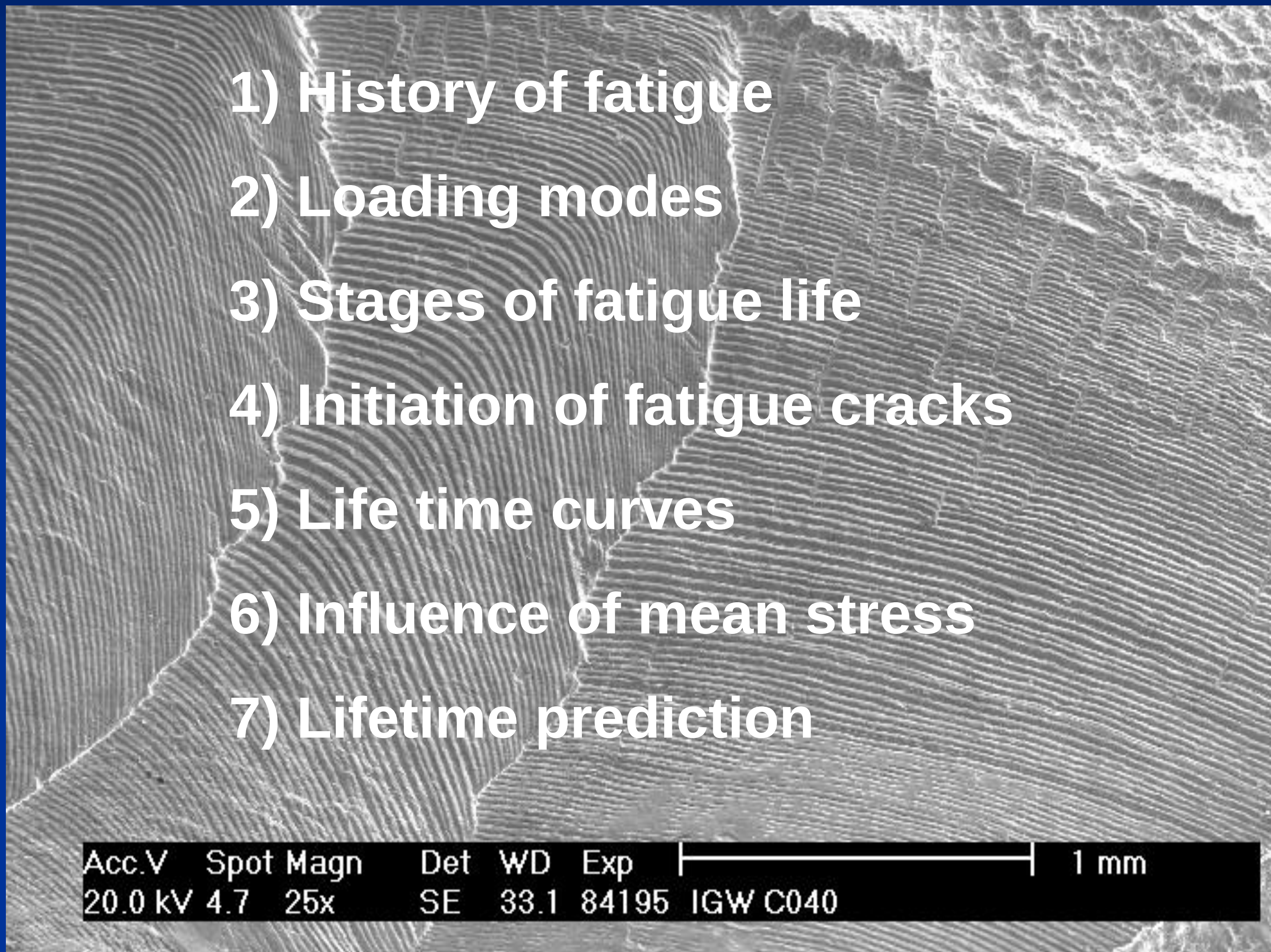
Fatigue of metallic materials

(Libor Pantělejev)

1) History of fatigue
2) Loading modes
3) Stages of fatigue life
4) Initiation of fatigue cracks
5) Life time curves
6) Influence of mean stress
7) Lifetime prediction



1) History of fatigue

1837 – Albert – first results of fatigue test (Clausthal)

1842 – Rankine, York – fatigue strength of railway's axle (London)

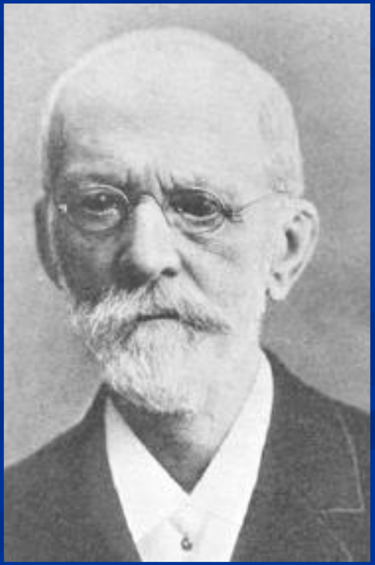
1853 – Morin –"Resistance des Matériaux" – „safe life approach" – inspection of axles of horse-drawn mail coaches (Paris)

1854 – Braithwaite – term "fatigue" was mentioned first time (description of a number service fatigue failures – water pumps, propeller shafts, levers, cranes etc.)

1858 – Wöhler – wide spread measurement of loading during service of four-wheeled and six-wheeled freight and passenger cars (results published in 1860)

1870 – “Wöhler’s law“– “Material can be induced to fail by many repetitions of stresses, all of which are lower than the static strength. The stress amplitudes are decisive for the destruction of the cohesion of the material. The maximum stress is of influence only in so far as the higher it is, the lower are the stress amplitudes which lead to failure“.

Wöhler therefore stated the stress amplitudes to be the most important parameter for fatigue life, but a tensile mean stress also to have a detrimental influence.



August Wöhler
(1819 – 1914)

Followers:
Smith, Haigh, Palmgren, Miner, Paris, Klesnil and others

2) Fatigue test at different loading modes:

Load (stress) control regime: σ_a = const.

high-cycle fatigue (Wöhler, Basquin)

Testing machine:

resonant testing machine
servo-hydraulic testing machine
ultrasonic testing machine (ultra-high cycle fatigue)

Strain control regime: ε_a = const.

Low-cycle fatigue (Manson – Coffin)

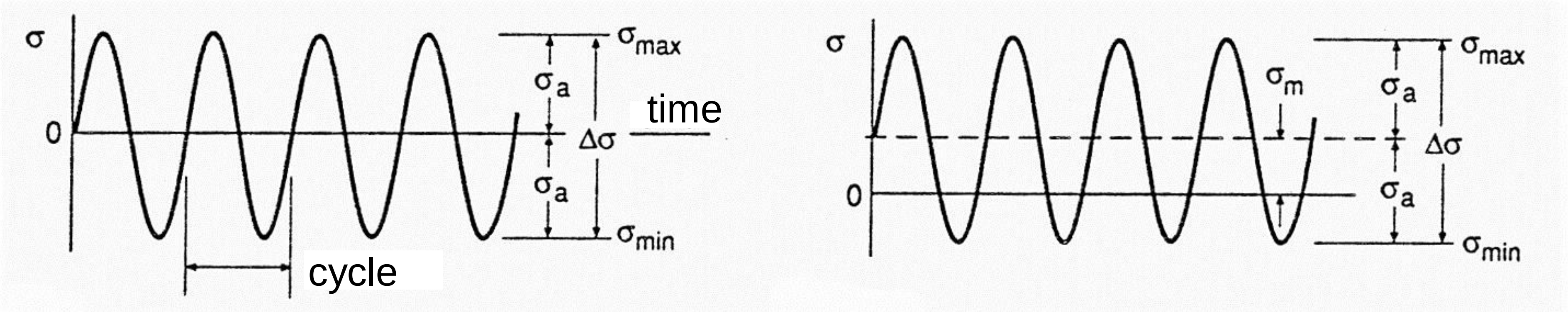
Testing machine:

servo-hydraulic testing machine

Basic characteristics of loading cycle

- resonant testing machines are working with sinusoidal loading cycle

- servo-hydraulic testing machines allow selection of type of the loading cycle e.g. triangular, trapezoidal, saw-like etc.



$\Delta\sigma$ – stress range ($\Delta\sigma = 2\sigma_a$)
σ_a – stress amplitude
σ_{max} – maximum stress
σ_{min} – minimum stress
σ_m – mean stress

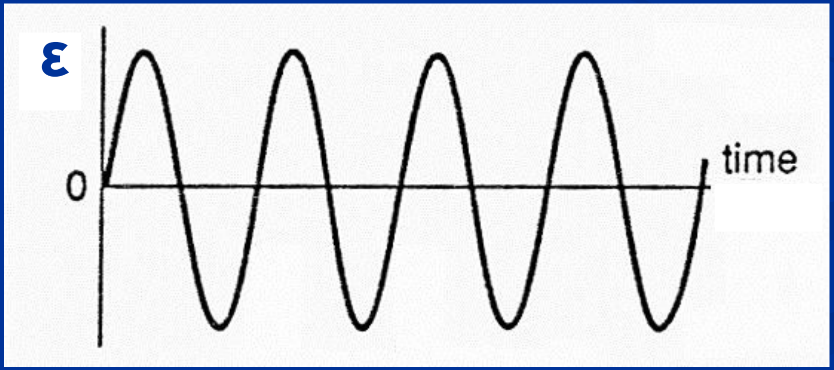
$$\sigma_a = \frac{\sigma_{\max} - \sigma_{\min}}{2}$$

$$\sigma_m = \frac{\sigma_{\max} + \sigma_{\min}}{2}$$

Strain controlled regime:

$\Delta\varepsilon$ – strain range ($\Delta\varepsilon = 2\varepsilon_a$)
ε_a – strain amplitude
ε_{max} – maximal strain
ε_{min} – minimal strain
ε_m – mean strain

Testing is conducted usually in symmetrical loading cycle



Parameters of loading cycle asymmetry

Stress ratio

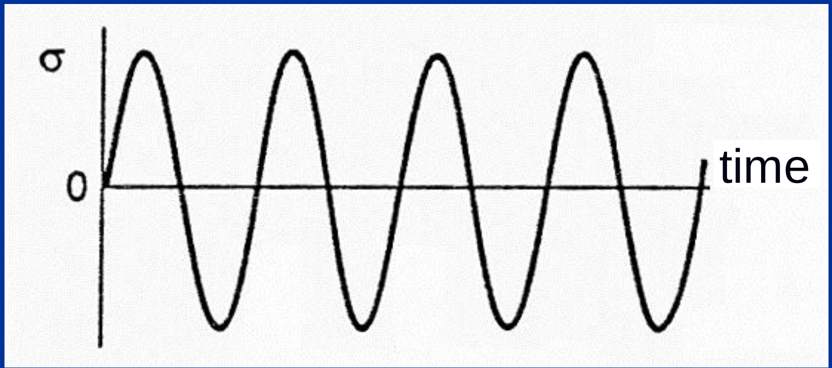
$$R = \frac{\sigma_{\min}}{\sigma_{\max}} \qquad P = \frac{\sigma_{\max}}{\sigma_a} \qquad A = \frac{\sigma_a}{\sigma_m}$$

Amplitude ratio

$$P = \frac{2}{1-R} \qquad A = \frac{1-R}{1+R} \qquad A = \frac{1}{P-1}$$

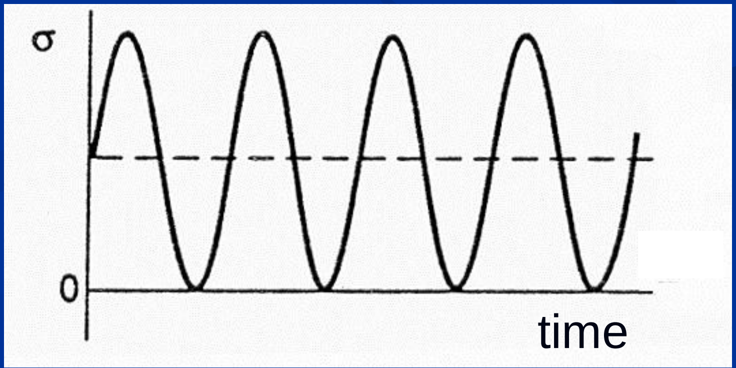
Symmetrical cycle:

R = -1, P = 1,
can not be described via parameter A – problem of singularity (division by zero)



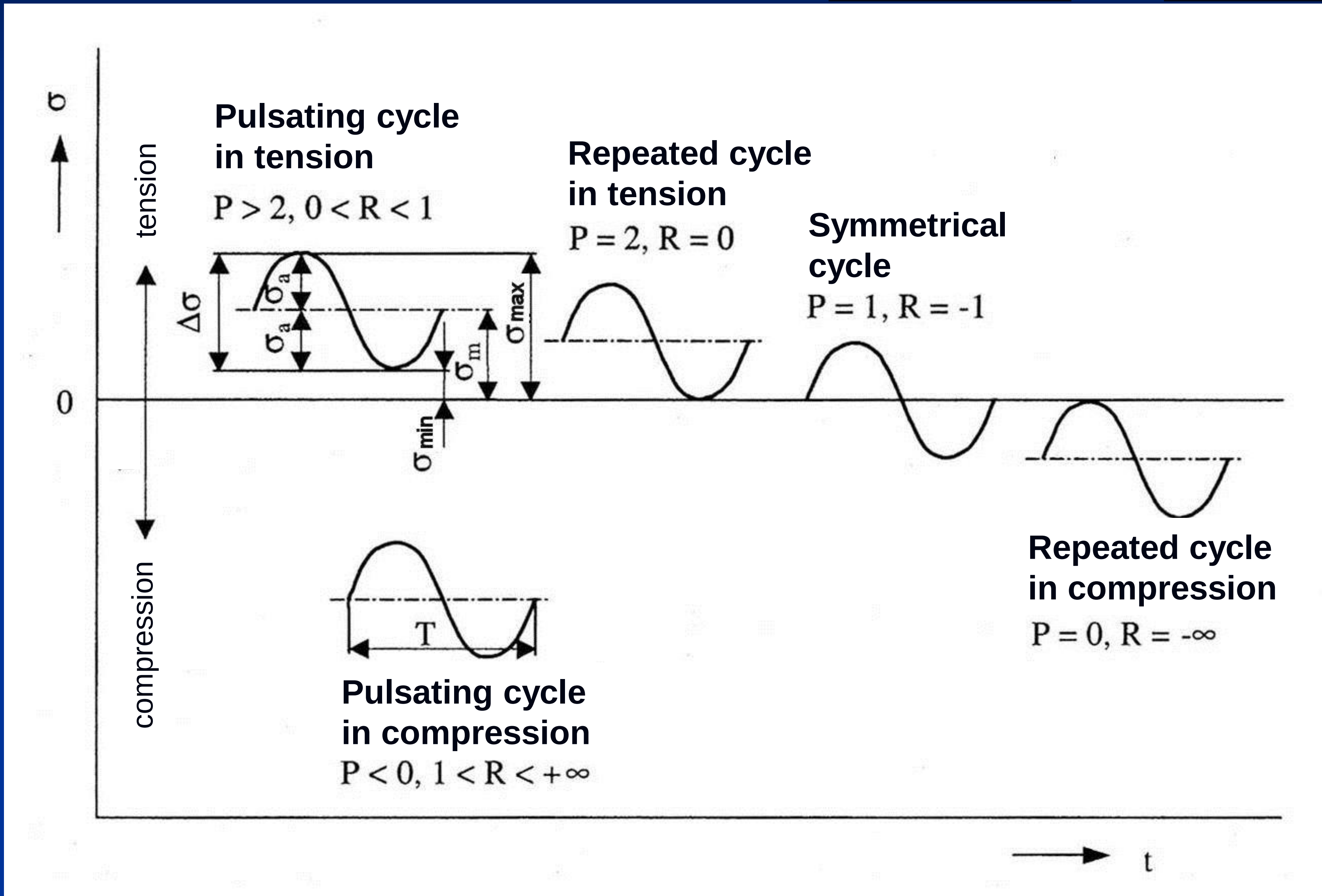
Repeated cycle:

R = 0, P = 2, A = 1



$$P = \frac{\sigma_{max}}{\sigma_a}$$

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

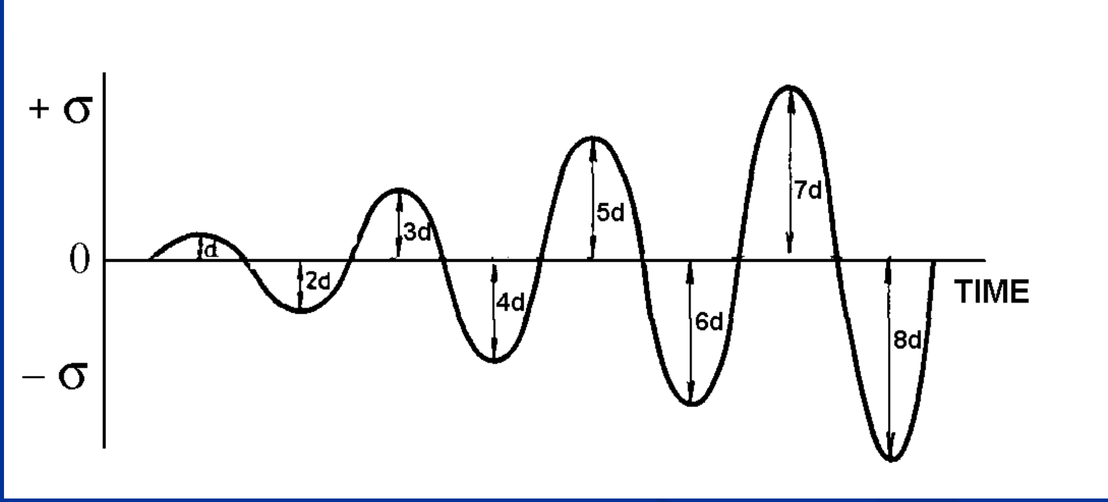


how to reach full load

Resonant testing machine:

- loading frequency is given by stiffness of the system (testing machine – tested specimen) – there is possibility partly to change the loading frequency by operator (add or remove of additional weight)

- full load is not reached immediately – loading ramp is inherent property of apparatus

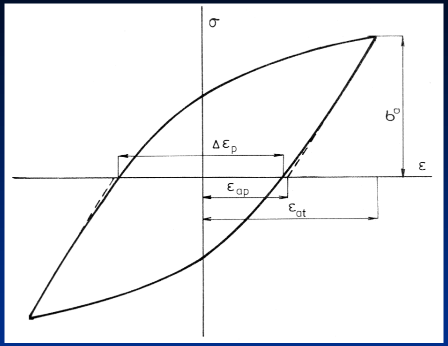


Servo-hydraulic testing machine:

- the loading ramp/full load can be reached immediately

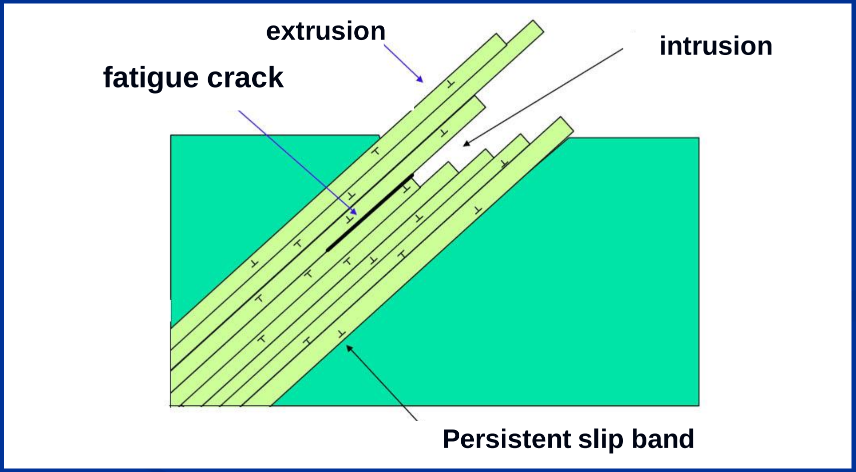
- loading ramp: either number of cycles to reach full load
or selection of the loading frequency (in the range given by testing machine).

3) Stages of fatigue life



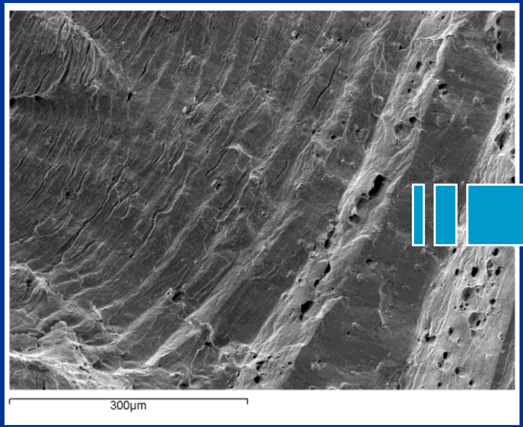
- Changes of mechanical properties

  cyclic softening/ hardening



- Crack initiation
  - surface layers
  - inhomogeneity

- Crack propagation



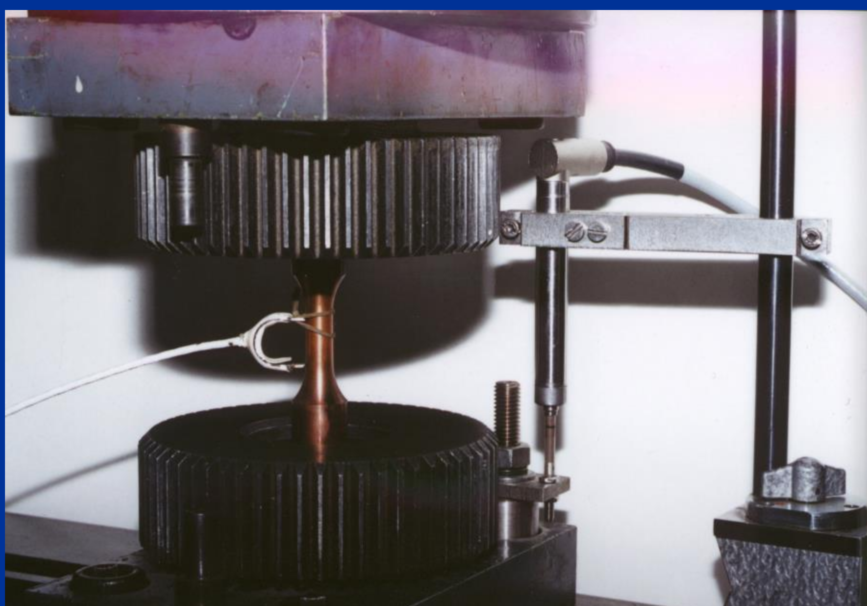
Final fracture

Changes of mechanical properties

Measurement of cyclic stress-strain response (hysteresis loop)

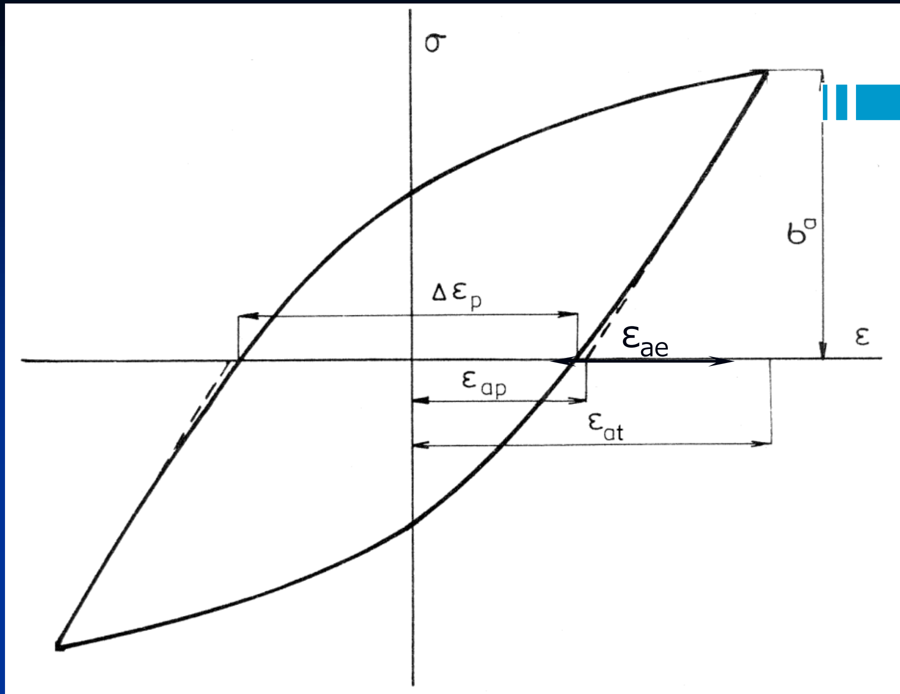
„clip-on“ extensometer:

- X-Y plotter
- digital reading - PC – more accurate in comparison with



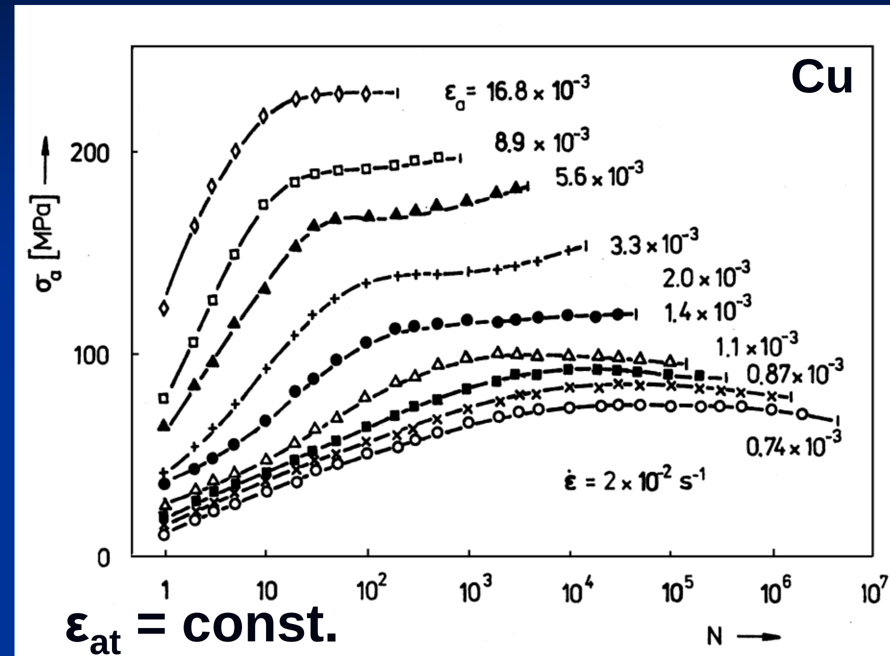
Reading of unidirectional strain (elongation):
- inductive transducer (inductor and movable core) – direct method (digital reading - PC)

- Displacement of hysteresis loops (hysteresis loop is sliding along axe X)



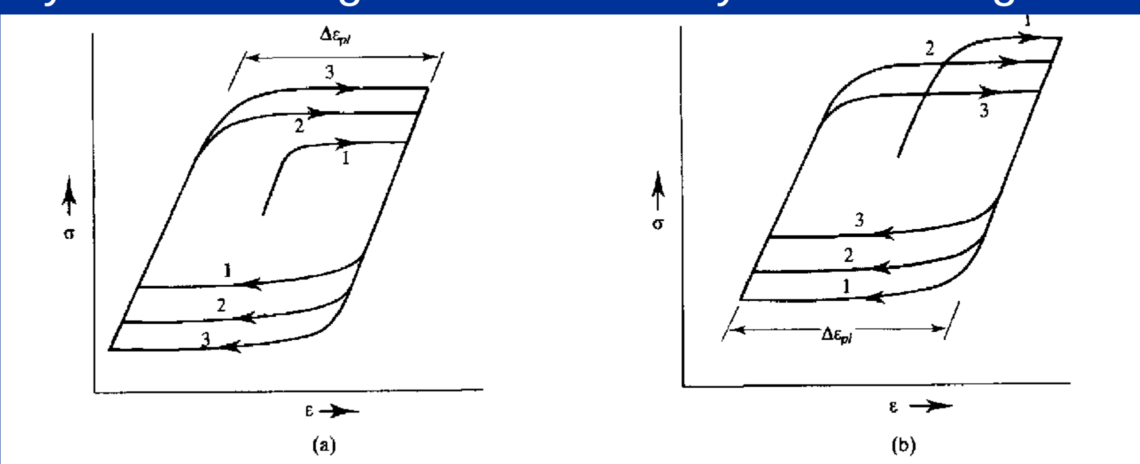
Softening/hardening curves

Cyclic stress-strain curve

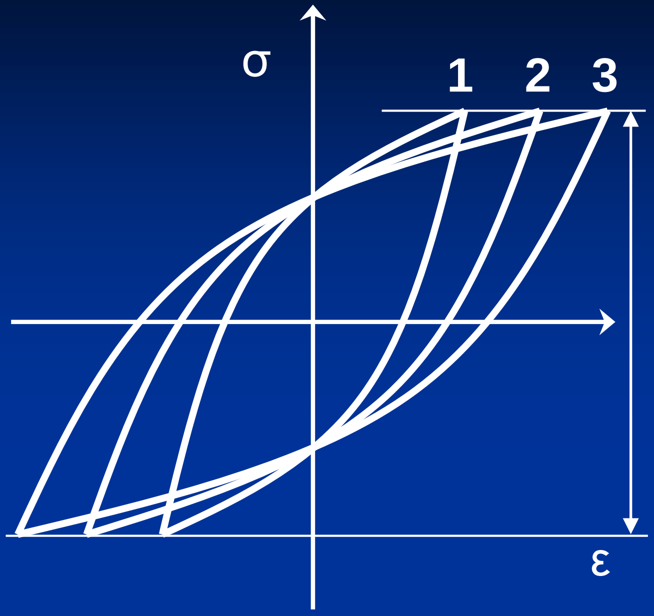


Manifestation of cyclic hardening

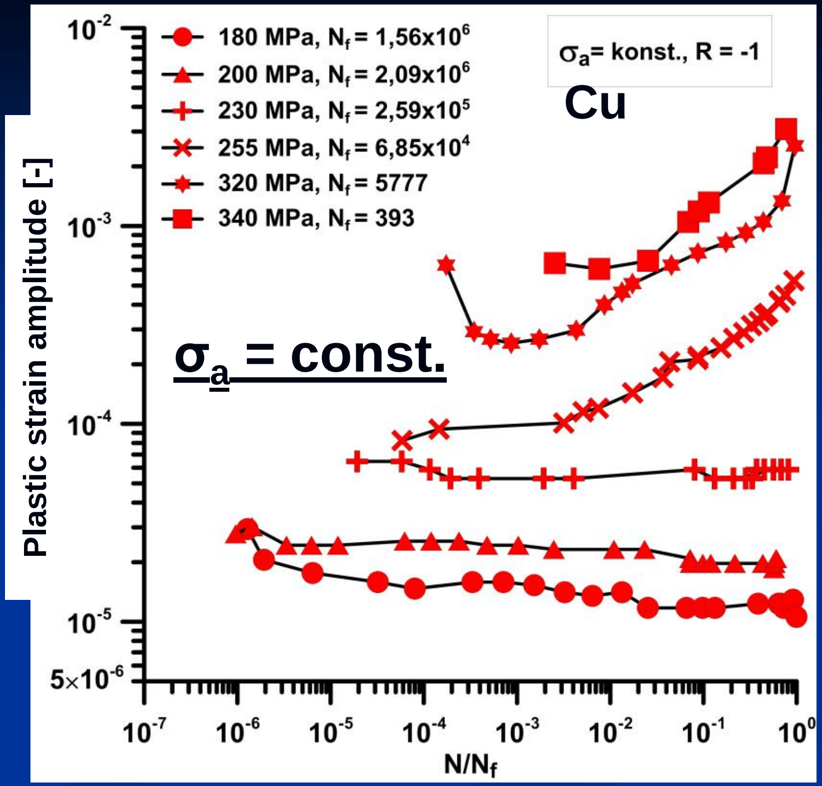
Manifestation of cyclic softening

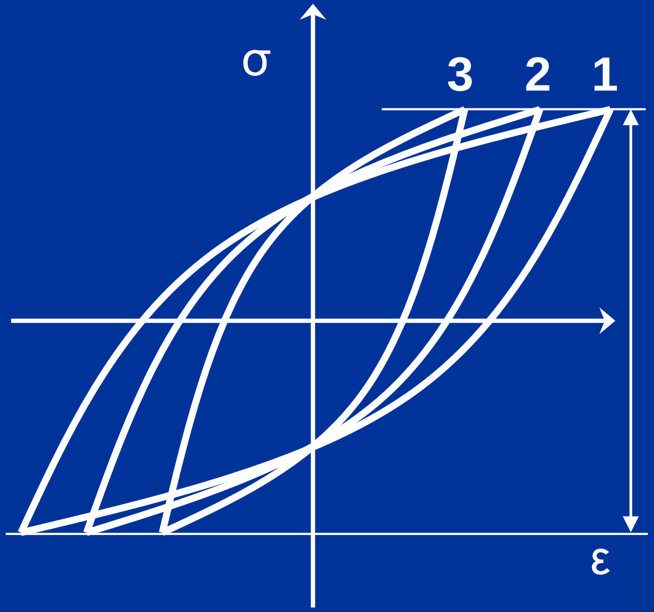


Cyclic softening



Δσ = const.



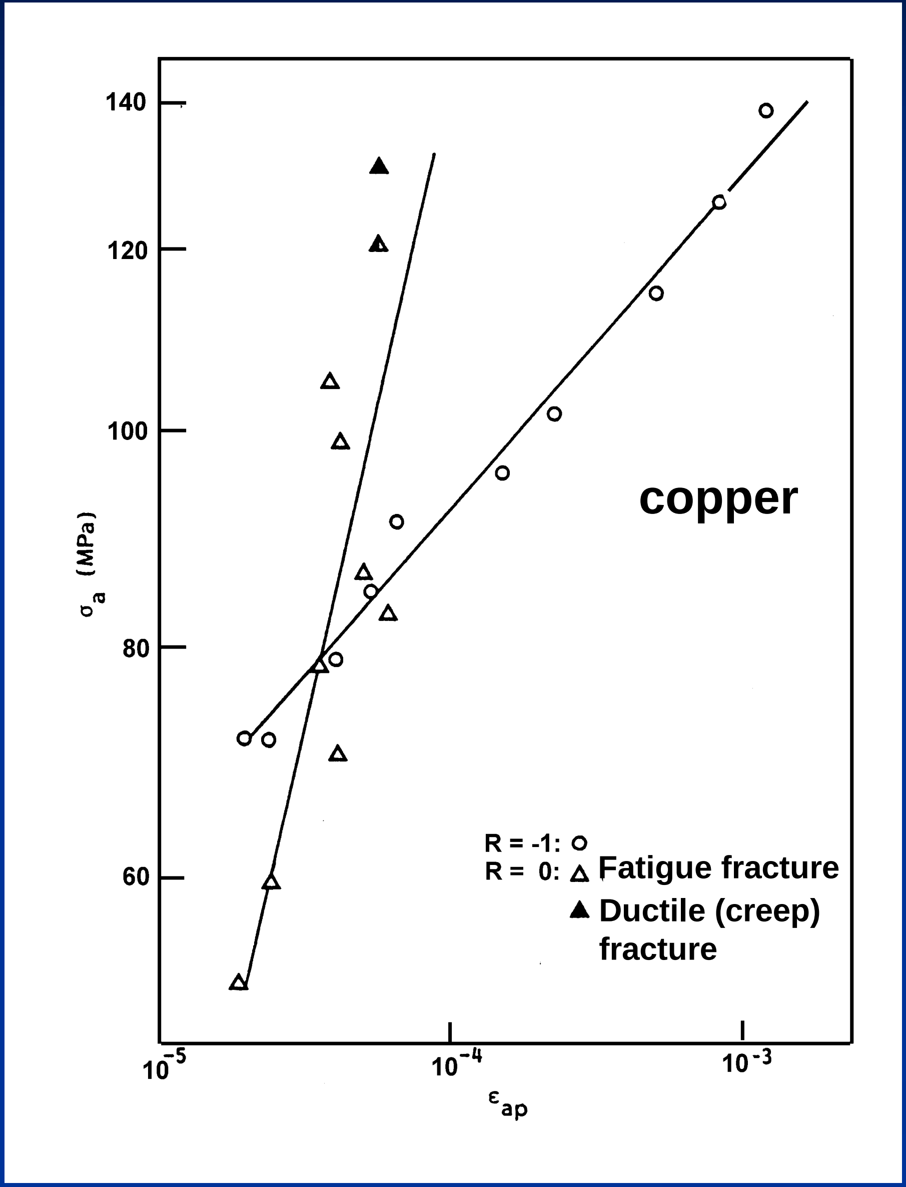


Cyclic hardening

Δσ = const.

Cyclic stress-strain curve (CSSC)

Description of the cyclic plastic response of material



Available for both type of loading (load/strain control):

- from the saturated states ($\varepsilon_{ap,sat}$ /$\sigma_{a,sat}$)

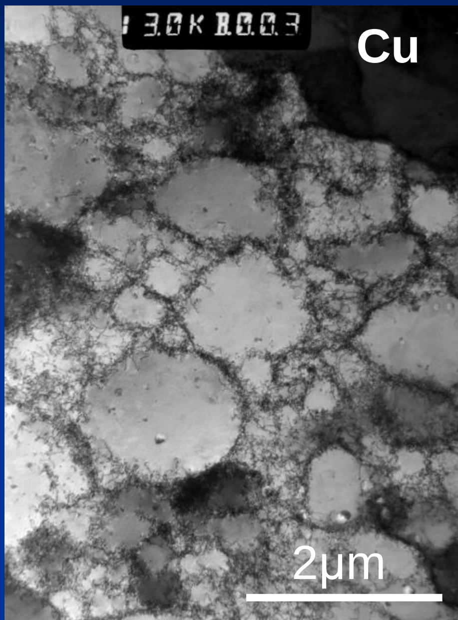
- for ½ N_f in the case of no saturation ($\varepsilon_{ap,50\%}$ /$\sigma_{a,50\%}$)

power law form is often used for description of CSSC:

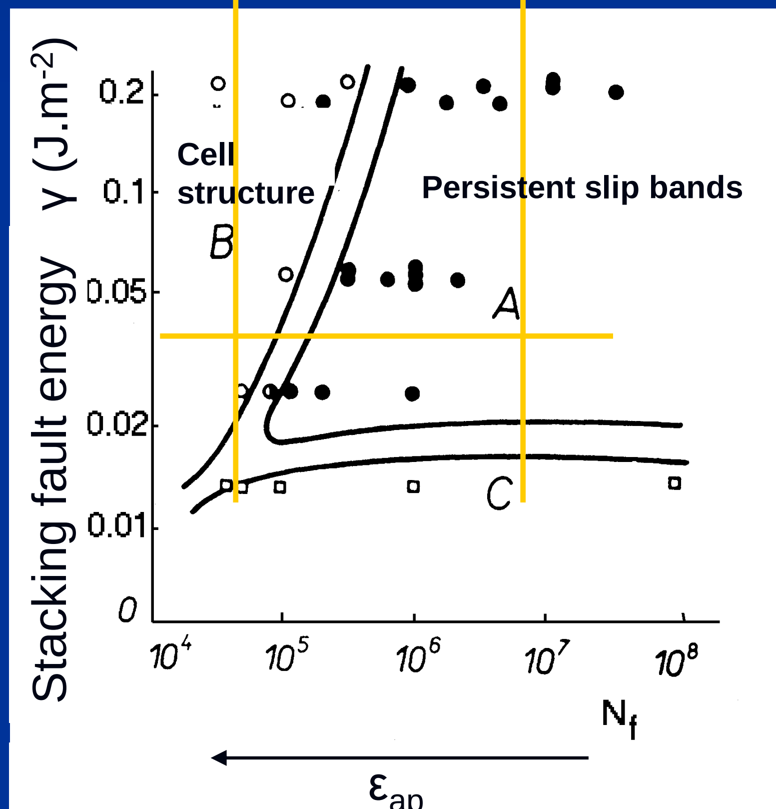
$$\sigma_a = K'\left(\varepsilon_{ap}\right)^{n'}$$

K´ - cyclic hardening coefficient
n´ - cyclic hardening exponent

Development of specific dislocation (sub)structure during loading



FCC metals



γ [J.m^{-2}]

Au 0,03
Cu 0,04
Al 0,14
Ni 0,2

Initiation of fatigue cracks

Homogeneous materials:

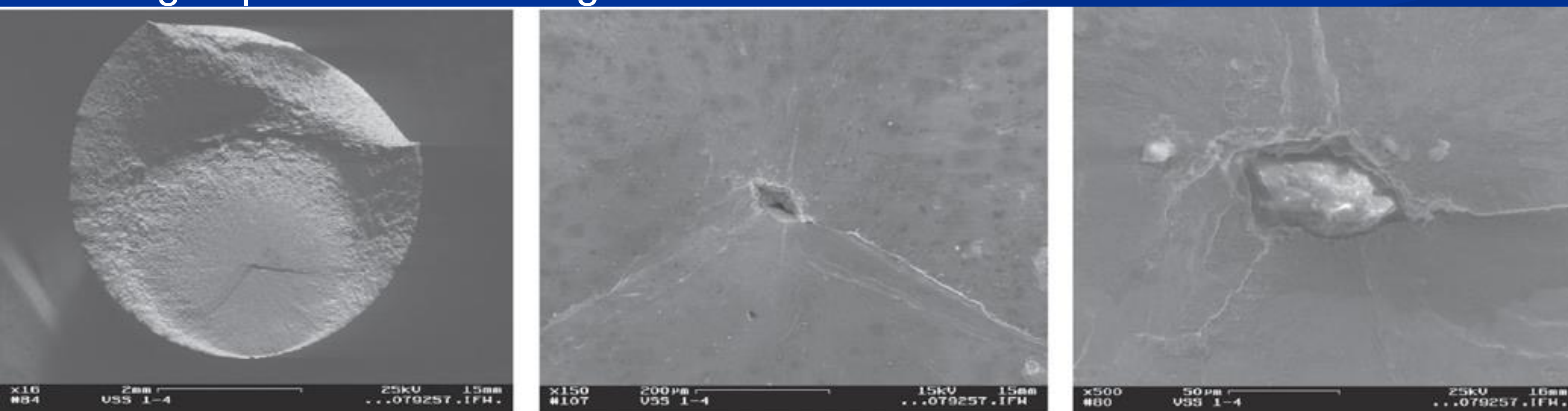
- surface initiation (specimen, component)

Inhomogeneous materials:

- interface between hardened surface layer and “softer” matrix (e.g. nitrocarburized steel etc.)

- Interface between inclusion and matrix (influence of inclusions – purity of pure metals and alloys)

For materials with prior cracks – it is assumed that initiation phase of fatigue process is missing



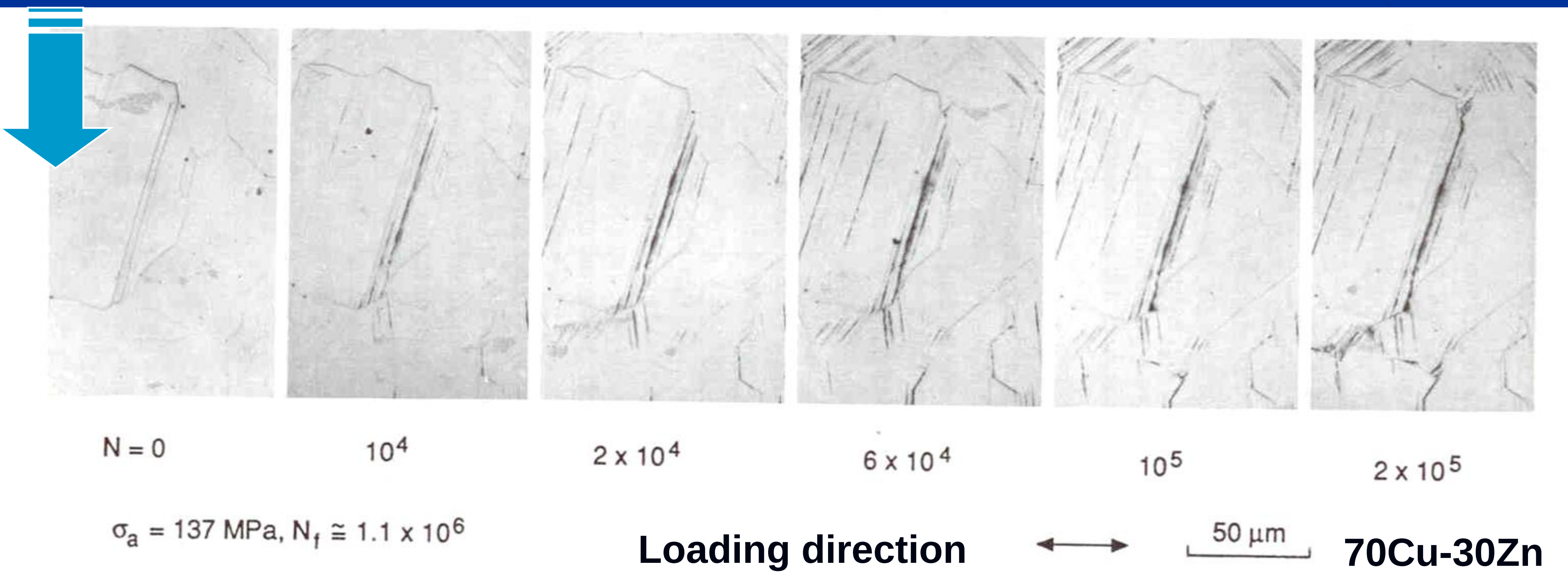
Basic type of crack initiation is focused to fatigue bands

Crack initiation in persistent slip bands

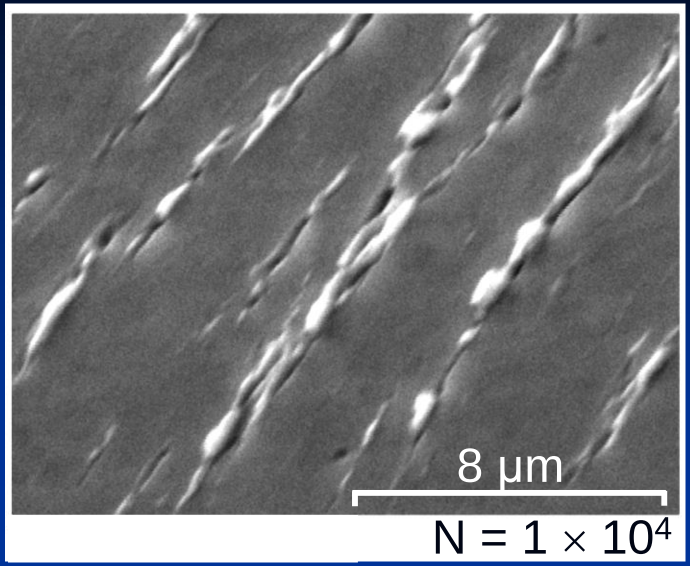
Fatigue bands – manifestation of cyclic plastic deformation
- evolution will start at the end of the stage of mechanical properties changes

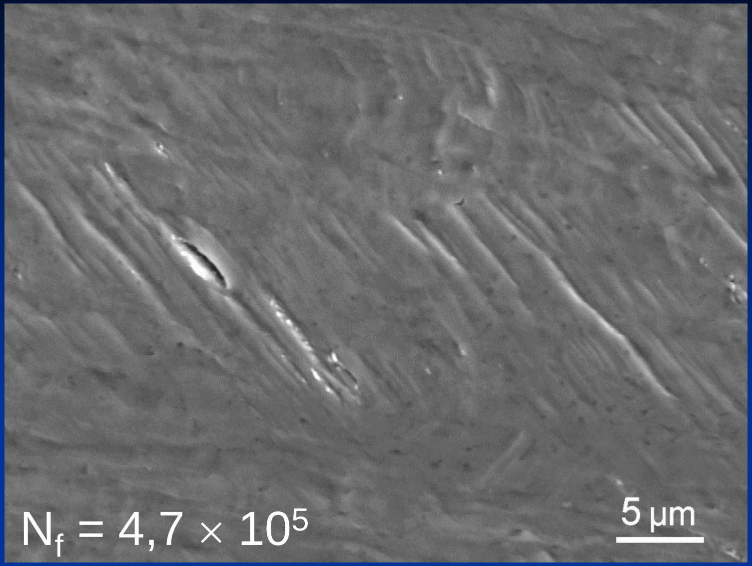
- progressive evolution of fatigue bands with increasing Nf

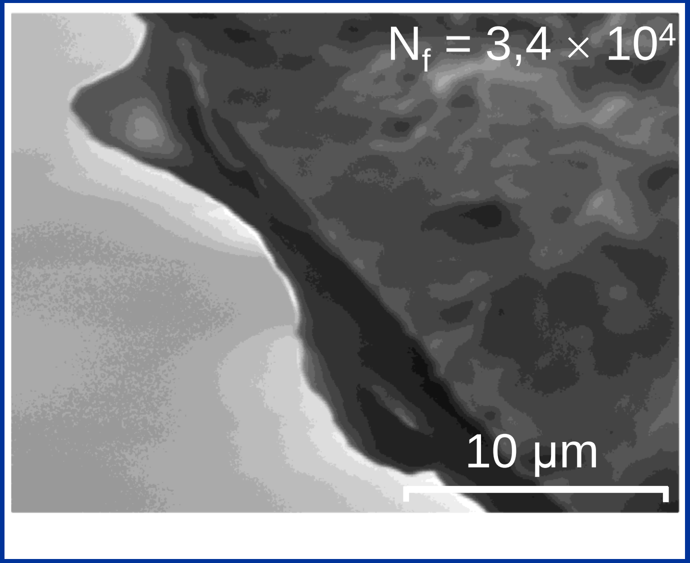
- surface relief evolution – intrusion/extrusion, intensity of bands is dependent on parameters of loading ($\sigma_m = 0$, $\sigma_m > 0$)

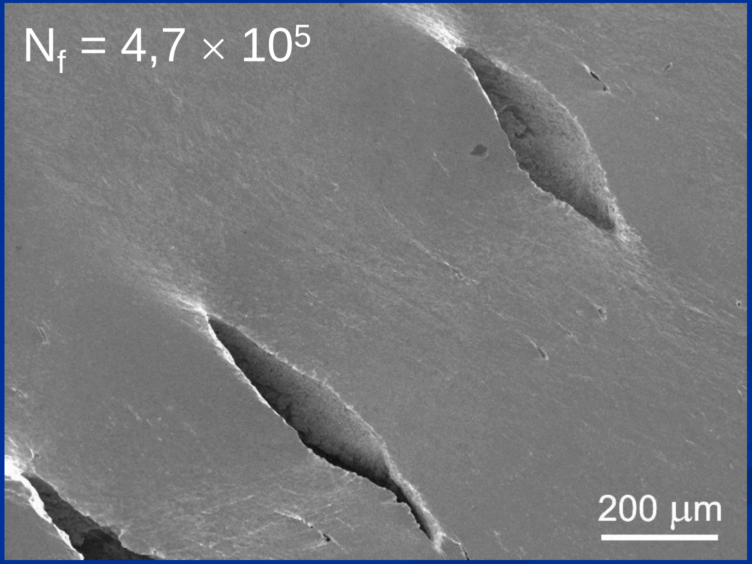


Persistent slip bands









R = -1
σ_a = 255 MPa

R = 0,1
σ_a = 160 MPa

Stage of crack initiation:

N_0 – number of cycle required for crack initiation

N_f – number of cycles to failure

Relative number of cycles N_0/N_f

N_0/N_f is dependent on:

a) Loading amplitude and asymmetry of cycle (N_0/N_f decreasing with increasing amplitude of loading)

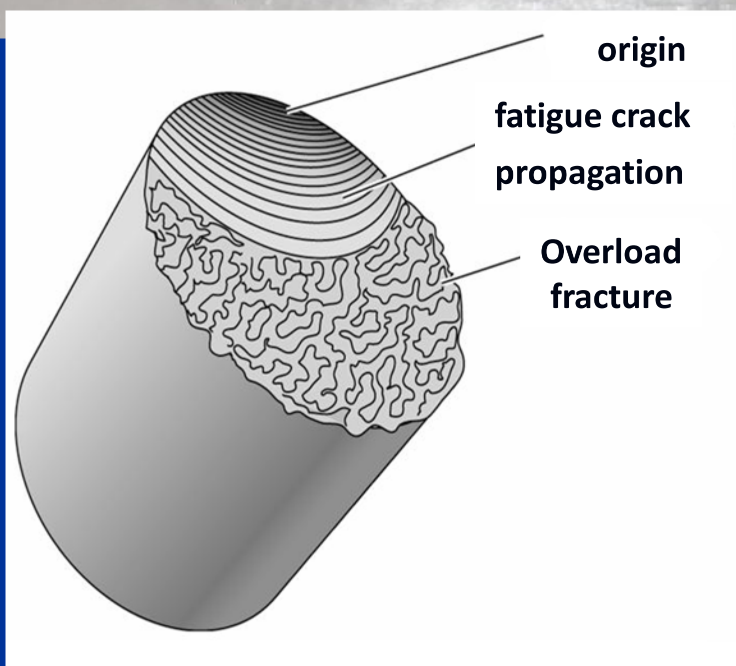
b) Geometry of specimen (structural parts) – influence of notches (stres concentrators)

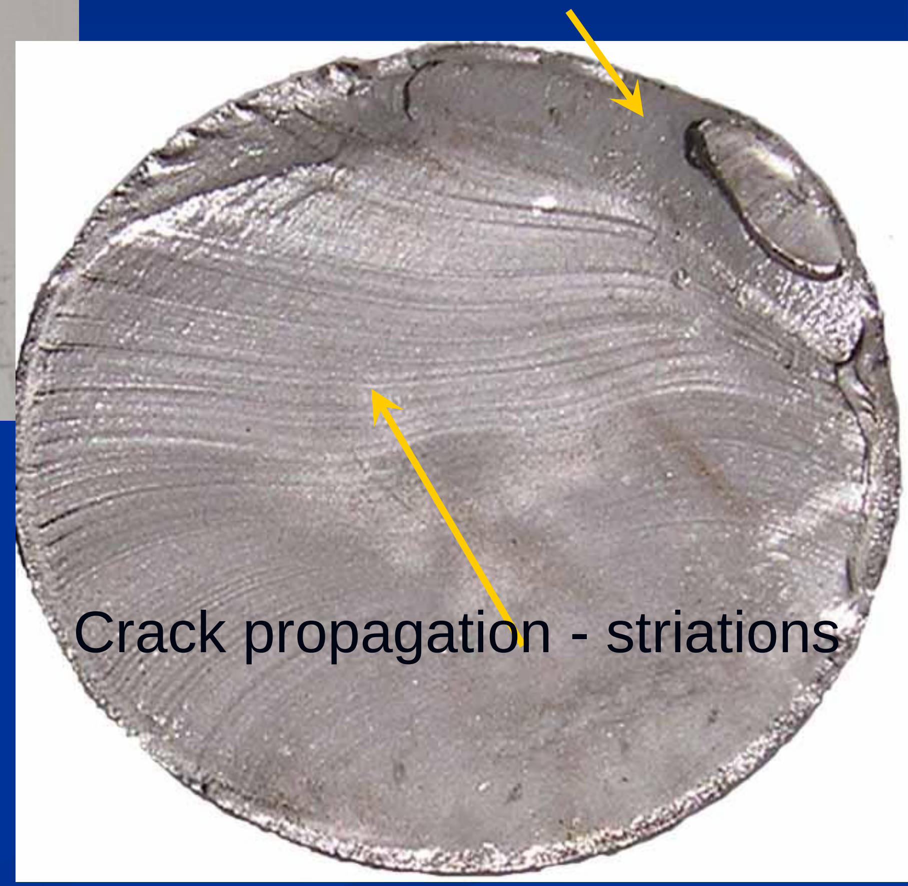
c) Microstructure (inclusions, hard locations)

d) Quality / roughness of surface layer (roughness, residual stresses, contact pitting, surface hardening)

e) Environment (corrosion pittings)

Fatigue fracture

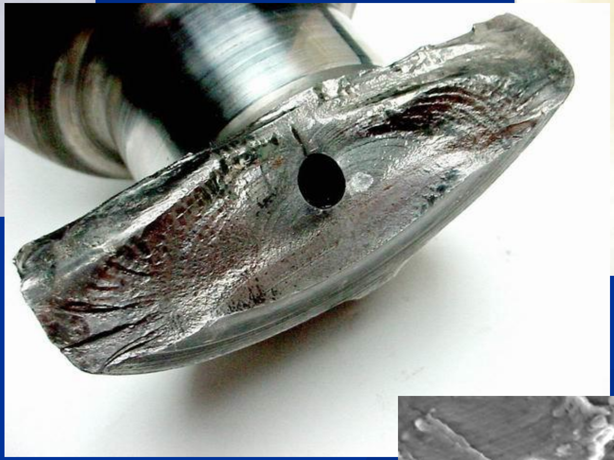




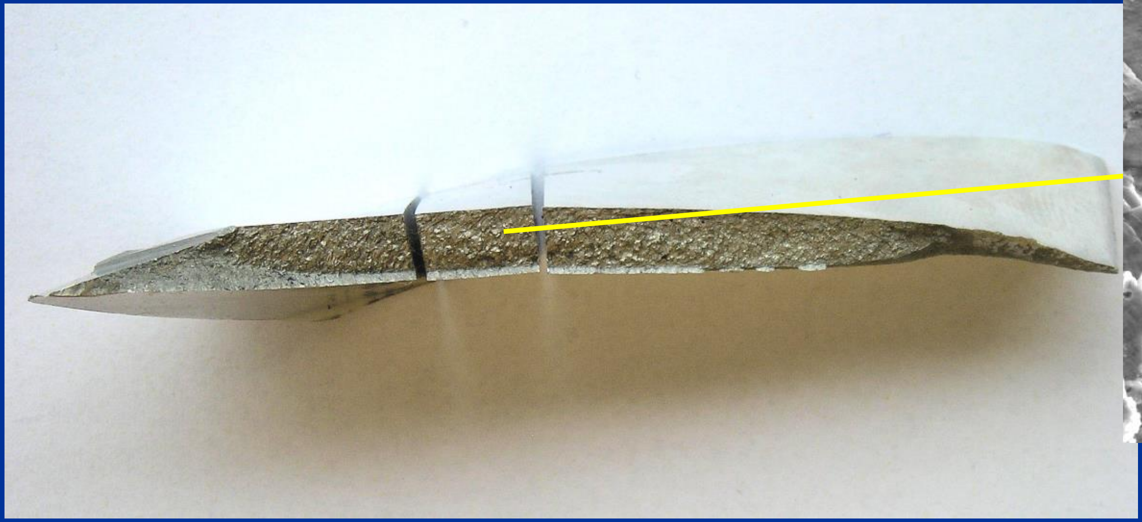
Shaft of tire crasher

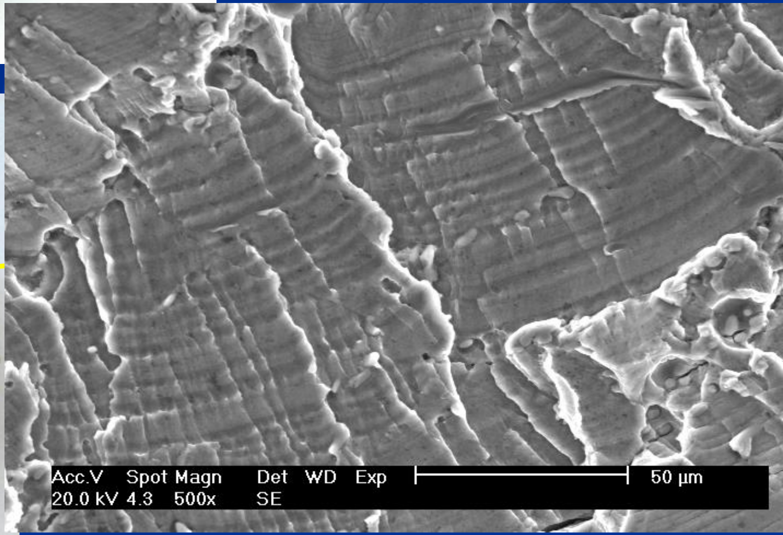
Shaft of pressing machine

Crankshaft



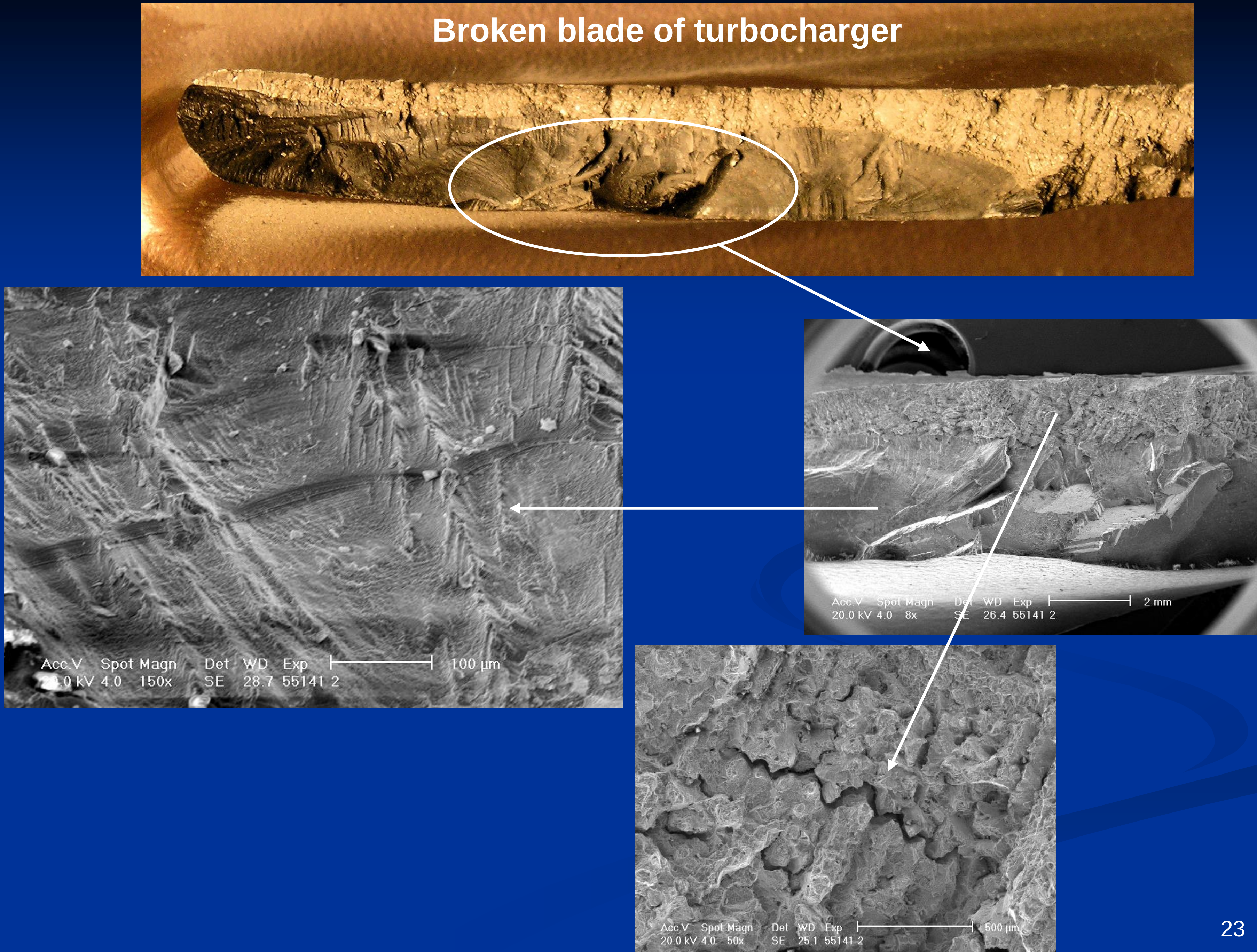
Compressor wheel blade



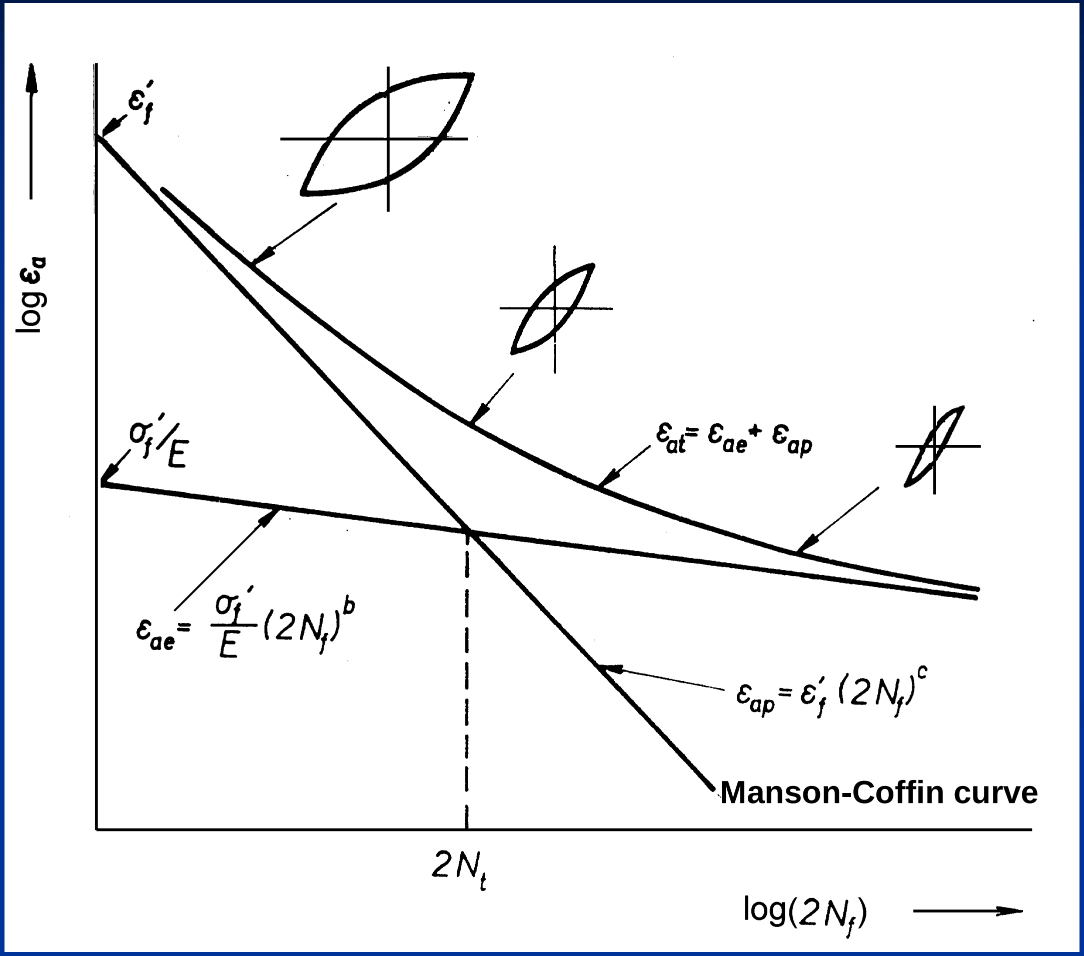



Initiation site
Acc.V Spot Magn Det WD Exp 200 µm
20.0 kV 4.0 100x SE

Broken blade of turbocharger



Manson – Coffin curve



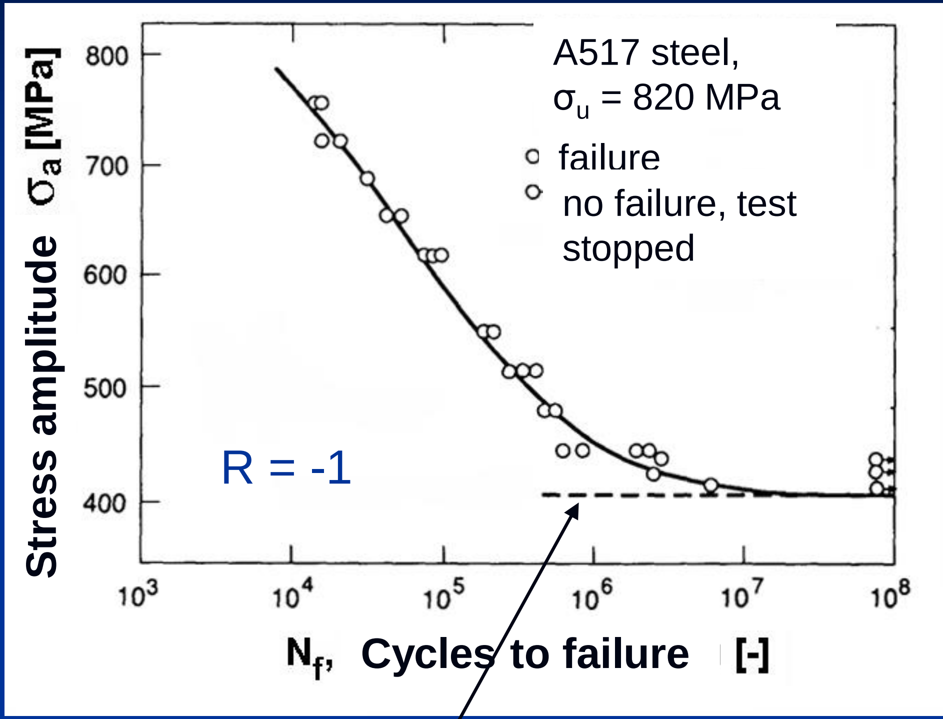
fatigue ductility exponent

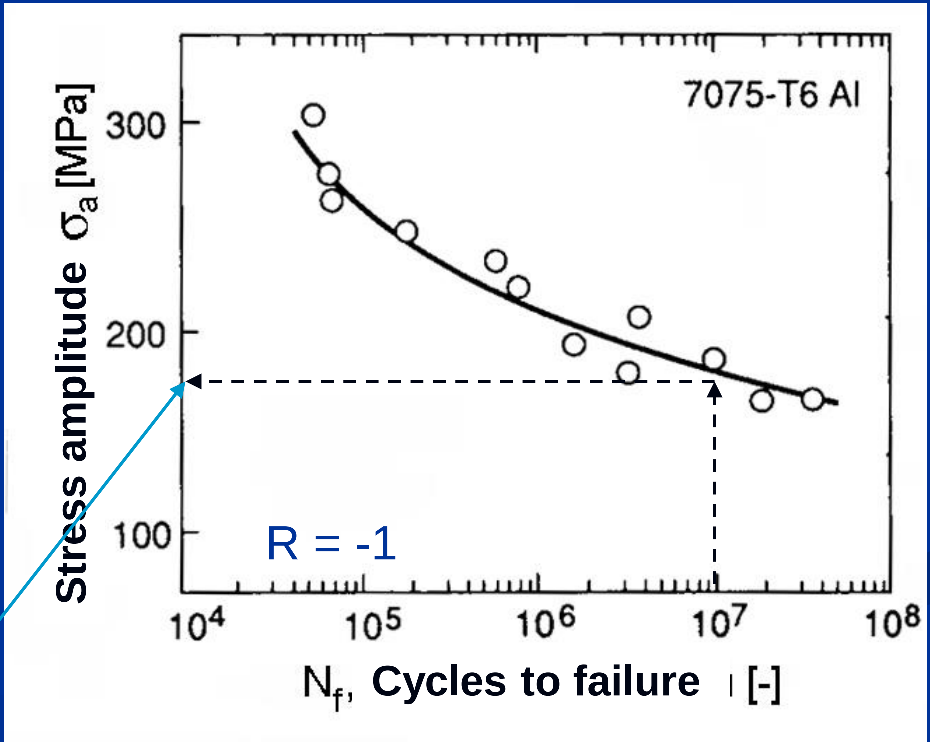
$$\varepsilon_{ap} = \varepsilon'_f \left(2N_f\right)^c$$

fatigue ductility coefficient

$$\varepsilon_{at} = \varepsilon_{ae} + \varepsilon_{ap} = \frac{\sigma'_f}{E}\left(2N_f\right)^b + \varepsilon'_f\left(2N_f\right)^c$$

(S-N curve)





Permanent fatigue limit

Fatigue limit for given N_f

Wöhler: $$\sigma_a = A N_f^B$$

fatigue strength exponent

Basquin: $$\sigma_a = \sigma'_f \left(2N_f\right)^b$$

fatigue strength coefficient

$$A = 2^b \sigma'_f, B = b$$

Fatigue life curves obtained for different loading regime (σ_a = const., ε_{ap} = const.)

It is possible to convert between one another through cyclic stress strain curve (CSSC).

$$\sigma_a = K'\left(\varepsilon_{ap}\right)^{n'}$$

$$\sigma_a = \sigma'_f\left(2N_f\right)^b$$

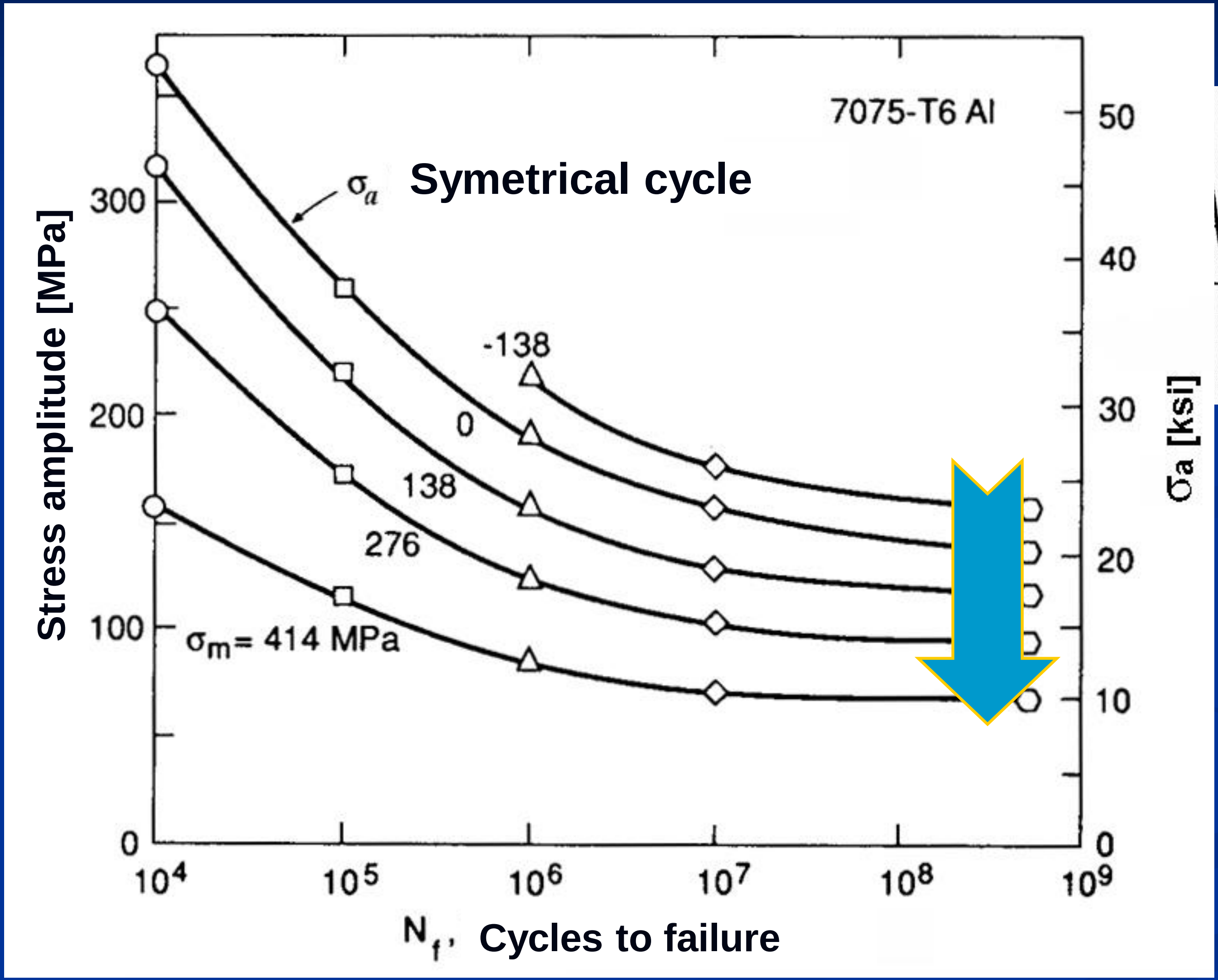
$$\varepsilon_{ap} = \varepsilon'_f\left(2N_f\right)^c$$

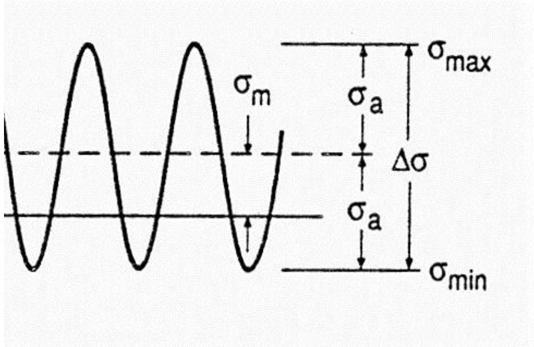
Parameters of fatigue life curves are not independent:

$$K' = \frac{\sigma'_f}{\varepsilon'^{n'}_f}$$

$$b = n'c$$

5) Influence of mean stress

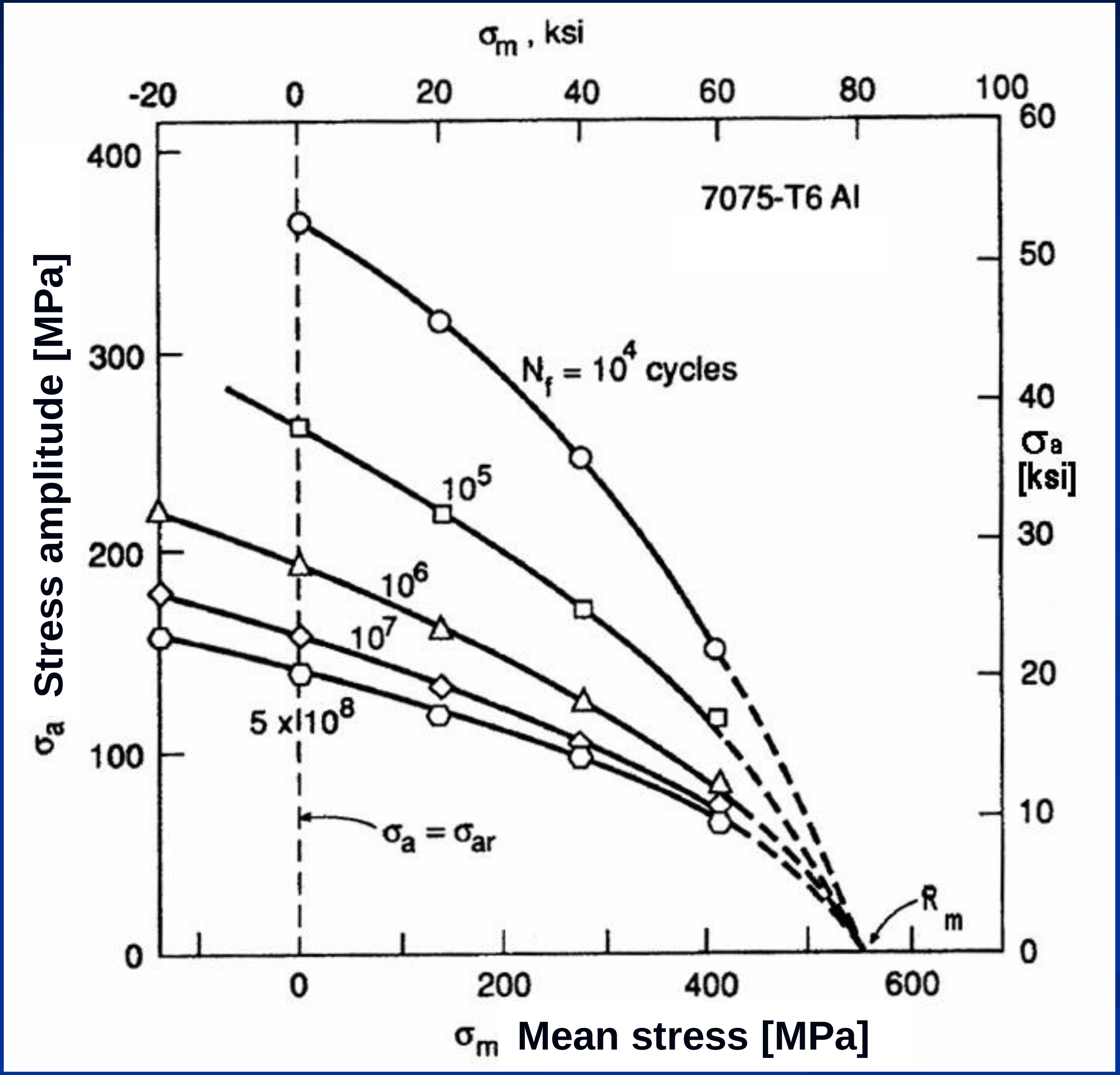




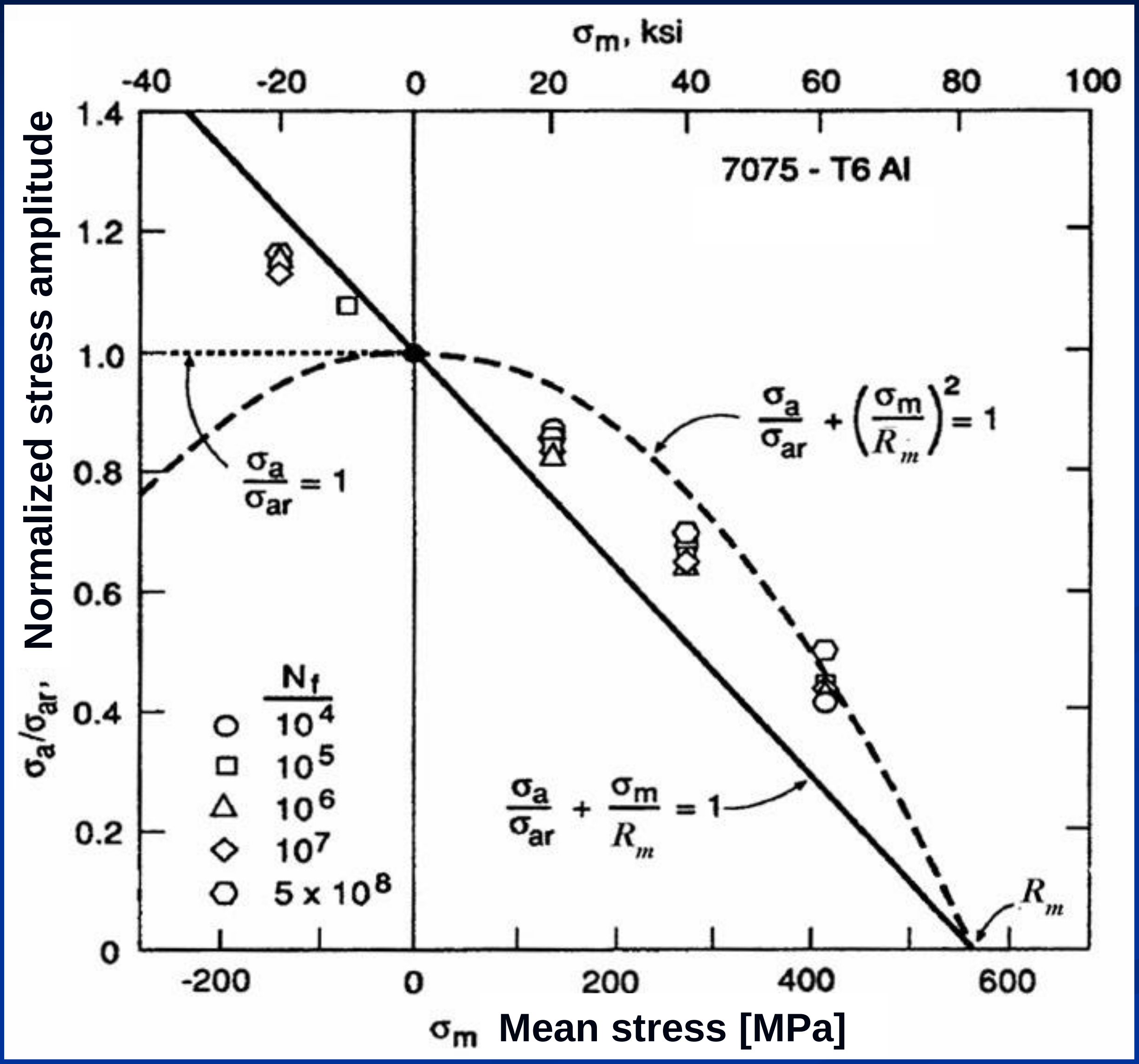
Constant-life diagram

$R_m = \sigma_u$

Ultimate tensile strength



Normalized Amplitude-Mean Stress Diagram



Goodman

$$\frac{\sigma_a}{\sigma_{ar}} + \frac{\sigma_m}{\sigma_u} = 1$$

σ_a – stress amplitude of common cycle
σ_{ar}– stress amplitude of symetrical (regular) cycle
σ_u – ultimate tensile strength
σ_e – yield strength

Gerber

$$\frac{\sigma_a}{\sigma_{ar}} + \left(\frac{\sigma_m}{\sigma_u}\right)^2 = 1$$

Soderberg

$$\frac{\sigma_a}{\sigma_{ar}} + \frac{\sigma_m}{\sigma_e} = 1$$

Wöhler:

$$\sigma_{ar} = AN_f^B$$

Basquin:

$$\sigma_{ar} = \sigma'_f \left(2N_f\right)^b$$

Goodman:

$$\frac{\sigma_a}{\sigma_{ar}} + \frac{\sigma_m}{\sigma_u} = 1$$

$$\Rightarrow$$

$$\sigma_{ar} = \frac{\sigma_a}{1 - \dfrac{\sigma_m}{\sigma_u}}$$

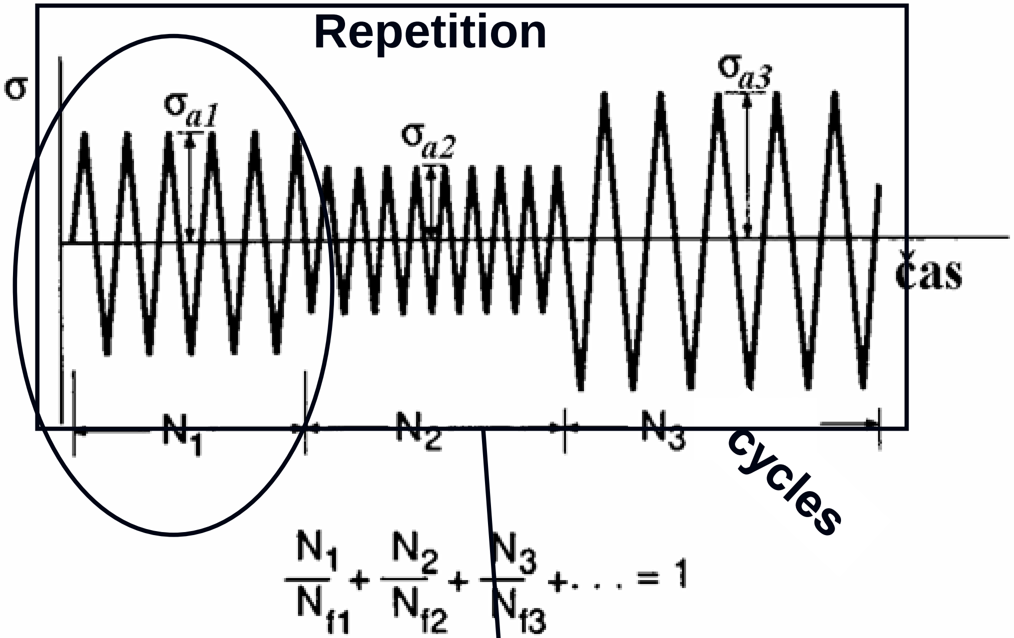
$$\sigma_a = A\left(1 - \frac{\sigma_m}{\sigma_u}\right)\left(N_f\right)^B$$

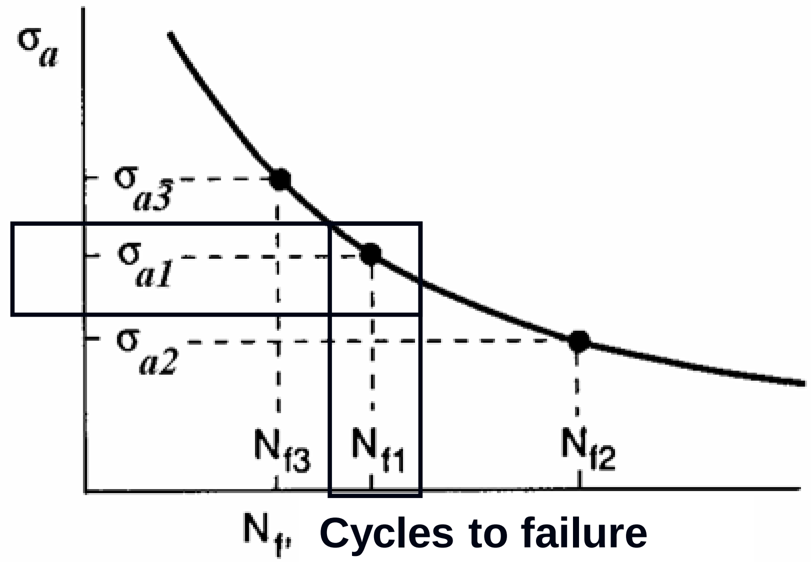
$$\sigma_a = \sigma'_f\left(1 - \frac{\sigma_m}{\sigma_u}\right)\left(2N_f\right)^b$$

For more accurate description σ'_f **is used in place of** σ_u

$$\sigma_a = \left(\sigma'_f - \sigma_m\right)\left(2N_f\right)^b$$

The Palmgren-Miner Rule





Failure is expected when

$$\frac{N_1}{N_f^1} + \frac{N_2}{N_f^2} + \ldots\ldots = \sum_{j=1}^{k} \frac{N_j}{N_f^j} = 1$$

Fraction of the life

$$B = \frac{1}{\frac{N_1}{N_f^1} + \frac{N_2}{N_f^2} + \frac{N_3}{N_f^3}}$$

Literature:

[1] DOWLING, N.E. *Mechanical behavior of materials.* Engelwood Cliffs, USA: PRENTICE-HALL, 1993, 773 s., ISBN 0-13-026956-5.

[2] SURESH, S. *Fatigue of Materials*. 2nd edition. Cambridge, UK: Cambridge University Press, 2003. 679 s. ISBN 0-521-57847-7.

[3] SCHÜTZ, W. A history of fatigue. *Engineering Fracture Mechanics*, 1996, Vol. 54, No. 2, s. 263–300. Available from www: http://www.sciencedirect.com/.