SMA Fracture Mechanics and Basics of Structural Fatigue

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Fundamental Aspects of Materials Science and Engineering (FAMSE)

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materials science and engineering

Text books/recommended reading

RUHR UNIVERSITÄT BOCHUM RUB

- M.A. Meyers, K.K. Chawla, Mechanical Behavior of Materials, Prentice Hall, New Jersey, 1999.
- S. Suresh, Fatigue of Materials, Cambridge Solid State Science Series, Cambridge 1991.
- G.E. Dieter, Mechanical Metallurgy, 3rd Edition, McGraw-Hill, Boston, 1986
- K. Heckel, Einführung in die technische Anwendung der Bruchmechanik, 2. Auflage, Hanser Verlag, 1983
- S. Gollerthan, M.L. Young, A. Baruj, J. Frenzel, W.W. Schmahl, Fracture mechanics and microstructure in NiTi shape memory alloys, Acta Mater., 57 (2009) pp. 1015-1025
- many others

Fracture Mechanics Basics

Fracture Mechanics:

A field of materials mechanics, which came to life in the middle of 20th century.

Failure of Liberty-Ships of the US trading fleet in the 1940s is claimed to be at the starting point of FM.

Today: We assume, that every component has cracks. FM helps to answer the following questions:

(1) How large is the critical crack length?
(2) How long can I tolerate the presence of a crack?
(3) How long does it take until a crack reaches its critical size by crack growth?
(4) Which surface quality do I need prior to service?
(5) How often do I have to inspect my component?

Titanic

Tepalcates-Bridge in Mexiko, 26. November 2003

Hip implant TiAl6V4

Münsterland 25. and 26. November 2005

strong snow -> icy cables + strong wind

Failures

280 000 people had no electricity for a few days

My colleague Prof. Michael Pohl, a well known failure analyst

Piece 26 of turbine rotor which failed in 1987 (Power Plant Irsching). Failure analyst Prof. M. Pohl (IFM-RUB) at Allianz Zentrum für Technik (AZT) in Ismaning, Februar 2000.

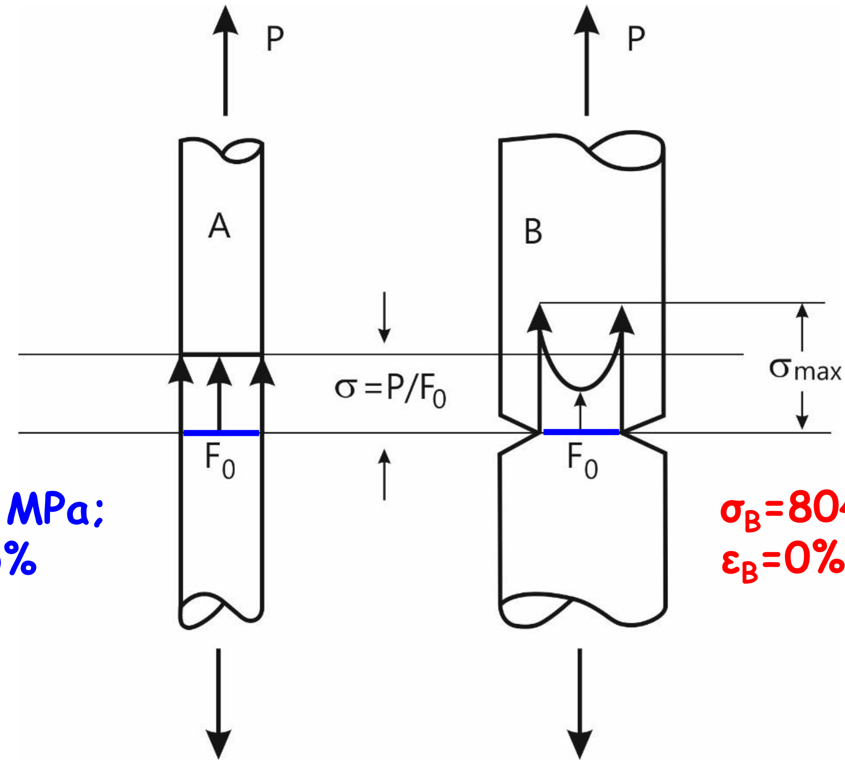
Research in Fracture Mechanics:

- there are always cracks
- when and how do cracks grow?

↓ Parameters for design and component life assessment

↘ Elementary deformation and damage mechanisms at crack tips?

Notches – geometry and strength:



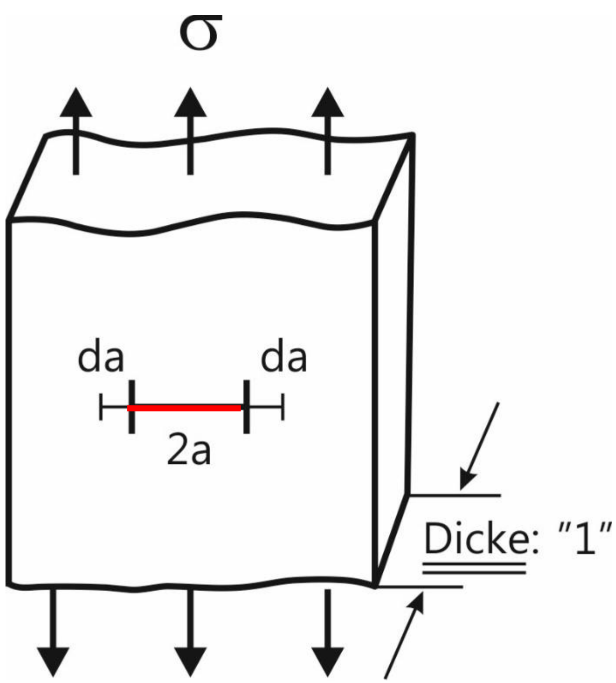
σ_B=540 MPa;
ε_B=17.5%

σ_B=804 MPa;
ε_B=0%

Smooth and notched pearlitic steel specimens

Notches completely change mechanical behaviour. The size of the cross section is not the only thing which matters.

The Griffith theory of brittle fracture:



Body of thickness 1
with Crack of length 2a

Energy balance:

(1) Volume elements close to crack are unloaded.
Elastic strain energy becomes available: ΔU_E.

Plane stress: $$\Delta U_E = \frac{\pi \cdot a^2 \cdot \sigma^2}{E}$$

Plane strain: $$\Delta U_E = \frac{(1-\nu^2)\cdot(\pi \cdot a^2 \cdot \sigma^2)}{E}$$

(2) Surface energy: $$\Delta U_S = 4 \cdot a \cdot \gamma$$

(3) Griffith: $$\frac{d(\Delta U_E)}{da} \geq \frac{d(\Delta U_S)}{da}$$

Result for plane stress

$$\sigma_{GRIFFITH} = \sqrt{\frac{2 \cdot \gamma \cdot E}{\pi \cdot a}}$$

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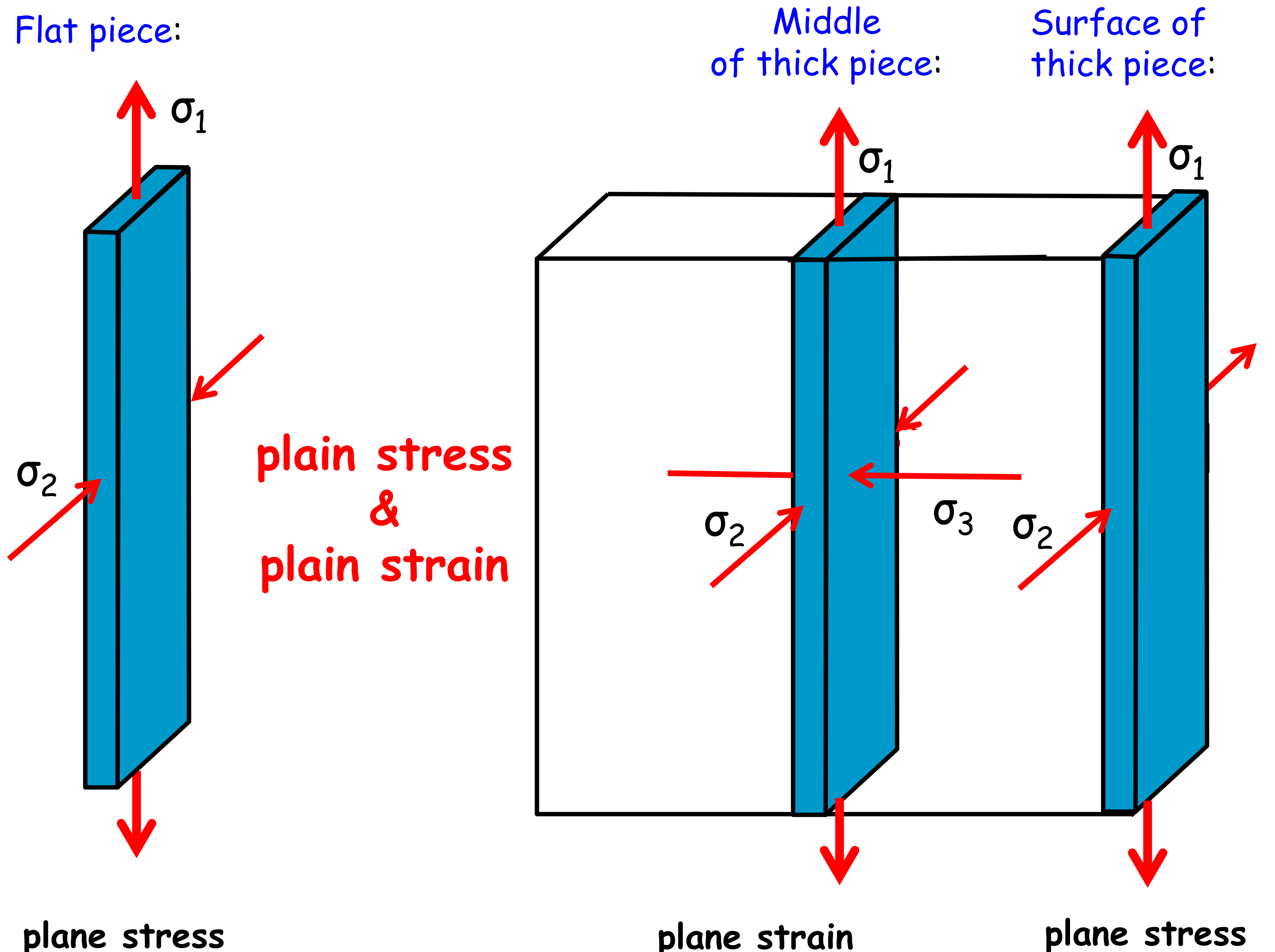
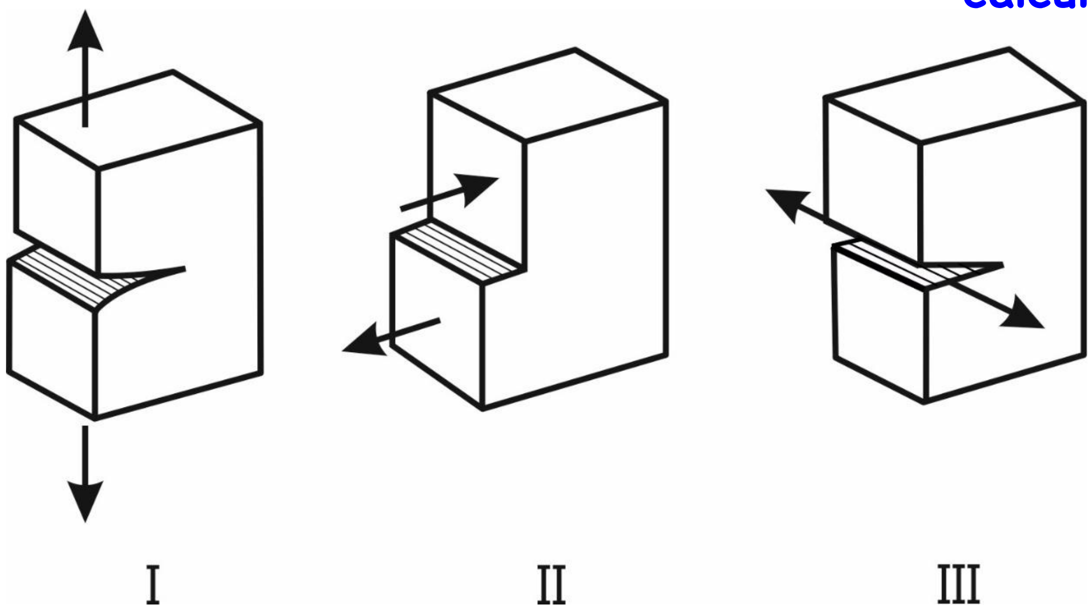

Flat piece:
σ1
σ2
plane stress
plain stress
&
plain strain
Middle
of thick piece:
σ1
σ2
σ3
plane strain
Surface of
thick piece:
σ1
σ2
plane stress

The three fracture modes:

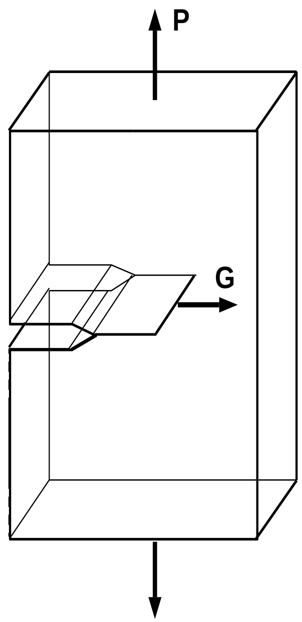
III: easiest to calculate



I: most important

Linear elastic fracture mechanics (LEFM)

The approach proposed by Irwin works much better than that of Griffith. Irwin proposed a Crack Extension force G, which can be measured. This crack extension force is directly related to K, the LEFM parameter which engineers use. Elastic strain energy decreases as crack grows:



$$G = -\frac{d\left(\Delta U_E\right)}{2 \cdot da}$$

We can derive for plane stress:

$$G = \frac{\pi \cdot a \cdot \sigma^2}{E}$$

When G reaches critical value G_{IC}: crack extension

$G > G_{IC}$ -> crack extension

(I – mode of fracture, C – „critical")

$$a \cdot \sigma^2$$

Through $G = \frac{\pi \cdot a \cdot \sigma^2}{E}$ the critical value depends on the product $a \cdot \sigma^2$.

Engineers work with stress intensity factor K:

$$K_I = \sigma \cdot \sqrt{\pi \cdot a}$$

We can calculate G from K:

$$G_I = \frac{K_I^{\,2}}{E}$$

We can say:

A crack grows in loading mode I, when G_I reaches a critical value G_{IC} . It is easy to physically interpret G_I.

But we can also say:

A crack grows in loading mode I, when K_I reaches a critical value K_{IC}. K_{IC} is the materials parameter which is used in industry. It has a peculiar unit ungewöhnliche Einheit (force divided by length $^{3/2}$)

$$MPa \cdot \sqrt{m}$$

We understand:

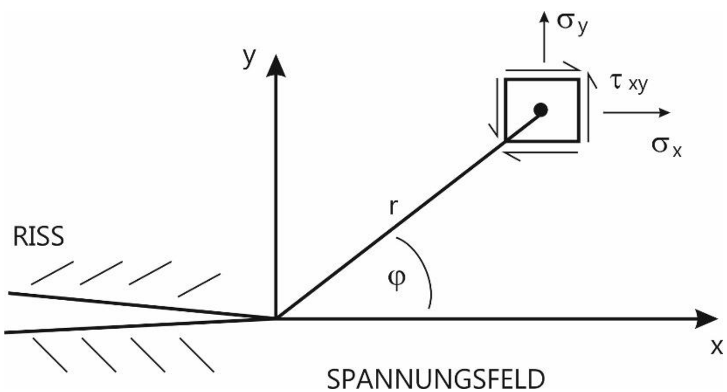
A crack grows when K_{IC} reaches a critical value (and of course, at the same time, G_{IC} also reaches a critical value).

Some K_{IC}-Values (for plane strain):

Metals:	10 – 280 MPa $m^{1/2}$
Ceramics:	0.5 – 5 MPa $m^{1/2}$
Polymers:	0.1 – 5 MPa $m^{1/2}$
Typical value for steel:	80 MPa $m^{1/2}$
Typical value for aluminium alloys:	30 MPa $m^{1/2}$

Stress fields at crack tips:

Analytical solutions of Sneddon



$$\begin{pmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{pmatrix} = \frac{K_I}{\sqrt{2 \cdot \pi \cdot r}} \cdot \begin{pmatrix} \cos\frac{\varphi}{2}\left(1 - \sin\frac{\varphi}{2} \cdot \sin\frac{3\varphi}{2}\right) \\ \cos\frac{\varphi}{2}\left(1 + \sin\frac{\varphi}{2} \cdot \sin\frac{3\varphi}{2}\right) \\ \cos\frac{\varphi}{2} \cdot \sin\frac{\varphi}{2} \cdot \cos\frac{3\varphi}{2} \end{pmatrix}$$

All stresses at a crack tip are proportional to K_I. This is where ist name comes from:

stress intensity factor

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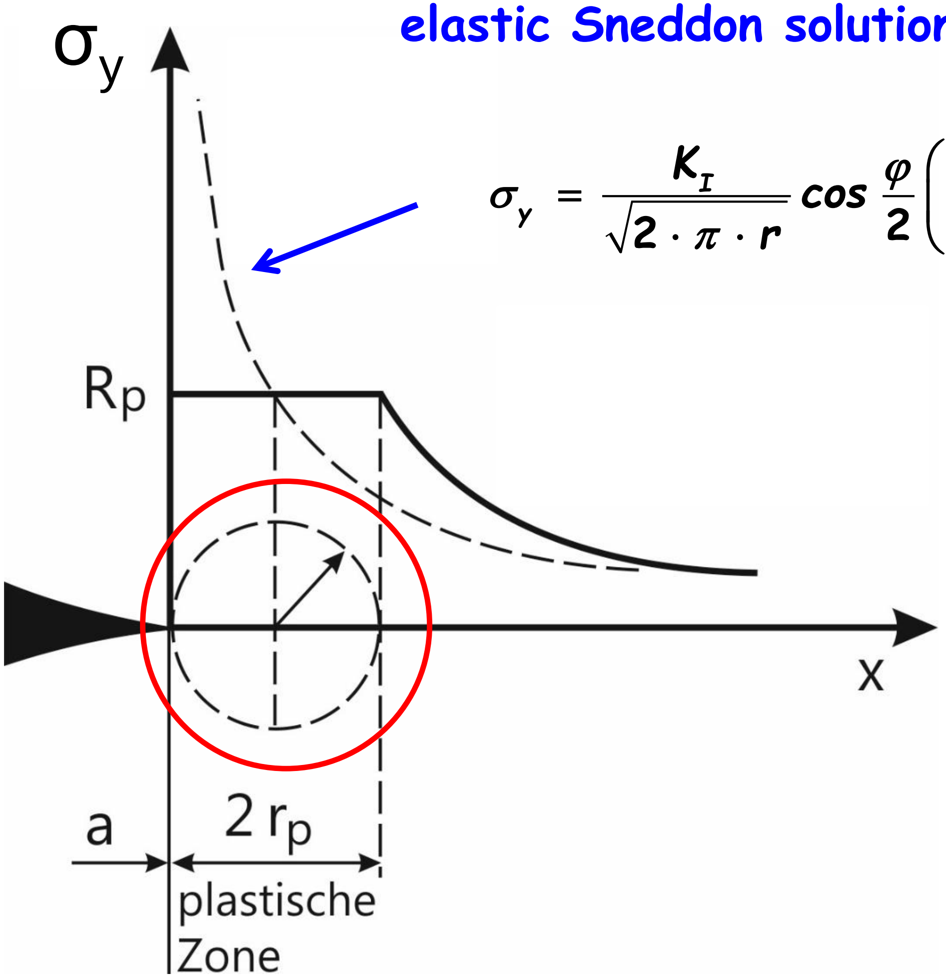
elastic Sneddon solution



$$\sigma_y = \frac{K_I}{\sqrt{2 \cdot \pi \cdot r}} \cos\frac{\varphi}{2}\left(1 + \sin\frac{\varphi}{2} \cdot \sin\frac{3\varphi}{2}\right)$$

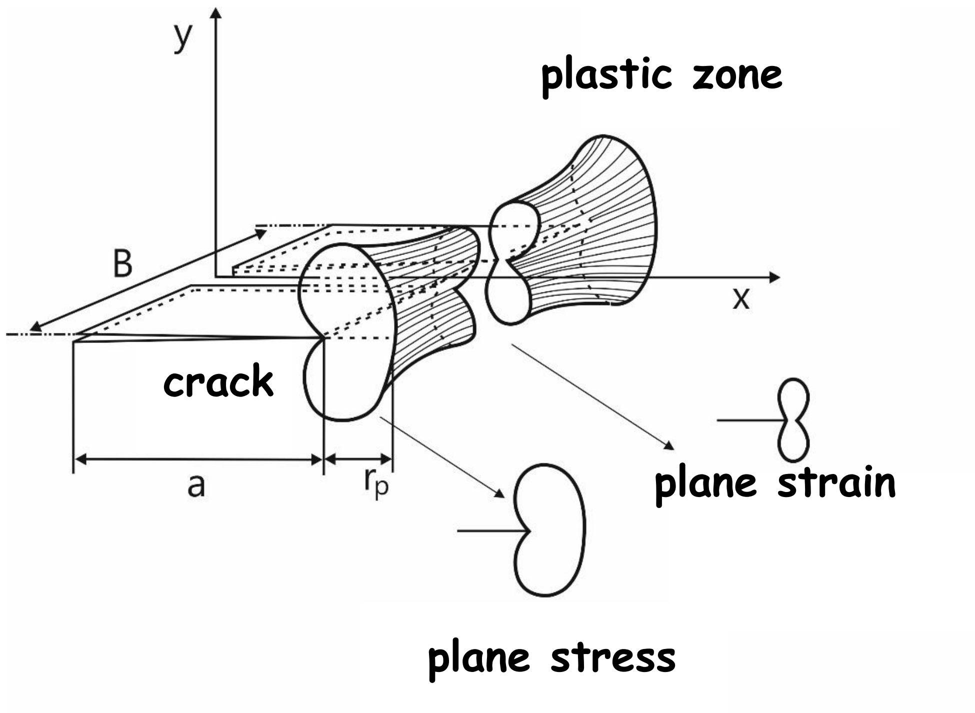
We understand:

The yield stress Rp represents a limit!

There is local yield at the crack tip, where a plastic zone forms.

σ_y in front of the crack tip as a function of distance in x-direction. Blue: purely elastic mathematical solution. Red: Formation of a plastic zone.

Plastic zones in thick specimens can have dog bone shapes:



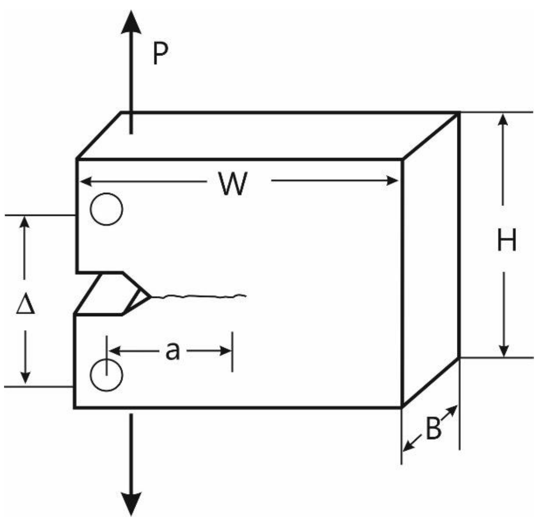
Abschätzung der Größe der plastischen Zone:

$$r_p = \frac{K_{IC}^2}{\pi \cdot \sigma_y^2}$$

Important: With increasing specimen thickness (with increasing B), the plane strain state (inside) becomes more important and the plane stress state (surface) becomes less important.

Problem: When the specimen begins to yield, we are no longer in the elastic regime. All calculations which were performed assuming elasticity, are no longer valid (Sneddon, Irwin).

But: When the size of the plastic zone is much smaller than the dimensions of a the fracture mechanics specimen (here compact tension or CT specimen, the deviations are small and we can tolerate this. There are however strict requirements defined by standards:



CT specimen, dimensions B, H, W.
Crack length a.

Requirement for plane strain:

$$B \geq 2,5 \cdot \left(K_{IC} / R_p\right)^2$$

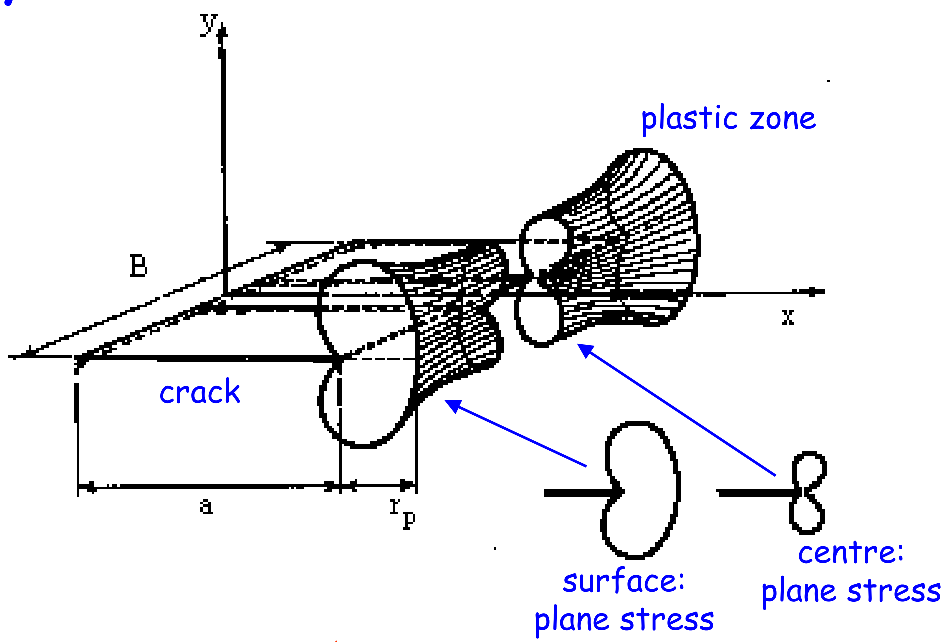
Requirement for validity of LEFM:

$$a, B \geq 2,5 \cdot \left(K_{IC} / R_p\right)^2$$

$$W \geq 5 \cdot \left(K_{IC} / R_p\right)^2$$

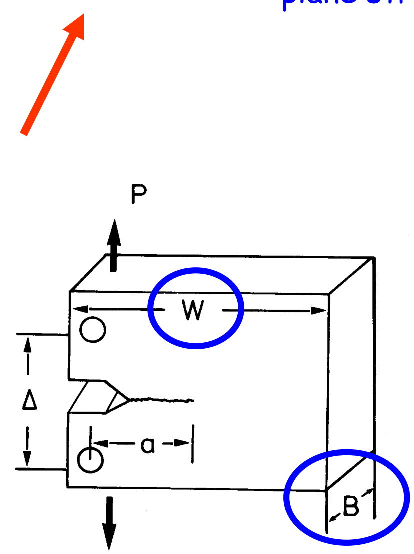
From my mechanical property class notes:

Plastic zone: r_p

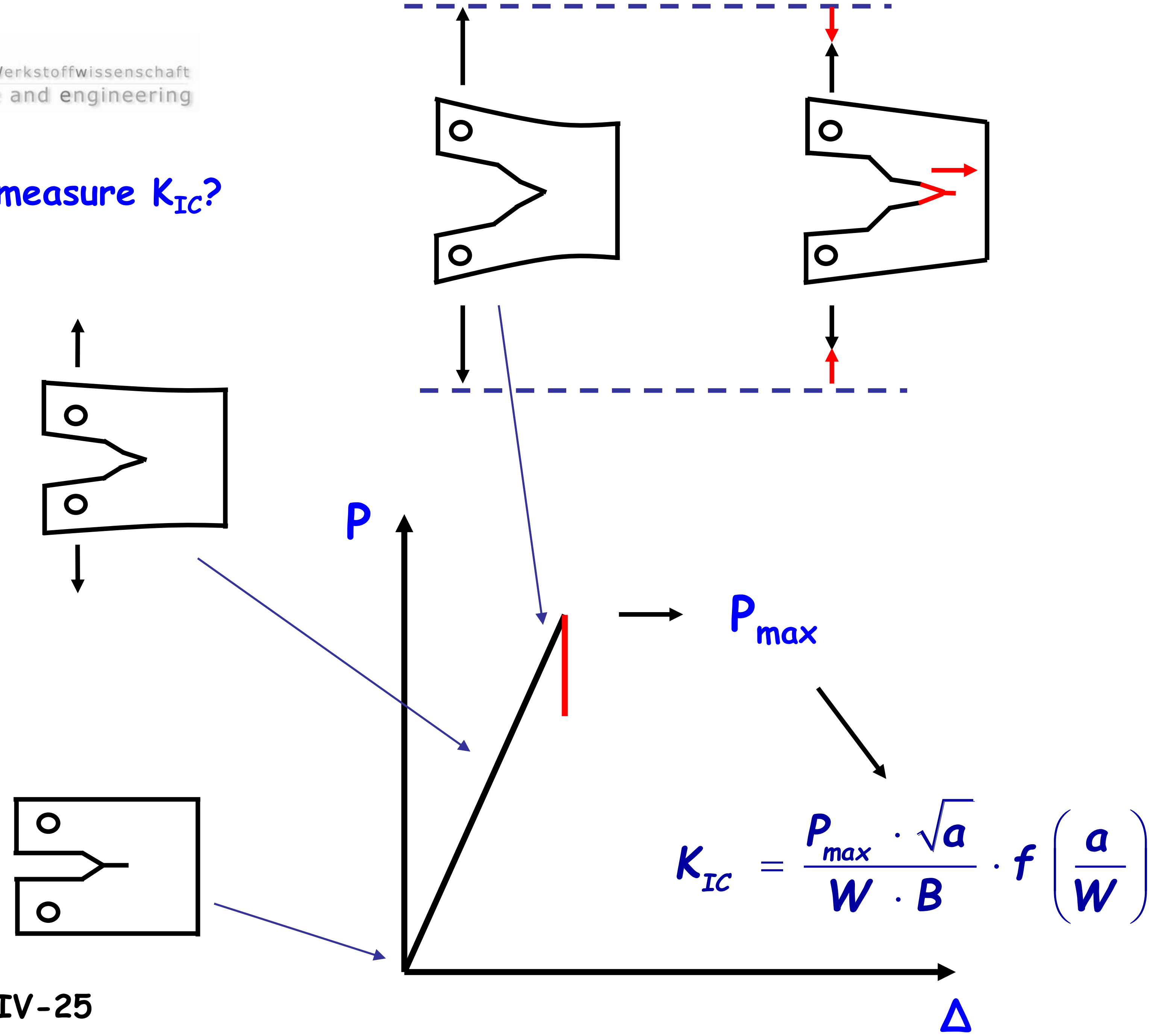


LEFM works when:

$$r_p << B, W$$



How do we measure K_{IC}?



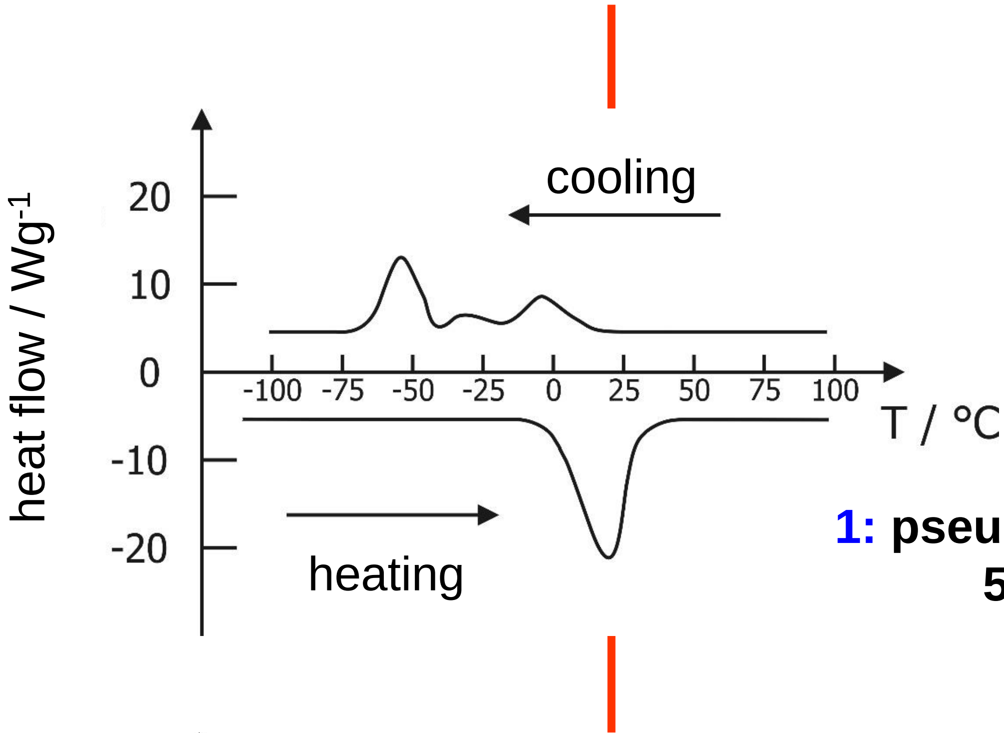
$$K_{IC} = \frac{P_{max} \cdot \sqrt{a}}{W \cdot B} \cdot f\left(\frac{a}{W}\right)$$

Section summary – fracture mechanics (FM)

Cracks can cause catastrophic failures. Fracture mechanics deals with cracks, it tells us when cracks start to *grow* (depending on loading condition and *geometry*). There are related loading parameters G and K, and there related critical parameters G_{IC} and K_{IC} where cracks start to *grow*. We understand the principle of a K_{IC} test. We understand that plastic zones can form at a crack tip and that this violates the pure elastic conditions. In real FM specimens, there are strict conditions for the validity of FM, specimen dimensions must be much *larger* than plastic zones. In thick CT-specimens, plastic zones can have a *dog* bone shape due to differences between plane strain in the center of the specimen and plane stress in the surface region.

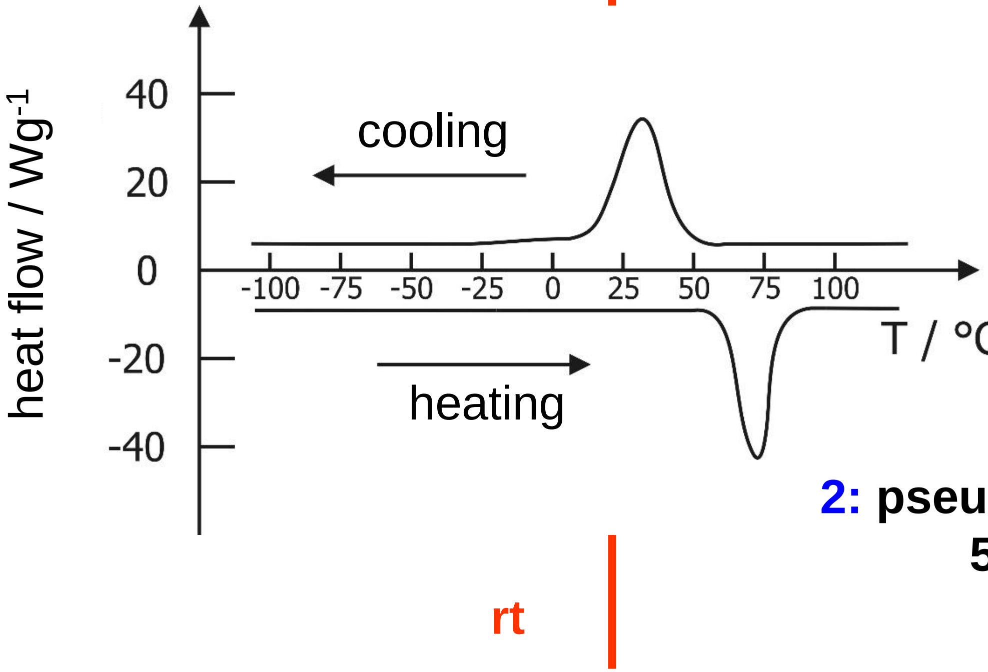
Fracture Mechanics of Shape Memory Alloys

2 NiTi materials

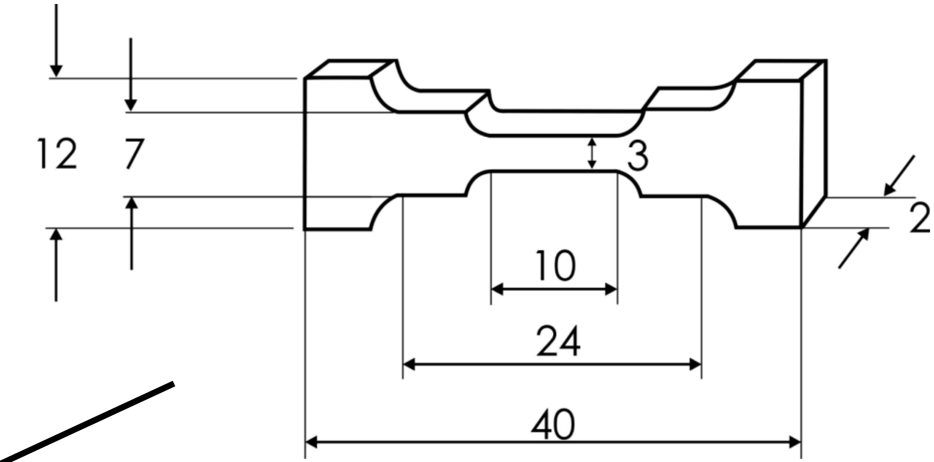


1: pseudoelastic NiTi
50.7%Ni

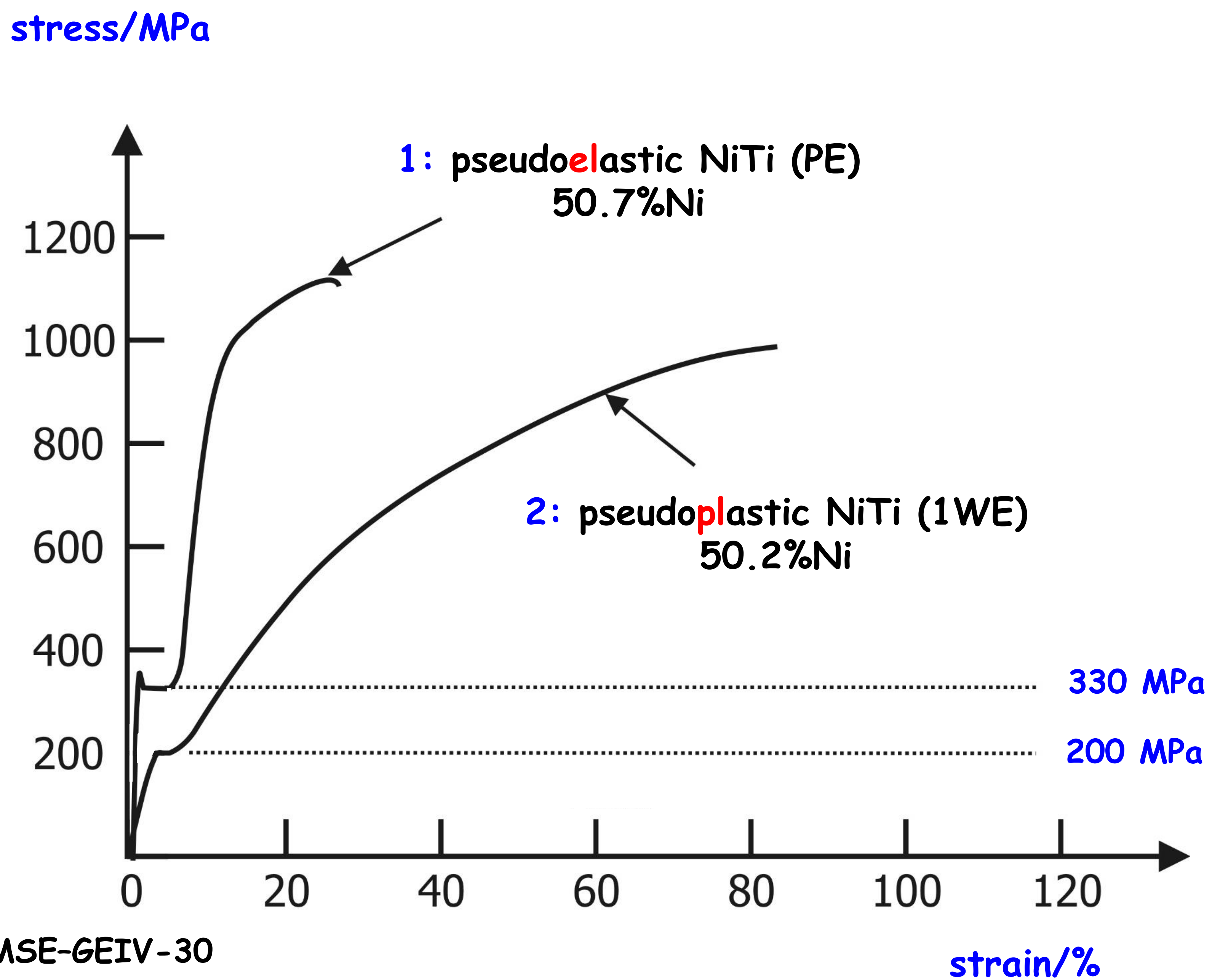
DSC



2: pseudoplastic NiTi
50.2%Ni



tensile testing



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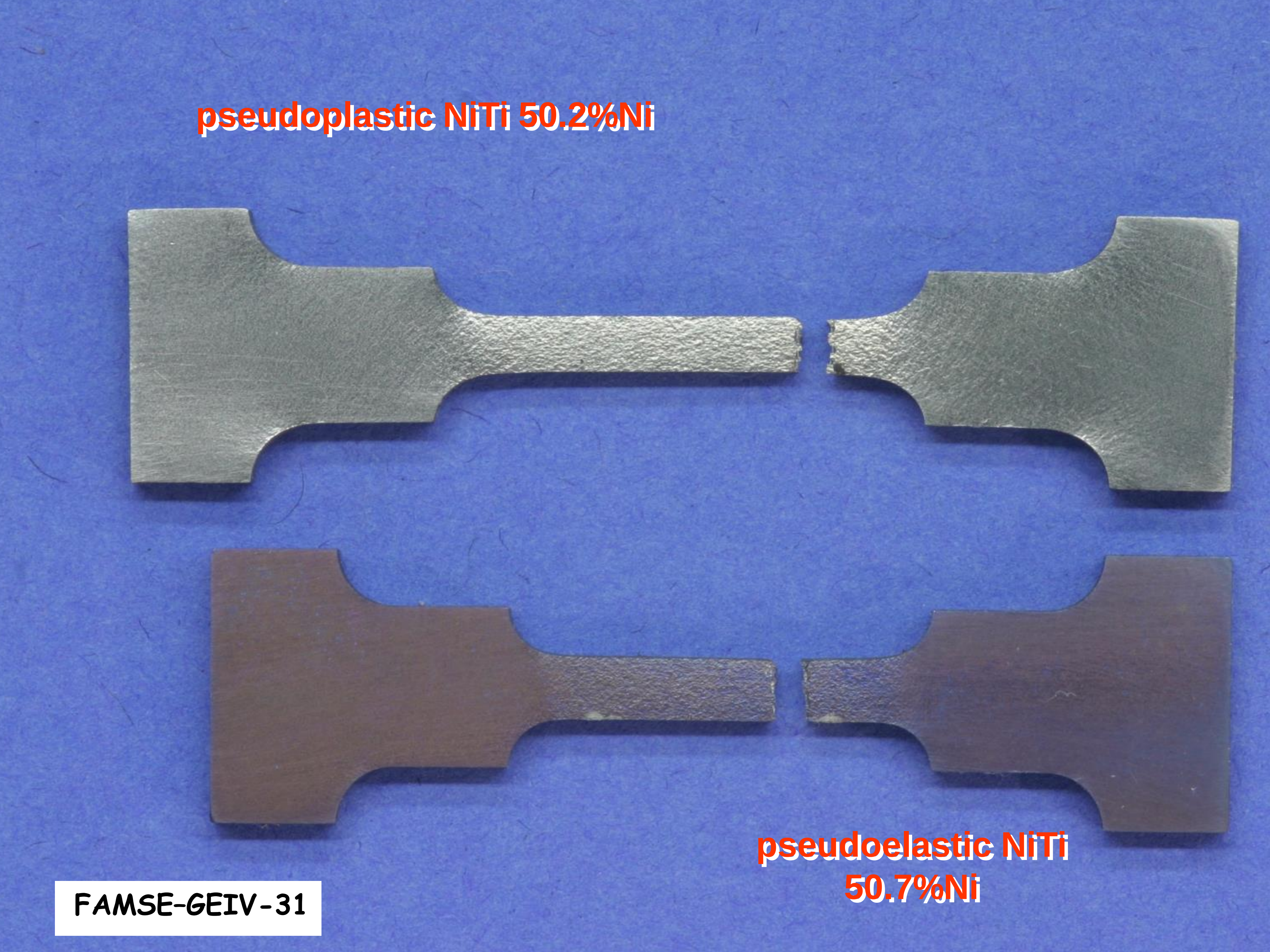
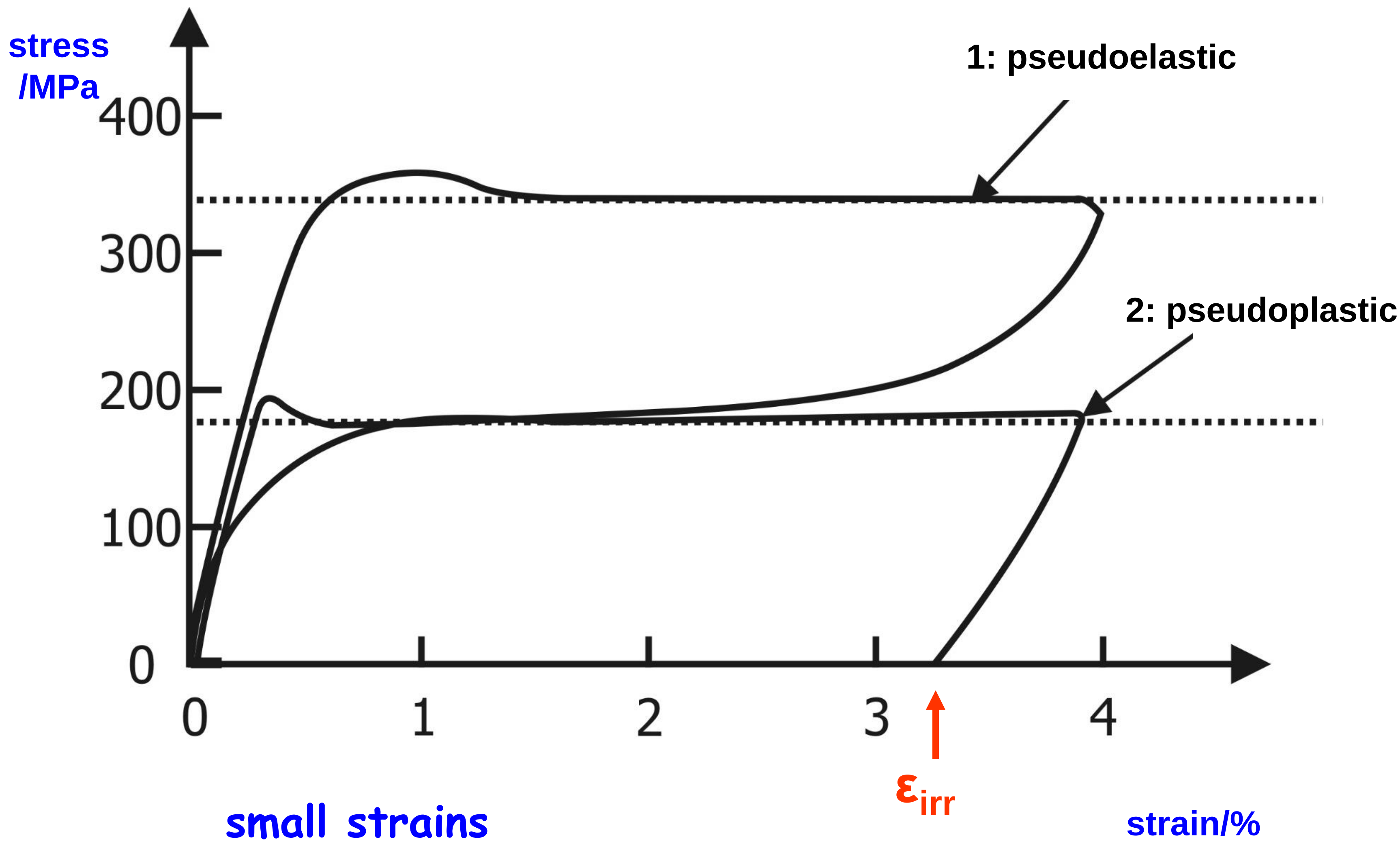

pseudoplastic NiTi 50.2%Ni
pseudoelastic NiTi
50.7%Ni
FAMSE-GEIV-31

fully reversible/irreversible loading/unlaoding characteristics



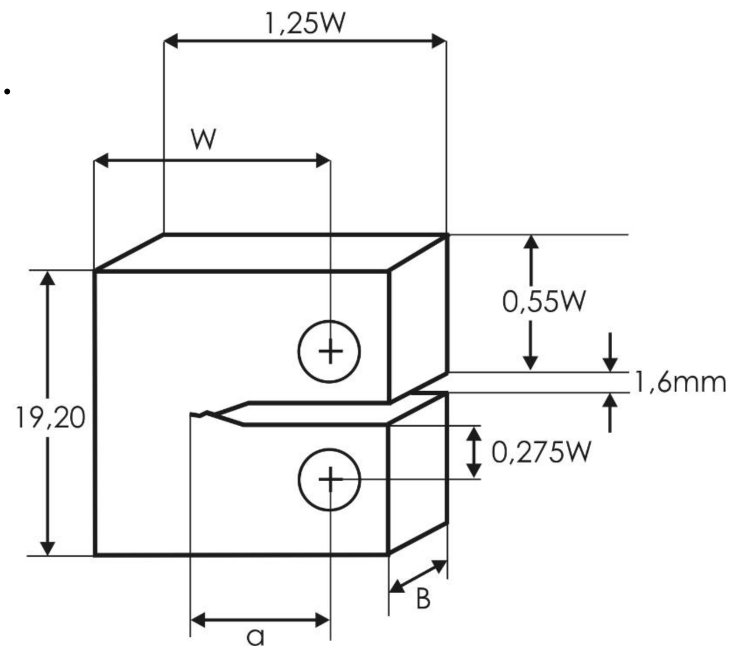
So far:

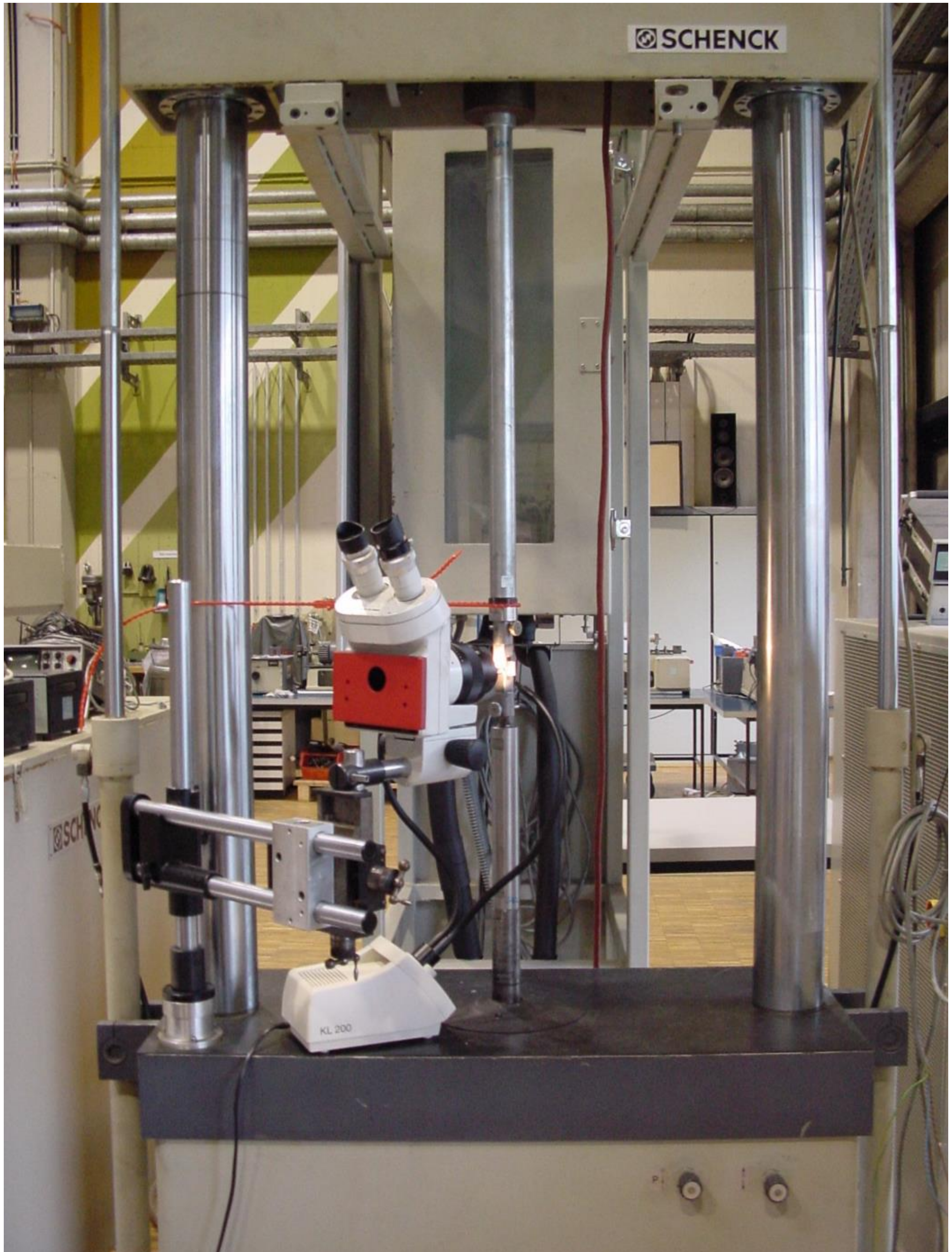
In uniaxial loading, the two materials behave completely different (as we would expect).

What about their behaviour in fracture mechanics tests?

Development of miniature size CT specimen

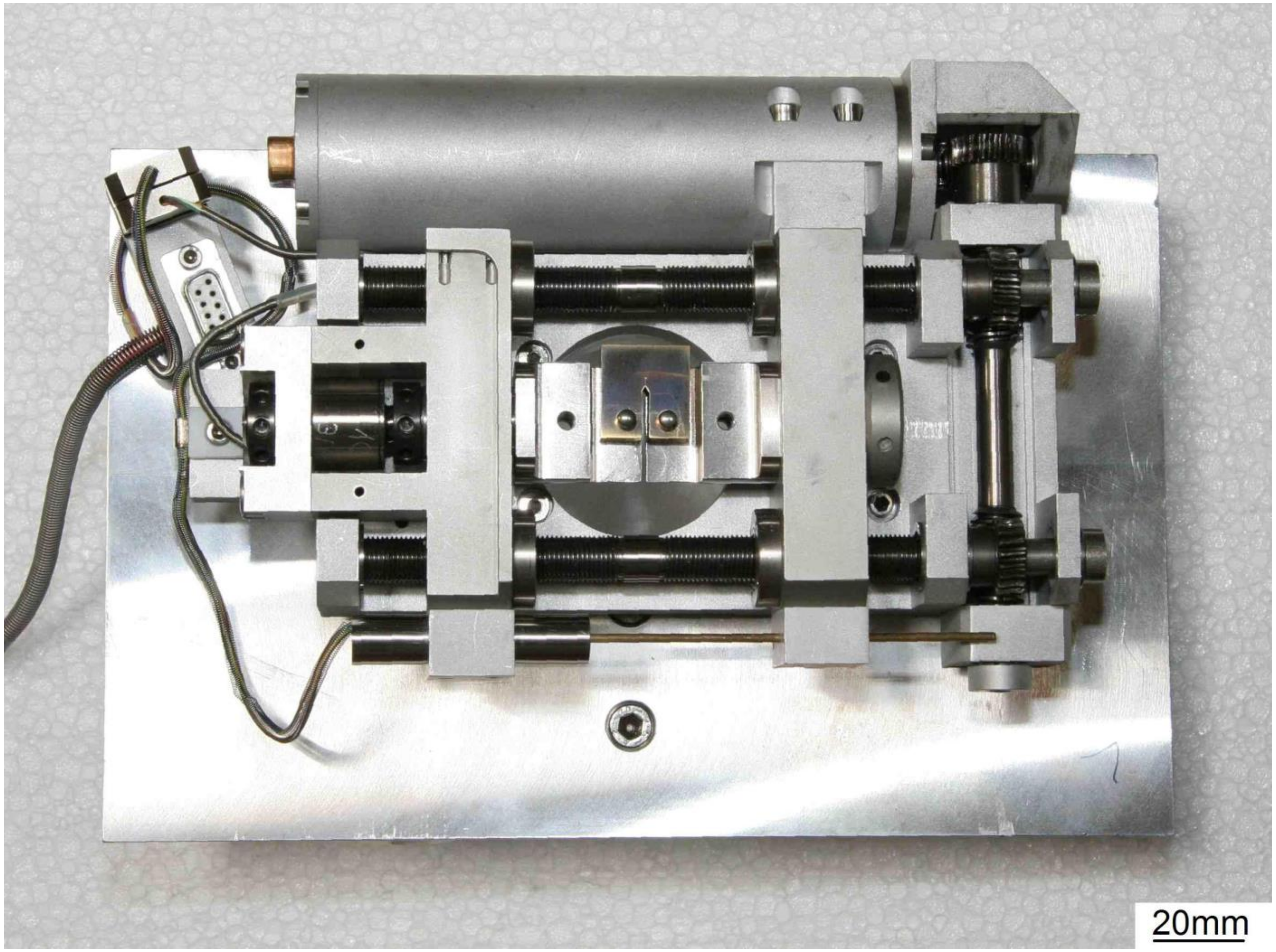
- CT-Probe as suggested by ASTM 399-90
  but scaled down for synchrotron radiation transp.
- Al 7075: comparison miniature CT specimen with
  standard size specimen
- adjust plane strain condition
  (variation of B)
- demonstrate independence on a/W-ratios
- result: W=16mm, **B=8mm**, a=7,4 - 9,8mm





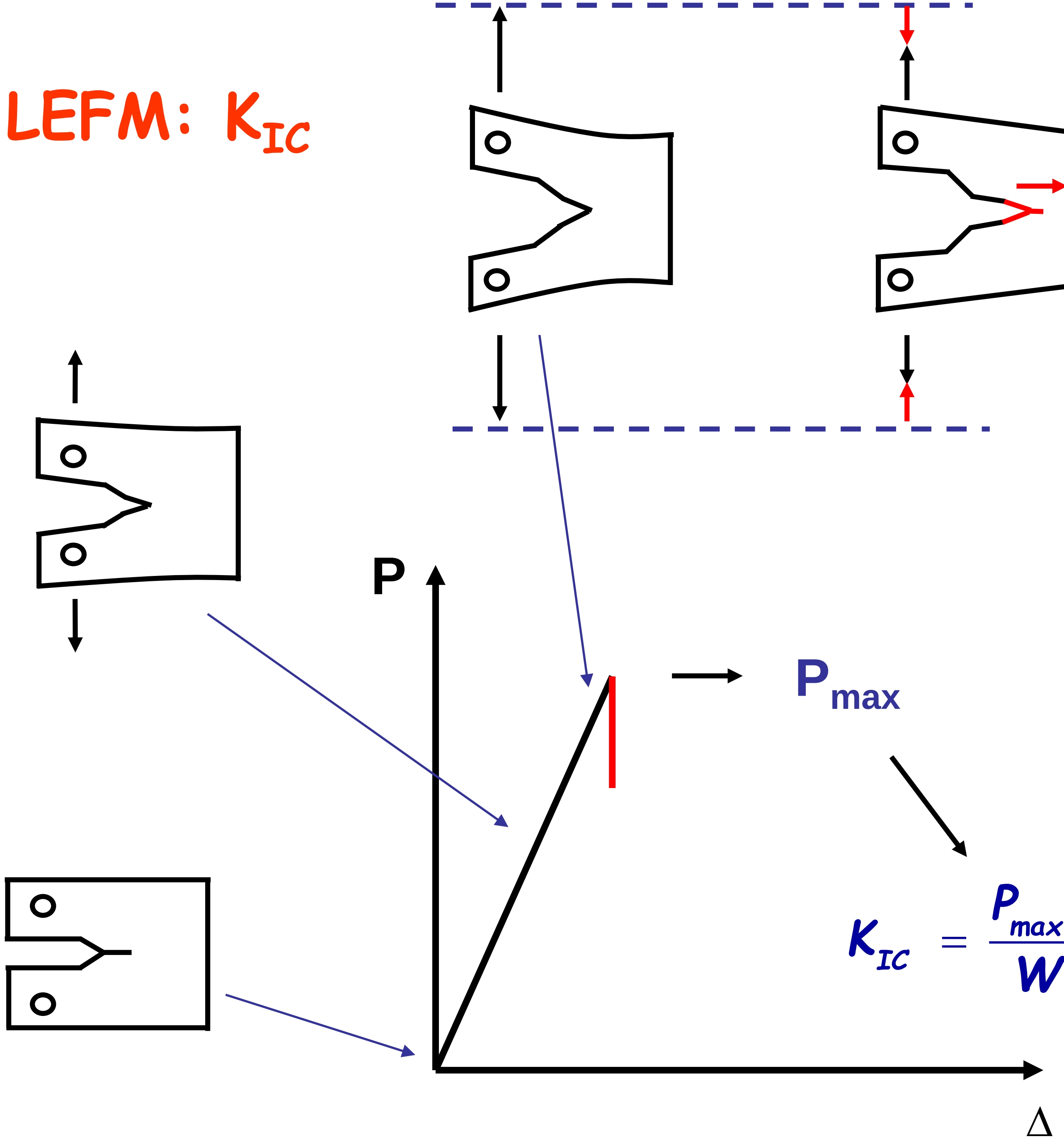
precracking in
Schenck PC160
to produce
sharp crack

cyclic loading
under appropriate
conditions
(tedious)



miniature tensile test rig from Kamrath and Weiss
(alternatively used: Zwick Z100)

LEFM: K_{IC}

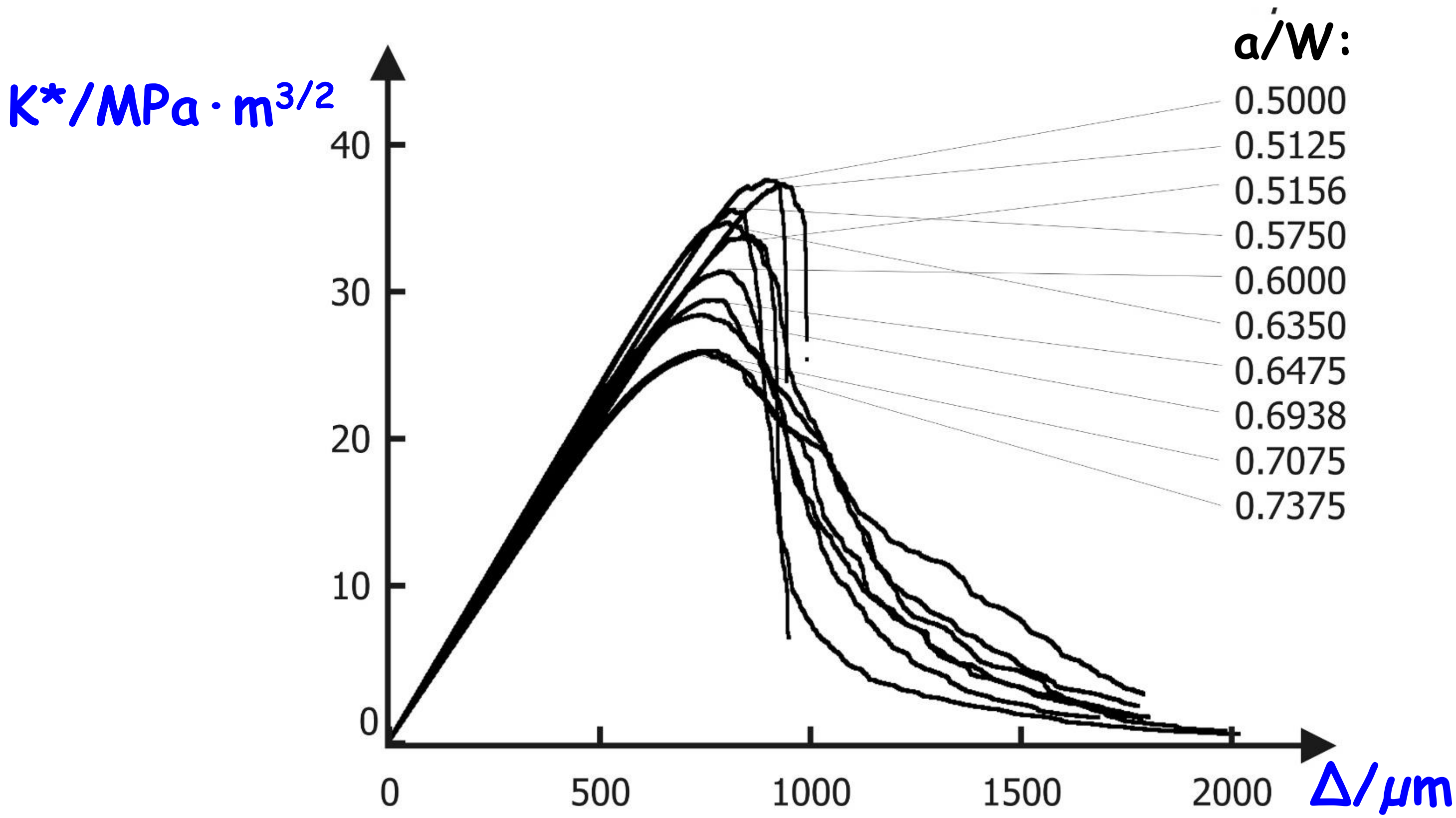


$$K_{IC} = \frac{P_{max} \cdot \sqrt{a}}{W \cdot B} \cdot f\left(\frac{a}{W}\right)$$

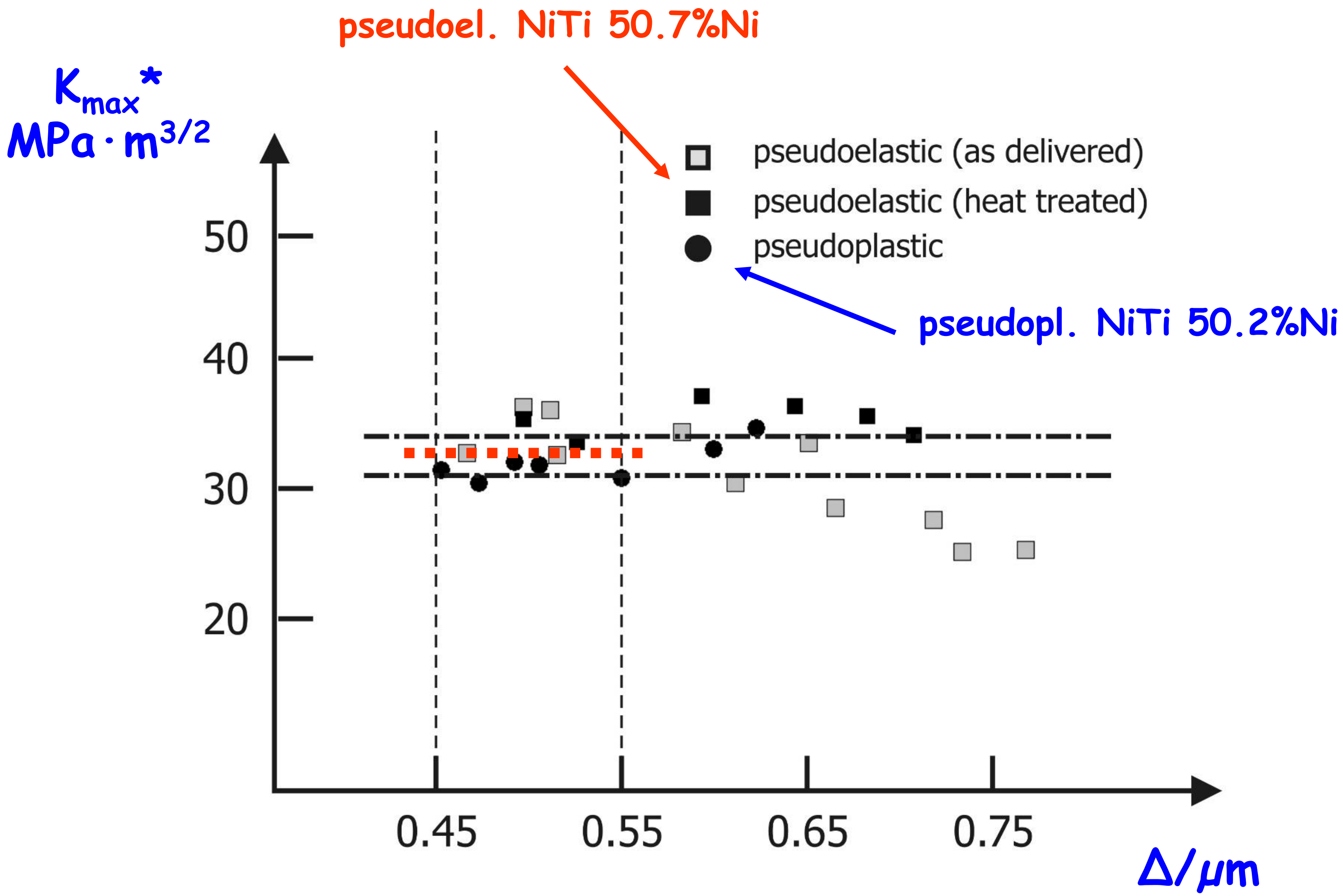
with: *W = 16 mm*

$$K^* = \frac{F}{B\sqrt{W}} \cdot f\left(\frac{a}{W}\right)$$

$$f\left(\frac{a}{W}\right) = \left(2 + \frac{a}{W}\right) \cdot \frac{0.886 + 4.64 \cdot \frac{a}{W} - 13.32 \cdot \left(\frac{a}{W}\right)^2 + 14.72 \cdot \left(\frac{a}{W}\right)^3 - 5.6 \cdot \left(\frac{a}{W}\right)^4}{\left(1 - \frac{a}{W}\right)^{3/2}}$$



K* data of pseudoelastic NiTi 50.7%Ni



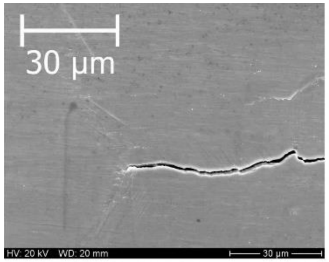
macroscopic crack growth at similar Kmax*

pseudopl. NiTi 50.2%Ni

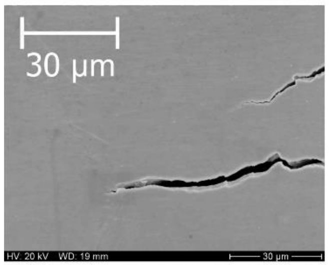
we can also obtain reasonable estimate of size of plastic zone

$$r_p = (1 / 6\pi) \left(\frac{K^*_{max}}{\sigma_{Plateau}} \right)^2 \approx 3\,mm$$

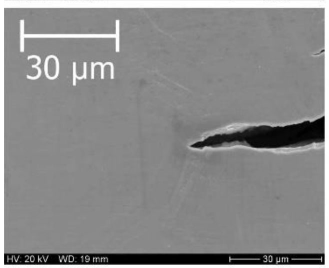
in-situ SEM



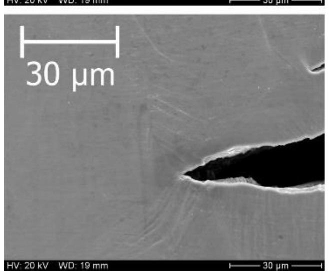
0 N



1250 N

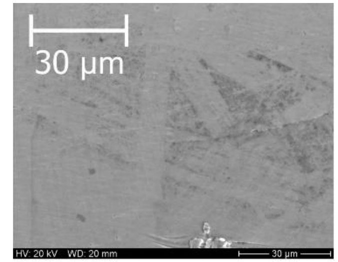


2750 N

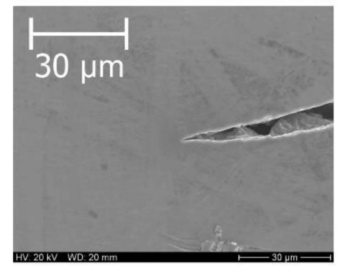


3500 N

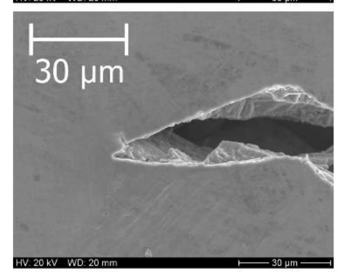
pseudoel. NiTi 50.2%Ni



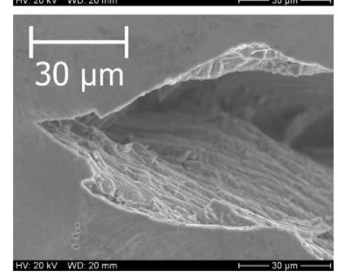
0 N



1250 N

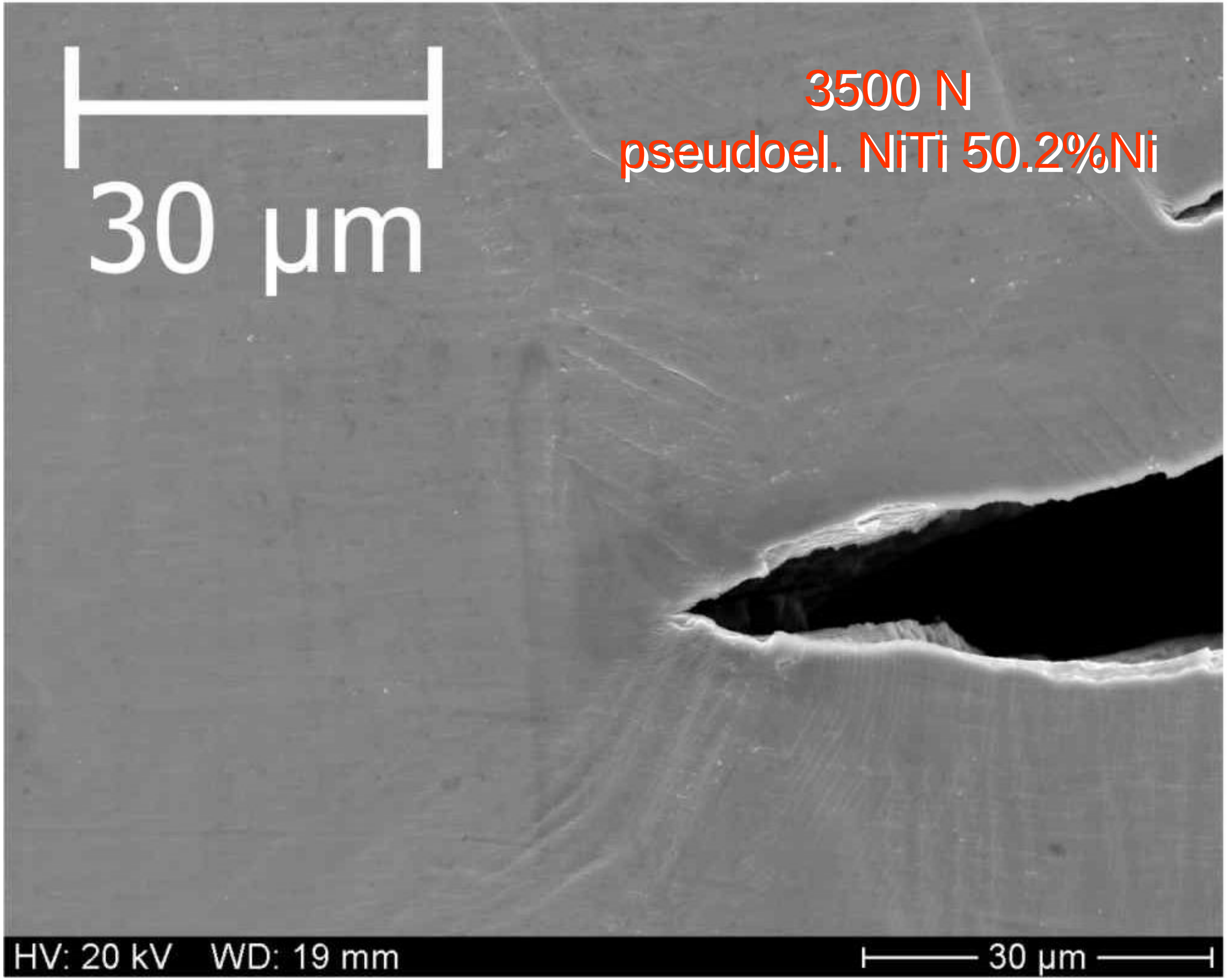


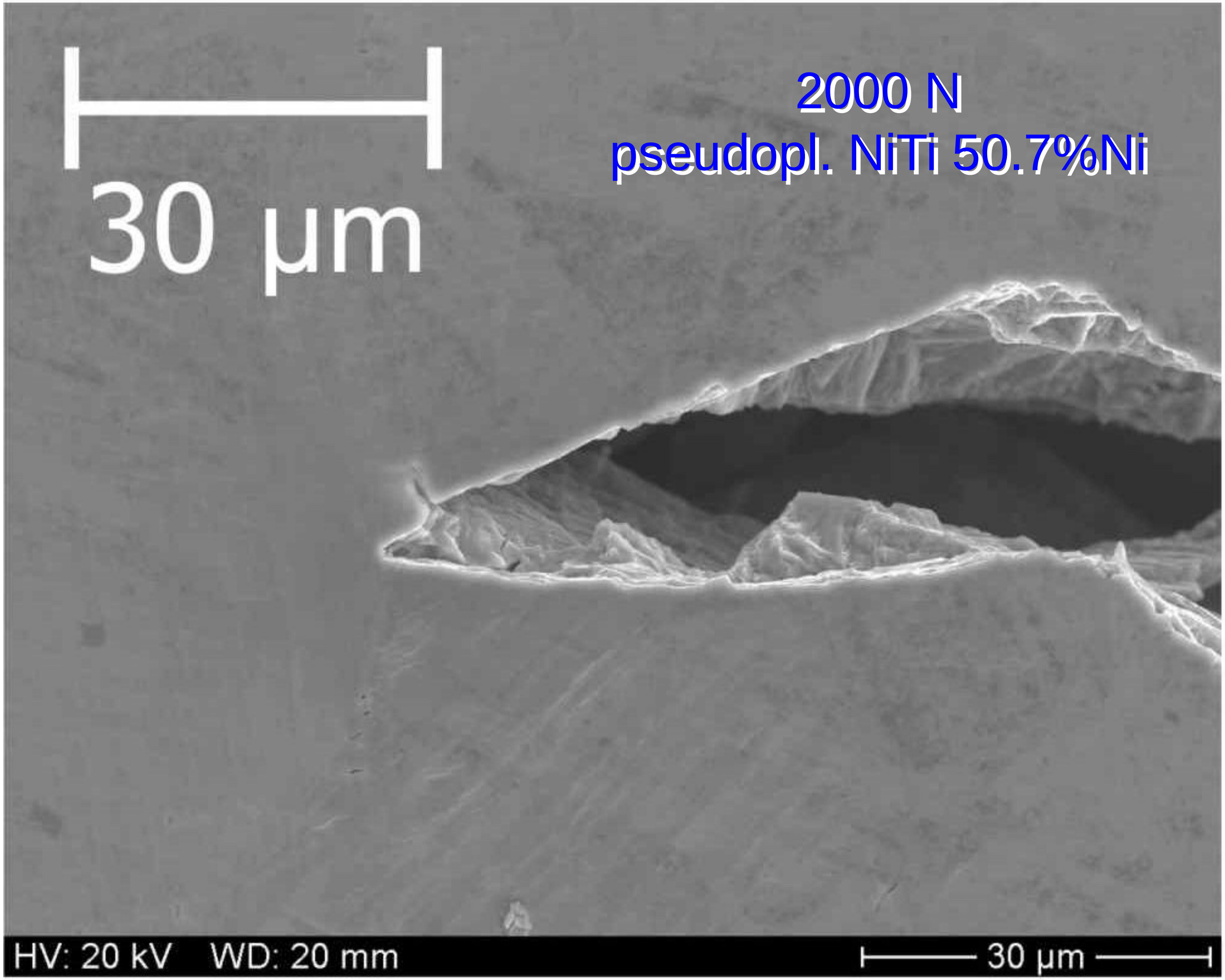
2000 N

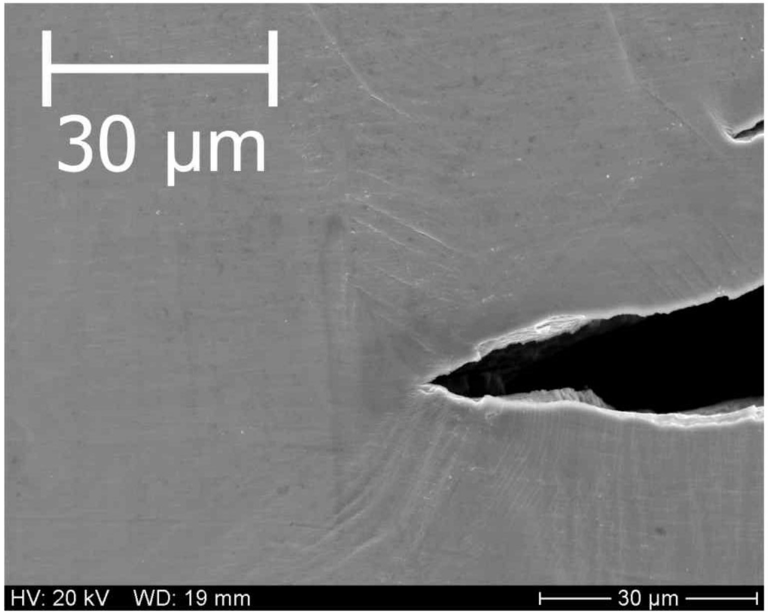


2700 N

pseudopl. NiTi 50.7%Ni

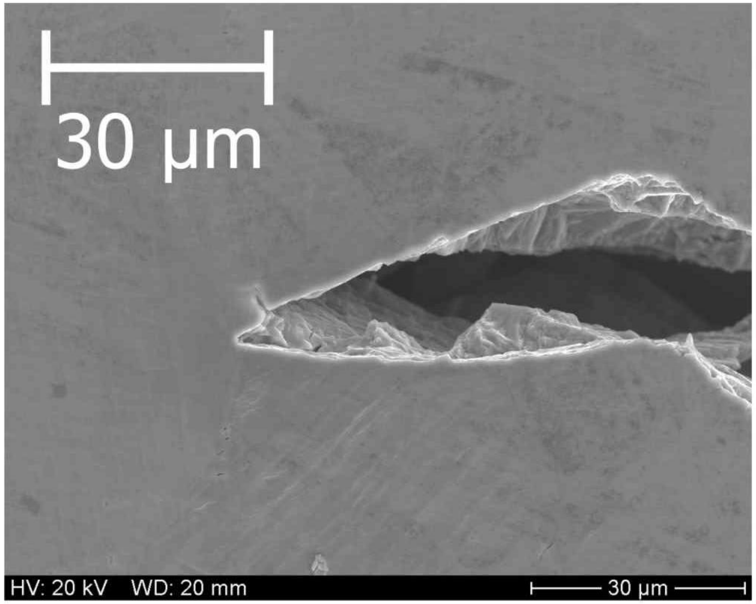

30 µm
3500 N
pseudoel. NiTi 50.2%Ni
HV: 20 kV WD: 19 mm
30 µm


2000 N
pseudopl. NiTi 50.7%Ni
30 µm
HV: 20 kV
WD: 20 mm
30 µm



pseudoel. NiTi 50.2%Ni

pseudopl. NiTi 50.7%Ni



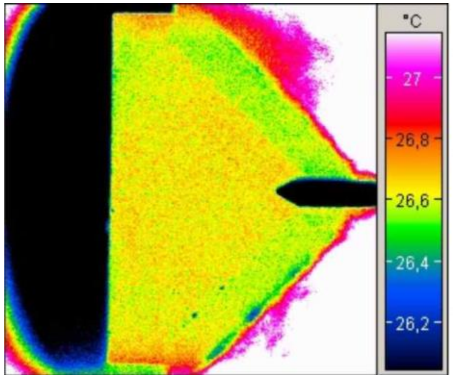
similar K_{max}*-Werte, because: in both cases cracks grow into martensite (stress induced/detwinned)

thermography

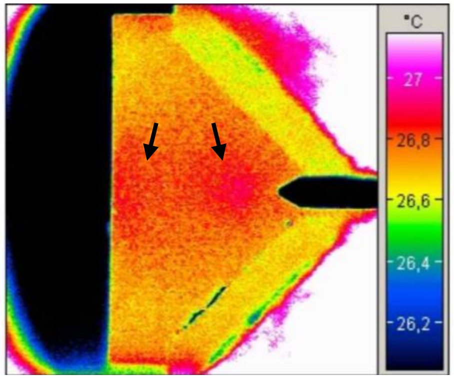
thermo camera:	VARIOTHERM from InfraTec (Dresden)
infrared light:	2 – 6 μm
object:	graphite coated
mechanical tests:	1,2 mm/min
sampling frequency:	5 Hz

objective: **show heats of transformation associated with crack propagation**

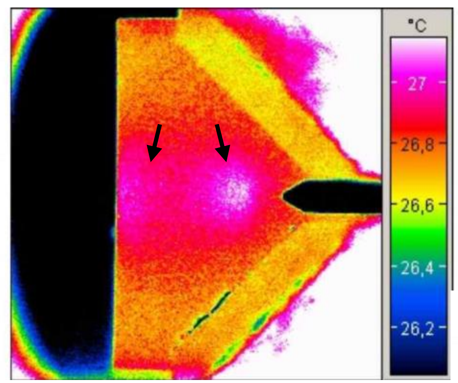
pseudoelastic NiTi loading



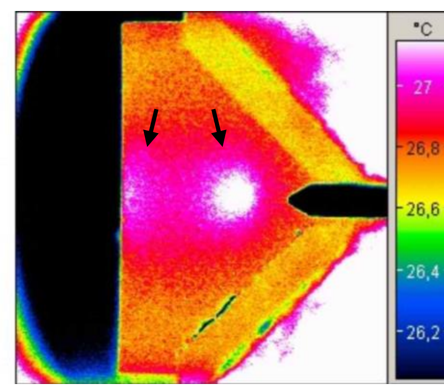
500 N



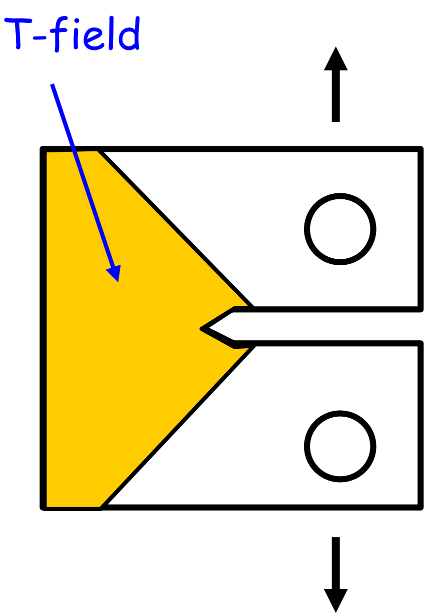
2600 N



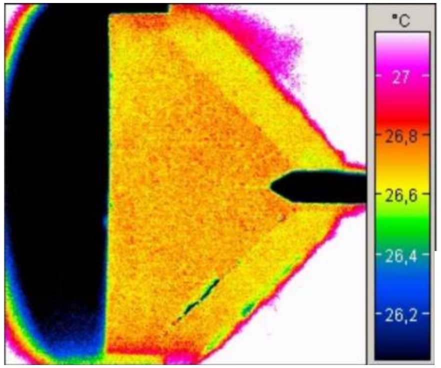
2670 N



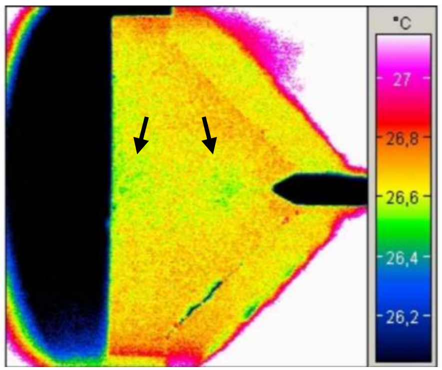
2700 N



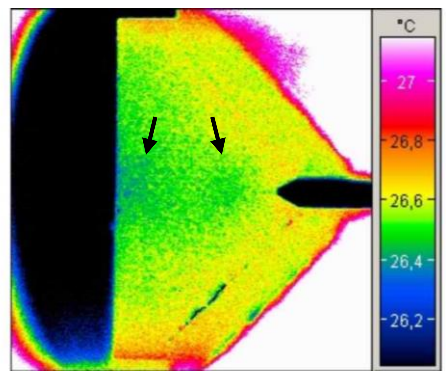
pseudoelastic NiTi unloading



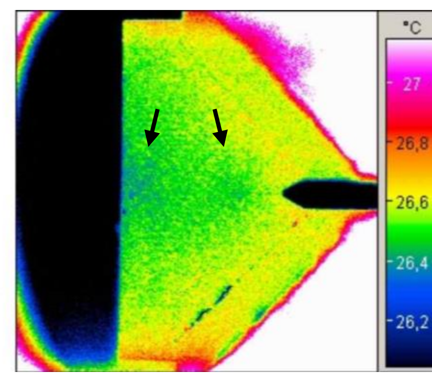
2700 N



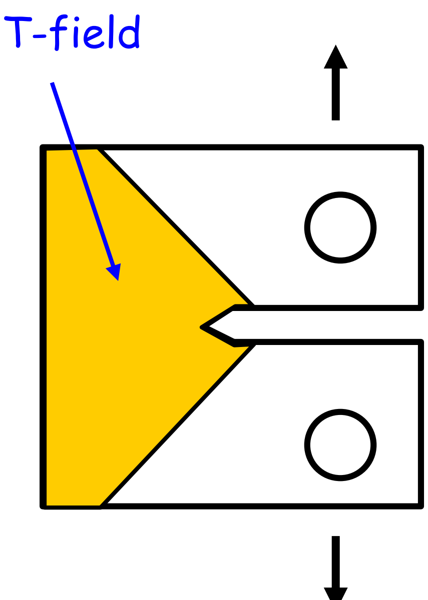
1400 N

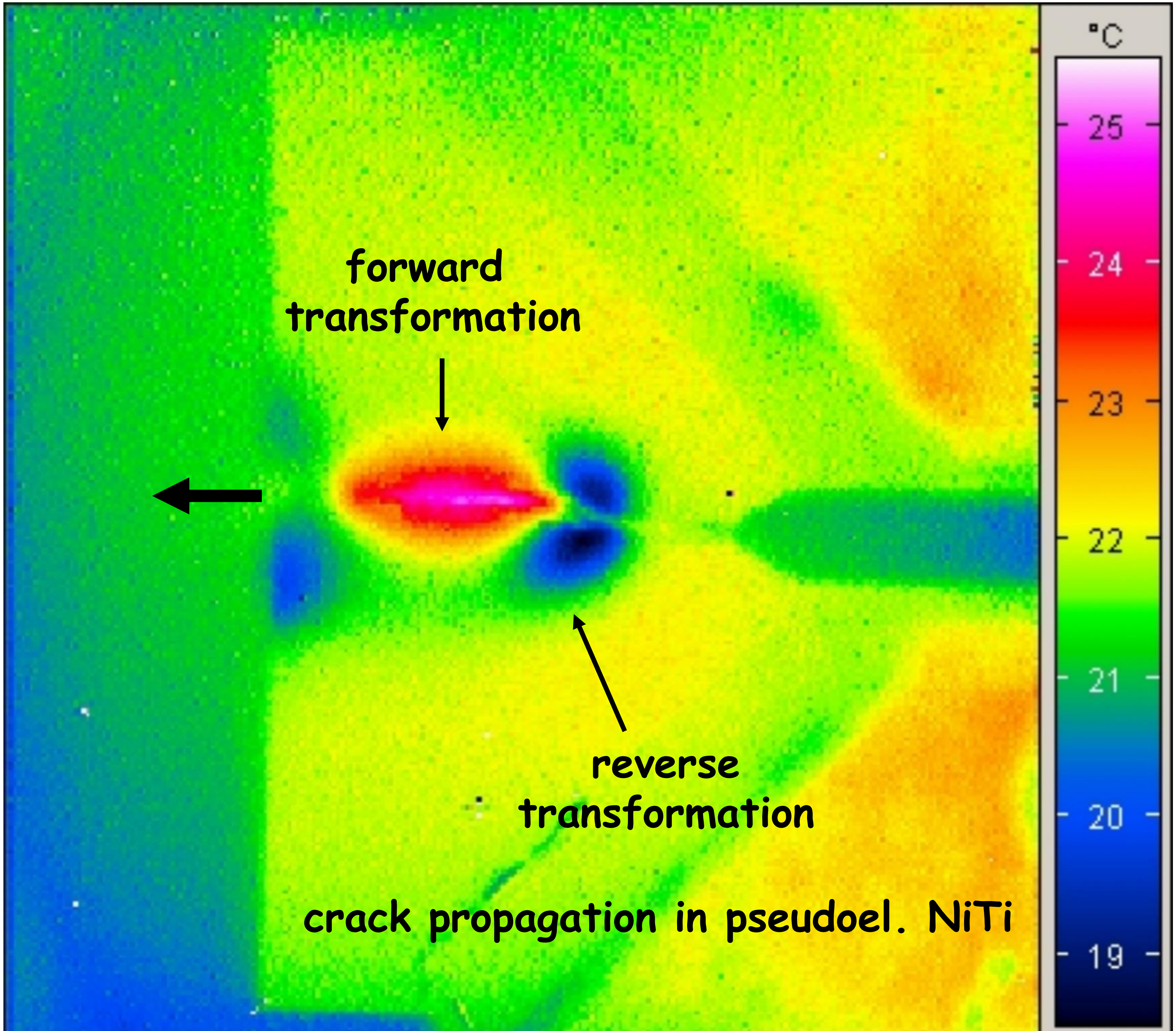


1300 N

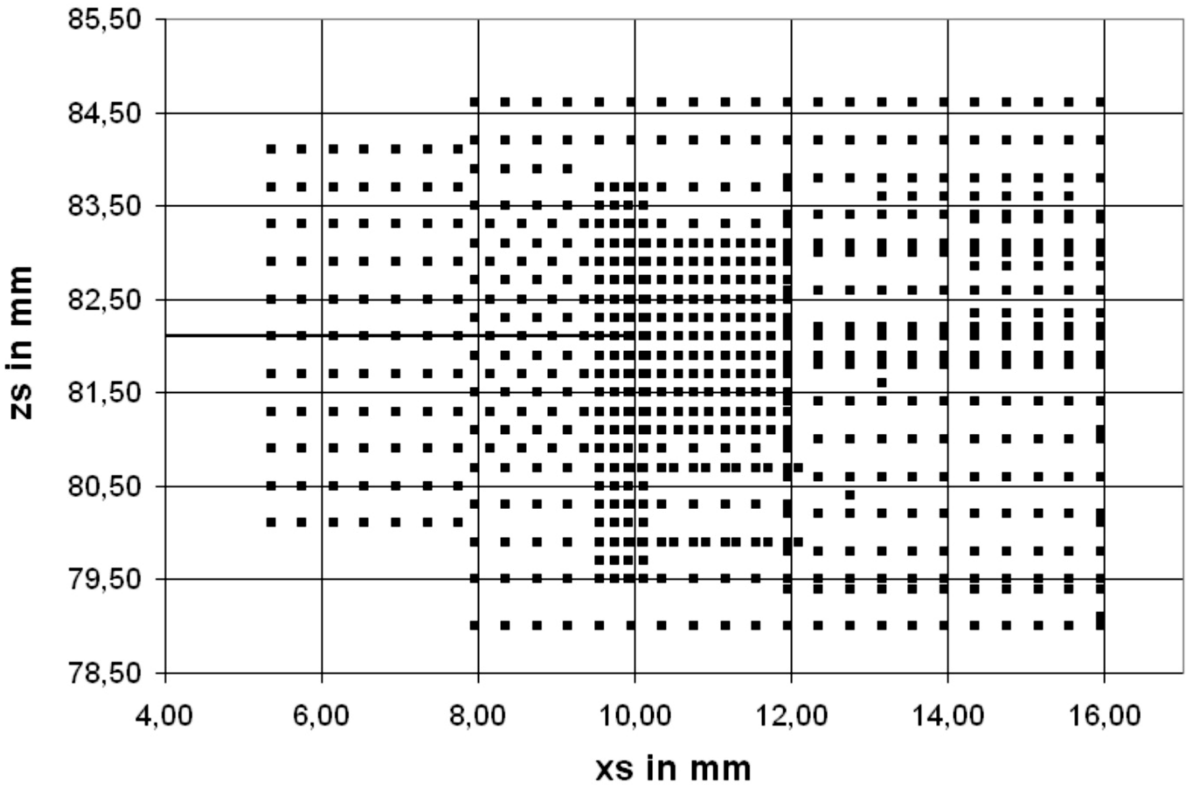


1250 N

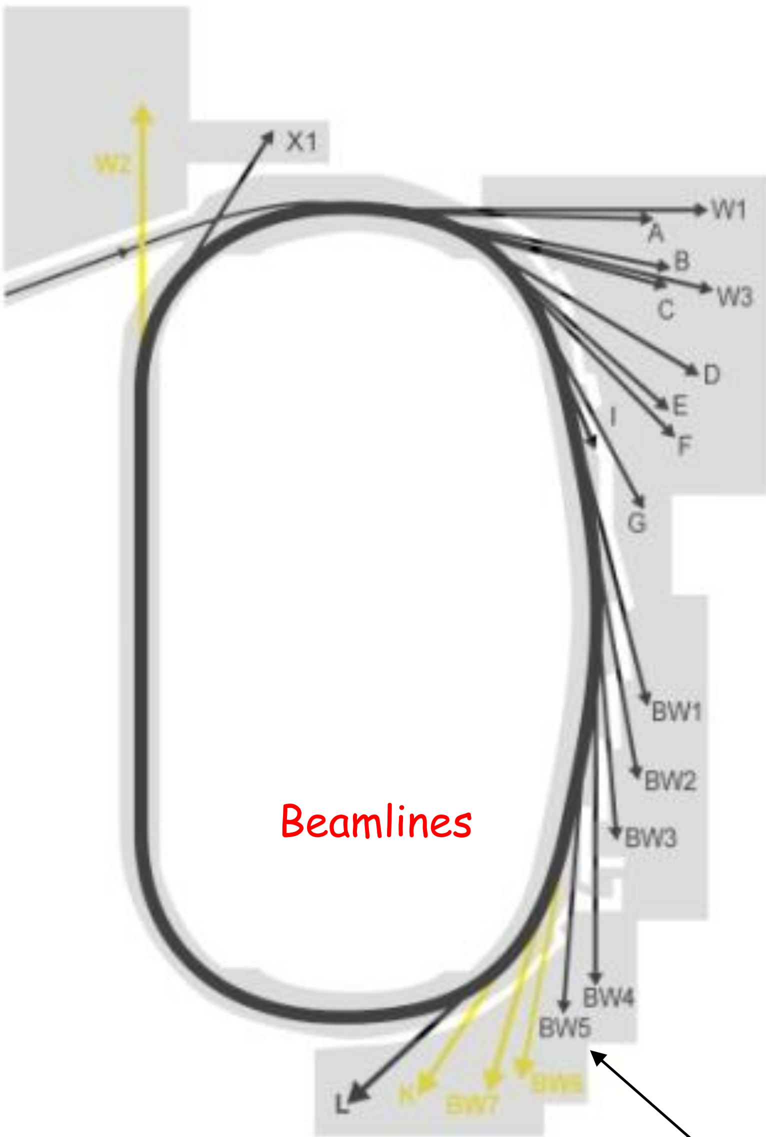



forward transformation
reverse transformation
crack propagation in pseudoel. NiTi
°C
25
24
23
22
21
20
19

experiments at HASYLAB/DESY (synchrotron beam line)

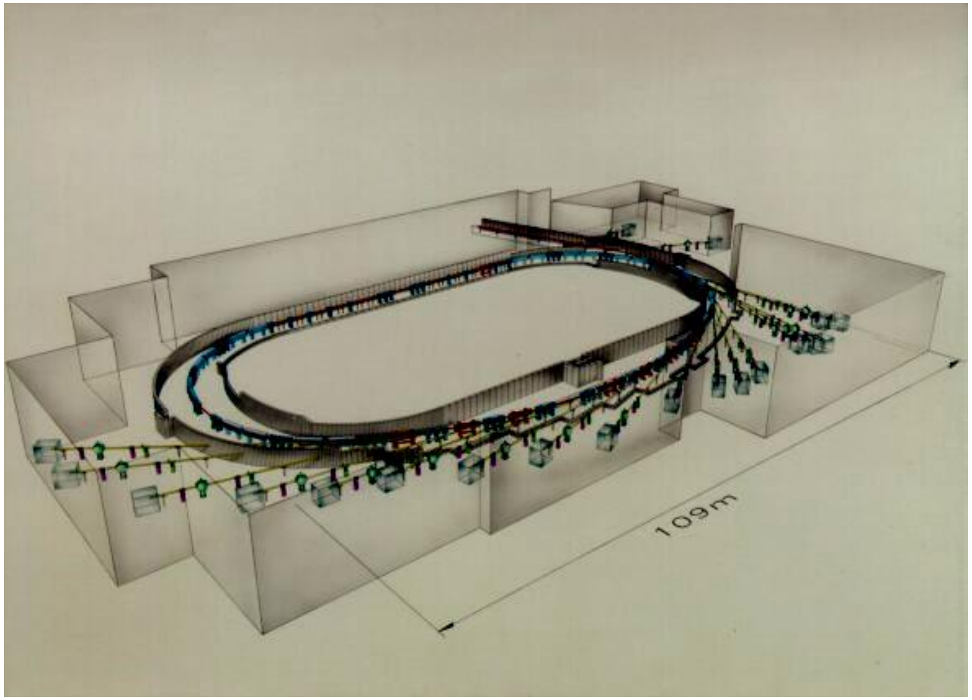


SEM and thermography results: diffraction positions selected



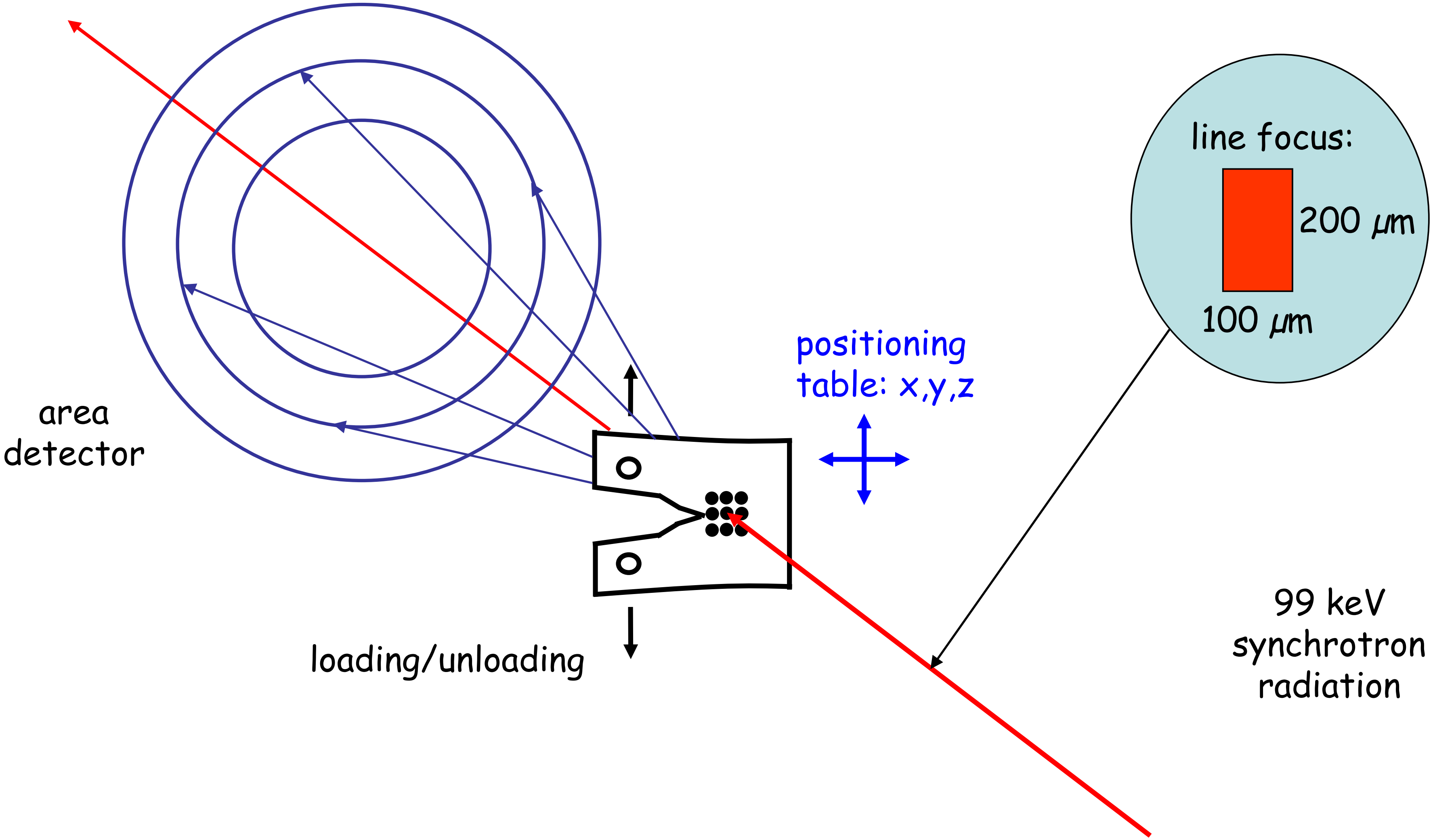
Beamlines

Beamline BW5



Doris III

HASYLAB/DESY

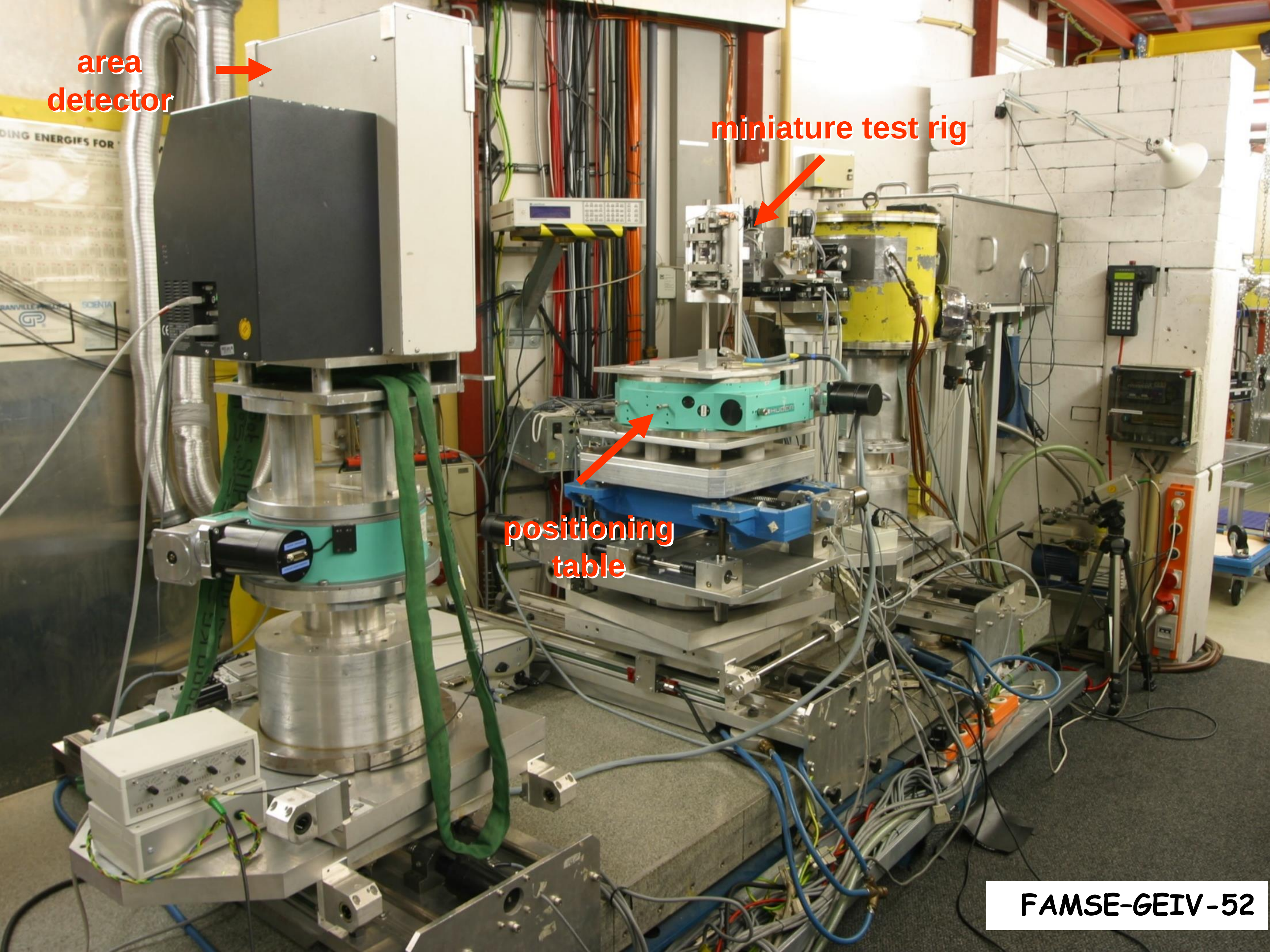


<u>experiments:</u>

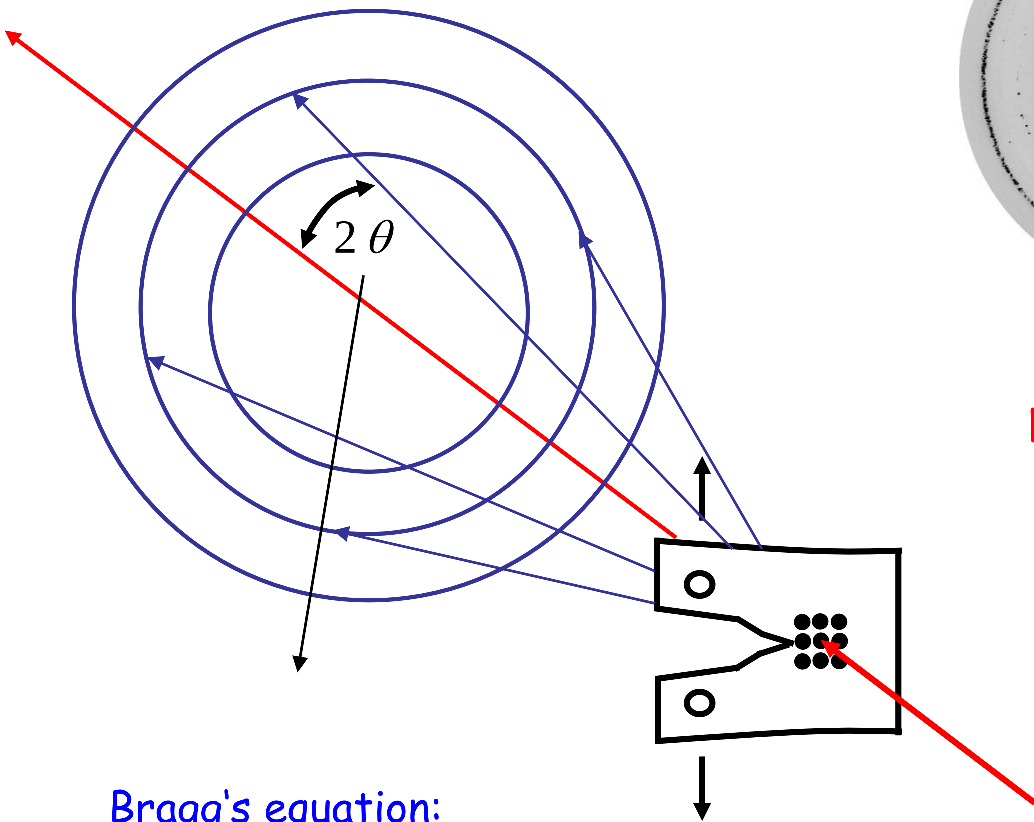
S. Gollerthan, A. Baruj, J. Frenzel, M. Wagner, M. Hasan, W.Schmahl
HASYLAB/DESY Nov./Dez. 2006

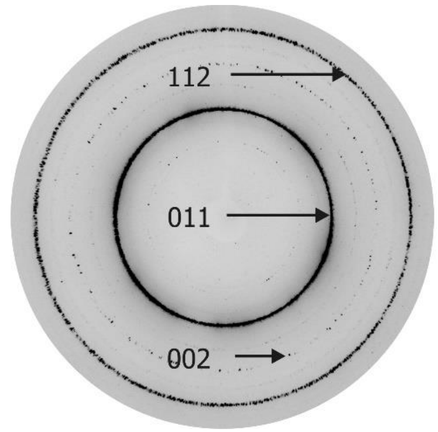
beamline BW5
HASYLAB/DESY
Doris III

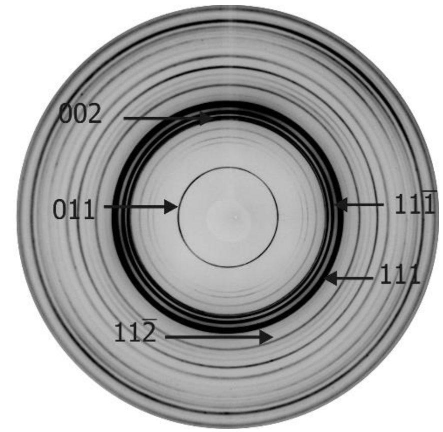
FAMSE–GEIV-51


area
detector
miniature test rig
positioning
table

Debye Scherrer rings







austenite
pseudoel. NiTi
50.7% Ni

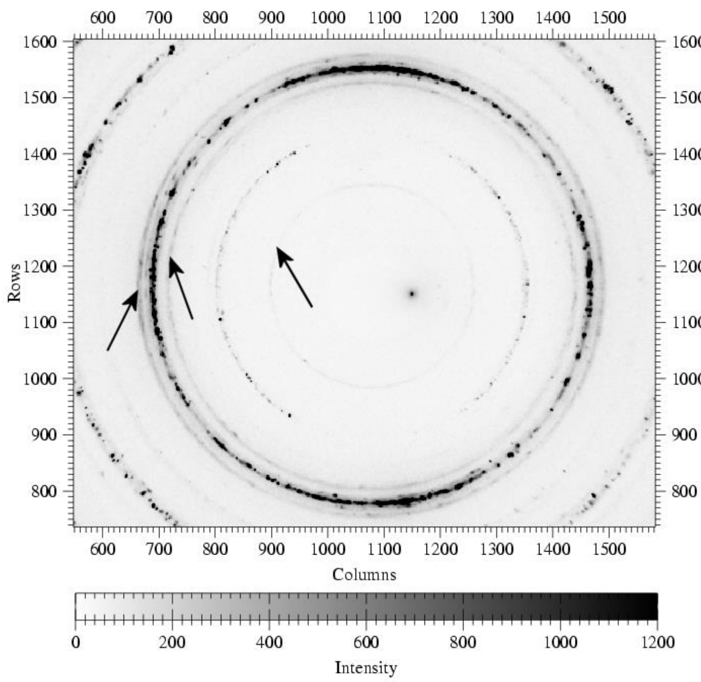
martensite
pseudopl. NiTi
50.2% Ni

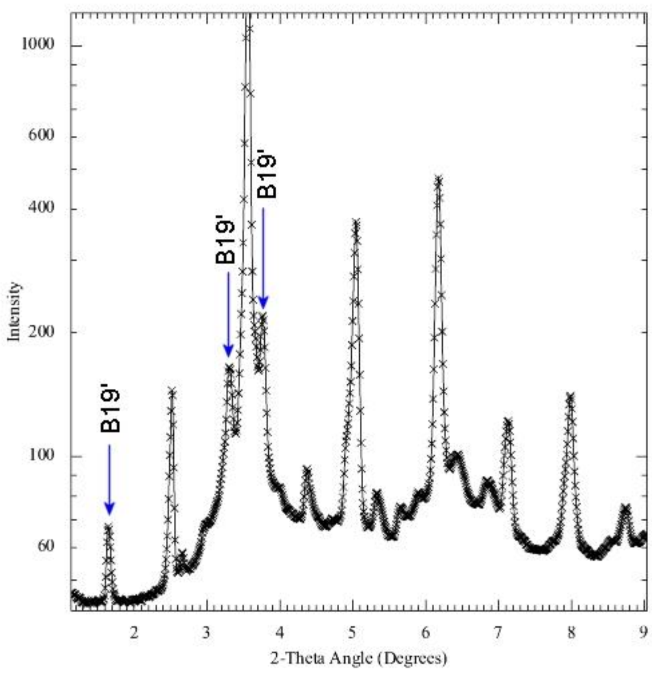
Bragg's equation:

$$n \cdot \lambda = 2 \cdot d \cdot \sin \theta$$

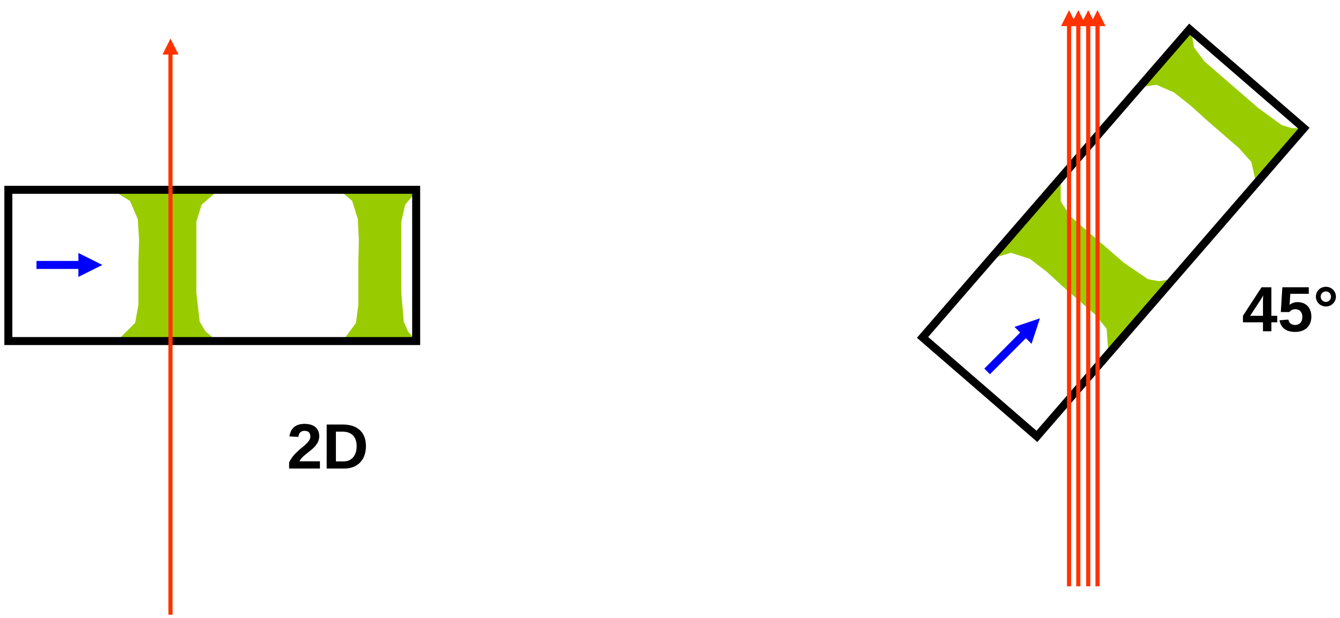
$$d_{h,k,l} = \frac{n \cdot \lambda}{2 \cdot \sin \theta}$$

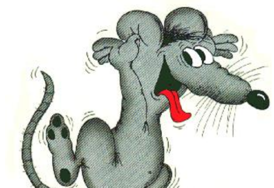
qualitative and quantitative analysis
Rietveld method – GSAS
A. Baruj, S. Gollerthan

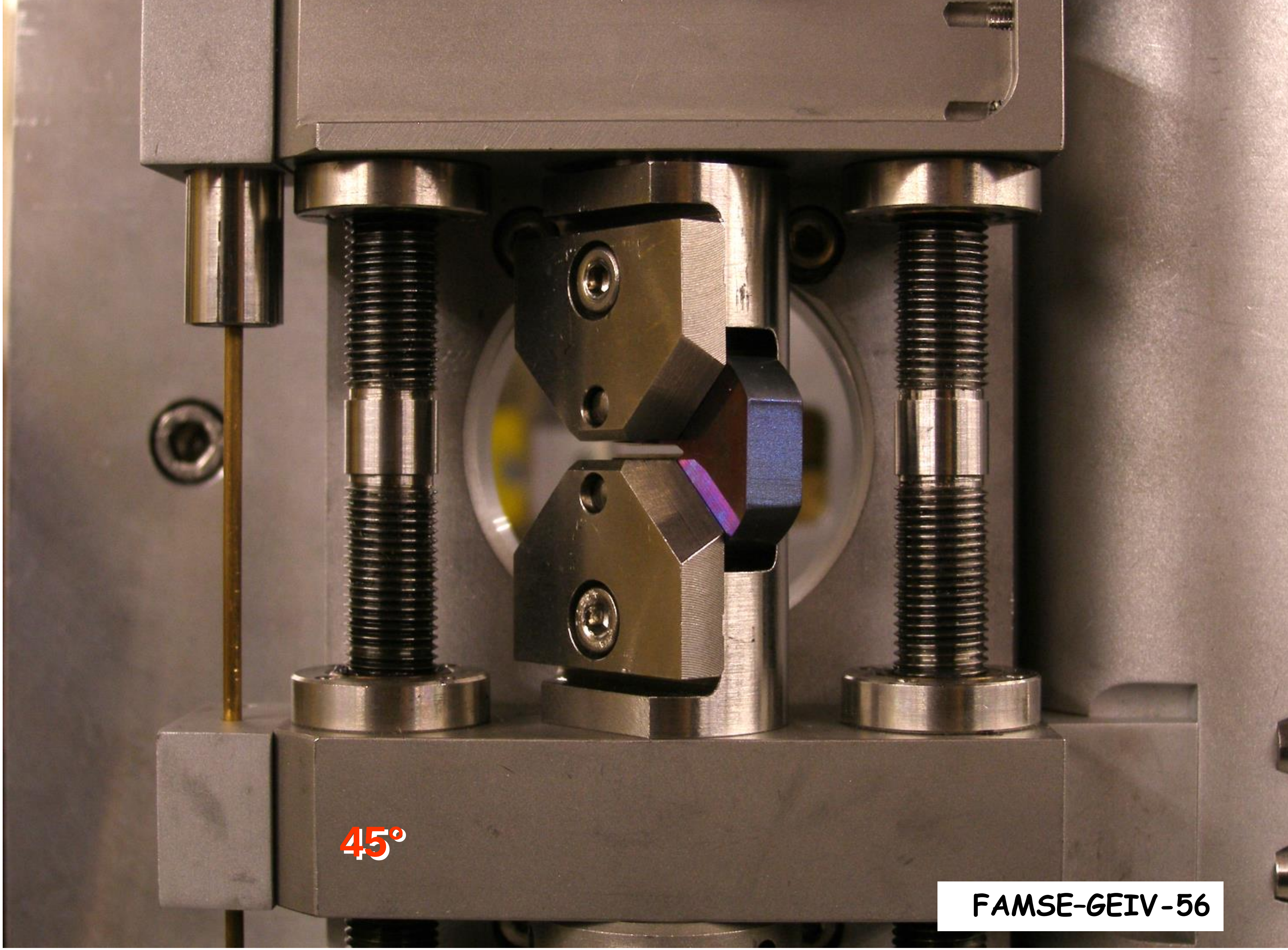


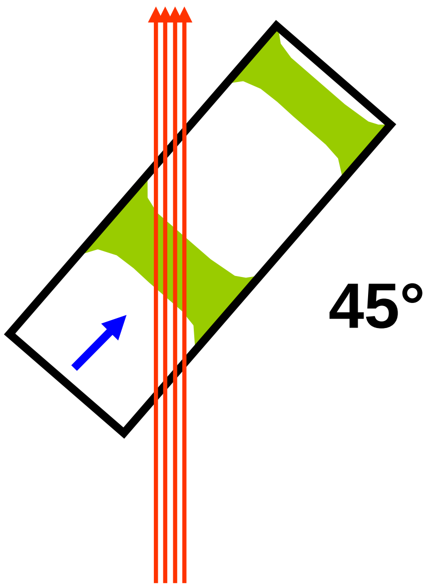


quantitative analysis
fit 2D, Rietveld method – GSAS
A. Baruj, S. Gollerthan

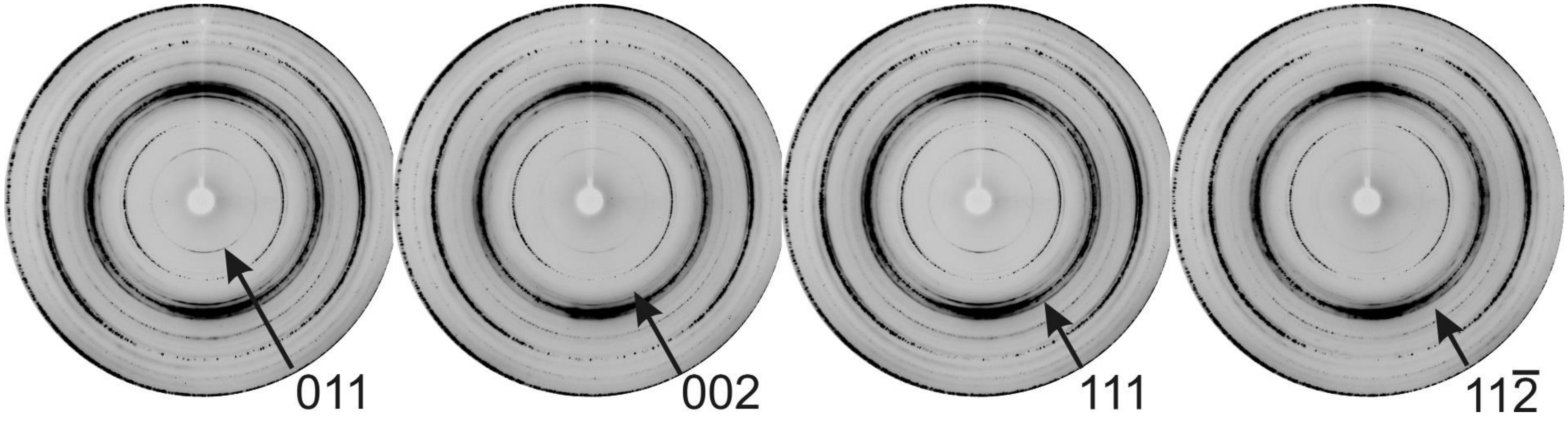

2D
45°




45°
FAMSE-GEIV-56



Martensit (B19') bei B/2

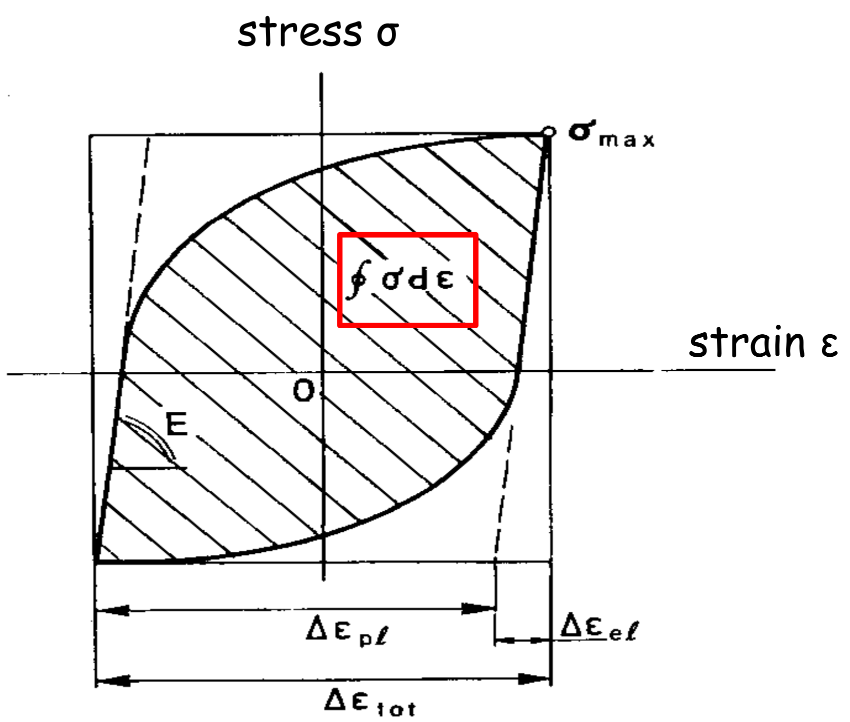


Section summary – fracture mechanics of shape memory alloys (FM SMAs)

1WE alloys (50.2 at.% Ni, martensite) and PE alloys (50.2 at.% Ni, austenite) can show very different tensile properties. Their critical K-parameters are the same. Because in both cases cracks grow into martensitic regions. One can observe heat effects which are associated with stress induced martensitic transformations. And one can detect martensite in front of the crack tip of a loaded PE specimens. We have seen why in-situ experiments (scanning electron microscope, thermo camera, synchrotron beam line) can be helpful to understand fracture mechanics of shape memory alloys.

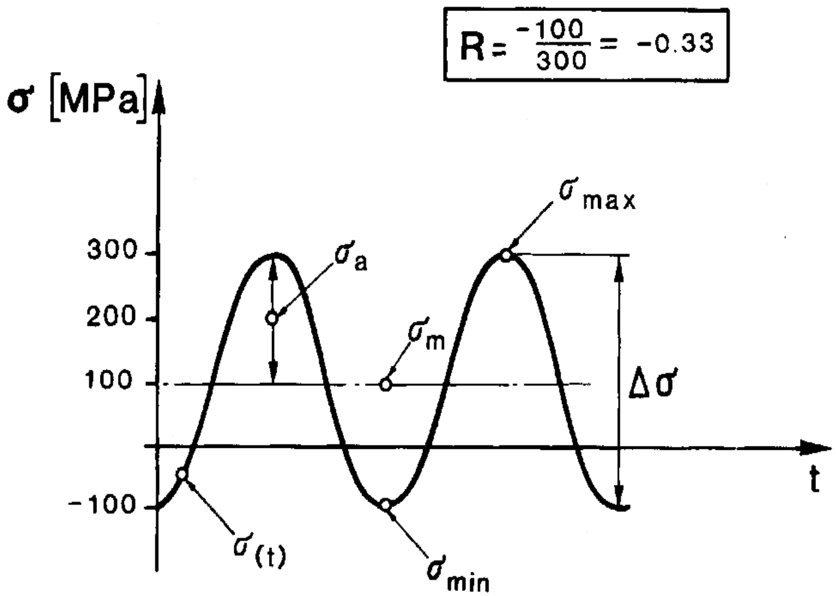
Basics of Structural Fatigue

Stress strain hysteresis:



area enclosed by σ-ε-hysteresis represents an energy

Example for load controlled fatigue test:



$$\sigma(t) = \sigma_m + \sigma_a \cdot \sin(2 \cdot \pi \cdot \nu \cdot t)$$

Ermüdungs-parameter

R-value: $R = \sigma_{min} / \sigma_{max}$

minimum stress: $\sigma_{min} = \sigma_m - \sigma_a$

mean stress: $\sigma_m = \frac{1}{2} \cdot (\sigma_{max} + \sigma_{min})$

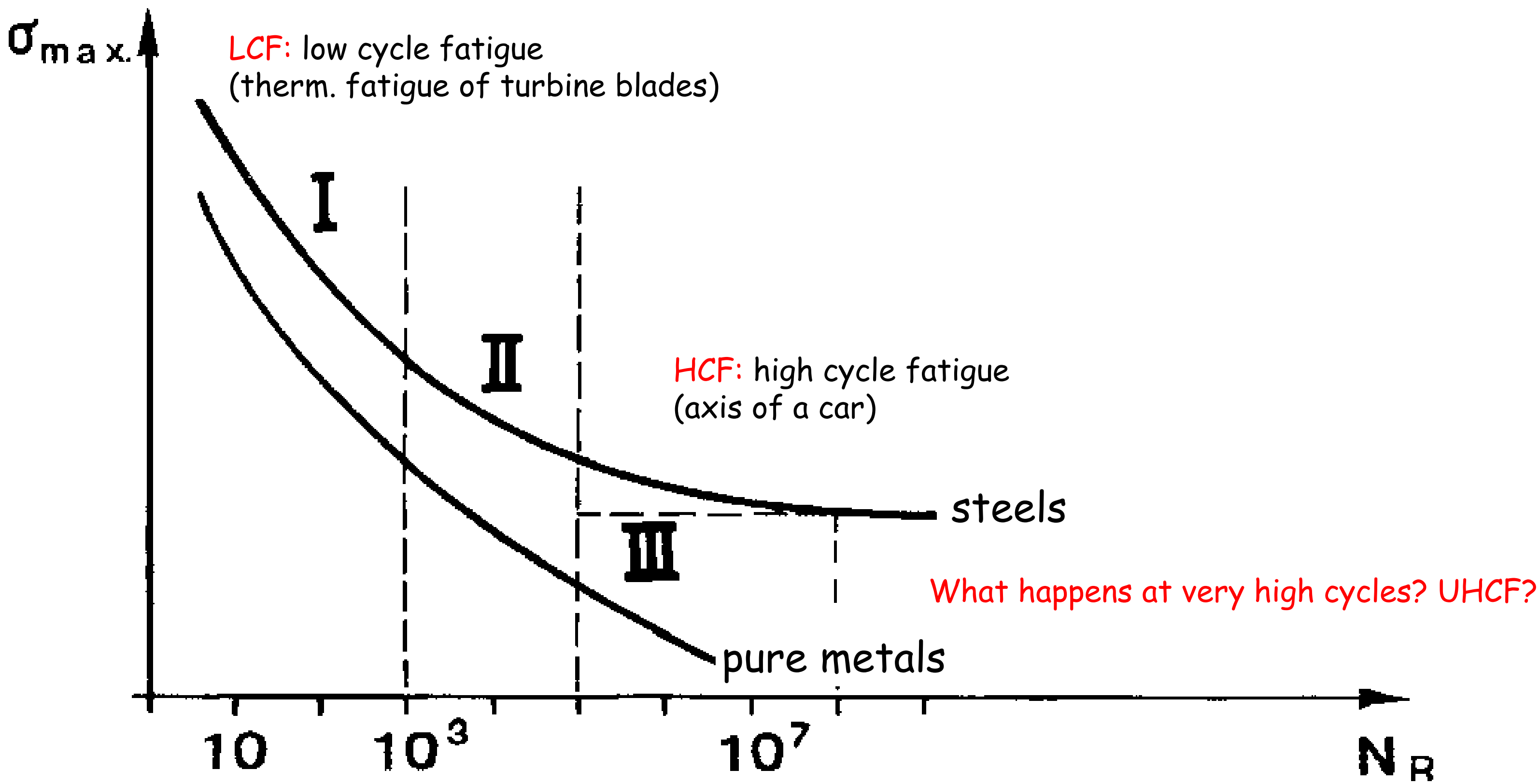
maximum stress: $\sigma_{max} = \sigma_m + \sigma_a$

stress amplitude: $\sigma_a = \frac{1}{2} \cdot (\sigma_{max} - \sigma_{min})$

also important: frequency, temperature, specimen geometry, environment

Wöhler's SN-curve:

We obtain this curve from many experiments!



The strain controlled fatigue test

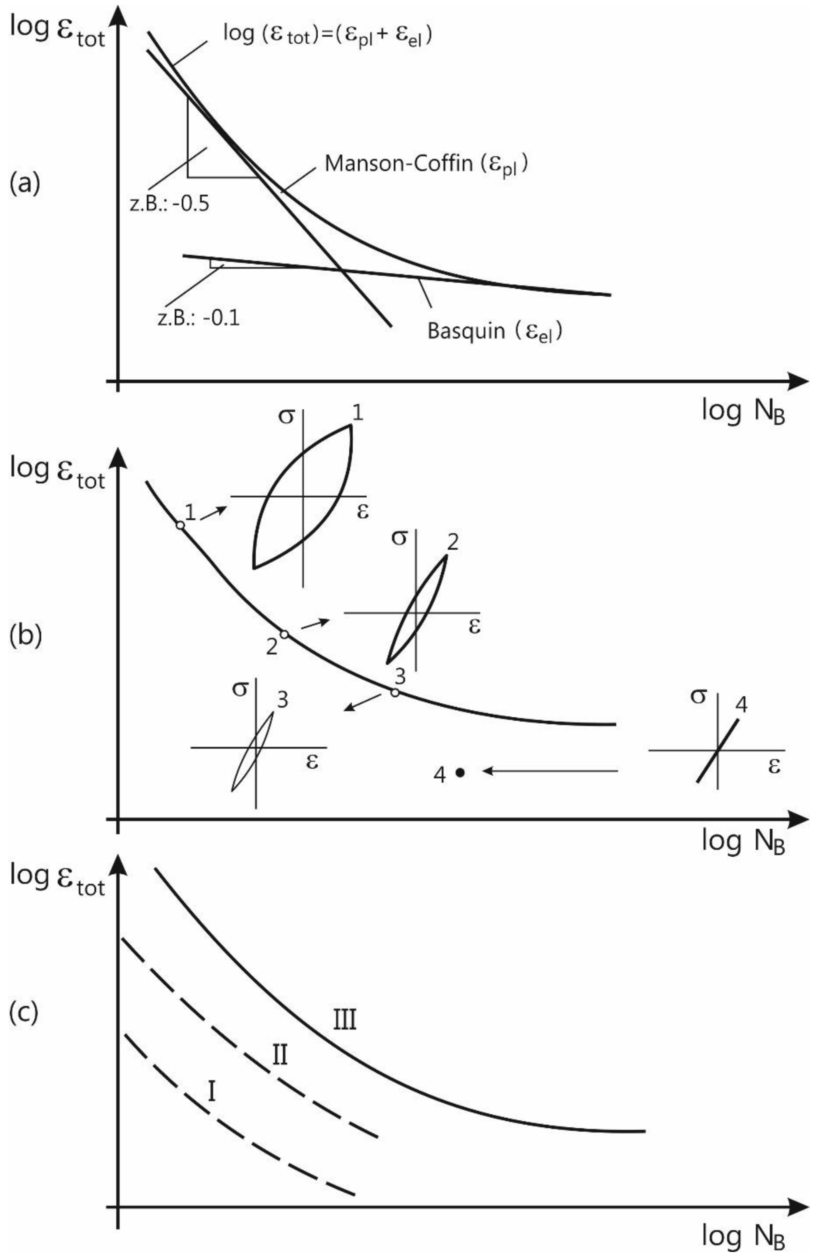
- we control the total strain
- we impose a cyclically changing total strain
- This total strain has an elastic and a plastic part

$$\varepsilon_{tot} = \varepsilon_{el} + \varepsilon_{pl}$$

- total strain amplitude:

$$\Delta\varepsilon_{tot}$$

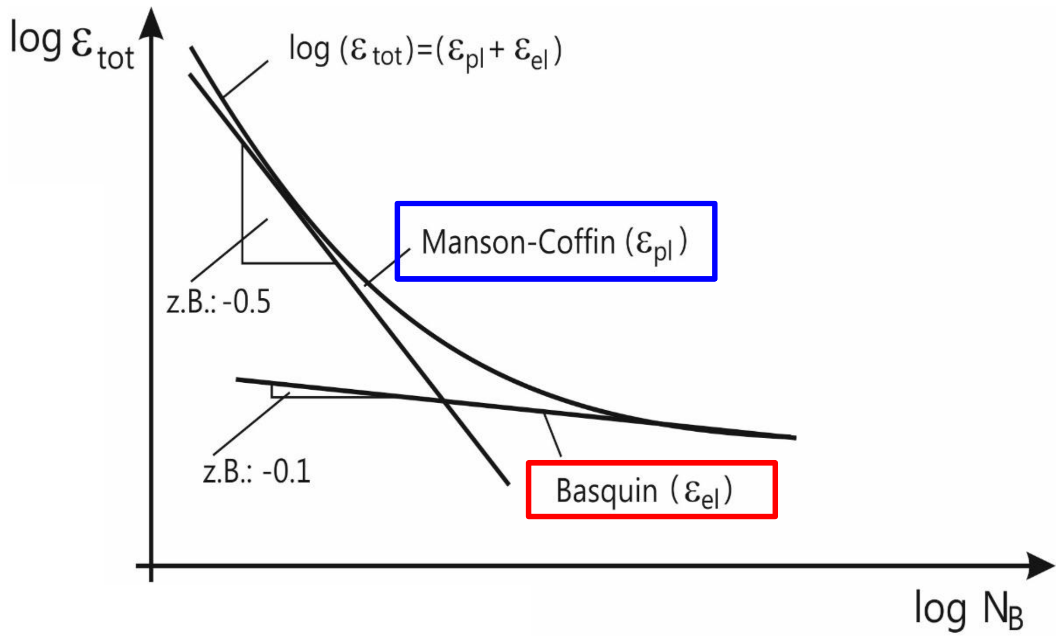
- often: tension -> $+\Delta\varepsilon_{tot}/2$ compression -> $-\Delta\varepsilon_{tot}/2$



Schematic illustration explaining

Total strain controlled fatigue testing

low number of cycles to failure: LCF - high numbers: HCF



We can describe regions of low and high numbers to failure

by two phenomenological equations:

$$\frac{\Delta\varepsilon_{pl}}{2} \cdot N_B^{\alpha} = konst.$$

Manson/Coffin

$$\left(\Delta\varepsilon_{el} \cdot E\right)^{\beta} \cdot N_B = konst.$$

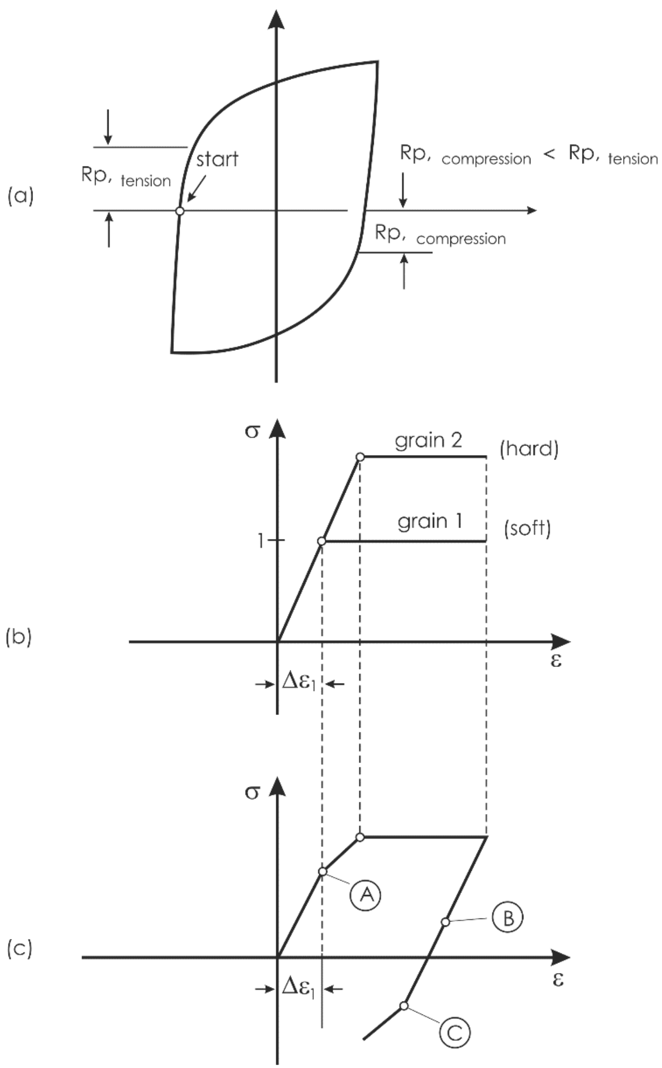
Basquin

We can combine the Manson/Coffin and the Basquin law into one phenomenological equation:

$$\Delta\varepsilon_{tot} = \alpha \cdot N_r^{-\gamma} + \beta \cdot N_r^{-\delta}$$

This phenomenological equation can work quite well. Engineers are sometimes happy, to have something like this. However, equations of this type do not provide insight into the physical nature of fatigue deformation and fatigue damage accumulation.

What is the Bauschinger effect?



(a) Bauschinger Effekt:

Yield stres in tension is not the same as yield stress in compression !

(b) and (c) Masing's explanation:

Soft grain yields earlier than hard grain (*A*).

Wenn hard grain starts yielding, soft grain has already plastically deformed.

On unloading we reach a point, where the soft grain is already fully unloaded, while the assembly is still in tension (B).

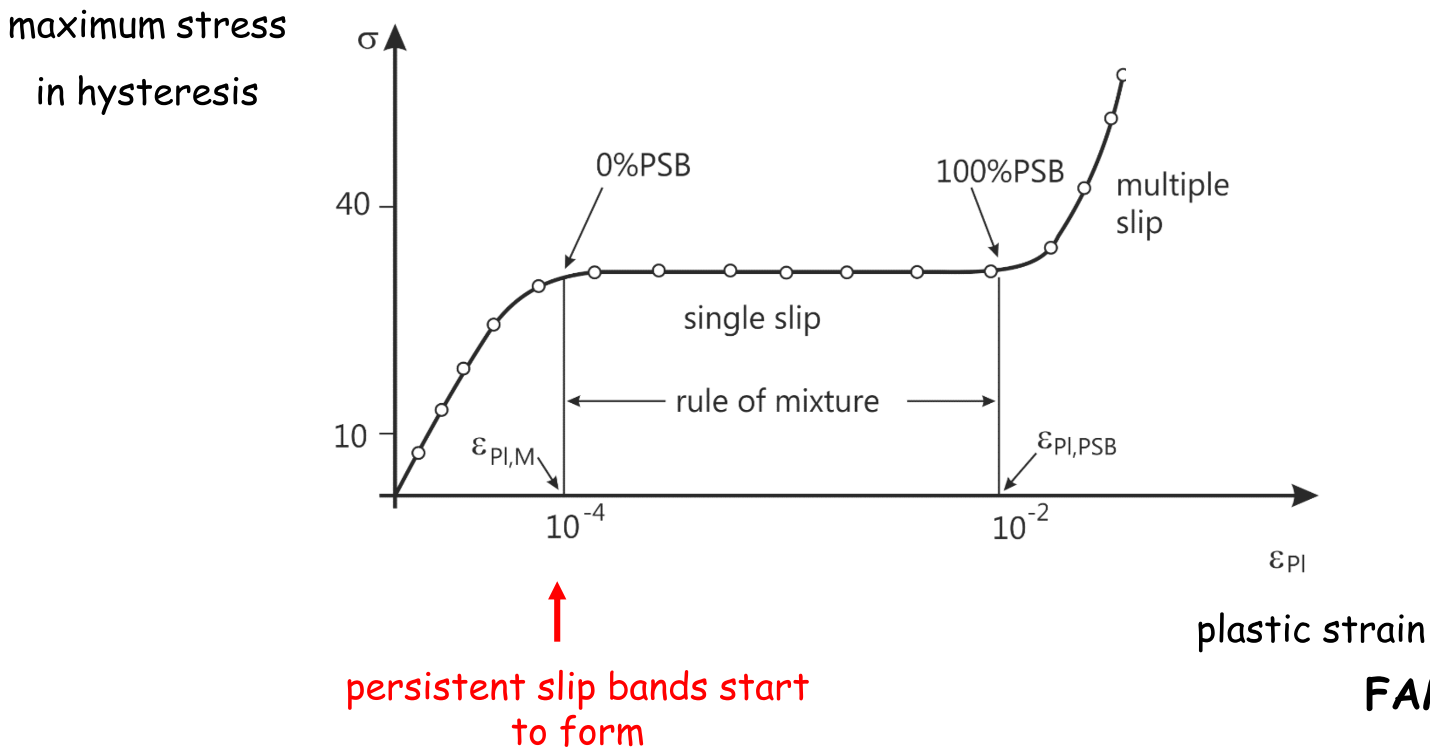
Soft grain gets into compression, when the assembly is still in tension..

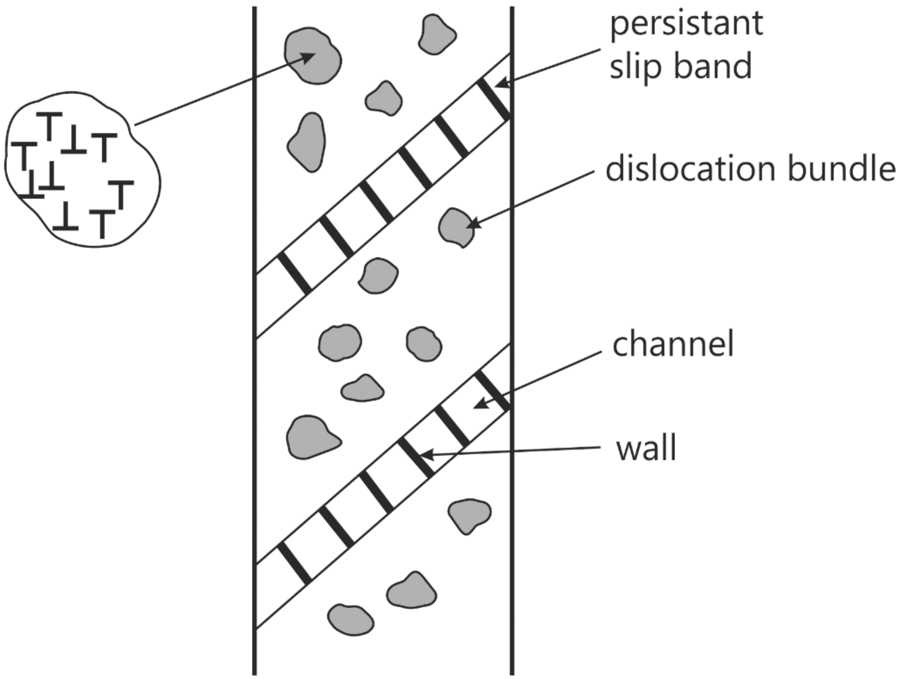
This is why in compression, soft grain starts to yield earlier (*C*).

Mughrabi's discovery of persistent slip bands in Cu- and Ag-single crystals:

Hael Mughrabi
at Honorary Symposium
TMS 2008

Mughrabi performed experiments in plastic strain control (!). He plotted the maximum stress of the hysteresis as a function of plastic strain and found the following behavior:



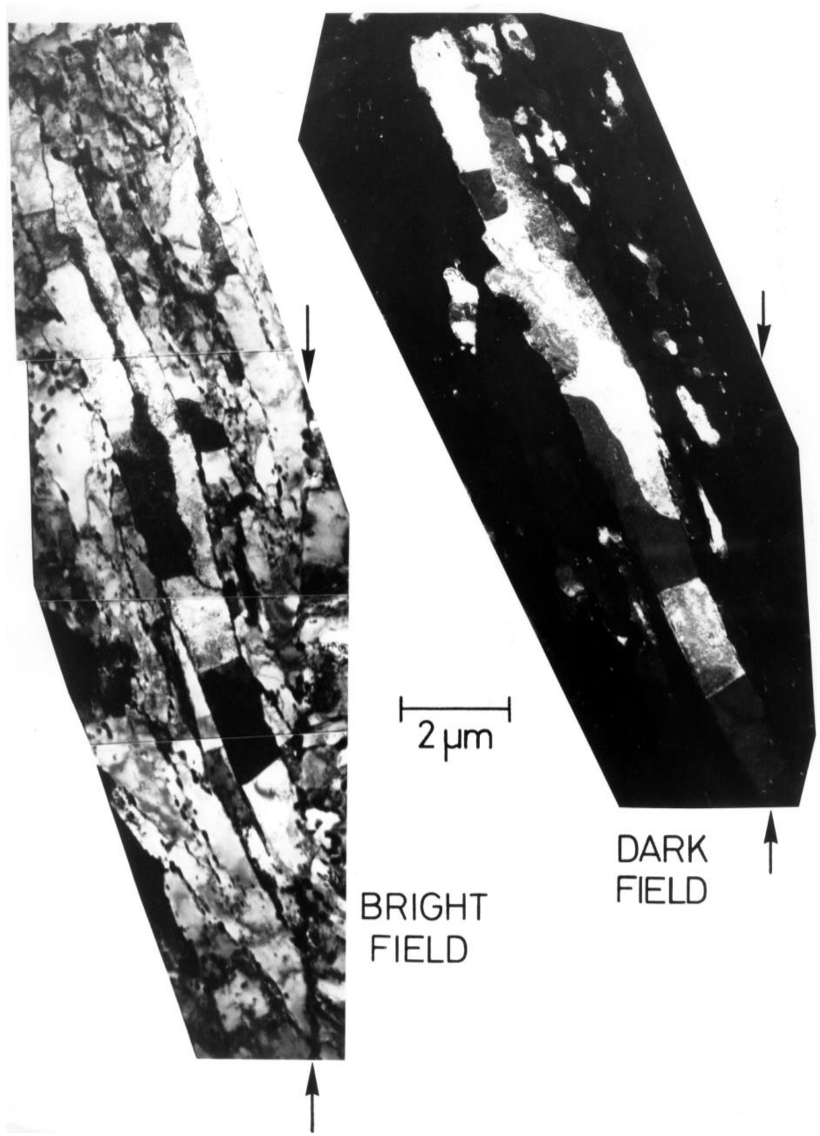


Mughrabi observed persistent slip bands (PSB) in TEM

After fatigue loading, one can find regions of localized deformation in steels. Here: Tempered martensite steel with 12% wt.-% Cr:

LCF:
vakuum
$\Delta\varepsilon = 2\%$
600°C

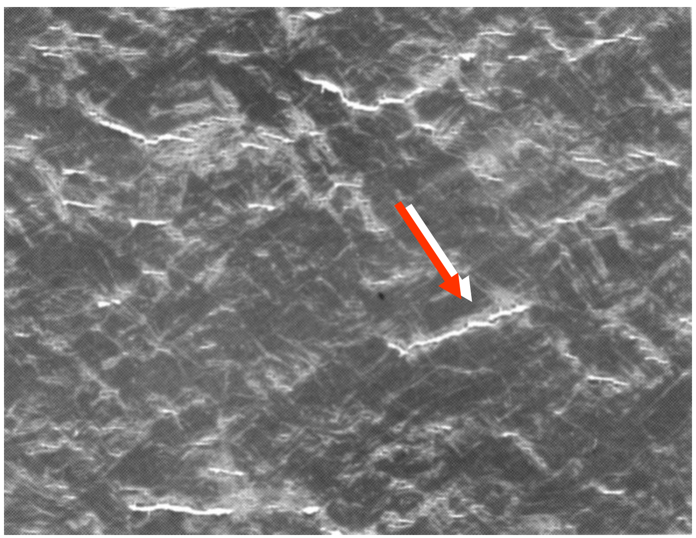
TEM images



J.C. Earthman,
G. Eggeler,
B. Ilschner,
Mat. Sci. Eng. A
1989

Crack initiation of fatigue cracks at the specimen surface and early crack growth:

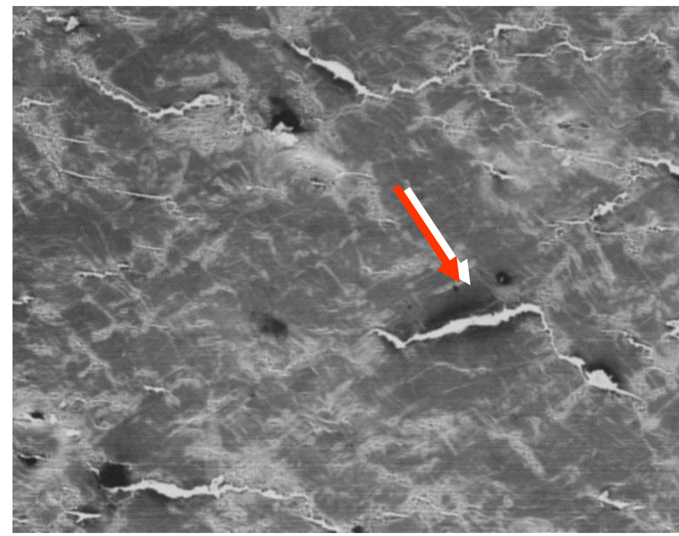
There is no doubt, that fatigue is governed by the formation of crack in the specimen surface.
Example: 12% Cr-steel, LCF: vacuum, $\Delta\varepsilon$ = 2%, 600°C



N = 250

200 μm

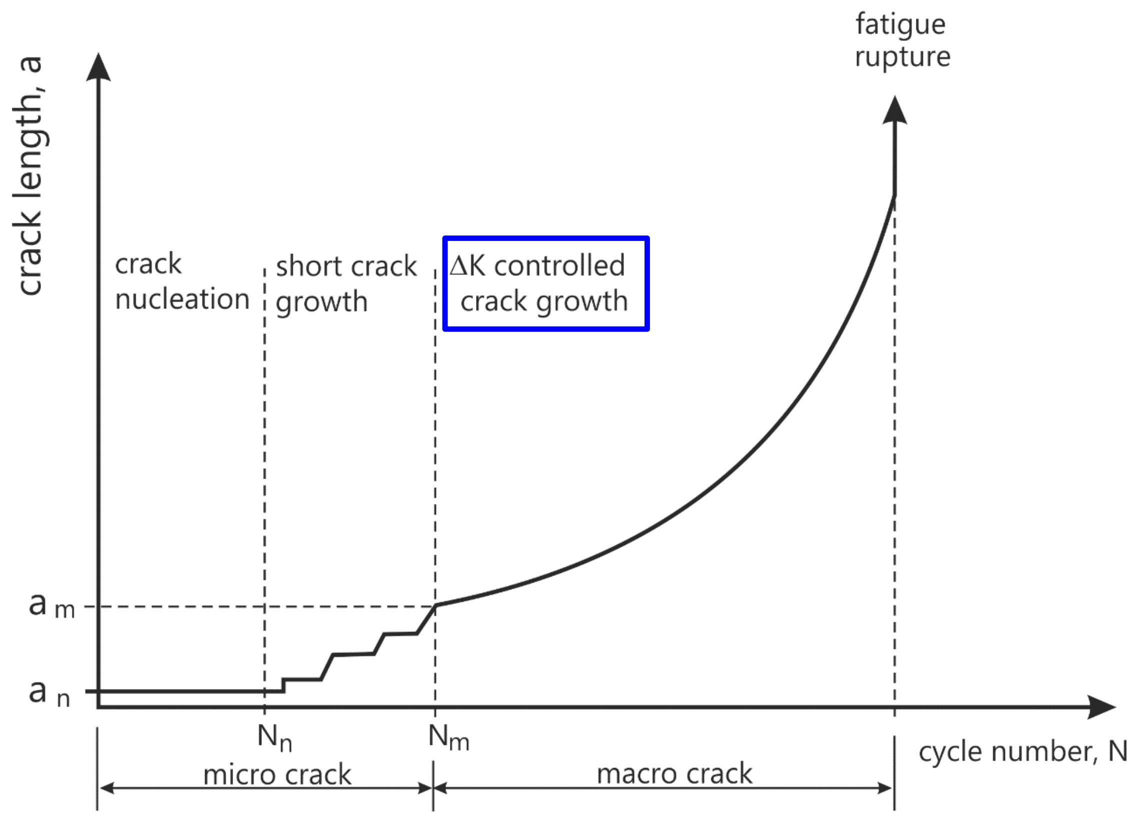
SEM micrographs



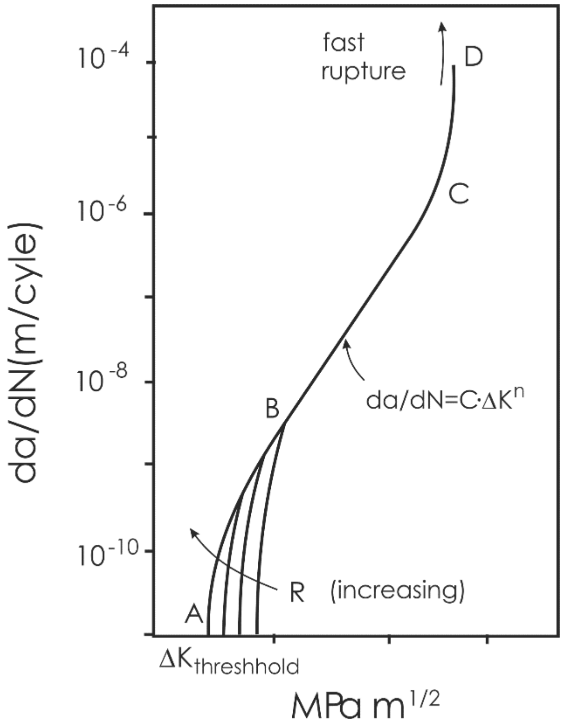
N = 350

J.C. Earthman, G. Eggeler, B. Ilschner, Mat. Sci. Eng. A, 1989

Evolution of crack length during fatigue:



ΔK: $\Delta K = K_{max} - K_{min}$. We can in principle use CT-specimens.

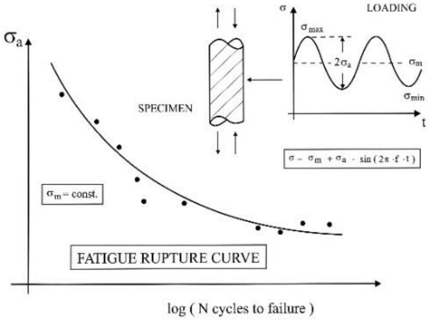


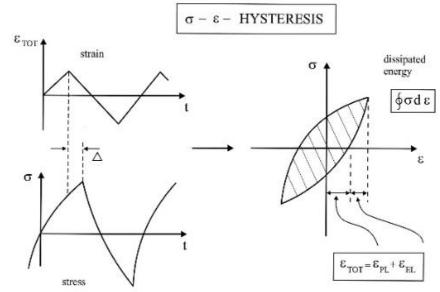
Important:

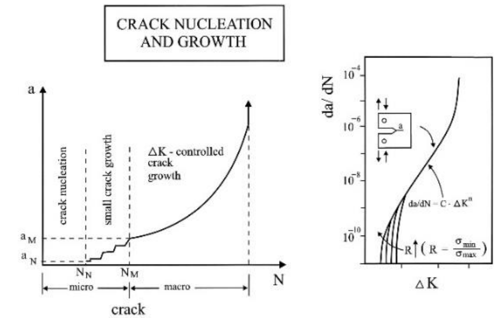
(1) There is a **threshold**, which depends on R-value, enviroment, …

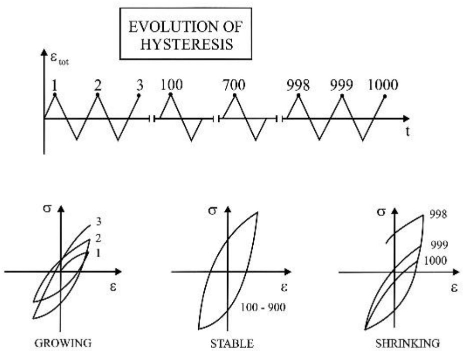
(2) There is a region, where the **Paris-law** is valid. In this region, crack growth does not depend on R.

$$\frac{da}{dN} = C \cdot \Delta K^n$$

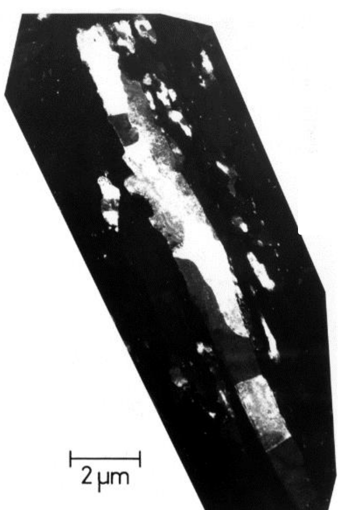


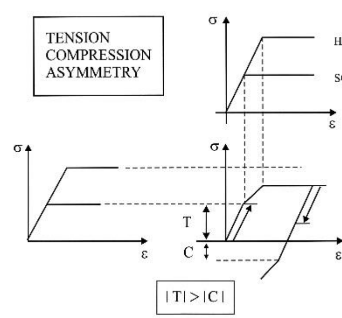


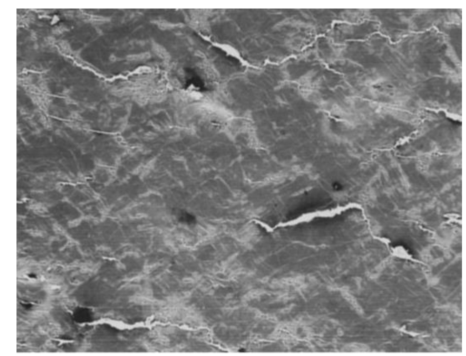




overview
summary
important
fatigue
concepts







surface
cracks
SEM

Summary

(1) Fracture mechanics basics. (Griffith stress: elastic strain energy vs. surface energy, plane strain / plane stress; Irwin: crack extension force G, crack growth when critical G_{IC} is reached, fracture mode I most important; engineers use K_{IC}, also because it appears in the equations which describe the stress distribution in front of a crack tip). deals with cracks, which can cause catastrophic failure in products such as biomedical implants, power plant vessels or bridges. Related loading parameters G and K, and their critical parameters G_{IC} and K_{IC}, can be used to model when/where cracks start to grow.

(2) Fracture mechanics of shape memory alloys. Pseudoelastic and pseudoplastic shape memory alloys differ strongly in tensile testing. But they show similar fracture behavior. Because in both systems, cracks grow into detwinned martensite

(3) Functional fatigue basics. Stress – strain hysteresis. Load controlled sinusoidal loading (with R-value, mean stress, stress amplitude …). Wöhler curve. Strain controlled fatigue. Bauschinger effect. Localized deformation – slip bands. Nucleation of surface cracks. Fatigue crack growth – Paris law.

Questions for self control

1. Why do we need fracture mechanics?
2. Which fracture modes do you know? What is the fracture mode I?
3. What is the differce between plane stress and plane strain, where do we need this?
4. What is the Griffith stress?
5. What is Irwin's crack extension force G?
6. What is the stress intensity factor K_I?
7. What is the fracture toughness K_{IC} and how do we measure it?
8. Which expressions describe the stress field ahead of a crack tip?
8. Explain why in metals plastic zones form ahead of a crack tip?
9. What is the geometry of a CT- and a SENT-specimen (drawing)?
10. What makes fracture mechanics of shape memory alloys difficult?
11. How can one detect martensitic tansformations ahead of a crack tip?
12. Describe the shape of a stress strain hysteresis during one load cycle (where signicant plastic strain accumulates)?
13. Draw a sinusoidal cyclic loading pattern and explain the parameters which characterize a fatigue experiment? What is the R-ratio?
13. What is a Wöhler plot?
14. What characterizes the three different fatigue regimes?
15. What was the contribution of Hael Mughrabi to fatigue research?
16. Why is crack initiation important and how do fatigue cracks grow?