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Torino, November 5, 2008

Fatigue Crack Initiation, Propagation and Failure at Very-High Numbers of Cycles

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Vienna, Austria

Contents

- **Very high cycle fatigue (VHCF), fatigue crack growth (FCG) and ΔK thresholds at ultrasonic frequency**

    Experimental procedure and results:

    S-N and (Δa/ΔN – ΔK) curves of different materials

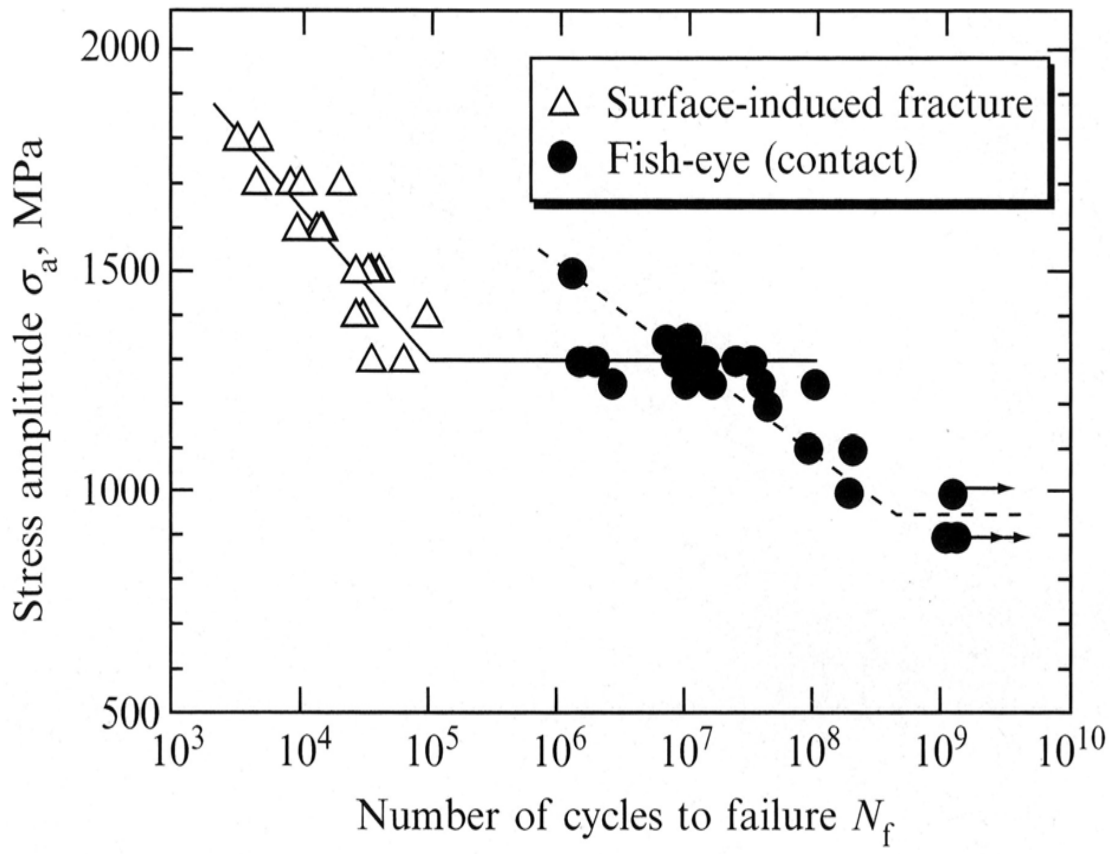
    Influence of environment and frequency

- **Plastic deformation, crack initiation, propagation and failure in copper in the VHCF range (20 kHz)**

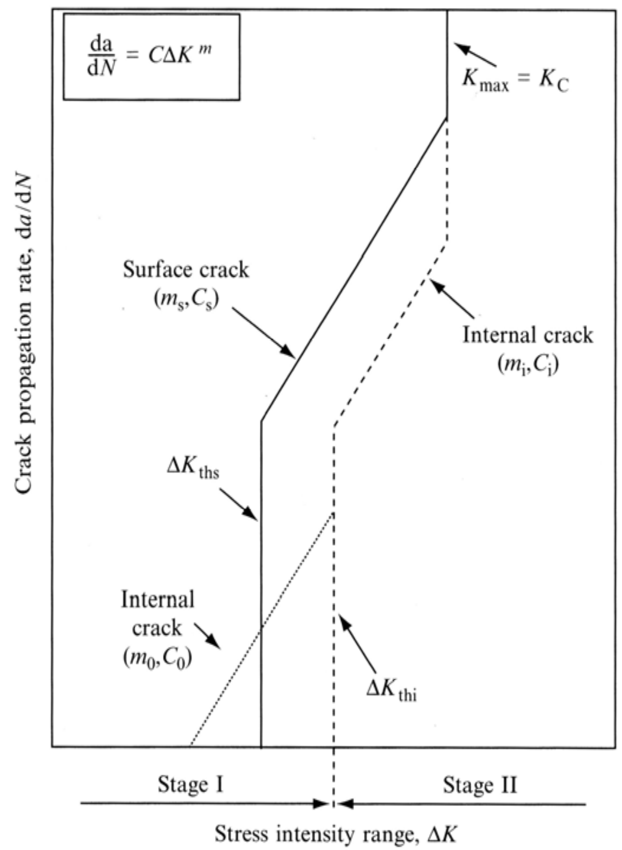
    Persistent slip bands (PSBs)

    Endurance limit , Δa/ΔN and ΔK threshold

VHCF and FCG Behaviour

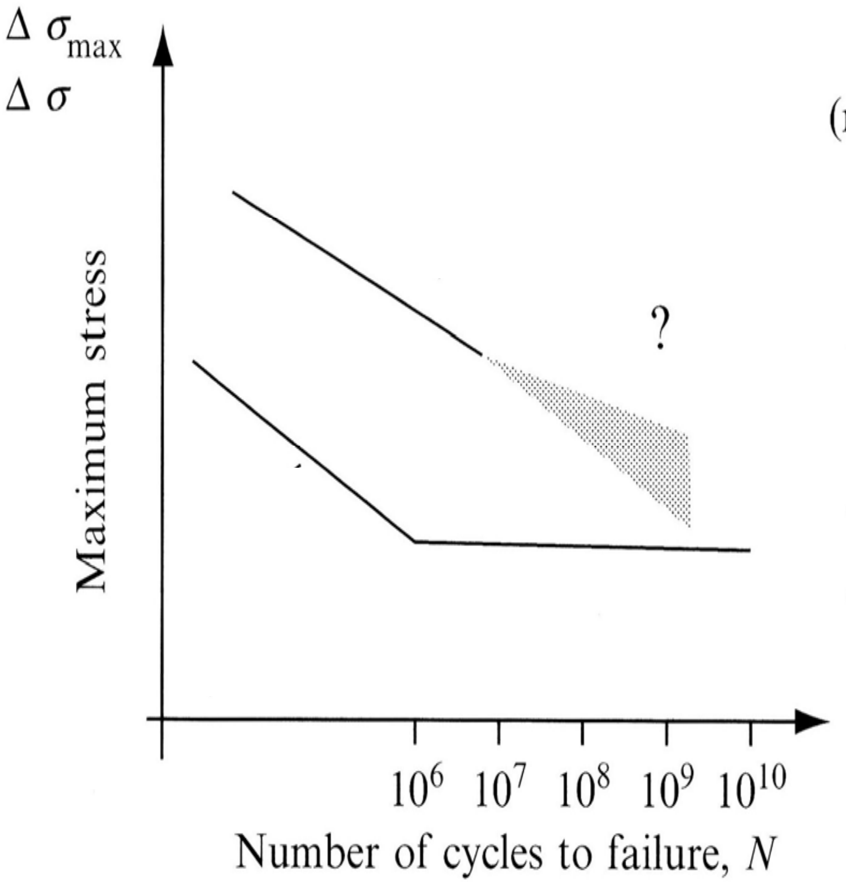


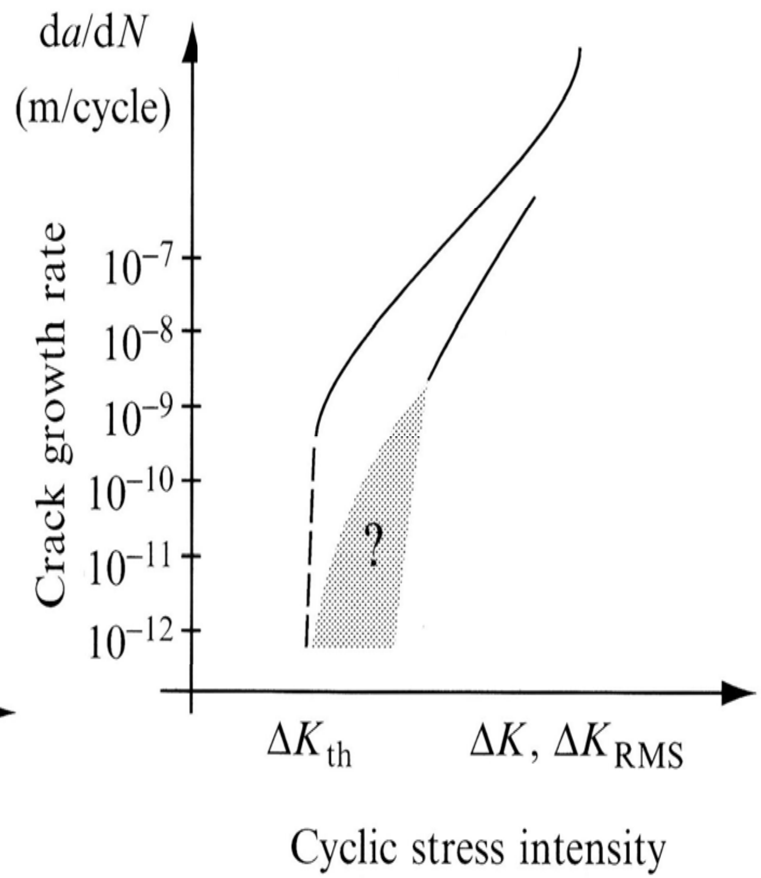
S-N diagram of high-carbon Cr-steel (Sakai et al 2002)



FCG behaviour of Surface and internal cracks (Tanaka & Akiniwa 2002)

Existence or Non-Existence of Endurance Limit and Threshold Stress Intensity





VHCF – Testing Times

Number of cycles	20 Hz	20 kHz
10^6	14 hours	50 sec
10^7	6 days	8 min
10^8	2 months	1.4 hours
10^9	1.7 years	14 hours
10^{10}	17 years	6 days
10^{11}	170 years	2 months

BOKU University
1915

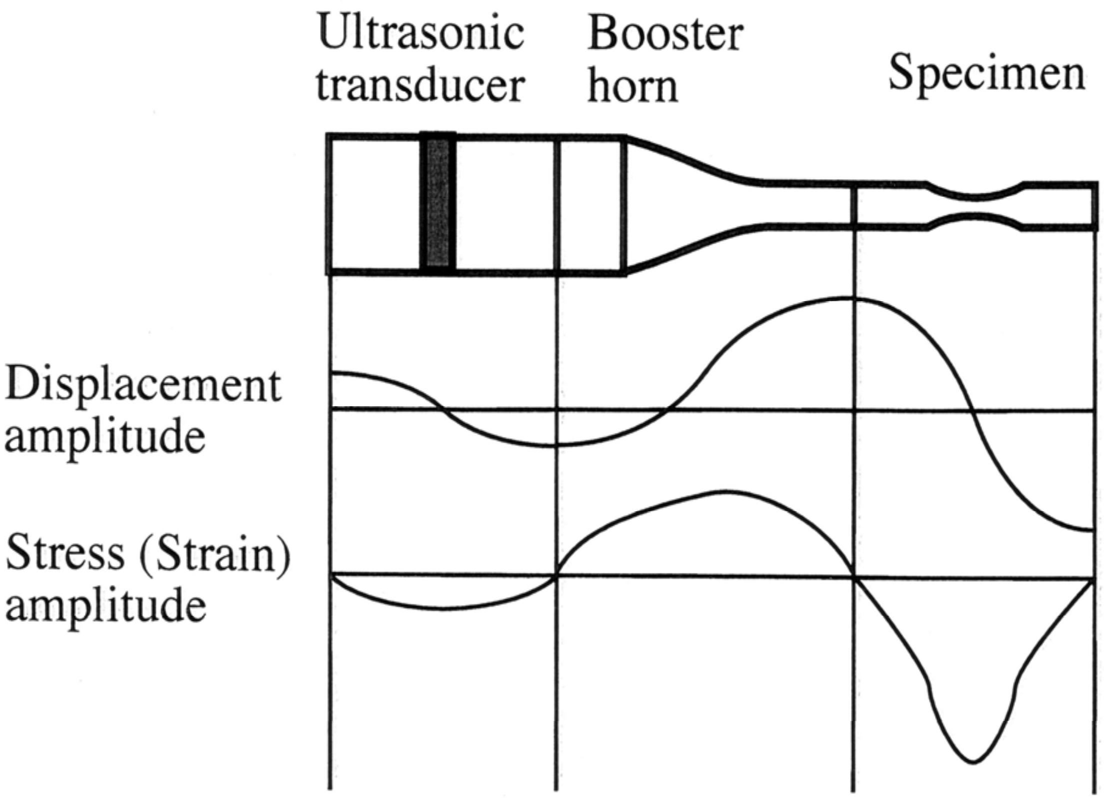
Ultrasound Measuring Technique

BOKU University
2004

Torino
5 novembre 2008

Stefanie Stanzl-Tschegg

Principle of Ultrasonic Resonance Fatigue Loading



Resonance vibration at approximately 20 kHz

•**Ultrasonic Transducer:** Piecoelectric, axial or torsional

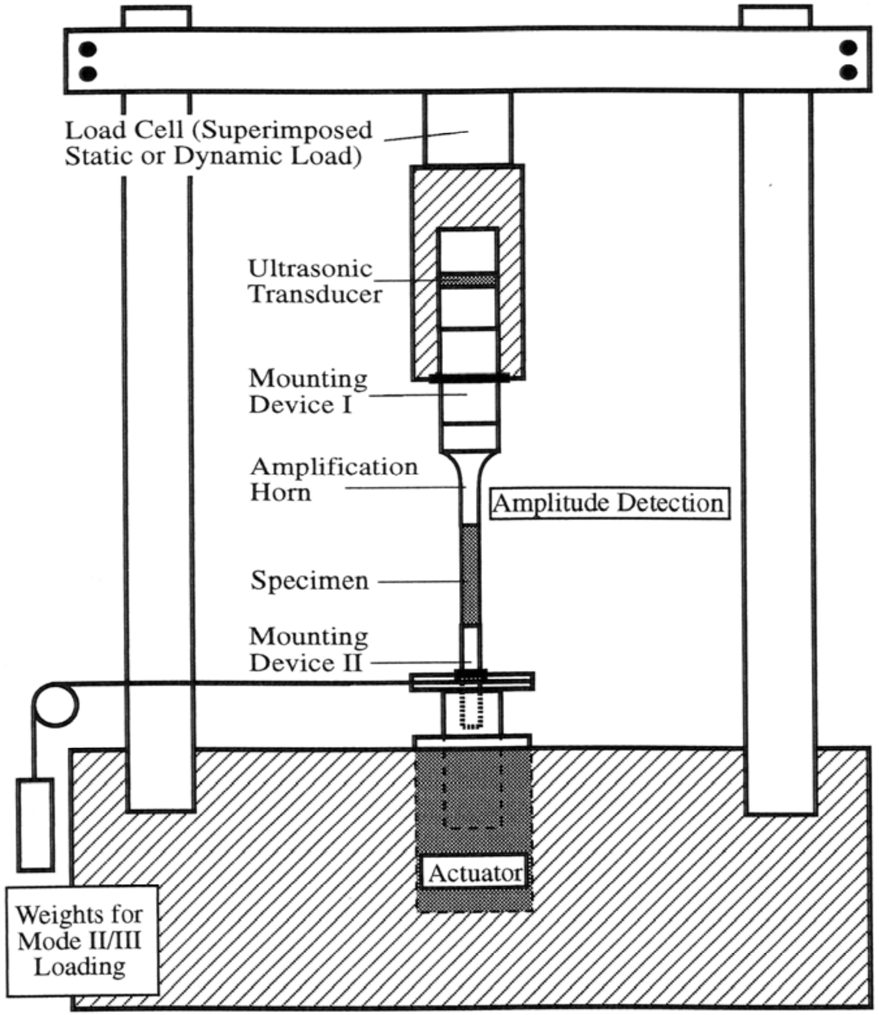
•**Magnification Horn:** Increases the vibration amplitude by a factor of 4 to 15

•**Specimen:** Length and shape follows resonance criteria, Surface condition is important Smooth or notched

Ultrasonic Fatigue Loading – Experimental Procedure

- **Frequency 19 kHz**
- **Fully reversed loading**
  (R=-1)
- Cooling (damping heat):
  compressed air
  pulse-pause sequences
  pulses: 150 ms (2700 cycles)
  periodic pauses: 2000-3000 ms
- **Induction sensor**
  measures vibration
  amplitudes
- **Closed loop control**
  of vibration amplitudes
  (total strain)

Ultrasound Testing Equipment



- Amplitude sensor

$\Delta l \rightarrow \varepsilon = \Delta l / l \rightarrow$

$\sigma = E \cdot \varepsilon \rightarrow \Delta K$

- Free specimen end → R = -1
- Both specimen ends fix→ R ≷ 1

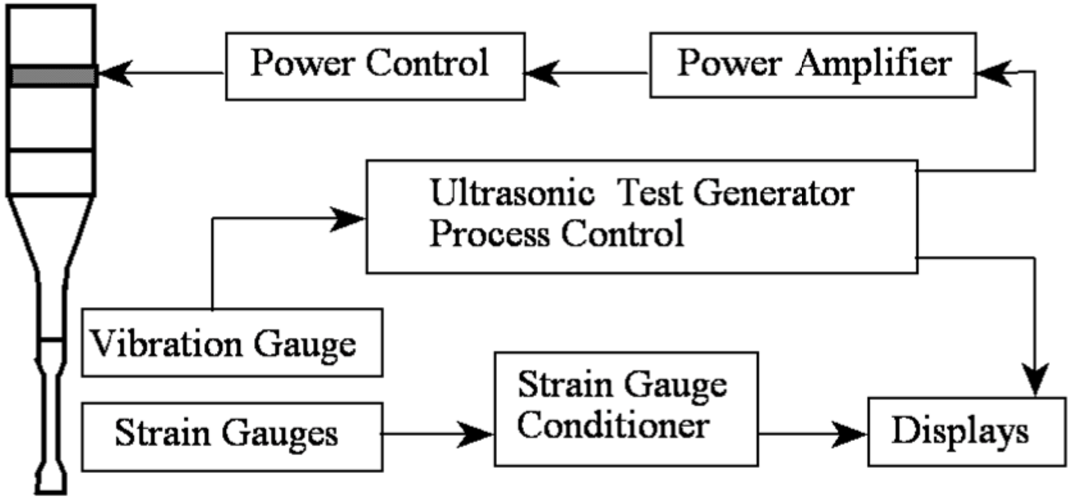
- Cooling Pulse-Pause

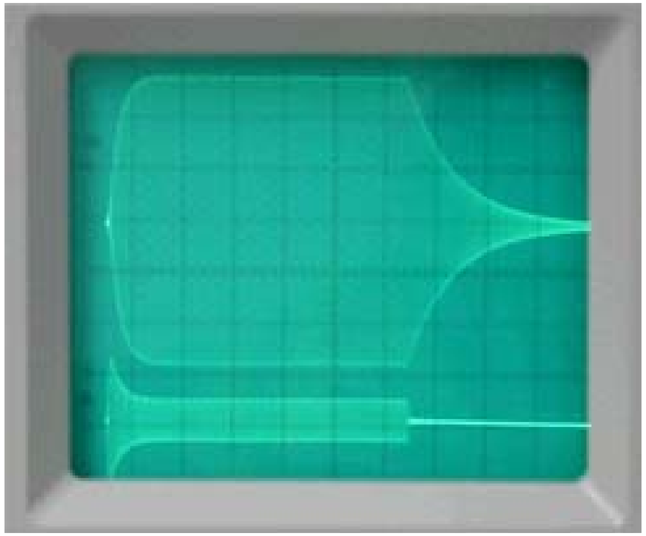
  + Compressed air

- Environmental chambers (corrosion, temperature, vacuum)

Ultrasonic Testing Procedure

Amplitude feed-back control





Determination of the process:

Vibration Amplitude: After calibration

Pulse and Pause: Depending on damping

Frequency limits: Stop when specimen failure

Control Circuits:

Vibration Amplitude: Accuracy ±1%

Resonance Frequency: Accuracy ±1 Hz (0.005%)

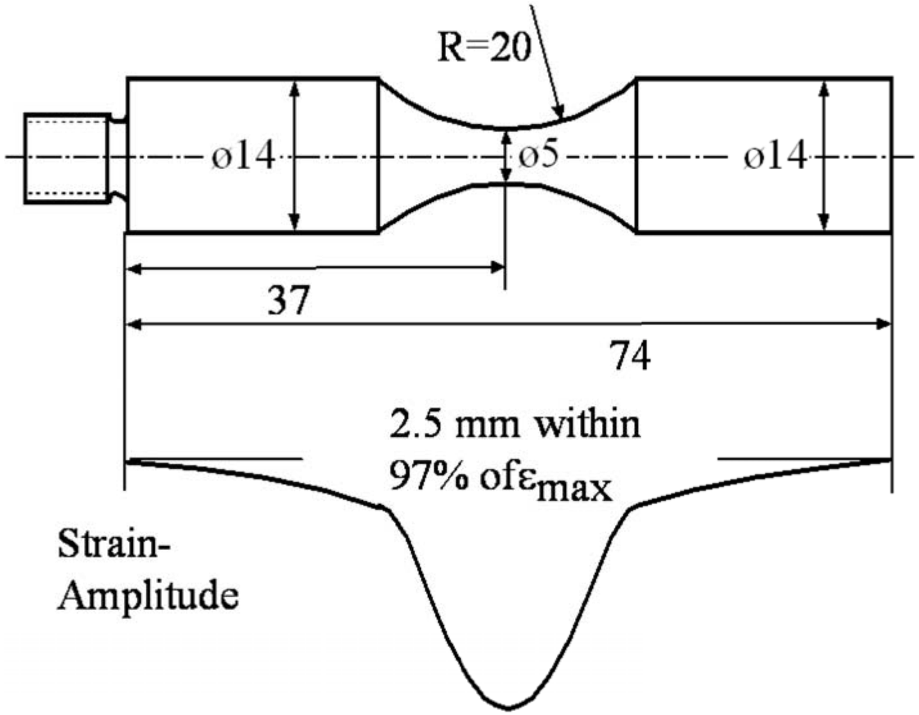
Pulse 50 ms - approx. 1000 amplitudes

Increase Time - approx. 100 amplitudes

Decay Time - depending on damping

Shapes of Fatigue Specimens

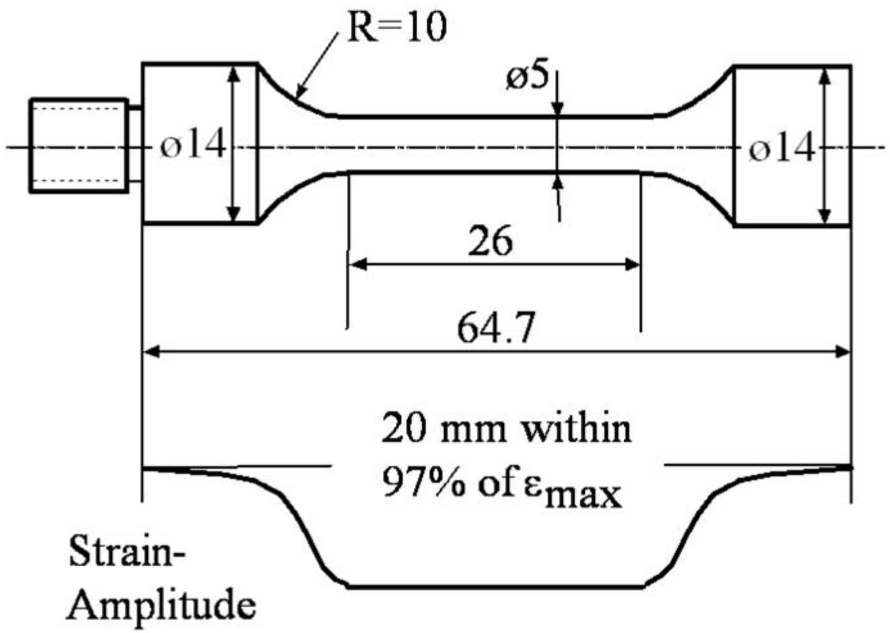
Wrought alloy



Amplification factor: 4.9

Loaded volume: 50 mm^3

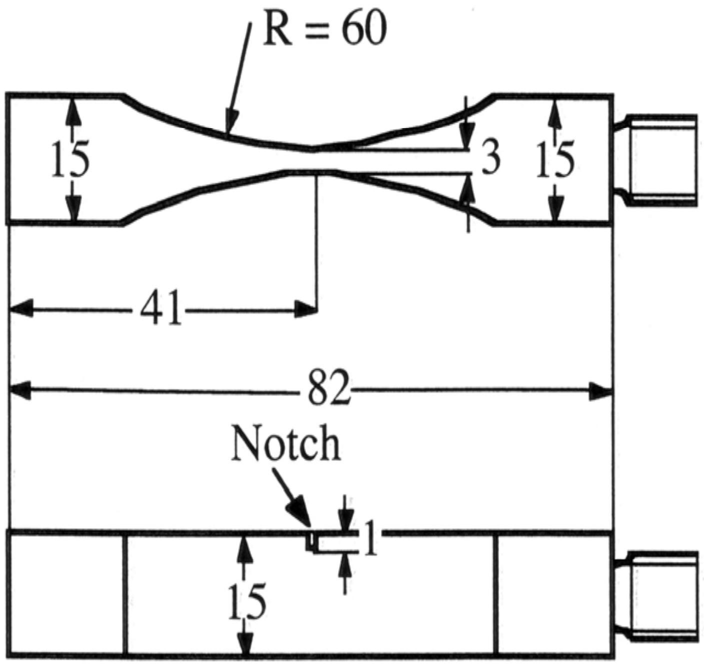
Cast alloy

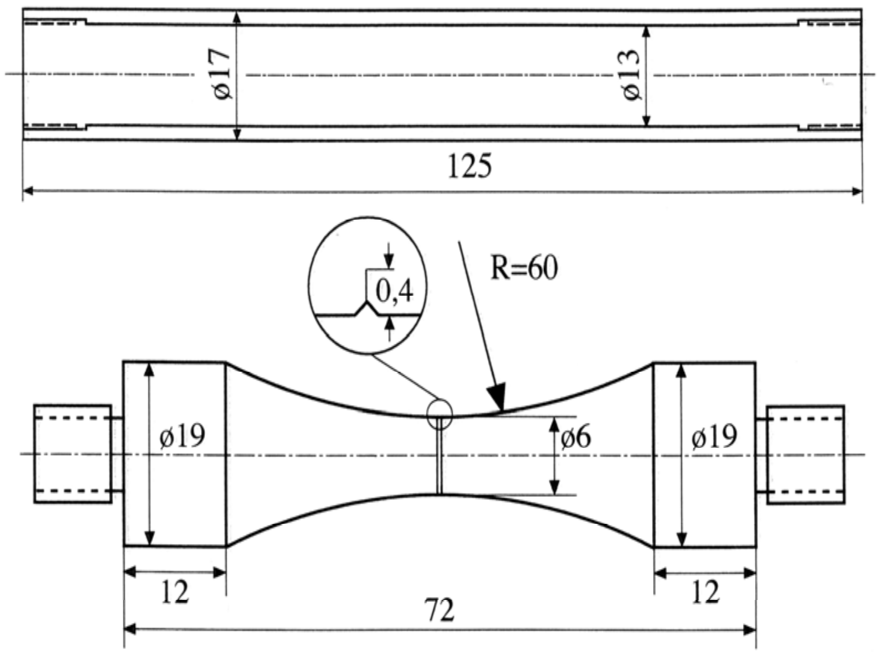


Amplification factor: 2.2

Loaded volume: 390 mm^3

Specimen Shapes - Fatigue Crack Growth





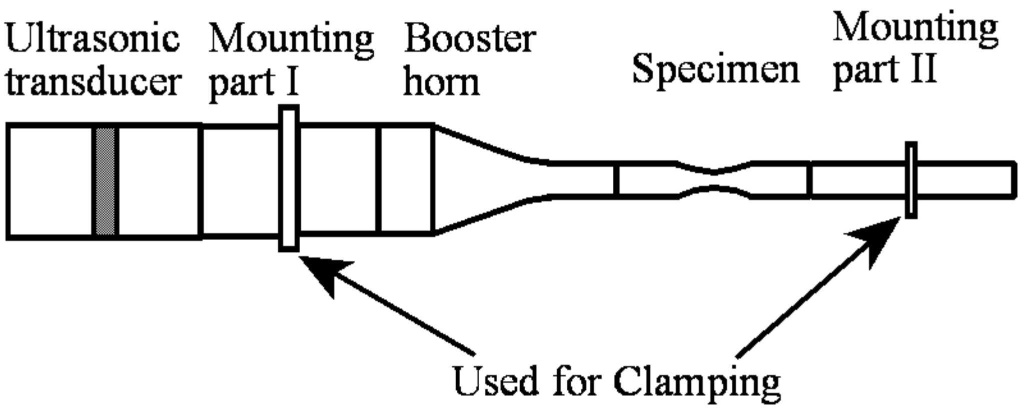
Fully Reversed Loading

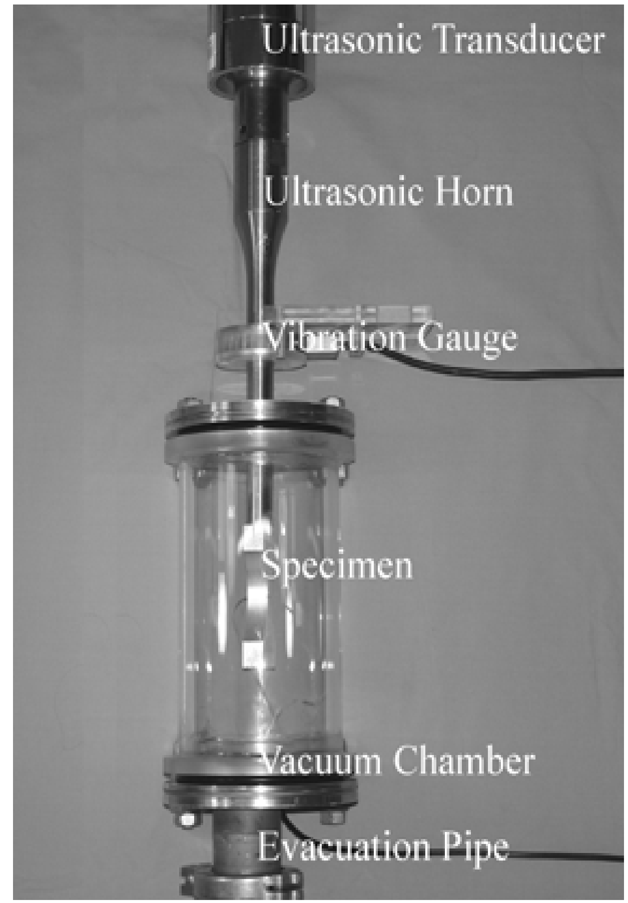
Superimposed and Mixed Mode Loading

Ultrasonic Fatigue Testing Procedure – Mechanical Components

Testing in different environments
Vacuum
High and low temperature
Corrosive Fluids

Testing at different loading conditions
Superimposed mean loads (R>-1)
Superimposed torsion moments

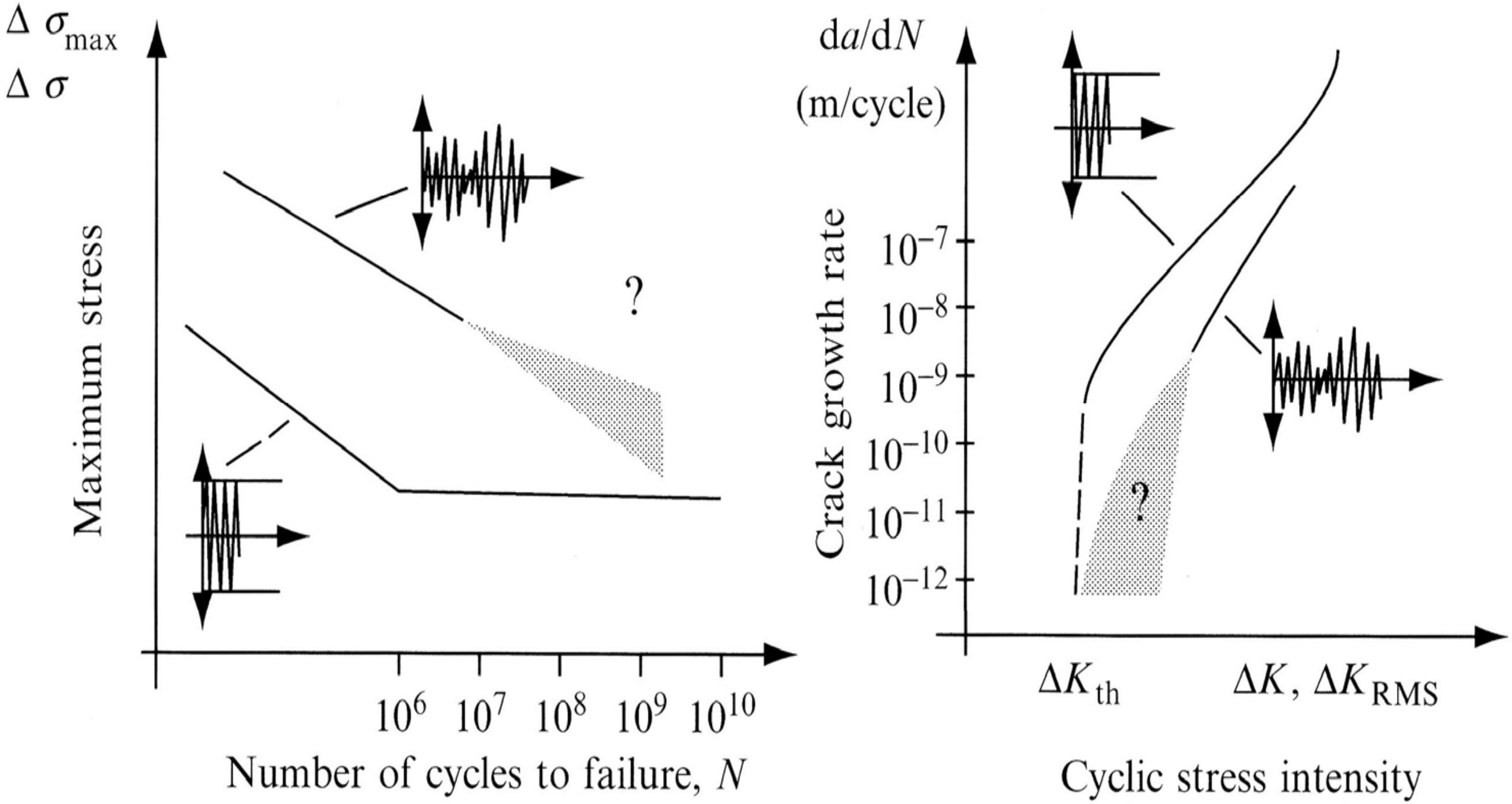




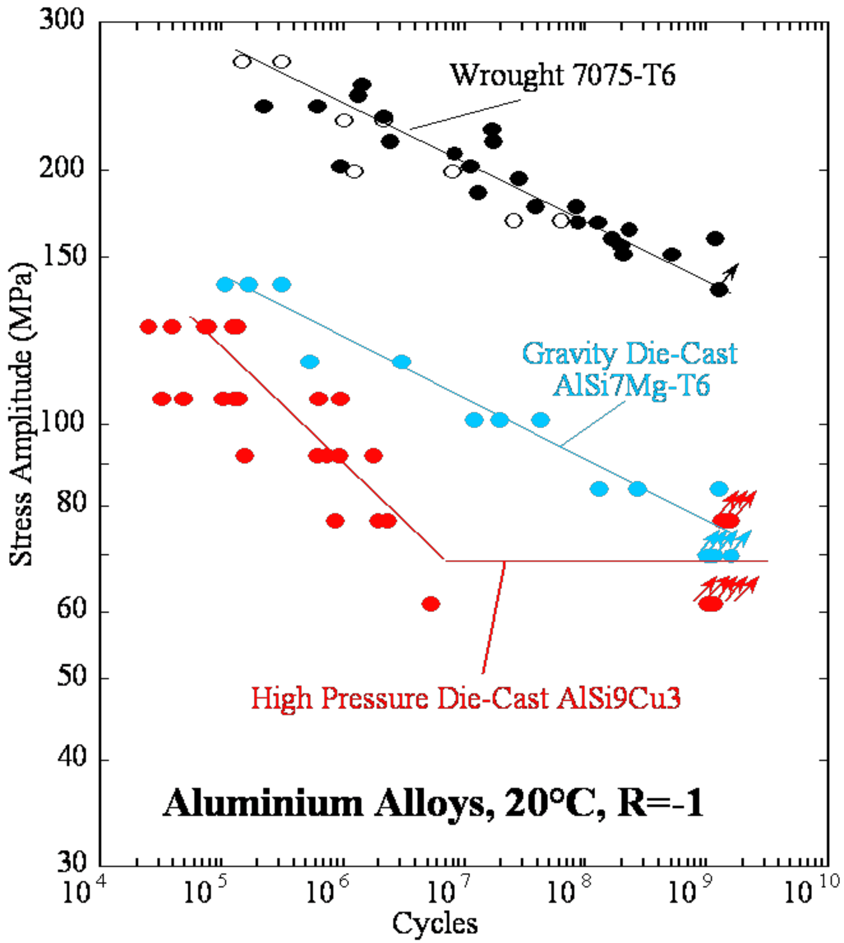
Testing in vacuum

Random loading

Endurance Limit - Threshold Stress Intensity

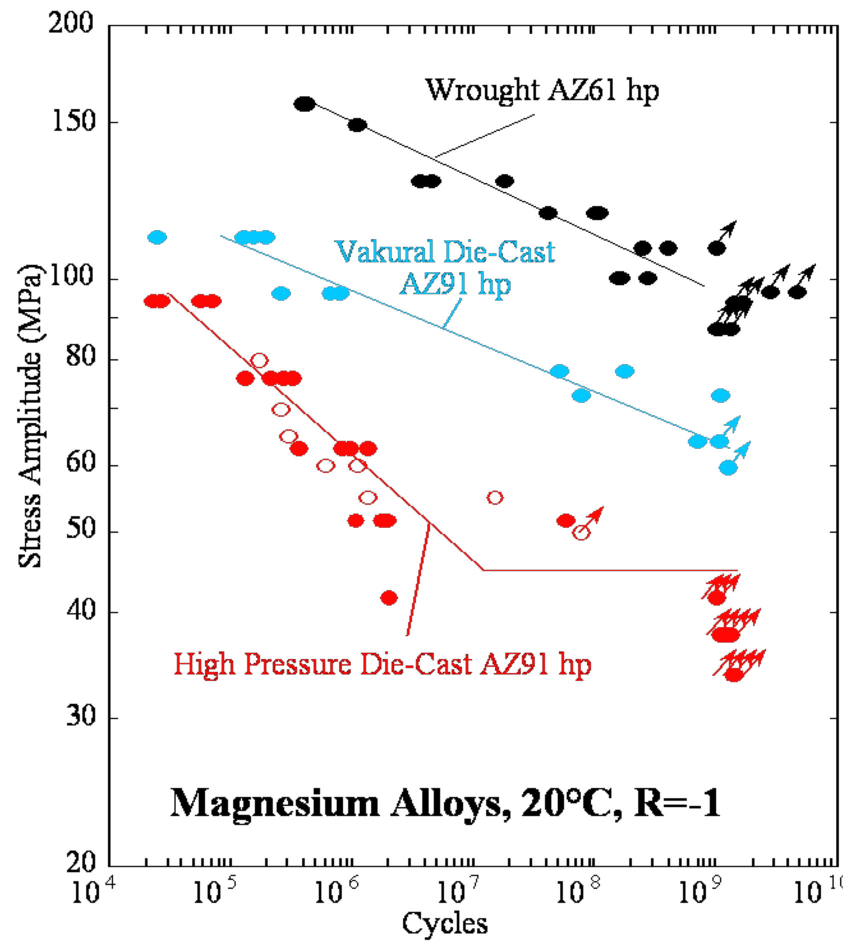


VHCF Aluminium and Magnesium Alloys
S-N Curves



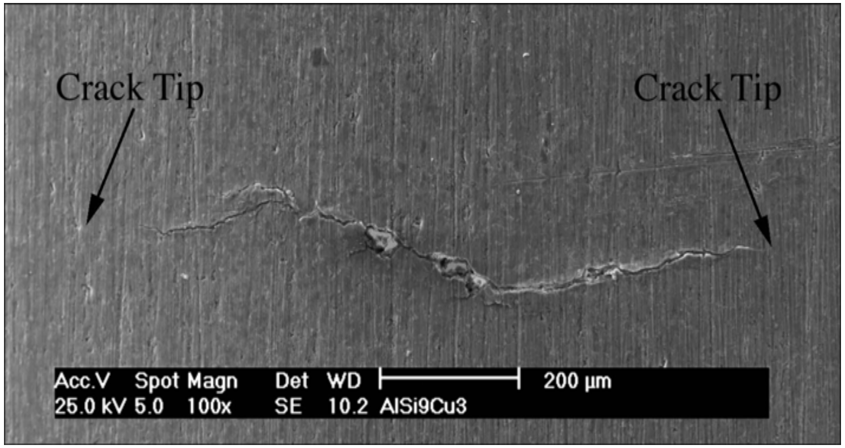
Papakyriacou M, Mayer H, Fuchs U, Stanzl-Tschegg SE, FFEMS 25, 2002.

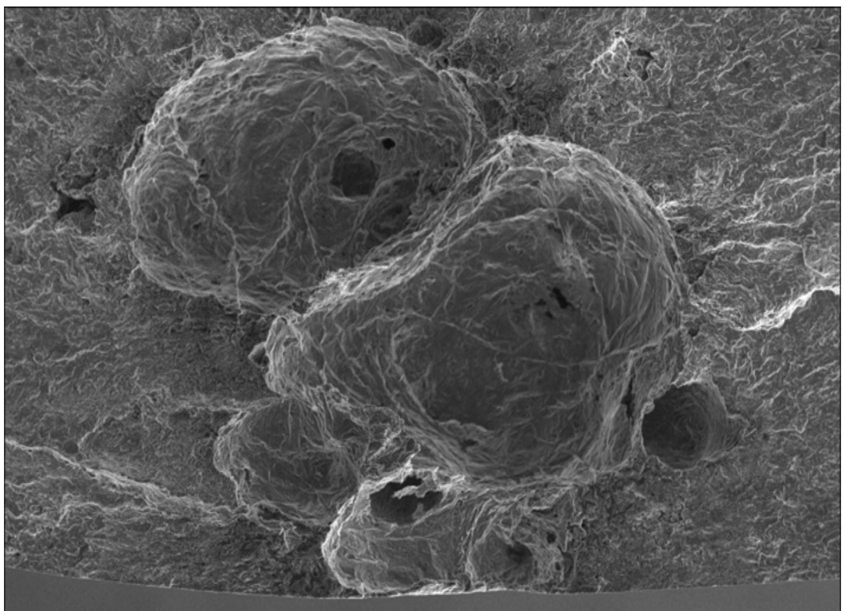
Stanzl-Tschegg SE, Proc. ATEM´93, 2003, 03-207



Mayer H, Papakyriacou M, Zettl B, Stanzl-Tschegg SE, Int J Fatigue, 25, 2003, 245-256

VHCF Aluminium and Magnesium Alloys





Non-propagating crack
High-pressure die cast **AlSi9Cu3**

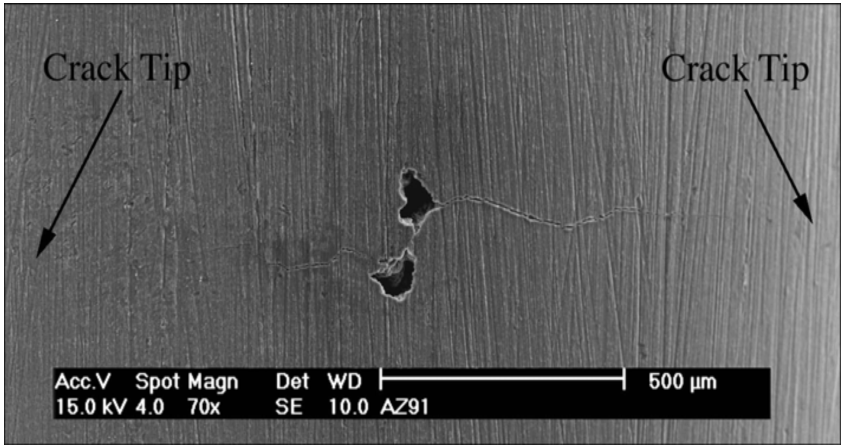
1.05×10^9 cycles, 47.5 MPa
(78 % of mean endurance
strength at 150 °C)

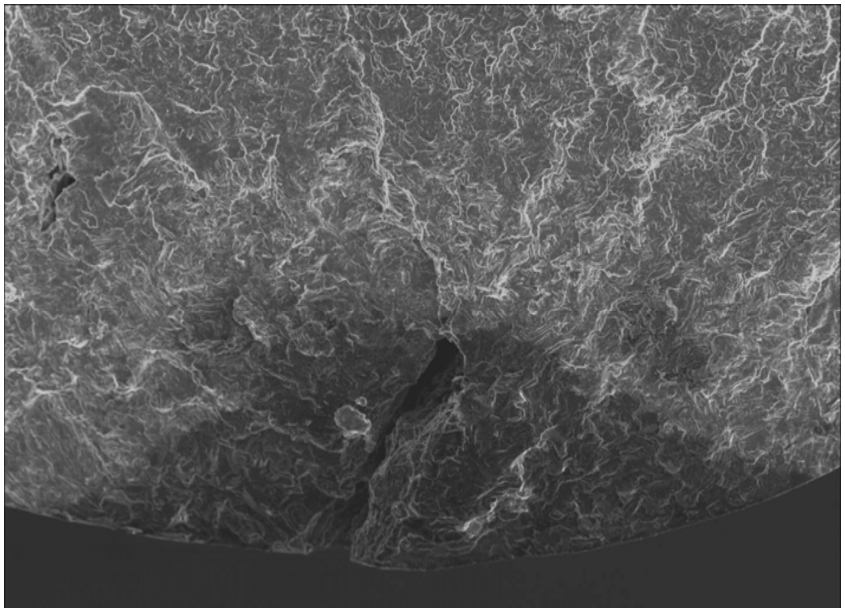
Maximum length of
non-propagating cracks: 1.2 mm

Fracture surface
(after increase of load)

Mayer H, Kolloquium Werkstoffe, Fertigung, Konstruktion, Siegen 2004

VHCF Aluminium and Magnesium Alloys





Non-propagating crack

High-pressure die cast **AZ91**

1.51×10^9 cycles, 38 MPa
(90 % of mean endurance
strength at 150 °C)

Maximum length of
non-propagating crack: 1.6 mm

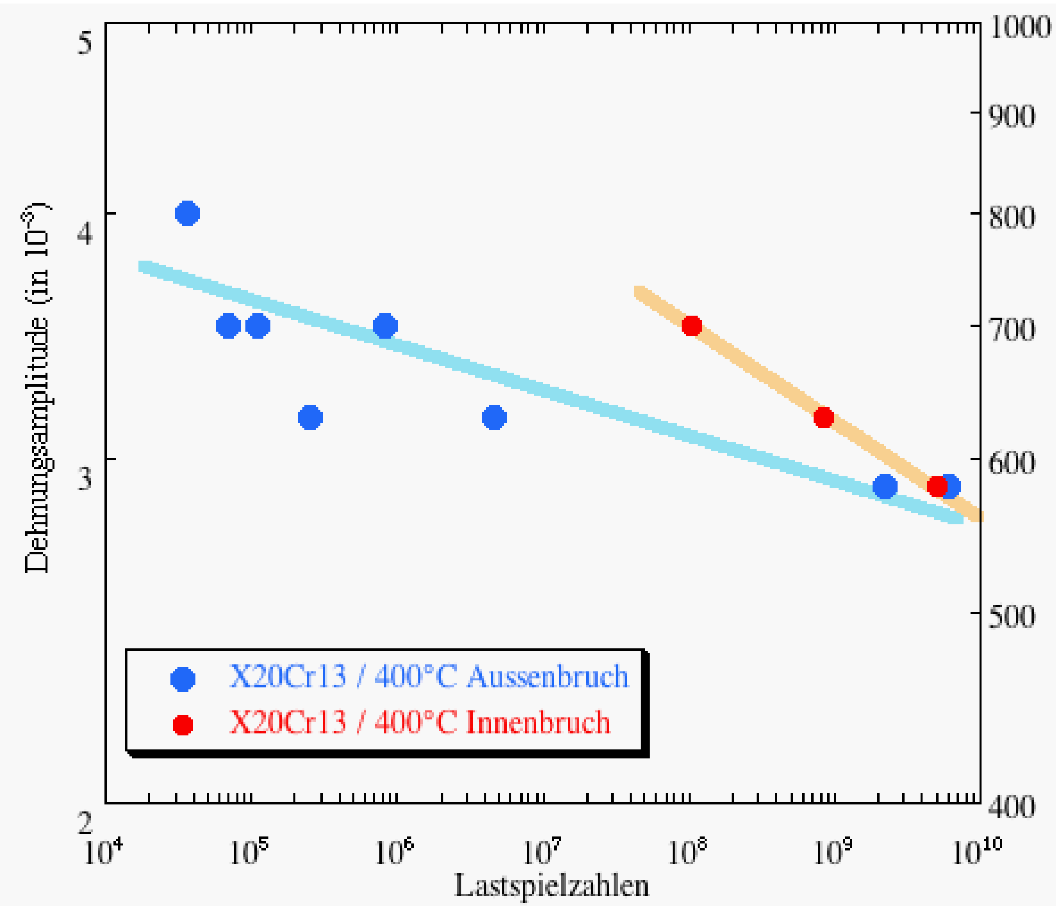
Fracture surface

(after increase of load)

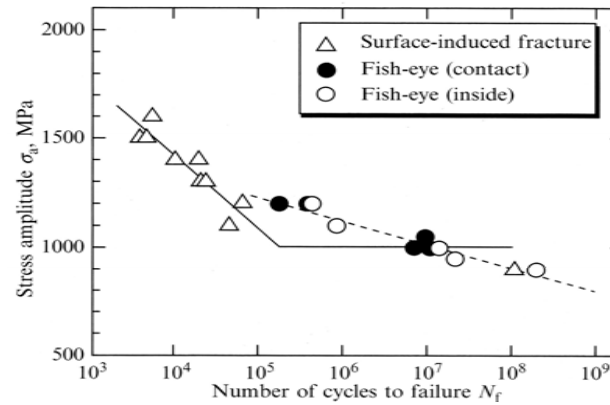
Mayer H, Kolloquium Werkstoffe, Fertigung, Konstruktion, Siegen 2004

VHCF X20Cr13 Steel

Axial 20 kHz tension-compression loading
X20Cr13: 11.3 Cr, 0.2 C, 0.22 Al
(940°C /oil quench/ hardening 400°C/2.5 h)



Similar *Sakai et al, 2002*



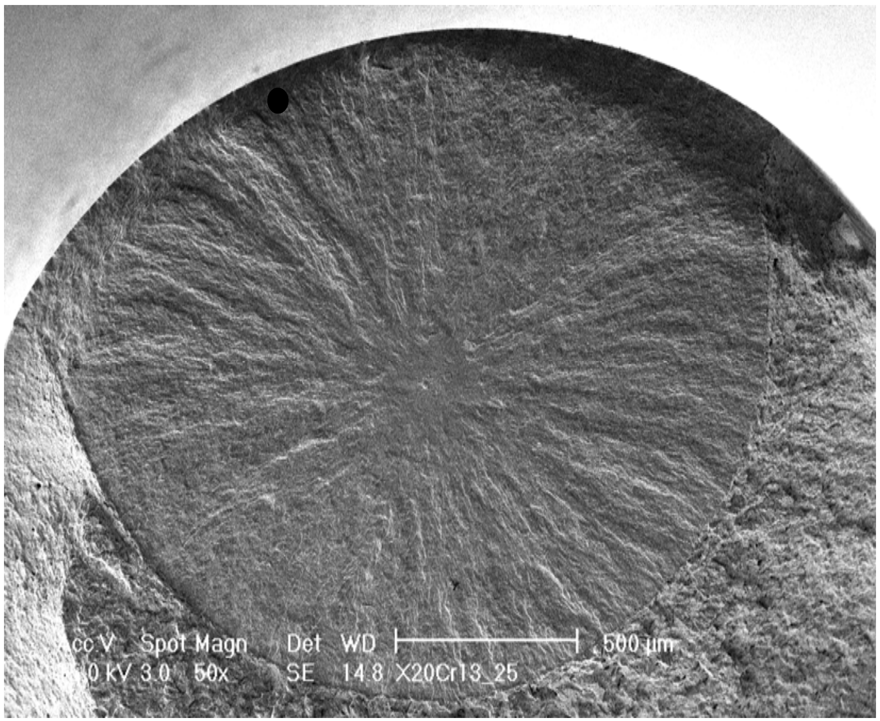
- **Crack initiation from surface**
- **Crack initiation $\geq 10^8$ cycles from internal inclusions**

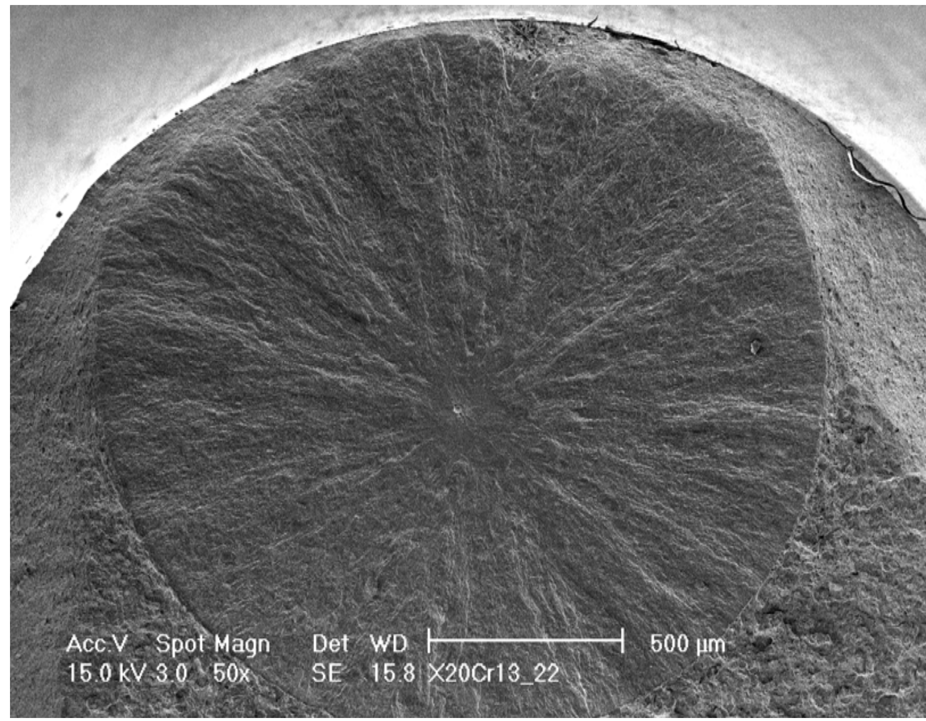
Stanzl-Tschegg, DGM Meeting Berlin, June 2006

Crack Initiation from Internal Inclusions

Axial 20 kHz Tension-Compression Loading

X20Cr13: 11.3 Cr, 0.2 C, 0.22 Al (940°C / oil quenched, hardening 400°C/2.5 h)



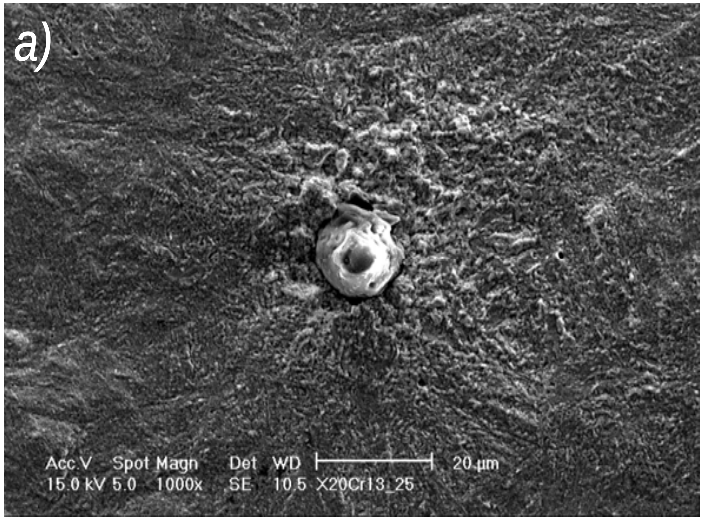


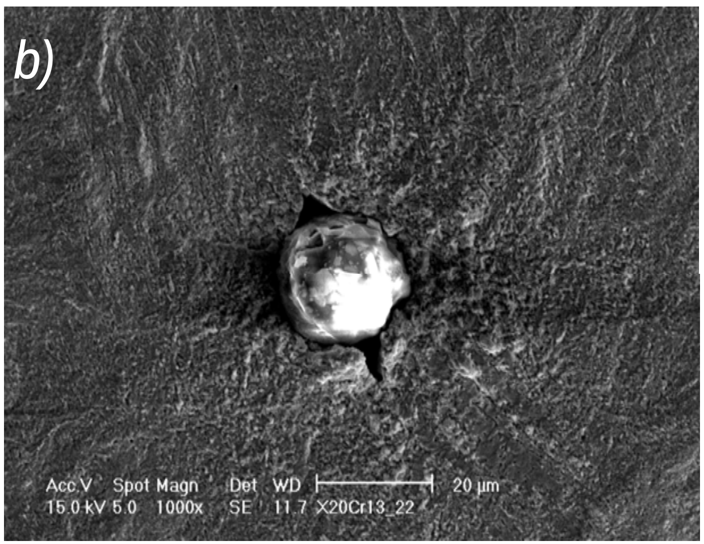
$\Delta\sigma$= 620 MPa, N_f = 8.48x10 ^{8}

$\Delta\sigma$ = 700 MPa, N_f = 1.3x10^8

Stanzl-Tschegg, DGM Meeting Berlin, June 2006

Crack Initiation from Interior Inclusions





Crack initiation from ca. 10-20 μm Al_2O_3, CaO, MnS, MgO inclusions after ca. $10^8 – 10^9$ cycles

EDAX Analysis (Wt%)

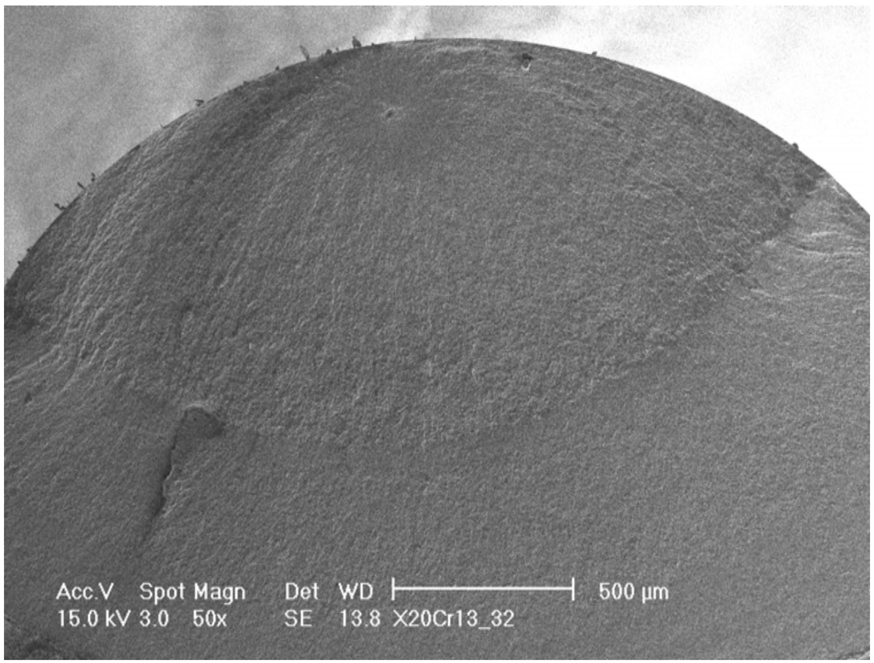
	a)	b)
Al:	22.40	18.44
S:	24.55	27.06
Ca:	17.74	22.59
Mn:	6.96	5.80
Mg	6.07	4.49
Fe:	5.34	8.81

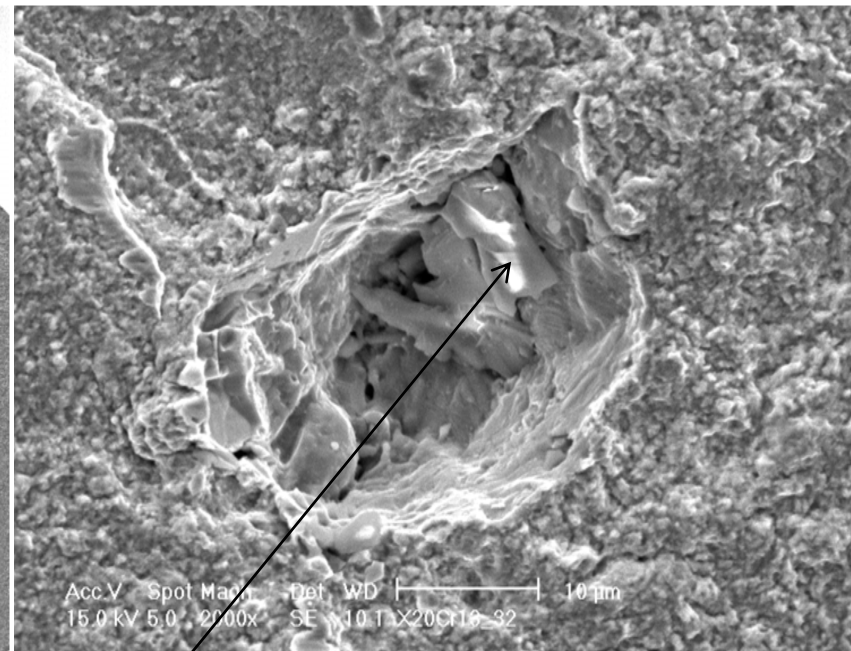
Stanzl-Tschegg, DGM Meeting Berlin, June 2006

Crack Initiation from Interior Inclusions

Axial 20 kHz Tension-Compression Loading

X20Cr13: 11.3 Cr, 0.2 C, 0.22 Al (940°C / oil quenched, hardening 400°C/2.5 h)





Interior crack initiation from

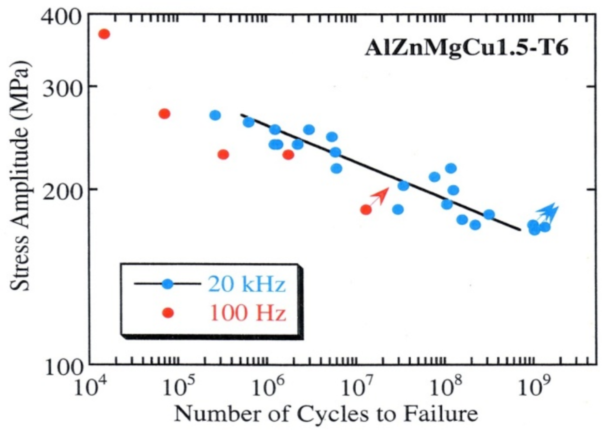
Carbide inclusion

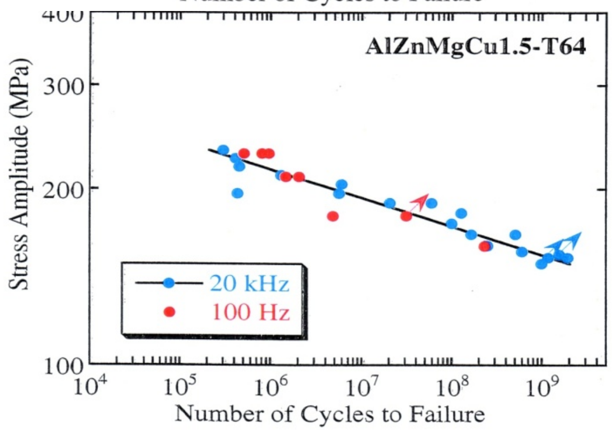
EDAX Analysis (wt%) Fe: 64.10

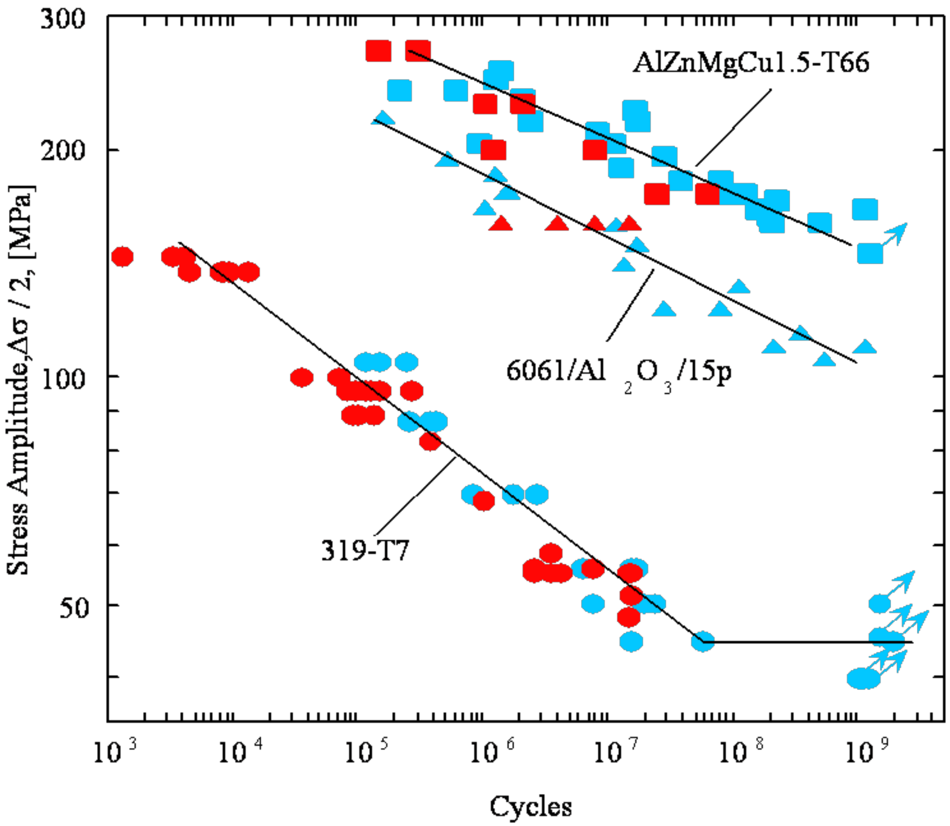
Cr: 10.01

Stanzl-Tschegg, DGM Meeting Berlin, June 2006

Frequency Effect?
S-N Curves   Al alloys





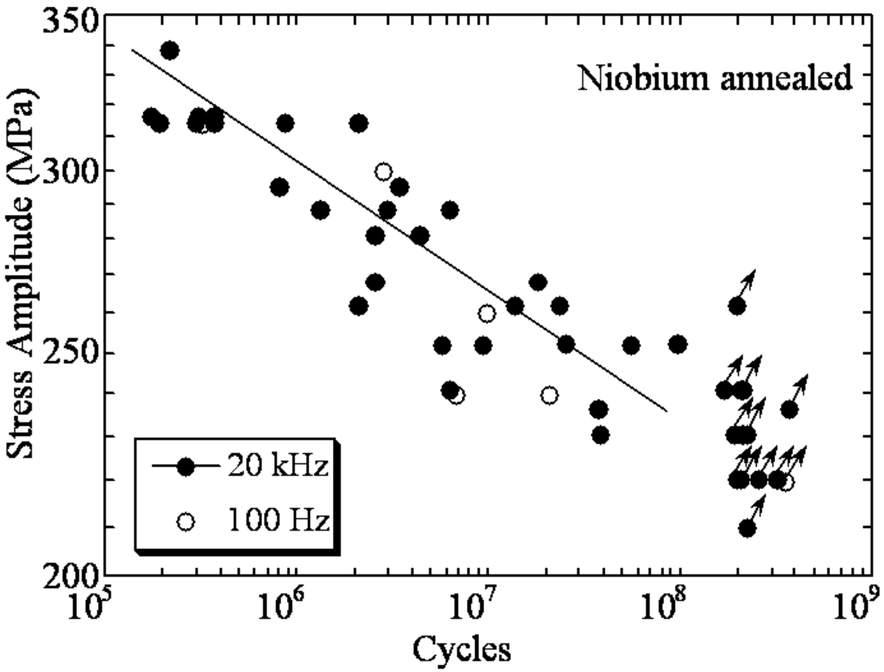


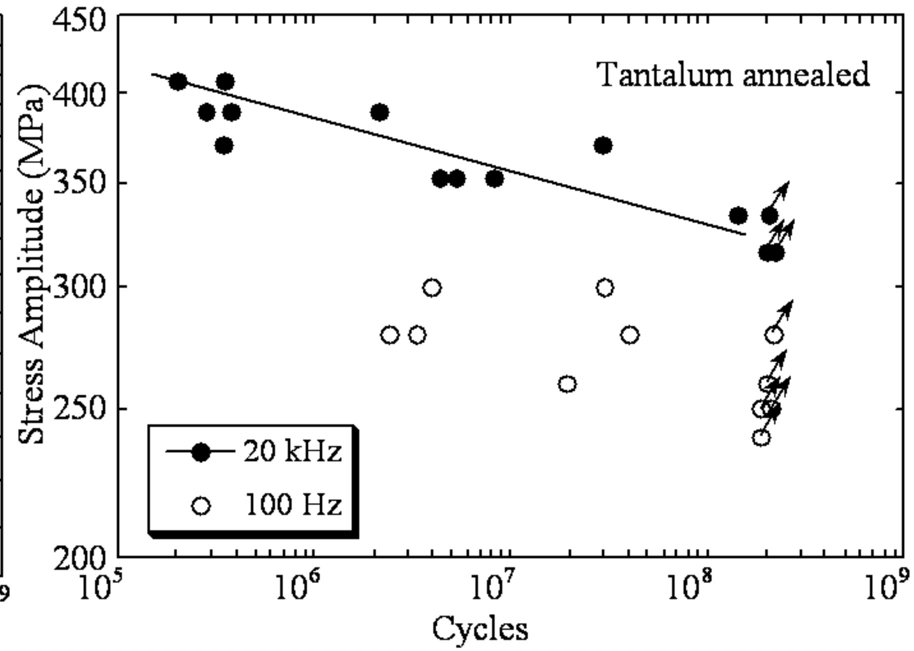
Mayer H, Papakyriacou M, Pippan R, Stanzl-Tschegg SE
Mat Sci Eng A314, 2001, 48-54

No frequency effect

Papakyriacou M, Mayer H, Fuchs U, Stanzl-Tschegg, Wei RP, FFEMS 25, 2002, 887-896

Frequency Effect?
S-N Curves Nb and Ta





Papakyriacou M, Mayer H, Plenk H, Pypen C, Stanzl-Tschegg SE, Mat Sci Eng A 308, 2001, 143-152

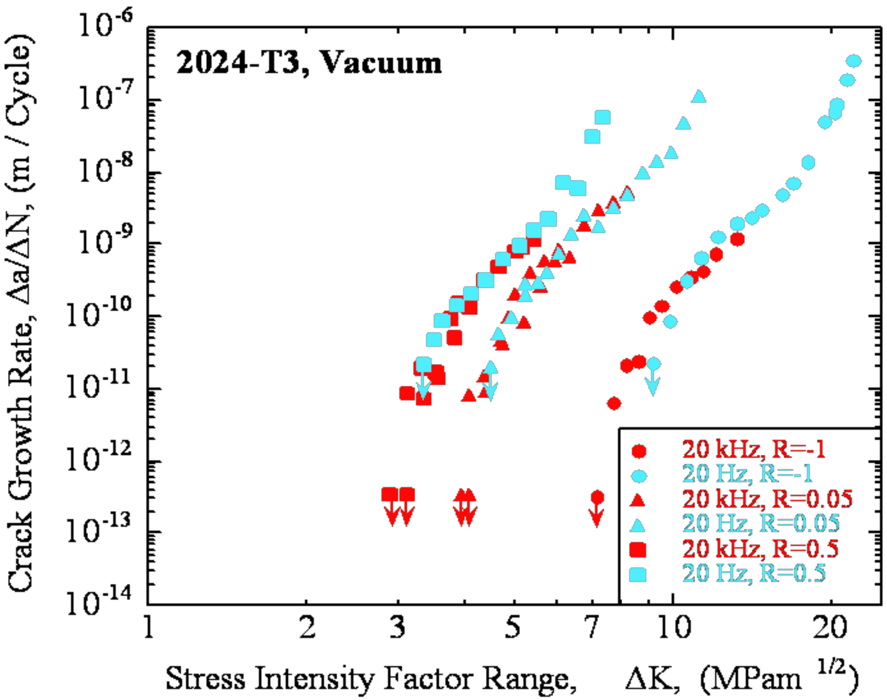
Yield strength $R_{p0.2}$ = 385 MPa
Endurance limit at $2x10^8$ cycles:
240 MPa - 20 kHz 220 MPa - 100 Hz

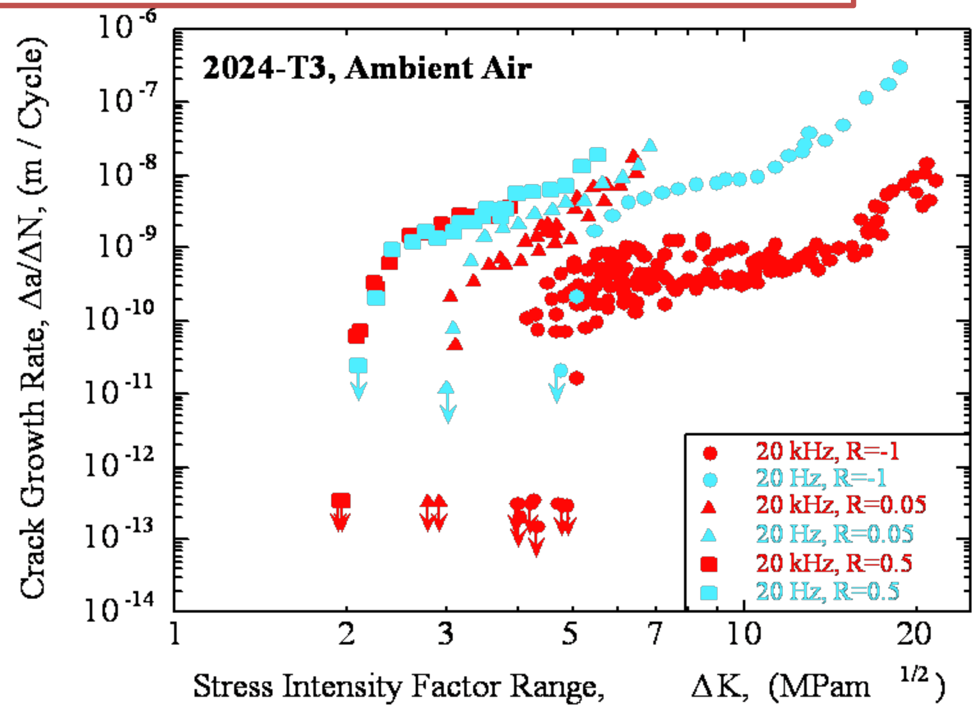
Niobium: **No frequency effect**

Yield strength $R_{p0.2}$ = 240 MPa
Endurance limit at $2x10^8$ cycles:
365 MPa - 20 kHz 290 MPa - 100 Hz

Tantalum: **Frequency effect**

Frequency Effect?
Fatigue Crack Growth in Humid Air





Holper B, Mayer H, Vasudevan AK, Stanzl-Tschegg, Int J Fatigue,26, 2004, 27-38

- **No** influence of plastic deformation rate on Δa/ΔN **(vacuum)**
- **Frequency effect** at Δa/ΔN > ca.10^{-9} m/cycle owing to air **humidity**
- **No frequency effect** on $\Delta K_{threshold}$

Frequency Effect on S-N and $\Delta a/\Delta N$ curves - Summary

Frequency effect present

- At high loads close to yield stress (e.g.Tantalum!)

→ Testing of strongly damping material problematic

- At higher crack growth rates in corrosive environment

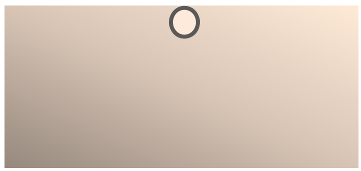
No frequency effect

- Al-alloys
- High-strength steels
- Titanium alloys Ti-6Al-7Nb and Ti-6Al-4V
- Mg – high pressure die cast alloy

Mechanisms of Fatigue Damage

Crack initiation mostly from SURFACE IMPERFECTIONS like


notches, scratches


inclusions

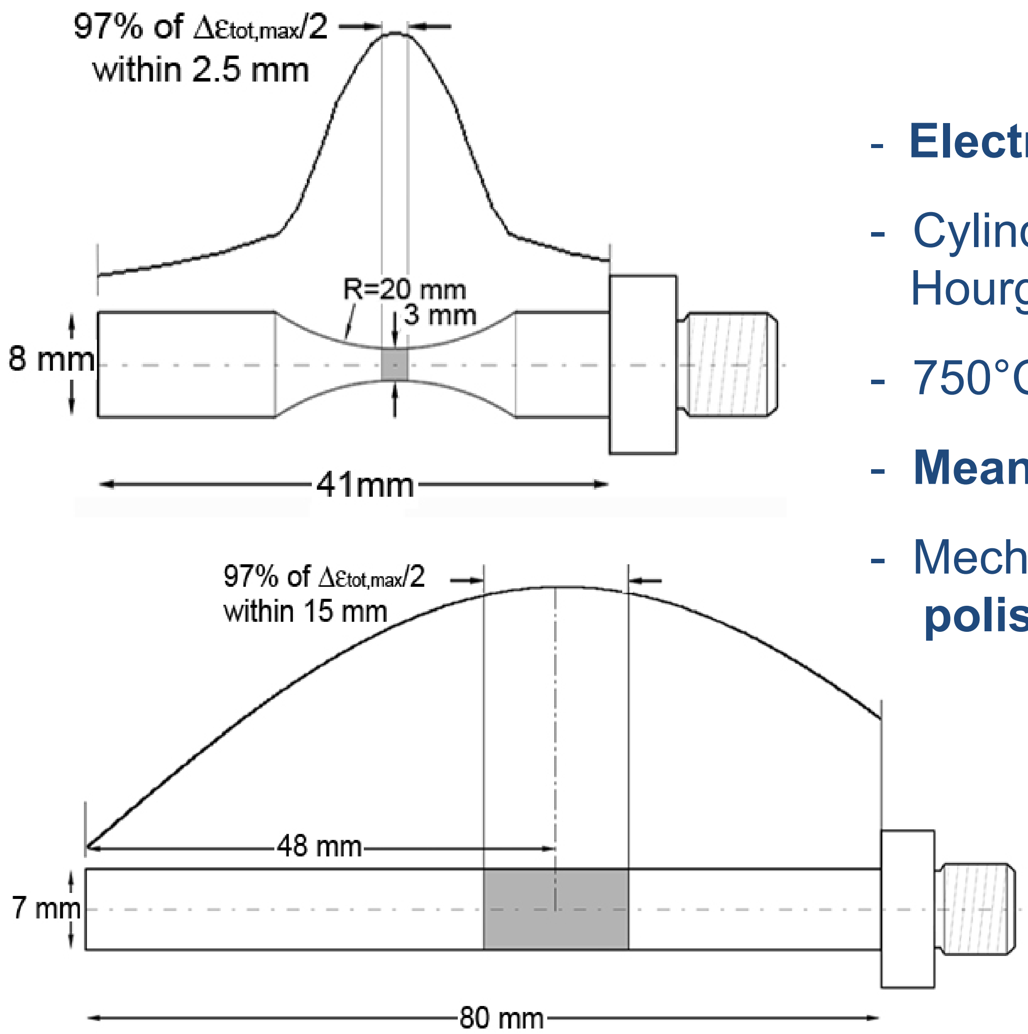

PSBs

or from INSIDE


inclusions,…

Relevance of PSBs in copper for crack initiation, propagation and life times (endurance limit?) in the VHCF range

Material and Specimen Shape



- **Electrolytic copper** (DIN1787/17672/1756)
- Cylindrical, 7 mm diameter, 80 mm long
  Hourglass **shape**, inner diameter: 3mm
- 750°C /75 min, vacuum/ air cooled
- **Mean grain size**: approximately **60 µm**
- Mechanical and electrolytical
  polishing (2V, 42 mA/cm²)
  - **Calibration**:
    Induction sensor at specimen end
    Strain gages along the whole specimen length to measure total axial strain amplitudes ε_{tot}

Experimental Procedure

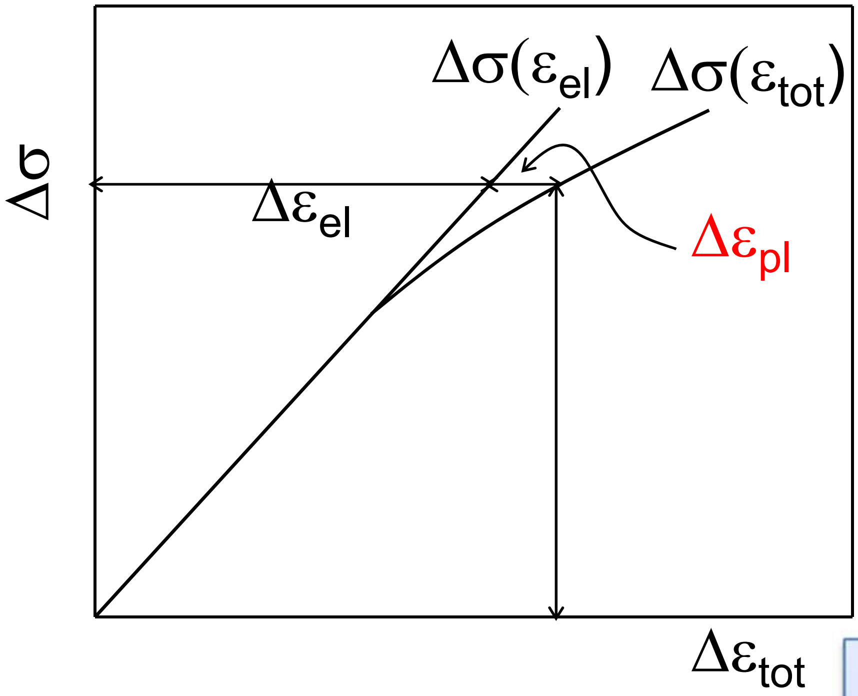
Ultrasonic test:

- Not stress ($\Delta\sigma/2$) controlled, but
- Displacement or ***total strain ($\Delta\varepsilon_{tot}/2$)*** (strain rate, $\Delta\varepsilon'_{tot}/2$) ***controlled***
- **Plastic strain** ($\Delta\varepsilon_{pl}/2$) control not possible

Therefore →

1. step: Calibration: Determine $\Delta\varepsilon_{pl}/2$
2. step: Experiment: Ramp loading

Determination of Stress Amplitude $\Delta\sigma/2$ in "ductile" material



Hooke´s Law:

$E = \Delta\sigma / \Delta\varepsilon_{el}$

and with:

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

$\Delta\varepsilon_{el}/2$	elastic cyclic strain
$\Delta\varepsilon_{pl}/2$	plastic cyclic strain
$\Delta\varepsilon_{tot}/2$	total cyclic strain

$\Delta\sigma/2 = \Delta\sigma_{el}/2$ cyclic stress

E =130 GPa Young´s modulus

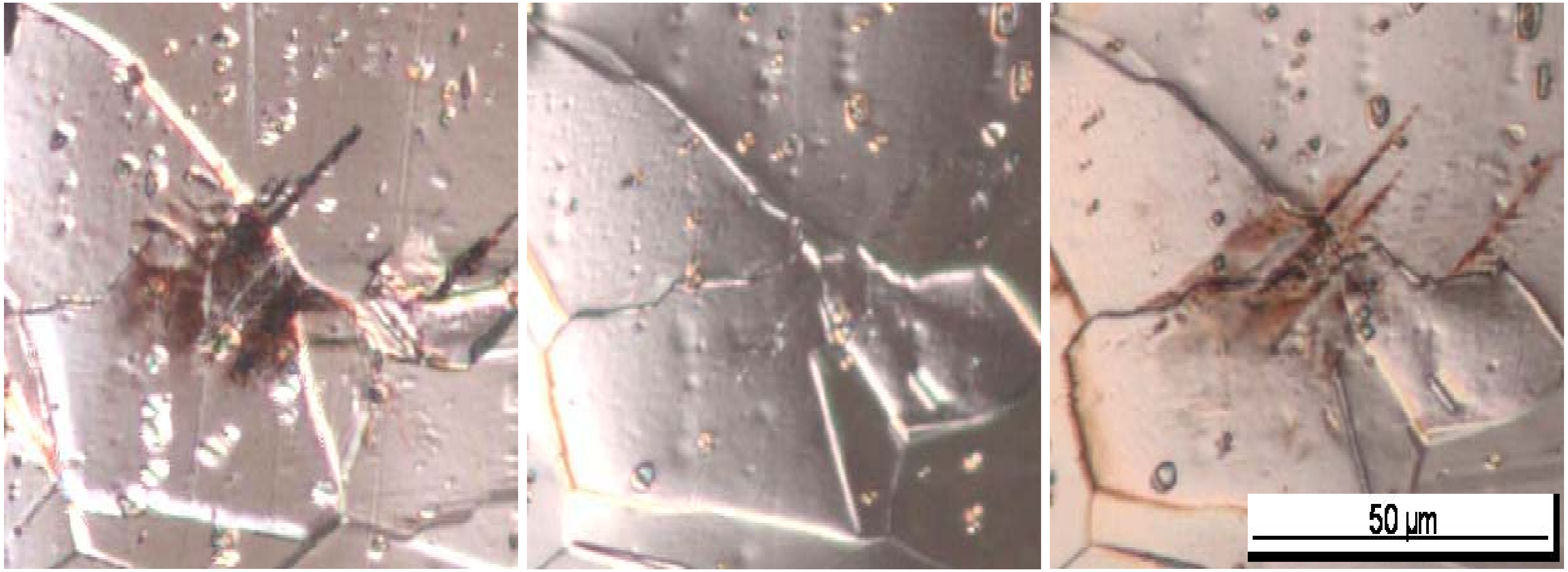
$$\Delta\varepsilon_{tot}/2 = \Delta\varepsilon_{el}/2 + \Delta\varepsilon_{pl}/2$$

$$\rightarrow \Delta\sigma/2 = E \cdot (\Delta\varepsilon_{tot}/2 - \Delta\varepsilon_{pl}/2)$$
$$= E \cdot \Delta\varepsilon_{el}/2$$

Identification of PSBs: Re-appearance of Slip Bands after Electropolishing PSBs and Reloading

→ „Conventional“ PSB threshold

$\Delta\sigma/2 \approx$ 63 MPa ($\Delta\varepsilon_{pl}/2 \approx 6.1\text{x}10^{-6}$)



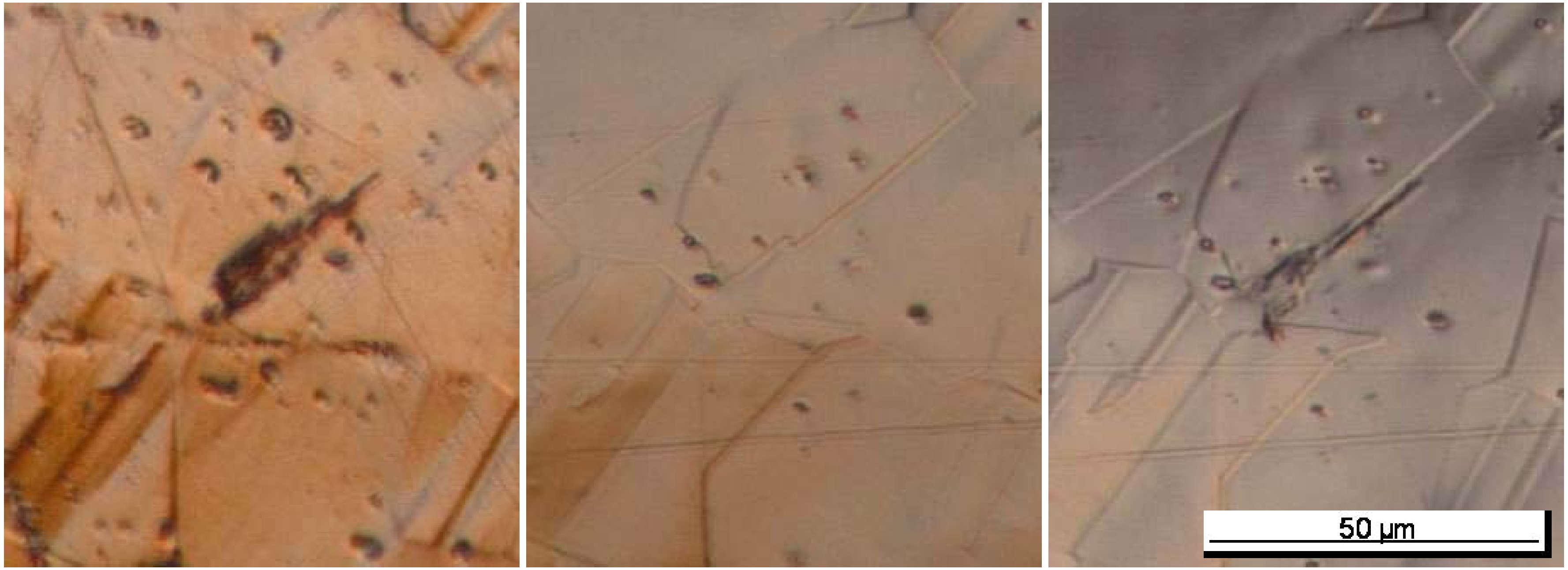
Initial loading $2\text{x}10^6$ **After polishing** **+ Reloading $2\text{x}10^6$ cycles**

Load direction: top to bottom.

PSBs in VHCF range also *below* PSB threshold

→ „VHCF“ PSB threshold

$\Delta\sigma/2 \approx$ 45 MPa ($\Delta\varepsilon_{pl}/2 \approx 3.6 \times 10^{-6}$), N $\approx 2 \times 10^{8}$

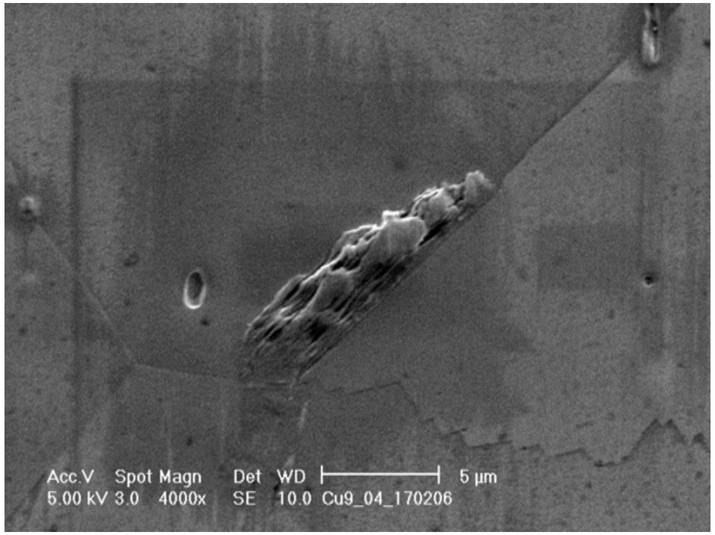


$\Delta\sigma/2 \approx$ 50 MPa ($\Delta\varepsilon_{pl}/2 \approx 4.1 \times 10^{-6}$)

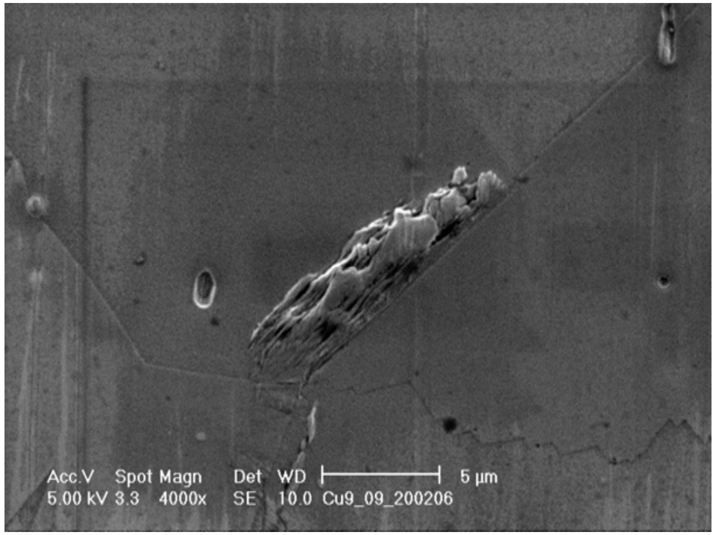
Initial loading 2×10^{8} cycles | **After polishing** | **+ Reloading 2×10^{6} cycles**

(Load direction: top to bottom)

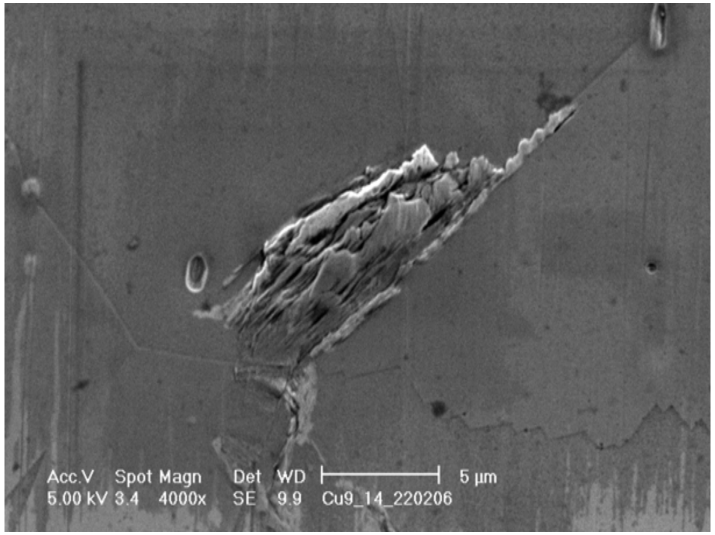
Structure and Development of PSBs (SEM)



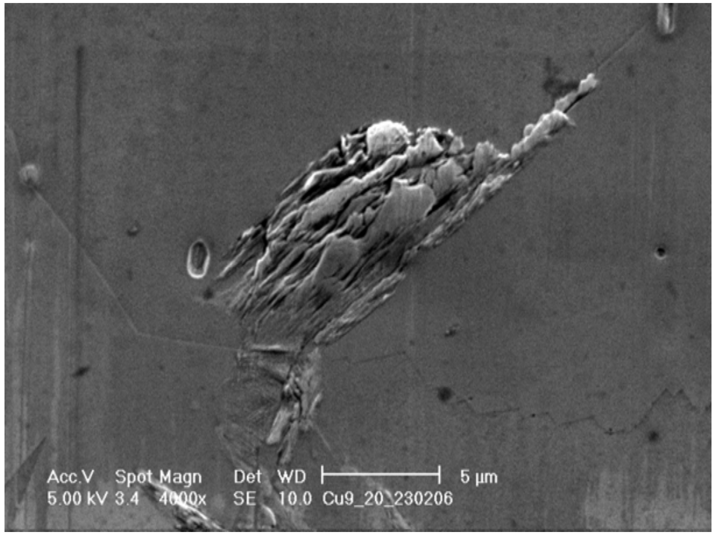
N = 7,0x10^{6}



N = 1,0x10^{7}



N = 5,0x10^{7}

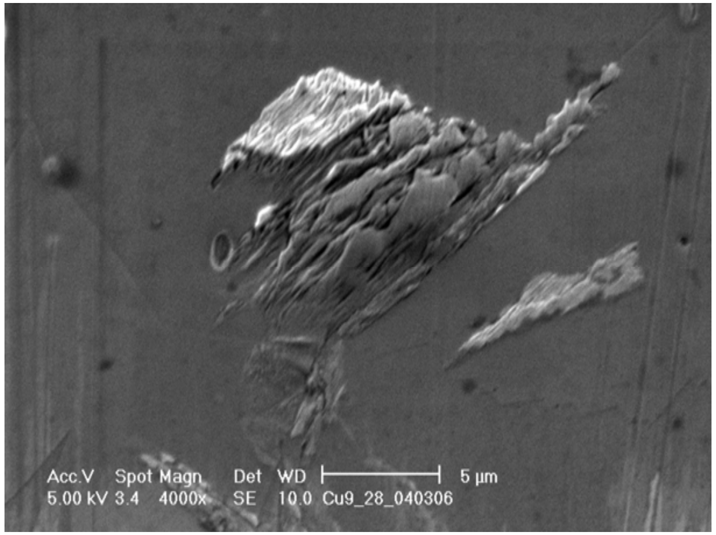


N = 1,0x10^{8}

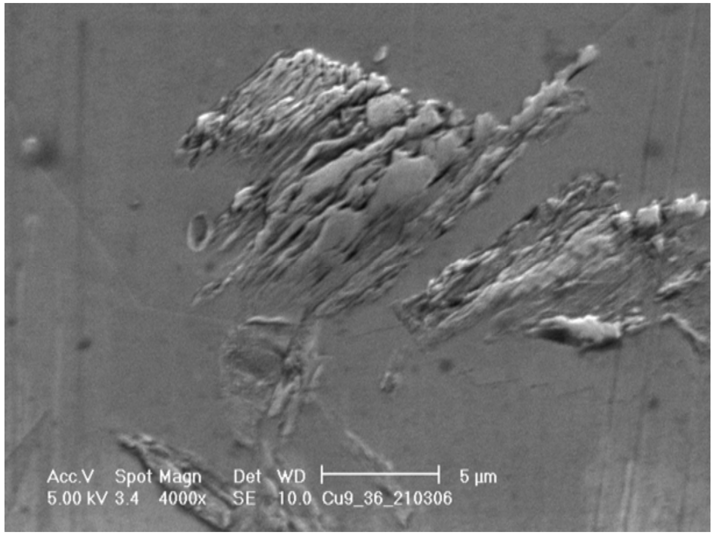
$\Delta\sigma =$ **59,2 MPa**

~ 3.0 MPa below PSB threshold

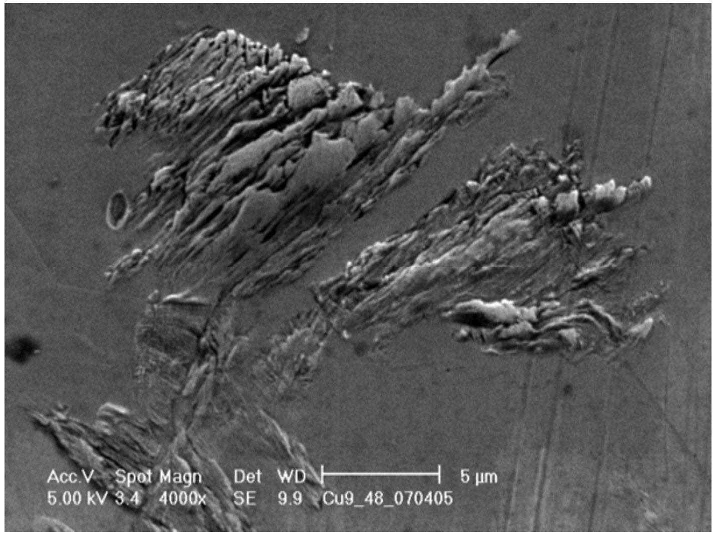
Structure and Development of PSBs (SEM)



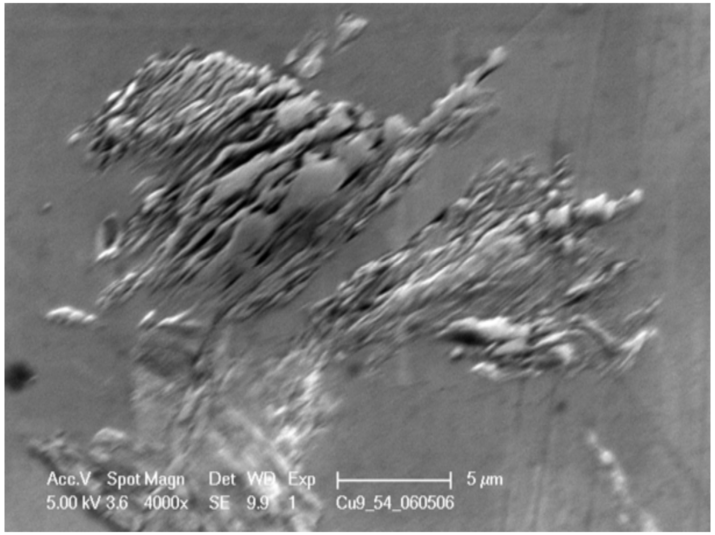
N = 3,3x10^{8}



N = 5,0x10^{8}



N = 1,0x10^{9}

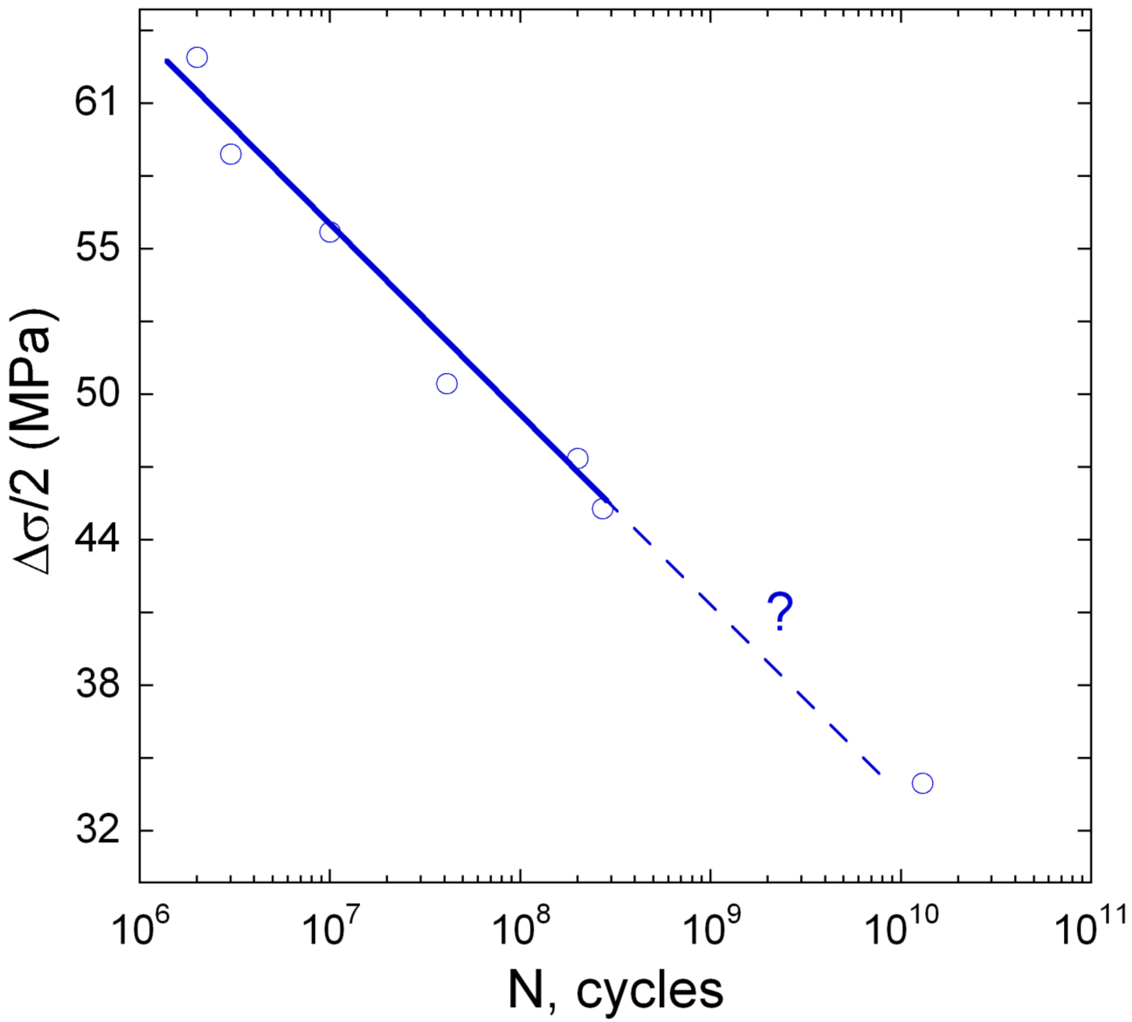


N = 2,0x10^{9}

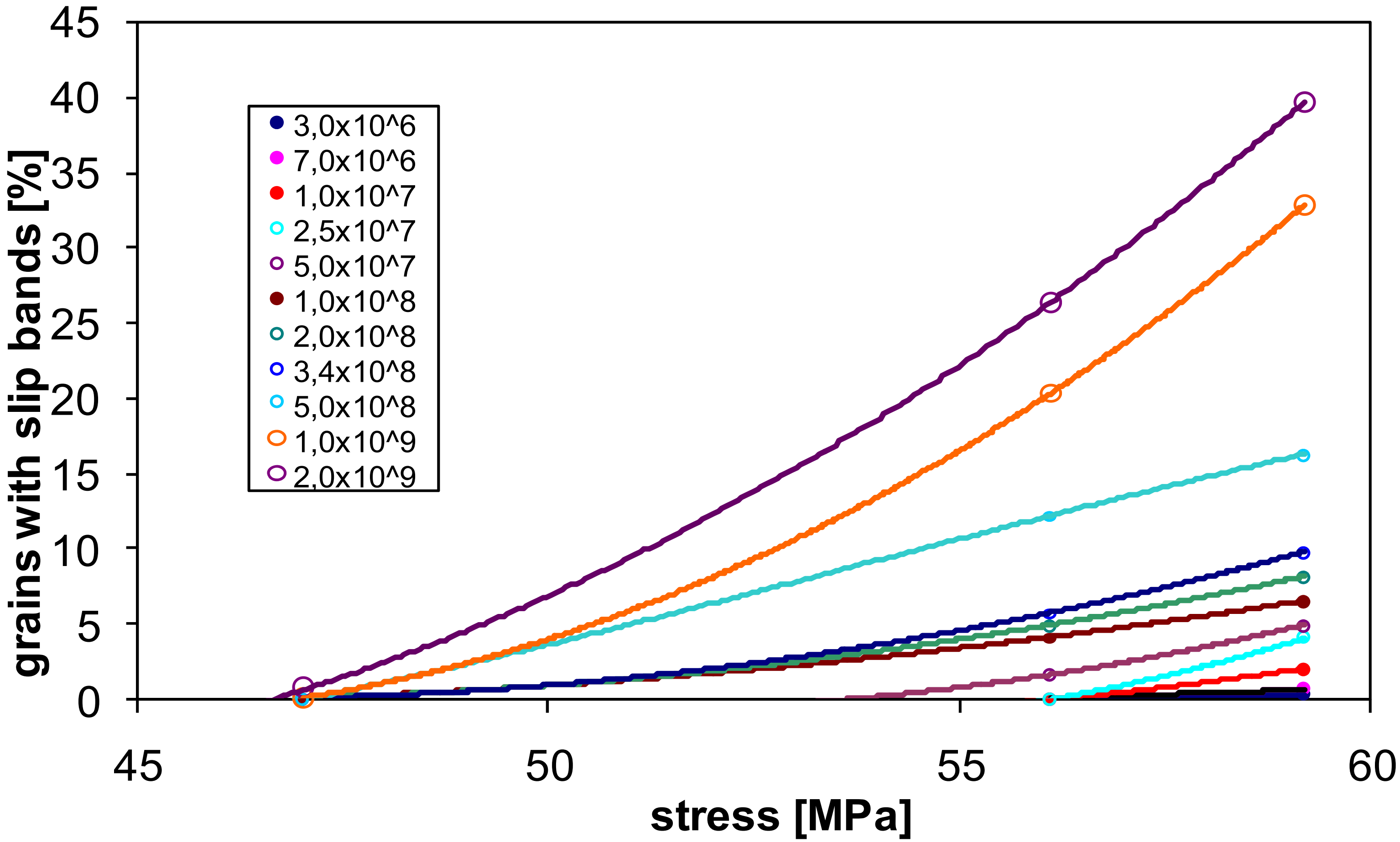
$\Delta\sigma =$ **59,2 MPa**

~ 3.0 MPa below PSB threshold

Slip Band Formation at and below PSB Threshold: Appearance of first (P)SB



Increasing Number of PSBs with Δσ/2 and N



GRUPPO ITALIANO FRATTURA (IGF)

Torino
5 novembre 2008

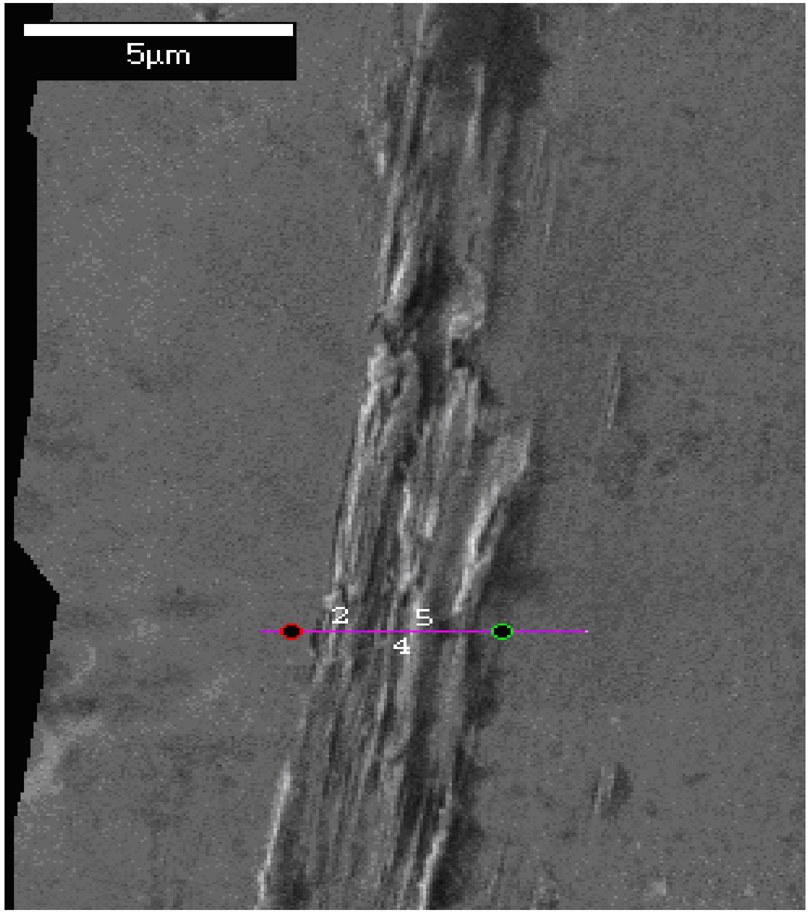
Stefanie Stanzl-Tschegg

PSB Structure and Surface Roughness

Measurement: **SEM and MeX – 3D** profile analysis software

$\Delta\sigma/2 = 62.1$ MPa

N = $5x10^7$ cycles



$\Delta\sigma/2 = 62.1$ MPa

N = $5x10^8$ cycles

PSB Structure and Surface Roughness

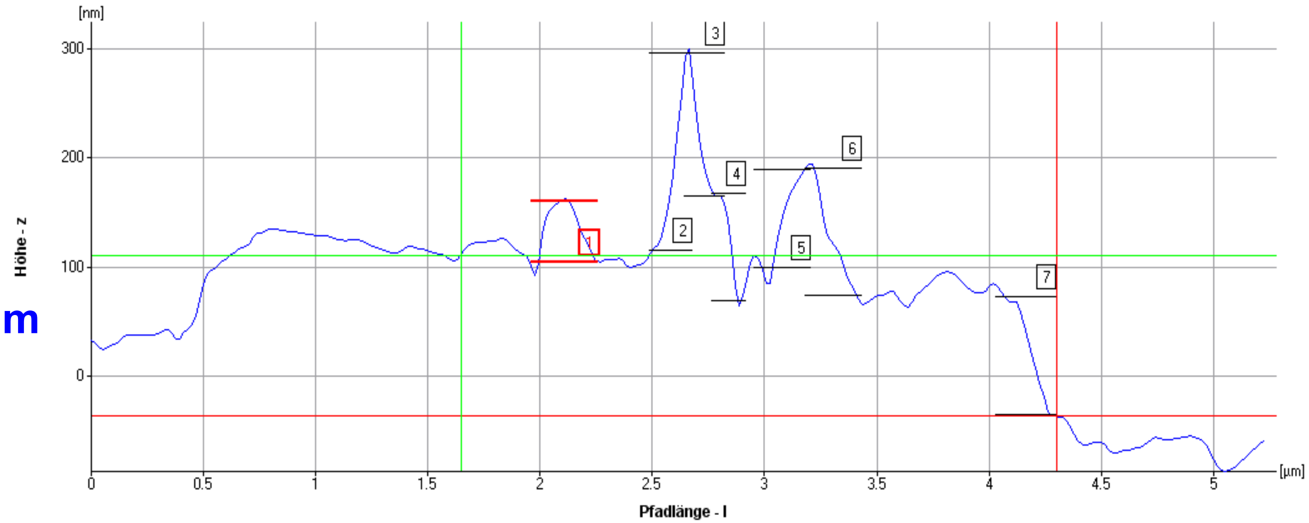
Measurement: **SEM and MeX – 3D** profile analysis software

$\Delta\sigma/2 = 62.1$ MPa

N = **5x10⁷** cycles

mean height = **111,83 nm**

RMS =117,49 nm

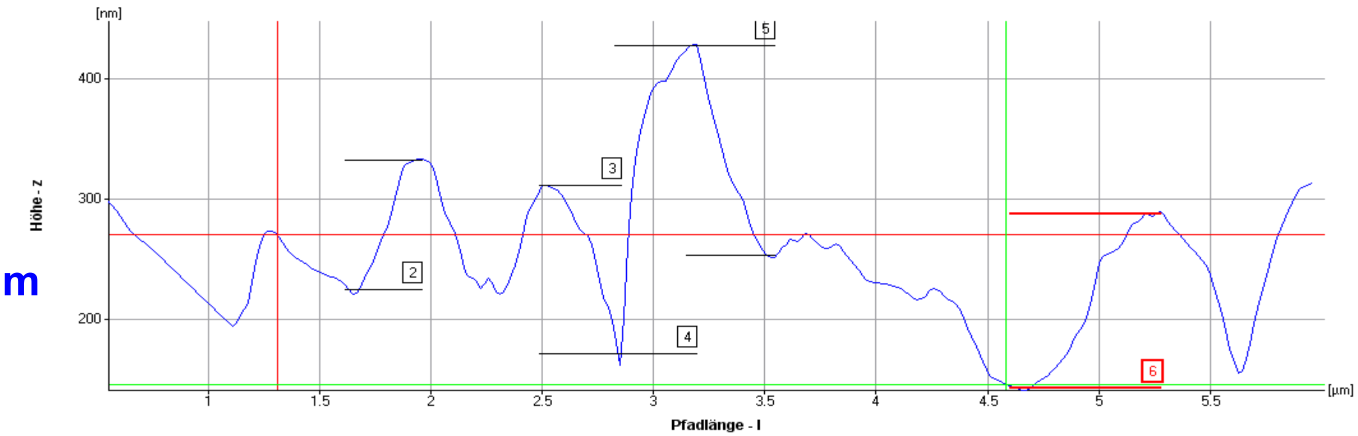


$\Delta\sigma/2 = 62.1$ MPa

N = **5x10⁸** cycles

mean height = **164,8 nm**

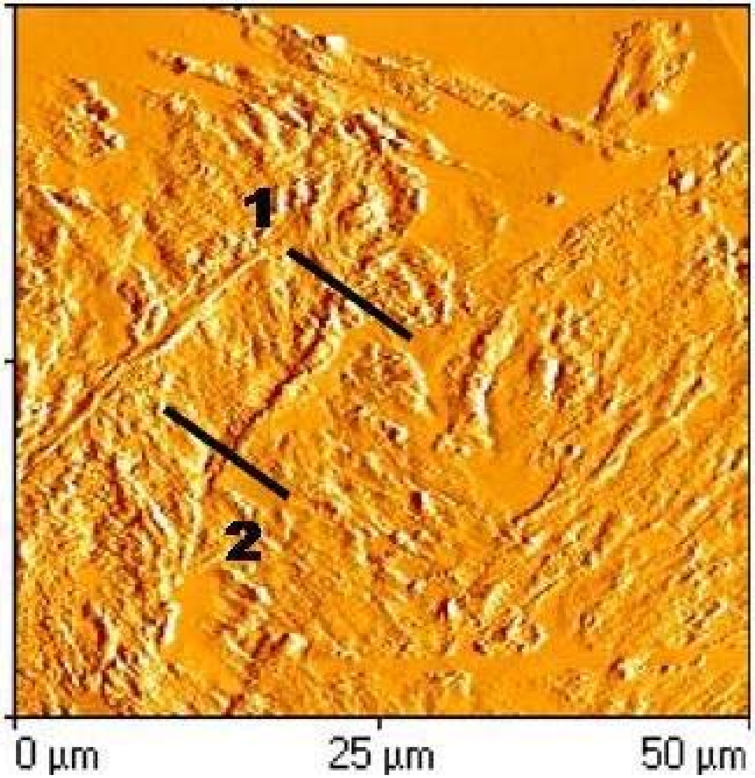
RMS =172,38 nm

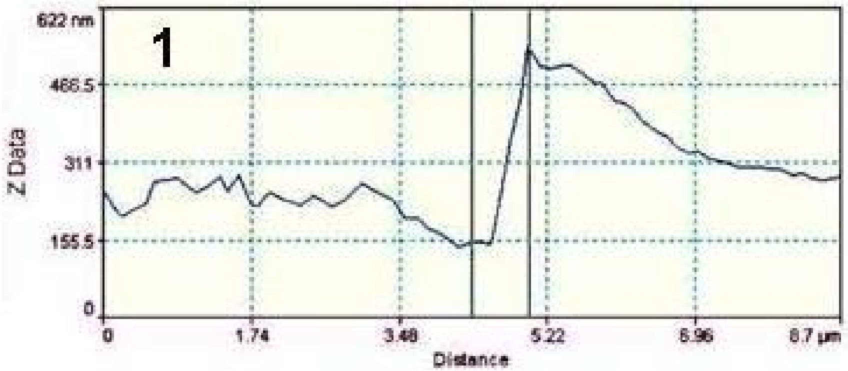


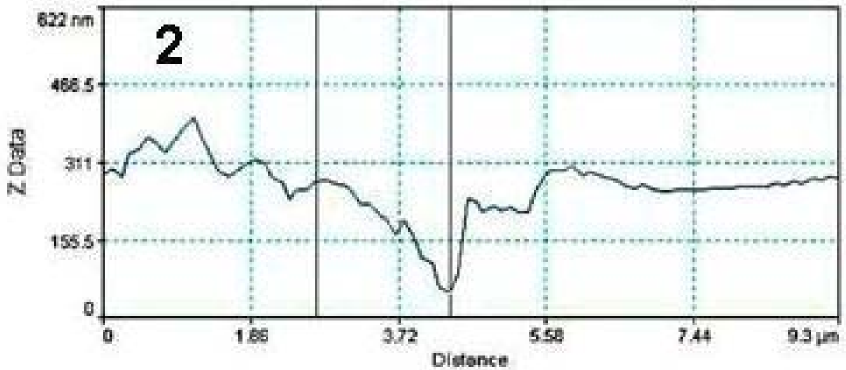
Measurement of Surface Roughness

AFM Topometric Explorer

in contact mode, set point 10 nA, Si_3N_4 pyramid tip, 50° angle, 50 nm radius





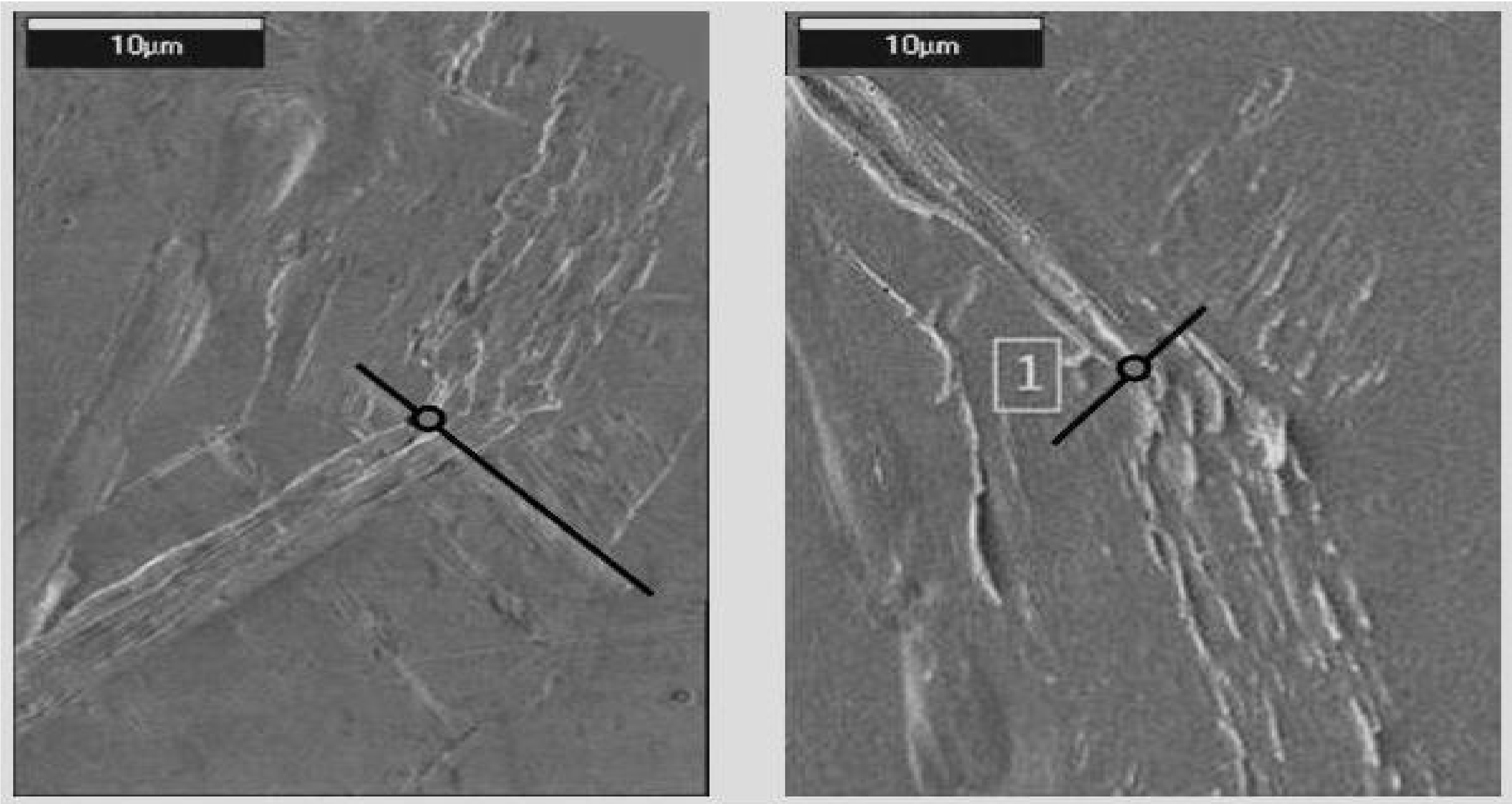


$\Delta\sigma/2$ = 53 MPa, N = 1,28x10^9 cycles

h_{max} ~ 400 nm, h_{min} ~ 230 nm

PSB Structure and Surface Roughness

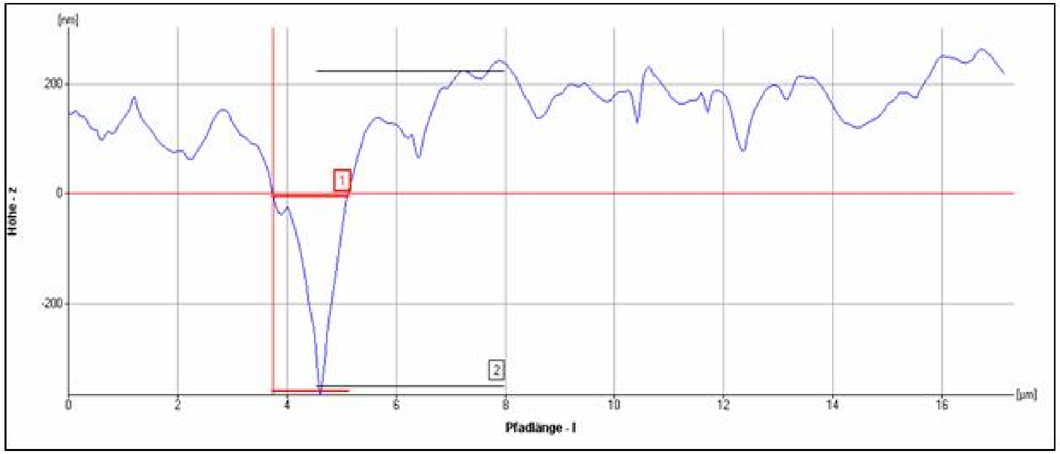
Plastic replica and SEM



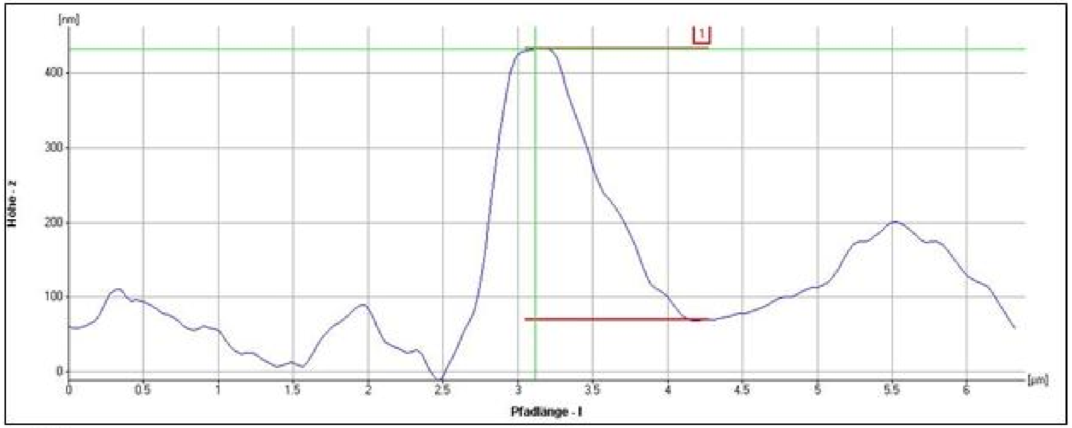
$\Delta\sigma/2$ = 100 MPa, N = 1 x 10^7 cycles

Surface Roughness

MeX – 3D profile analysis software



(a)



(b)

$\Delta\sigma/2$ = 100 MPa

N = $1x10^7$

Direct SEM:

Intrusion depth:

353 nm

Replica:

Intrusion depth:

362 nm

Summary: Surface Roughness

Increase of surface roughness with $\Delta\sigma/2$ and N

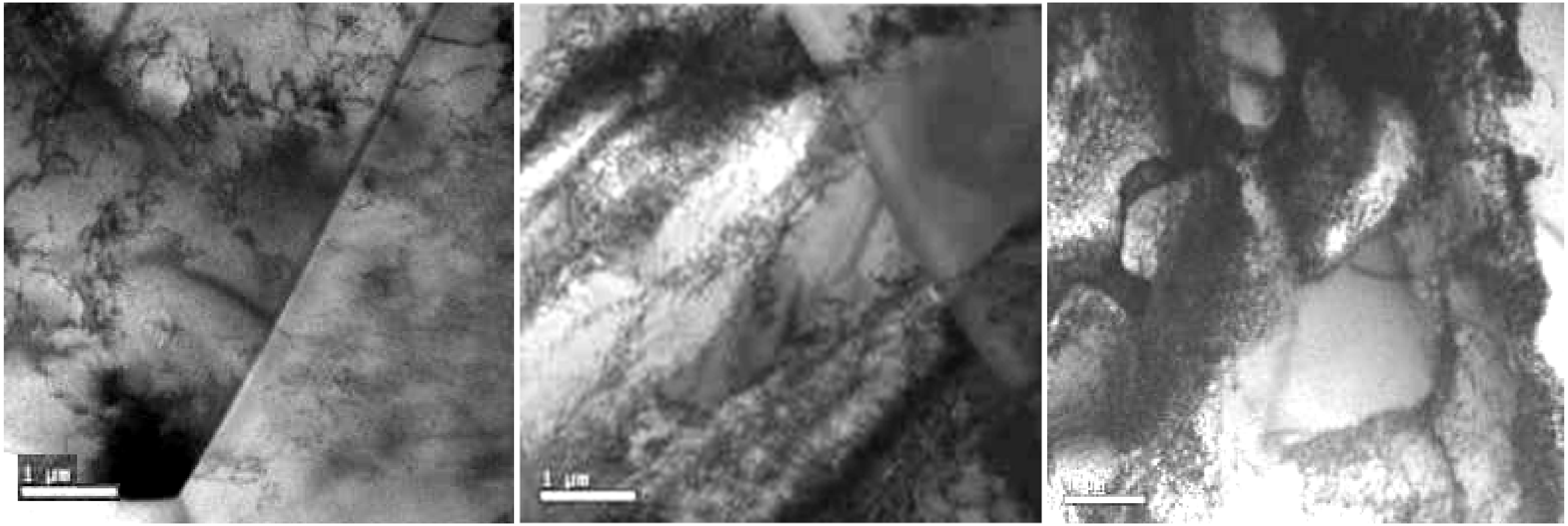
	Roughness		
$\Delta\sigma/2$	Mean	Min.	Max.
34 MPa	~ 20 nm	~ 14 nm	~ 30 nm
↓	↓	↓	↓
60 MPa	~ 200 nm	~ 80 nm	~ 350 nm
↓	↓	↓	↓
100 MPa	~ 400 nm	~200 nm	~1000nm

E.g. Surface roughness ~ 200 nm for $\Delta\sigma/2$ ~ 60MPa, N ~ 10^{10} (mean of three measuring techniques) - high local variation.

Dislocation structure (TEM)

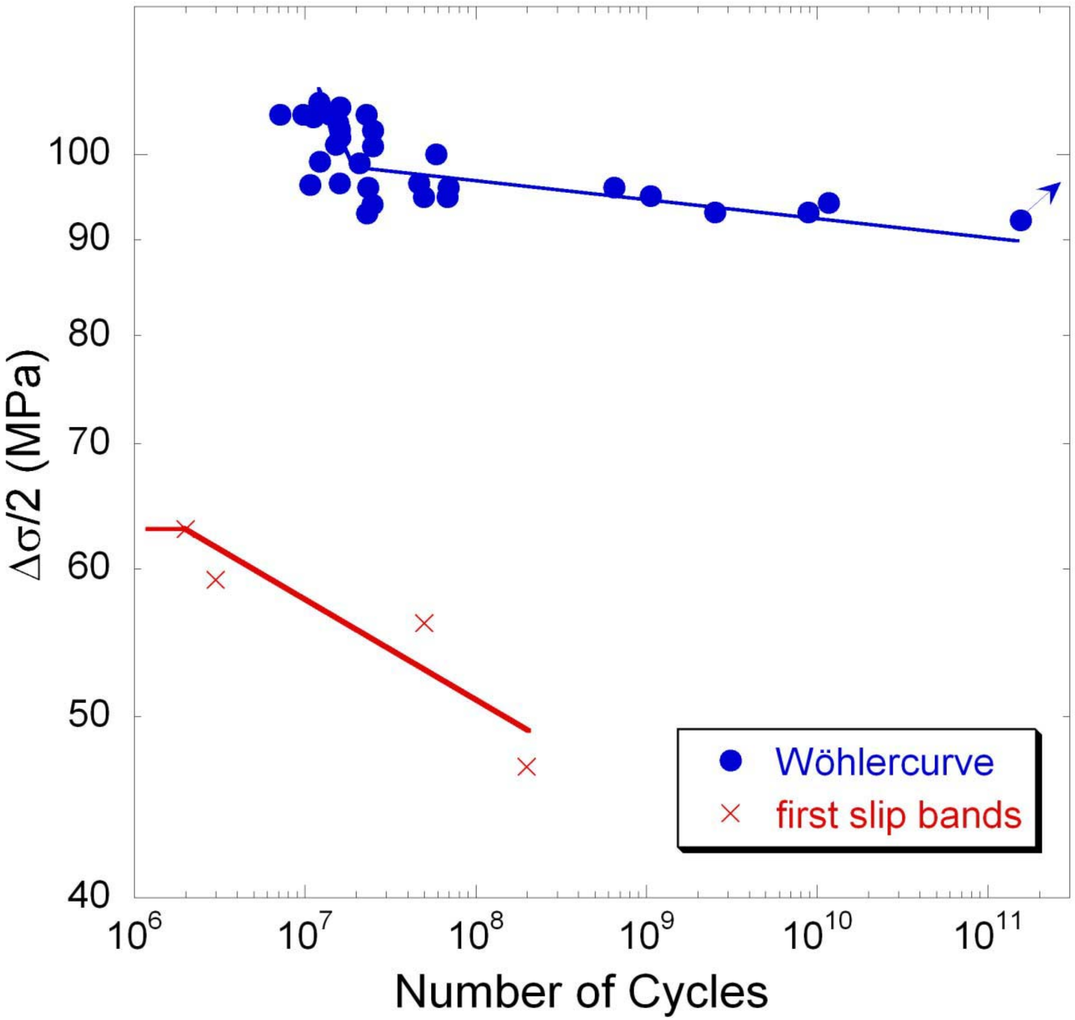
$\Delta\sigma/2 \approx$ **64 MPa** **(~ 1 MPa above PSB Threshold (≤ 63 MPa))**

1,5x10^{10} cycles



Dislocations clusters and cells

Fatigue life diagram, 19 kHz: Wöhler (S-N) plot



Failure:

$\Delta\sigma/2$ ~ 93-97 MPa

N_f ~ $3x10^7$-**$1.1x10^{10}$**

No failure:

$\Delta\sigma/2 \leq$ 92.2 MPa

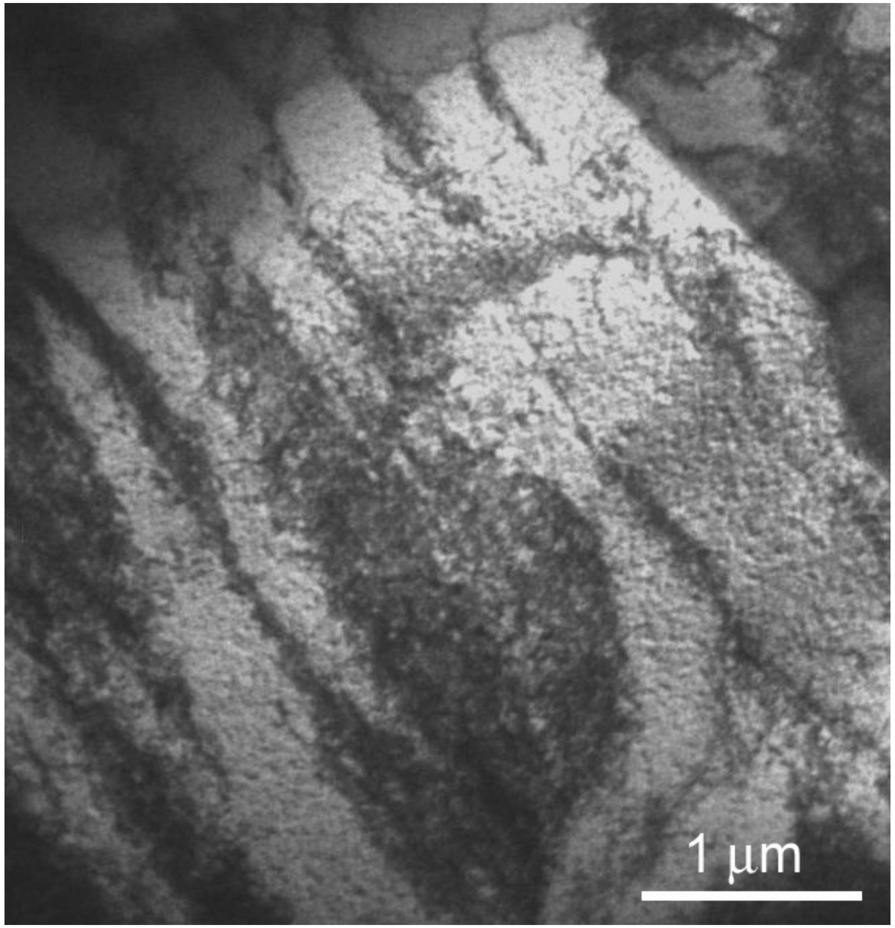
until N = **1.7×10^{11}** cycles

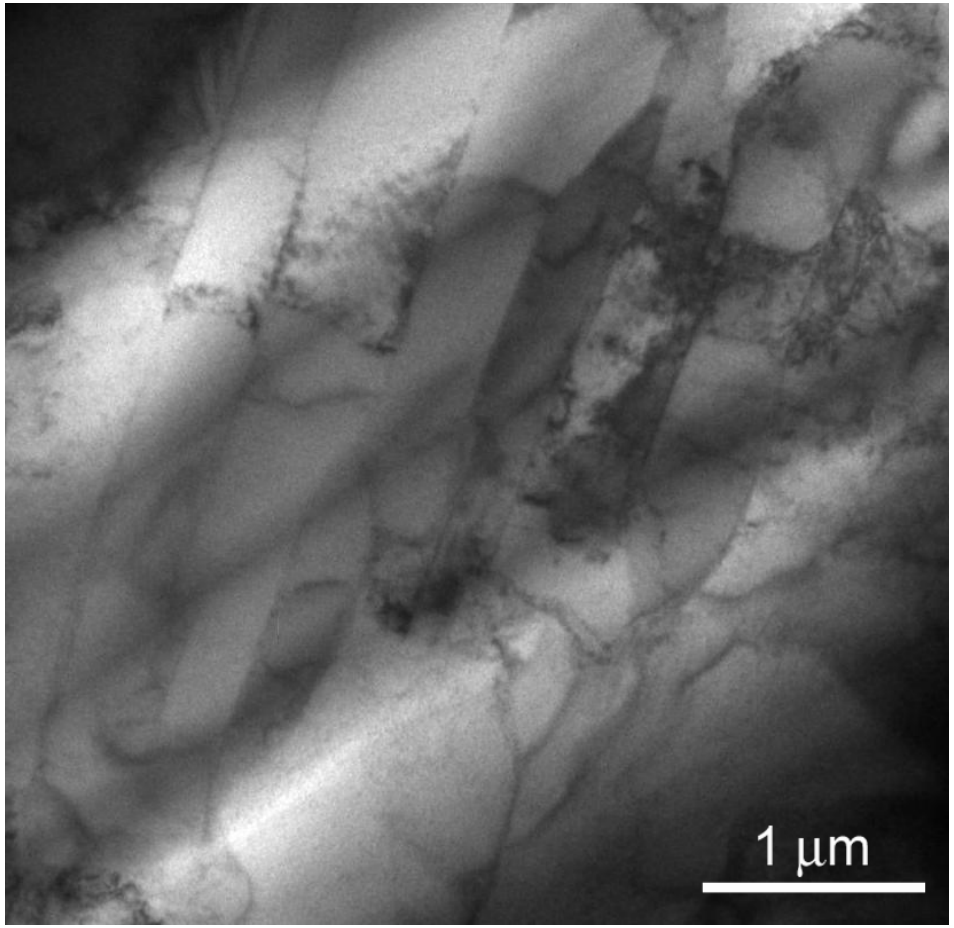
„VHCF“ PSBs:

$\Delta\sigma/2$: ~ **45** – 61.7 MPa

N ~ 10^6 - **$2x10^8$** cycles

Dislocation structure (TEM) close to endurance limit





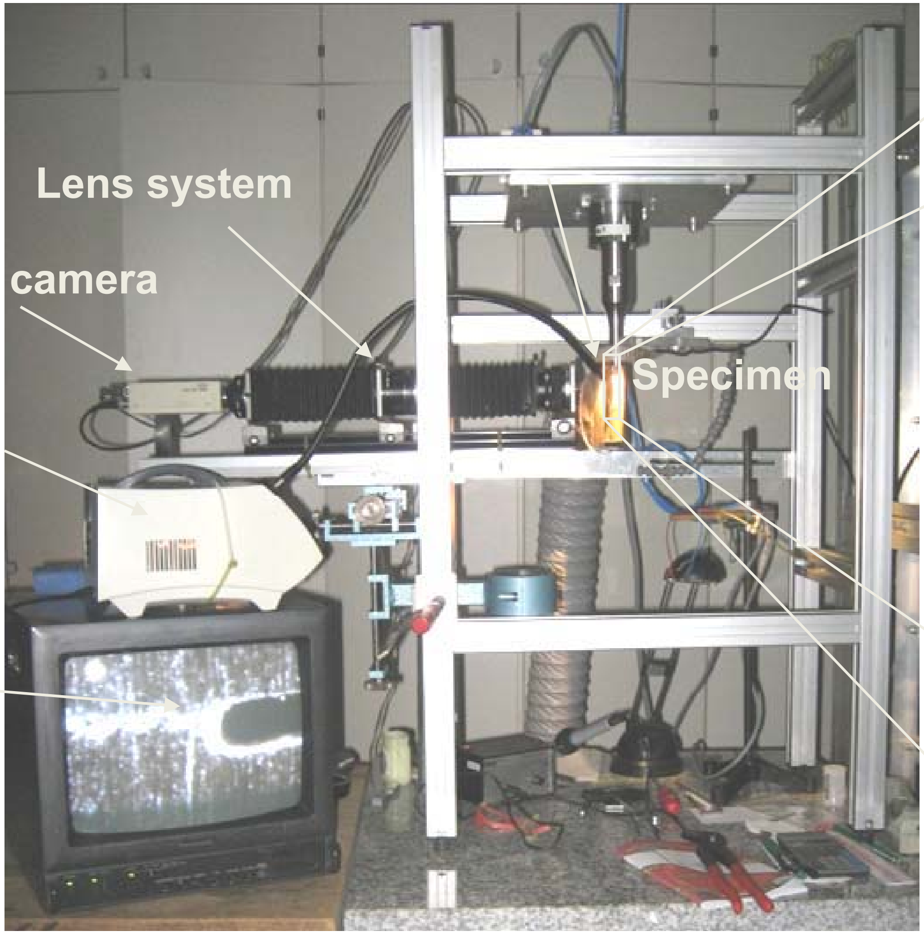
$\Delta\sigma/2 \approx 94$ MPa, N = $1{,}2\text{x}10^{10}$ **~ 1 MPa above fatigue limit (≤ 93 MPa)**

PSB Threshold ("conventional" as well as "VHCF") and Endurance Limit are Different

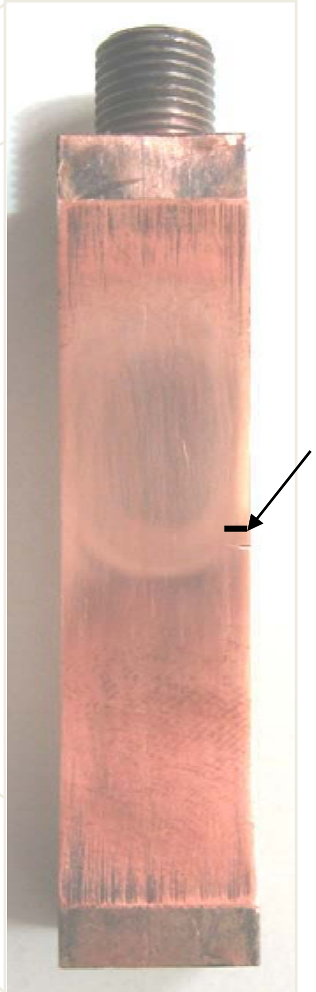
	„Conventional" PSB Threshold ($N \sim 10^6$)	„VHCF" PSB Threshold ($N \sim 2.6x10^8$)	„Endurance Limit" ($N_f = 1.14x\ 10^{10}$)
$\Delta\varepsilon_{tot}/2$	4.88×10^{-4}	3.49×10^{-4}	7.27×10^{-4}
$\Delta\varepsilon_{pl}/2$	6.1×10^{-6}	3.6×10^{-6}	2.1×10^{-5}
$\Delta\sigma/2$	63 MPa	45 MPa	93 MPa

How does ΔK_{th} correlate with $\Delta\sigma_o$?
→ Fracture Mechanical Measurements

Measurement of Crack Propagation



Measurement set-up

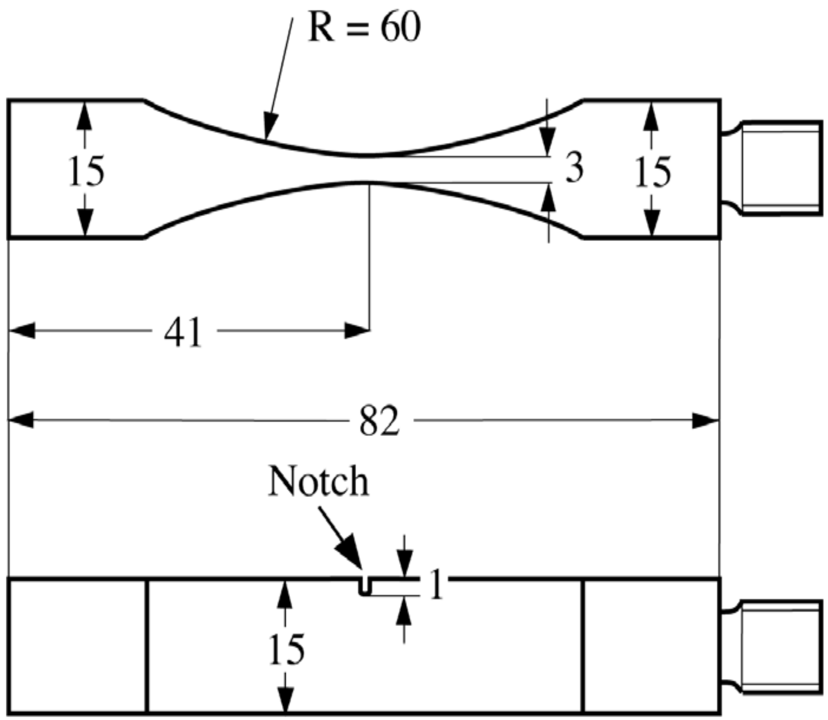


SEN specimen

Ultrasound Fracture Mechanics

Crack propagation and cyclic stress intensities

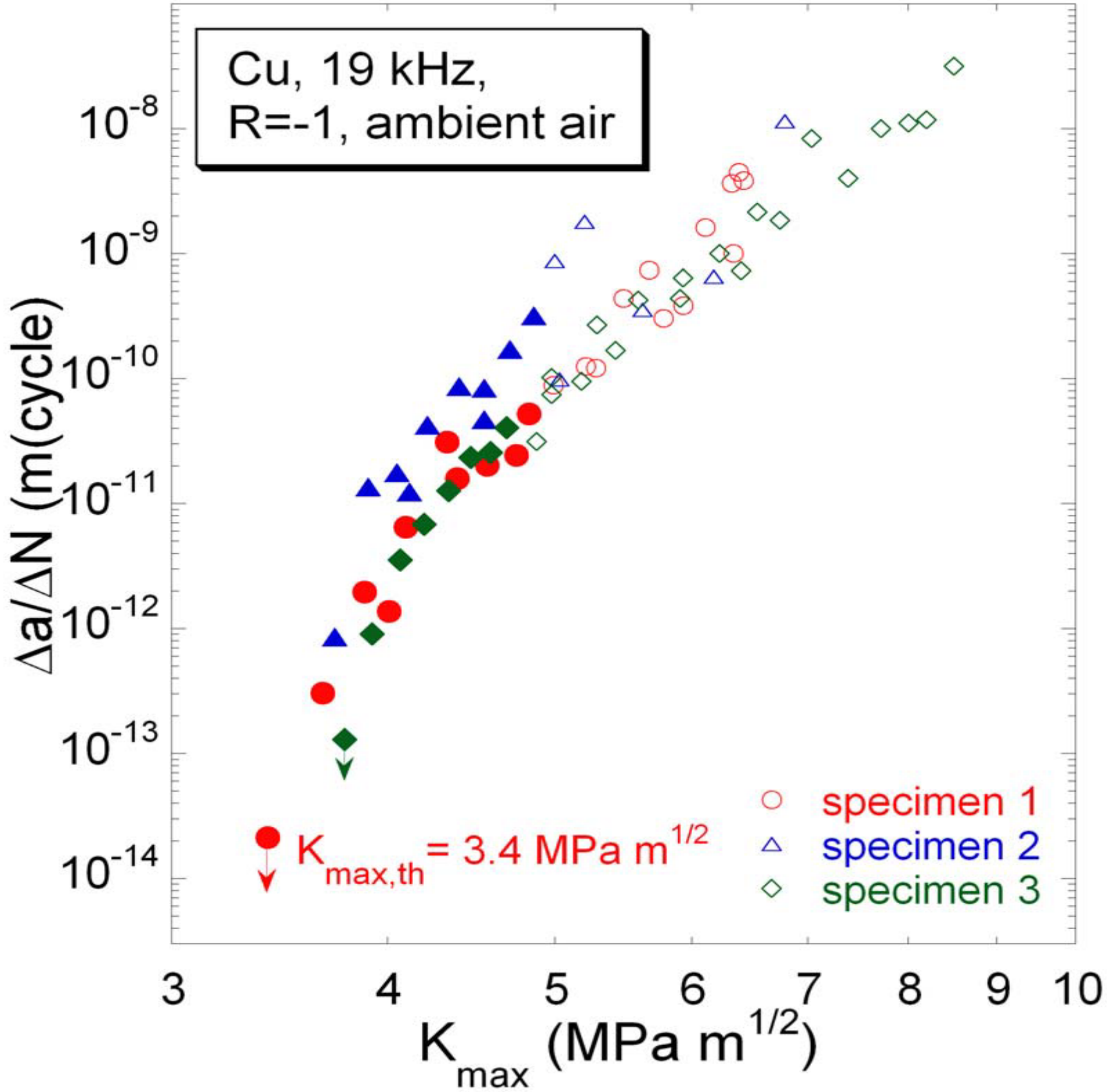
Notched specimens



$$K_{max} = \varepsilon_{max} \cdot E \cdot \sqrt{\pi a} \cdot Y\left(\frac{a}{W}\right)$$

$$Y = 1.12 - 0.04 \cdot \left(\frac{a}{W}\right) + 0.53 \cdot \left(\frac{a}{W}\right)^2 + 7.8 \cdot \left(\frac{a}{W}\right)^3 - 24.0 \cdot \left(\frac{a}{W}\right)^4$$

Δa/ΔN vs. ΔK/2 (= K_{max}) Curve



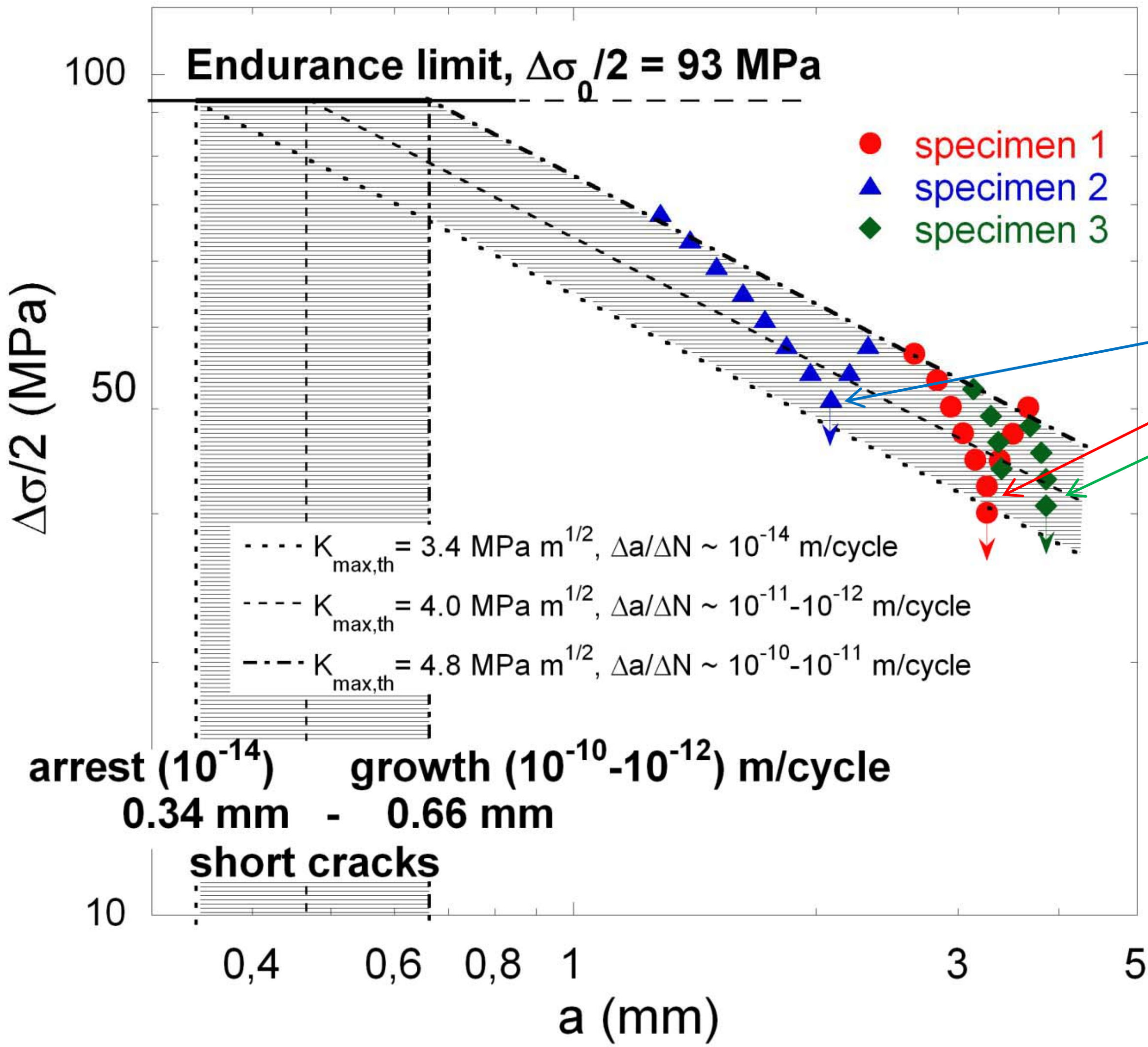
Long crack threshold

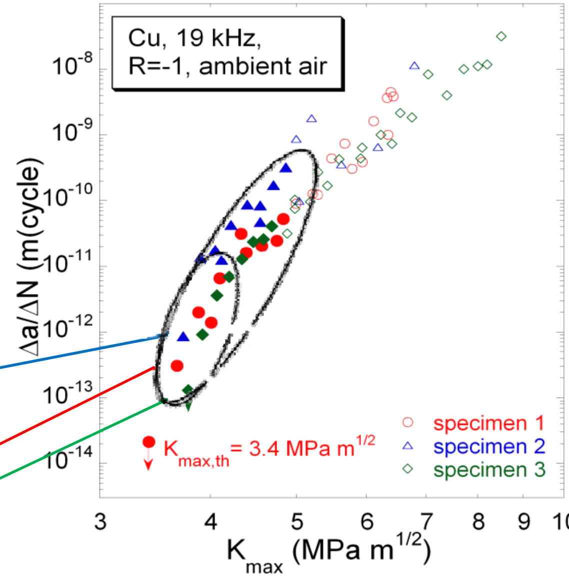
$K_{max,th}$ =

3.4 - 4.8 MPa m ½

for Δa/ΔN = **10^{-14}** – 10^{-10} m/cycle

Comparison ΔK_0 - $\Delta\sigma_0/2$ (Kitagawa Diagram)

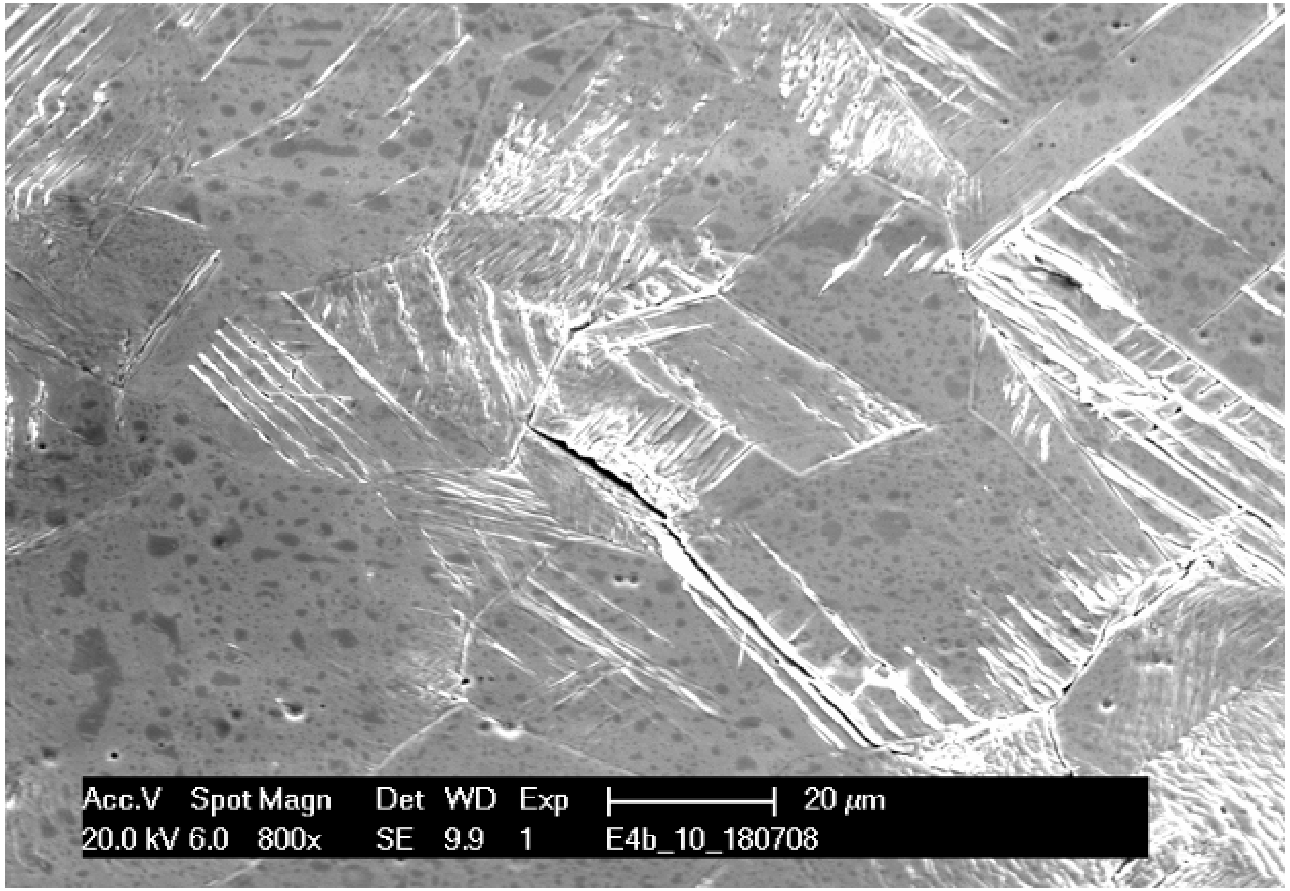




Short-crack length = **0.34 mm**
for $K_{max,th}$ = 3.4 MPa $m^{1/2}$

Longer short-crack lengths
(up to ~0.66 mm)
for higher $K_{max,th}$ values

Reasons for difference of PSB Threshold and Endurance Limit?



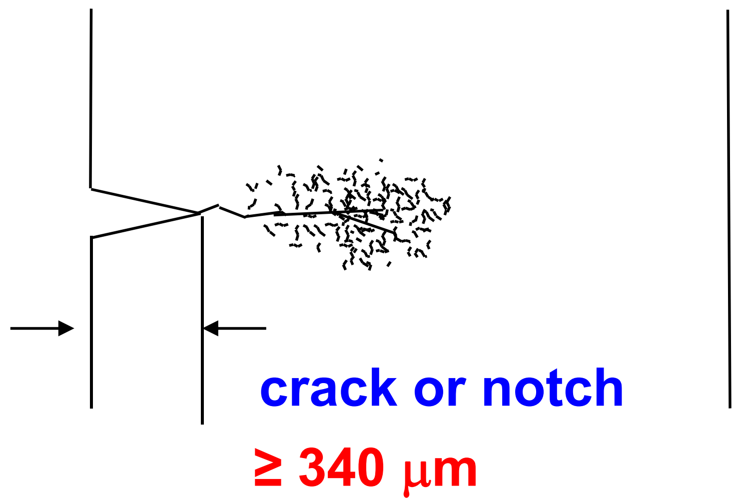
Numerous small cracks, but *no long crack* below endurance limit ($\Delta\sigma/2$ ~ 87 MPa)

Formation of LONG cracks above endurance limit, but only SMALL cracks below endurance limit

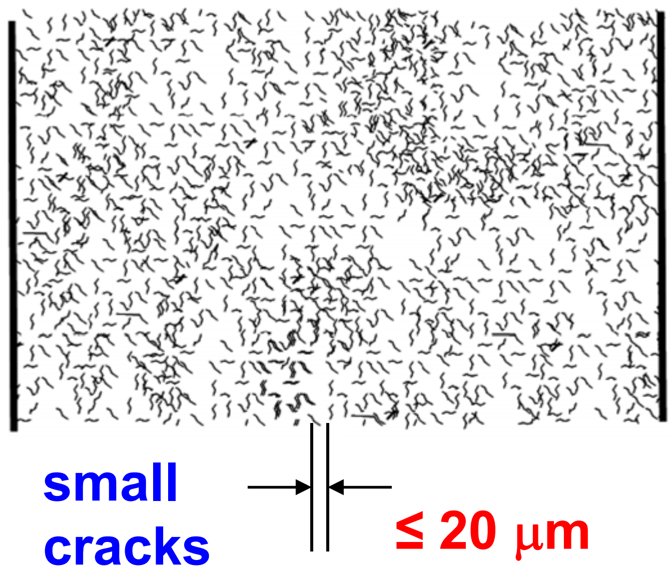
Formation of long propagating cracks (VHCF, 19 kHz)

- at $\Delta\sigma$ and $\Delta\varepsilon_{pl}$ values ~ 50% above "conventional" PSB threshold
- necessary "short" crack (or notch) length (from Kitagawa diagram) ≥ 340 μm
- at "conv." PSB threshold crack length actually only ≤ 20μm

$\Delta\sigma \geq 93$ MPa:



$\Delta\sigma \leq 63$ MPa



Evolution of Damage (VHCF, 19 kHz)

slip bands → **PSBs intrusions** → **Intrusions → more and deeper**

Below endurance limit, above PSB threshold:

numerous non-propagating small cracks
→ stress relaxation of loaded volume

Above endurance limit, $\Delta\sigma$ or ΔK high enough for

long propagating crack → **failure**

Summary

- **Ultrasonic fatigue technique** most efficient for VHCF testing.
- **S-N curves** beyond 10^8 up to several $\mathbf{10^{11}}$ cycles → question on existence or non-existence of **fatigue limit** may be answered („fish-eye“ fractures…).
- Analogous: (Δ**a/ΔN vs. ΔK) curves** down to $\mathbf{10^{-14}}$ **m/cycle** → (non)-existence of $\Delta K_{threshold}$
- **No frequency effect** for most technical alloys.
- **Frequency influence** for very ductile materials and in corrosive environment ABOVE $\Delta K_{threshold}$

Summary

- Tests on **polycrystalline copper**:

- PSBs form below „conventional“ PSB threshold (63 MPa)
PSB formation depends on amplitude AND number of cycles („VHCF threshold“: 45 MPa)

- **Endurance limit** ($\Delta\sigma_0$): Failure at $\Delta\sigma$ = 93 MPa after **1.1×10^{10} cycles**. No failure below $\Delta\sigma_0$ within 2×10^{11} cycles.

- **Correlation of ΔK_{th}, $\Delta\sigma_0$ and relevance of PSB threshold**
Kitagawa diagram →
Critical short-crack length is ~340 μm for ΔK_{th}
At/below PSB threshold: actual crack length ~ 20μm →
No long crack propagation → **no failure**

Thanks for your attention!