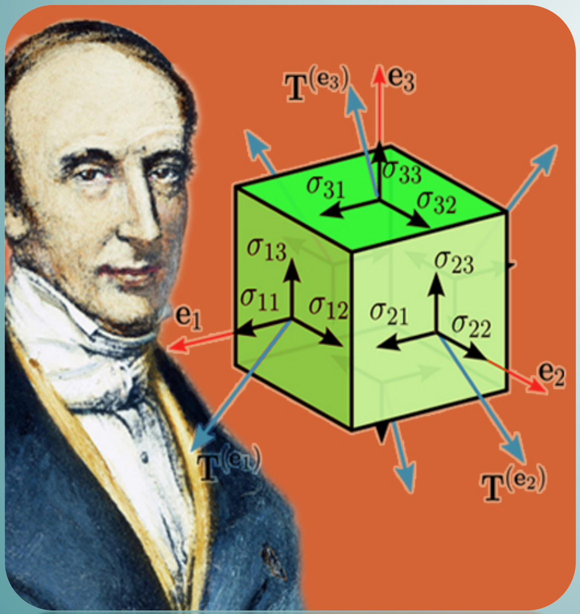
Mechanical Properties of Materials, Processing and Design

Topic 5. Fatigue of materials



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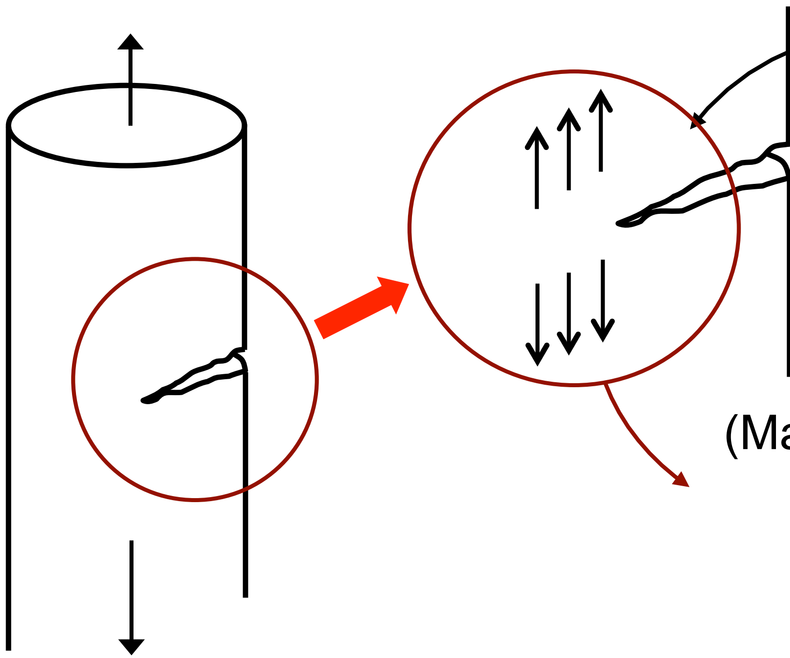
5.1. INTRODUCTION

PHENOMENOLOGY OF FATIGUE:



- Manufacturing.
- **Produced by cracking**.
- **Damaged in operation**.

(Material + defects)
+
Solicitation

Vs.

Local critical condition to fracture

(Toughness)

- Experience shows that structural components subjected to **oscillating stresses in time** can manifest crack damage **even with low stresses**.
- This phenomenon is called **fatigue**.

5.1. INTRODUCTION

HISTORICAL EXAMPLES:

- LIBERTY SHIPS (1943).
- ACCIDENT OF ALOHA AIRLINES FLIGHT B-737 (1988).
- ACCIDENT OF THE PRESTIGE (2002).
- ALEXANDER KIELLAND DECK COLLAPSE (1980).

5.1. INTRODUCTION

LIBERTY SHIPS (1943):

- In the beginning of World War II, German navy sank British freighters three times faster than the latter were able to build them.
- USA colaborated with Great Britain by supplying Liberty freighters. Unlike traditional boats, made with riveted plates, Liberty ones were monolithic structures completely welded.

5.1. INTRODUCTION

LIBERTY SHIPS (1943):

- Everything worked well until December of 1943, when a Liberty ship was sailing between Siberia and Alaska…
- 400 ships, out of 2400, experienced fractures of various kinds, 90 of them very serious. 20 of the ships halved spontaneously.
- All this was due to a 'slight' change in the manufacturing process.
- **CAUSES:** fragile welding, with the presence of defects. Embrittlement effect of the low temperatures.

5.1. INTRODUCTION

ACCIDENT OF ALOHA AIRLINES FLIGHT B-737 (1988):

- Partial detachment of the fuselage while it was flying.
- Disappearance of one of the air hostesses.
- **CAUSES:** processes of **fatigue** leading to **fracture** in the **junction of the fuselage**.

5.1. INTRODUCTION

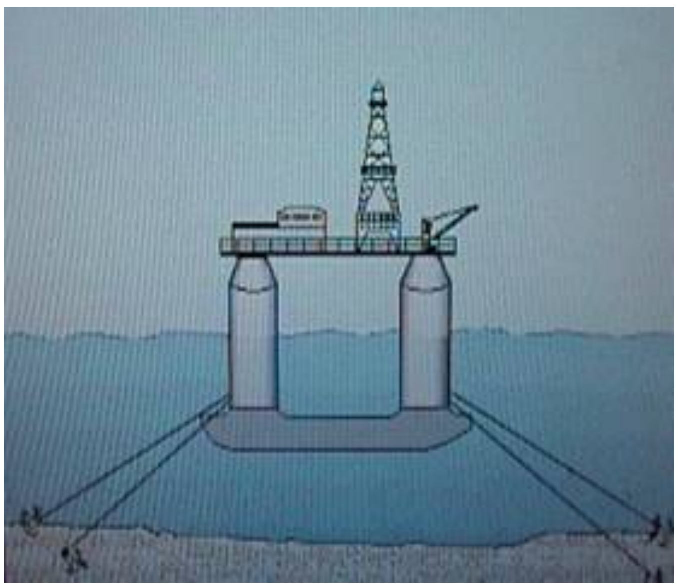
ACCIDENT OF THE PRESTIGE (2002):

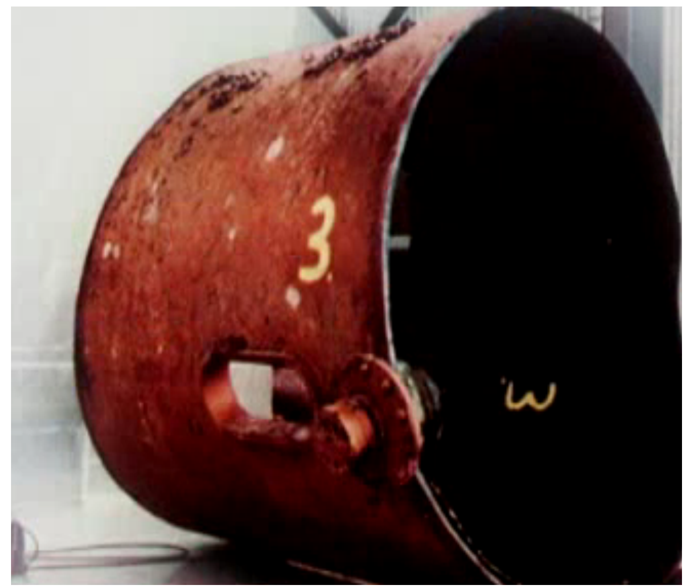
- 77000 Tm of fuel were spilled.
- **CAUSES:** accumulation of damage due to **thermal and mechanical fatigue** that led to the total fracture of the ship. (Standing Commission for Maritime Accident and Incident Investigations).

5.1. INTRODUCTION

ALEXANDER KIELLAND DECK COLLAPSE (1980):

- North Sea: 123 dead.
- **CAUSES:** sonar welding in one of the pontoons.





For curious minds:

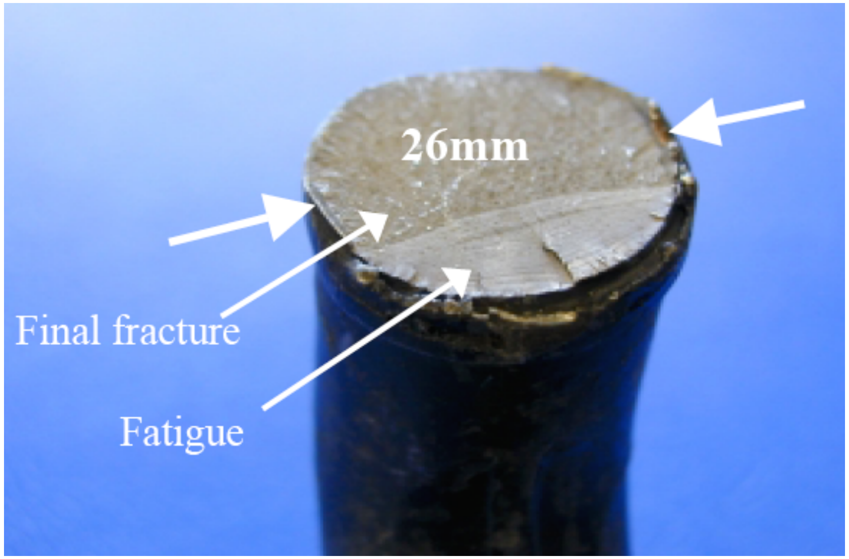
- http://www.youtube.com/watch?v=7QVn3NUW_aQ

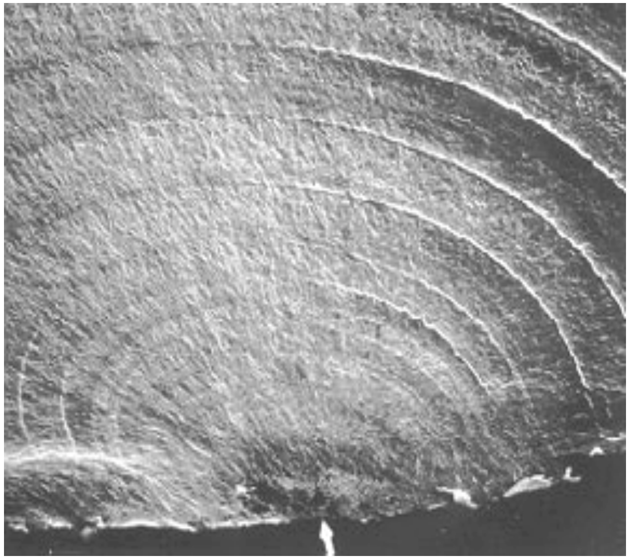
5.1. INTRODUCTION

FATIGUE DEFINITION:

- Failure mode in materials that involves initiation and propagation of cracks in elements subjected to varying stresses over time.
- It is called 'subcritical process' because it is a phenomenon that takes place before fracture (and that can lead to it).

Typical morphology of fracture: INITIATION AND PROPAGATION:





5.1. INTRODUCTION

19th Century: early scientific studies:

- ALBERT (1829), fatigue tests on iron chains.
- PONCELET (1829) AND RANKINE (1843), WÖHLER (1850-1870), breakage of train rails after many cycles with low stress.

20th Century: emergence of MF and application of fatigue:

- OROWAN and TAYLOR (1930) develop dislocation concept.
- GRIFFITH (1921) and IRWIN (since 1950) lay the foundations of FM.
- PARIS (1961): application of FM to fatigue processes.
- Other authors: extension to various materials and structural situations

5.1. INTRODUCTION

KEY IDEAS:

- Monotonous loads do not produce fatigue damage. They must be **oscillating** over time.
- It has been estimated that the **costs associated** with fracture of components and structures in the U.S.A. account for a 4% of the GDP.
- There have been **thousands of accidents**, sometimes with fatal consequences.
- Currently there is a **characterization and analysis tool** available that spot fatigue in both design of components stage and inspection and performance assessment.
- 20th and 21st Centuries: **fatigue design codes** of structural elements and components. Eg: Eurocode, ASME, API, FITNET…

5.1. INTRODUCTION

GENERAL SCHEME:

The fatigue life evaluation can be done from **two perspectives**:

1) Estimation of the **total life** of the element (**initiation + propagation**). It has its origin in the studies of Wöhler, Basquin and Goodman (19th Century), and it is based on experimental and statistical studies. The design parameter is the endurance.

2) Evaluation of the component life through **propagation**, assuming the existence of certain size cracks. This perspective starts with FM and Paris work (60's).

5.1. INTRODUCTION

INTRINSIC PROBLEMS IN THE FATIGUE ANALYSIS:

1) Laboratory results show that it is a **random phenomenon** and, therefore, difficult to predict: identical specimens tested under similar conditions manifest different fatigue behaviors. Different probability distributions have been used to model the random behavior of fatigue: normal distribution, extreme values, Birnbaum-Sanders or Weibull.

2) It is difficult translate experimental results to real situations.

3) In many cases, it is impossible to know beforehand the **operation conditions** of the component (eg, wind, waves…).

4) The same can be said about environmental conditions; furthermore, they normally generate difficult synergetic mechanisms (impossible?) to evaluate / predict.

5.1. INTRODUCTION

TYPES OF FATIGUE

NON-CRACKED COMPONENTS

There are no initial cracks and fatigue is controlled by the initiation phase.

CRACKED COMPONENTS

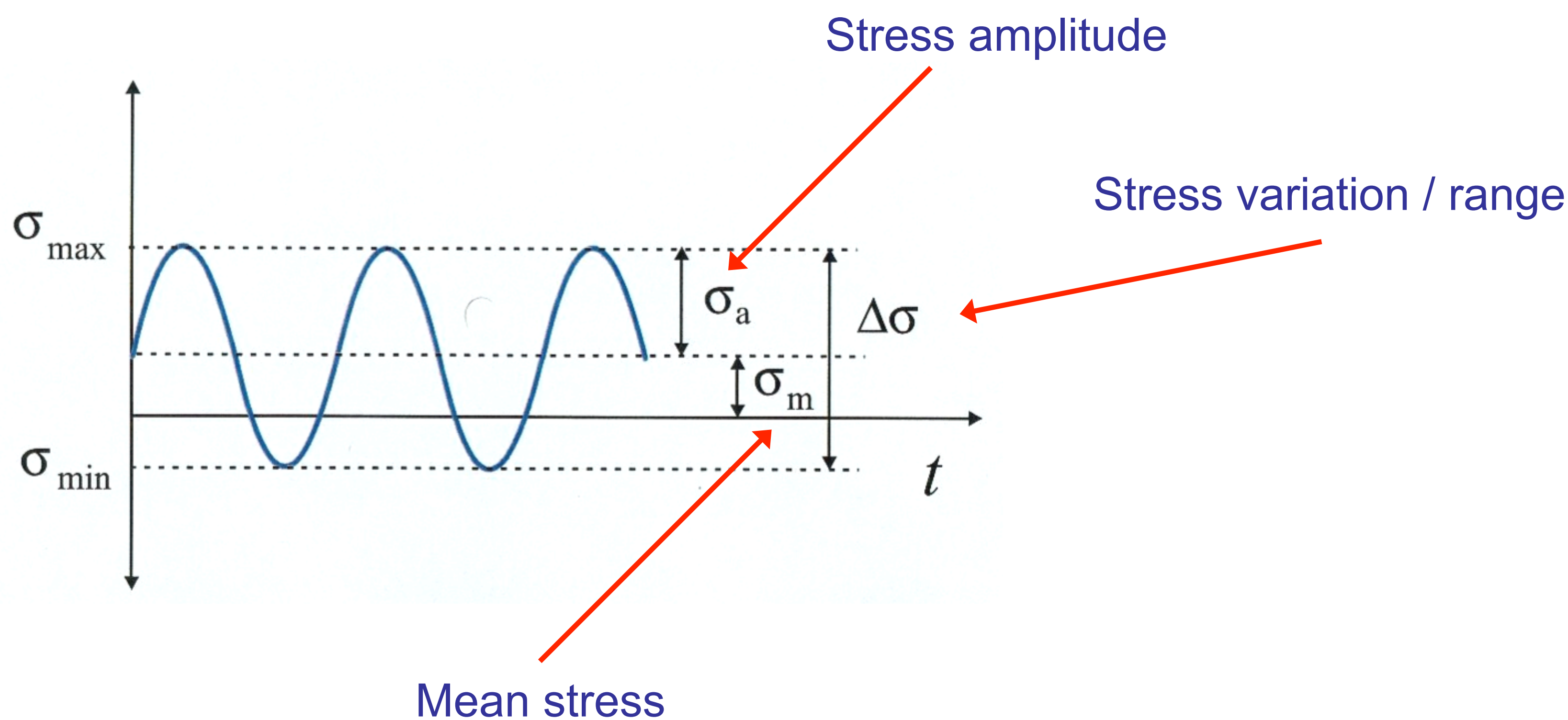
There are cracks from the beginning of the analysis and fatigue is controlled by the propagation phase.

High cycle fatigue **(S-N curves):**
- More than 10,000 cycles to failure.
- Lower stresses than the elastic limit.

Low cycle fatigue **(ε–N curves):**
- Less than 10,000 cycles to failure.
- Higher stresses than the elastic limit.

5.2. CYCLIC LOADS

- Particular case (easy) of oscillating loads.
- Evolution of stresses during a cyclic loading process.



5.2. CYCLIC LOADS

PARAMETERS THAT CARACTERIZE A FATIGUE PROCESS:

Stress range/variation: $\Delta\sigma = \sigma_{\max} - \sigma_{\min}$

Stress amplitude: $\sigma_a = \dfrac{\sigma_{\max} - \sigma_{\min}}{2}$

Mean stress: $\sigma_m = \dfrac{1}{2}\left\{\sigma_{\max} + \sigma_{\min}\right\}$

Stress ratio: $R = \dfrac{\sigma_{\min}}{\sigma_{\max}}$

Frecuency: measured in Hz (s^{-1}).

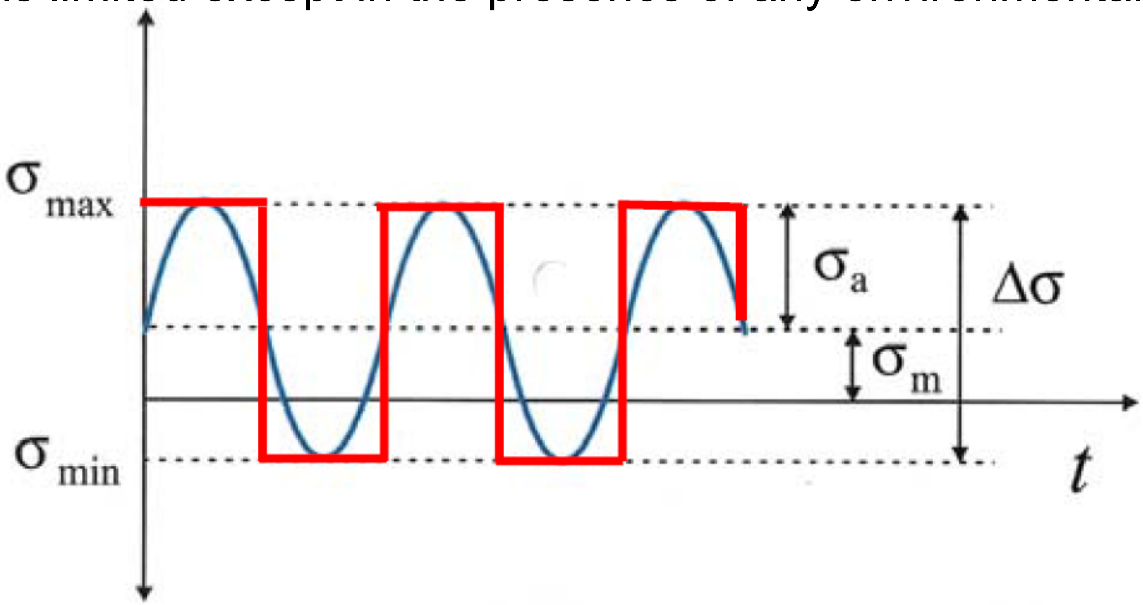
Experience shows that its influence on crack growth is limited unless it goes accompanied by environmental effects, such as humidity or high temperatures.

5.2. CYCLIC LOADS

PARAMETERS THAT CARACTERIZE A FATIGUE PROCESS:

INFLUENCE OF THE SHAPE OF THE FUNCTION:

- Sine, square, trapezoidal, etc. wave.
- As in the case of frequency, experience shows that its influence on the crack growth is limited except in the presence of any environmental condition.



5.2. CYCLIC LOADS

<u>Suggested exercises</u>:

1) Obtain the mean stress, stress amplitude and stress range assuming: σ_{min} = –100 MPa y σ_{max} = 250 MPa.

5.3. TOTAL FATIGUE LIFE

TYPES OF FATIGUE

NON-CRACKED COMPONENTS

There are no initial cracks and fatigue is controlled by the initiation phase.

CRACKED COMPONENTS

There are cracks from the beginning of the analysis and fatigue is controlled by the propagation phase.

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- More than 10,000 cycles to failure.
- Lower stresses than the elastic limit.

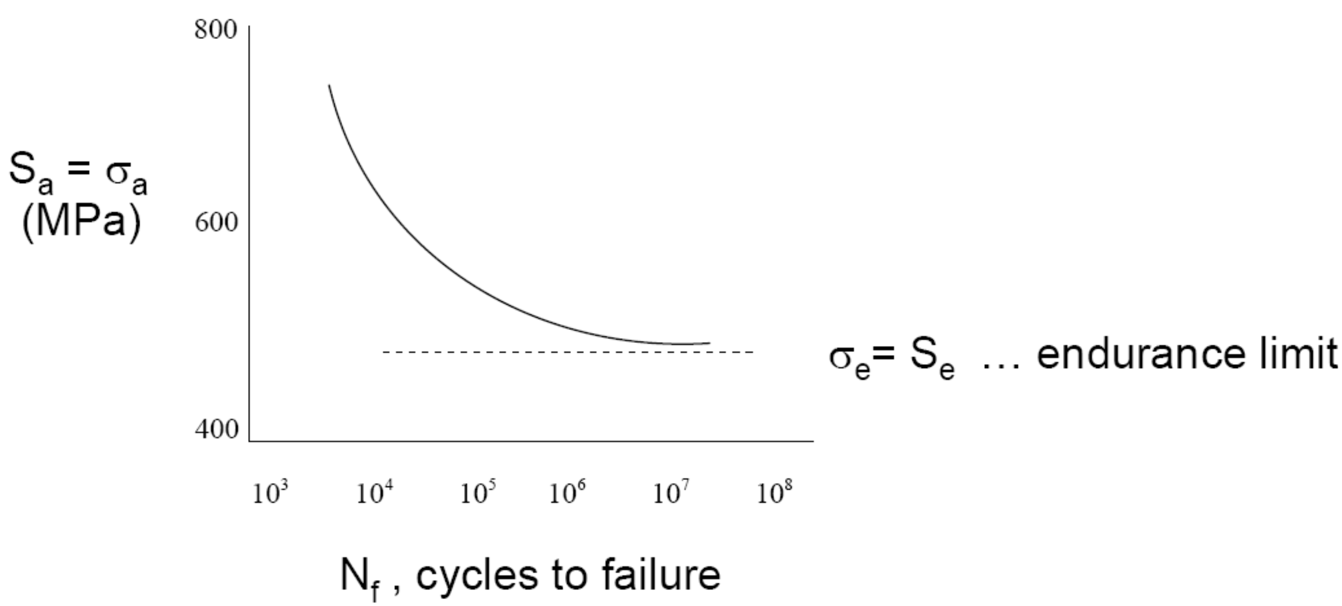
Low cycle fatigue **(ε–N curves):**
- Less than 10,000 cycles to failure.
- Higher stresses than the elastic limit.

5.3. TOTAL FATIGUE LIFE

- It was the first approach of fatigue analysis: presented by Wöhler (1860).
- Sine, square, trapezoidal, etc. Wave.
- It includes the processes of crack **initiation**, **propagation** and **final fracture** of the component.
- There are **two analysis methods** of fatigue based on total life considerations:
  - **HIGH CYCLE FATIGUE (HCF):** S-N curve (Wöhler curve).
  - **LOW CYCLE FATIGUE (LCF):** ε-N curve.

5.4. S-N CURVES (HCF)

- Alternative stresses (**σ_m = 0, R = –1**): σ_a Vs. N_f (semi-logarithmic scale).
- In many materials there is a minimum amplitude (**fatigue or endurance limit, σ_e**) below which there is no fatigue. In practice, it is consider infinite life for $N_f = 10^7$ cycles.
- Recently, researchers (Bathias, Murakami, and Stanzl-Tschegg) have found on certain materials failure due to fracture below fatigue limit for a very high number of cycles (10^9 - 10^{10}).



5.4. S-N CURVES (HCF)

Example:

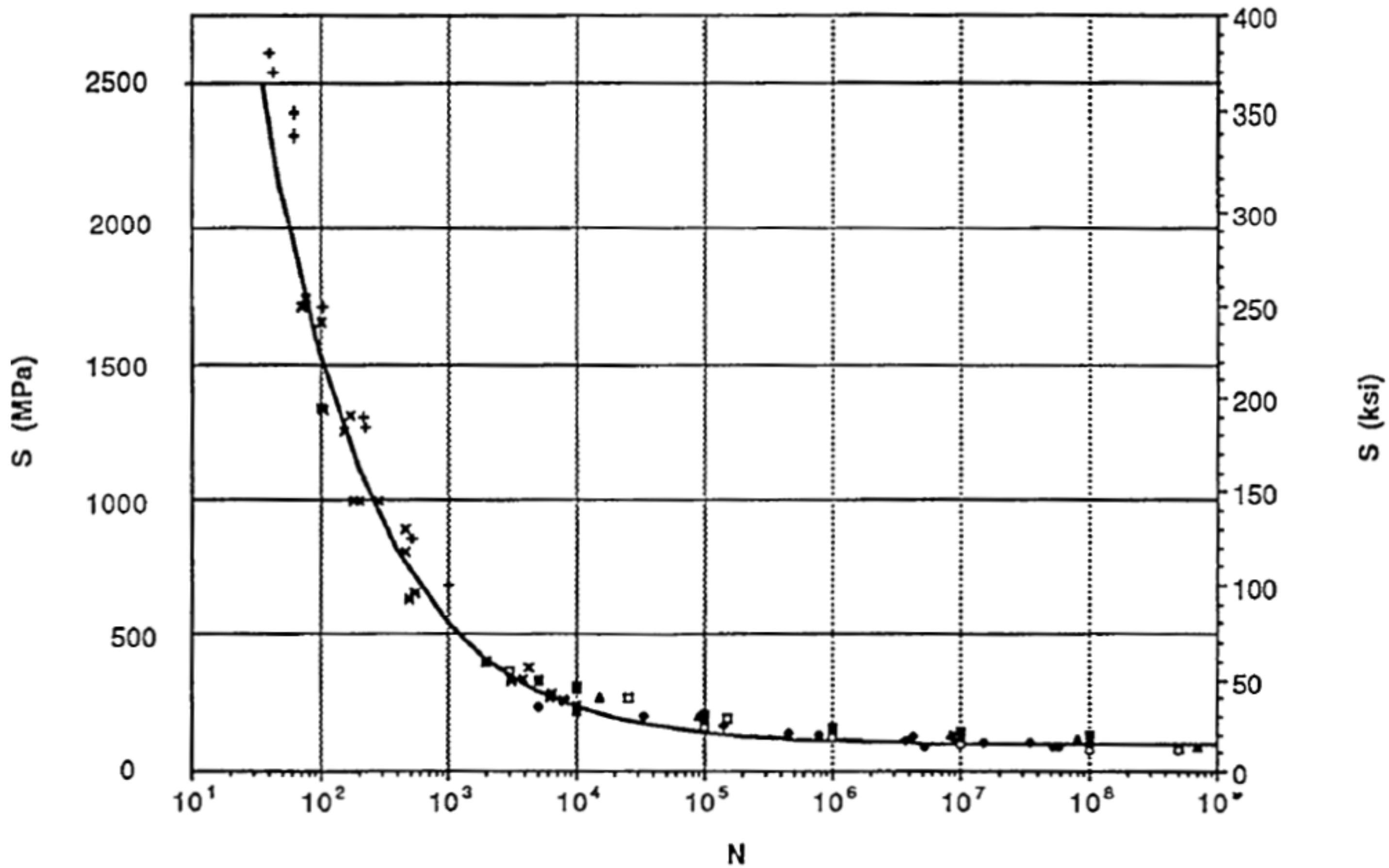


Fig. 1 Fit to fully reversed 6061-T6 fatigue data.

5.4. S-N CURVES (HCF)

BASQUIN'S LAW (1910)

- Valid if: $\sigma_m = 0$; (equivalently, $\sigma_{max} = -\sigma_{min}$ or $R = -1$).

$$\Delta\sigma \cdot N_f^a = C_1$$

- Material constants are obtained from experimental data:
  - Typically "a" varies between 1/15 and 1/8 in steel.

5.4. S-N CURVES (HCF)

<u>Suggested exercise</u>:

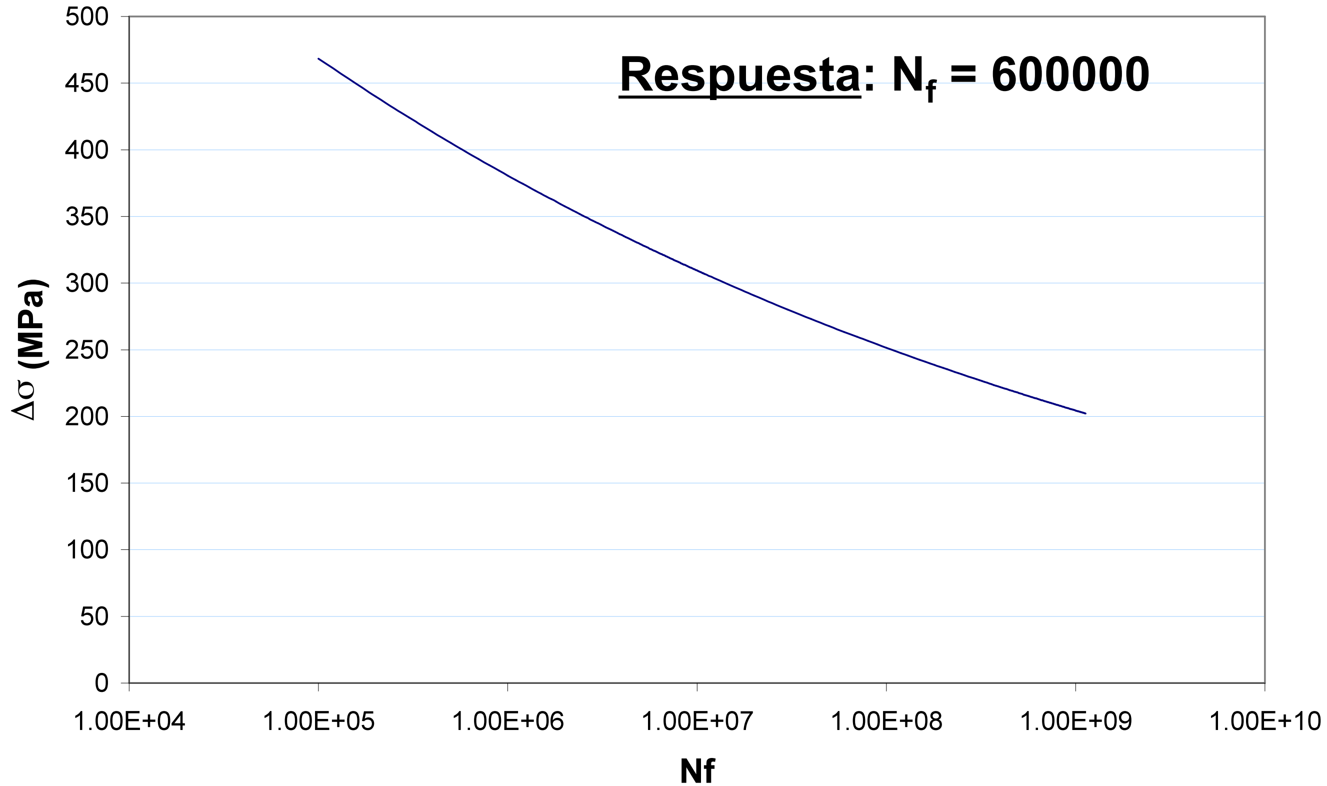
1) Apply Basquin's law to estimate the number of cycles resisted by a structural component subjected to the following conditions:

σ_{min} = –200 MPa; σ_{max} = 200 MPa; a = 0.090; C_1 = 1320

Is it possible to answer the same question if σ_{min}= –200 MPa and σ_{max} = 200 MPa? Justify the answer.

5.4. S-N CURVES (HCF)

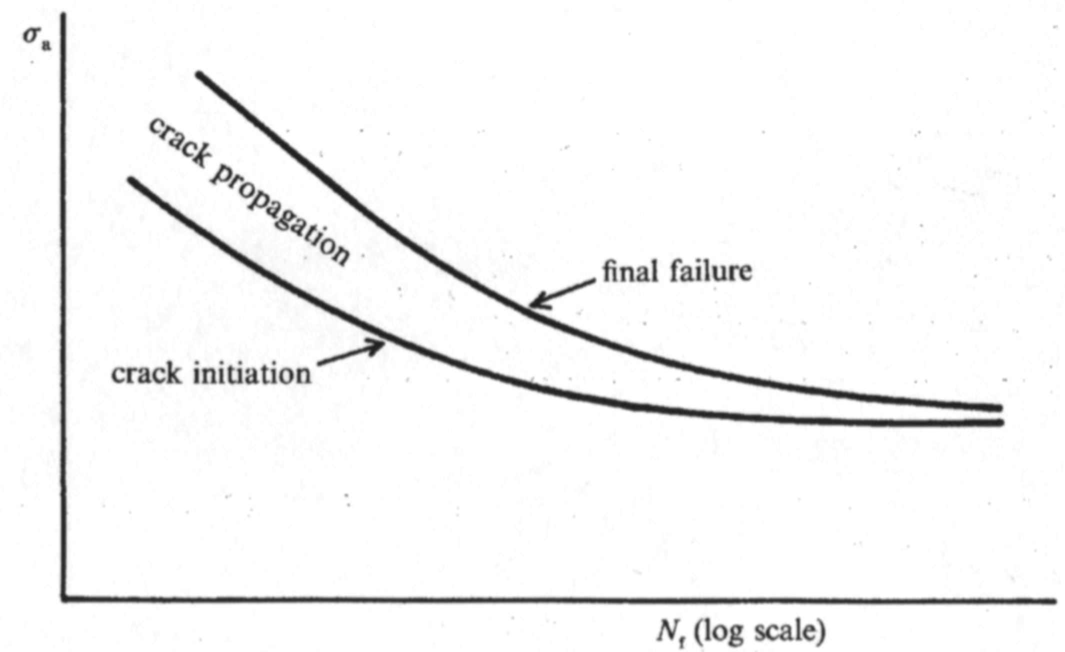
Suggested exercise:



- Basquin's law is only applicable when R = –1 (alternative stresses), therefore, it is not possible to answer to the second question.

5.4. S-N CURVES (HCF)

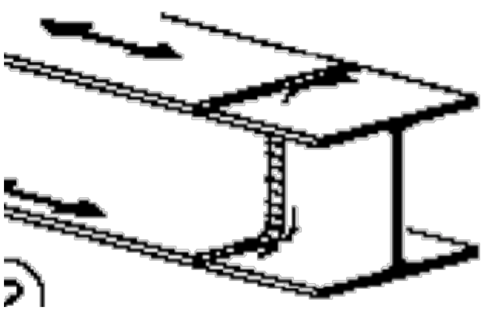
- The total life of an uncracked component has three stages:
  - Initiation period.
  - Propagation period.
  - Final break.
- S-N procedure (or Basquin's) doesn't distinguish between each of these stages.

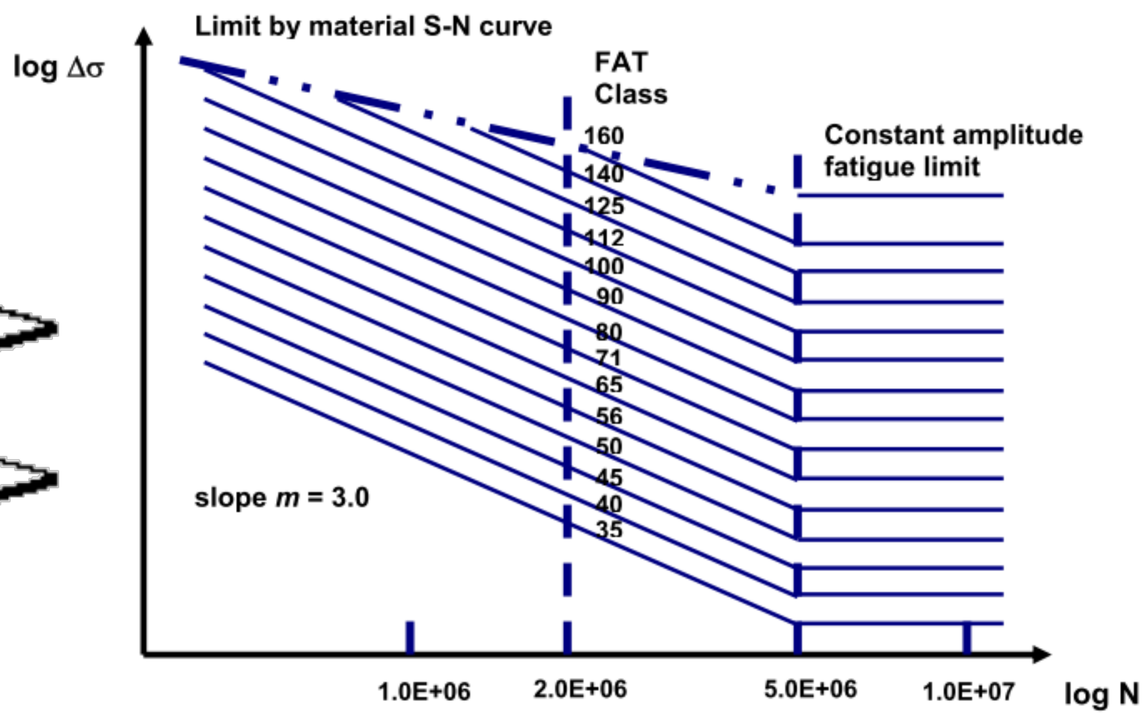


5.4. S-N CURVES (HCF)

• Example of S-N curves of welded joints:

FAT Class: 63





5.4. S-N CURVES (HCF)

SITUATIONS NOT GIVEN IN THE S-N CURVES:

a) Nonzero mean stress: $\sigma_m \neq 0$.

b) Variable amplitude over time: $\Delta\sigma$ (t).

- Each of these situations is faced by applying **empirical models**.

$$\sigma_m \neq 0 \Rightarrow \left\{ \right.$$

Models:

- Soderberg.
- Goodman.
- Gerber.

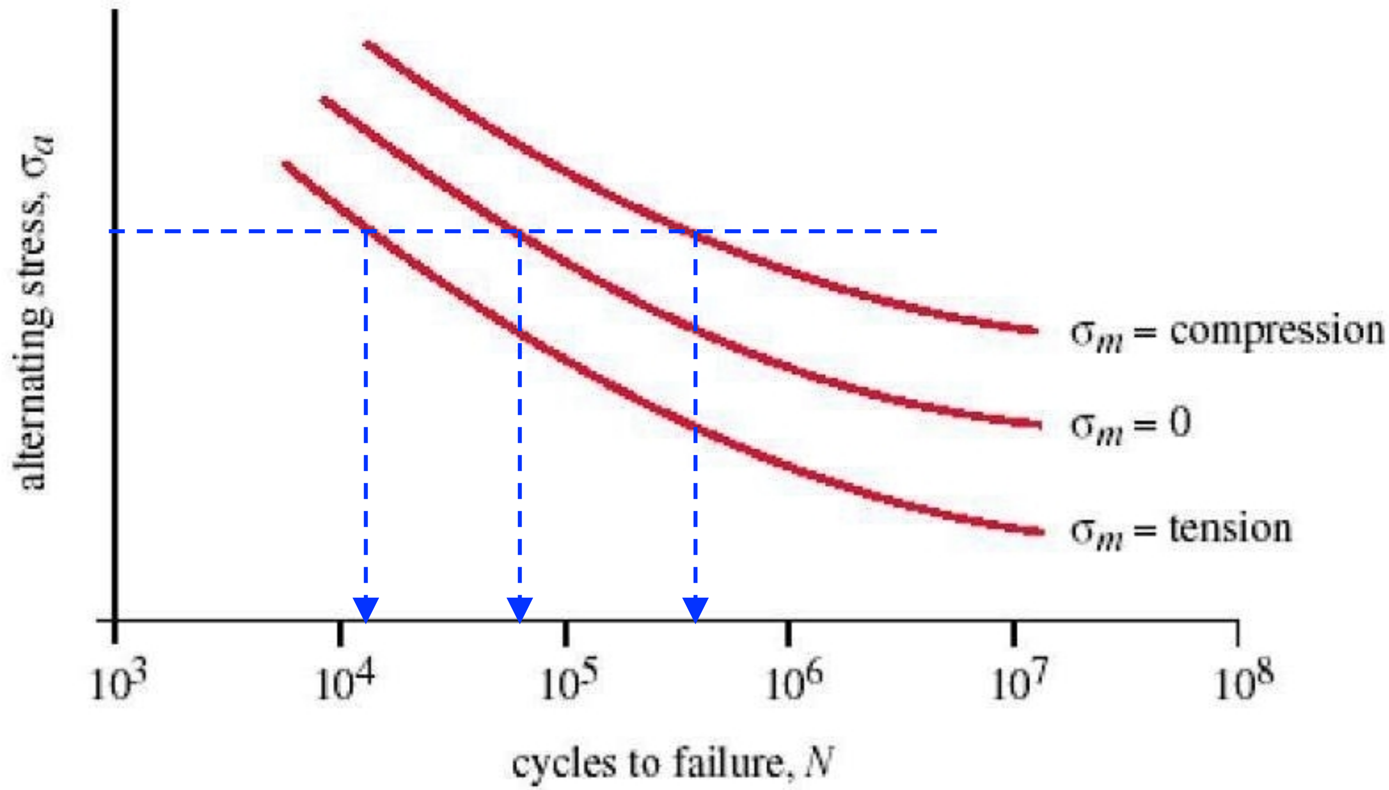
$$\Delta\sigma(t) \Rightarrow$$

Palmgren – Miner law (accumulated damage)

5.4. S-N CURVES (HCF)

a) Nonzero mean stress: $\sigma_m \neq 0$:

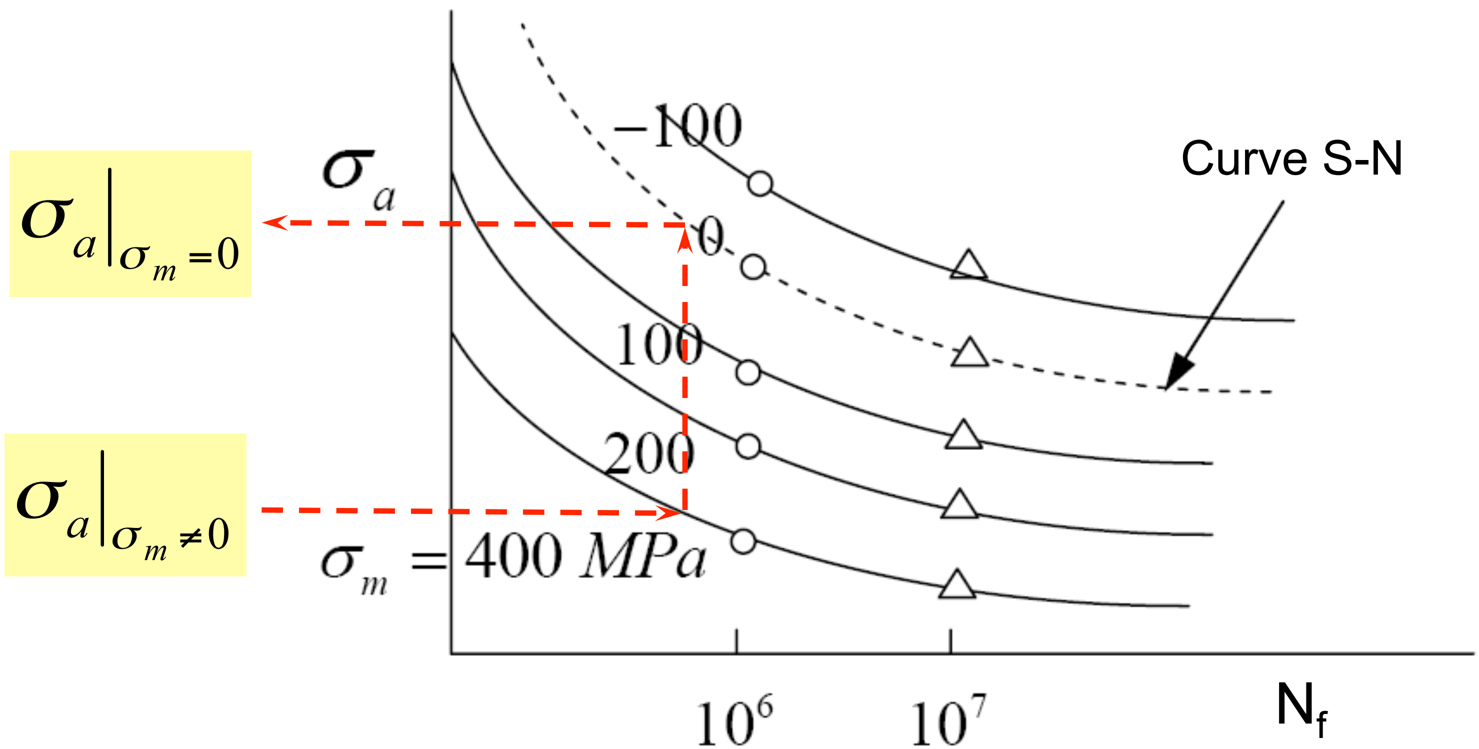
- Experimental data shows than when σ_m increases, N_f decreases.



5.4. S-N CURVES (HCF)

a) Nonzero mean stress: $\sigma_m \neq 0$:

- Empirical models that allow to obtain stresses amplitude that, with σ_m = 0, produces the same damage (same number of cycles resisted) than the applied amplitude ($\sigma_m \neq 0$) have been developed.



5.4. S-N CURVES (HCF)

a) Nonzero mean stress: $\sigma_m \neq 0$:

Soderberg:

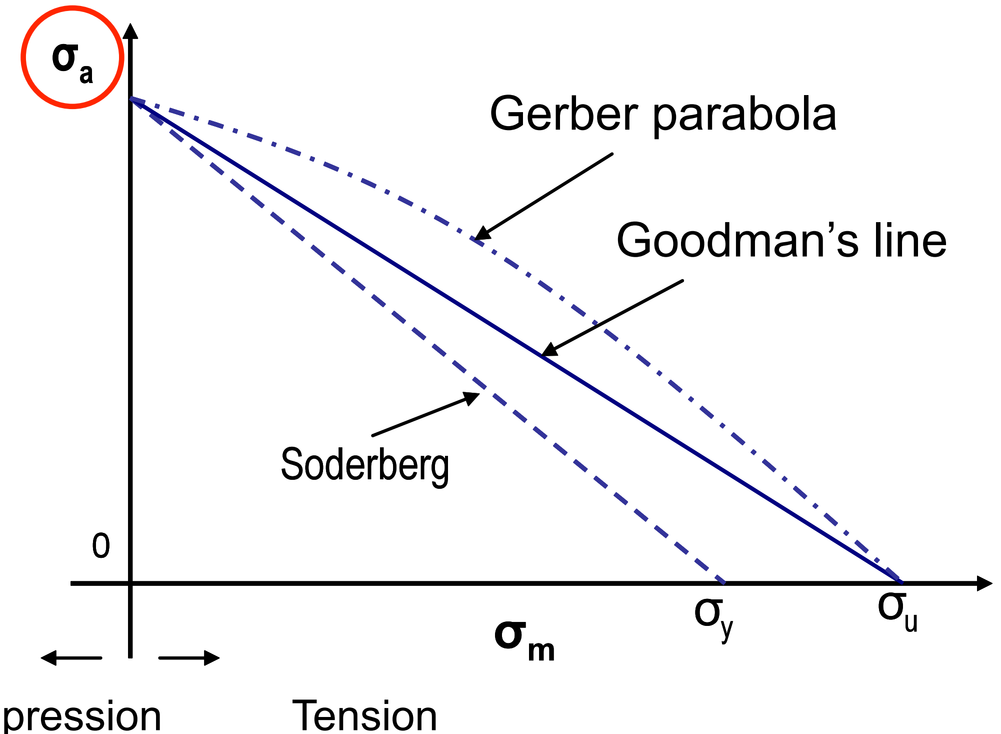
$$\sigma_a\Big|_{\sigma_m \neq 0} = \sigma_a\Big|_{\sigma_m = 0}\left\{1 - \frac{\sigma_m}{\sigma_Y}\right\}$$

Goodman:

$$\sigma_a\Big|_{\sigma_m \neq 0} = \sigma_a\Big|_{\sigma_m = 0}\left\{1 - \frac{\sigma_m}{\sigma_{TS}}\right\}$$

Gerber:

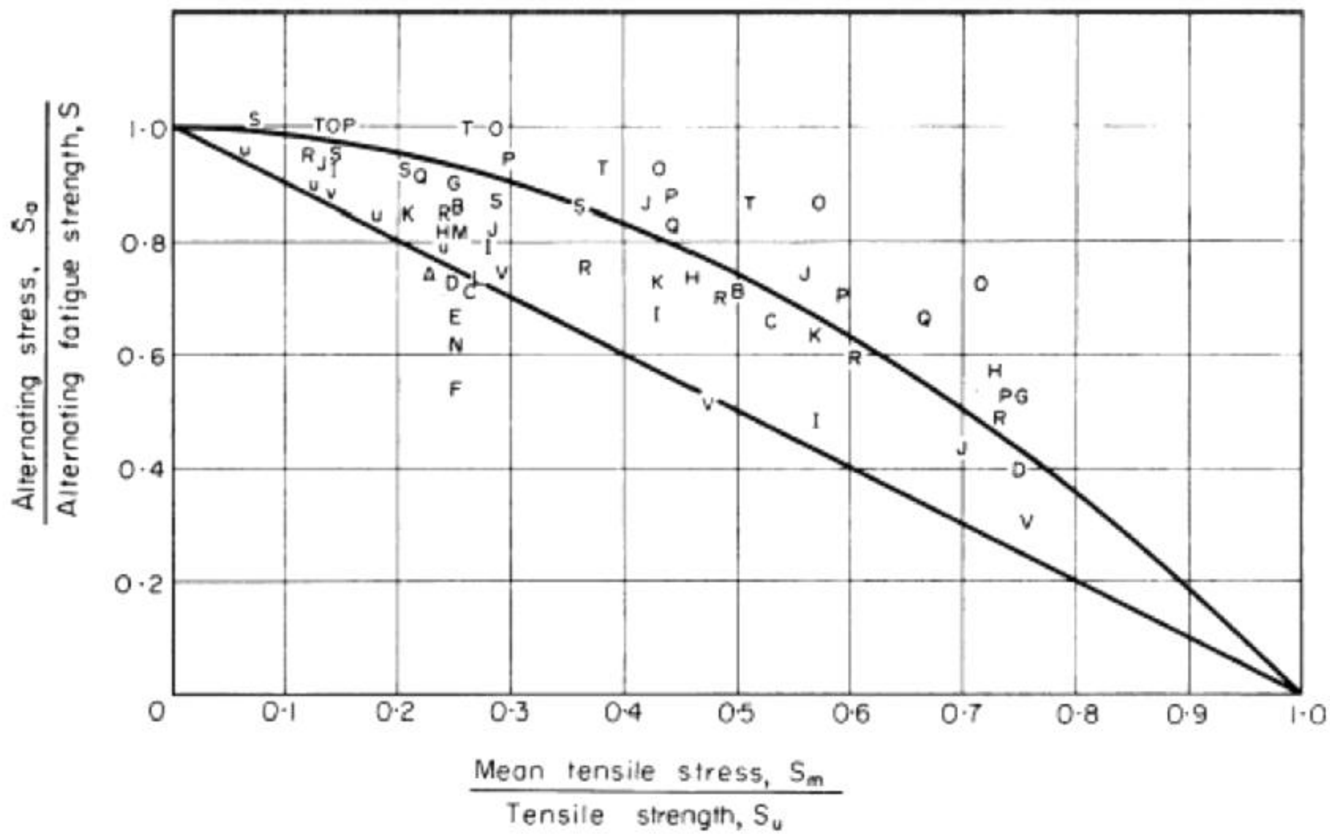
$$\sigma_a\Big|_{\sigma_m \neq 0} = \sigma_a\Big|_{\sigma_m = 0}\left\{1 - \left(\frac{\sigma_m}{\sigma_{TS}}\right)^2\right\}$$



- The various empirical methods available propose simple functions that depend on the parameter, $\sigma_{a(\sigma m = 0)}$. (which determines N_f in the conventional S-N curve).

5.4. S-N CURVES (HCF)

a) Nonzero mean stress: $\sigma_m \neq 0$:



Based on 5 x 10⁸ Cycles. (From P. G. Forrest, *Fatigue of Metals*, Pergamon Press, London, 1962)

5.4. S-N CURVES (HCF)

a) Nonzero mean stress: $\sigma_m \neq 0$:

GENERAL COMMENTS:

- Most of the experimental data are between Gerber and Goodman curves.
- The expression proposed by Goodman works well with brittle materials, being really conservative for ductile materials and, finally, Gerber expression is adequate for ductile materials.
- Soderberg's line is, usually, too conservative (which is not necessarily bad, given the great uncertainties in any fatigue situation).

5.4. S-N CURVES (HCF)

a) Nonzero mean stress: $\sigma_m \neq 0$:

Some References on Fatigue Design

C.C. Osgood — Fatigue Design, 2nd Ed. 1982

R.C. Juvinall — Engineering Considerations of Stress, Strain, and Strength, 1967

H.O Fuchs and R. I. Stephens — Metal Fatigue in Engineering, 1980

J.A. Graham — Fatigue Design Handbook, SAE, 1968

A.F. Madayag — Metal Fatigue: Theory and Design 1969

J.A. Ballantine, J.J. Conner, and J.L. Handrock — Fundamentals of Metal Fatigue Analysis, 1990

N.E. Dowling — Mechanical Behavior of Materials, 1993

5.4. S-N CURVES (HCF)

<u>Suggested exercise</u>:

1) From the following parameters of Basqin's law:

a = 0.090; C_1 = 1320

Obtain the S-N curves for σ_m = –200, –100, 0, 100 and 200 MPa, respectively. Suppose that the elastic limit of the material is σ_Y = 600 MPa.

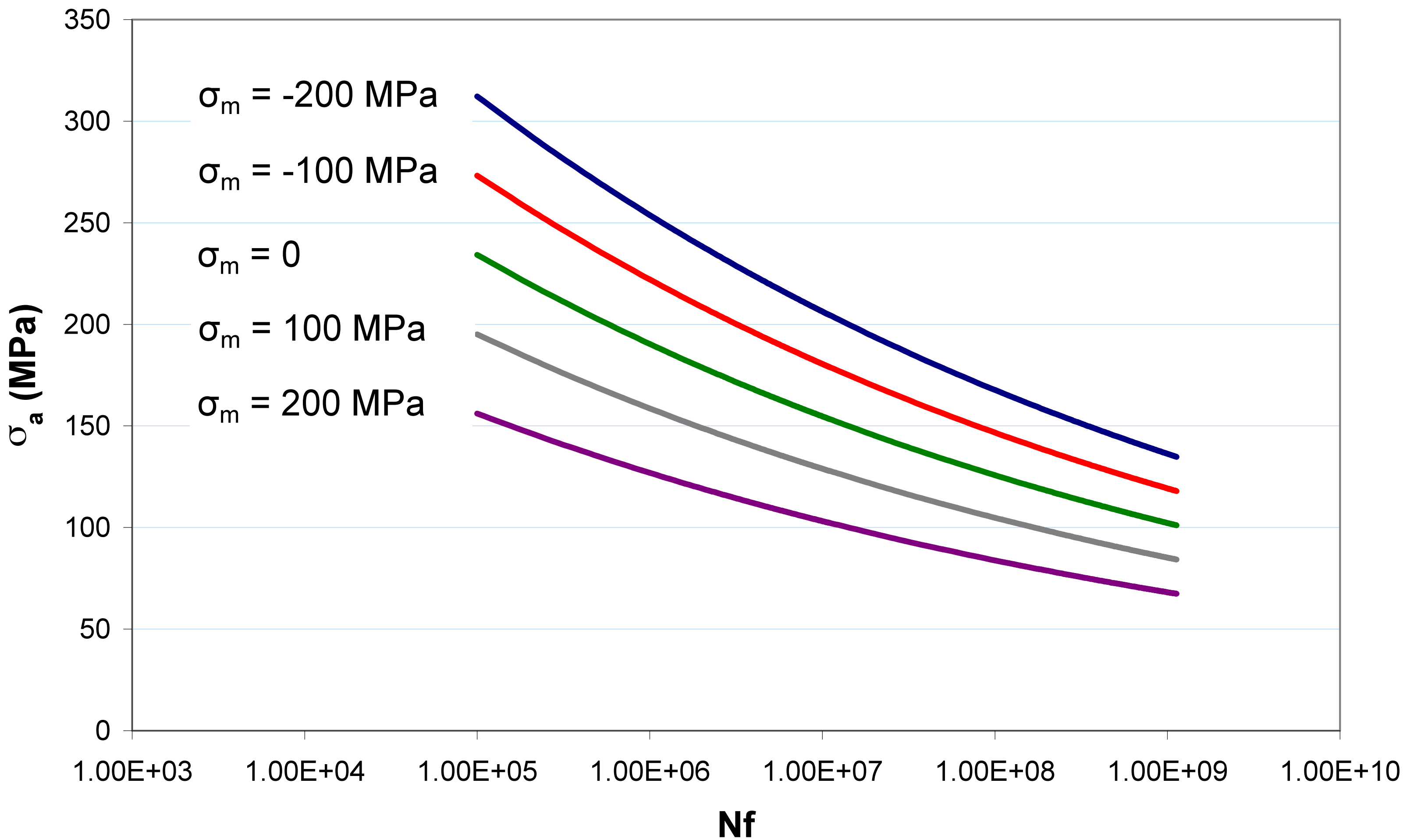
$$\Delta\sigma \cdot N_f^a = C_1 \Rightarrow \sigma_a\big|_{\sigma_m=0} = \frac{C_1}{2} N_f^{-a}$$

$$\sigma_a\big|_{\sigma_m\neq 0} = \sigma_a\big|_{\sigma_m=0} \left\{1 - \frac{\sigma_m}{\sigma_Y}\right\} \Rightarrow \sigma_a\big|_{\sigma_m=0} = \frac{\sigma_a\big|_{\sigma_m\neq 0}}{\left(1-\dfrac{\sigma_m}{\sigma_Y}\right)}$$

$$\boxed{\sigma_a\big|_{\sigma_m\neq 0} = \frac{C_1}{2}\left(1-\frac{\sigma_m}{\sigma_Y}\right)\left(N_f\right)^{-a}}$$

5.4. S-N CURVES (HCF)

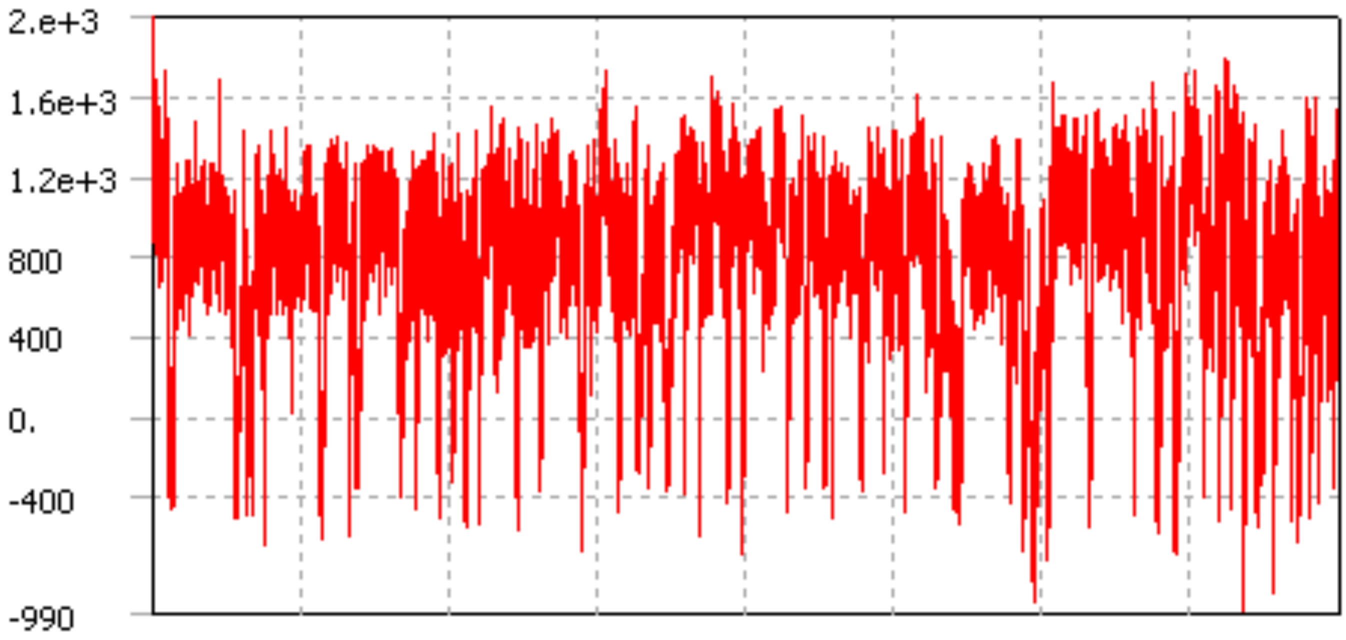
Suggested exercise:



5.4. S-N CURVES (HCF)

b) Variable amplitude over time $\Delta\sigma$ (t)

- **How to solve a situation like this?**



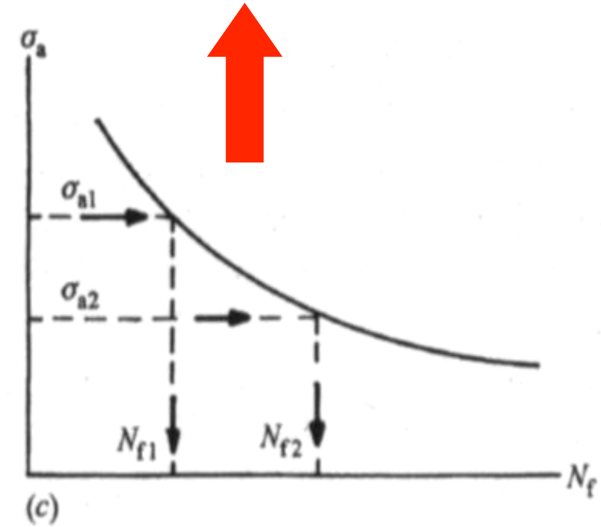
- Scientific literature provides a series of **accumulated damage models**. Among them, **Palmgren-Miner** law (or Miner's rule, 1945) is highlighted.

5.4. S-N CURVES (HCF)

b) Variable amplitude over time Δσ (t)

SEQUENCE OF ACTIONS (MINER'S RULE):

- Correct the data to R = –1 (Soderberg, Goodman, Gerber, etc.).
- Sort the data in i = 1..M blocks of constant amplitude.
- Calculate the associated damage to each "i" block: $d_i = \frac{N_i}{N_{fi}}$
- Get the total damage: $D = \sum_i \frac{N_i}{N_{fi}}$
- Break condition: $D = 1$



5.4. S-N CURVES (HCF)

<u>Suggested exercise</u>:

1) An aluminum alloy, usually used in aeronautical components, presents a behavior in fatigue, analyzed with Basquin's law, with the parameters a = 0.090; C_1 = 1100. A structural component, made with that alloy is still in service after $3.5 \cdot 10^8$ cycles in the following condition: σ_a = 75 MPa, R = –1.

Determine the maximum admissible stress amplitude to ensure, at least, 10.000 cycles of life remaining (assuming R = –1).

5.4. S-N CURVES (HCF)

Suggested exercise:

1) An aluminum alloy, usually used in aeronautical components, presents a behavior in fatigue, analyzed with Basquin's law, with the parameters a = 0.090; C_1 = 1100. A structural component, made with that alloy is still in service after $3.5 \cdot 10^8$ cycles in the following condition: σ_a = 75 MPa, R = –1.

Determine the maximum admissible stress amplitude to ensure, at least, 10.000 cycles of life remaining (assuming R = –1).

$$\frac{N_1}{N_{f1}} + \frac{N_2}{N_{f2}} = 1$$

$$\Delta\sigma \cdot N_f^a = C_1 \quad \Rightarrow (2 \cdot 75)\left(N_{f1}\right)^{0.09} = 1100 \quad \Rightarrow N_{f1} = 4.12 \cdot 10^9$$

$$\frac{3.5 \cdot 10^8}{4.12 \cdot 10^9} + \frac{10000}{N_{f2}} = 1 \quad \Rightarrow N_{f2} = 10929$$

$$\Delta\sigma \cdot N_f^a = C_1 \quad \Rightarrow (2 \cdot \sigma_{a2})(10929)^{0.09} = 1100 \quad \Rightarrow \sigma_{a2} = 238\ MPa$$

5.4. S-N CURVES (HCF)

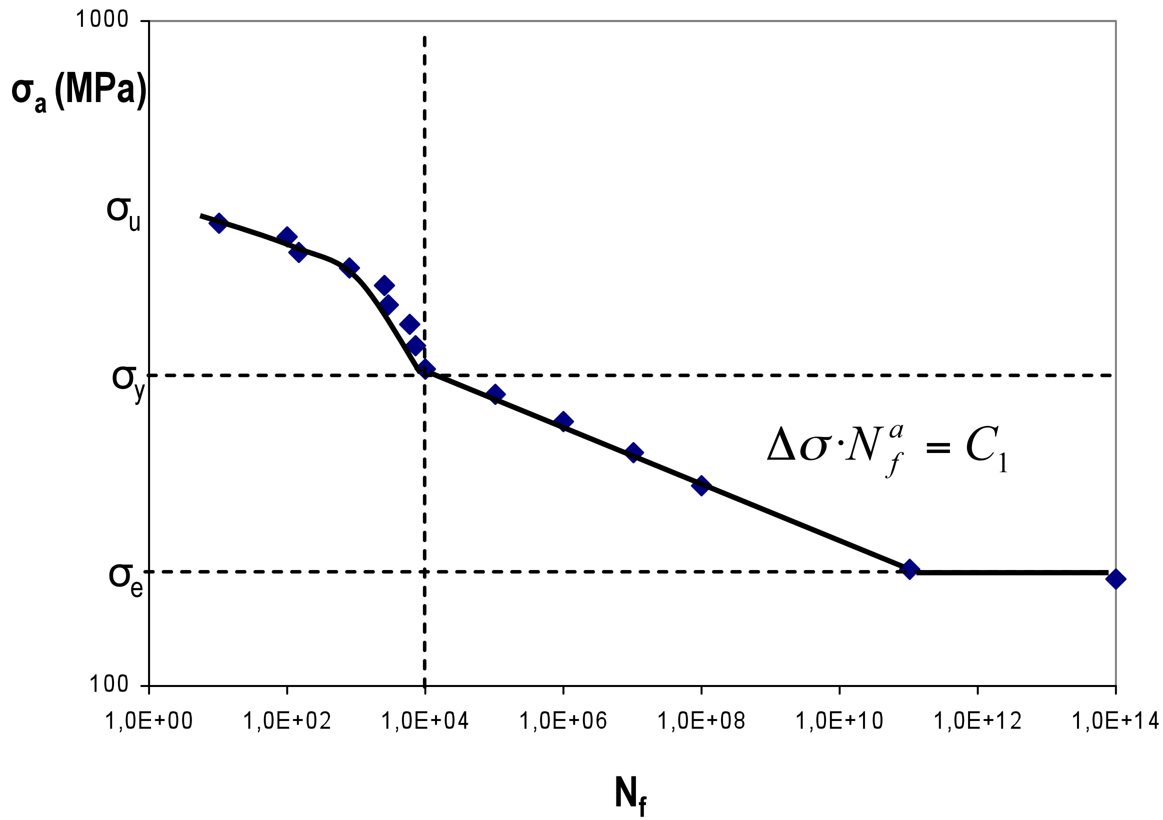
b) Variable amplitude over time Δσ (t)

GENERAL COMMENTS:

- It is an approximate but useful model. However, it has some **significant limitations**:
  - It ignores the intrinsically random nature of fatigue processes.
  - Miner's rule considers that each block operates independently of one another. Therefore, it does **not consider** that the **order in which the sequences of blocks with constant amplitude is applied** can significantly affect the final result. In some cases, blocks with a low amplitude followed by others with a higher amplitude cause a greater damage than what the model predicts.
  - It doesn't allow to take into account the effects of **overloading** (which can slow down the movement of a crack).

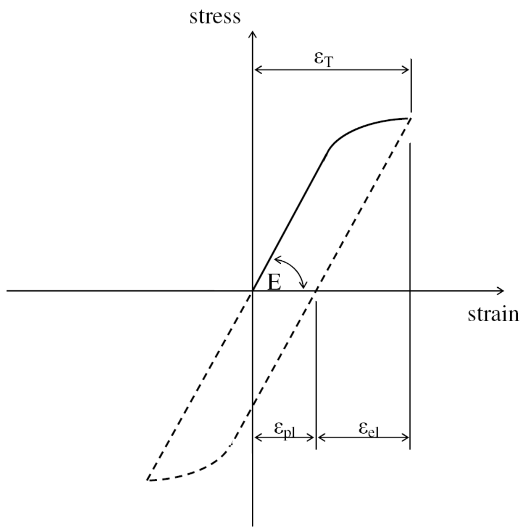
5.5. ε-N CURVES

- If stresses exceed the elastic limit, Basquin's law does not represent faithfully the fatigue behavior of the material.
- This kind of process is called Low Cycle Fatigue (**LCF**), as normally: $N_f < 10000$.



5.5. ε-N CURVES

- It is experimentally proved that the phenomenon is better described working with deformations:
- Total deformation (elastic+ plastic): $\varepsilon_T = \varepsilon_{el} + \varepsilon_{pl}$

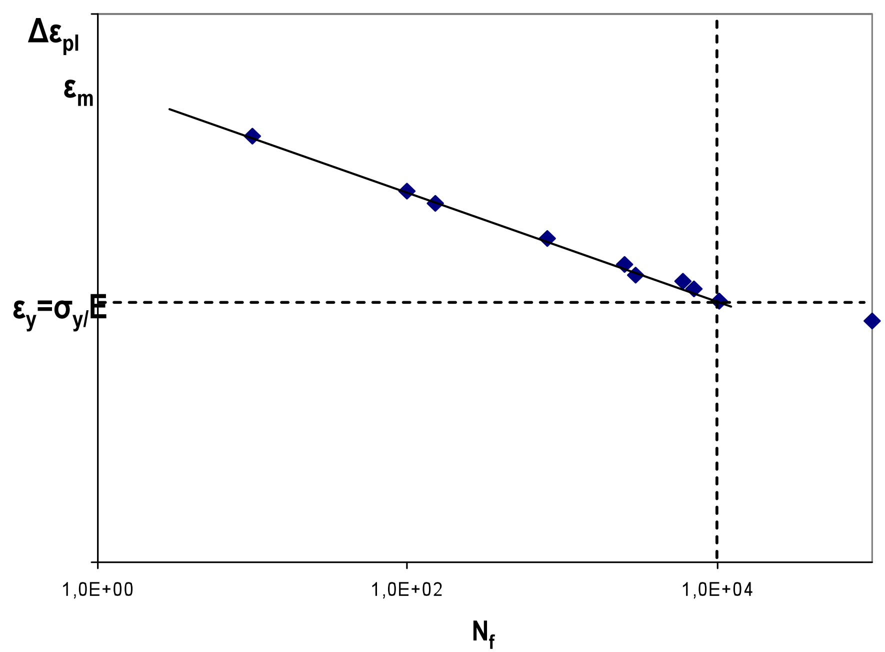


- The external stress is represented by the variation of plastic deformation, $\Delta\varepsilon_{pl}$, leading to the **Coffin-Manson law (1954)**:

$$\Delta\varepsilon_{pl} \cdot N_f^b = C_2$$

Typically:

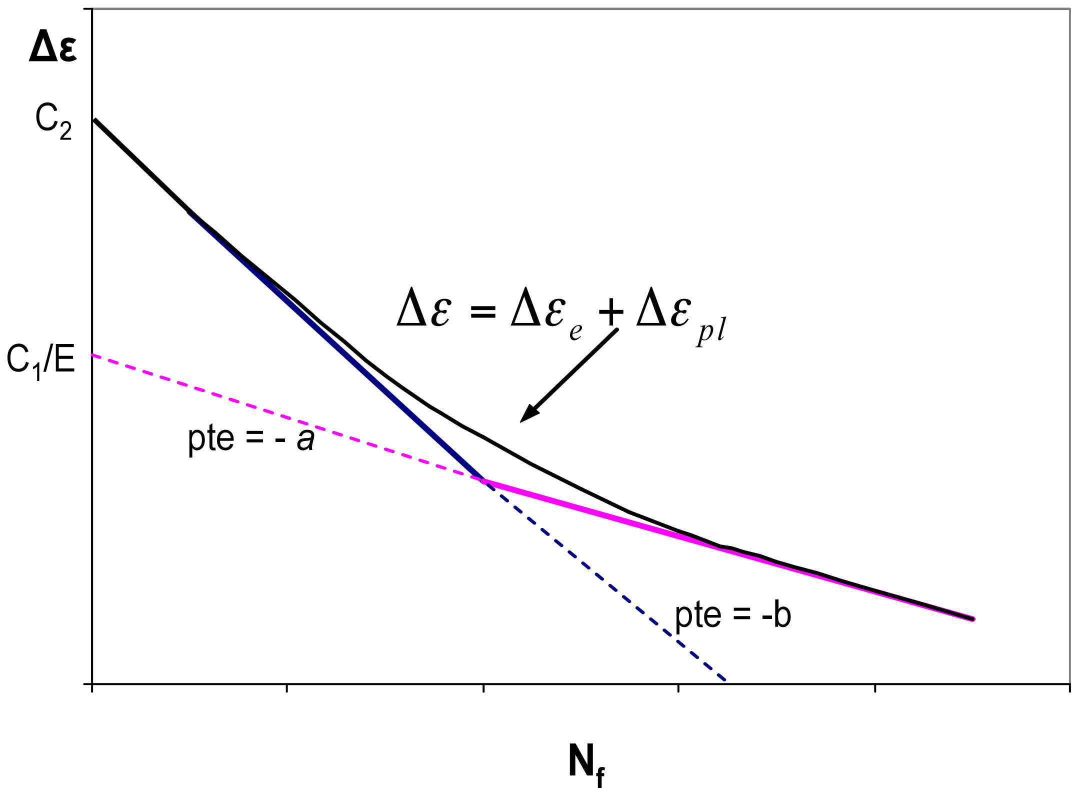
(b ~ 0.5 - 0.7)



5.6. GLOBAL APPROACH

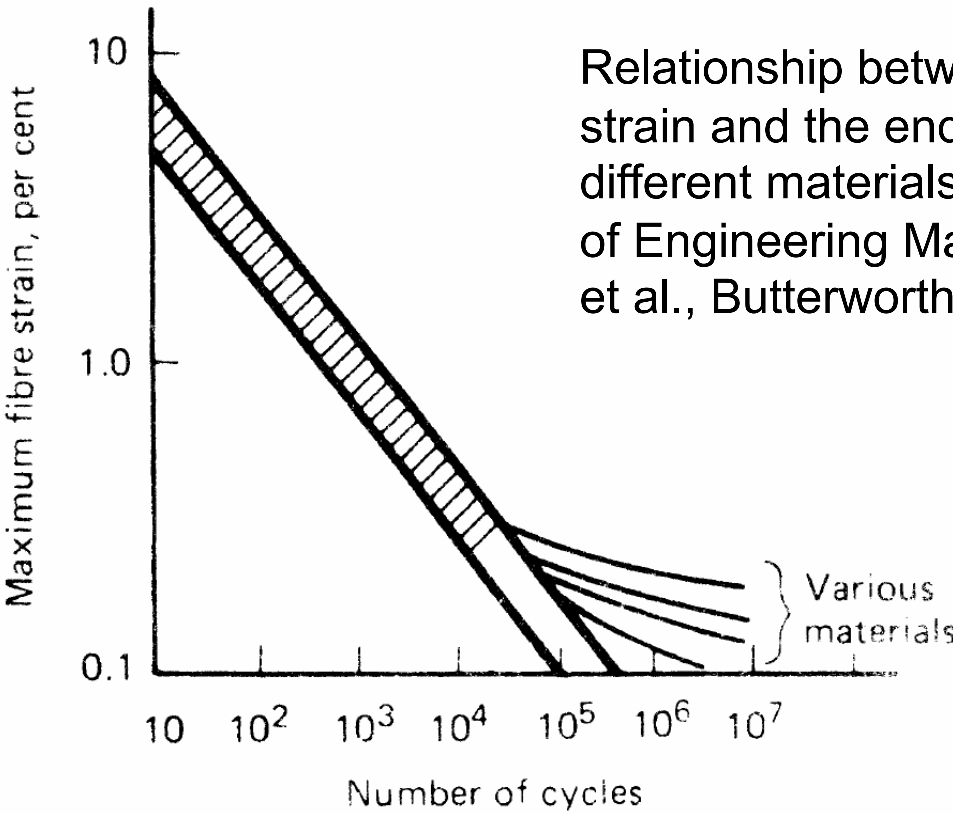
General Approach HCF/LCF:

$$\Delta\varepsilon = \Delta\varepsilon_e + \Delta\varepsilon_{pl} = \frac{\Delta\sigma}{E} + \Delta\varepsilon_{pl} = \frac{C_1}{E} N_f^{-a} + C_2 N_f^{-b}$$



5.6. GLOBAL APPROACH

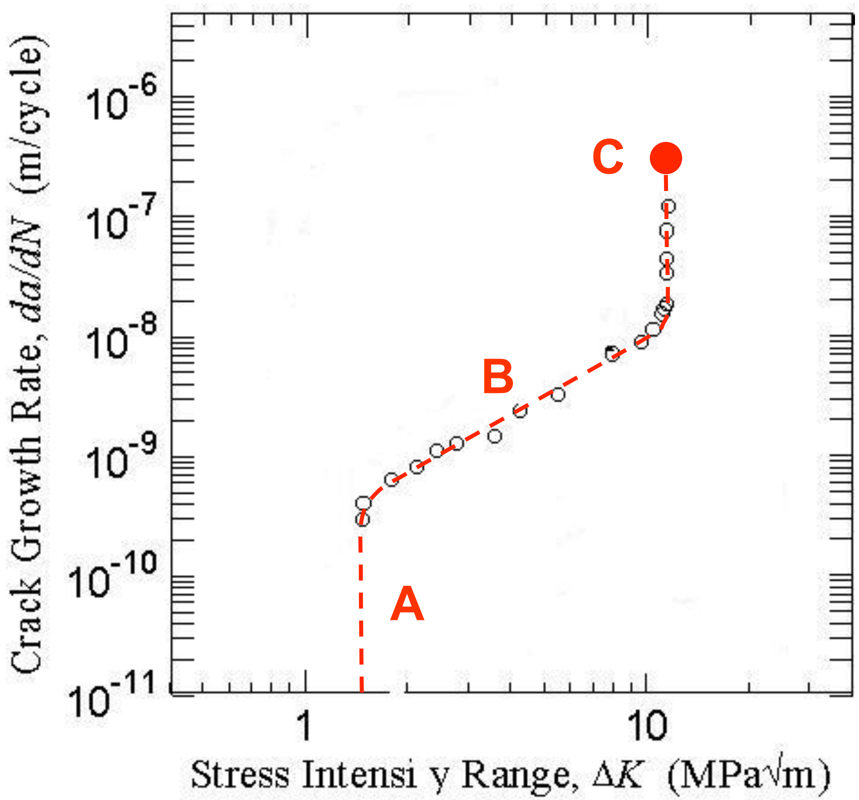
General Approach HCF/LCF:



Relationship between the maximum strain and the endurance limit for different materials (Selection and Use of Engineering Materials, J.A. Charles et al., Butterworth-Heinemann, 2001).

5.7. FATIGUE CRACK GROWTH

- In 1961 MFEL ideas were first applied to crack growth by Paris, Gómez and Anderson.
- It was experimentally observed that the crack growth rate, da/dN, depends on the stress intensity factor increase, ΔK:



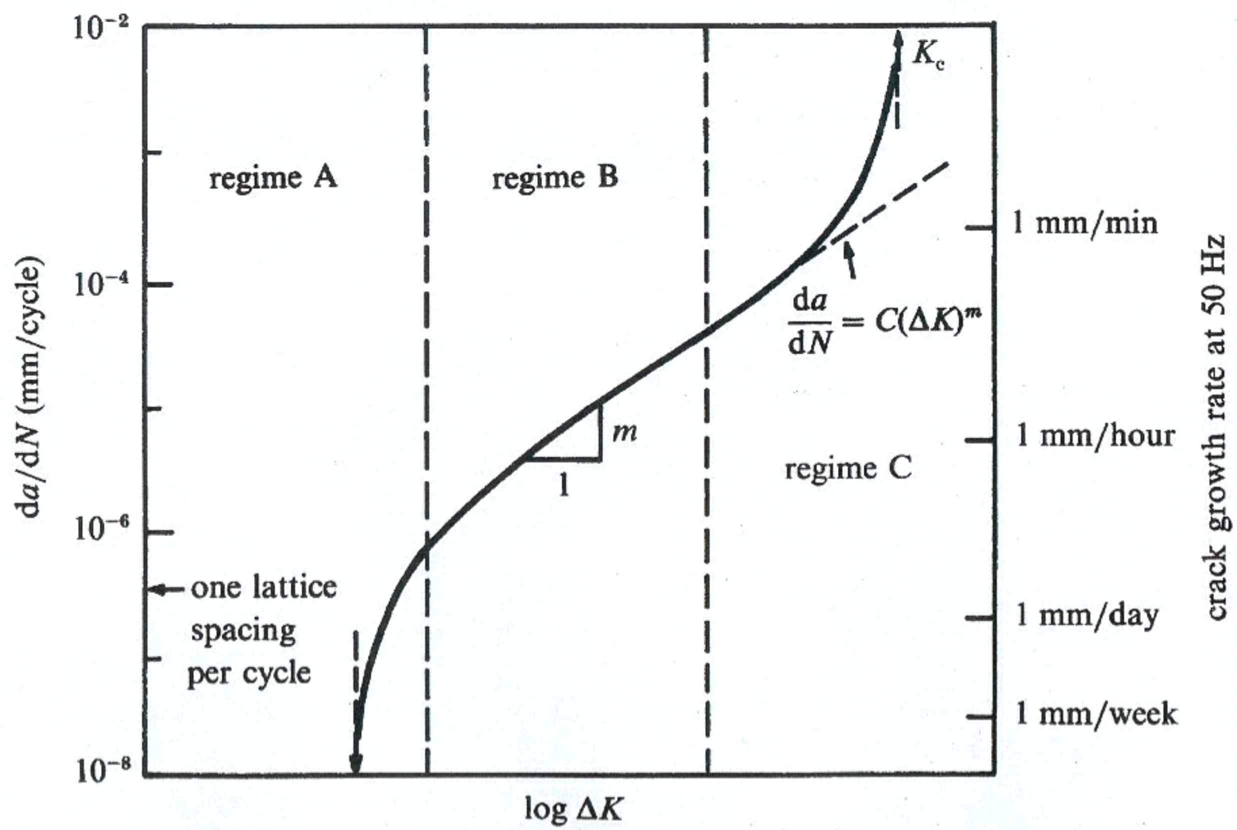
- Phenomenologically, three behavior regions can be distinguished:

5.7. FATIGUE CRACK GROWTH

A. Slow growth (close to threshold).

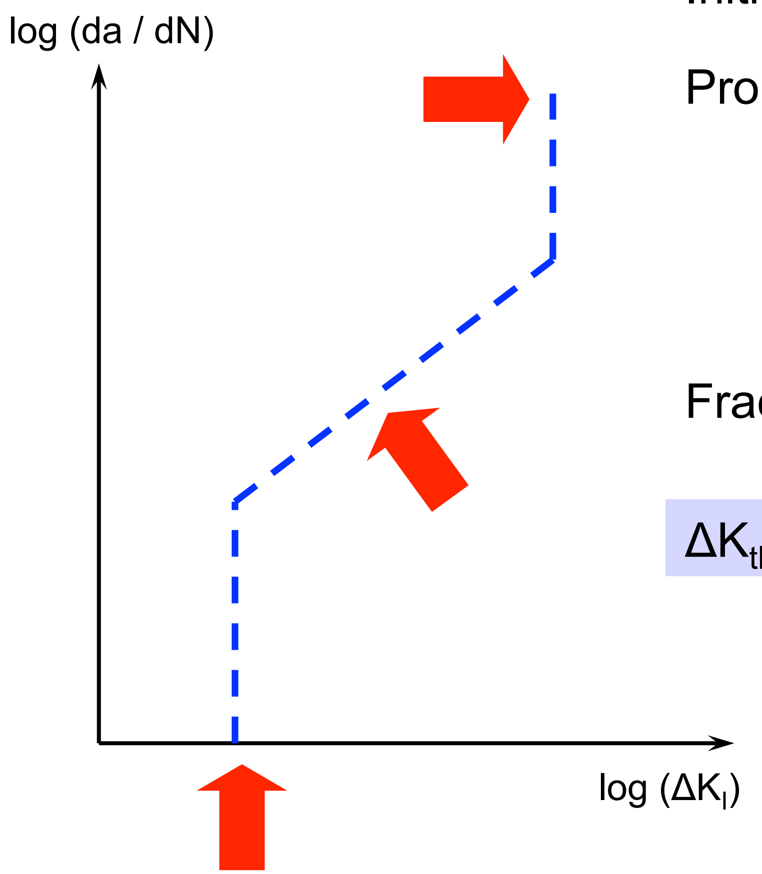
B. Growth with an intermediate rate (Paris regime).

C. Growth at a high rate (close to fracture).



5.7. FATIGUE CRACK GROWTH

MODELING OF THE PHENOMENON:



Initiation condition: $\Delta K_I \geq \Delta K_{th}$

Propagation rate (Paris equation):

$$\frac{da}{dN} = C\left(\Delta K_I\right)^m$$

Fracture condition (MFEL): $K_I\left(\sigma_{max}\right) = K_{Ic}$

ΔK_{th}, C, m, K_{Ic}: Properties of the material.

Table 1: Numerical parameters in the Paris equation.

alloy	m	A
Steel	3	10^{-11}
Aluminum	3	10^{-12}
Nickel	3.3	4×10^{-12}
Titanium	5	10^{-11}

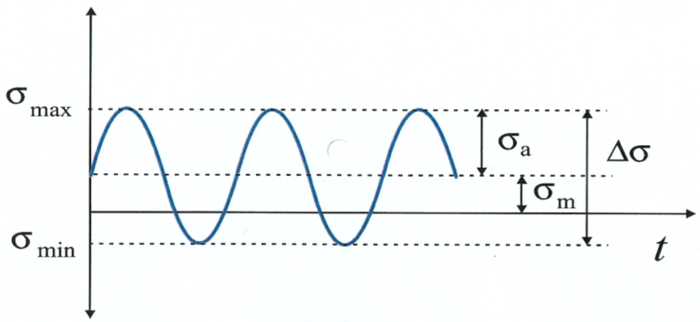
5.7. FATIGUE CRACK GROWTH

REGIME A:

- Simplified, the FIT range, ΔK, must exceed a threshold ΔK_{th}, that depends on the material, so that the movement of the crack occurs.
- In practice, what happens is that, when $\Delta K < \Delta K_{th}$, the crack propagates at undetectable rates.
- **Practical definition:** when the growth rate of the crack falls below 10^{-8} mm/cycle, it is considered that the crack has stopped; in this situation, ΔK is called ΔK_{th}.
- This limit represents a mean propagation rate lower than the interatomic space per cycle. How is this possible?
- It is considered that there is a great number of cycles in which there is no movement at all, that is, the crack grows an interatomic space in one cycle and then it stabilizes for several cycles.

5.7. FATIGUE CRACK GROWTH

REGIME B: the integration of Paris law lets us determine the remaining number of cycles to failure:



- Si $\sigma_{min} > 0$: $\Delta K_I = K_I(\sigma_{max}) - K_I(\sigma_{min})$
- Si $\sigma_{min} < 0$: $\Delta K_I = K_I(\sigma_{max})$

$$\frac{da}{dN} = C(\Delta K_I)^m \Rightarrow \frac{da}{dN} = C\left[M\,\Delta\sigma\sqrt{\pi\,a}\right]^m \Rightarrow \frac{da}{a^{m/2}} = C(M\,\Delta\sigma)^m\,\pi^{m/2}\,dN$$

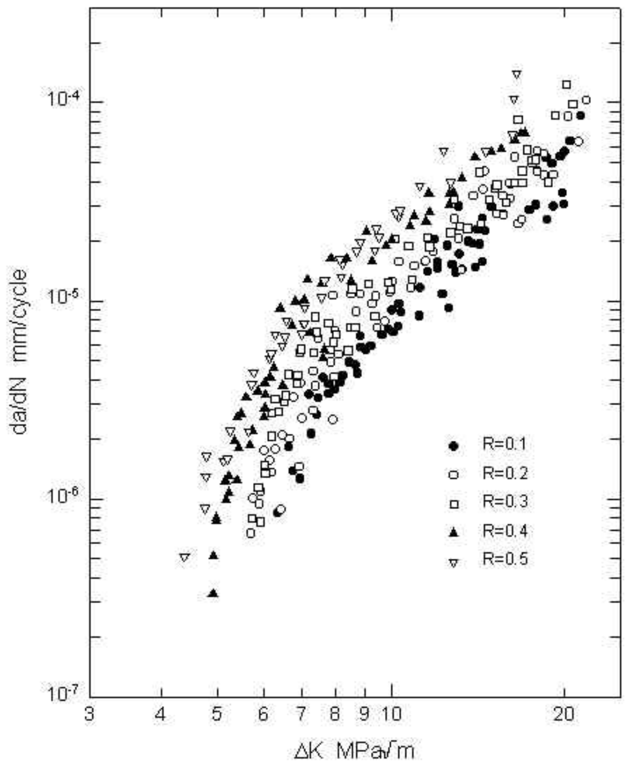
$$\int_{a_0}^{a_c}\frac{da}{a^{m/2}} = C(M\,\Delta\sigma)^m\,\pi^{m/2}\int_0^N dN \Rightarrow N = \frac{1}{C(M\,\Delta\sigma)^m\,\pi^{m/2}}\int_{a_0}^{a_c}\frac{da}{a^{m/2}}$$

$$\int_{a_0}^{a_c}\frac{da}{a^{m/2}} = C(M\,\Delta\sigma)^m\,\pi^{m/2}\int_0^N dN \Rightarrow N = \frac{1}{C(M\,\Delta\sigma)^m\,\pi^{m/2}}\int_{a_0}^{a_c}\frac{da}{a^{m/2}}: \begin{cases} m \neq 2: & N = \dfrac{a_c^{1-\frac{m}{2}} - a_0^{1-\frac{m}{2}}}{\left(1-\dfrac{m}{2}\right)C(M\,\Delta\sigma)^m\,\pi^{m/2}} \\ m = 2: & N = \dfrac{\ln\left(\dfrac{a_c}{a_0}\right)}{C(M\,\Delta\sigma)^m\,\pi^{m/2}} \end{cases}$$

5.7. FATIGUE CRACK GROWTH

REGIME B:

- Typical parameters of the material, m and C, are experimentally determined.
- In metals m it varies typically between 2 and 4, while for ceramics and polymers it can be up to 100.
- In those cases in which M is not independent of the crack length, the integral should be solved numerically.
- The model assumes that the crack growth is independent of the stress rate: $R = \sigma_{min} / \sigma_{max}$.



5.7. FATIGUE CRACK GROWTH

REGIME B:

- The integration of Paris law requires knowing the initial and final crack lengths, a_0 y a_c:
- How to experimentally determine the **initial crack length**?:
  - There are several techniques: visual inspection, ultrasounds, X-rays, etc.
  - If an equipment with a resolution of 'x' can not detect cracks it must be assumed, conservatively, the existence of a 'x' sized crack.
- How to determine the **final crack length** (assuming that it is the break one)?

$$K_I(\sigma_{\max}) = K_{Ic} \quad \Rightarrow \quad M\,\sigma_{\max}\sqrt{\pi\, a_c} = K_{Ic} \quad \Rightarrow \quad a_c = \frac{1}{\pi}\left(\frac{K_{Ic}}{M\,\sigma_{\max}}\right)^2$$

5.7. FATIGUE CRACK GROWTH

REGIME B:

- From the previous analysis raises a really important idea: **even when there are detected cracks on a component or structure it is not necessary to stop using and remove it!**
- For this statement to make sense we must evaluate the remaining life.
- The component can continue working as long as it is periodically inspected.

5.7. FATIGUE CRACK GROWTH

REGIME C:

- Failure of an structure or a component after a fatigue process can occur by two different mechanisms:
  - For high values of ΔK the propagation rate grows really fast until it gets to the final **Fracture** when the fracture toughness of the material is reached:
    - Ex: many steels at low temperature.
  - **Plastic collapse** of the remaining section:
    - Ex: room temperature in ductile materials.

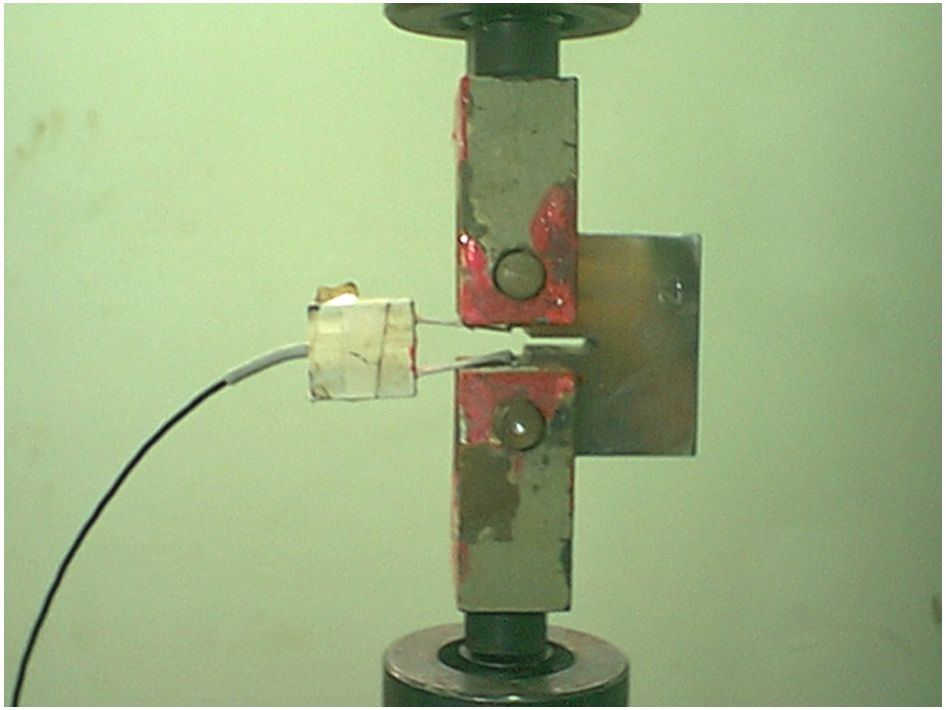
5.8. DETERMINATION OF PARIS LAW

- **Objective:** determination of Paris law:
  - *Methodology: based on MFEL crack propagation rate is determined depending on ΔK:*
    1. Election of the typical specimen in MF (CT, SENB...).
    2. Load application system (Constant amplitude).
    3. Crack propagation tracking method depending on N.
    4. Obtaining the mean propagation rate in zone II.
    5. Threshold determination ΔK_{th}.
    6. Logarithmical representation of da/dN-log ΔK and adjustment with Paris parameters.
- **Normative:** ASTM E-647.

5.8. DETERMINATION OF PARIS LAW

1. Election of the typical **specimen** in MF (CT).

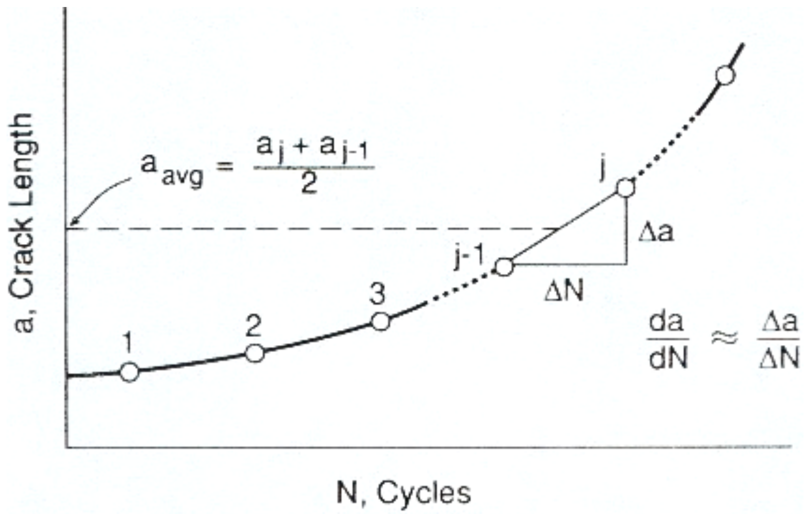
2. **Load** application system (Constant amplitude).

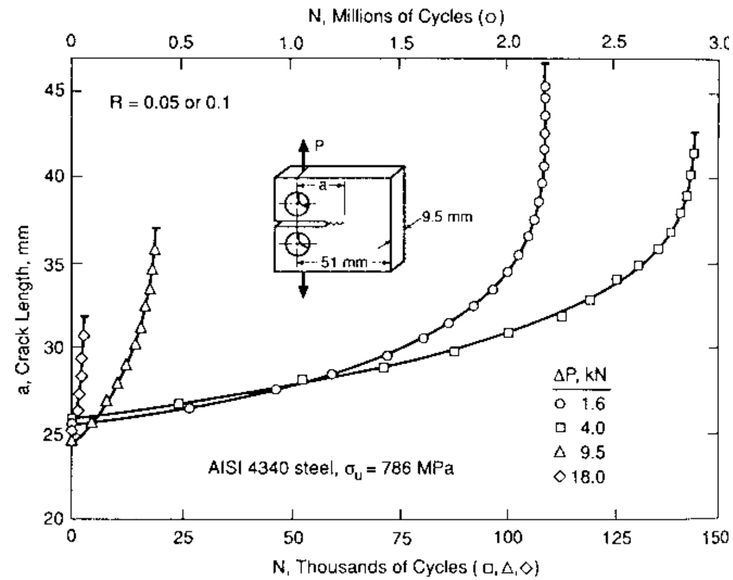


$$\Delta K = \frac{\Delta P}{B\sqrt{W}} f\left(\frac{a}{W}\right)$$

5.8. DETERMINATION OF PARIS LAW

3. Crack propagation tracking method depending on time (f) or N cycles: optical methods, flexibility…

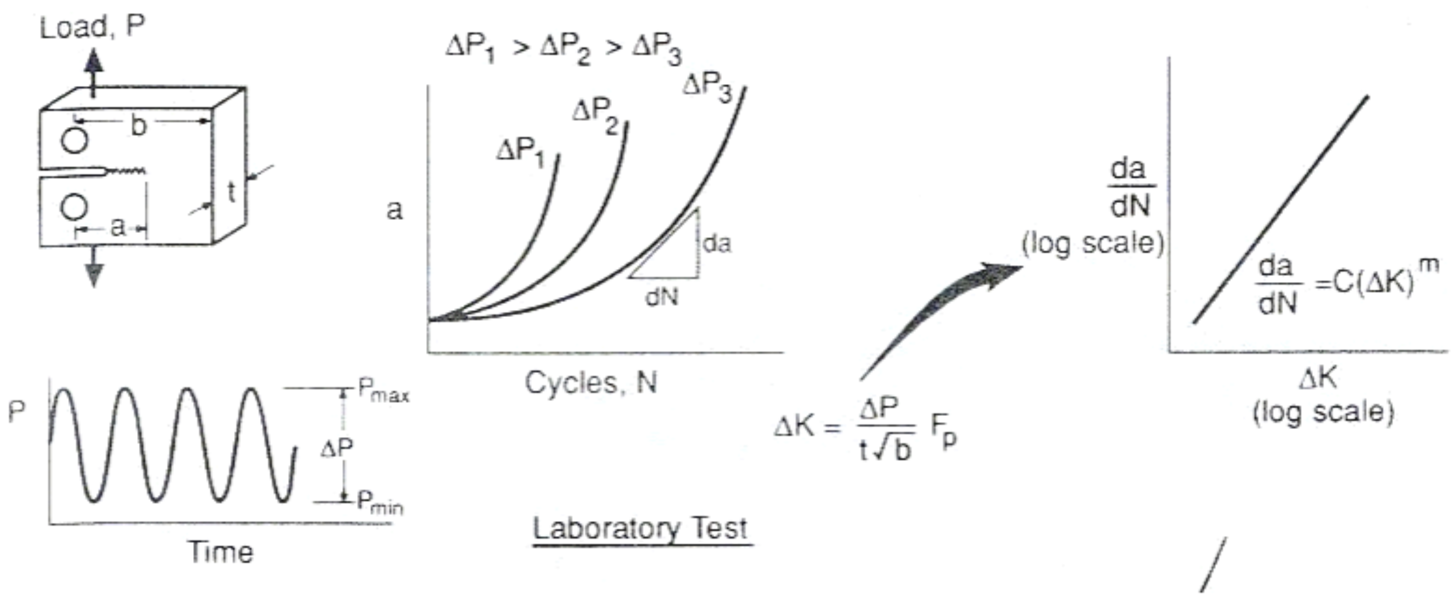




5.8. DETERMINATION OF PARIS LAW

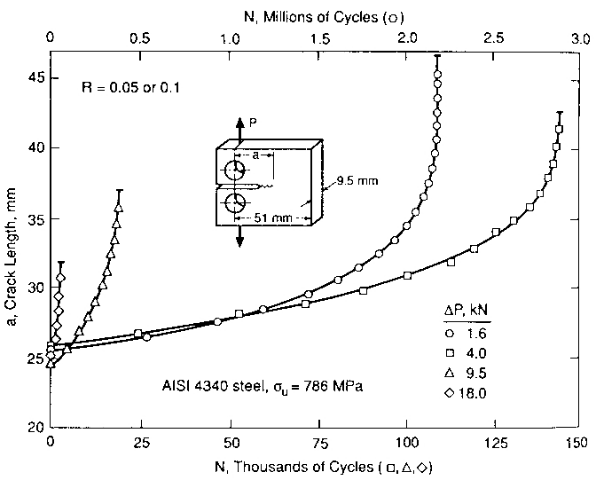
4. Obtaining the mean propagation rate in zone II.

5. Logarithmical representation of da/dN-log ΔK and adjustment with Paris parameters.

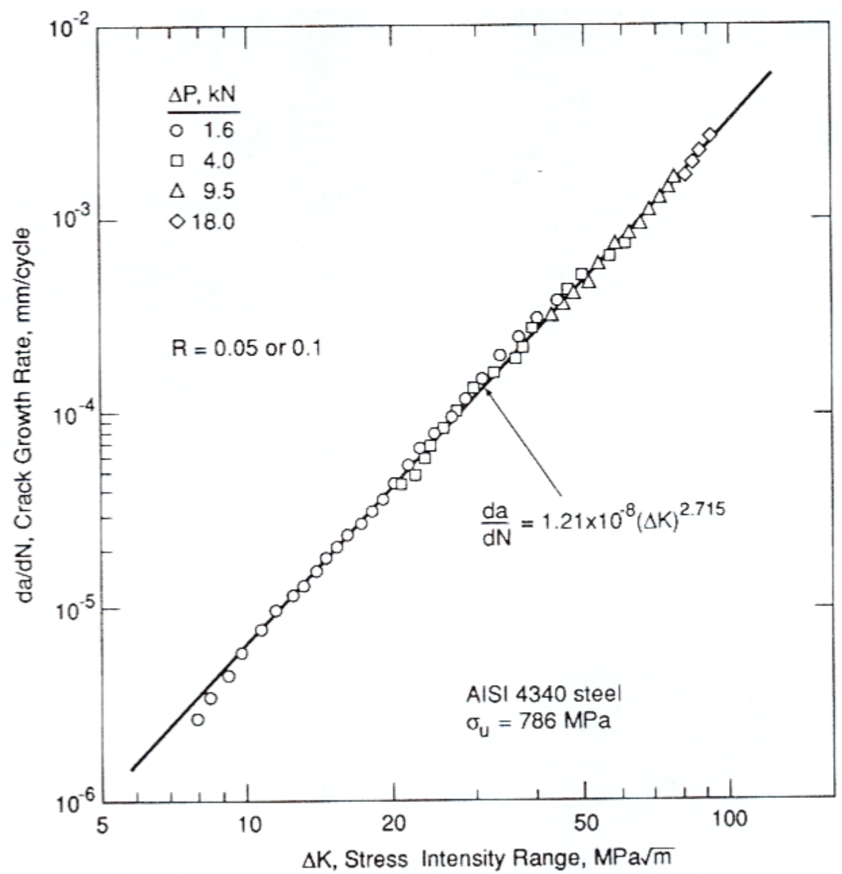


5.8. DETERMINATION OF PARIS LAW

- **Example:** determination of da/dN_{II}, m and C in steels AISI4130.



$$\Delta K = \frac{\Delta P}{B\sqrt{W}} f\left(\frac{a}{W}\right)$$



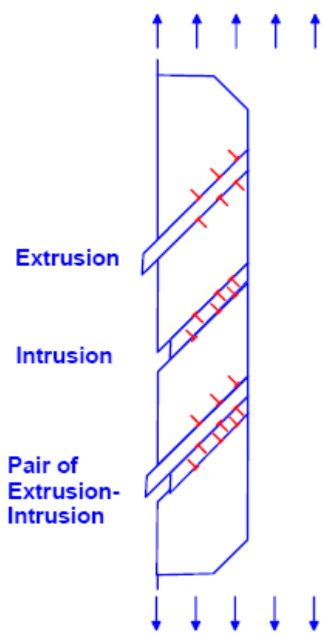
5.9. FACTORS INFLUENCING THE PROPAGATION

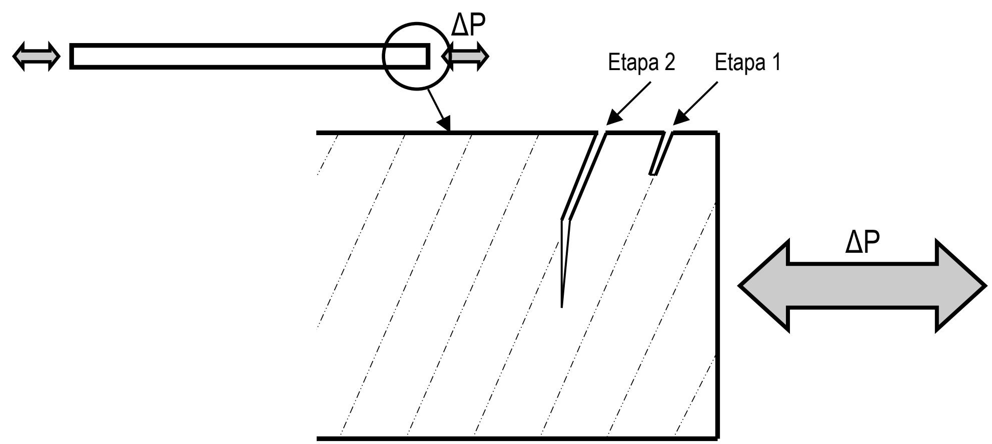
Regime	A Slow growth	B Paris zone	C Fast growth
Microscopy break	Mode II (shear) Fragile facets	Striations (mode I) Waves plane	Cleavages, microslits.
Influence of the microstructure	High	Low	High
R Effect	High	Low	High
Atmosphere effect	High	*	Low
Tensional level Plastic zone	$r_c < d_g$	$r_c > d_g$	$r_c >> d_g$
*Depends on the atmosphere, frequency and material SCC, FC.			

5.10. FATIGUE MICROMECHANISM

NON CRACKED COMPONENTS:

- **Low Cycle Fatigue:** plasticizing caused by high stresses applied generates a roughness on the surface of the component or structure. That roughness causes the crack to form, in a first stage along a slip plane (phase that essentially corresponds with the initiation) and finally (second stage) perpendicularly to the variation of the acting stresses, as will be seen for the case of Fatigue of Cracked Components.





5.10. FATIGUE MICROMECHANISM

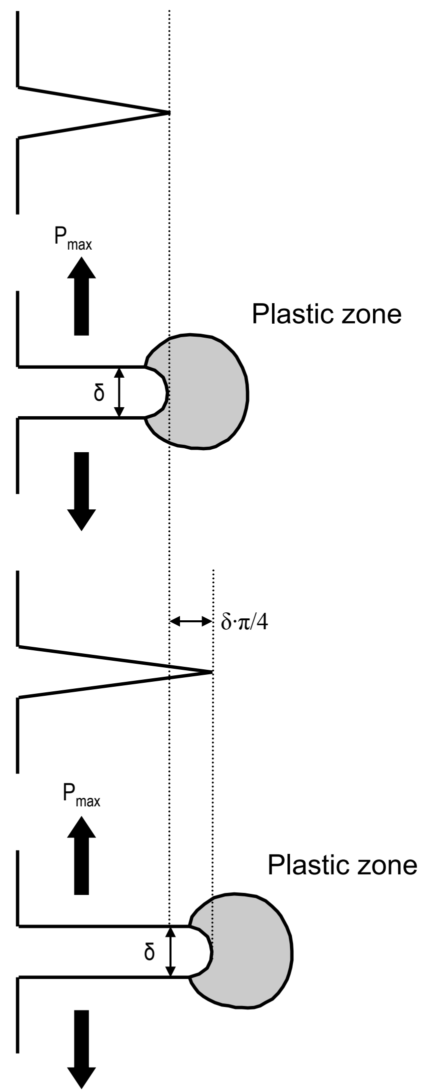
NON CRACKED COMPONENTS:

- **High Cycle Fatigue:** even if the applied stress is lower than the elastic limit, there will be a local plasticization wherever there is a notch, a scratch or a change in section that acts as a stress concentrator. This local plasticization will generate the appearance of cracks in a similar way as it occurs in Low Cycle Fatigue, consuming the initiation of most part of fatigue life.
- From all that has been said, we can deduce that the existence of stress concentrators greatly limits the fatigue life of High Cycle Fatigue.

5.10. FATIGUE MICROMECHANISM

CRACKED COMPONENTS:

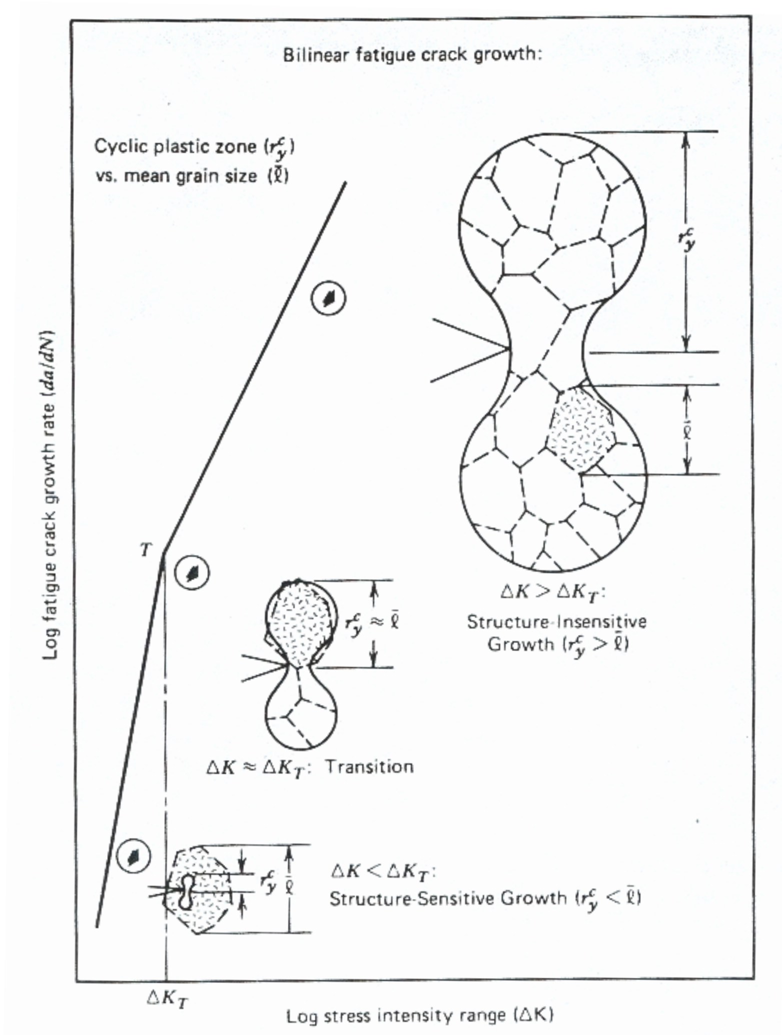
- The application of tension stresses generates a plastic zone in the crack front that makes this last one to round off a certain magnitude, δ, generating a new crack surface. Once the maximum tension, as the loading cycle goes, the tensions decrease and the new created surface folds forward, causing the crack extension (approximately π · δ/4).
- The process is repeated on each loading cycle.



5.10. FATIGUE MICROMECHANISM

CRACKED COMPONENTS:

- **Regions A and B.**
- Propagation modes:

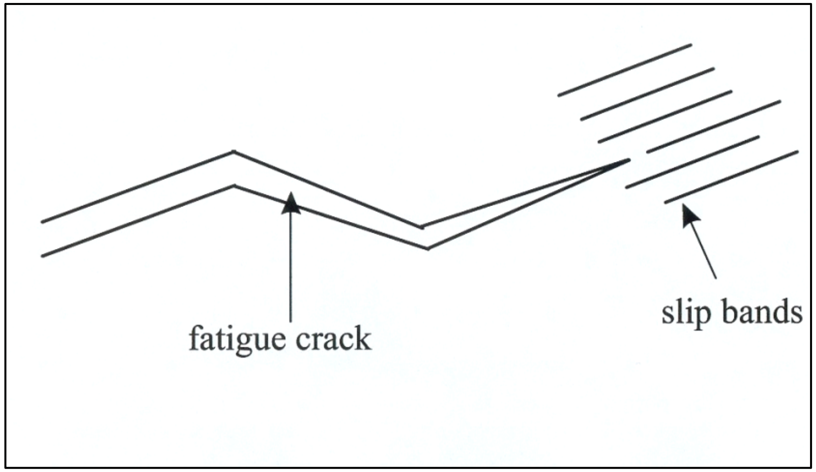


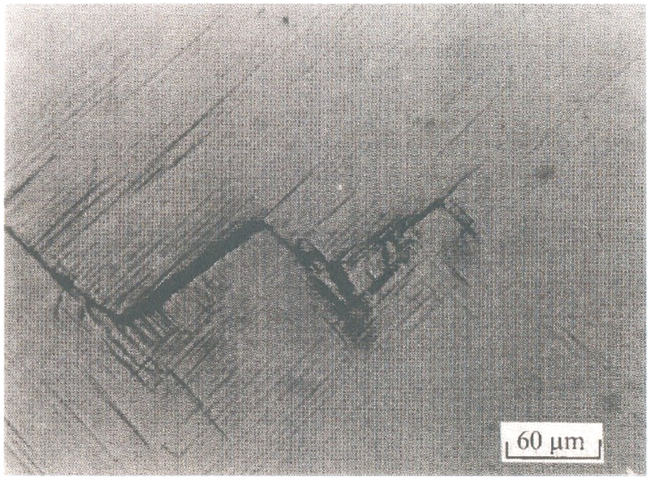
5.10. FATIGUE MICROMECHANISM

CRACKED COMPONENTS:

Region A:

- **Threshold area:** $r_y < d$. Propagation takes place through the slip planes. Mode II of fracture (shear)



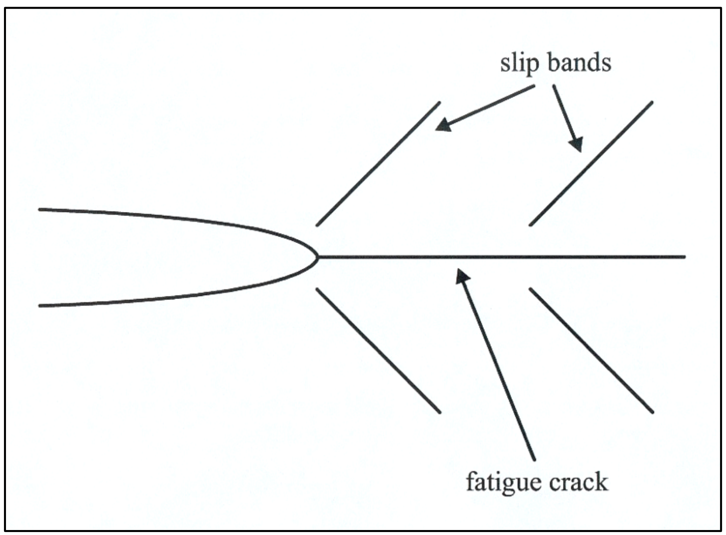


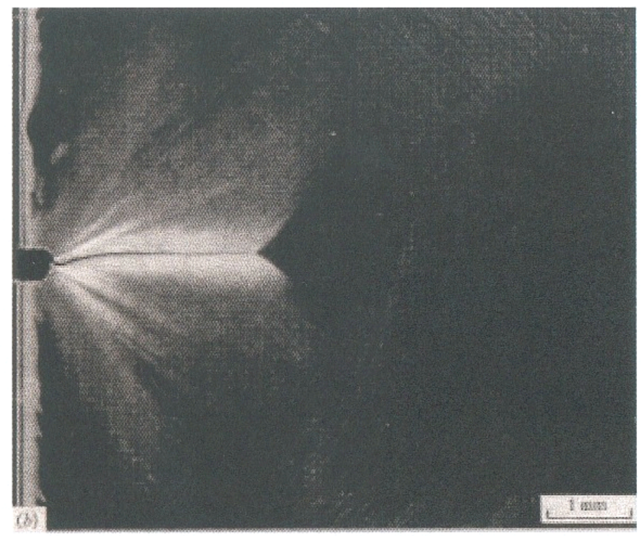
5.10. FATIGUE MICROMECHANISM

CRACKED COMPONENTS:

Region B:

- **Zone II Paris Law:** r_y > d. The implication of many simultaneous slip planes causes the crack to propagate through the intersection between them. STRIATIONS – Fracture mode I (tension):





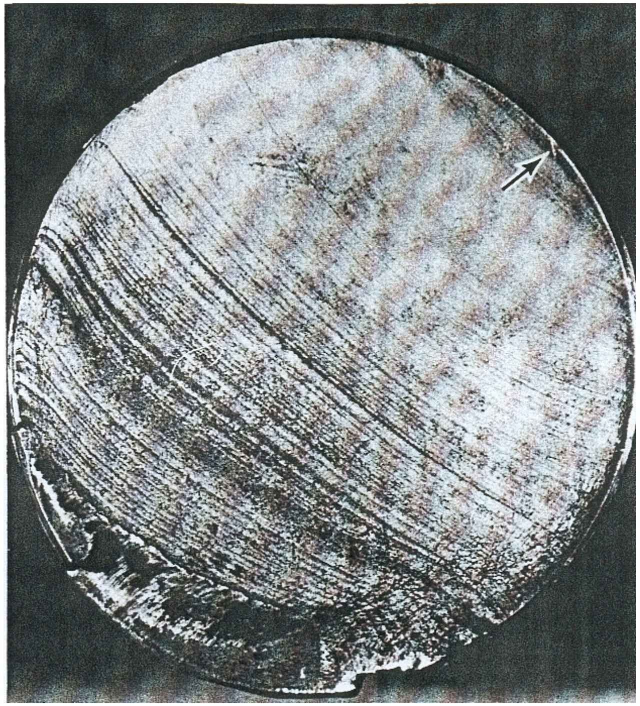
5.10. FATIGUE MICROMECHANISM

FRACTOGRAPHIC ASPECTS:

Regime B:

- A crack that propagates due to fracture leaves some characteristic marks known as **striation or beach lines**. Those marks are, usually, the clearest evidence of a fracture caused by fatigue.

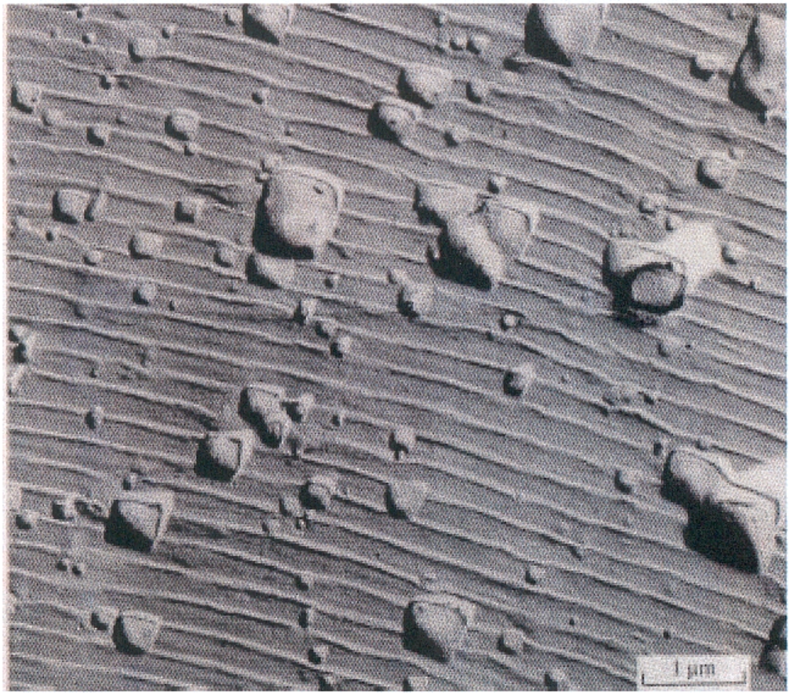
- Striation are the marks that the propagation of cracks in several cycles leaves on the propagation surface.



5.10. FATIGUE MICROMECHANISM

Regime B:

$$\frac{da}{dN} \approx \Delta\delta_t = \beta \frac{(\Delta K)^2}{\sigma'_y E'}$$

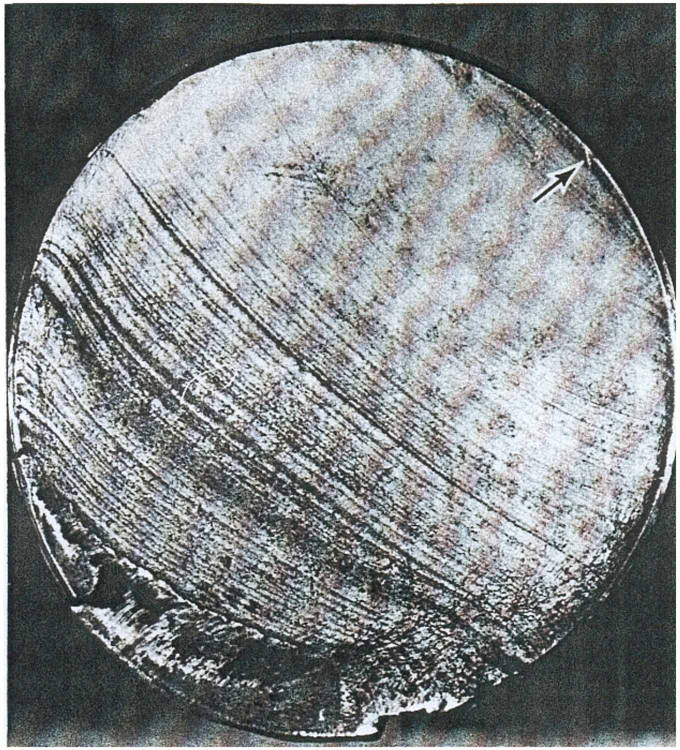


5.10. FATIGUE MICROMECHANISM

Regime C:

- In the final break section growth lines dissapear, while the following can be developed:

  1. Micromechanisms of **cleavage** and/or **ductile tearing** if the break is due to fracture.
  2. **Microvoids** if it is due to a plasticizing process of the remaining section.



5.11. FATIGUE DESIGN

SAFE-LIFE:

- **Philosophy:** crack free elements.
- **Stages:**
  - Determination of load spectrum
  - Estimate the useful life of the material with laboratory tests.
  - A safety coefficient is applied.
  - **Initiation of crack propagation.** At the end of the estimated life, the component is removed even when it still has left a remarkable life.
  - Periodic inspections.
  - Ex: pressure vessel, jet engines.

5.11. FATIGUE DESIGN

SAFE-LIFE / Tolerable damage:

- **Philosophy:** presence of cracks, tolerable until the reach a critical size.
- **Periodic inspections:** design of inspection periods to detect the crack before it reaches the critical size.
- **Stages:**
  - A component is removed when its estimated life is coming to an end: Detectable crack smaller than critical size.
  - Ex: aeronautical industry.

5.11. FATIGUE DESIGN

REAL CASE:

- **Approach:** fatigue problems analysis in gas turbines of the type F-100 used in airplanes F-15 and F-16 of USAF.
- **Traditional approach (Safe-life):** after a statistical study, 1000 pieces were removed when only one of them had a crack that was < 0.75 mm.
- **New approach (Fail-Safe):**
  - From 1986 to 2005, 3200 engines of the USAF inventory were analyzed. In each engine, 23 components were analyzed.
  - Save foreseen by not justified removals: 1,000,000,000$.