order of 1 nm per cycle.
- At the grain boundary, the crack may slow or halt.
- Eventually, the crack may propagate into the next grain, especially if the grain is preferentially oriented with shear planes near 45° from the loading direction.



Crack Propagation

Stage II crack growth (tensile mode)

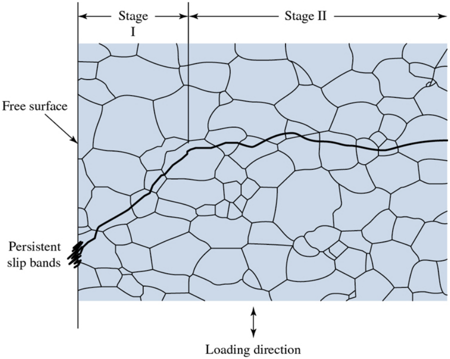
- When the crack has grown across approximately 3 to 10 grains, it is sufficiently large to form a stress concentration at its tip that forms a tensile plastic zone.
- Several microcracks in near vicinity may join, increasing the size of the tensile plastic zone.
- The crack is now vulnerable to being "opened" by a tensile normal stress.



Crack Propagation

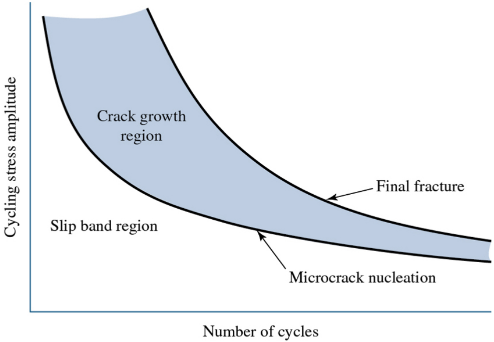
Stage II crack growth (tensile mode)

- The "opened" crack now starts Stage II crack growth by growing perpendicular to the applied load.
- The crack grows particularly when opened in tension.
- Compressive stress does not tend to open the crack, and therefore contributes little to crack growth.



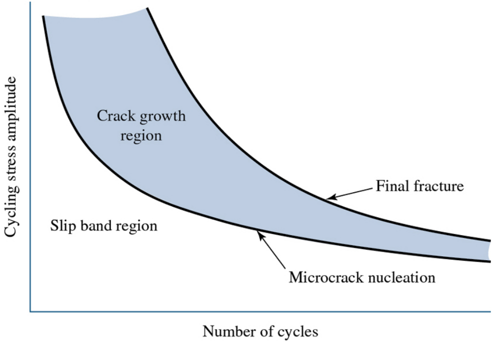
Crack Growth & Nucleation vs Cycle Life

- At higher stress levels, a crack initiates quickly, and most of the fatigue life is growing a crack.
- At lower stress levels, a large fraction of the fatigue life is spent to nucleate a crack, followed by a quick crack growth.
- If the stress level is low enough, it is possible that a crack never nucleates, or that a nucleated crack never grows to fracture.



Crack Growth & Nucleation vs Cycle Life

- **High-cycle** fatigue domain deals with long fatigue life (say, greater than 10000 cycles) due to low loads, elastic stresses and strains.
- **Low-cycle** fatigue domain deals with short fatigue life, due to which loads, mostly plastic stresses and strains.



Fatigue Life Methods

Fatigue-Life Methods predict life in number of cycles to failure for a specific level of loading.

Three major fatigue life methods in use:

- **Strain-life method**
  - Focuses on crack nucleation (Stage I)
  - Detailed analysis of plastic deformation at localized regions
- **Linear-elastic fracture mechanics (LEFM) method**
  - Focuses on crack propagation (Stage II)
  - Predicts crack growth with respect to stress intensity
- **Stress-life method**
  - Estimates life to fracture, ignoring details of crack nucleation and propagation
  - Based on comparison to experimental test specimens

Fatigue Life Methods

- All three methods have a place in fatigue design.
- For monitoring the actual growth rate of a crack, LEFM is the prime tool.
- For low-cycle domain in the presence of a notch, strain-life is optimal.
- For high-cycle domain, both strain-life and stress-life are applicable. Strain-life is more accurate, but requires significantly more overhead.
- Stress-life is great for beginning engineers, occasional fatigue analysis, rough estimates, and observing the impact of various factors on the fatigue life.

Fatigue Design Criteria

Four design philosophies have evolved to provide strategies for safe designs

1. **Infinite-life design**
   - Design for infinite life by keeping the stresses below the level for crack initiation

2. **Safe-life design**
   - Design for a finite life, for applications subject to a limited number of cycles
   - Due to the large scatter in actual fatigue lives under similar conditions, large safety factors are used

Fatigue Design Criteria ... contd.

3. **Fail-safe design**
   - Incorporates an overall design such that if one part fails, the system does not fail
   - Uses load paths, crack stoppers, and scheduled inspections
   - For applications with high consequences for failure, but need low factors of safety, such as aircraft industry

4. **Damage-tolerant design**
   - Assumes existence of a crack, and uses LEFM to predict the growth, in order to dictate inspection and replacement schedule.
   - Best for materials that exhibit slow crack growth and high fracture toughness.

Stress-Life Method

- The Stress-Life Method relies on studies of test specimens subjected to controlled cycling between two stress levels, while counting cycles to ultimate fracture.
- Known as constant amplitude loading
- Reasonable model for many real situations, such as rotating equipment
- Provides a controlled environment to study the nature of fatigue

Constant Amplitude Stress Terminology

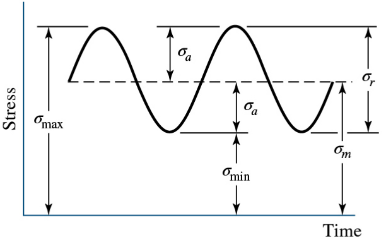
$\sigma_{\min}$: minimum stress

$\sigma_{\max}$: maximum stress

σ_m : midrange stress

σ_a : alternating stress
or stress amplitude

σ_r : stress range



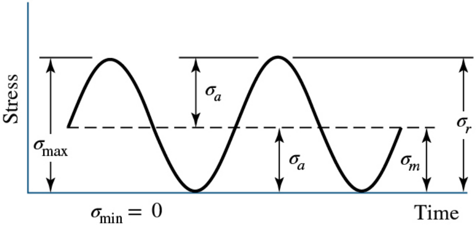
σ_a must be positive

σ_m can be positive or negative

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

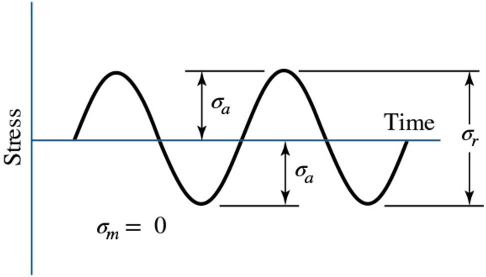
$$\sigma_m = \frac{\sigma_{\max} + \sigma_{\min}}{2}$$

Special case: Repeated Stress



Stress cycles from zero to a maximum

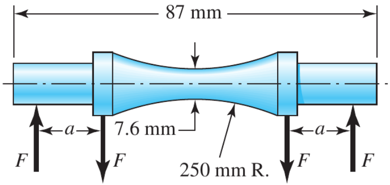
Special case: Completely Reversed Stress



Stress cycles with equal magnitudes of tension and compression around a mean stress of zero

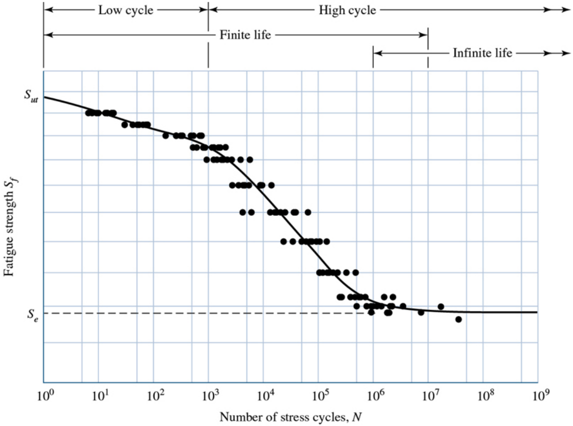
Completely Reversed Stress Testing

- Most stress-life fatigue testing is done with completely reversed stresses
- Then the modifying effect of nonzero mean stress is considered separately
- A common test machine is R. R. Moore high-speed rotating-beam machine
- Specimen *subject to pure bending* with no transverse shear
- Each rotation subjects a stress element on the surface to a completely reversed bending stress cycle
- Specimen is carefully machined and polished



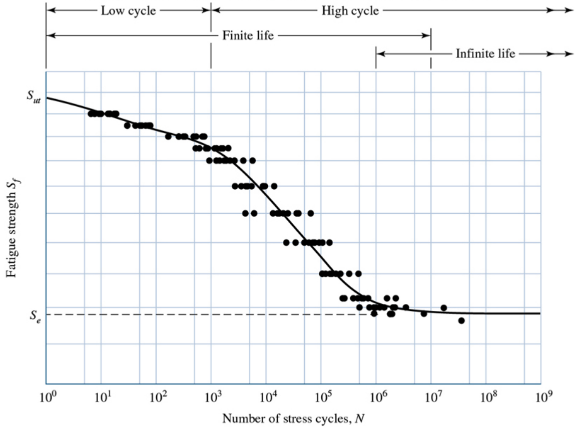
The *S*-*N* Diagram

- Number of cycles to failure at varying stress levels is plotted on log-log scale
- Known as Wöhler curve, or stress-life diagram, or *S*-*N* diagram



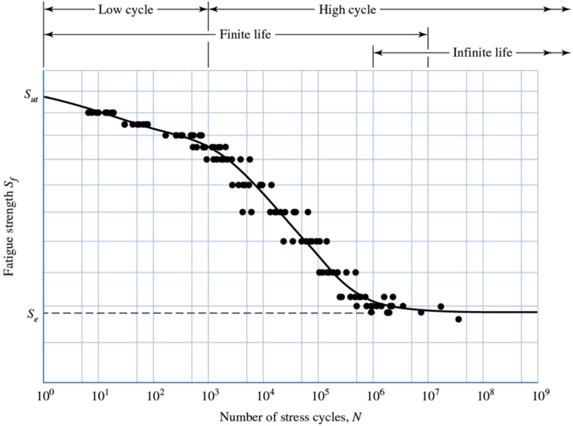
The *S-N* Diagram

- Many specimens are tested to failure at each level of completely reversed stress.
- The curve typically passes through the mean of the test data at each stress level.



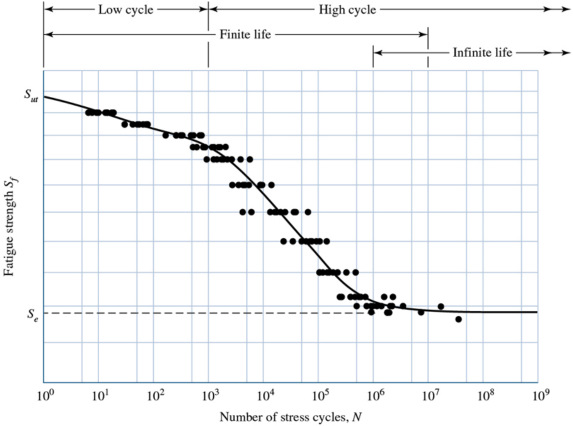
The *S*-*N* Diagram

- Fatigue failure with less than 1000 cycles is known as low-cycle fatigue, and is often considered quasi-static.
- Yielding usually occurs before fatigue in this zone, minimizing the need for fatigue analysis.
- Low-cycle fatigue often includes plastic strain, and is better modeled with strain-life method.



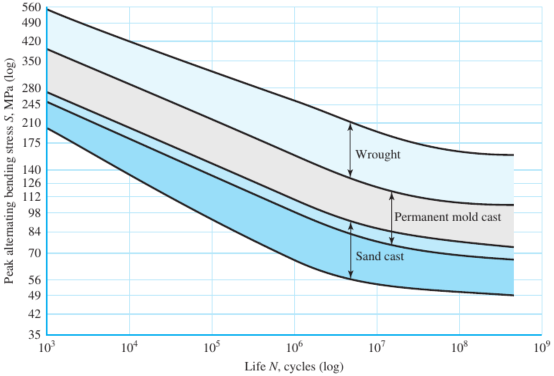
The *S*-*N* Diagram

- Ferrous metals usually exhibit a bend, or "knee", in the *S*-*N* diagram where it flattens.
- The fatigue strength corresponding to the knee is called the **endurance limit** S_e.
- Stress levels below S_e predict infinite life.



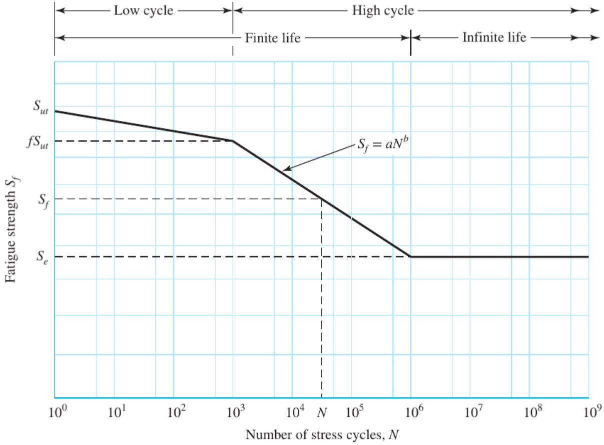
S-*N* Diagram for Non-Ferrous Metals

- Non-ferrous metals and plastics often do not have an endurance limit.
- Fatigue strength is reported at a specific number of cycles.



S-*N* bands for representative Al alloys

Idealized *S-N* Diagram for Steels



For steels, an idealized S-N diagram can be represented by three lines, representing the median of the failure data.