دانشگاه صنعتی اصفهان
دانشکده مکانیک

Fatigue

Introduction

Key Idea: Fluctuating loads are more dangerous than monotonic loads.

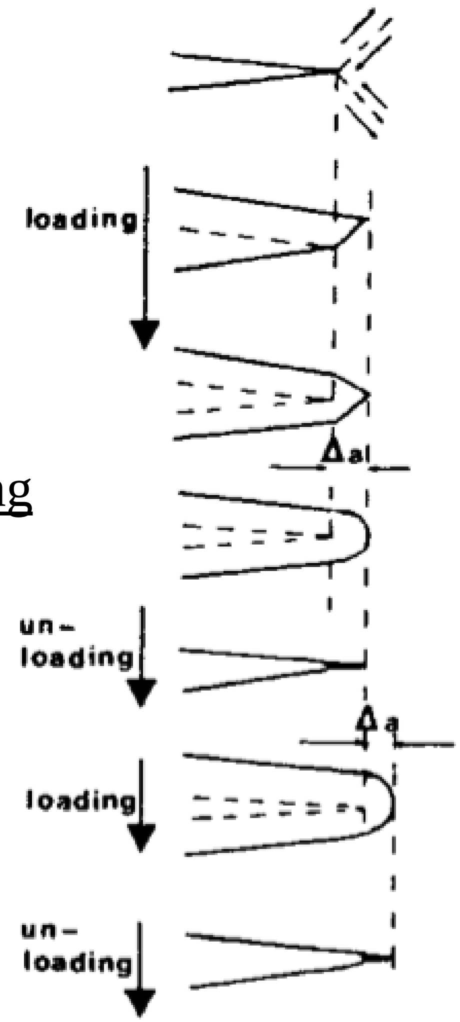
Fatigue occurs occur always and everywhere and is a major source of mechanical failure.

Fatigue fracture is prevalent!

- Deliberately applied load reversals (e.g. rotating systems)
- Vibrations (machine parts)
- Repeated pressurization and depressurization (airplanes)
- Thermal cycling (switching off electronic devices)
- Random forces (ships, vehicles, planes)

Introduction

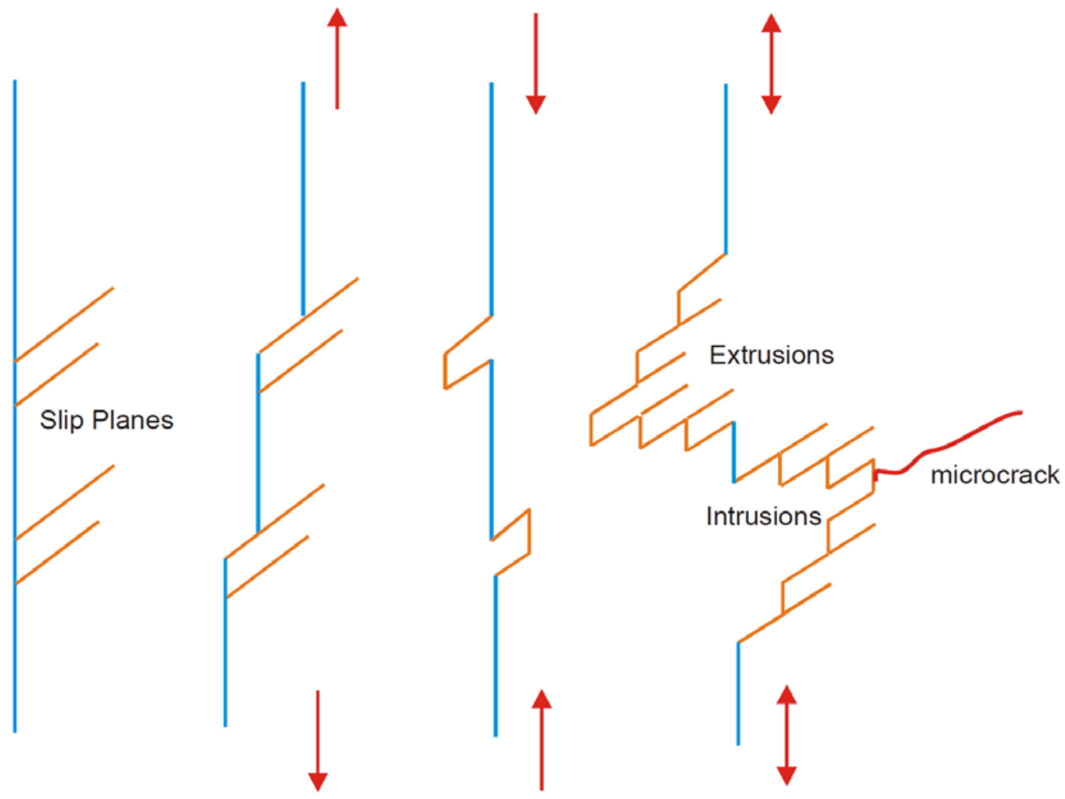
- Fatigue occurs when a material is subjected to repeated loading and unloading (cyclic loading).
- Under cyclic loadings, materials can fail (due to fatigue) at stress levels well below their yield strength or crack propagation limit-> fatigue failure.
- ASTM defines fatigue life, N_f, as the number of stress cycles of a specified character that a specimen sustains before failure of a specified nature occurs.



Fatigue – Threshold regime

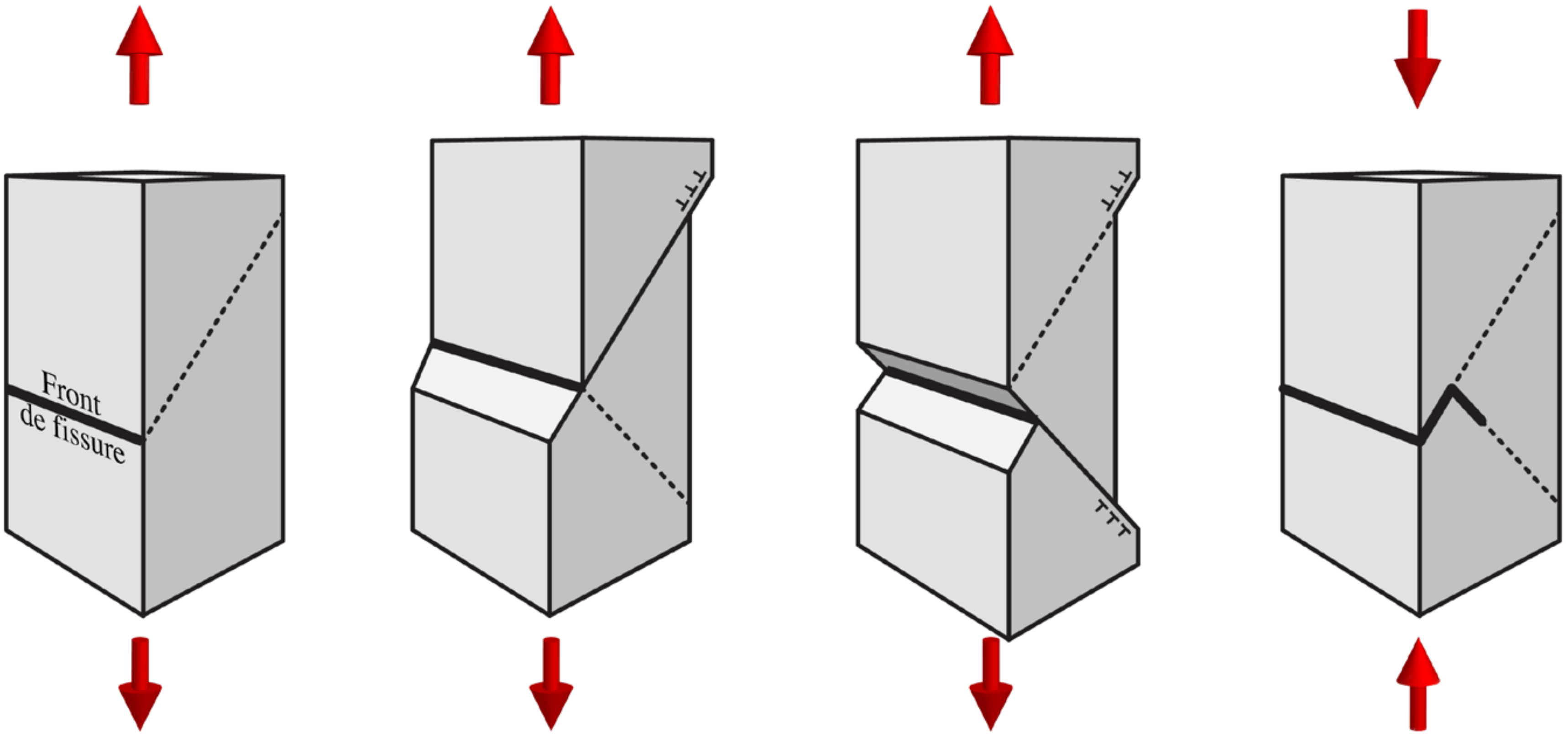
- It has been known for a long time that a component subjected to fluctuating stresses may fail at stress levels much lower than its monotonic fracture strength. The underlying failure process involves a gradual cracking of the component and is called Fatigue.
- Fatigue is an insidious time-dependent type of failure and can occur without any obvious warning. It is believed that more than 90 percent of all mechanical failures can be attributed to fatigue. There are normally three distinct stages in the fatigue failure of a component, namely: Stage I:*Crack Initiation*, Stage II:*Incremental Crack Growth*, and Stage III:*Final Fracture*.
- Fatigue crack initiation usually occurs at free surfaces because of the higher stresses and the higher probability of the existence of defects at these locations. Nevertheless, even at highly-polished defect-free surfaces, fatigue cracks can initiate through repeated microplastic deformations which result in the formation of “intrusions” and “extrusions” on the surface. The former can act as local stress concentration sites which may eventually lead to the formation of microcracks.

Fatigue – Threshold regime

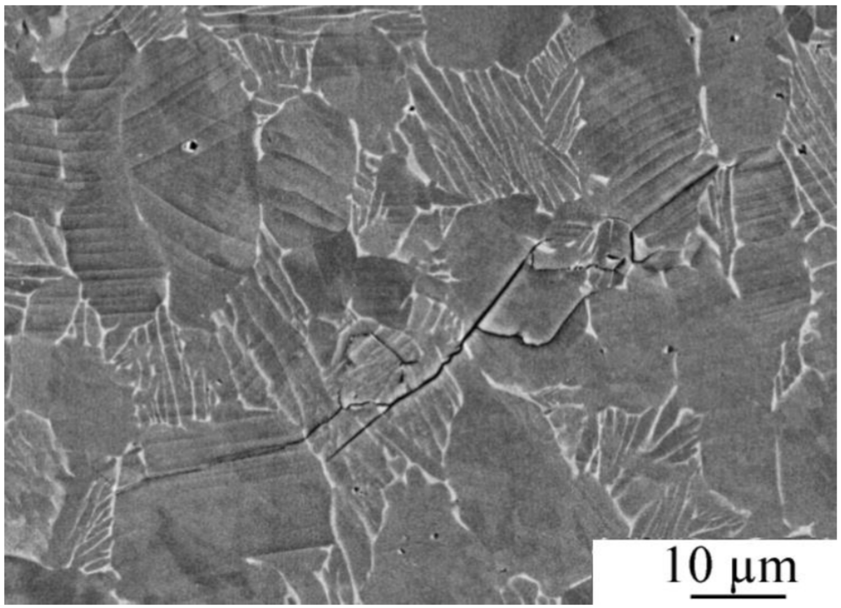


Schematics of fatigue crack initiation (Stage I).

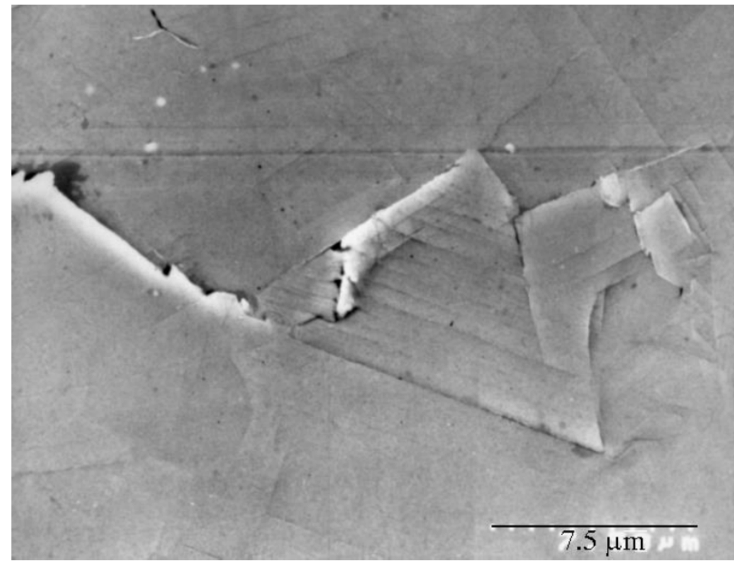
Fatigue – Threshold regime



Schematics of fatigue crack initiation (Stage I).



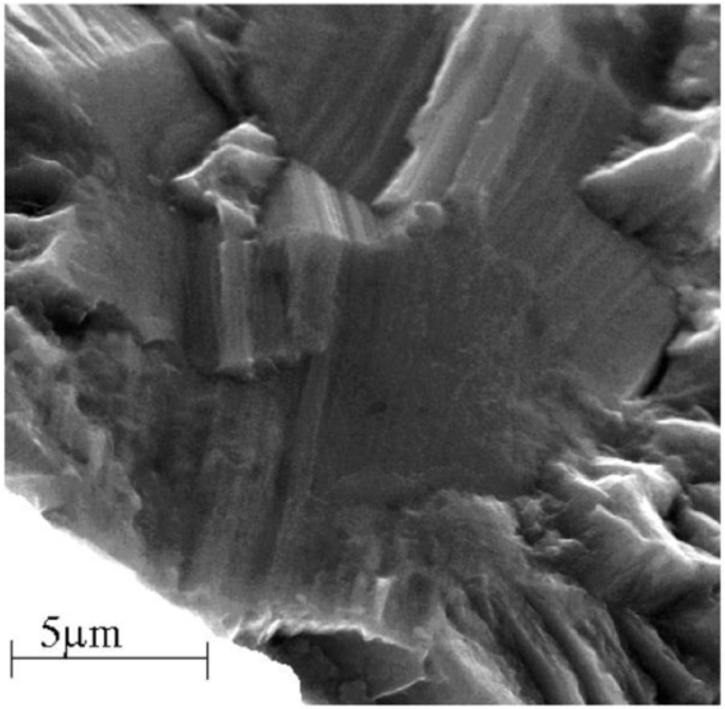
Titanium alloy TA6V [Le Biavant, 2000]. The fatigue crack grows along slip planes.



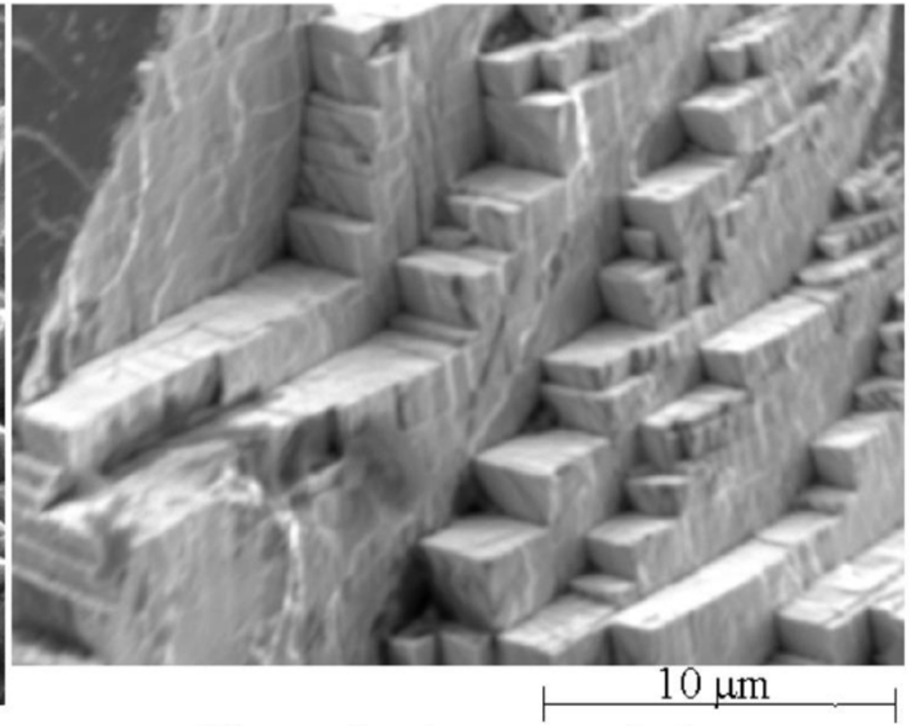
N18 nickel based superalloy at room temperature, [Pommier,1992]. The crack grows at the intersection between slip planes

Schematics of fatigue crack initiation (Stage I).

Fatigue – Threshold regime – fracture surface



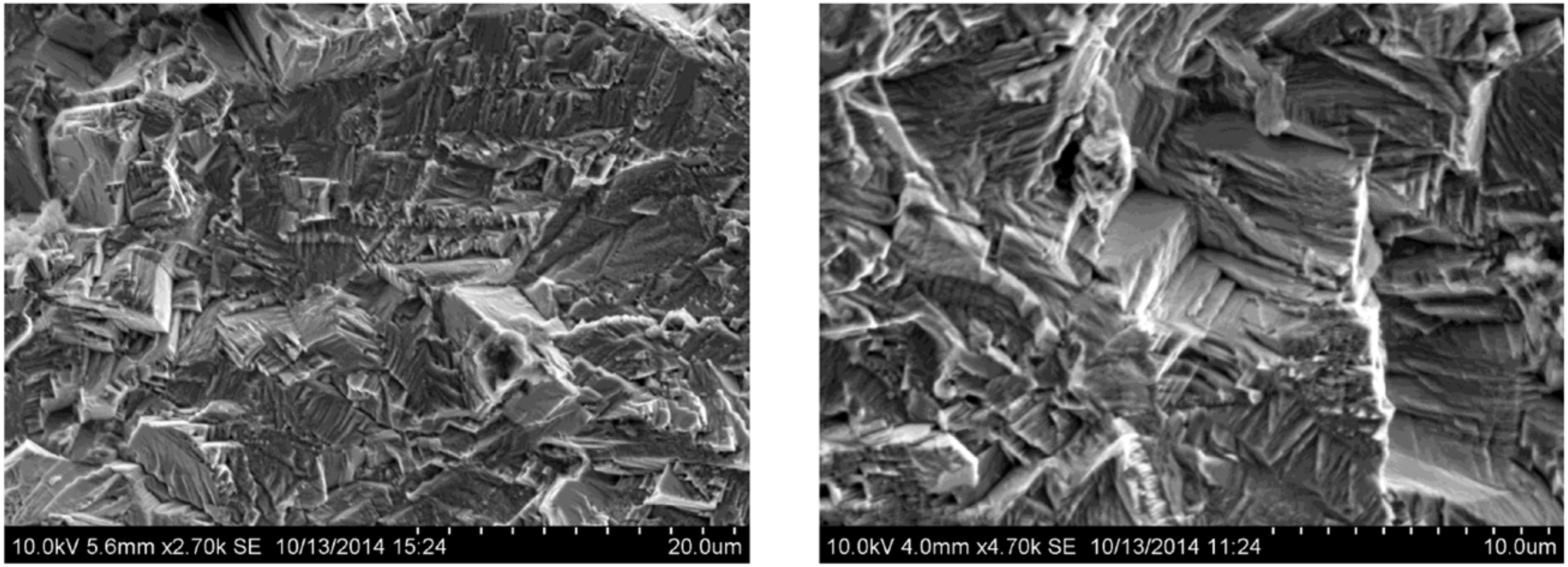
Titane TA6V (20°C)
(cliché M. Sampablo-Lauro)



alliage de chrome-cobalt
(cliché M. Puget)

“pseudo-cleavage” facets at the initiation site

Fatigue – Threshold regime – fracture surface



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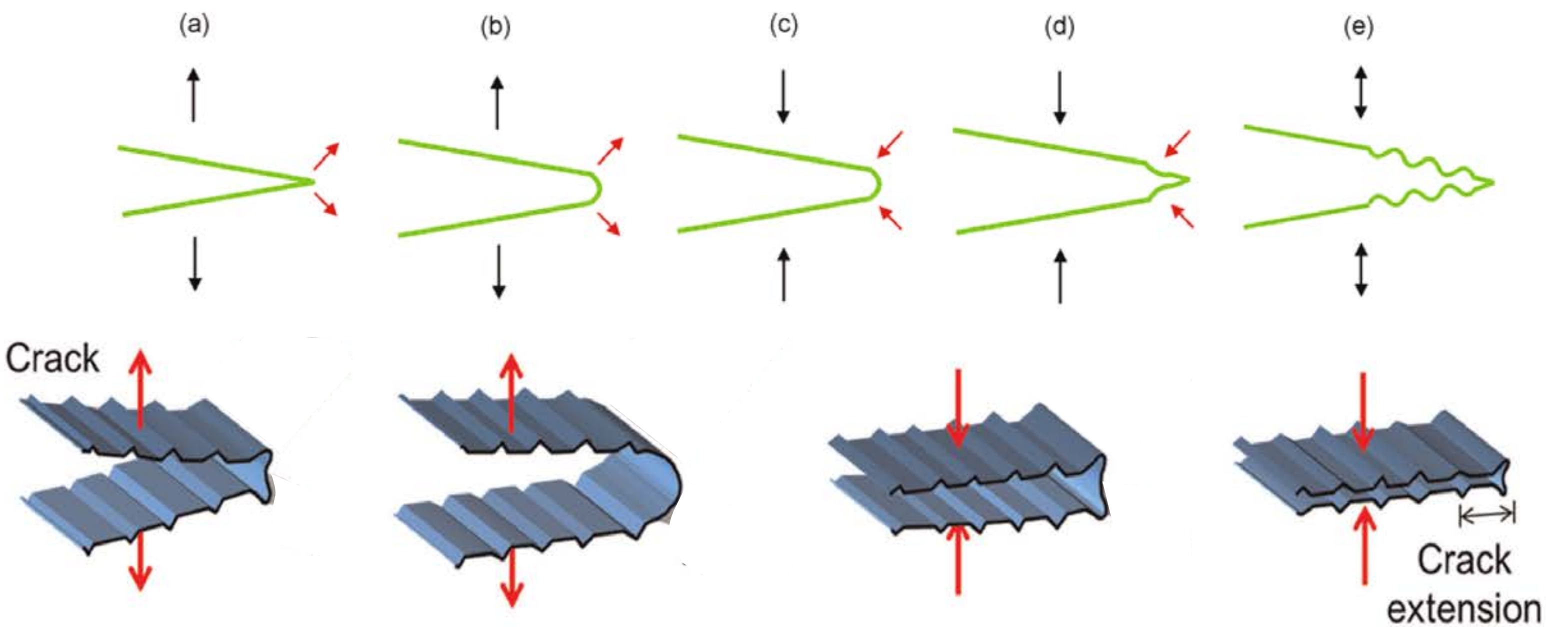
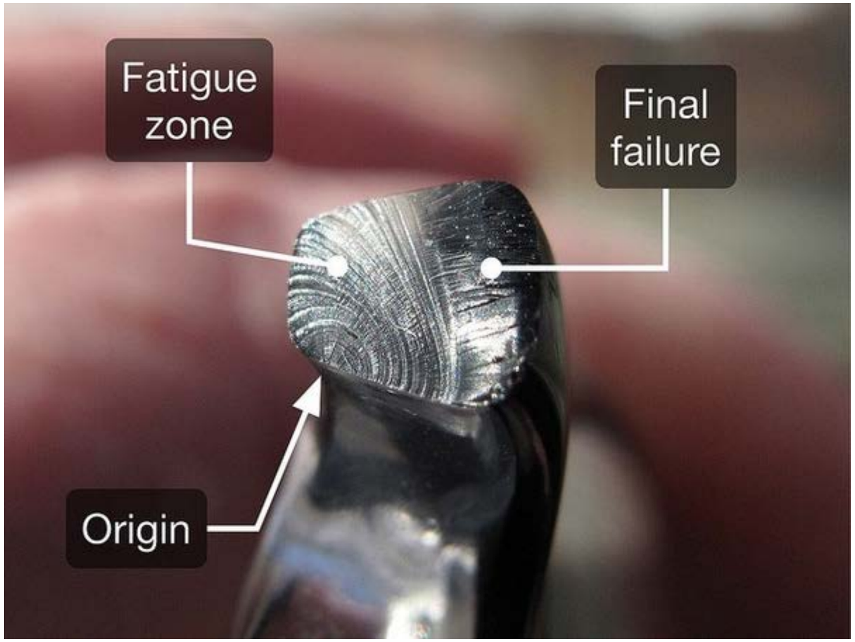
- Fatigue crack propagation occurs through repeated crack tip blunting and sharpening effects which are in turn caused by microplastic deformation mechanisms operating at the crack tip



Schematics of fatigue crack propagation(Stage II) (2D and 3D).

Fatigue – Stage II

- A macroscopic examination of fatigue failures reveals several distinct fracture surface markings. In general, the fracture surface is flat with no sign of significant plastic deformation, except for the portion related to the final rupture. For fatigue failures which occur over a long period of time, the fracture surface may contain characteristic markings which are called "beach markings". These markings, which are recognizable even by naked eye, reflect the occurrence of different *periods* of crack growth.



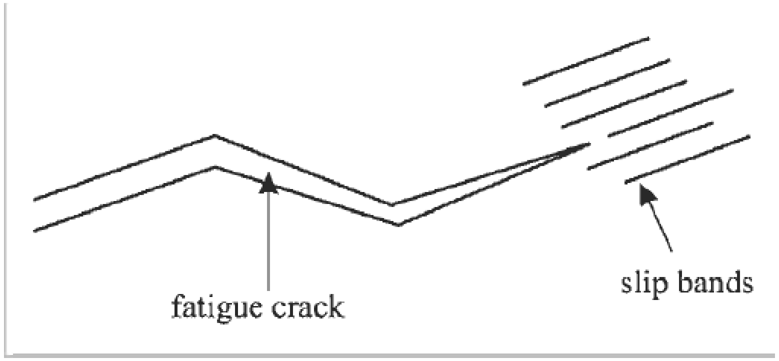
Fracture appearance of different stages of fatigue failure, including the beach markings.

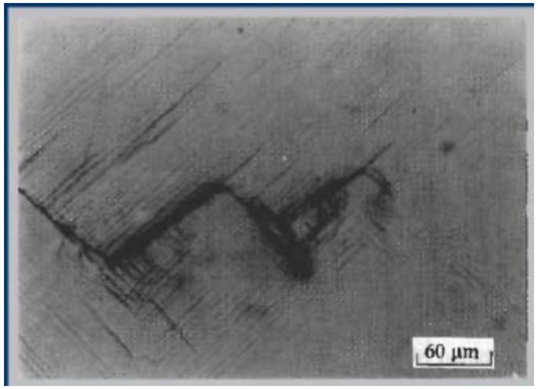
Fatigue Striations

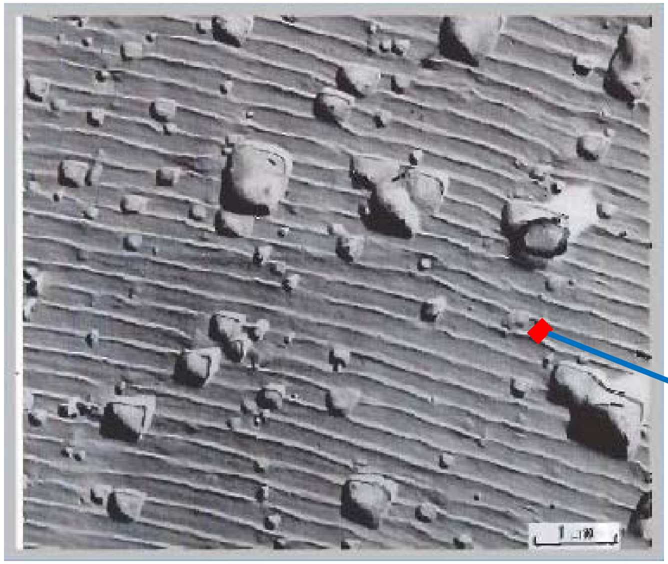
- On the other hand, there are extremely fine markings called “striations”, which represent the crack growth due to individual loading cycles and can only be seen at very high magnifications using electron microscopes.

Fatigue crack growth:

Microcrack formation in accumulated slip bands due to repeated loading







Fracture surface of a 2024-T3 aluminum alloy

Striation caused by individual microscale crack advance incidents

Classification of Fatigue

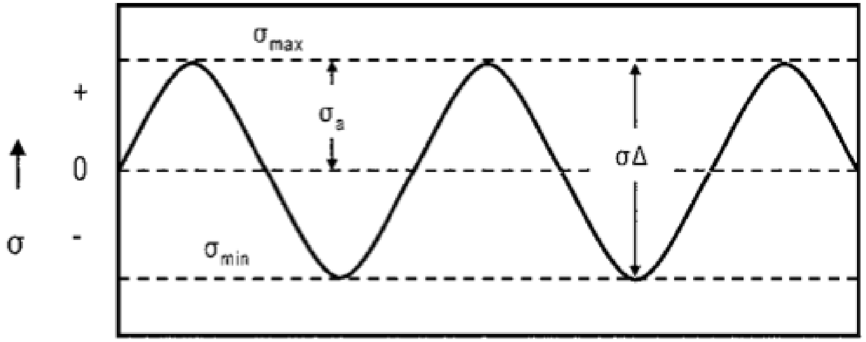
Table 7.1 Classification of fatigue damage

Fatigue	Failure cycles N_R	Pertinent stress	Strain ratio $\Delta\varepsilon^p/\Delta\varepsilon^e$	Energy ratio $\Delta W^p/\Delta W^e$
Very high cycle fatigue	$> 10^7$	$< \sigma_F$	≈ 0	≈ 0
High cycle fatigue	10^5 to 10^6	$< \sigma_Y$	≈ 0	≈ 0
Low cycle fatigue	10^2 to 10^4	σ_Y to σ_U	1 to 10	1 to 10
Very low cycle fatigue	1 to 20	$\approx \sigma_U$	10 to 100	10 to 100

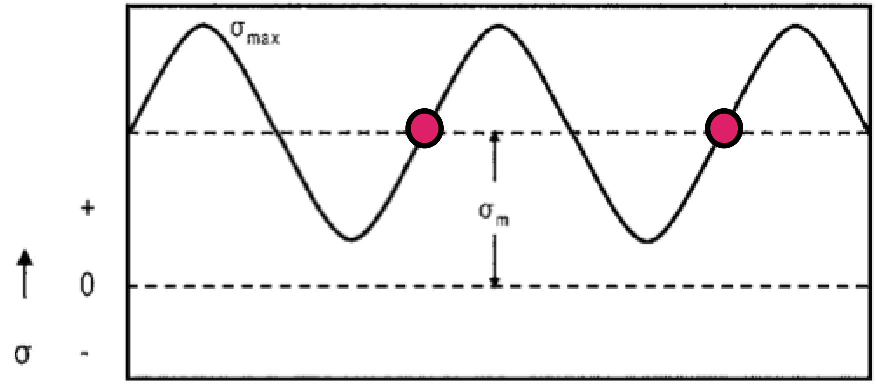
- Very high cycle and high cycle fatigue:
  - Stresses are well below yield/ultimate strength.
  - There is almost no plastic deformation (in terms of strain and energy ratios)
  - Fatigue models based on LEFM theory (e.g. SIF K) are applicable.
  - Stress-life approaches are used (stress-centered criteria)
- Low cycle and very low cycle fatigue:
  - Stresses are in the order of yield/ultimate strength.
  - There is considerable plastic deformation.
  - Fatigue models based on PFM theory (e.g. J integral) are applicable.
  - Strain-life approaches are used (strain-centered criteria)

Cyclic loadings

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



Fully Reversed Loading



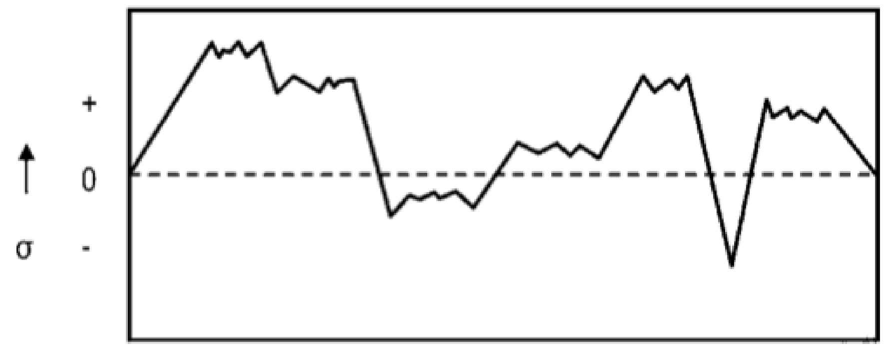
Tension-Tension with Applied Stress

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

$$\sigma_a = 0.5(\sigma_{max} - \sigma_{min})$$

$$\sigma_m = 0.5(\sigma_{max} + \sigma_{min})$$

$$R = \frac{\sigma_{min}}{\sigma_{max}}$$ load ratio



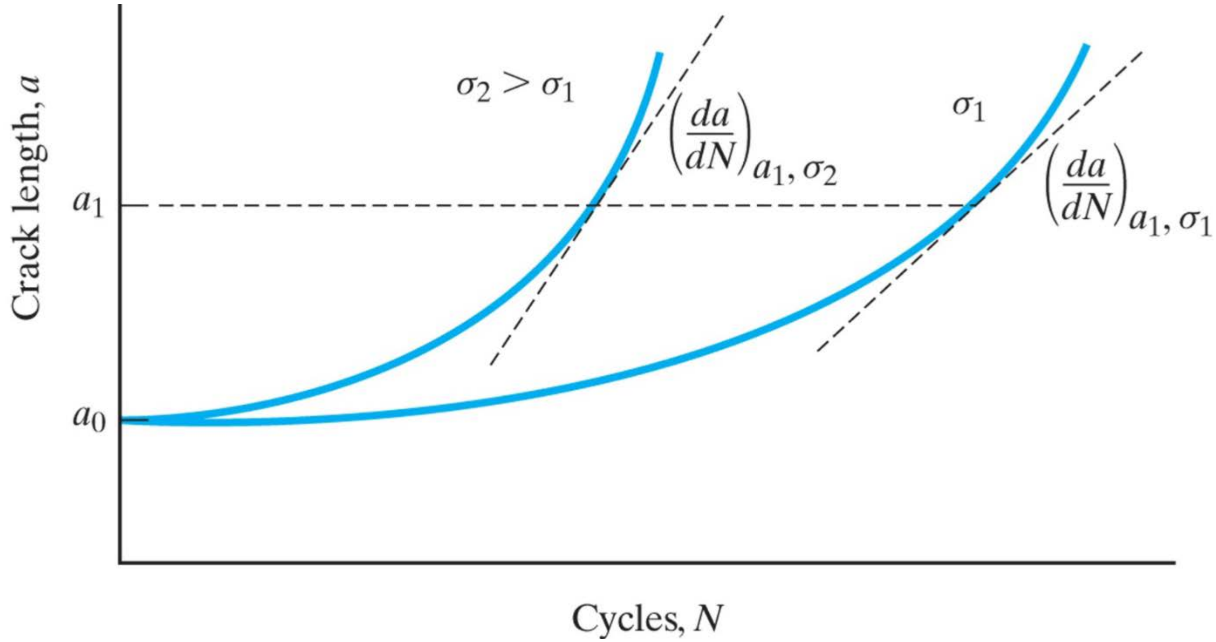
Random or Spectrum Loading

Cyclic vs. static loadings

- Static: Until K reaches K_c, crack will not grow
- Cyclic: K applied can be well below K_c, crack grows still!!!
- 1961, Paris et al. used the theory of LEFM to explain fatigue cracking successfully.
- Methodology: experiments first, then empirical equations are proposed.

crack growth rate

1. Initially, crack growth rate is small
2. Crack growth rate increases rapidly when a is large
3. Crack growth rate increases as the applied stress increases



The Figure Illustration of crack growth with number of stress cycles, N, at two different stress levels. Note that, at a given stress level, the crack growth rate, da/dN, increases with increasing crack length, and, for a given crack length such as a_1, the rate of crack growth is significantly increased with increasing magnitude of stress.

Fatigue

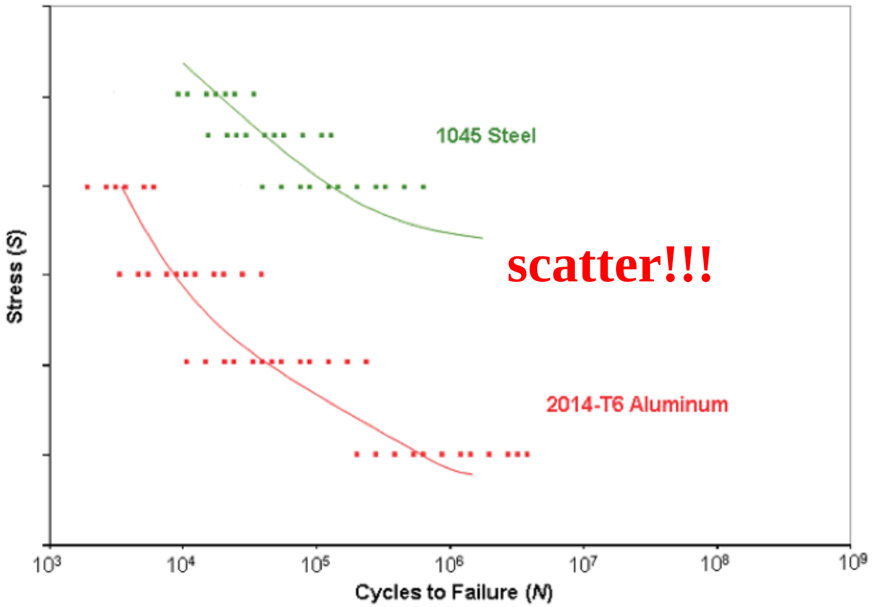
- Fatigue problems in engineering design are treated by three different approaches:

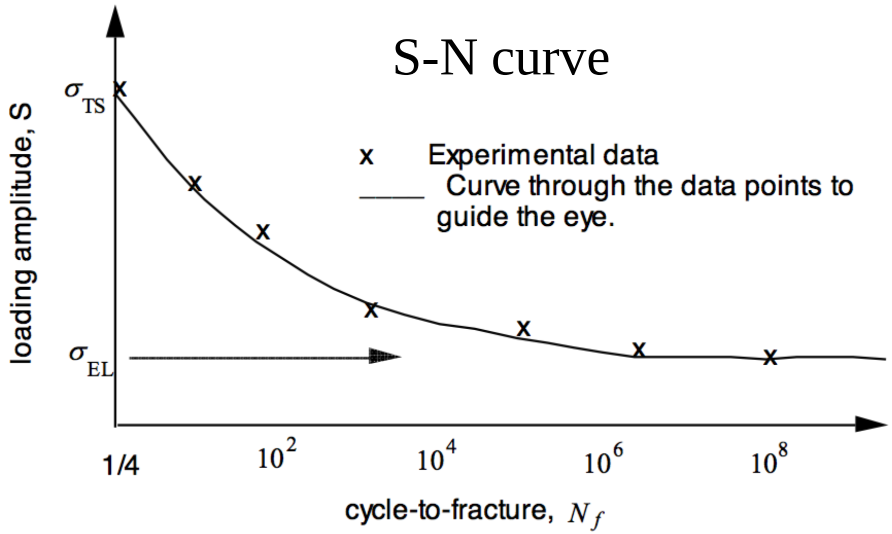
  - Classical Fatigue Approach
  - Low Cycle Fatigue Approach
  - Fracture Mechanics Approach

Classical Fatigue Approach

S-N curve

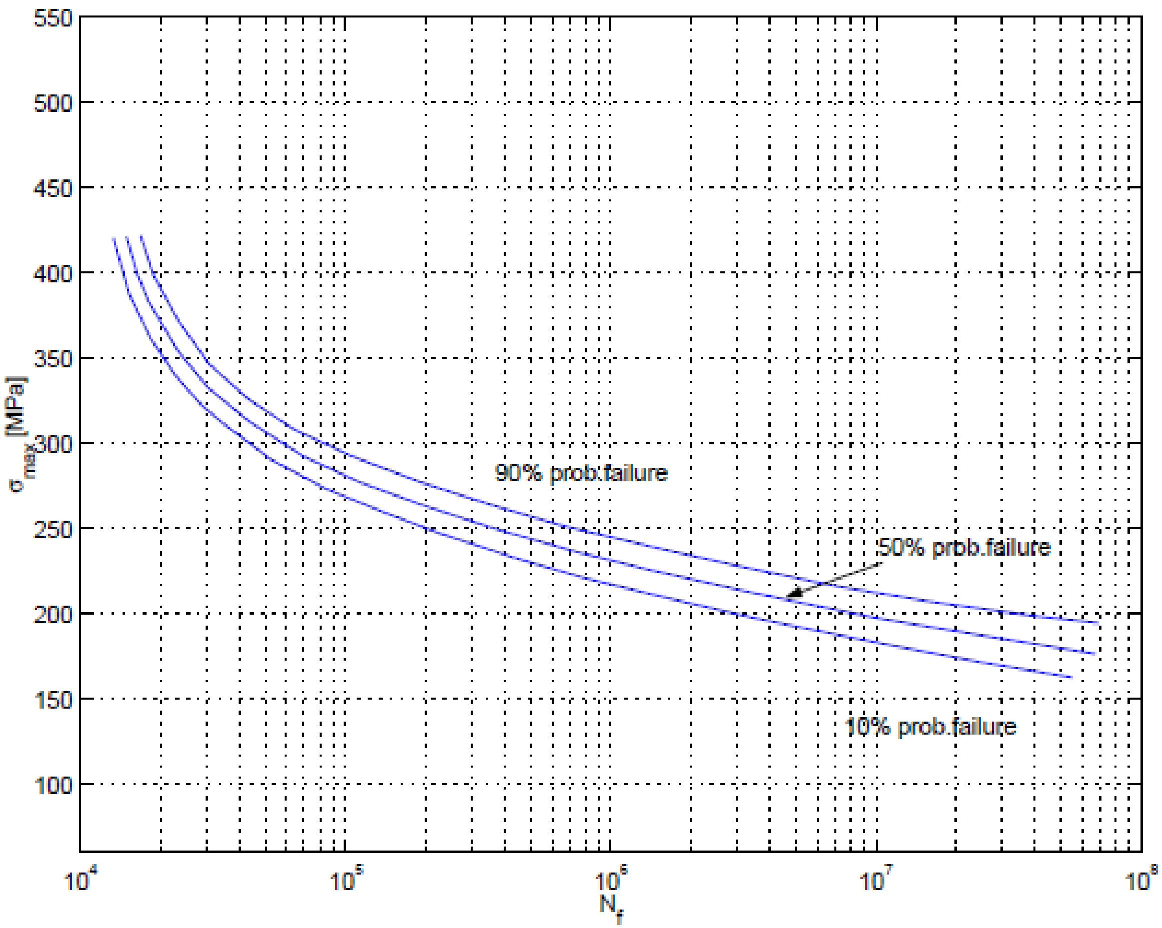
Reminder: ASTM defines *fatigue life*, N_f, as the number of stress cycles of a specified character that a specimen sustains before failure of a specified nature occurs.





Classical Fatigue Approach

S-N-P curve: scatter effects



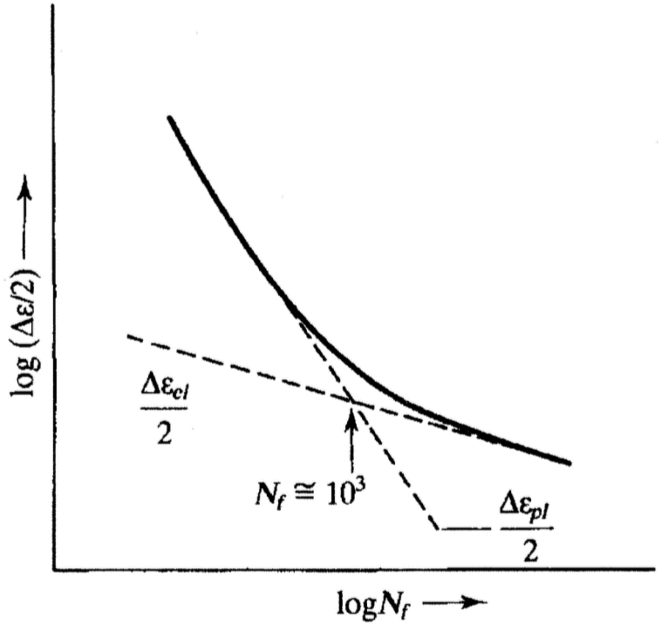
P-S-N-curves

Low-cycle fatigue

- Where the stress is high enough for plastic deformation to occur, the accounting of the loading in terms of stress is less useful and the strain in the material offers a simpler and more accurate description. This type of fatigue is normally experienced by components which undergo a relatively small number of straining cycles.

Coffin-Manson relation

$$\frac{\Delta\varepsilon_p}{2} = \varepsilon_p'(2N)^c$$



$\Delta\varepsilon_p/2$ is the plastic strain amplitude;

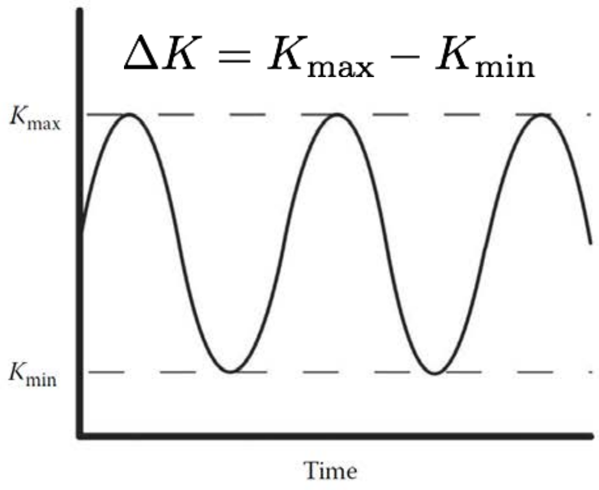
ε_f' is an empirical constant known as the fatigue ductility coefficient, the failure strain for a single reversal;

$2N$ is the number of reversals to failure (N cycles);

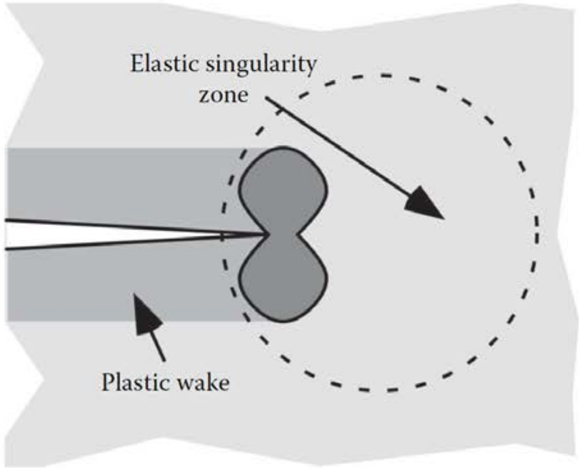
c is an empirical constant known as the fatigue ductility exponent.

Fracture Mechanics Approach

Constant variable cyclic load



small-scale yielding (SSY)



$$R = K_{min}/K_{max}$$

$$\Delta K = K_{max} - K_{min}$$

$$\Delta K = K_{max} - K_{min} = K_{max}\left(1 - R\right)$$

crack growth rate

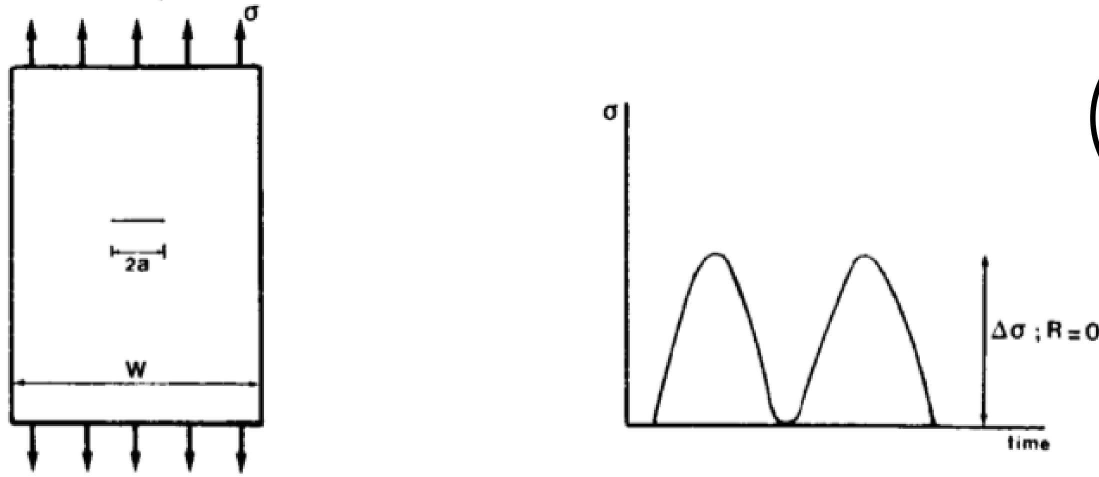
$$\frac{da}{dN} = f_1(\Delta K, R)$$

crack growth models

Crack growth data

$$K = \sigma\sqrt{\pi a}$$

1

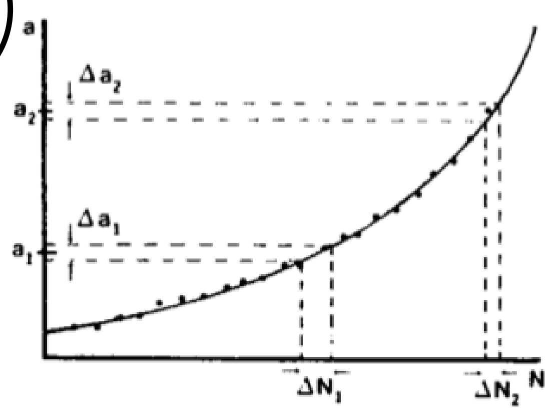


2

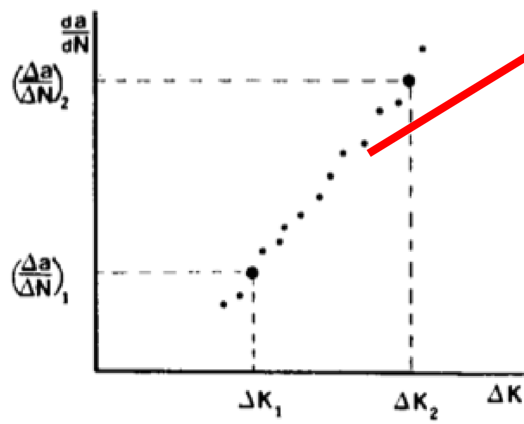
(a)

$$\frac{da}{dN} = f_1(\Delta K, R)$$

3



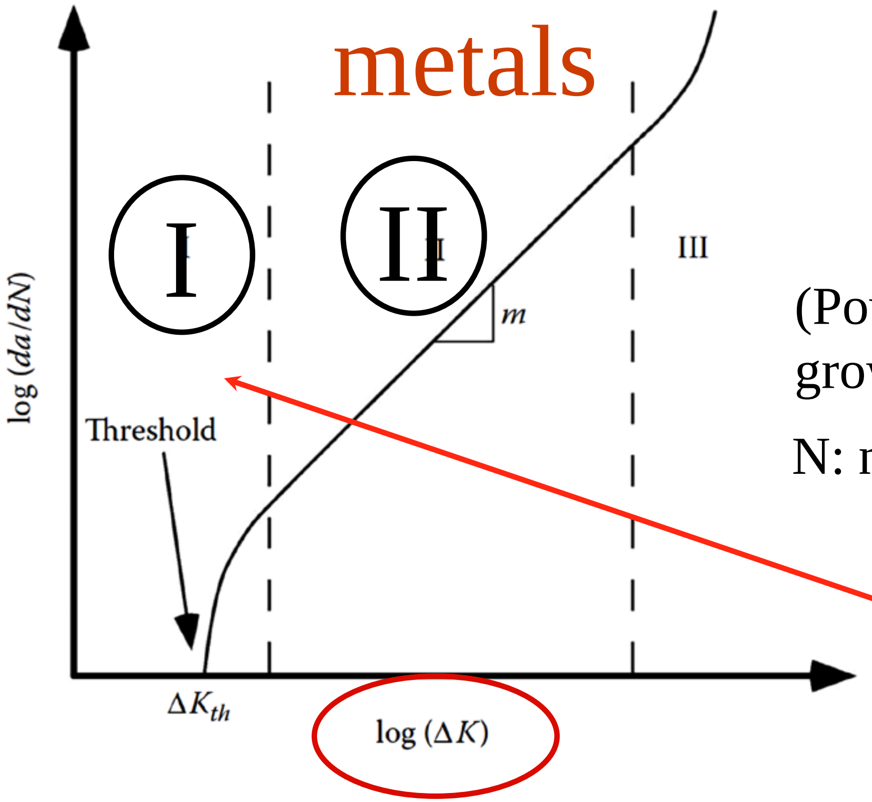
(b)



(c)

Paris' law (fatigue)

- Paris' law can be used to quantify the residual life (in terms of load cycles) of a specimen given a particular crack size.
- Paris' law is the most popular fatigue crack growth model



Fatigue crack growth behavior in metals

Paris' law $\frac{da}{dN} = C(\Delta K)^m, \ \Delta K = K_{\max} - K_{\min}$

$2 \leq m \leq 7$

(Power law relationship for fatigue crack growth in region II)

N: number of load cycles

For region I:

$\Delta K \leq \Delta K_{\text{th}}$: no crack growth

(dormant period) 10^{-8} mm/cycle