Aalto University
School of Engineering

MEC-E8006 Fatigue of Structures

Lecture 1: Fatigue phenomena

Learning outcomes

After the lecture, you

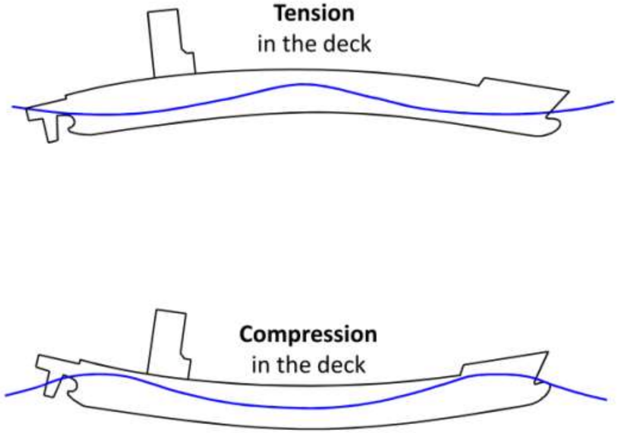
- *understand* fatigue phenomena
- *understand* the fatigue process and microstructure effect
- *know* fractography and analysis of fracture surfaces

Contents of Lecture

- **Importance of fatigue design**
- **Brief history of fatigue research**
- **Fatigue definition**
- **Fatigue damage process**
- **Fractography and fracture surface analysis**

Importance of fatigue design

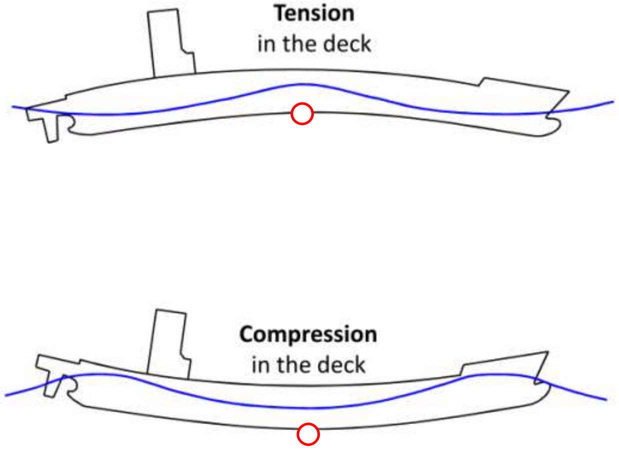
- **Many structures and vehicles are affected by time varying loading**
  - For instance, a ship has about 10^8 load cycles during its lifetime

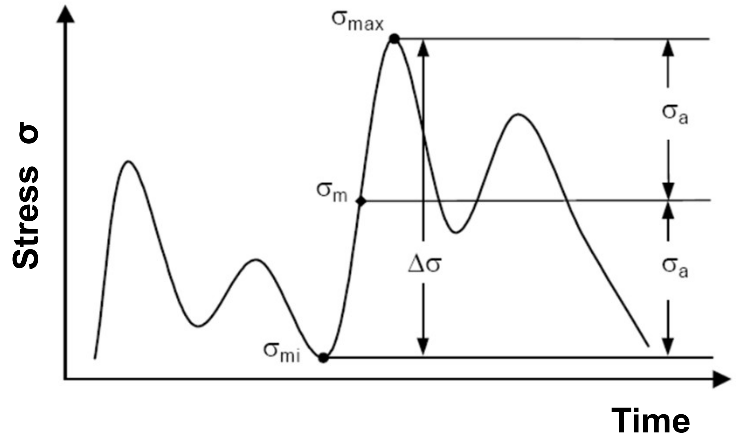


A 300 m long 4500TEU Container vessel

Importance of fatigue design

- **Many structures and vehicles are affected by time varying loading**
  - For instance, a ship has about 10^8 load cycles during its lifetime





Stress range

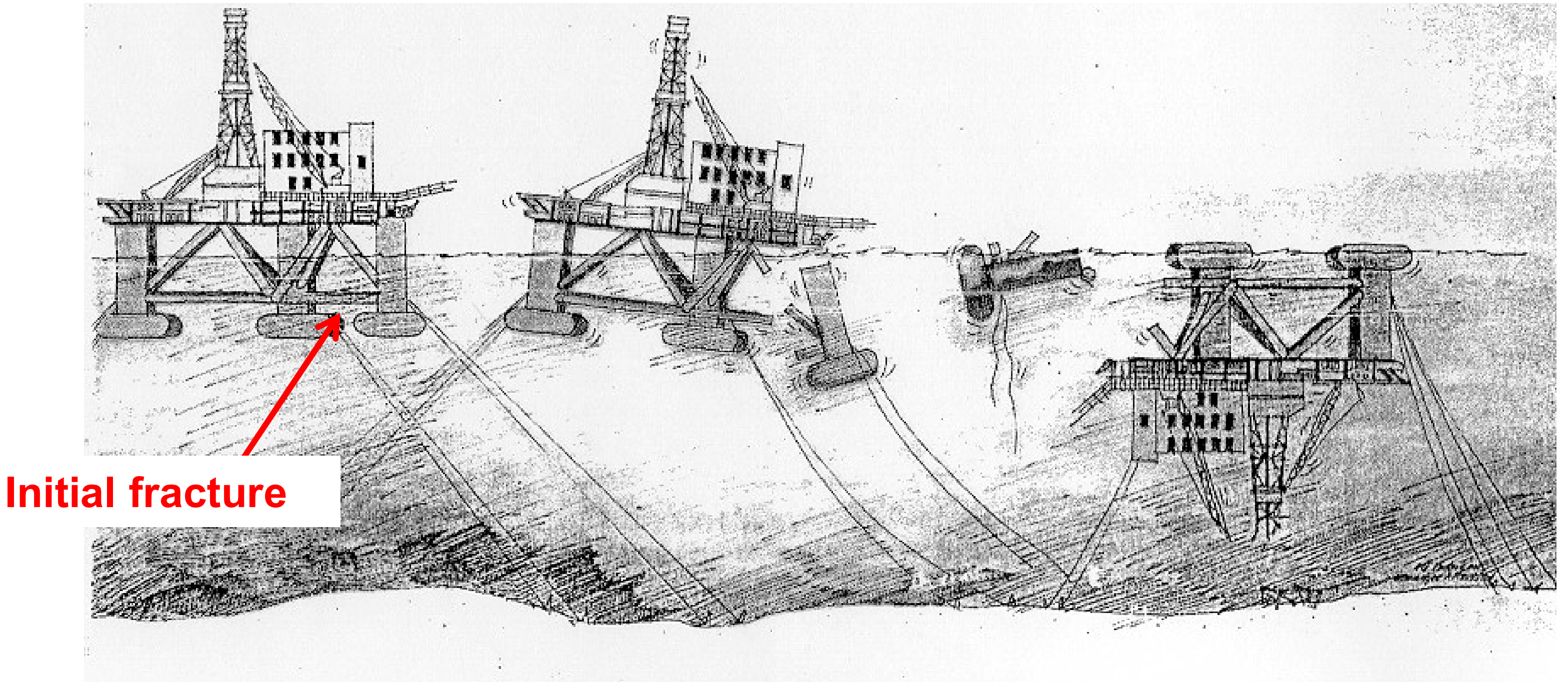
$$\Delta\sigma = \sigma_{max} - \sigma_{min}$$

Mean stress

$$\sigma_m = (\sigma_{max} + \sigma_{min}) / 2$$

Importance of fatigue design

Failure of the Alexander L. Kielland platform, Norway, 1980

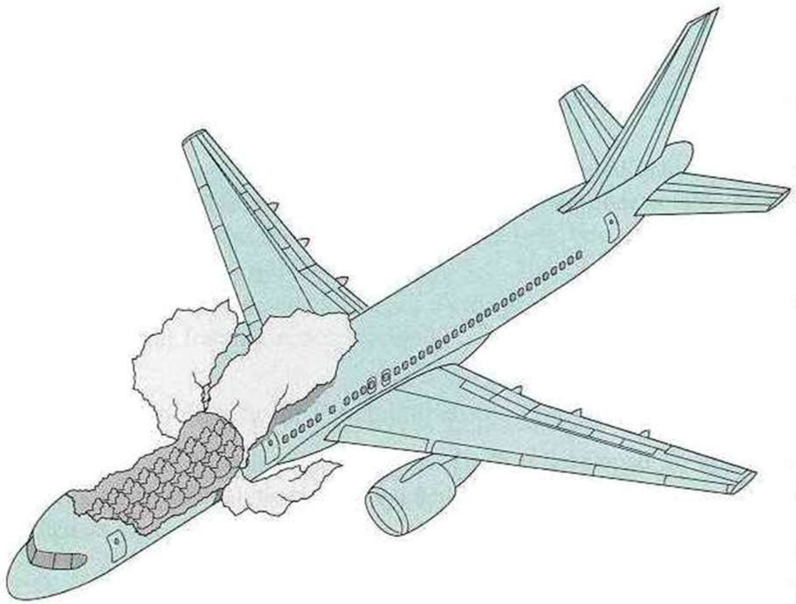


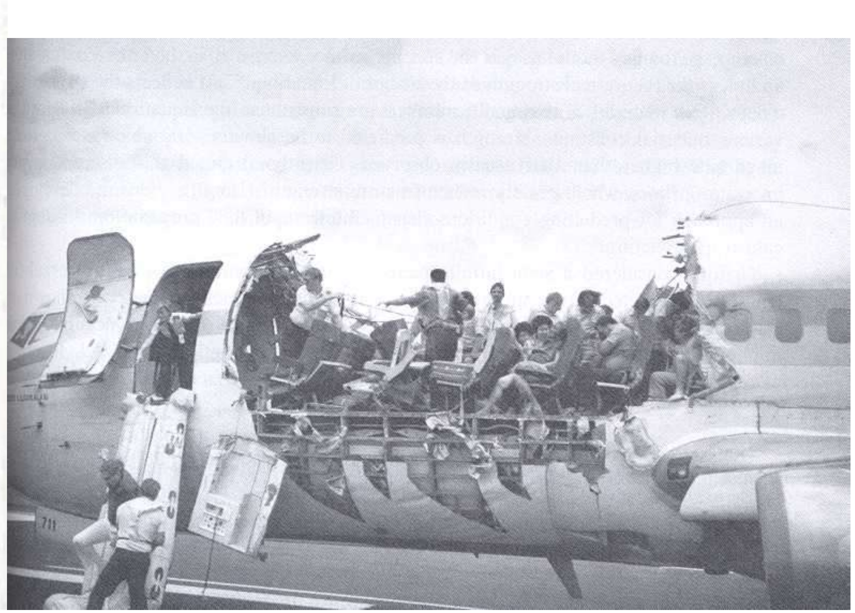
Importance of fatigue design

Failure of the Alexander L. Kielland platform, Norway, 1980

Importance of fatigue design

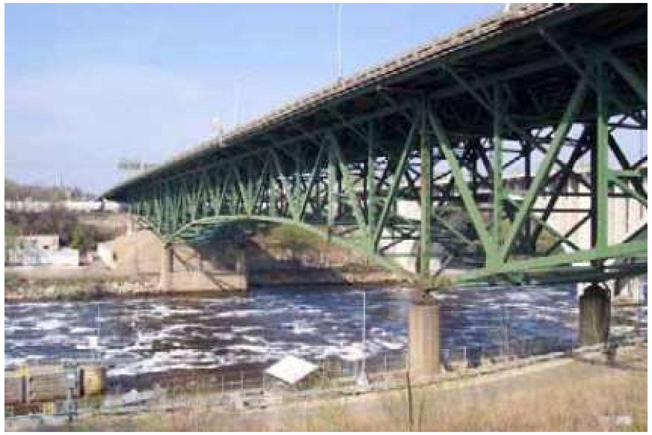
Aloha Airlines Flight 243, Hawaii 1988





Importance of fatigue design

Bridge 9430, USA, 2007

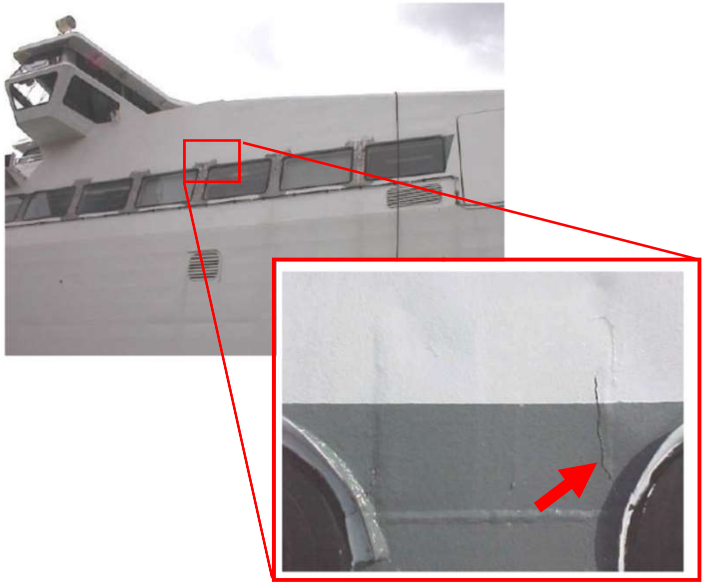


View 2001

I-35W Mississippi River bridge
August 1, 2007

Importance of fatigue design

- **The most fractures are due to fatigue**
  - Structural optimization aiming for a light and cost-efficient structure
  - Increasing demand for the utilization of new materials such as high strength steel
- **Fatigue design has special challenges**
  - Large and complex structure
  - For instance, ship hull includes thousands of cut steel parts and hundreds kilometers of weld seams

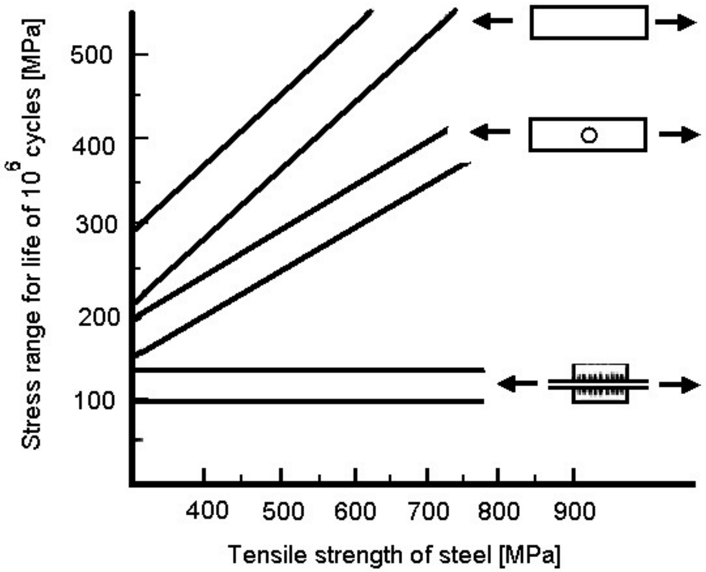


Importance of fatigue design

Many affecting factors

- **Load history**
  - Stress range, maximum stress, load frequency
- **Geometry effect**
  - Production technology
- **Material**
  - Steel, aluminum, etc.
- **Environment**
  - Corrosion, temperature, etc.

Typical Random Load Histories



Importance of fatigue design

Many affecting factors

"Internal" factors

(at the end of the manufacturing process)

- Material
- Dimension
- Surface finishing
- Shape
- Surface treatments

"External" factors

(due to operating conditions and environments)

- Average stress
- Loading type (e.g. tension VS bending)
- Temperature and environment
- Load history
- Load variations

Brief history of fatigue research

1828: Wilhelm Albert tested mine host under cyclic loading

1850s: August Wöhler systematic fatigue testing, begin of development of fatigue design

1900s: James Alfred Ewing revealed the origin of fatigue failure in microscopic cracks

1910: O. H. Basquin introduced a log-log relationship for S-N curves, based on Wöhler's tests

1945: A. M. Miner formulated Palmgren's (1924) linear damage hypothesis for fatigue design

1960s: L. F. Coffin and S. S. Manson found the relationship between plastic strain amplitude and fatigue life

1960s: P. C. Paris showed that fatigue crack growth can be described using fracture mechanics (stress intensity factor)

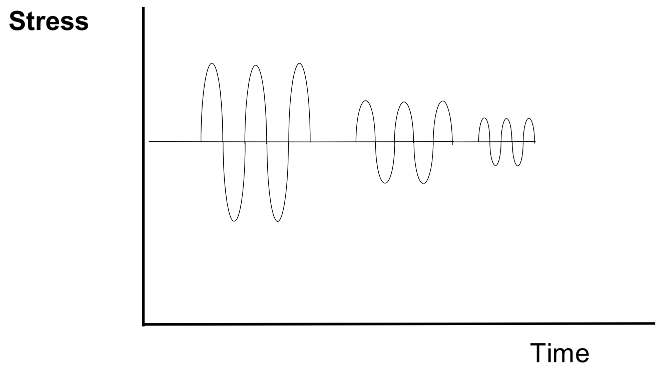
1968: T. Endo and M. Matsuishi created the rainflow-counting algorithm to characterize random loadings

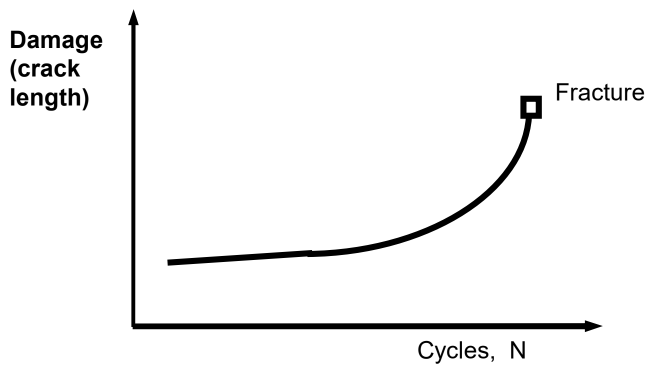
1970: W. Elber revealed the importance of crack closure on fatigue crack growth and introduced effective stress intensity concept

Fatigue definition

Fatigue - the 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 that may culminate in *cracks* or *complete fracture* after a sufficient number of fluctuations.

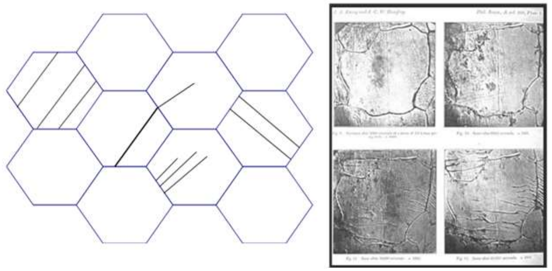
(Am. Soc. for Testing and Materials (ASTM) definition)



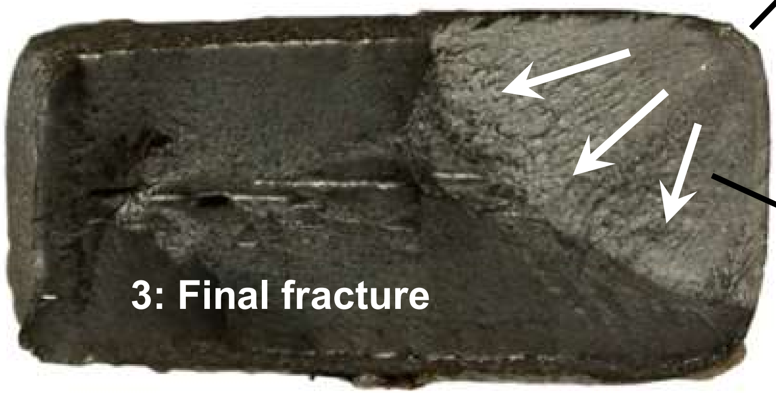


Fatigue process

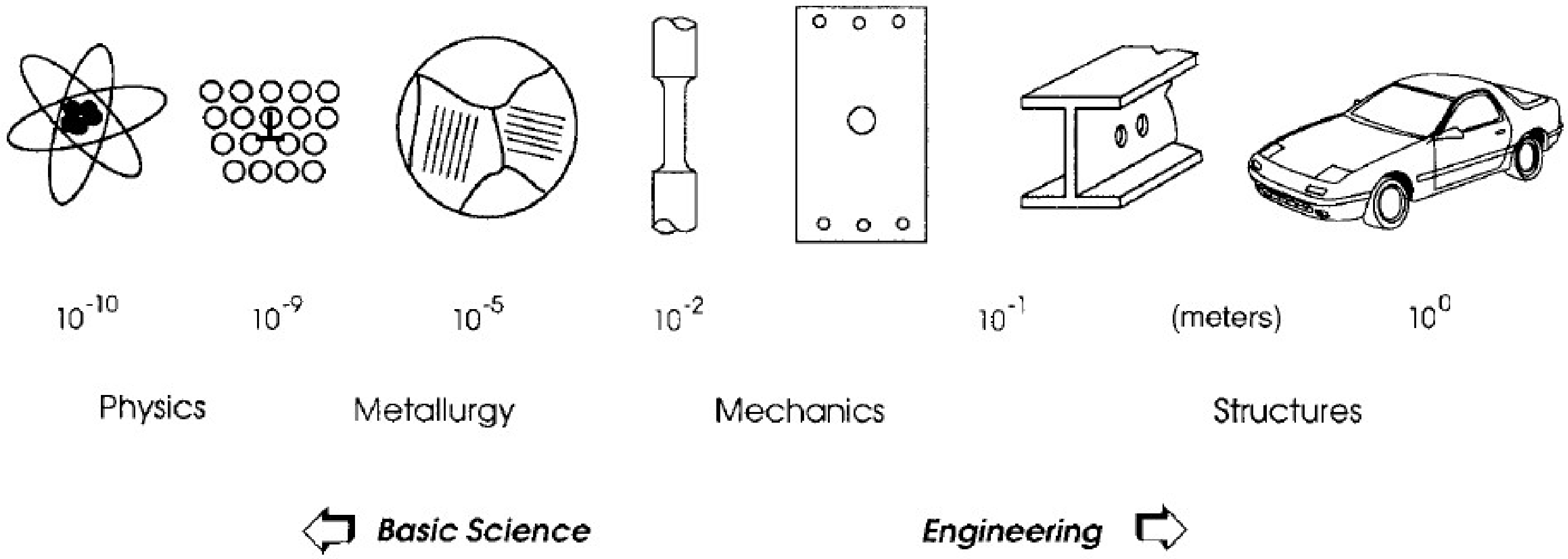
- **Fatigue crack initiates from the high stress location and propagates under cyclic loading until final fracture**



Fatigue crack nucleation in micro-scale



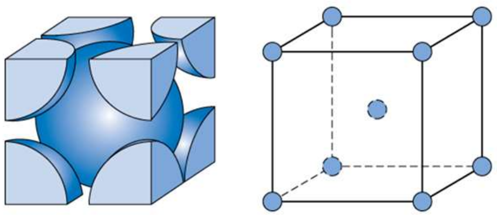
Size scales and disciplines in engineering material



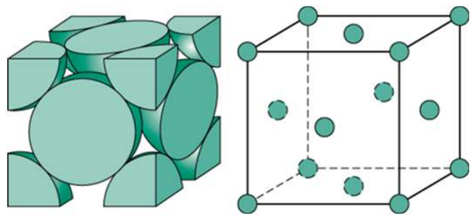
Fatigue of materials

Crystal structures of metals

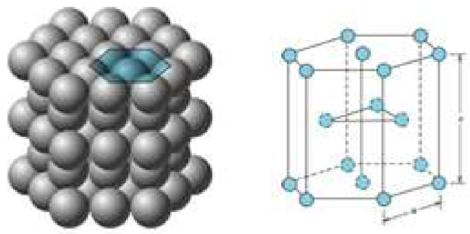
Material	Lattice	Emax[111] (GPa)	Emin[100] (GPa)
a-Fe	BCC	284.5	132.4
Al	FCC	75.5	62.8
Cu		190.3	66.7
Mg	HCP		
a-Ti			



BCC



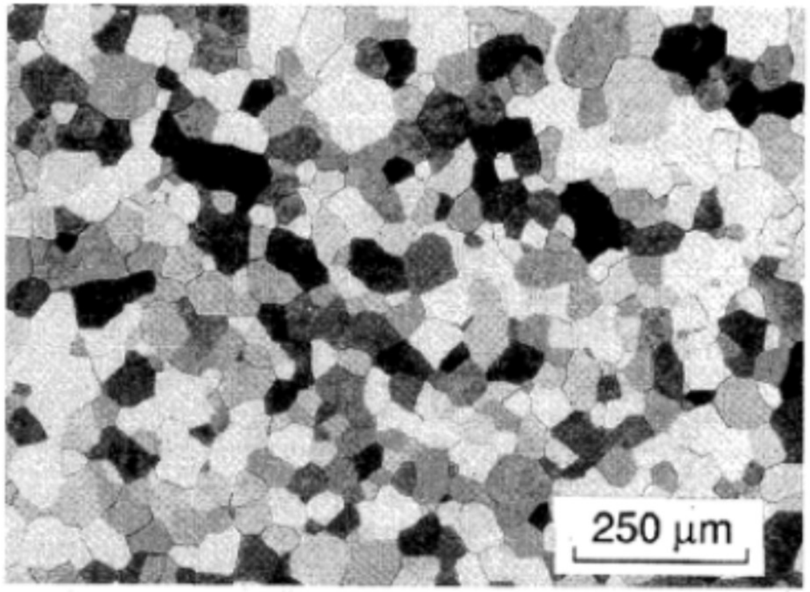
FCC

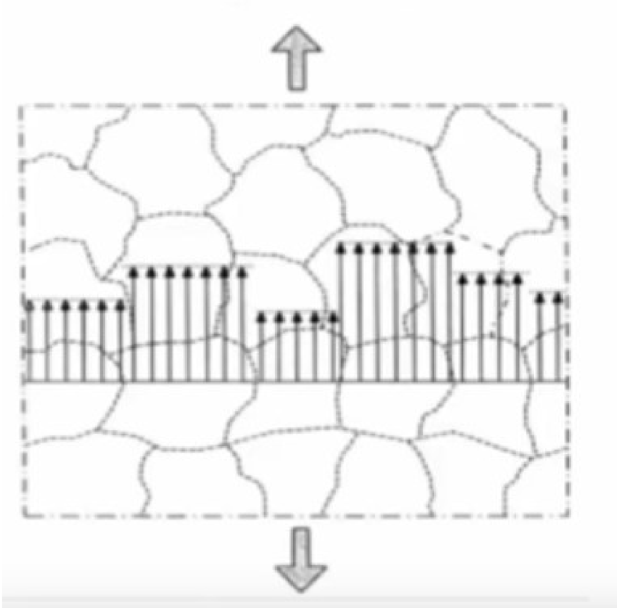


HCP

Crystal grain structure

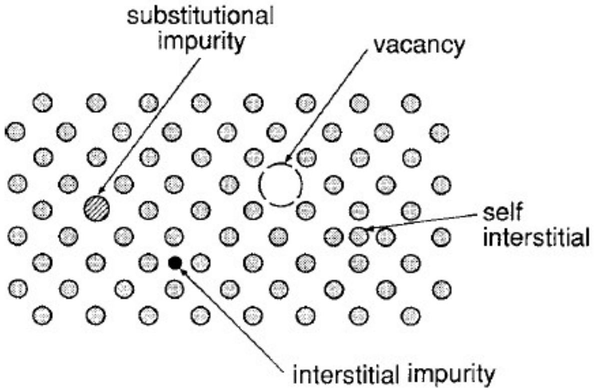
Grain size and shape
Variation of the crystal orientation from grain to grain



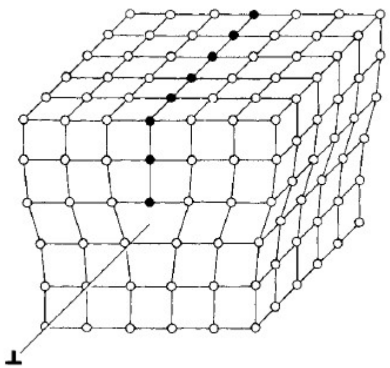


Defects in crystals

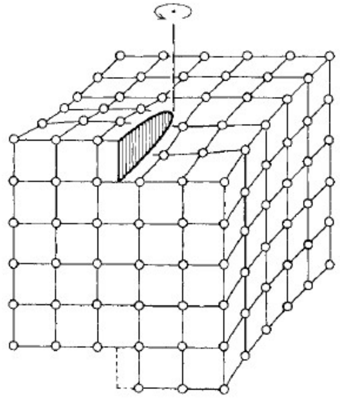
Point defect



Line defect or dislocation



edge dislocation



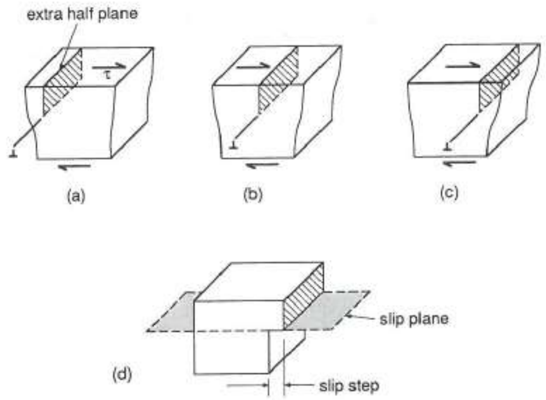
Screw dislocation

https://www.youtube.com/watch?v=-t6btGjGKYU edge dislocation

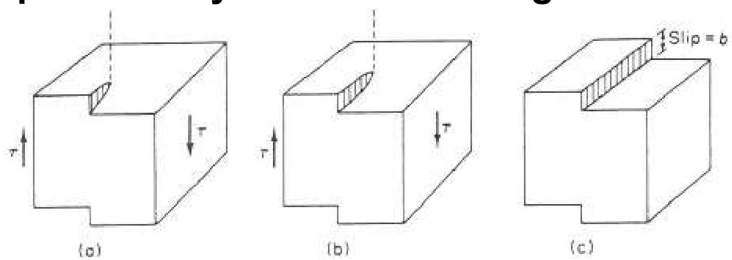
https://www.youtube.com/watch?v=TxJOP3hA6To screw dislocation

Plastic deformation by dislocation motion

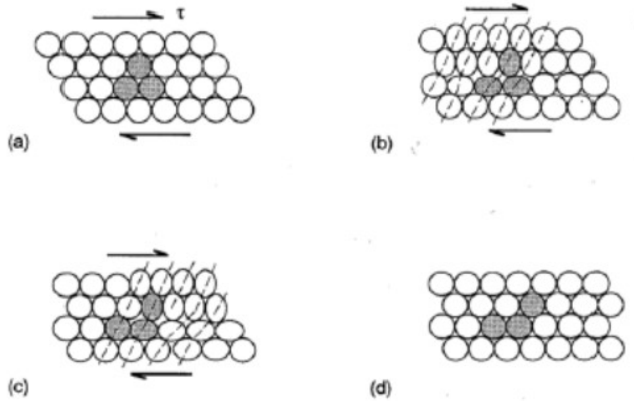
The plane in which the dislocation line moves is called slip plane.



Slip caused by the motion of edge dislocation.

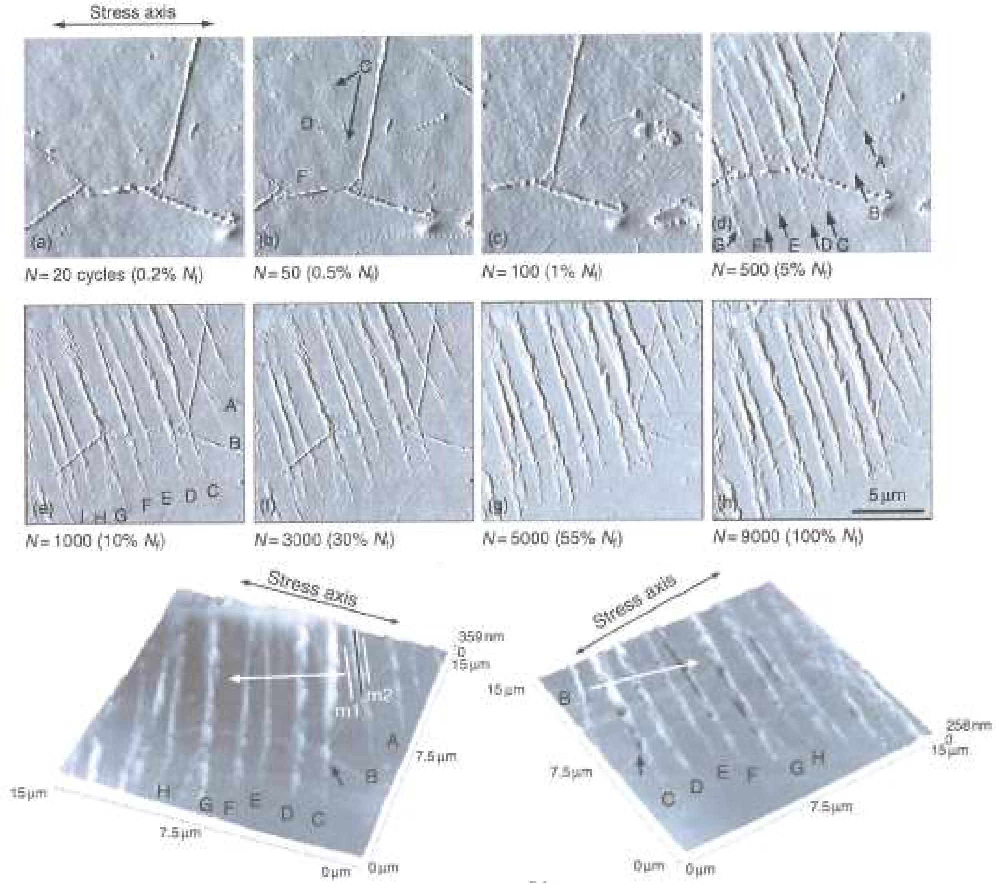


Slip caused by the motion of screw dislocation.



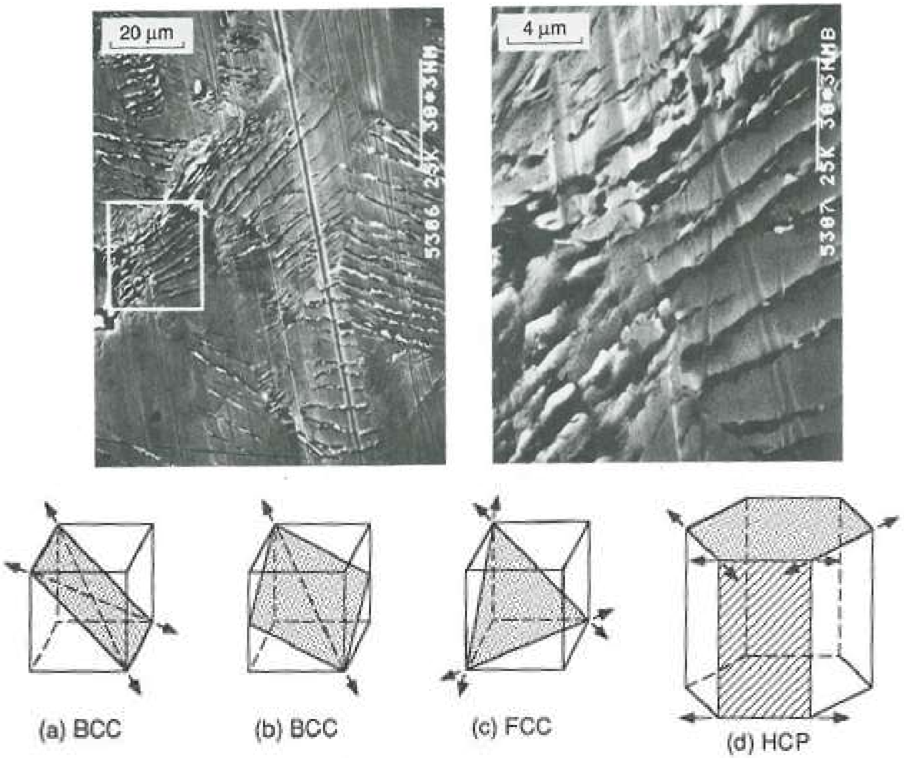
dislocation motion.

Process of slip band damage



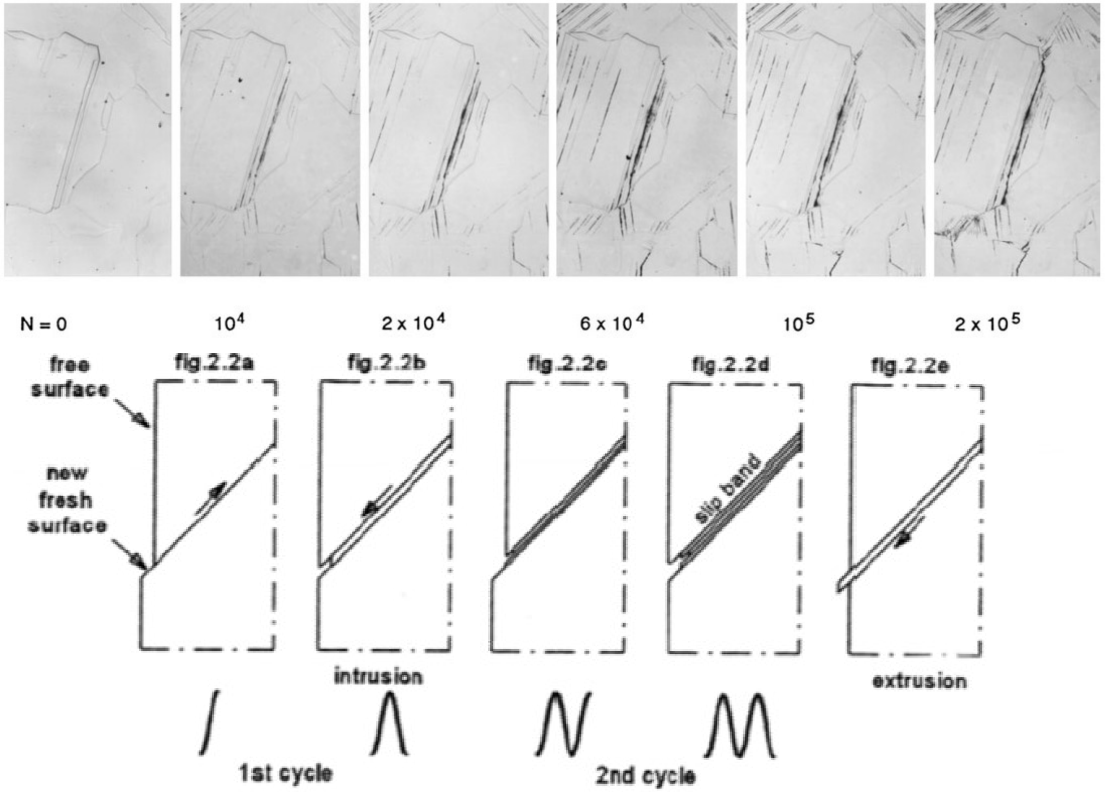
Slip occurs in metals within individual grain by dislocation moving along crystallographic planes. Slip is localization of plastic strain.

Slip band and slip step



For a given crystal structure, slip is easier on certain planes and within these planes in certain direction. These prefered planes are called as closed-pack planes.

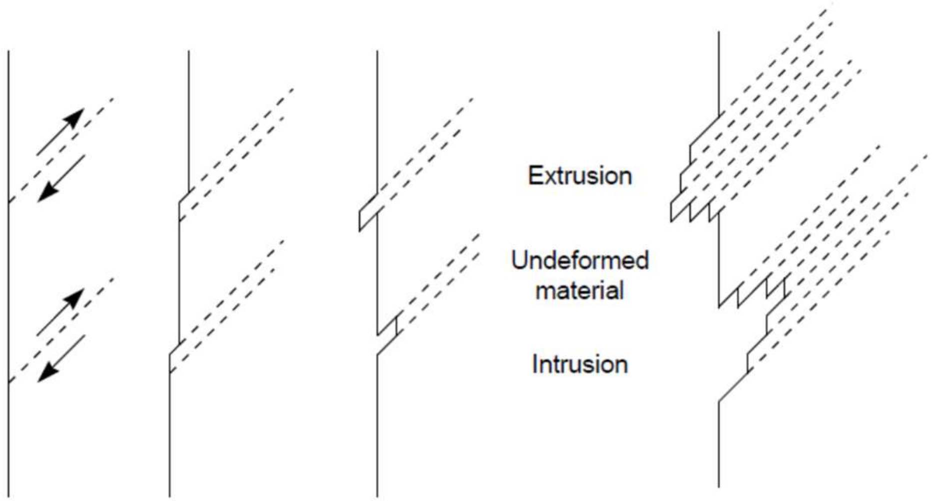
Process of slip band damage

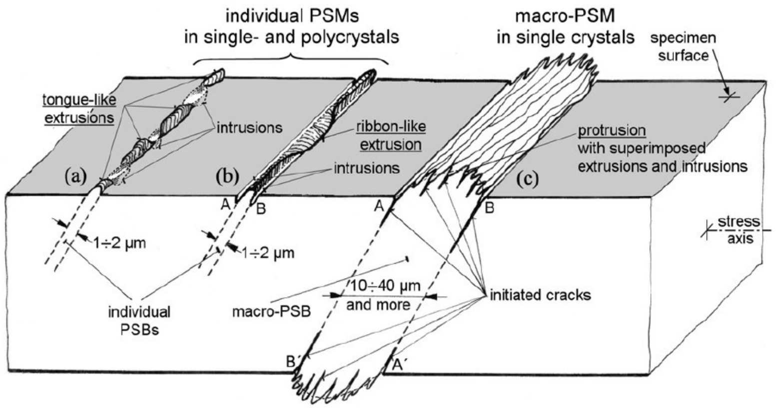


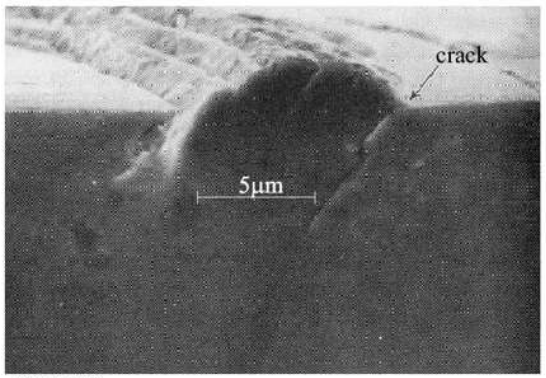
Slip bands are regions where there is intense deformation due to shear motion between crystal planes. The plastic deformation is often concentrated in slip bands.

Aalto University
School of Engineering

Fatigue of materials and structures



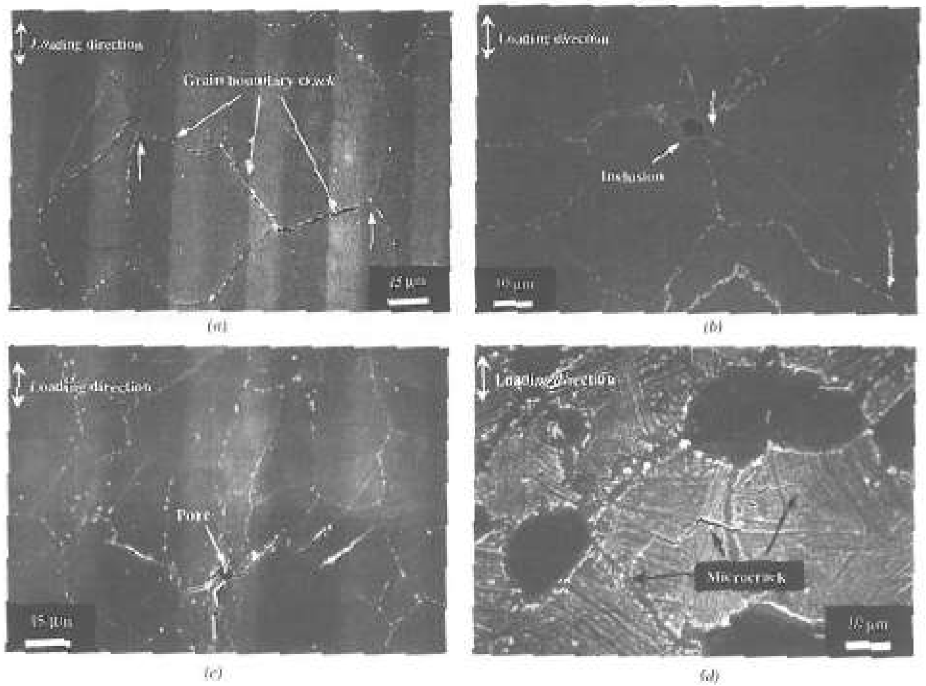




(Suresh 1991)

Crack nucleation occurs due to slip under fatigue loading

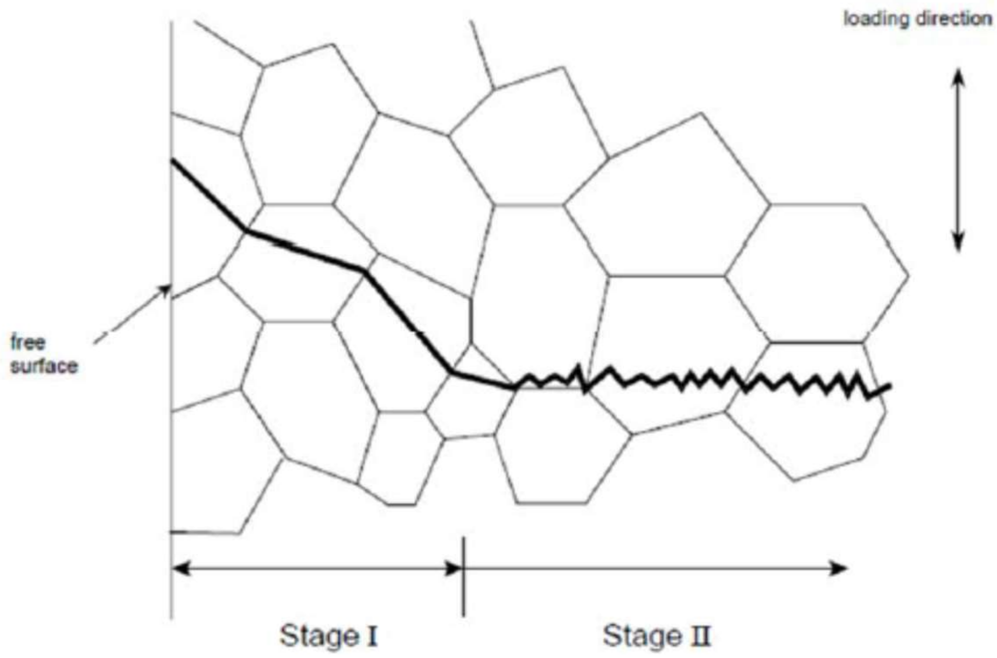
Fatigue of material and structures



Fatigue micro crack nucleates due to two main mechanisms:

1. **Along slip bands**
2. **At or near material discontinuities like second phase, voids, inclusions, grain boundaries or pores**

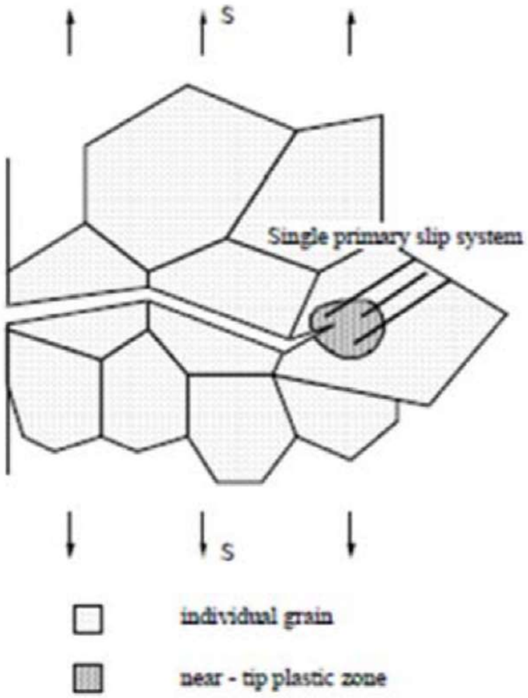
Fatigue of materials and structures



- **Stage I: Fatigue cracks that nucleate in local shear bands initially tend to grow in a plane of maximum shear stress range.**
- **Stage II: Crack grows in a zig zag manner controlled primary by maximum tensile stress-range.**

Fatigue of materials and structures

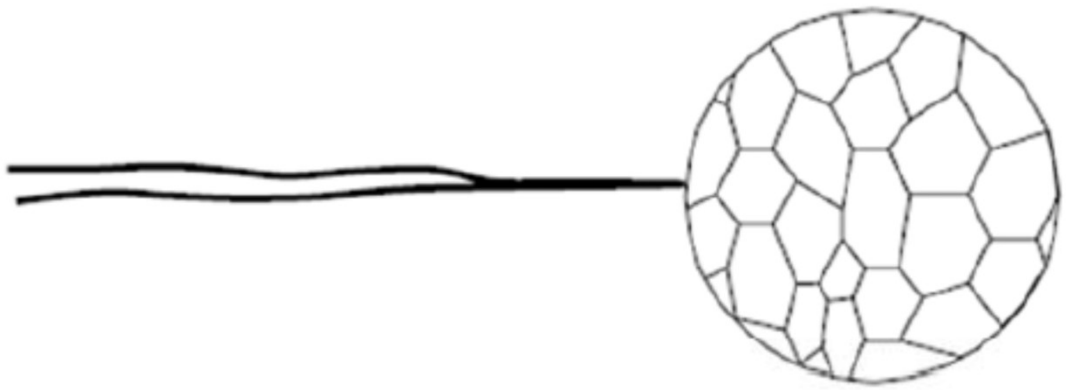
Stage I



This growth is quite small usually on the order of several grains and thus, growth of microcracks strongly influenced by the slip characteristics of material, material grain size and the extent of plasticity near the crack tip.

Fatigue of materials and structures

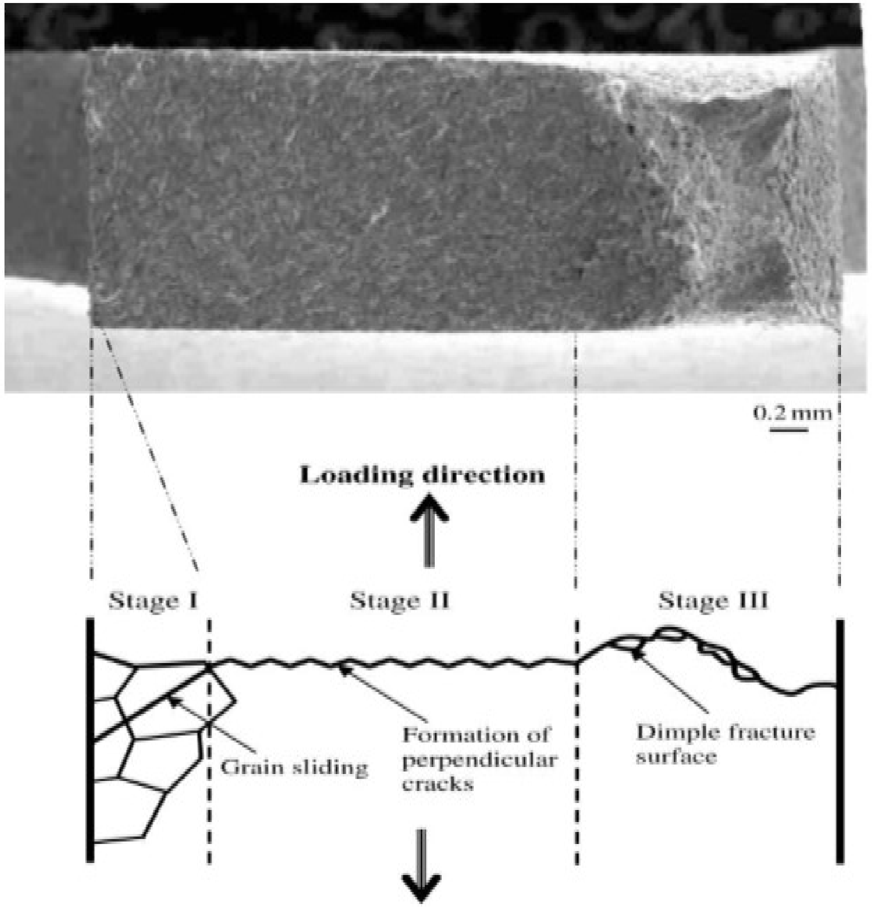
Stage II



- **Plastic zone size is much larger than the material microstructure so that the microstructure does not play such important role.**

- **The high plastic stress and strain ahead of crack tip due to notch root plasticity or crack tip plasticity directly enhanced driving force.**

Different stages of fatigue crack progress

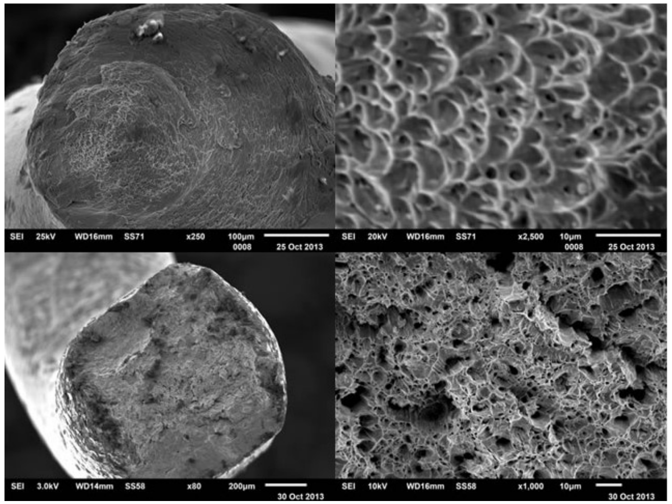


Microscopic fatigue crack growth

An electro microscopic analysis of fractured surfaces reveal a wide range of fatigue crack growth mechanism.

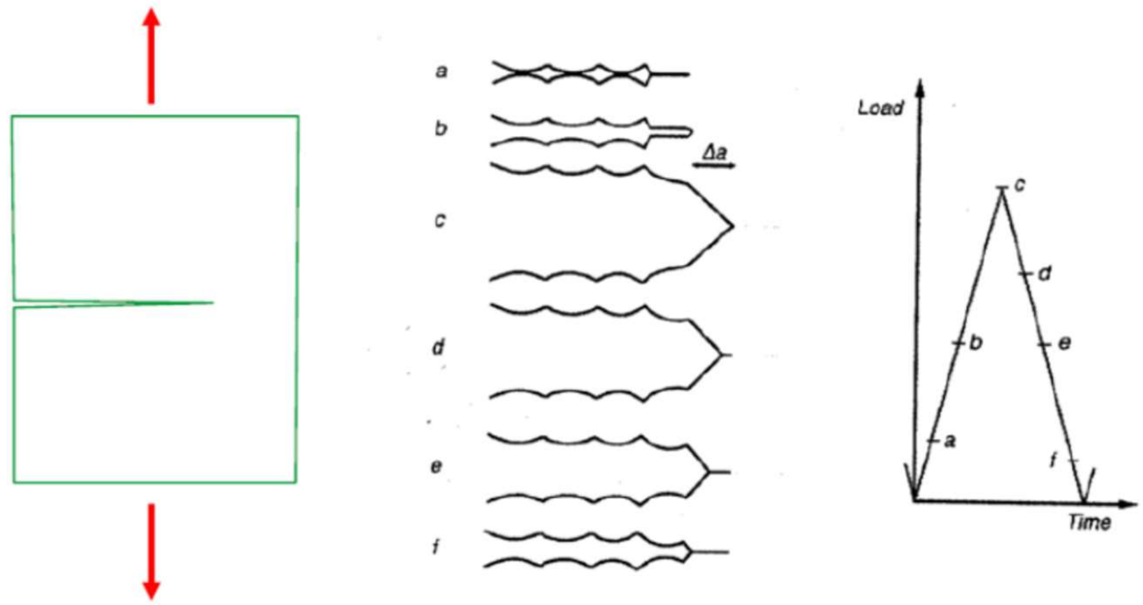
Three more common models of fatigue crack growth mechanism:

1. **Striation formation**
2. **Microvoid coalescence**
3. **Microcleavage**



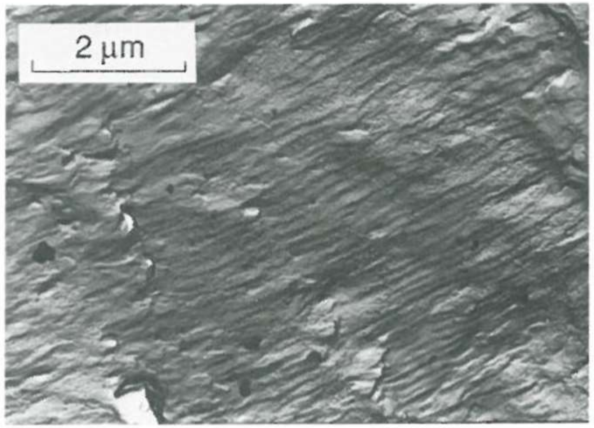
Microscopic fatigue crack growth

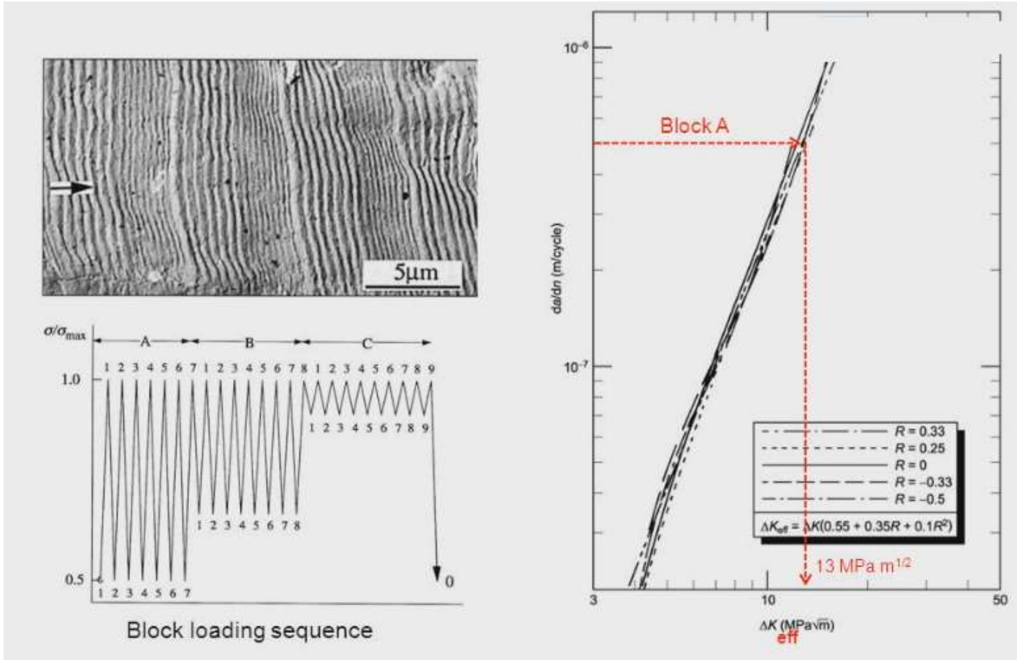
Striation

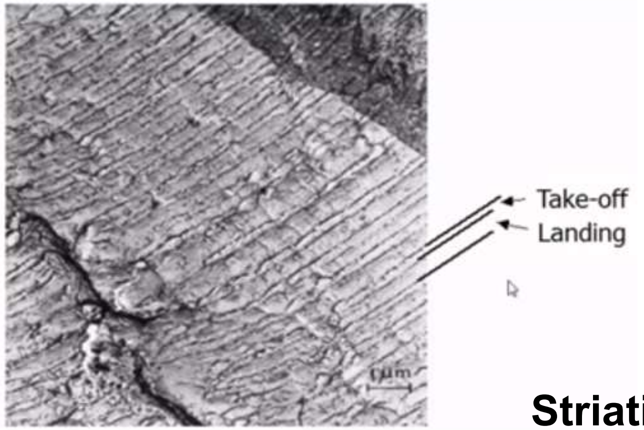


Striation is the progress of the crack on each cycle. Striation forming by a plastic crack tip blunting mechanism during the loading and unloading portion of the fatigue cycle.

Microscopic fatigue crack growth



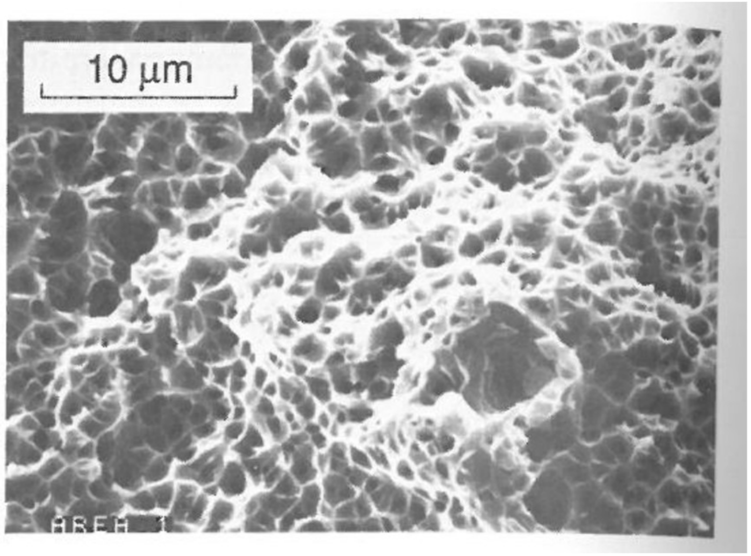




Striation has observed to represent one load cycle

Microscopic fatigue crack growth

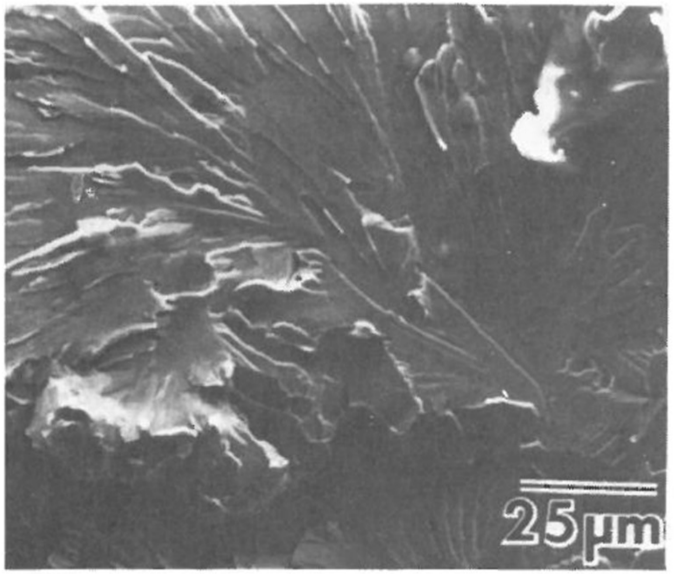
Microvoid coalescence



- **This a high-energy microscopic process which is observed in ductile material that there is little restriction on dislocation movement and slip is abundant.**
- **Microvoids grow during plastic flow of the material.**
- **Shear result in elongated dimples.**

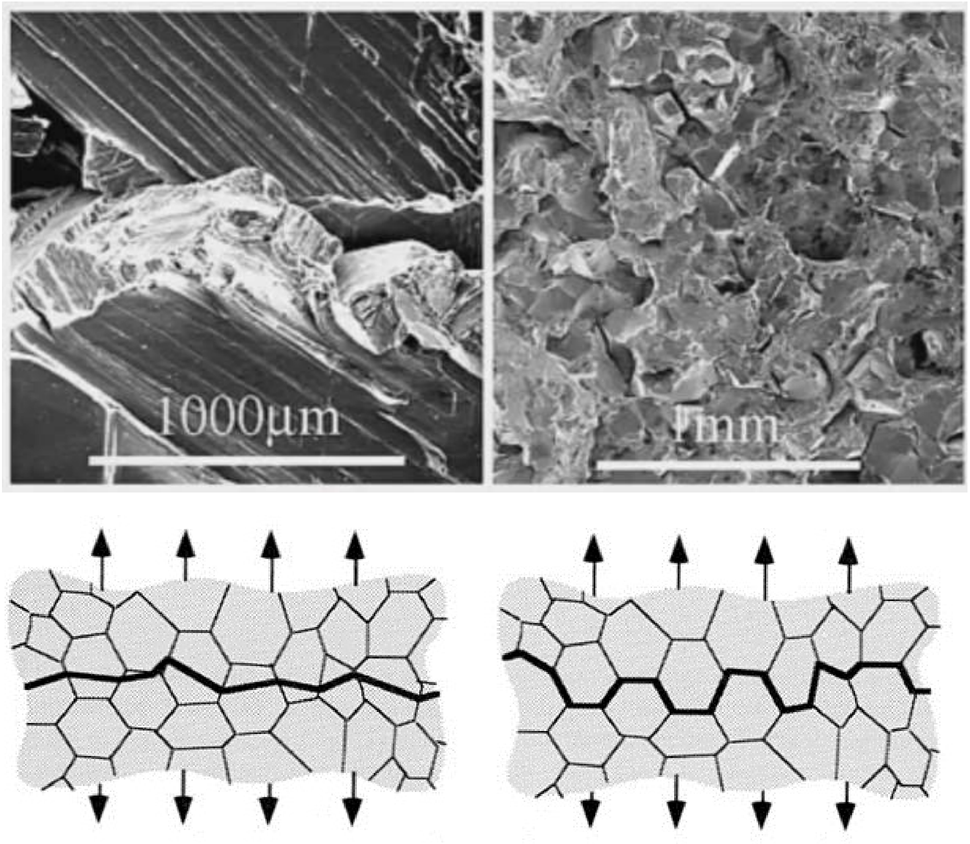
Microscopic fatigue crack growth

Micro-cleavage



- This is low-energy crack growth process.
- It involves fractured along specific crystallographic planes where atomic bond are weak.
- We may have more than 1 cleavage plane, with different activation energy; e.g. single crystal silicon;
- Brittle of fast fracture happen without plastic deformation.

Microscopic fatigue crack growth



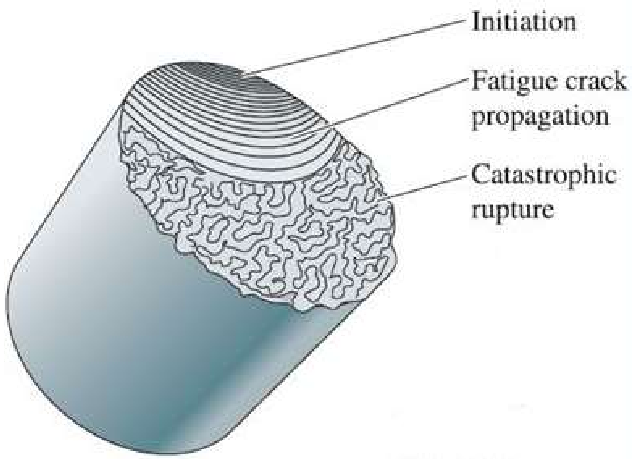
Transgranular
(e.g. room temperature)

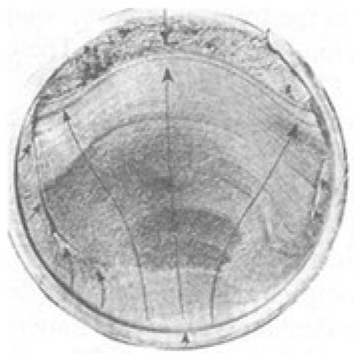
Intergranular
(e.g. high temperature)

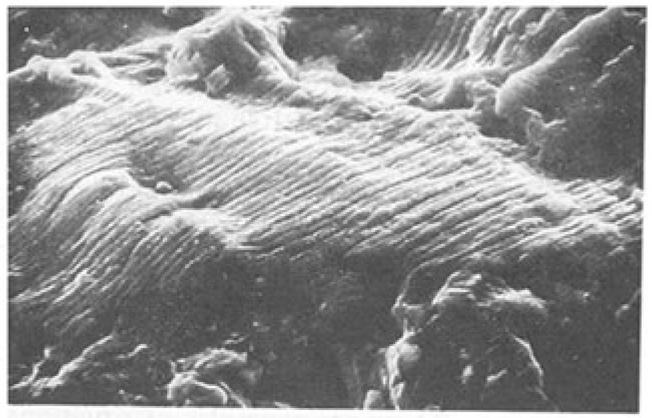
Fatigue surface, general characteristics

Fatigue failure surfaces have three characteristics features:

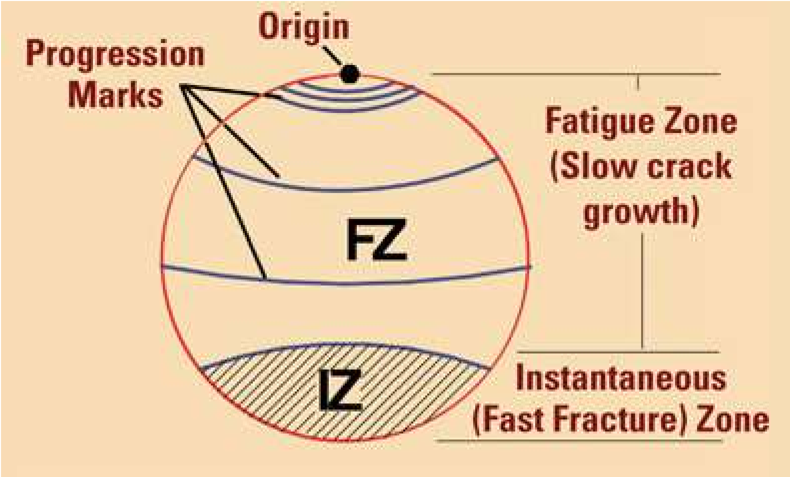
- **A surface or near-surface defect as the origin of crack**
- **Striation corresponding to slow, intermittent crack growth**
- **Dull, fibrous brittle fracture surface (rapid growth)**

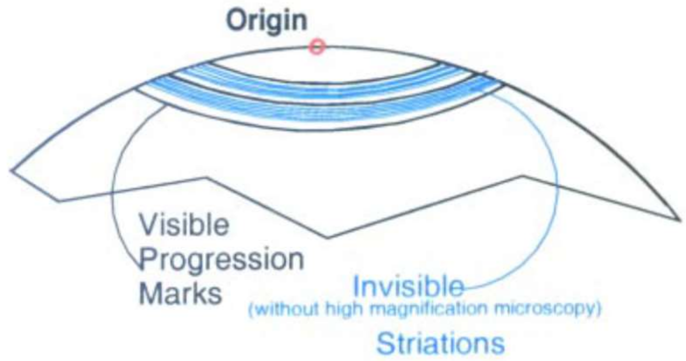






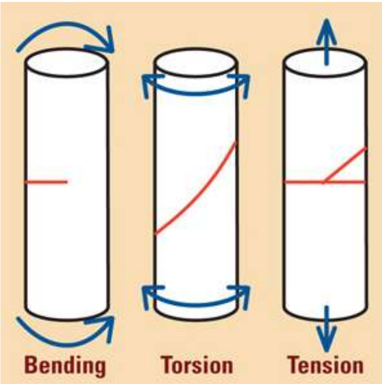
Fatigue surface general characteristics

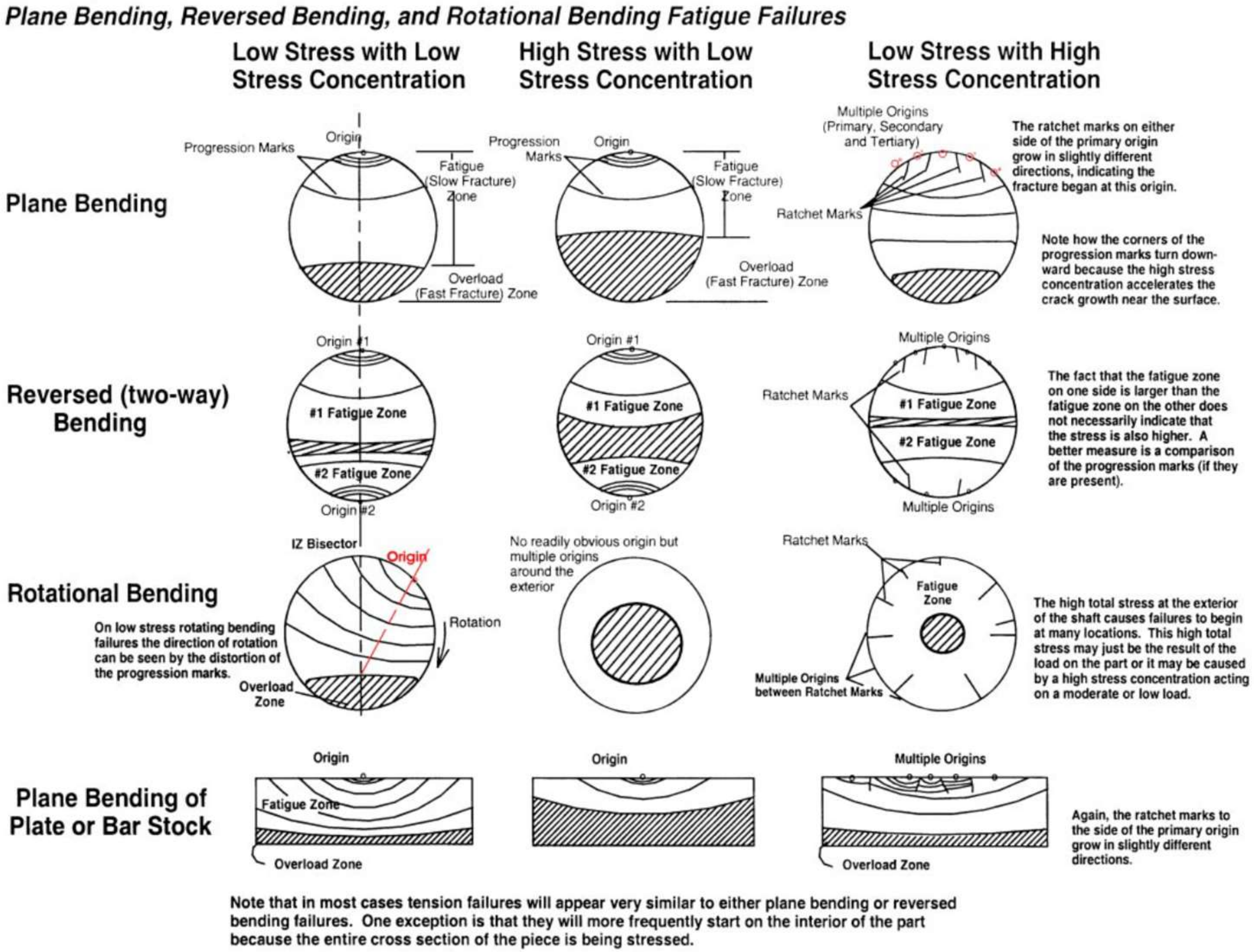




Beach mark or progression mark shows the progress of crack at various stage such as start up or shut down forces. Progression mark depicts the variation of applied stress ranges.

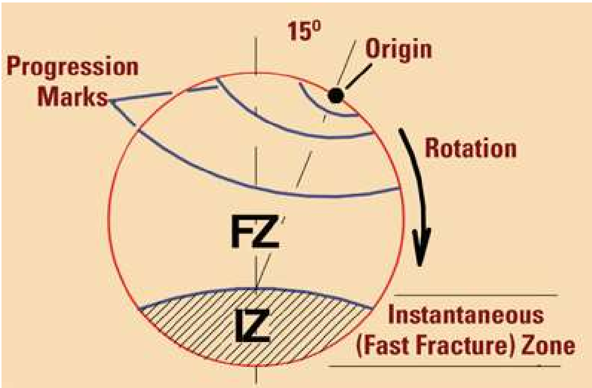
Example



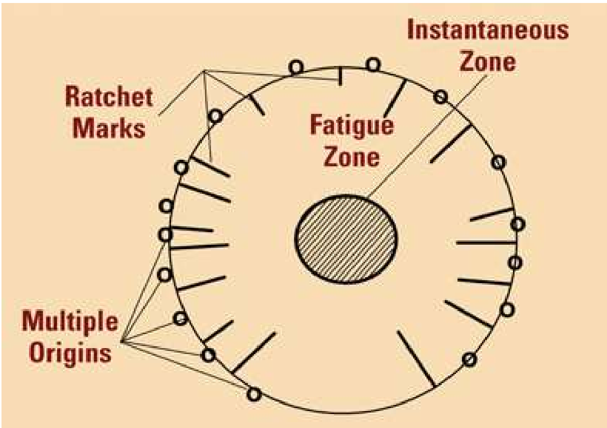


N. W. Sachs, Understanding the Surface Features of Fatigue Fractures: How They Describe the Failure Cause and the Failure History, JFAPBC (2005) 2:11-15.

Example



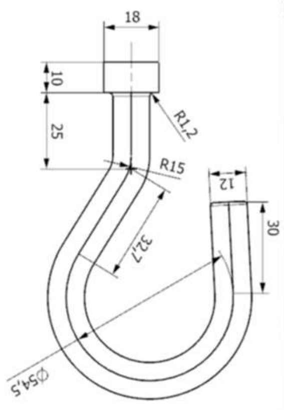
Single origin

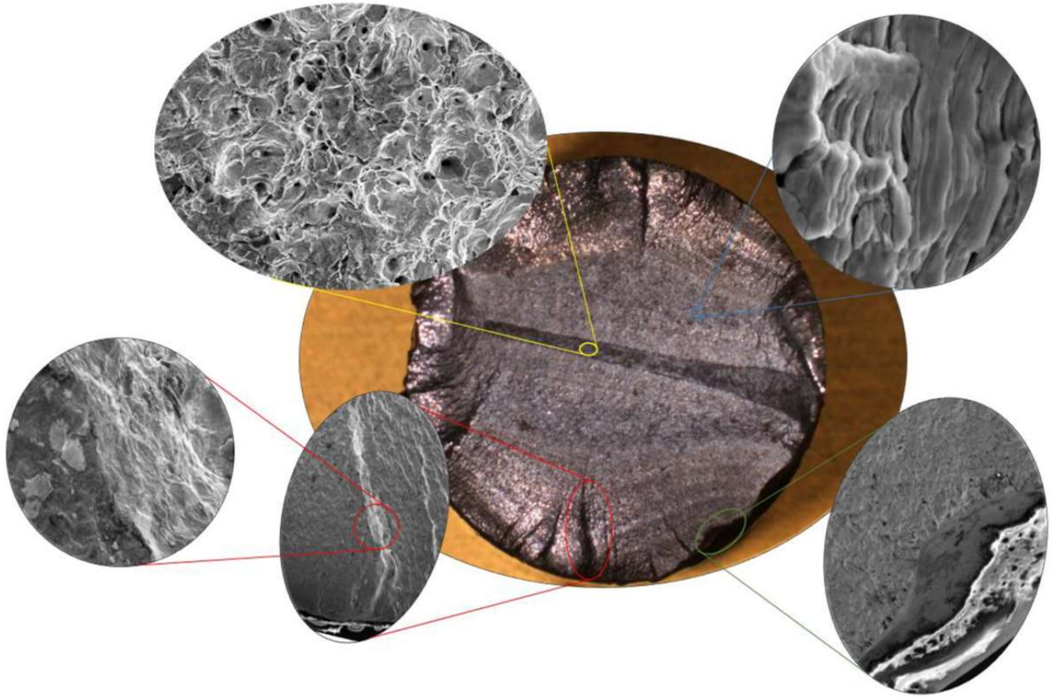


Multiple origins

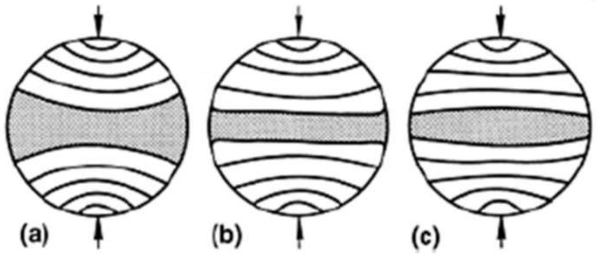
N. W. Sachs, Understanding the Surface Features of Fatigue Fractures: How They Describe the Failure Cause and the Failure History, JFAPBC (2005) 2:11-15.

Example



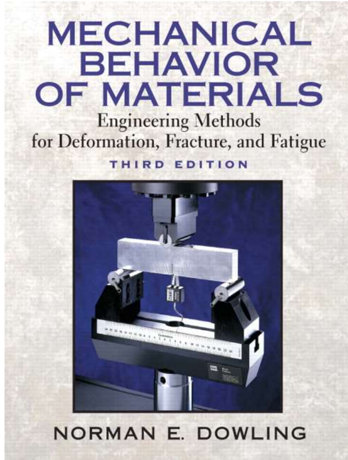


Reverse bending loading



A. Jacob, T. Kankkunnen, C. Chaves, Group 7 research project for fatigue of structures course, Fall semester 2017.

Readings – Course material



Course book

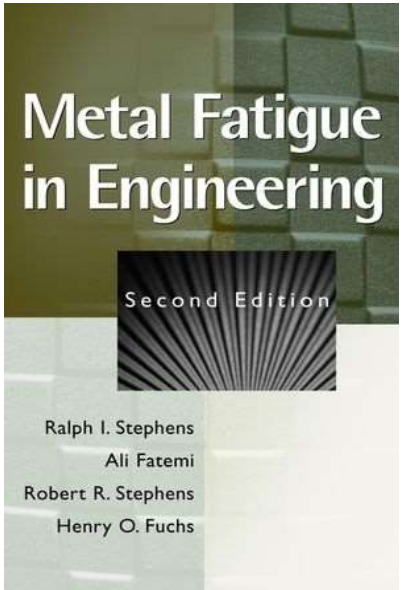
Mechanical Behavior of Materials Engineering Methods for Deformation, Fracture, and Fatigue, Norman E. Dowling

- Section: 2.3-2.4
- Section: 9.5

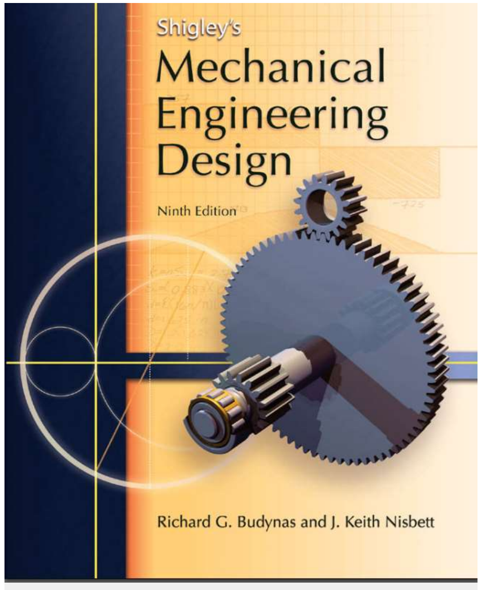
Optional reading materials given in MyCourses webpages

- Sachs, N.W. 2005. Fracture features: Understanding the Surface Features of Fatigue Fractures: How They Describe the Failure Cause and the Failure History, Journal of Failure Analysis and Prevention, 2:11-15.
- W. Schlitz, W. 1996. A history of fatigue, Engineering Fracture Mechanics, 54:263-300.

Readings – Other references



Chapter 1 and 3



Chapter 6: 6-1 and 6-2

Assignment 1-1: Fatigue Mechanics

Select an article form Engineering Failure Analysis journal and write a summary of the article. The summary report should be short (max. A4) and it should include the description of the following issues:

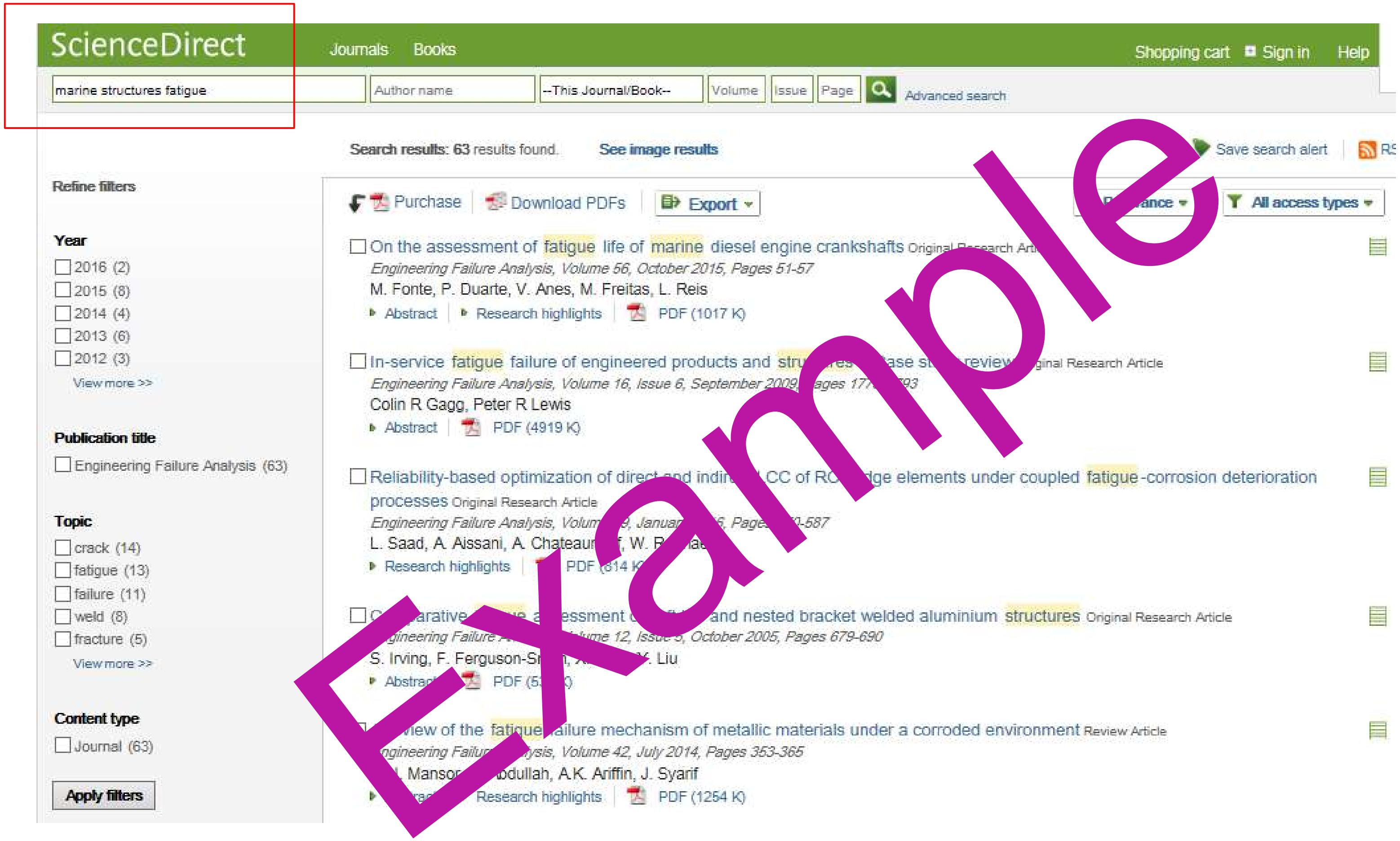
- Analyzed structure and failure location
- Fatigue mechanics (crack initiation, propagation, final failure)
- Possible reasons for the failure and main affecting factors

www: http://www.journals.elsevier.com/engineering-failure-analysis/

Report delivery

- In PDF-format using to MyCourses page (https://mycourses.aalto.fi)

Assignment 1-1: Fatigue Mechanics



Assignment 1-1: Fatigue Mechanics

Engineering Failure Analysis 56 (2015) 51–57

Contents lists available at ScienceDirect

Engineering Failure Analysis

journal homepage: www.elsevier.com/locate/engfailanal

ELSEVIER

On the assessment of fatigue life of marine diesel engine crankshafts

CrossMark

M. Fonte [a], P. Duarte [a], V. Anes [b], M. Freitas [b], L. Reis [b,*]

[a] Escola Superior Náutica (ENIDH), Portugal

[b] IDMEC, Instituto Superior Técnico, Universidade de Lisboa, Portugal

Example

ARTICLE INFO

Article history:
Received 30 October 2014
Received in revised form 31 March 2015
Accepted 20 April 2015
Available online 28 April 2015

Keywords:
Marine diesel engine
Crankshafts failure
Fatigue strength assessment
Fatigue life

ABSTRACT

The fatigue strength and its correct assessment play an important role in design and maintenance of marine crankshafts to obtain operational safety and reliability. Crankshafts are under alternating bending on crankpins and rotating bending combined with torsion on main journals, which mostly are responsible for fatigue failure. The commercial management success substantially depends on the main engine in service and of its design and in particular the crankshaft design strictly follows the rules of classification societies. The present study provides an overview on the assessment of fatigue life of marine engine crankshafts and its maintenance taking into account the design improving in the last decades, considering that accurate estimation of fatigue life is very important to ensure safety of components and its reliability. An example of a rebuilt crankshaft failure is also presented and the probable root case of damage, and at the end some final remarks are presented.

(a)