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Fatigue Strength and Analysis

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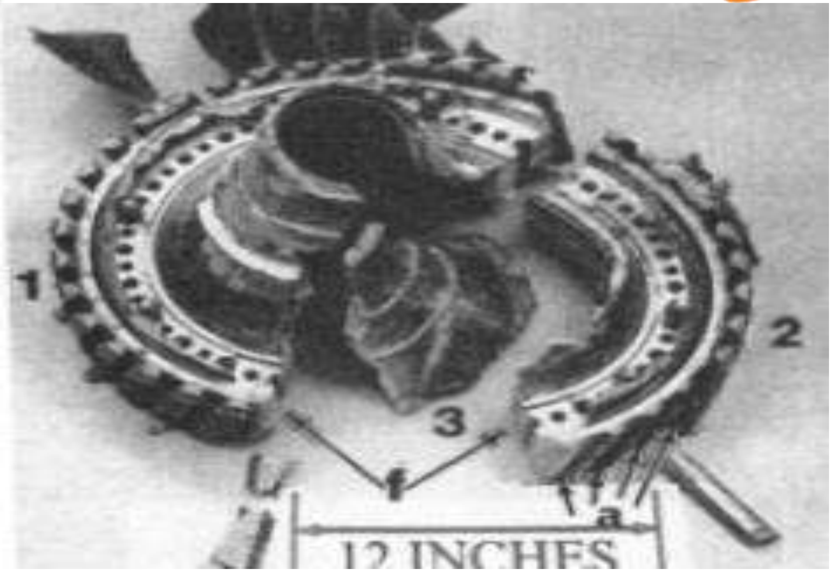
Fatigue Fracture

Definition of Terms

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 mechanical load."



Failure

- Failure means that a machine fails to perform.
- The term of failure is widely used in reliability engineering. It may happen even without destruction.

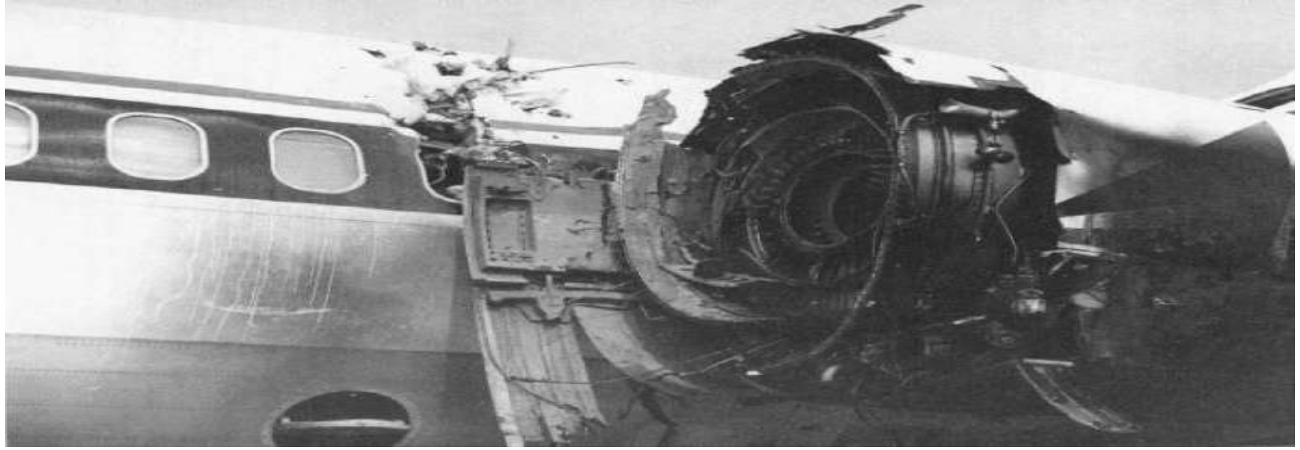


Fig.1.1 Damaged Airplane(left) and fractured fan hub(right)

Classification of Fracture Types

Brittle fracture

- No apparent plastic deformation takes place before fracture, but once fractured, the crack propagates rapidly.
- Once fractured, the destruction continues to proceed after force removal.

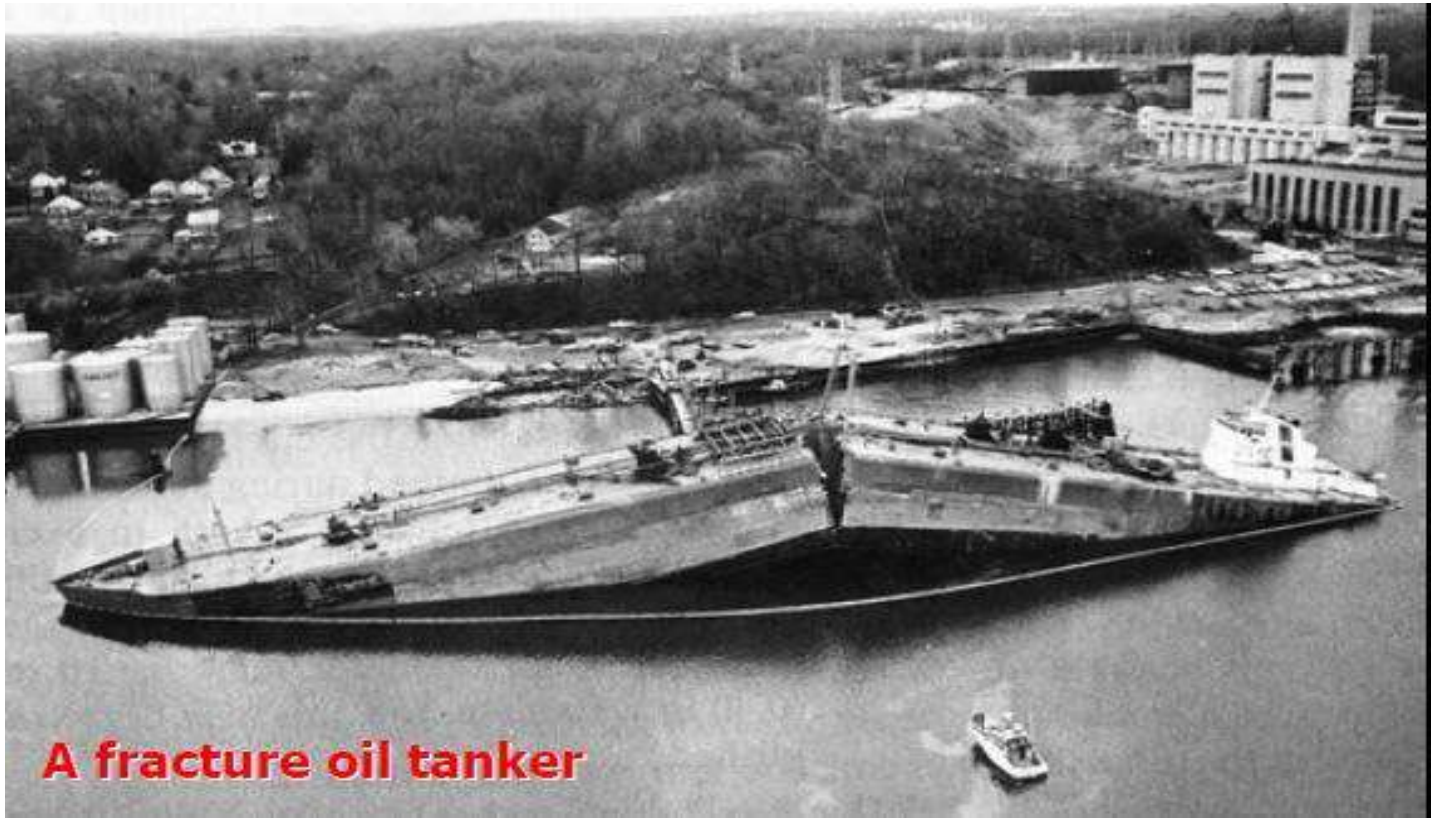
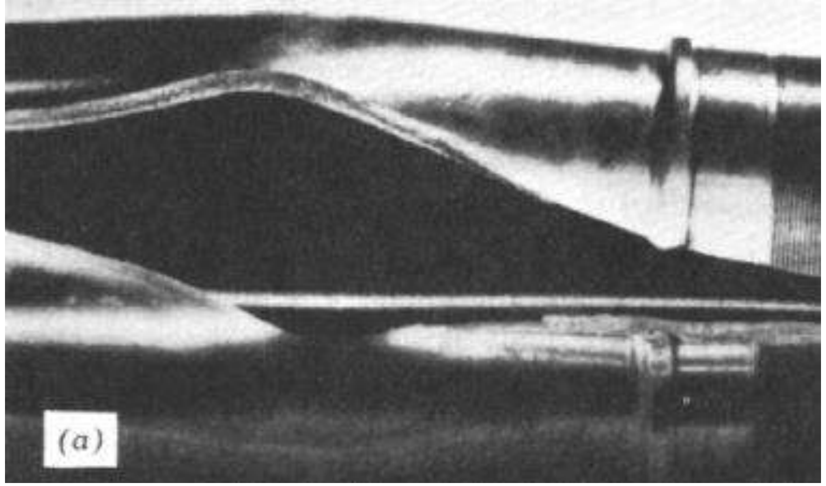


Fig.1.2 An oil tanker that fractured in a brittle manner

Classification of Fracture Types

Ductile Fracture

- Extensive plastic deformation takes place before fracture.
- Relatively slow and stable crack propagation
- Crack propagation is stable in that cracks are in equilibrium at each point, so crack propagation stops when a load is removed, and an extra load must be applied for further crack propagation.



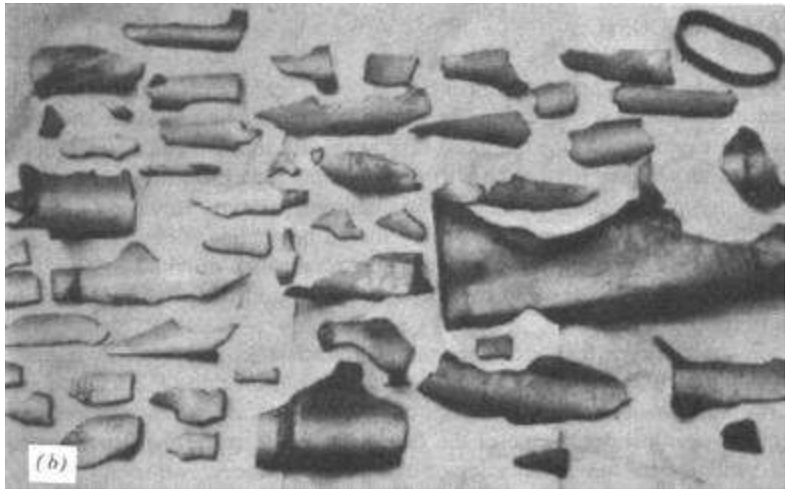


Fig.1.3 A pipe ductile fracture
(left, one piece large deformation)

brittle fracture(right, many pieces small deformation)

Classification of Fracture Types

Fatigue fracture

- General definition: “A destruction as a result of repeated loading and unloading”
- Definition in ASTM(American Society for Testing and Material):

“it is a process of progressively 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)

Classification of Fracture Types

Creep fracture

- Time dependent deformation even with a constant load at over a certain temperature.
- Creep deformation accelerates at some point, resulting in a rupture.

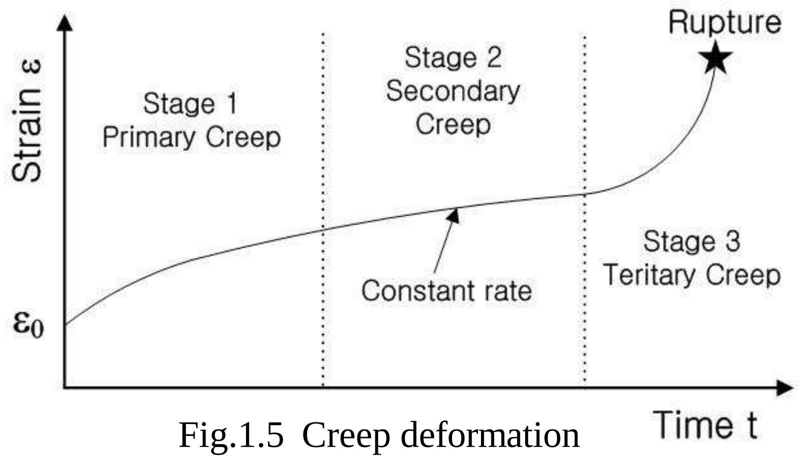


Fig.1.5 Creep deformation

Delayed fracture and environment assisted fracture

- Even though a static tensile stress is much lower than the yield stress, the material behaves more brittle and thus suddenly ruptures without apparent plastic deformation.
- Environment assisted fracture is also called as environment sensitive fracture.

Fracture Type and Material Strength

Strength of materials

- Strength of the material is considered in two cases: with and without flaws (or cracks), and basic strength is normally without flaws.

Fatigue strength

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

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 loads at high temperatures (e.g., thermal stress).
- - Stress corrosion cracking, hydrogen embrittlement cracking → environmental strength

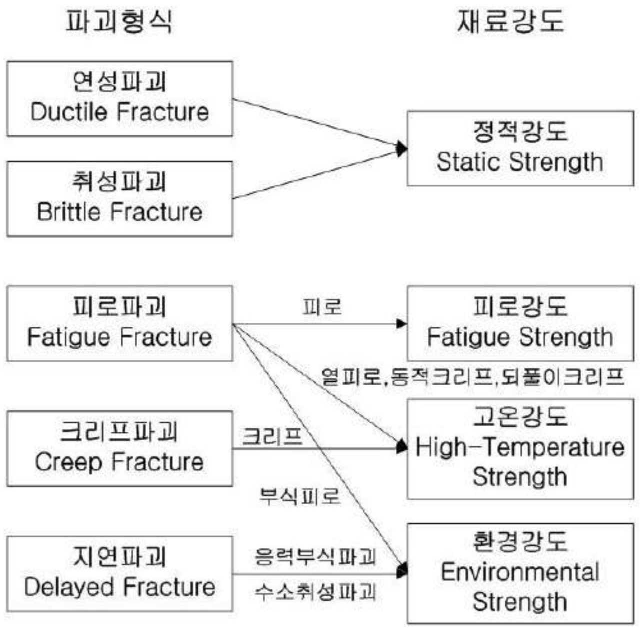


Fig.1.6 Fracture and material strength

Characteristics of Fatigue Fracture

Cyclic loading

- Fatigue occurs as a result of repeated loading and unloading.
- All the machines and structures get cyclic loading in nature, so most of fractures result from fatigue

Lower yield stress or the proportional limit

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

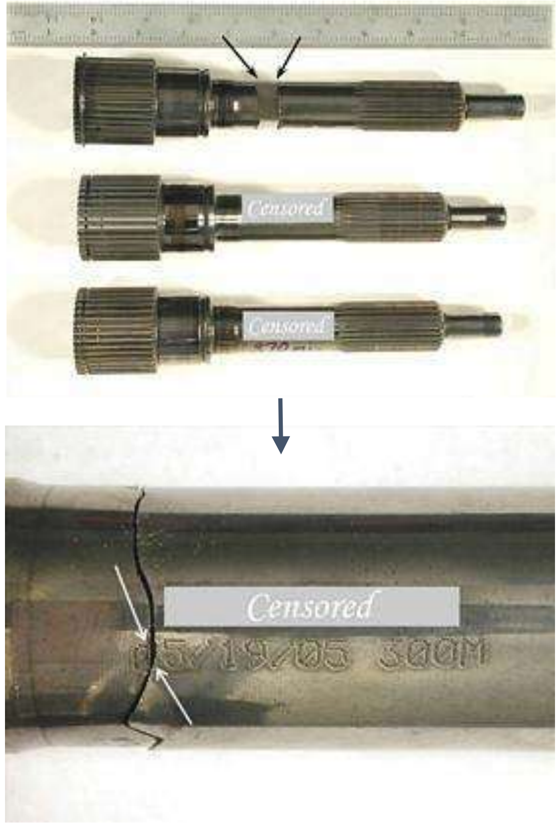
Fatigue limit or endurance limit

- 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.

Characteristics of Fatigue Fracture

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.



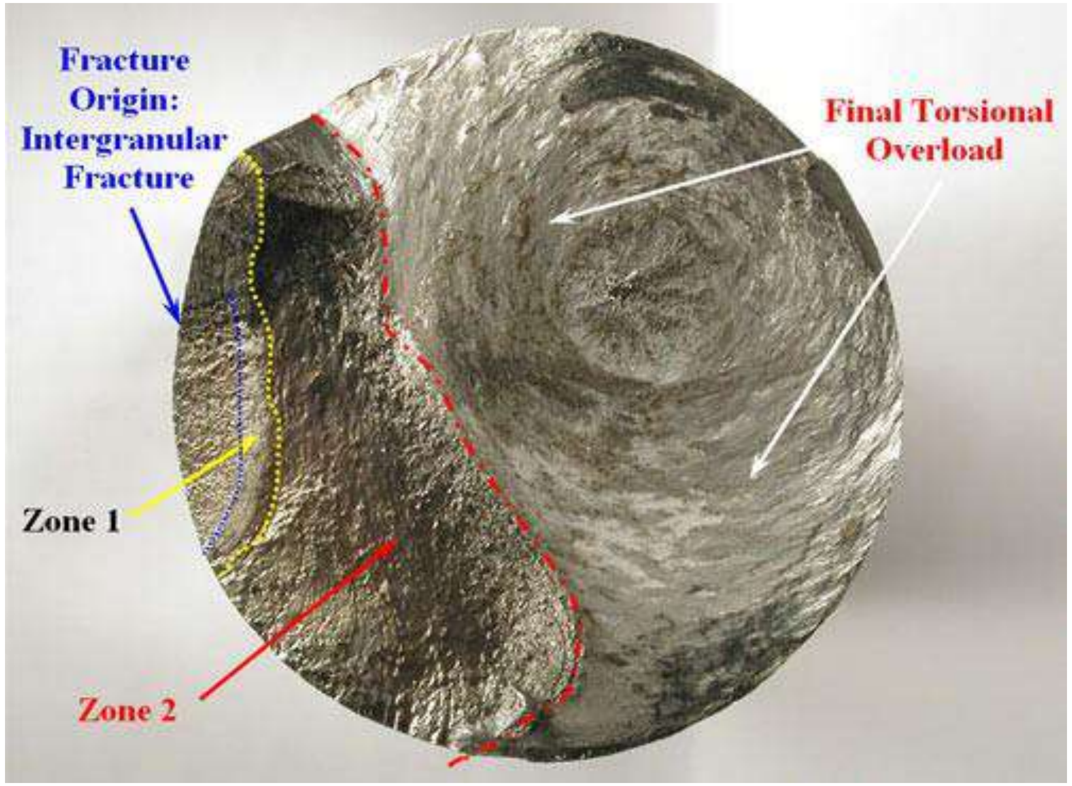


Fig.1.7 Example of fatigue failure (right : Enlargement of the region indicated by white arrow in left-below figure)

Example of Fatigue Failure Accident

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 occurred at the corner of automatic direction finding (ADF) window in the upper part of fuselage
  - Casualties : 29 passengers and 6 crews died.
  - After the experimental study to find failure cause, full scale fatigue testing and low-cycle fatigue testing have become crucial.

Fig.1.8 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.

Example of Fatigue Failure Accident

Crash of American Airlines DC10 (1979. 05. 25.)

– Accident cause : Left engines dropped off from the wing during taking off. Because of asymmetry, the plane crashed. This is entirely due to errors in maintenance and, as a result, the FAA (Federal Aviation Administration, U.S.) failed to identify standard maintenance procedures.

– Casualties : 272 people died.

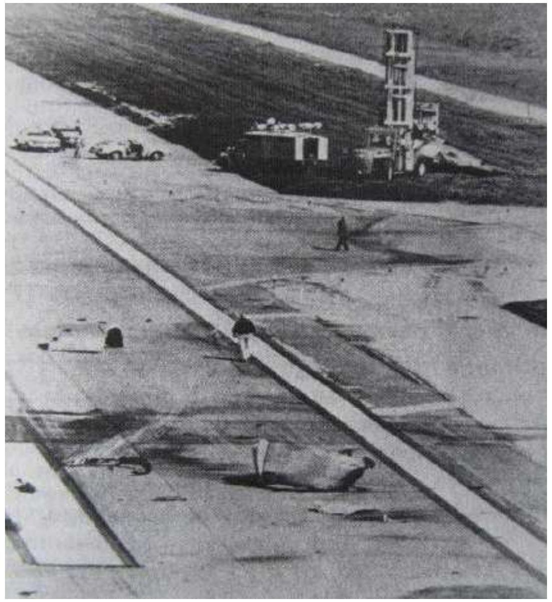


Fig.1.9 Flight 191 in an unrecoverable bank moments before the crash. Its No. 1 engine had been severed on the runway

Example of Fatigue Failure Accident

- Crash of drilling vessel Alexander L Kielland at the north sea oil field (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.

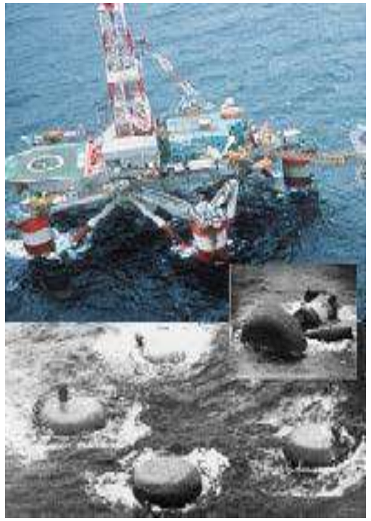


Fig.1.10 Alexander L Kielland accident

Example of Fatigue Failure Accident

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.1.11 ICE-1 accident

Example of Fatigue Failure Accident

Seongsu Bridge collapse(1994. 10. 21)

- Seongsu bridge links the Seongsudong 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.1.12 Collapses of the Sung Soo Bridge

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Fatigue Load Form

Fatigue Load

- Unlike other failures, fatigue fracture fails structural systems with damage accumulation as a result of repeating loading and unloading, this cyclic loading is called fatigue loading.

Fatigue Load form

1. Arbitrary fatigue loading

- Fatigue load fluctuates randomly in terms of cycles, amplitudes, and frequency, so-called random loading. Random loading is defined as irregularly fluctuating loading namely irregular loading.

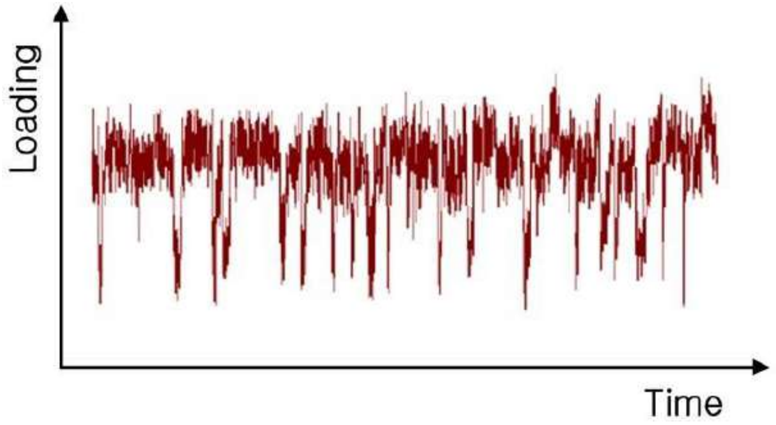

Fig.2.1 Actual fatigue loading (random loading, irregular loading)

Fatigue Load Form

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.

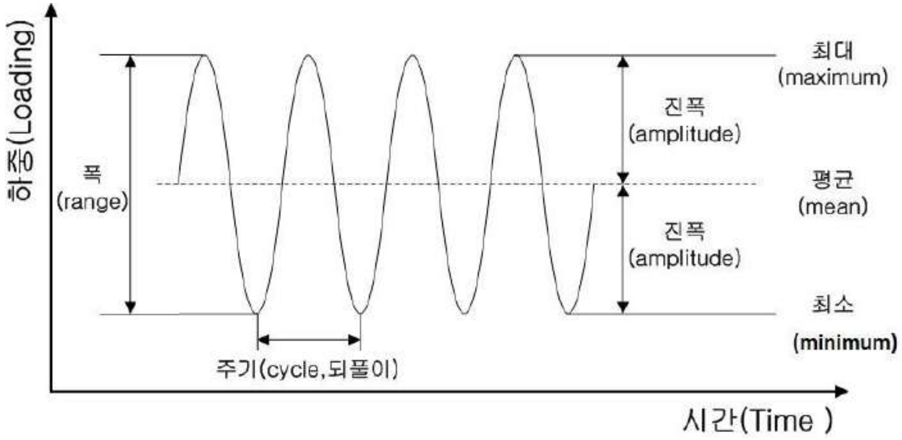

Fig.2.2 Constant amplitude loading

Fatigue Load Form

- Load ratio or stress ratio R

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

- Amplitude ratio A

$$A = \frac{load\ amplitude}{average\ load} = \frac{P_a}{P_{\mathrm{m}}} = \frac{\sigma_a}{\sigma_{\mathrm{m}}}$$

- Various constant amplitude loading

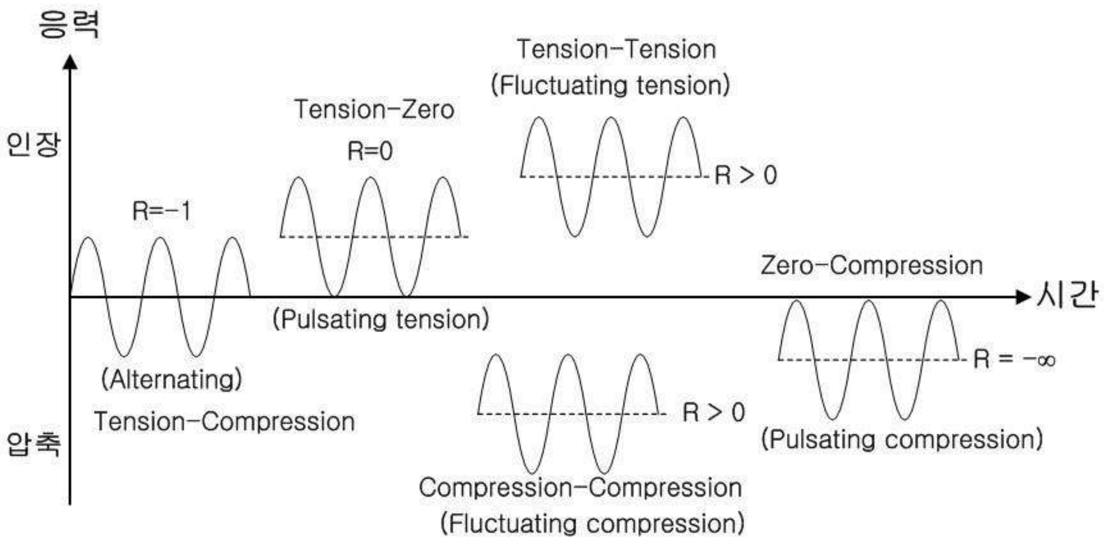

Fig.2.3 Various constant amplitude loading

Fatigue Load Form

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.

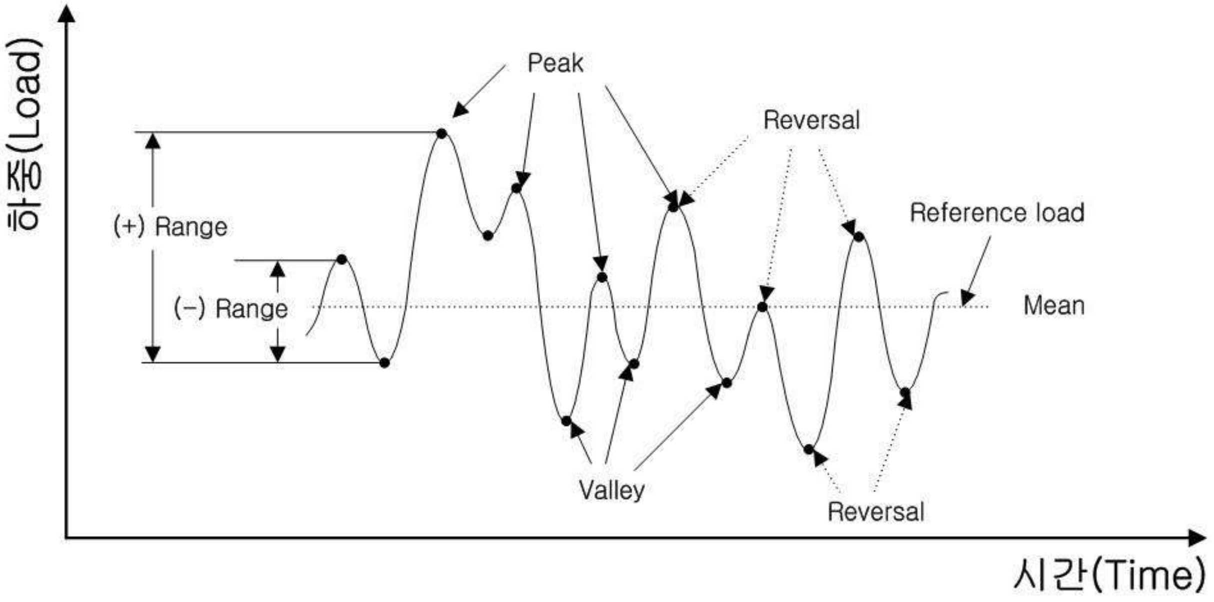

Fig.2.4 Variable loading

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Macroscopic Features

Three regions of macroscopic fatigue fracture surface

1. **The first region**

– The region having beach marks (or clamshell marks), where 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.

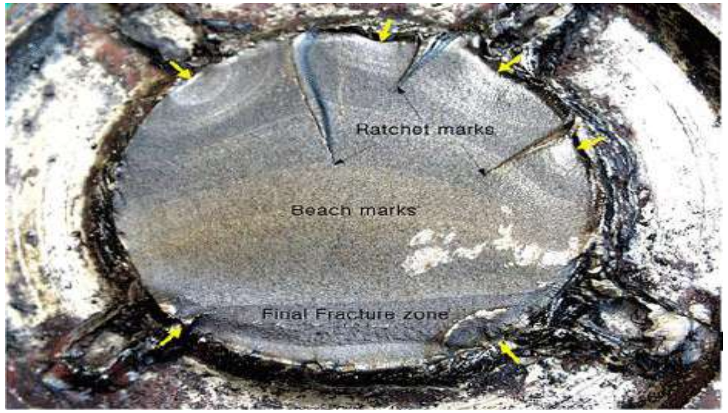


Fig.3.1 Fatigue Surface of Charge Roller

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.

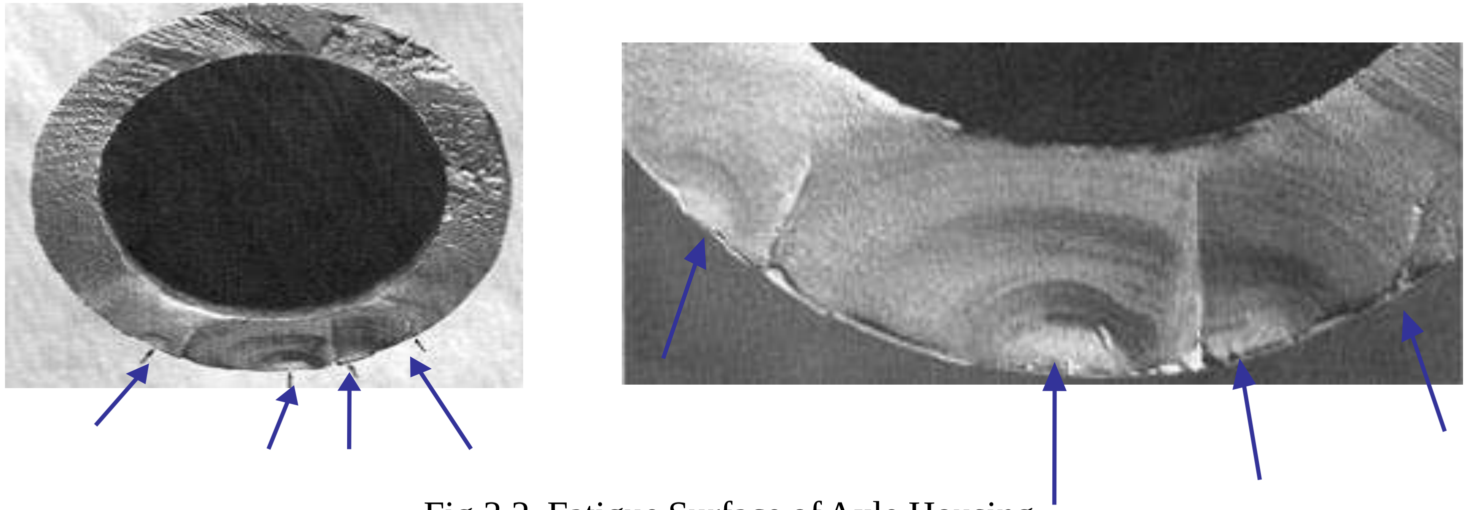


Fig.3.2 Fatigue Surface of Axle Housing

Macroscopic Features

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 1st region is darker than that of the 2nd region. It is because the 1st region exposes to the air longer than the 2nd region.

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.

Macroscopic Features

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.

Macroscopic Features

Macroscopic features according to the applied load and notch

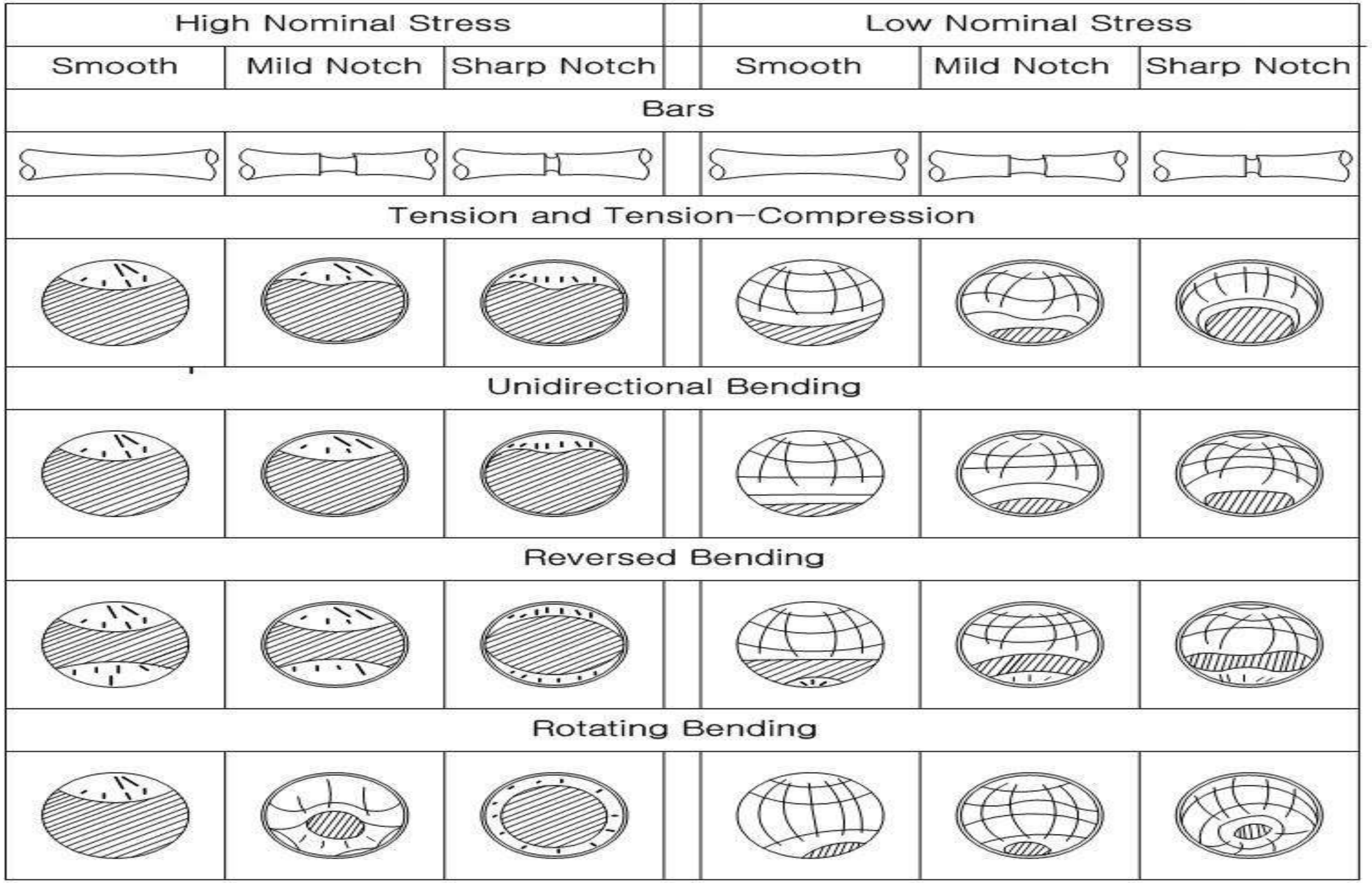


Fig.3.3 Various affecting factors and macroscopic aspects of fatigue surface

Macroscopic Features

Fracture by torsional load (with notch)

- If cracks occurs and propagates due to large shear stress, there is no clear feature (e.g. 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.

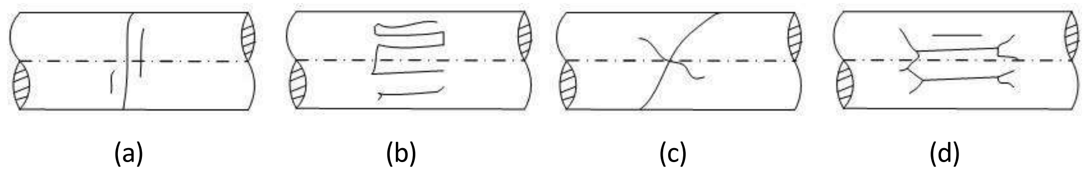


Fig.3.4 Crack configuration of material without notch under torsion

Macroscopic Features

Fracture by torsional load (with notch)

- If there is notch, relatively large stress occurs at the notch, and cracks grow along 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.

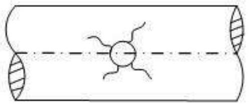
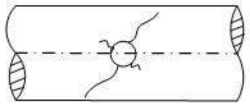
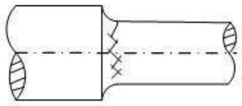
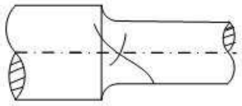
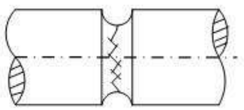
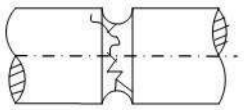
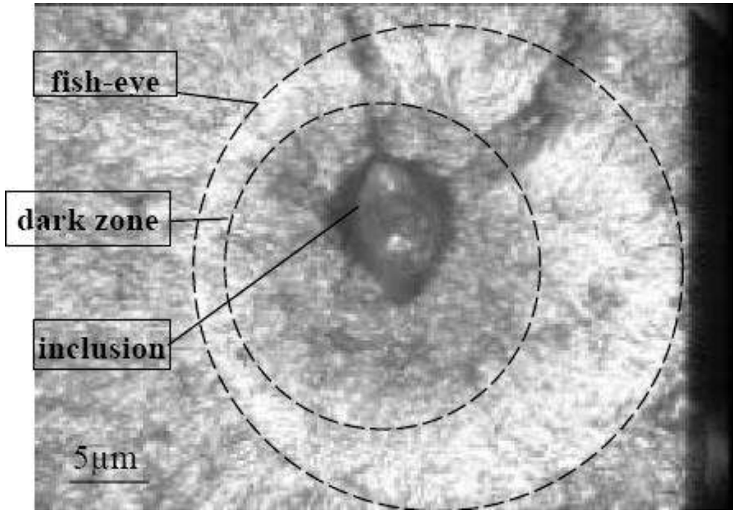
	High loading	Low loading
Circular notch		
Stepped notch		
Circum-ferential notch		

Fig.3.5 Crack configuration of material with notch under torsion

Macroscopic Features

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.



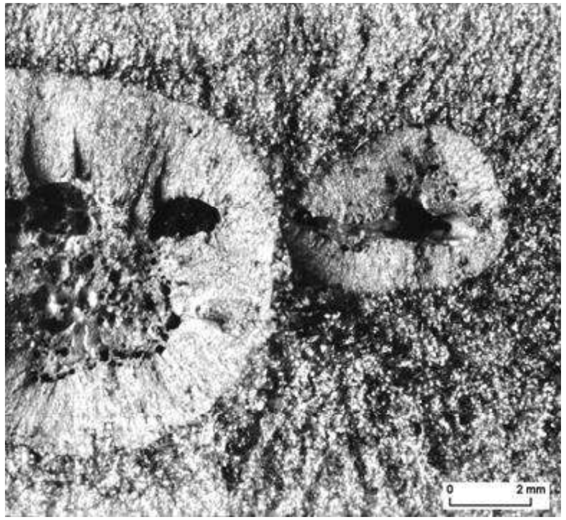


Fig.3.6 Fish eye

Microscopic Features

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 (growth 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.

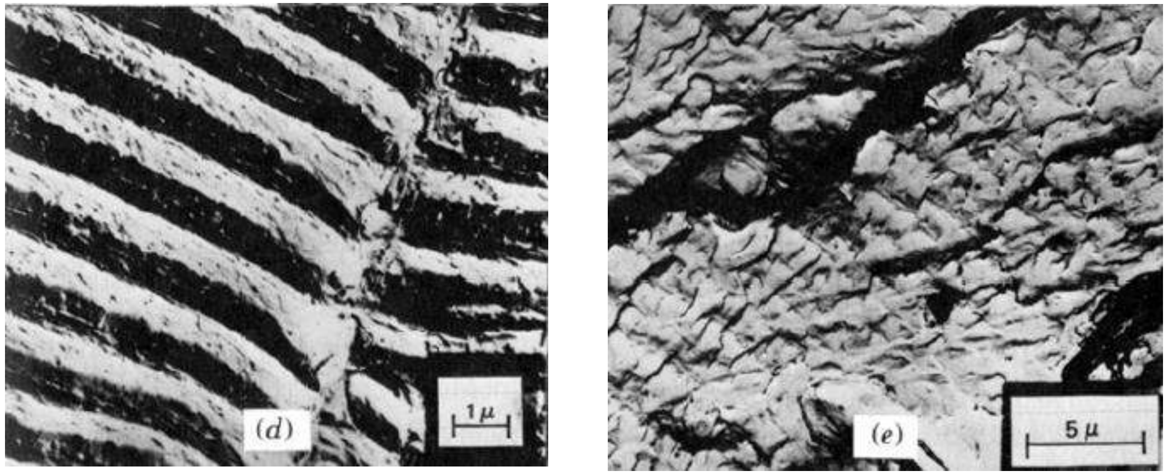


Fig.3.7 Striation (ductile, brittle)

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 the surface of maximum tensile stress.

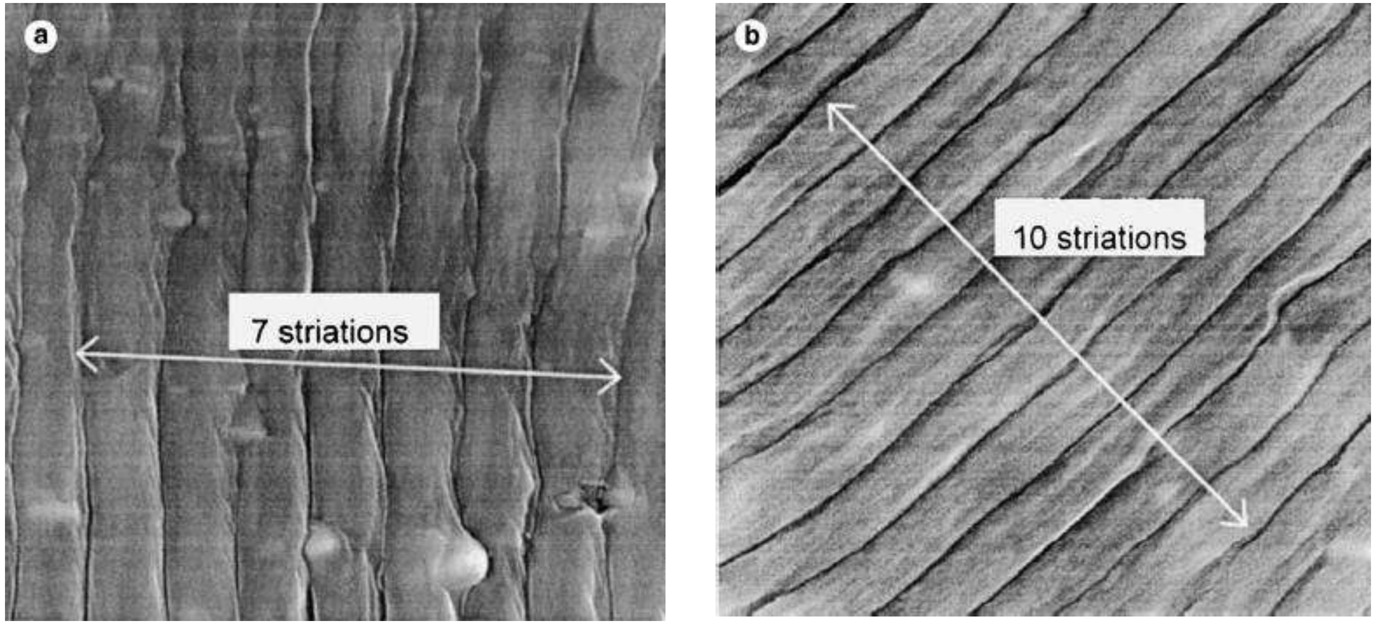


Fig.3.8 Ductile Striation, Aluminum 2024-T3

Microscopic Features

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.]

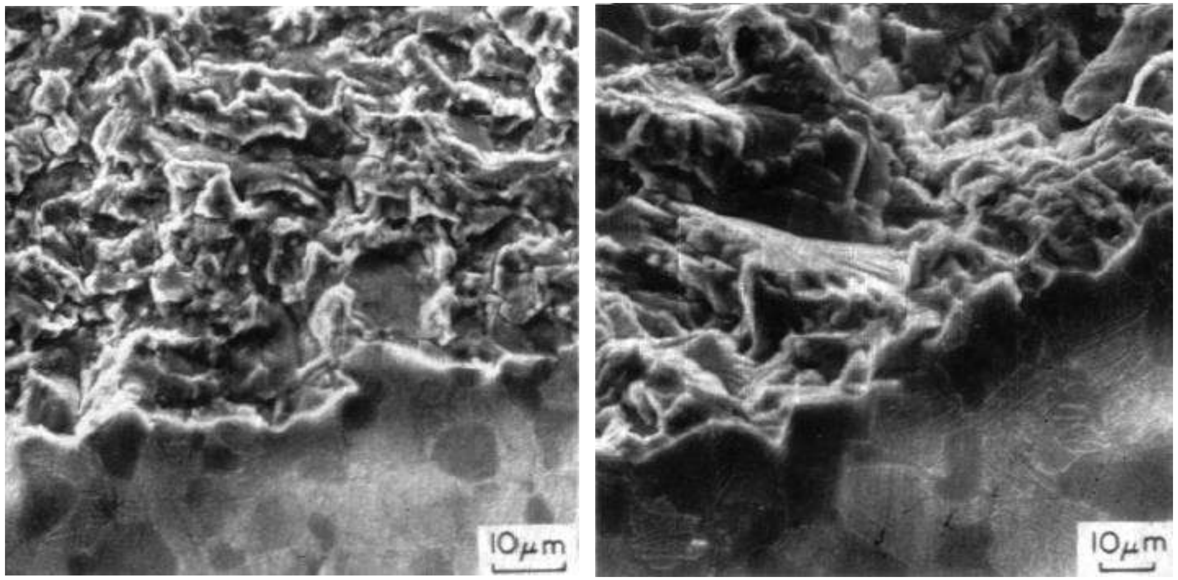


Fig.3.9 Plateau, Ti-6, Al-4 V

Brittle striation

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

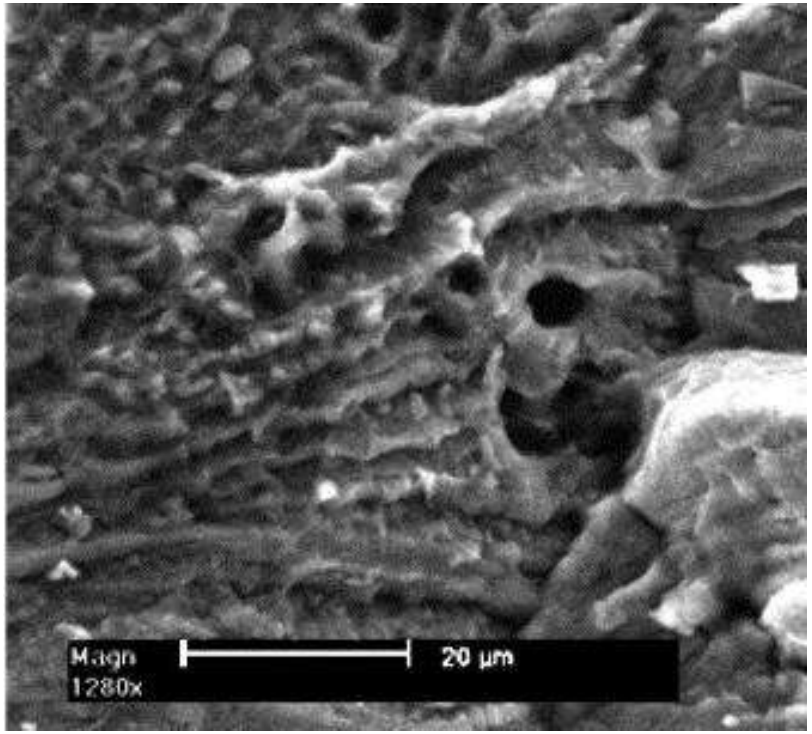


Fig.3.10 Brittle Striation, Aluminum 7075-T6

4 Fatigue Life Regime & Fatigue Design

Fatigue Life

Fatigue life

- Fatigue life is the number of stress cycles that a specimen sustains before it fails. It has two characteristic periods: crack initiation and propagation. 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 shown below .
- S-N diagram depends on applied loading and life regime (low cycle fatigue and high cycle fatigue).

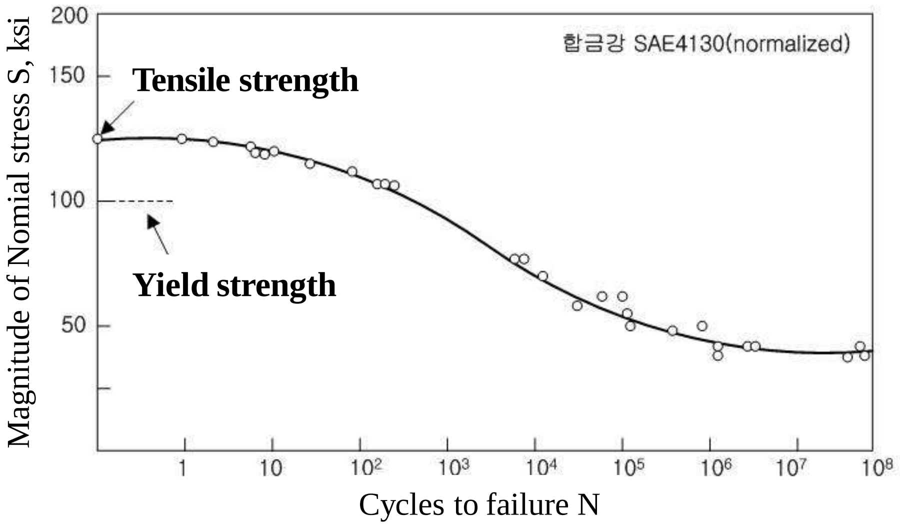
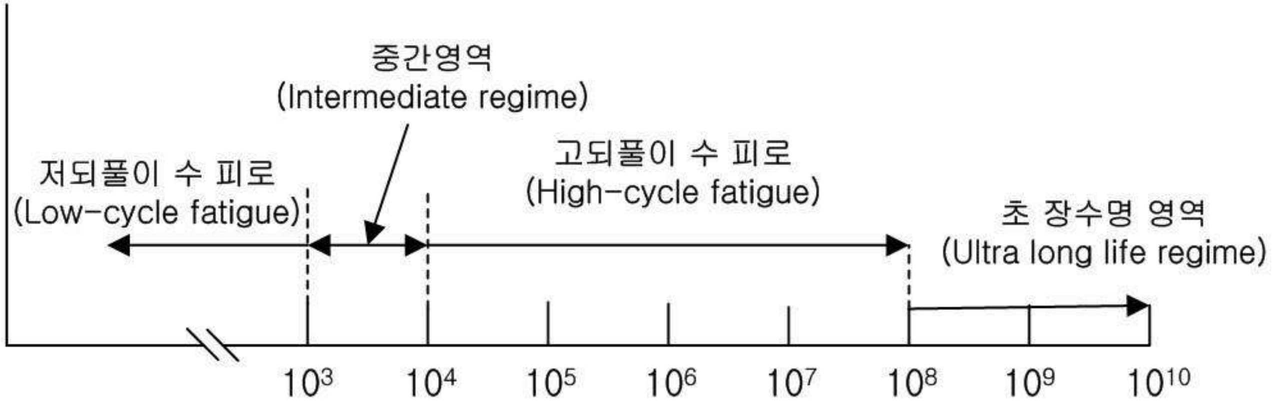


Fig.4.1 S-N diagram, SAE4130

Classification of Fatigue Life Regime

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



Fatigue Life, N

Fig.4.2 Fatigue Life regime

Characteristic of Fatigue Life Regime

1. Low-cycle fatigue (or Plastic fatigue)

- Where the stress is high enough to generate plastic deformation, the stress is of no concern but the strain describes the failure better.
- In the low-cycle fatigue test, it is ideal to control the amplitude of a plastic strain. Practically, a total strain can be 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.

Characteristic of Fatigue Life Regime

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.

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.

Fatigue Design

1. Concept of fatigue design

(1) Infinite life design

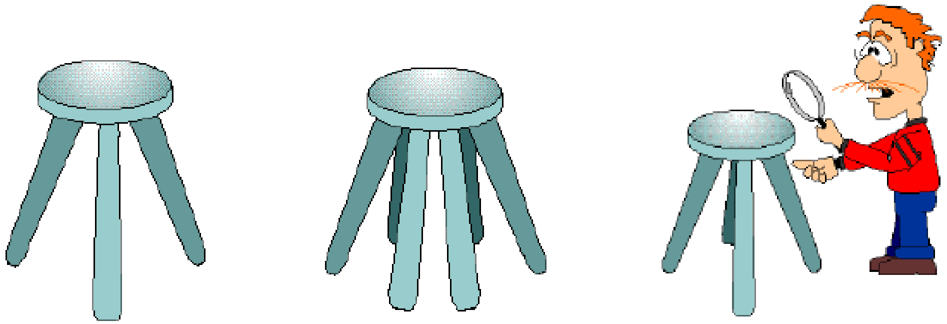
(2) Safe-life design

(3) Fail-safe design

(4) Damage-tolerant design

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

Fatigue Design

3. Safe-life design

- Turbine of power plant, wing of airplane, etc.
- Calculate cyclic maximum stress
- Design the strength of a product that should ensure a designed life for a given load cycle.
- Crack initiation is more considered.

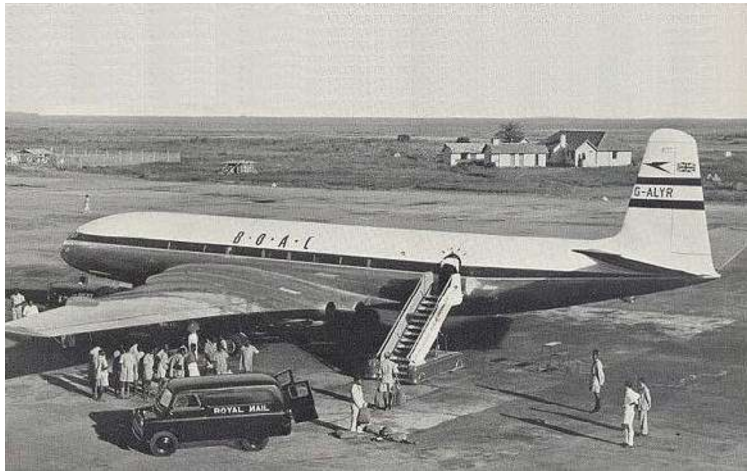


Fig.4.4 Commercial airplane applied safe-life design concept

(1952, DeHavilland Comet, first commercial airliner)

4. Fail-safe design

- A method that a structure is designed not to fail before the detected failure is repaired.
- This method comes from the fatigue design of airplane.
- A method having multiple load paths (intentional weak link), a method having many redundancy (redundancies), a method having crack stopper or crack arrester (early detection).
- Periodic examination is required to detect initial failure.

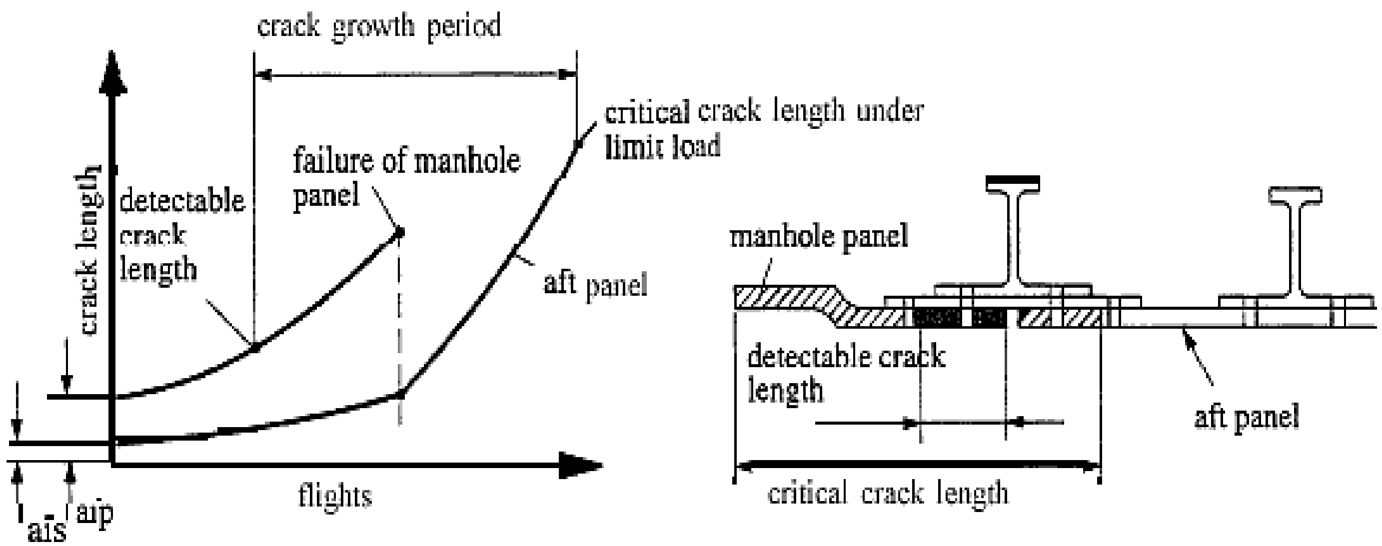


Fig.4.5 Fail-safe design concept (multiple-load path, inspectable for less than one complete load path failure)

Fatigue Design

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 an 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.

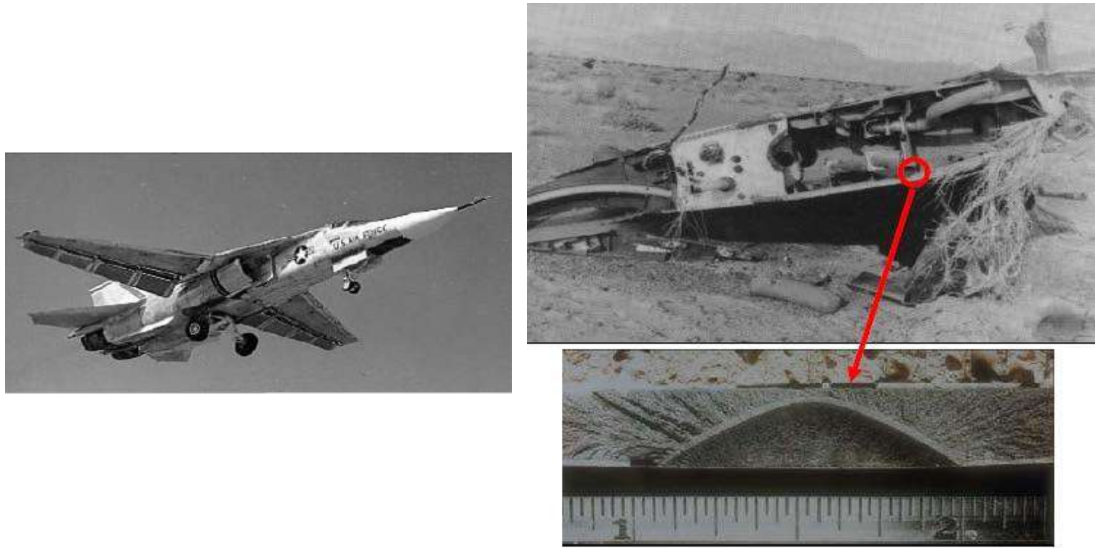


Fig.4.6 F-111 crash(1969.12.12, before applying damage-tolerant design, 100 flight hours)

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

THANK YOU
FOR LISTENING