Fatigue Strength and Analysis

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Fatigue Strength and Analysis

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1.1 Definition of Terms

1.1.1 Fracture ?

- A fracture is the (local) separation of an object or material into two, or more
- Definition in fracture mechanics

  "A process of forming a new surface through irreversible process under certain mechanical load."

1.1.2 Failure ?

- Failure means that a machine fails to perform.
- The term of failure is widely used in reliability engineering. It may happen, even there is no destruction, or may not happen, there is destruction though.

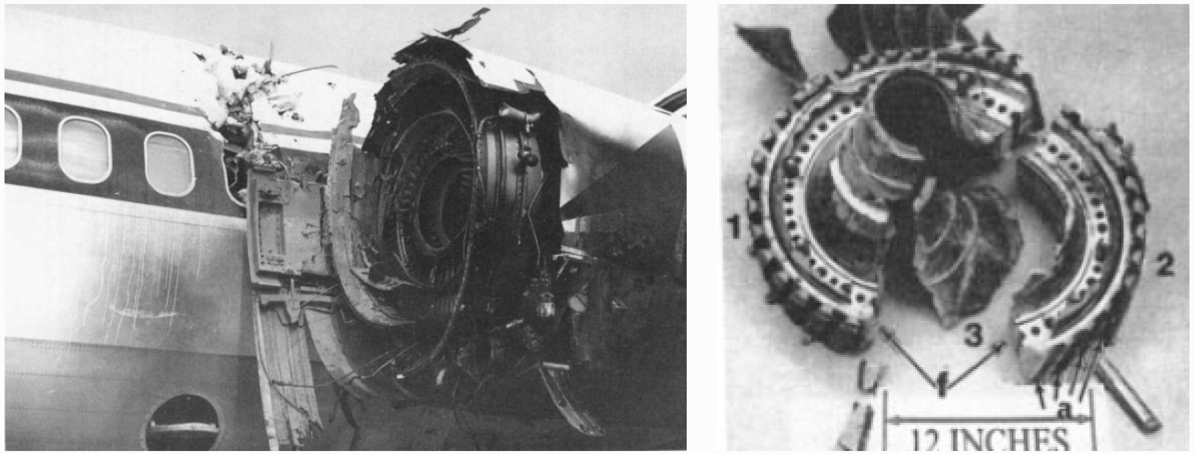


Fig.1.1 Damaged Airplane(left) and fractured fan hub(right)

1.2 Classification of Fracture Types

1.2.1 Brittle Fracture

- No apparent plastic deformation takes place before fracture, but when fracture happens, the crack propagates rapidly.
- Even if the load is removed, the destruction will not be disappeared.

Fig.1.2 An oil tanker that fractured in a brittle manner

1.2 Classification of Fracture Types

1.2.2 Ductile Fracture

- Extensive plastic deformation takes place before fracture.
- Relatively slow and stable crack propagation
- Crack propagation is stable that cracks are in equilibrium at each point, so crack propagation stops when we remove the load, and for the anew crack propagation it is necessary to impose a load.

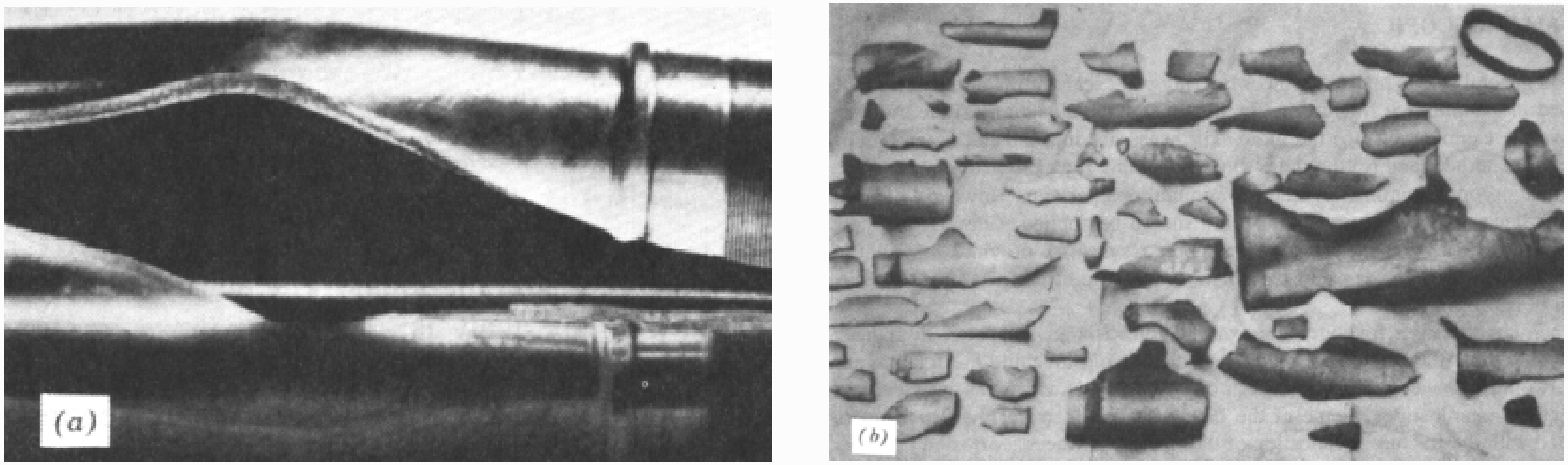


Fig.1.3 A pipe ductile fracture(left, one piece large deformation) and brittle fracture(right, many pieces small deformation)

1.2 Classification of Fracture Types

1.2.3 Fatigue Fracture

- General definition

"A destruction under repeated loading and unloading condition"

- Definition in ASTM(American Society for Testing and Material)

"it is a process of progressive localized permanent structural change occurring in a material subjected to conditions that produce fluctuating stresses and strains at some point or points and which may culminate in cracks or complete fracture at a sufficient number of fluctuations"

- Fatigue fracture(generalization)

"A material received external or internal repeated loading (cyclic loading) changes in local organization due to the repeated load, eventually leads to cracks or fracture process"

Fig.1.4 Aloha Airlines Flight 243, Boeing 737-200, April 28 1988, Honolulu, Hawaii
(undetected cracks in fuselage skin, corrosion in the joint as a result of disbonding)

1.2 Classification of Fracture Types

1.2.4 Creep Fracture

- Deformation increases with time, in the case of a material loaded constant load at over certain temperature.
- Creep deformation and fracture at some point, leading to increased acceleration of the type.

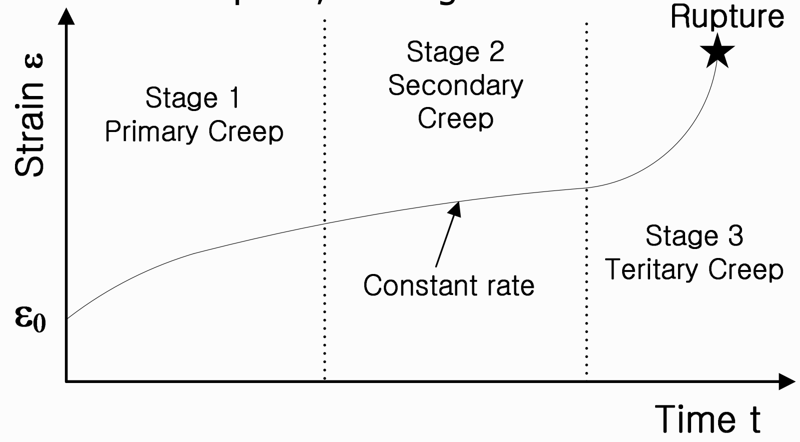


Fig.1.5 Creep deformation

1.2.5 Delayed Fracture and Environment Assisted Fracture

- When materials under static tensile loading, even though the size is much lower than the yield stress, if the loading are loading long, it significantly changed to the destruction abruptly without apparent plastic deformation.
- Environment assisted fracture is also called as environment sensitive fracture.

1.3 Fracture Type and Material Strength

1.3.1 Strength of Materials

Strength of the material is considered in the case of having cracks and flaws or not, and basic strength is normally in the case of having not defective.

1.3.2 Fatigue Strength

Fatigue is very important in terms of strength of materials, and fatigue strength is one of important parameters in the mechanical design.

1.3.3. Relationship between fracture type and material strength

- Ductile fracture, brittle fracture -> static strength.
- Fatigue Fracture -> Fatigue Strength.
- Creep Fracture -> Creep Strength(high temp.)

  * When materials receives repeated load at high temperatures, the representative of this repeated loading at high temperatures is thermal stress.
- Stress corrosion cracking, hydrogen embirttlement cracking -> environmental strength

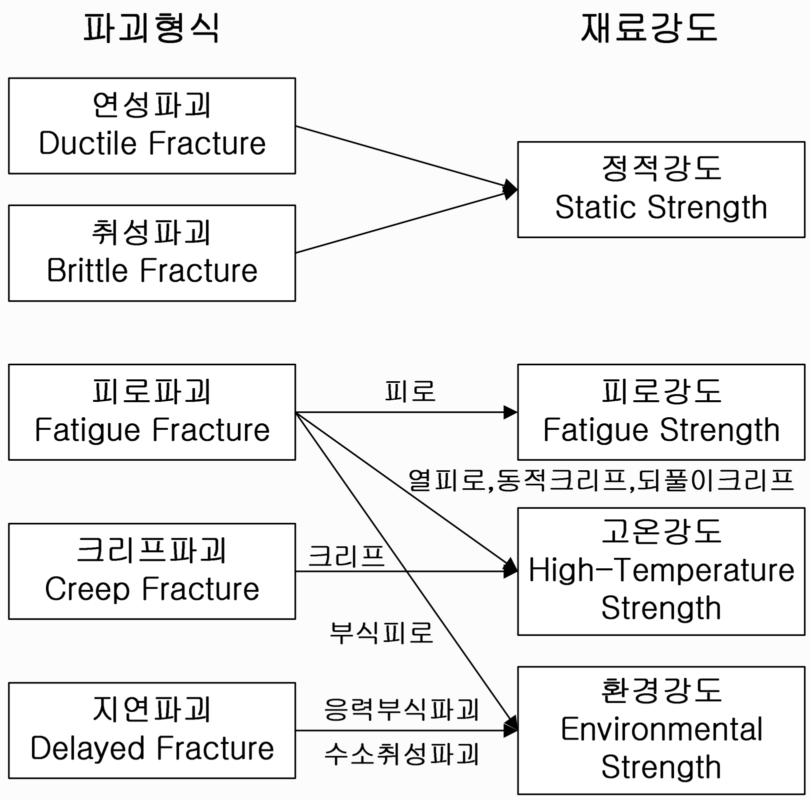


Fig.1.6 Fracture and material strength

1.4 Characteristics of Fatigue Fracture

1.4.1 Cyclic Loading

- Fatigue is occurred by repeated loading and unloading.
- All the machines and structures get cyclic loading in nature, so most of fractures comes by fatigue.

1.4.2 Lower yield stress or the proportional limit

- Although cyclic stress range is smaller than static fracture stress or yield stress, fatigue fracture occurs.

1.4.3. Fatigue limit or endurance limit

- Fatigue limit and endurance limit are all expressions used to describe a property of materials: the amplitude (or range) of cyclic stress that can be applied to the material without causing fatigue failure.

1.4.4. Macro-microscopic features of fracture surfaces

- On the surface of fatigue fracture, macro-microscopic features exist.
- By examining the fracture surface, we can estimate the cause of the fracture, the location of crack, and the amplitude of the load.

1.5 Examples of Fatigue Failure Accident

1.5.1 Crash of the world's first commercial jet, Comet (1954.1.10)

The plane - a British Overseas Airways Corporation(BOAC) jet, Comet – was crashed on its way from Rome to London.

- Accident cause : Fuselage damage caused by fatigue fracture occured in the corner of automatic direction finding(ADF) window in the upper part of fuselage
- Casualties : 29 passengers and 6 crews died.
- After experimental study for attribution, full scale fatigue testing and low-cycle fatigue testing have become crucial.

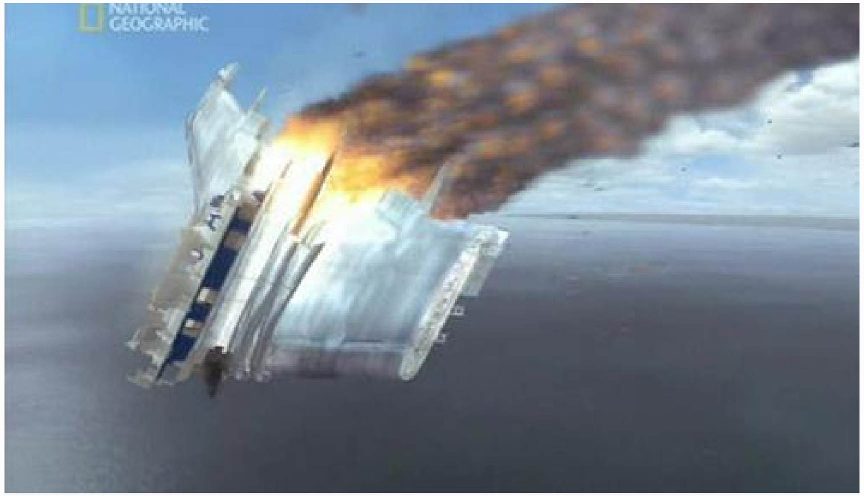


Fig.1.7 The crash of a BOAC De Havilland Comet on 10 January 1954. The aircraft went down into the sea off Elba 20 minutes after taking off from Rome.

1.5 Examples of Fatigue Failure Accident

1.5.2 Crash of American Airlines DC10 (1979.5.25)

- Accident cause : Contributing to the cause of the accident were the vulnerability of the design of the pylon attach points to maintenance damage and the fact the FAA failed to identify substandard maintenance procedures.
- Casualties : 272 people died.

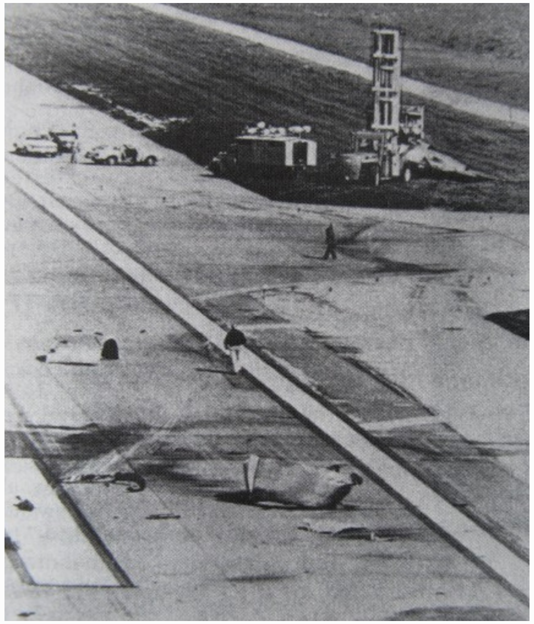


Fig.1.8 Flight 191 in an unrecoverable bank moments before the crash. Its No. 1 engine had been severed on the runway

1.5 Examples of Fatigue Failure Accident

1.5.3 Crash of drilling vessel Alexander L Kielland at the north sea oil filed (1980.3.27)

- Accident cause : Rig collapsed due to a fatigue crack in one of its six bracings, which connected the collapsed D-leg to the rest of the rig. The poor profile of the fillet weld contributed to a reduction in its fatigue strength.
- Casualties : 123 people died.

Fig.1.9 Alexander L Kielland accident

1.5 Examples of Fatigue Failure Accident

1.5.4 German high speed train ICE-1 Derailed (1998.6.3)

The Eschede train disaster was the world's deadliest high-speed train accident. It occurred on 3 June 1998, near the village of Eschede in the Celle district of Lower Saxony, Germany.

- Accident cause : The ICE 1 trains were equipped with single-cast wheels, known as monobloc wheels. Once in service it soon became apparent that this design could, as a result of metal fatigue and out-of-round conditions, lead to resonance and vibration at cruising speed.
- Casualties : 101 people died, 105 people injured.

Fig.1.10 ICE-1 accident

1.5 Examples of Fatigue Failure Accident

1.5.5 Seongsu Bridge Collapse(1994. 10. 21)

Seongsu bridge links the Seongdong and Gangnam districts. The central section of the bridge (over 50m in length) was suddenly collapsed on October 21, 1994.

- Accident cause : Improper welding of the steel trusses of the suspension structure beneath the concrete slab roadway.
- Casualties : 32 people died and 17 were injured.

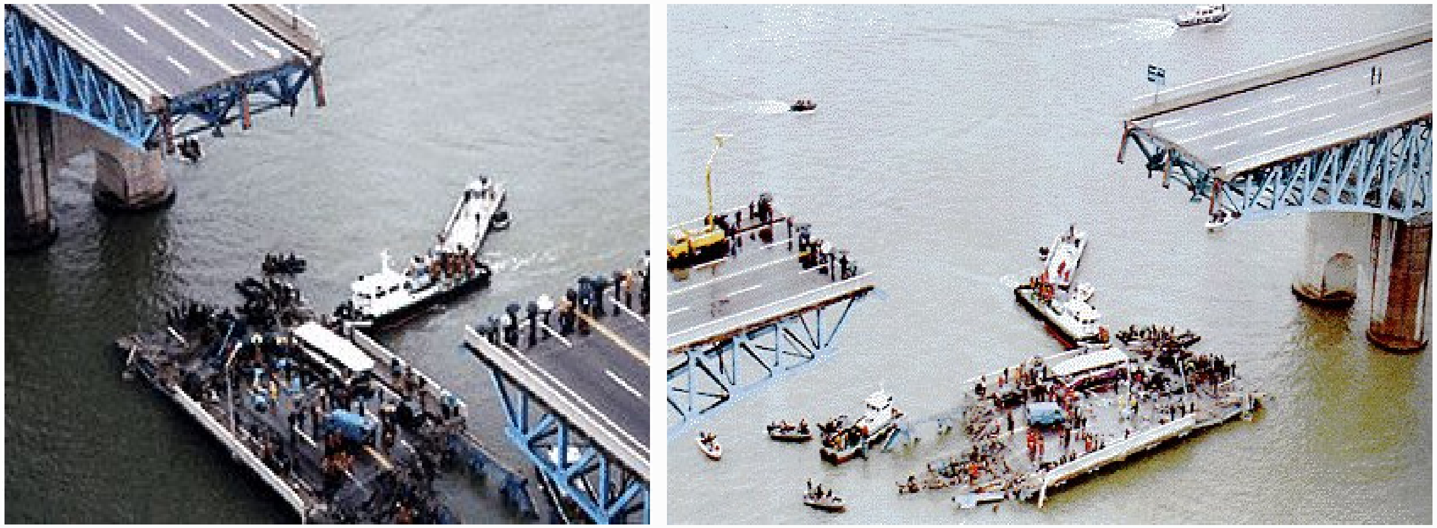


Fig.1.11 Collapses of the Sung Soo Bridge

2. Fatigue Load

Fatigue Strength and Analysis

- 1. Fatigue Fracture
- 2. Fatigue Load
  - 2.1 Fatigue Load
  - 2.2 Fatigue Load Form
- 3. Fatigue Fracture Surface
- 4. Fatigue Life Regime & Fatigue Design

2.1 Fatigue Load / 2.2 Fatigue Load Form

2.1.1 Fatigue Load ?

The most different thing of fatigue fracture with other fractures is to be occurred under repeating loading and unloading, this cyclic loading received to the material is called fatigue loading.

2.2.1 Fatigue Load Form

2.2.1.1 Physical Fatigue

The load size of the fatigue load received to actual structural elements fluctuates irregularly of course, the period of load change such as frequency also fluctuates so-called random loading. Random loading is defined as irregularly fluctuating loading namely irregular loading.

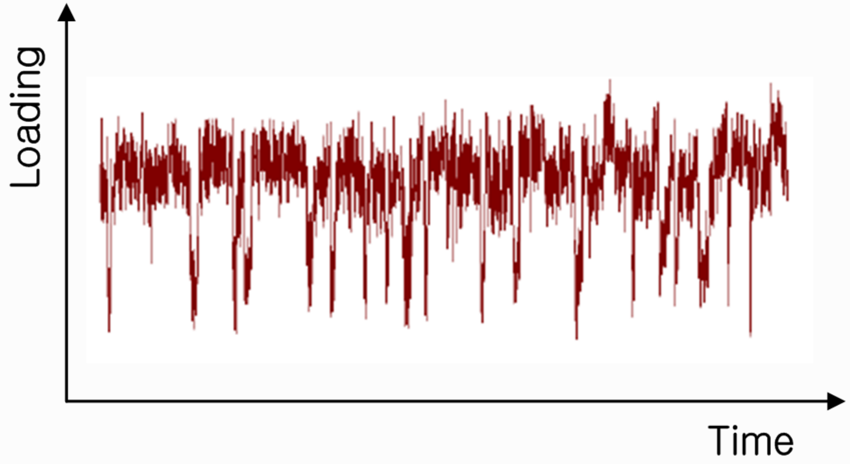


Fig.2.1 Actual fatigue loading (random loading, irregular loading)

2.2 Fatigue Load Form

2.2.1.2 Constant amplitude loading

- Random loading is complex and difficult to handle, so constant amplitude loading is usually used to evaluate the basic fatigue phenomenon.
- Constant amplitude loading is a loading with a constant amplitude and period.
- Cycle: Period from the minimum(or maximum) to the next minimum(or maximum) of waveform.
- Amplitude and mean are usually used as representative mechanical quantities for fatigue load.

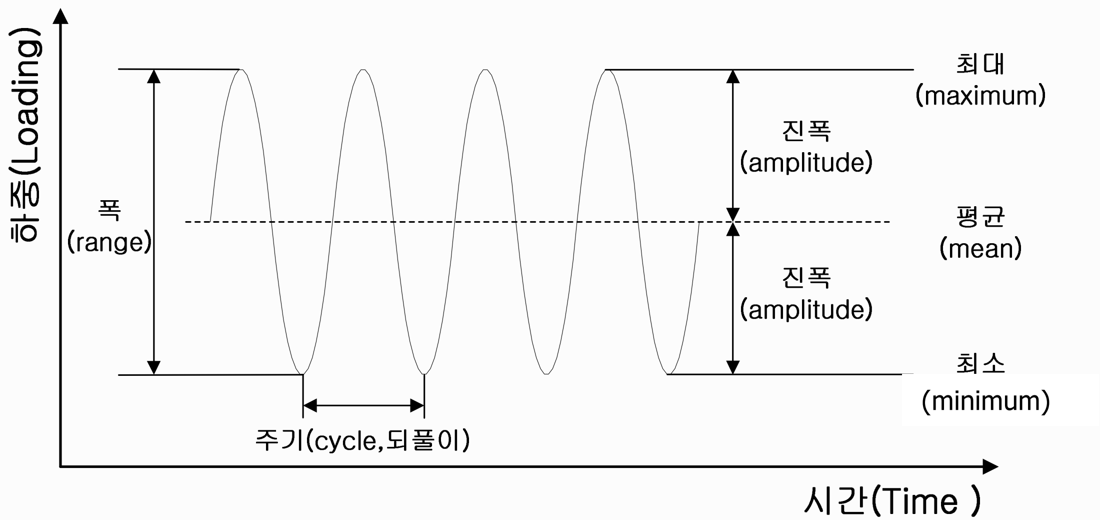


Fig.2.2 Constant amplitude loading

2.2 Fatigue Load Form

- load ratio or stress ratio R

$$R = \frac{\text{minimum load}}{\text{maximum load}} = \frac{P_{min}}{P_{max}} = \frac{\sigma_{min}}{\sigma_{max}}$$

- amplitude ratio A

$$A = \frac{\text{load amplitude}}{\text{average load}} = \frac{P_a}{P_m} = \frac{\sigma_a}{\sigma_m}$$

- Various constant amplitude loading

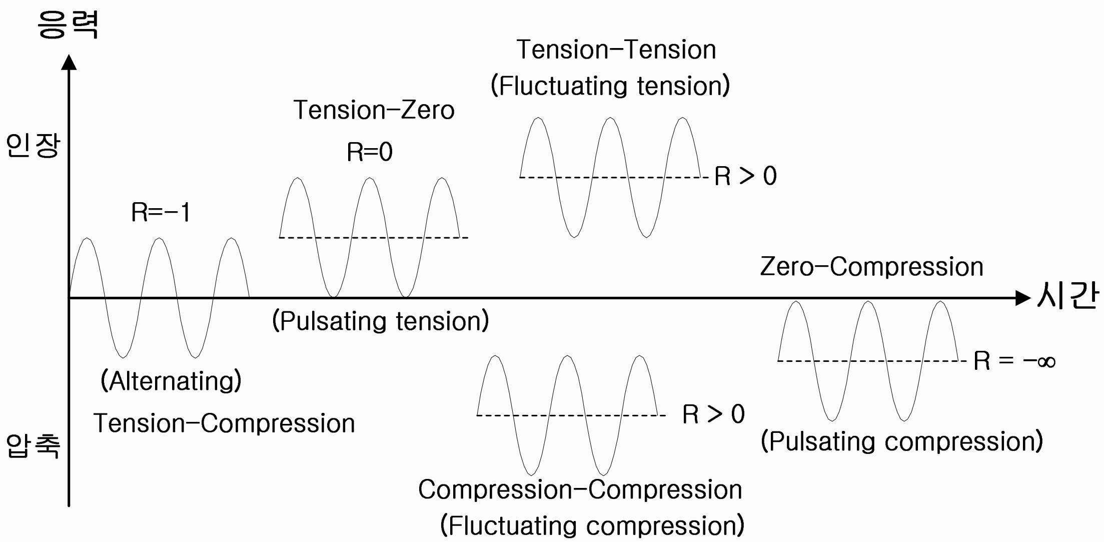


Fig.2.3 Various constant amplitude loading

2.2.1.3 Variable Load

- The amplitude is not constant. it is also called irregular loading or spectrum loading.
- Peak, Valley, +Range, -Range.
- Reversal.
- Reference loading : Average load about all load history.

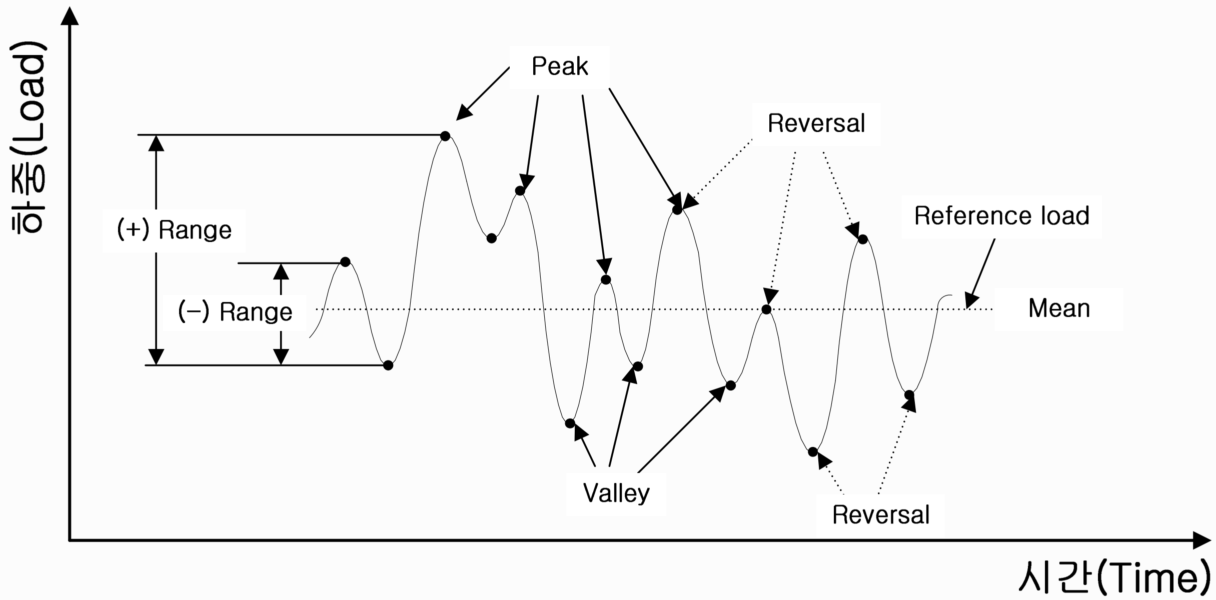


Fig.2.4 Variable loading

3. Fatigue Fracture Surface

Fatigue Strength and Analysis

- 1. Fatigue Fracture
- 2. Fatigue Load
- 3. Fatigue Fracture Surface
  - 3.1 Macroscopic Features
  - 3.2 Microscopic Features
- 4. Fatigue Life Regime & Fatigue Design

3.1 Macroscopic Features

3.1.1 Three regions of macroscopic fatigue fracture surface

3.1.1.1 The first region

- The region having beach marks (or clamshell marks). In this region, crack growth rate is relatively slow.

** beach mark

- It is a series of concentric half-moon shaped lines; they can also be nearly straight and parallel. These lines indicate where the crack front actually stopped in its progress. The crack does not start again until the load, which initiated the crack in the first place, is applied again. If the load is removed then the crack stops and a new mark is made.
- We can know crack growth direction and location of an initial crack from beach marks.

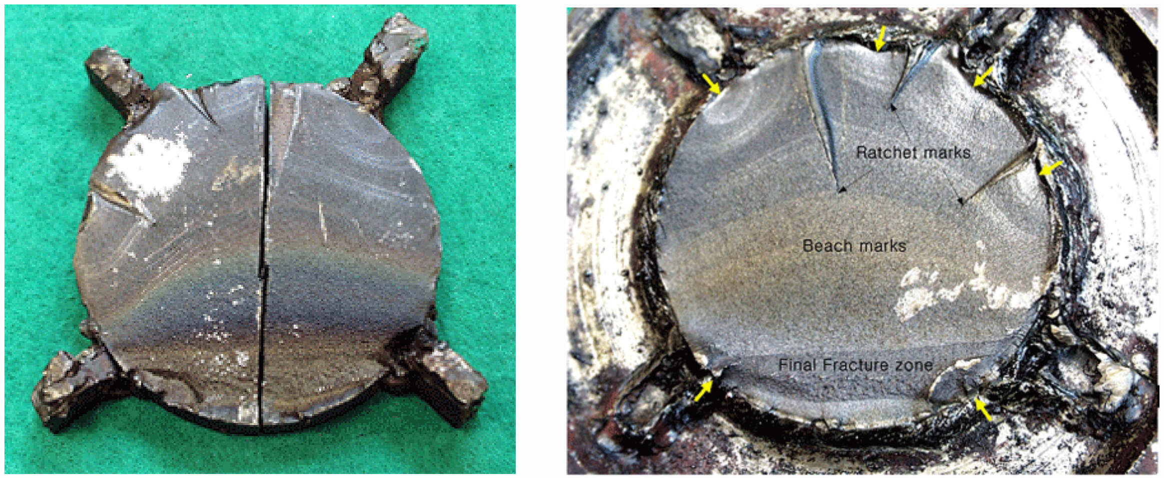


Fig.3.1 Fatigue Surface of Charge Roller

3.1 Macroscopic Features

- Rotational direction of the broken axle housing can be examined by beach mark. It is because cracks tend to grow rapidly in the opposite direction in general.
- The below figure shows the fatigue fracture surface of Axle Housing. Four sources of fatigue cracks can be found. Each beach mark locates around the fatigue crack sources, and the final fracture occurred at the top.

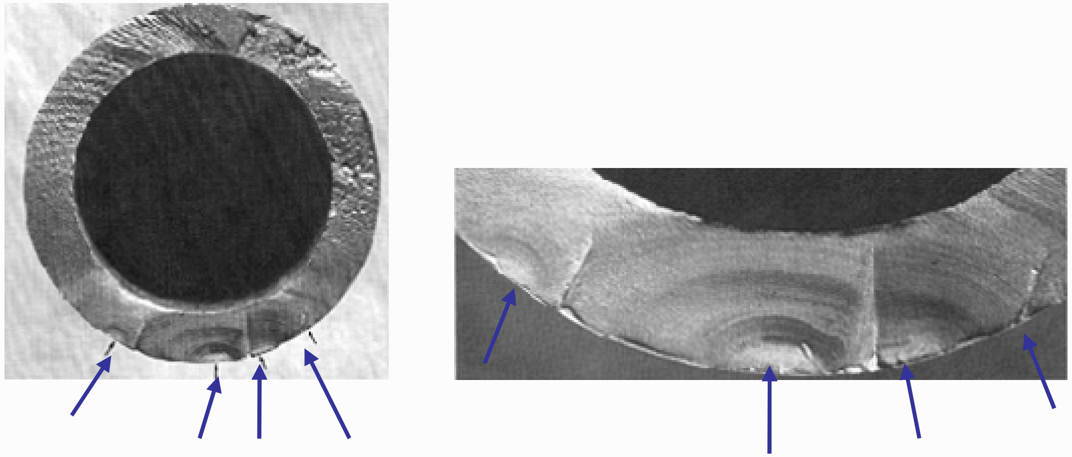


Fig.3.2 Fatigue Surface of Axle Housing

3.1.1.2 The second region

- The region that crack grows relatively quickly.
- This area is more rough and irregular than the first region because the amplitude of the load increases due to reduction of the loaded area.
- The brightness of the 1st region is darker than that of the 2nd region. It is because oxide material remains on the surface due to the slow crack growth rate in the 1st region.

3.1 Macroscopic Features

3.1.1.3 The third region

- The region of final fracture
- The final fracture can be a brittle or ductile fracture depending on material properties and environmental conditions.
- If the final fracture occur in a brittle manner (or cleavage form), the fracture surface is smooth and bright.
- If the final fracture region is large, it means the amplitude of load is large.
- If the final fracture region is small, it means the amplitude of load is small.

3.1.2 The final fracture location and loading

- Size and location of the final fracture region is dependent on the size of load.
- Normally, the location of the final fracture region is located on the center when the load is large, and it moves from the center to outer as the load becomes low. It is because the fracture occurs at one weak spot when the load is low. The crack initiates and propagates at the spot and leads to the final fracture.
- The sharpness of a notch also affects the location of fracture surface.

3.1.3 Macroscopic features according to the applied load and notch

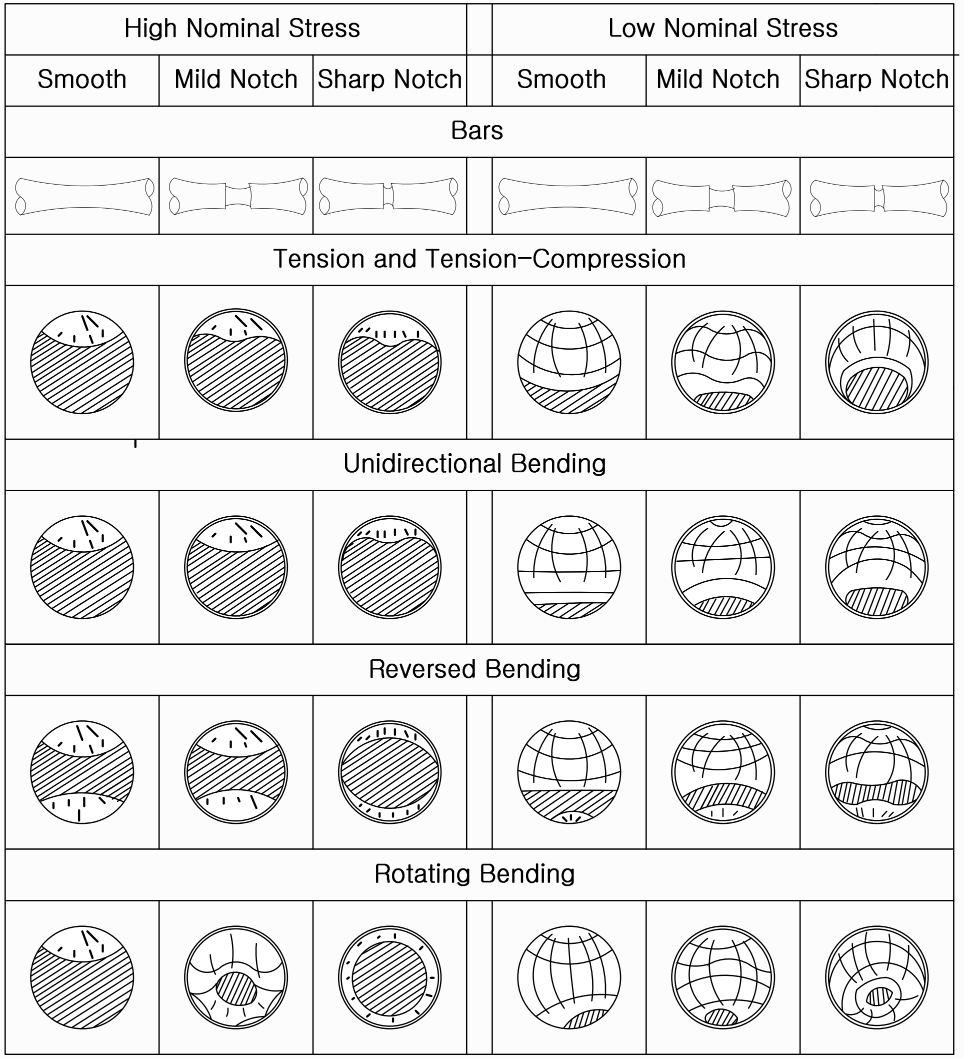


Fig.3.3 Various affecting factors and macroscopic aspects of fatigue surface

3.1.4 Fracture by torsional load (without notch)

- If cracks occurs and propagates due to large shear stress, there is no clear feature (eg. beach marks) of the fracture surface in general.
- If the cracks propagates due to tensile stress in case only torsional load is applied to the shaft, it is easier to find some features of the fractures surface.
- Crack configuration of material without notch under torsion
  (a) Cracks propagate due to the maximum stress that is perpendicular to the axis of the shaft.
  (b) Cracks propagate due to the maximum stresses that are perpendicular or parallel to the axis of the shaft.
  (c) Cracks propagate on the surface of maximum principal stress. In this case, tensile stress is dominant.
  (d) Cracks initiates on the surface of maximum stress that is parallel to the axis of shaft. After that, cracks propagate on the surface of maximum principal stress.

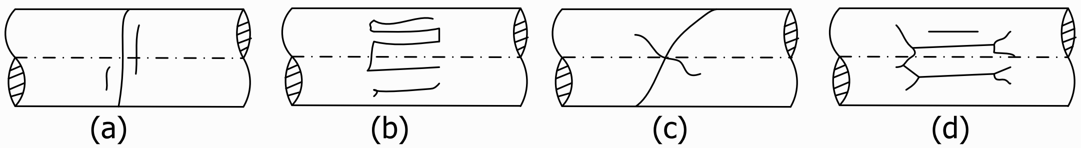


Fig.3.4 Crack configuration of material without notch under torsion

3.1.5 Fracture by torsional load (with notch)

- If there is notch, relatively large stress occurs at the notch, and cracks grow along to the maximum principal stress surface.
- If the load is high, cracks grow on two maximum principal stress surfaces.
- If the load is low, cracks normally grow on one maximum principal stress surface.

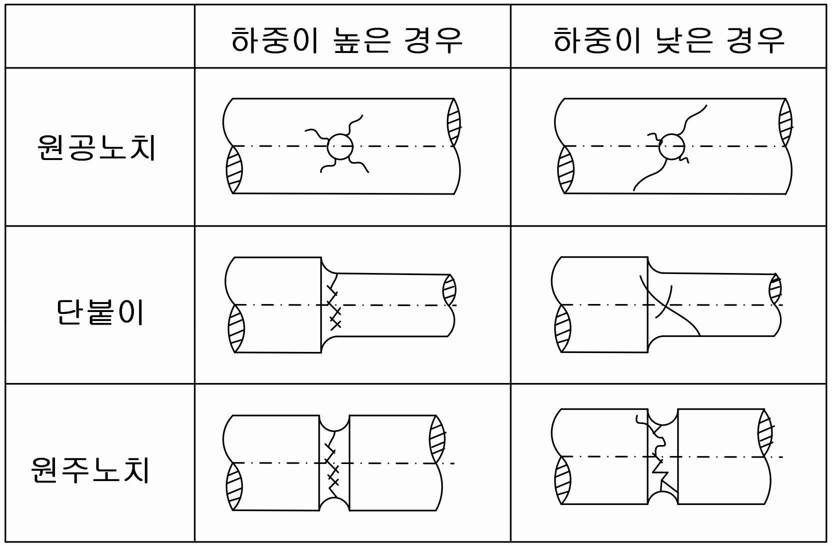


Fig.3.5 Crack configuration of material with notch under torsion

3.1.6 Fish Eye

- Fatigue fracture typically occurs on the surface of the material, but also it can occur inner part of the material in the case of hardening the surface of the material.
- In this case, white small round shape is occurred on the fatigue fracture surface (see below figure). It is called fish eye.
- Cracks propagates from inclusion.

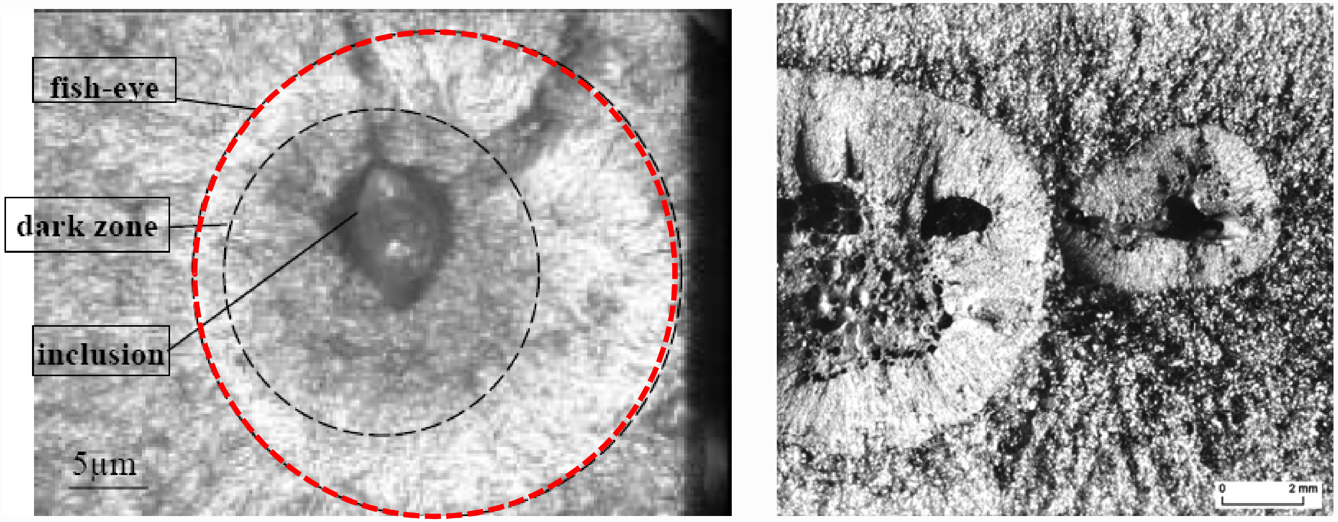
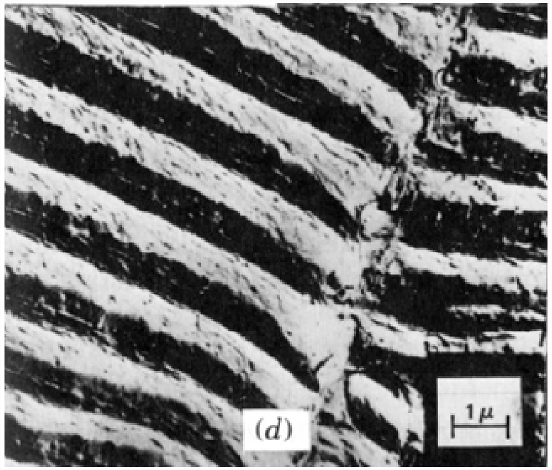


Fig.3.6 Fish eye

3.2 Microscopic Features

3.2.1 Striation

- Microscopic fine stripes are found by scanning electron microscopy on the fatigue fracture surface.
- Striations indicate the location of the crack front, and they are perpendicular to the direction of crack growth.
- The interval of two striations is same with the period of cyclic load (growthness per 1 cycle = growing speed)
- When the striation is observed on the fracture surface, it means that the fracture is caused by fatigue, and the growing speed of fatigue fracture can be calculated using the striation interval.



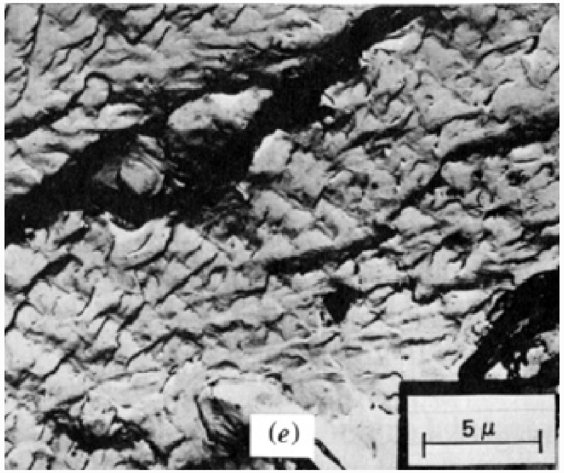


Fig.3.7 Striation (ductile, brittle)

3.2 Microscopic Features

3.2.2 Ductile Striation

- Ductile striation is sometimes called plastic striation, and it is relatively clear because it has relatively large plastic deformation.
- In general, ductile striation is built up on the surface that is perpendicular to surface of maximum tensile stress.

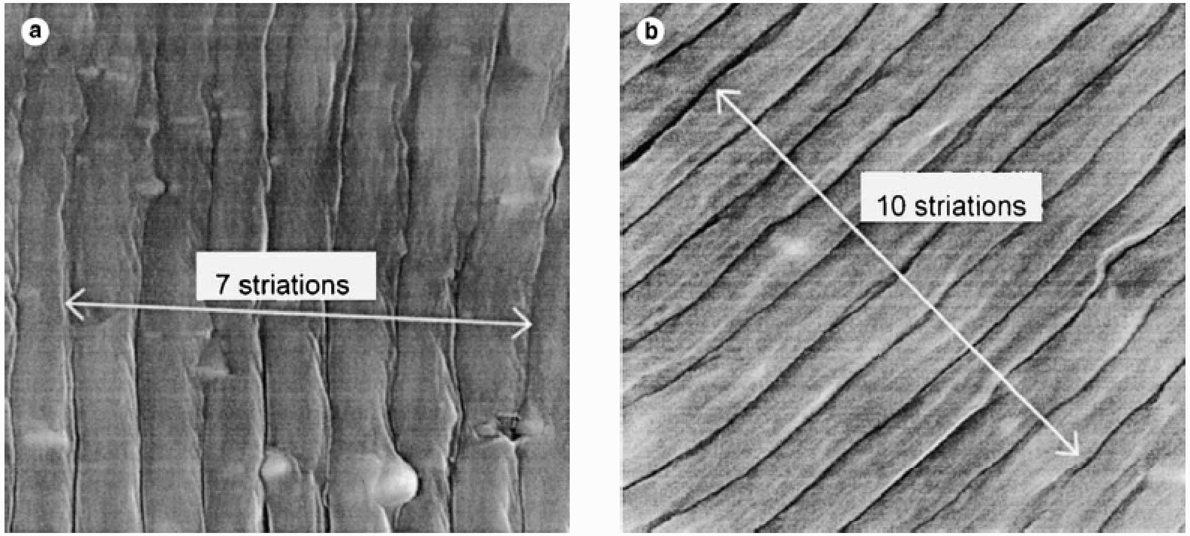


Fig.3.8 Ductile Striation, Aluminum 2024-T3

3.2 Microscopic Features

3.2.2 Plateau

- Ductile striation is made on the long strip-shaped region along the direction of crack propagation. This region is called plateau.
- The striation shows up only when the crack growth rate is fast. [The interval of striation observed on the fatigue fracture surface is from 0.1 μ to several μ in general. Thus, crack growth rate per cycle (da/dN) is about 10^{-6} m/cycle or 10^{-7} m/cycle.]

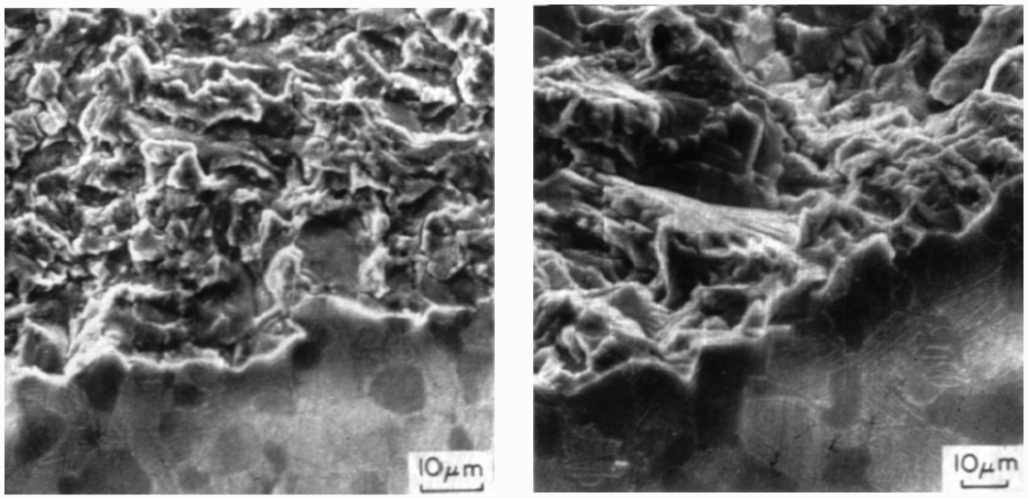


Fig.3.9 Plateau, Ti-6, Al-4 V

3.2 Microscopic Features

3.2.3 Brittle Striation

- Brittle striation is found easily when the crack grows in corrosive environment.
- Fatigue fracture surfaces show very flat.

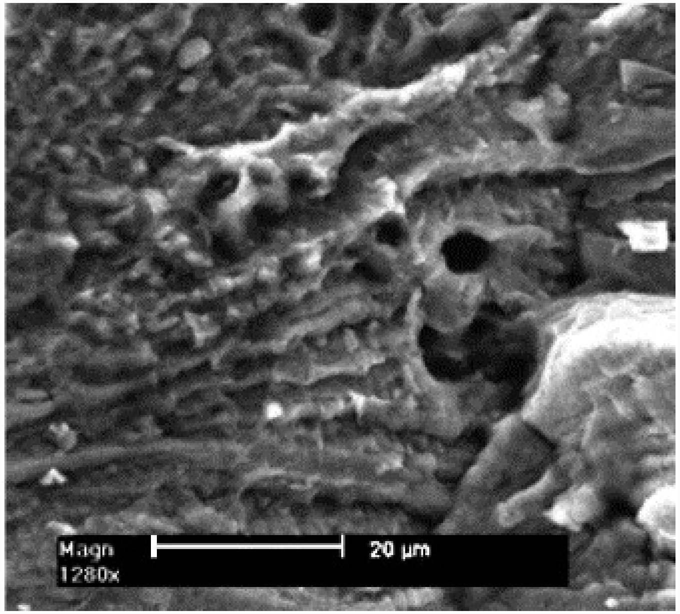


Fig.3.10 Brittle Striation, Aluminum 7075-T6

4. Fatigue Life Regime & Fatigue Design

Fatigue Strength and Analysis

- 1. Fatigue Fracture
- 2. Fatigue Load
- 3. Fatigue Fracture Surface
- 4. Fatigue Life Regime & Fatigue Design
  - 4.1 Fatigue Life
  - 4.2 Classification of Fatigue Life Regime
  - 4.3 Characteristic of Fatigue Life Regime
  - 4.4 Fatigue Design

4.1 Fatigue Life

4.1.1 Fatigue Life

- Fatigue life is the number of stress cycles of a specified character that a specimen sustains before failure of a specified nature occurs. It consist of crack initiation and propagation periods. It depends on loading and shape of a material.
- S-N diagram is a graph of the magnitude of a cyclic stress (S) against the logarithmic scale of cycles to failure (N) as show below .
- S-N diagram depends on applied loading and life regime (low cycle fatigue and high cycle fatigue).

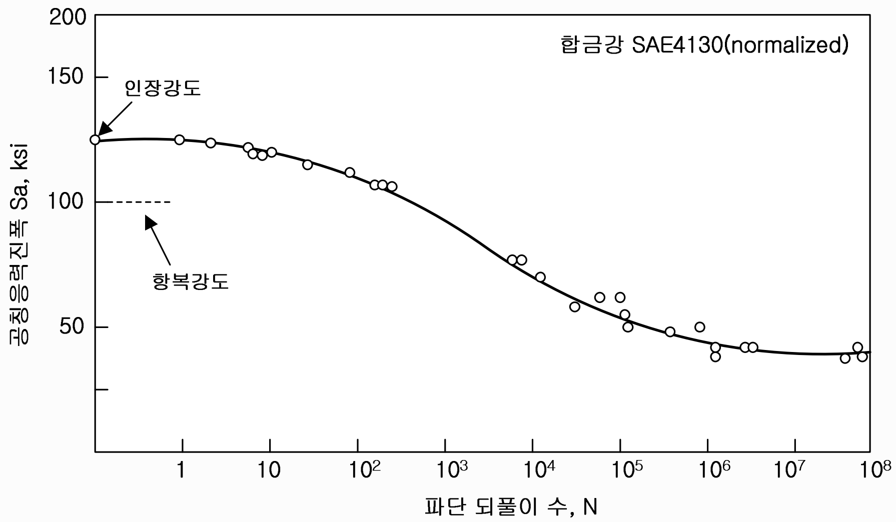


Fig.4.1 S-N diagram, SAE4130

4.2 Classification of Fatigue Life Regime

4.2.1 Classification of Fatigue Life Regime

- Low-Cycle fatigue (LCF).
- High-Cycle Fatigue (HCF).
- Classification criterion: $N=10^4$(in some cases $N=10^5$) : There is no concrete criterion.
- Practical classification
  - -> $N<10^3$: LCF Regime
  - -> $N>10^4$: HCF Regime
  - -> $10^3 <N<10^4$: Intermediate life regime
  - -> $10^9 <N<10^{10}$: very high cycle regime

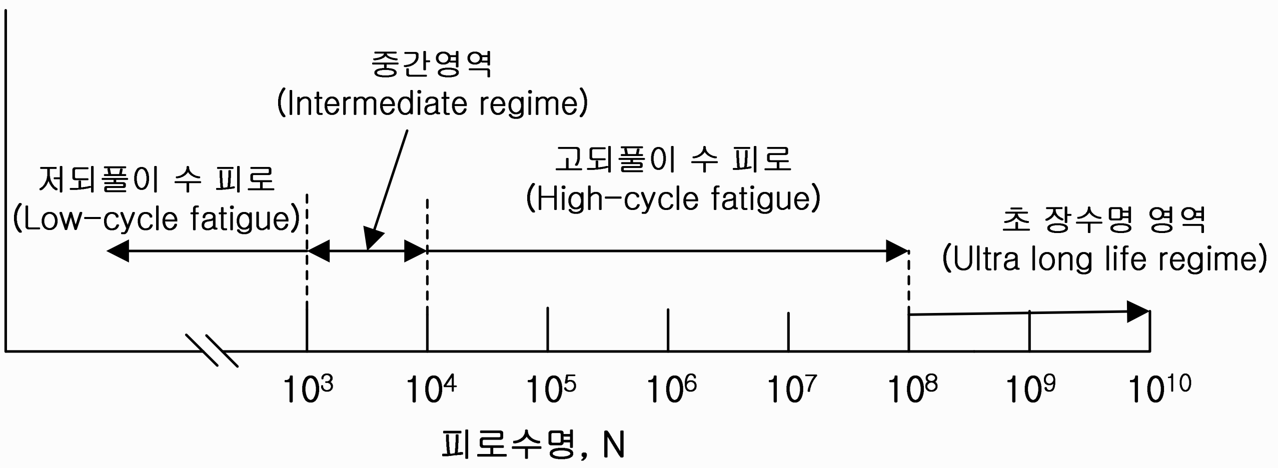


Fig.4.2 Fatigue Life regime

4.3 Characteristic of Fatigue Life Regime

4.1.3 Characteristic of Fatigue Life Regime

4.1.3.1 Low-Cycle Fatigue (or Plastic fatigue)

- Where the stress is high enough for plastic deformation to occur, the account in terms of stress is less useful and the strain in the material offers a simpler description.
- In the low-cycle fatigue test, it is ideal to control the amplitude of a plastic strain. Practically, total strain is controlled because it is easier.
- Because of the large plastic strain, the fracture happens very fast; thus, the life is highly dependent on the crack propagation period.

4.3 Characteristic of Fatigue Life Regime

4.1.3.2 High-Cycle Fatigue

- Most region experiences elastic strain and the region of plastic strain is very small. Thus, the life depends on the crack initiation.
- Fatigue limit: If the stress is less than a fatigue limit, the fatigue fracture cannot occur.
- Fatigue limit is decided as the stress level having $N=10^7$ in case of steel like material
- Because of long life, the environment effect is important.
- The life is affected by the uncertainty of material uniformity; thus, the statistical approach is necessary.

4.1.3.3 Intermediate life regime

- Both crack initiation and crack propagation are important.
- In many cases, the interpolation from the results of high-cycle or low-cycle fatigue is used.

4.4 Fatigue Design

4.4.1 Concept of Fatigue Design

(1) Infinite life design

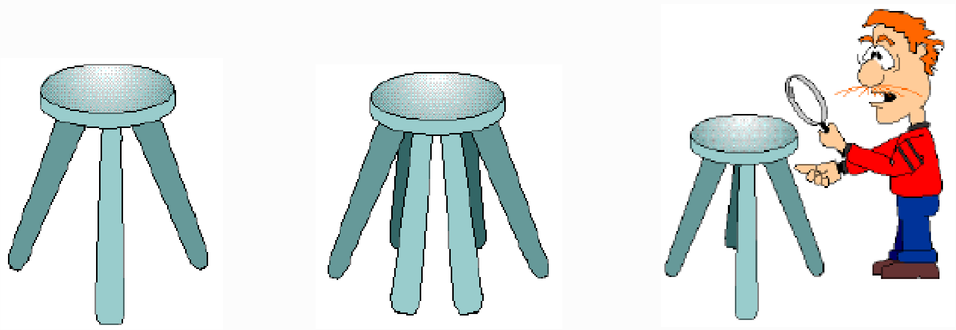
(2) Safe-life design

(3) Fail-safe design

(4) Damage-tolerant design

4.4.2 Infinite Life Design

- A design method based on fatigue limit
- It is a traditional and simple method.
- It has a problem of an overdesign. It is widely used for products that require high reliability and safety.



(a) Safe-life (b) Fail-safe (c) Damage Tolerance

Fig.4.3 Concept of fatigue design

4.4.3 Safe-Life Design

- Turbine of power plant, Wing of airplane, etc.
- Calculate cyclic maximum stress
- Design the strength of a product. The strength should be larger than fatigue life of a proper life cycle.
- Crack initiation is more considered.

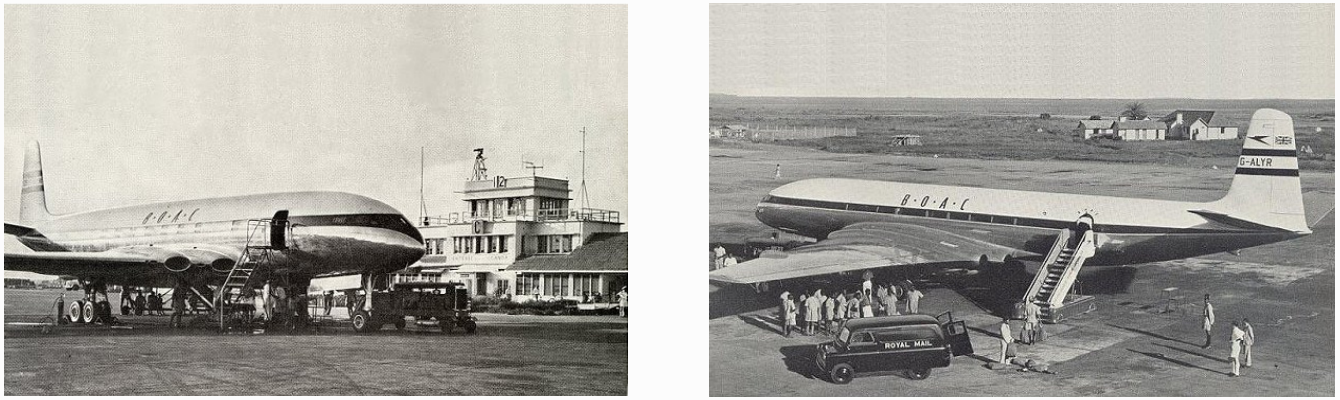


Fig.4.4 Commercial airplane applied safe-life design concept (1952, DeHavilland Comet, first commercial airliner)

4.4.4 Fail-safe Design

- A method that a structure is designed not to fail before the detected failure is fixed.
- This method comes from the fatigue design of airplane.
- A method having multiple load paths, a method having many redundancy, a method having crack stopper or crack arrester.
- Periodic examination is required to detect initial failure.

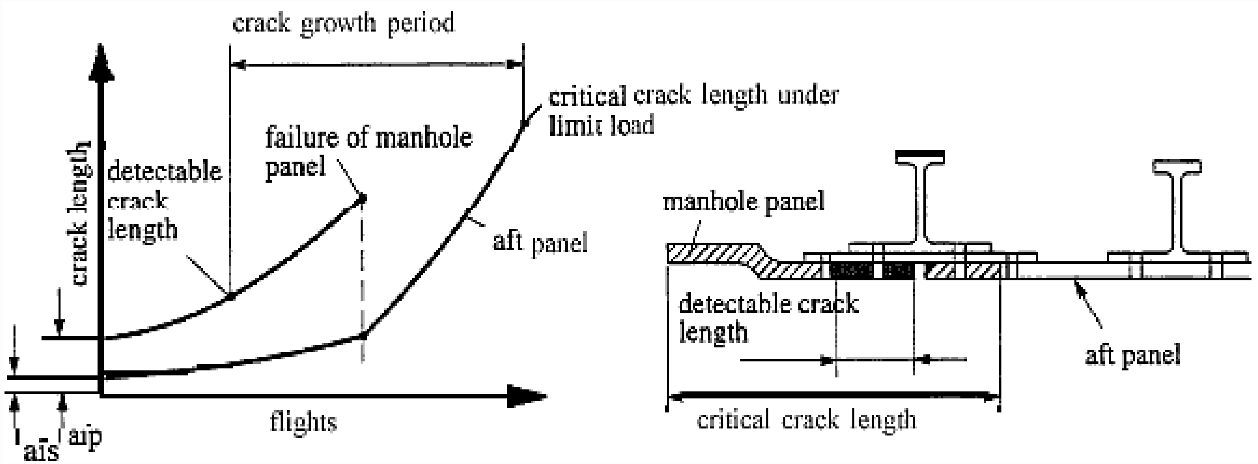


Fig.4.5 Fail-safe design concept (multiple-load path, inspectable for less than one complete load path failure)

4.4 Fatigue Design

4.4.5 Damage-tolerant Design

- This method assumes that a crack pre-exists in a structure.
- A structure is designed not to fail in a periodic maintenance period although the structure has a initial crack.
- Considerations: Initial crack length, crack propagation speed, maintenance period, fracture toughness etc.
- A material having slow crack growth and high fracture toughness is proper.

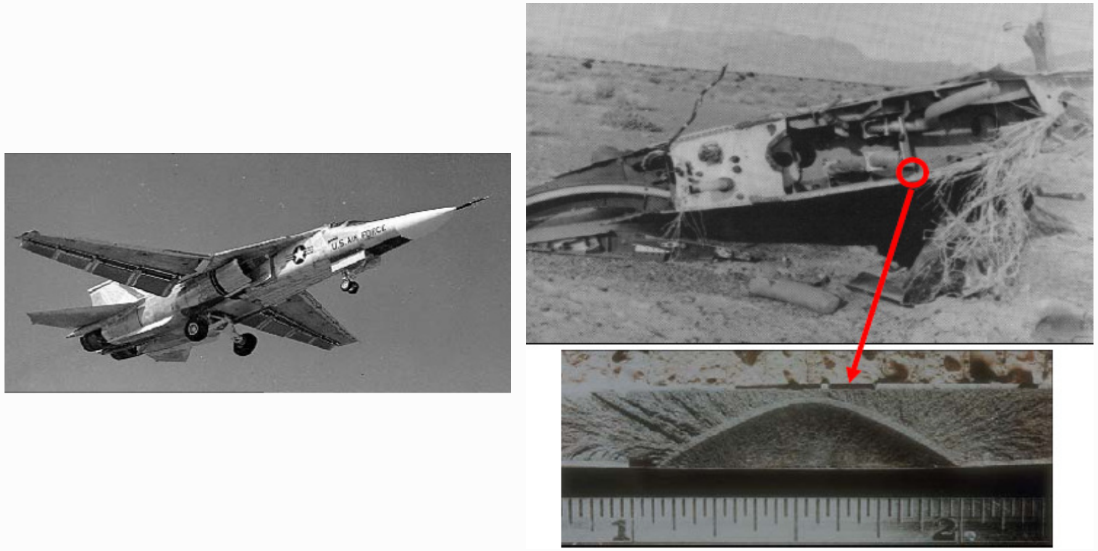


Fig.4.6 F-111 crash(1969.12.12, before applying damage-tolerant design, 100 flight hours)

Fig.4.7 B-1 First airplane applied damage-tolerant design concept