Microstructural Mechanisms of Fatigue Damage in the UHCF Regime:

Current Status, Mechanisms and Open Questions

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Friedrich-Alexander-Universität Erlangen-Nürnberg

Founded in 1743

The Castle: Central Administration

School of Engineering,
Founded in 1966

METAL FATIGUE

FATIGUE OF MATERIALS:

Evolution of damage (initiation and propagation of cracks) and, ultimately, failure resulting from periodic loadings (alternating tension and compression).

→ **Fatigue failure after N_{f} cycles**

Fatigue Failures at Very Large Numbers of Cycles

High-speed train accident, Eschede, 1999

Other examples:

- Transport engineering
- Roller bearings
- Components with high frequency vibrations, e.g. in turbine engineering

UltraHigh-Cycle Fatigue (UHCF, VHCF)

High Cycle Fatigue (HCF):

typically $N_f \leq 10^6 - 10^7$ cycles to failure

UltraHigh-Cycle Fatigue (UHCF) or Very High Cycle Fatigue (VHCF):

typically: $\mathbf{N_f \geq 10^8 - 10^9}$ cycles to failure

VHCF Conference Series since 1998

- GIGACYCLE FATIGUE
- ULTRAHIGH CYCLE FATIGUE (UHCF)
- VERY HIGH CYCLE FATIGUE (VHCF)

CONFERENCE SERIES:

- Fatigue Life in Gigacycle Regime, Paris, 1998 (VHCF-1)
- Fatigue in the Very High Cycle Regime , Vienna, 2001 (VHCF-2)
- Third International Conference on Very High Cycle Fatigue, Ritsumeikan University, 2004 (VHCF-3)
- Fourth International Conference on Very High Cycle Fatigue, (VHCF-4), University of Michigan, Ann Arbor, August 2007.

Is there a Finite Fatigue Limit?

Euromech 382
Fatigue Life in Gigacycle Regime
Paris, June 29 – July 1, 1998
Co-Chairs: *Claude Bathias*
Stefanie Stanzl-Tschegg

V HCF-1

Blackwell Science Ltd. *Fatigue Fract Engng Mater Struct* **22**, 559–565 ,1999

There is no infinite fatigue life in metallic materials

C. BATHIAS
Laboratoire de mécanique de la rupture, CNAM/ITMA, 2 rue Conté, 75003 Paris, France

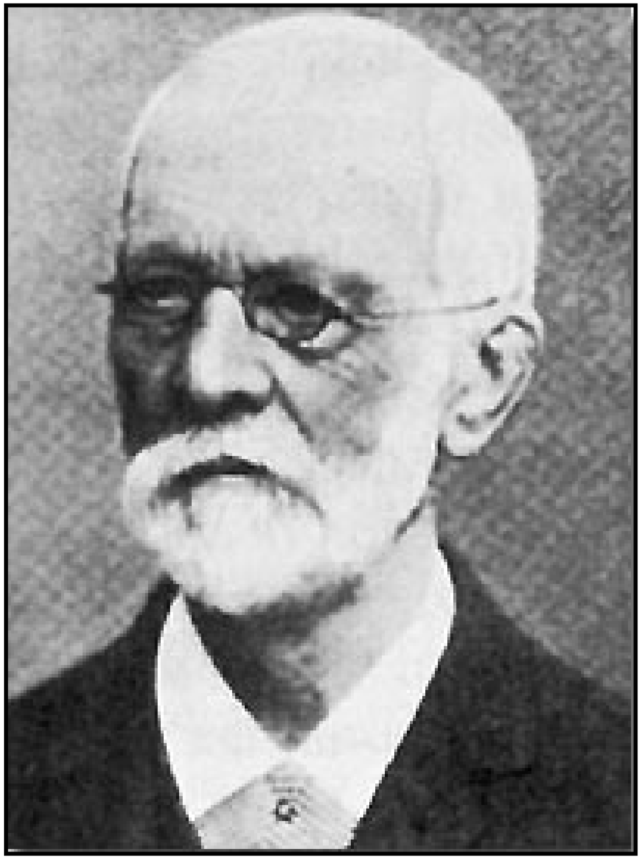
Contents

- The Wöhler (S-N) fatigue life diagram
- The cyclic stress-strain (css) curve
- Conversion of Wöhler plots into Coffin-Manson plots
- via the css-curve and vice versa

- UHCF of „type II“ materials such as high-strength steels containing inclusions, subsurface „fish-eye“ fractures.
- UHCF of ductile, single-phase „type I“ materials (e.g. copper)
- „Multistage“ fatigue life diagrams of type I and type II materials
- Microstructural fatigue damage mechanisms ?

August Wöhler (1819-1914)

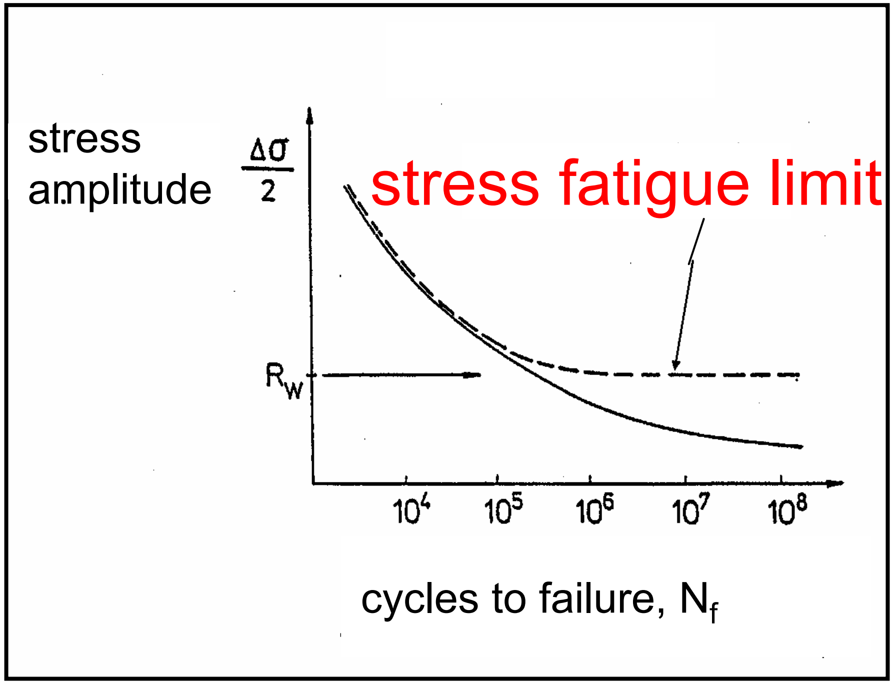
- 1841 – 1843: August Borsig, Berlin
- 1869 – 1874: Director, Norddeutsche AG für Eisenbahnbedarf, Berlin
- 1870 : Continuation of Wöhler's work at Berliner Gewerbeakademie, (later: Preussische Königliche Mechanisch-Technische Versuchsanstalt, Berlin), a predecessor of Bundesanstalt für Materialprüfung, Berlin

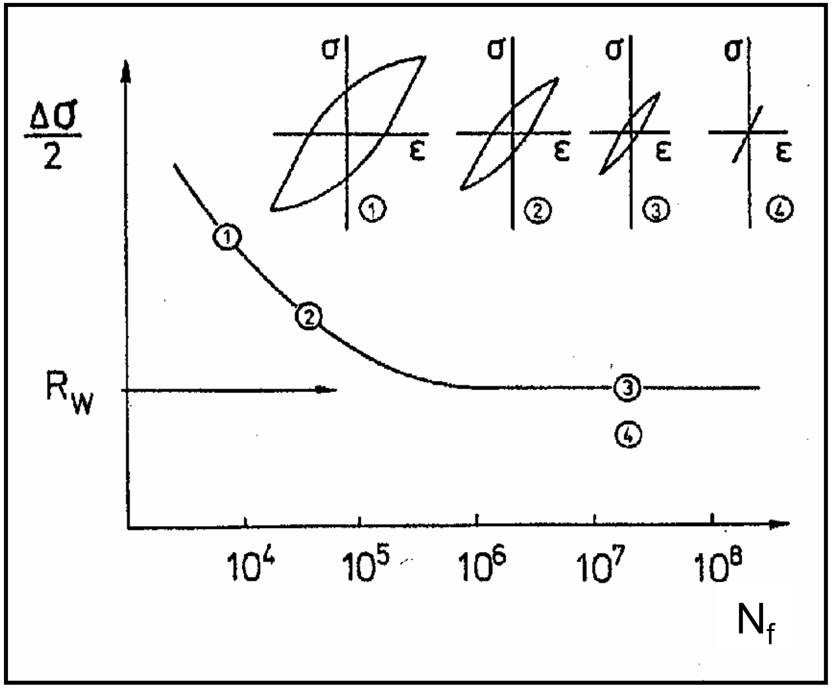


Wöhler (S-N) Plot, Stress Fatigue Limit, Stress and Strain

Fatigue Life Diagram

Stress and Strain





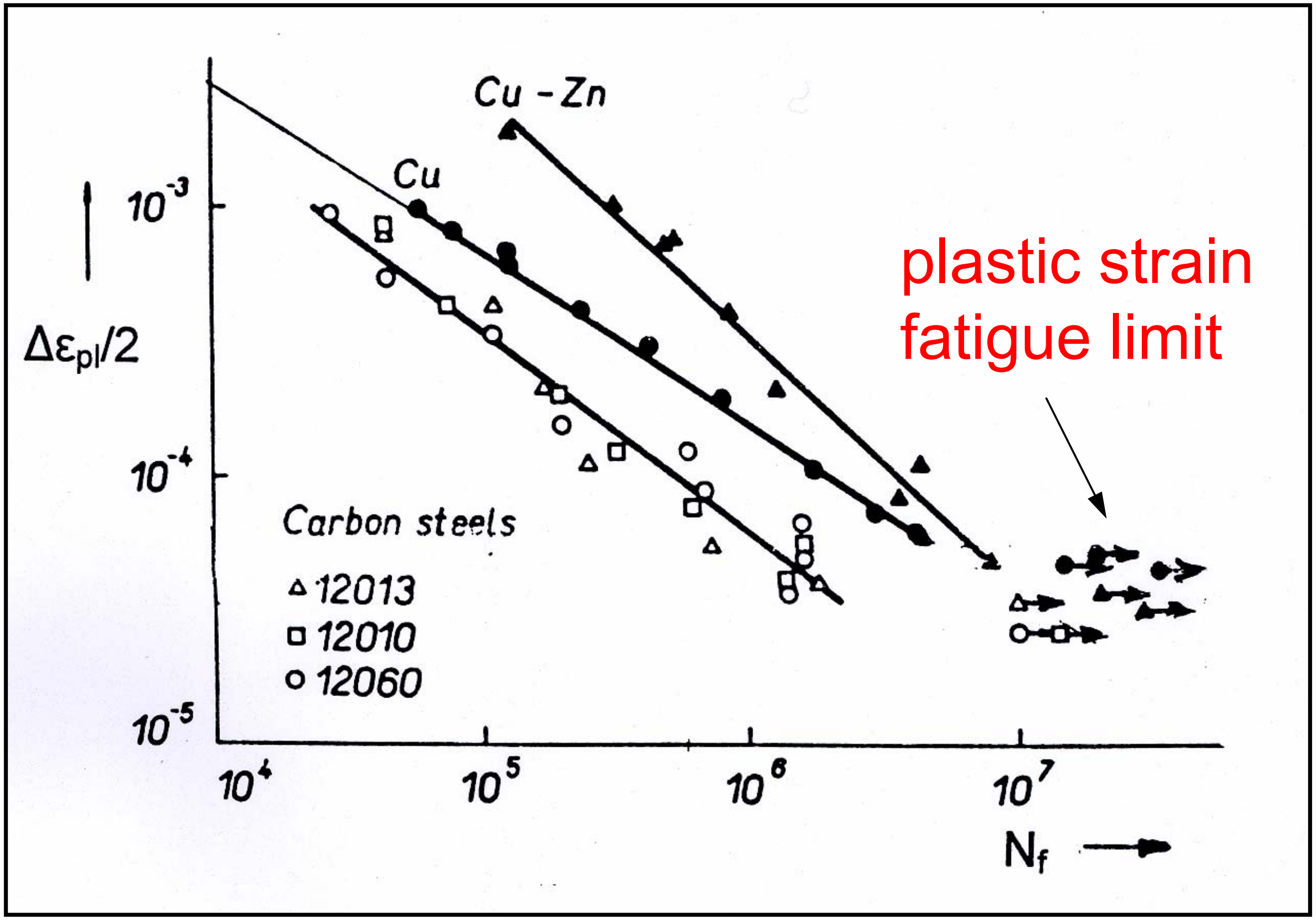
The Fatigue Tests of August Wöhler

Example of a test series of August Wöhler, 1866

83 v. Bannwarth, Herstellung des Freimauerwerks am Gerichtsgebäude in Hagen. 84

No. des Versuchs.	Querschnitt des Stabes	Gröfste	Kleinste	Länge des Stabes zwischen den Stützpunkten	Durch die Anspannung veranlafste bleibende Biegung	Zahl der Biegungen bis zum Bruch	Bemerkungen
		Faserspannung in der Mitte des Stabes					
		Ctr.		Zoll			
Tabelle II. Gufs-Federstahl von Krupp 1864 geliefert. Ungehärtet.							
1	Querschnitt wie in Tab. I.	900	0	30	$\frac{5}{32}$	72000	
2	desgl.	900	200	-	$\frac{9}{32}$	81000	
3	desgl.	900	300	-	$\frac{7}{32}$	156000	
4	desgl.	900	400	-	$\frac{5}{16}$	225000	
5	desgl.	900	500	-	$\frac{1}{32}$	1238000	
6	desgl.	900	600	-	$\frac{1}{16}$	Nicht gebrochen, hat bis jetzt 1442000 Biegungen ertragen.	
7	desgl.	800	0	-	$\frac{1}{96}$	117000	
8	desgl.	800	100	-	$\frac{1}{24}$	99000	
9	desgl.	800	200	-	$\frac{1}{32}$	176000	
10	desgl.	800	300	-	$\frac{1}{32}$	619000	
11	desgl.	800	400	-	$\frac{1}{64}$	Nicht gebrochen, hat bis jetzt 1762000 Biegungen ertragen.	
12	desgl.	700	0	-	-	197000	
13	desgl.	700	100	-	-	286000	
14	desgl.	700	200	-	-	701000	
15	desgl.	700	250	-	-	Nicht gebrochen, hat bis jetzt 2522000 Biegungen ertragen.	
16	desgl.	700	300	-	-	899600	In Folge Ungleichmäfsigkeit im Material $2\frac{1}{4}$ Zoll aufser der Mitte gebrochen.

The Plastic Strain Fatigue Limit in the Coffin-Manson Plot



(P. Lukaš, M. Klesnil and J. Polák, 1973)

Mutual Transformation of Fatigue Life Curves via Cyclic Stress-Strain Curve

The Cyclic Stress-Strain Curve (CSSC)

relates the cyclic saturation stress σ_s, i.e. $\Delta\sigma_s/2$, to the plastic strain amplitude $\Delta\varepsilon_{pl}/2$:

$$\sigma_s = k\left(\frac{\Delta\varepsilon_{pl}}{2}\right)^{n'}$$

Example: copper,
k = 8237 MPa,
n' = 0.46

Hence, following Lukás, Klesnil and Polák (1974):

The Wöhler (S-N) curve $N_f = N_f(\Delta\sigma_s/2)$, and the Coffin-Manson curve $N_f = N_f(\Delta\varepsilon_{pl}/2)$ can be transformed mutually into each other.

Type I and Type II Materials

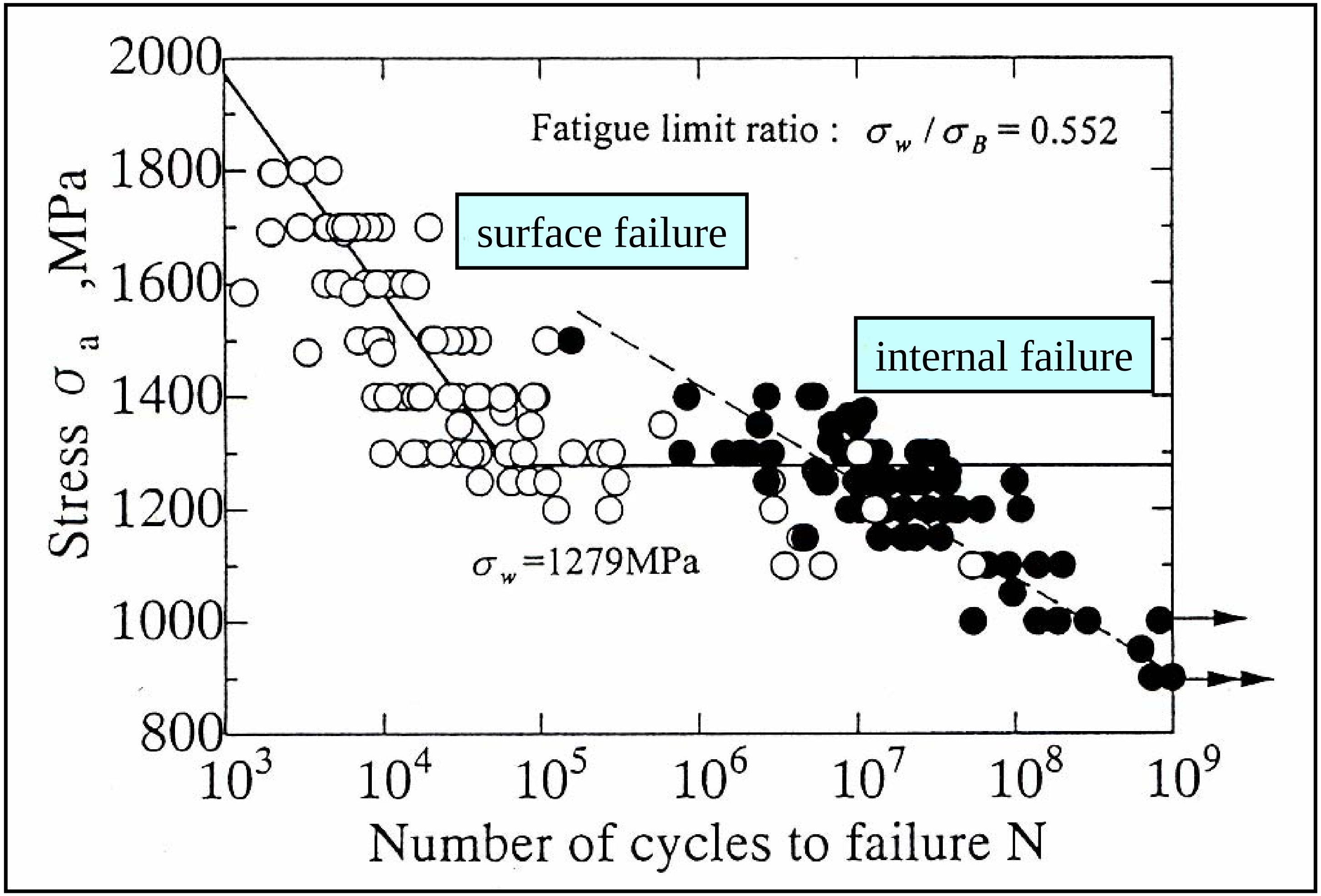
It is expedient to distinguish between

- **Type I materials (such as Cu, Ni, Al)**: ductile, single-phase, no heterogeneities such as inclusions, pores, etc.

and

- **Type II materials (such as HSLA-steel or cast materials)**: high-strength, containing heterogeneities such as inclusions and pores

Multistage Fatigue Life Diagram of High Carbon Chromium Steel

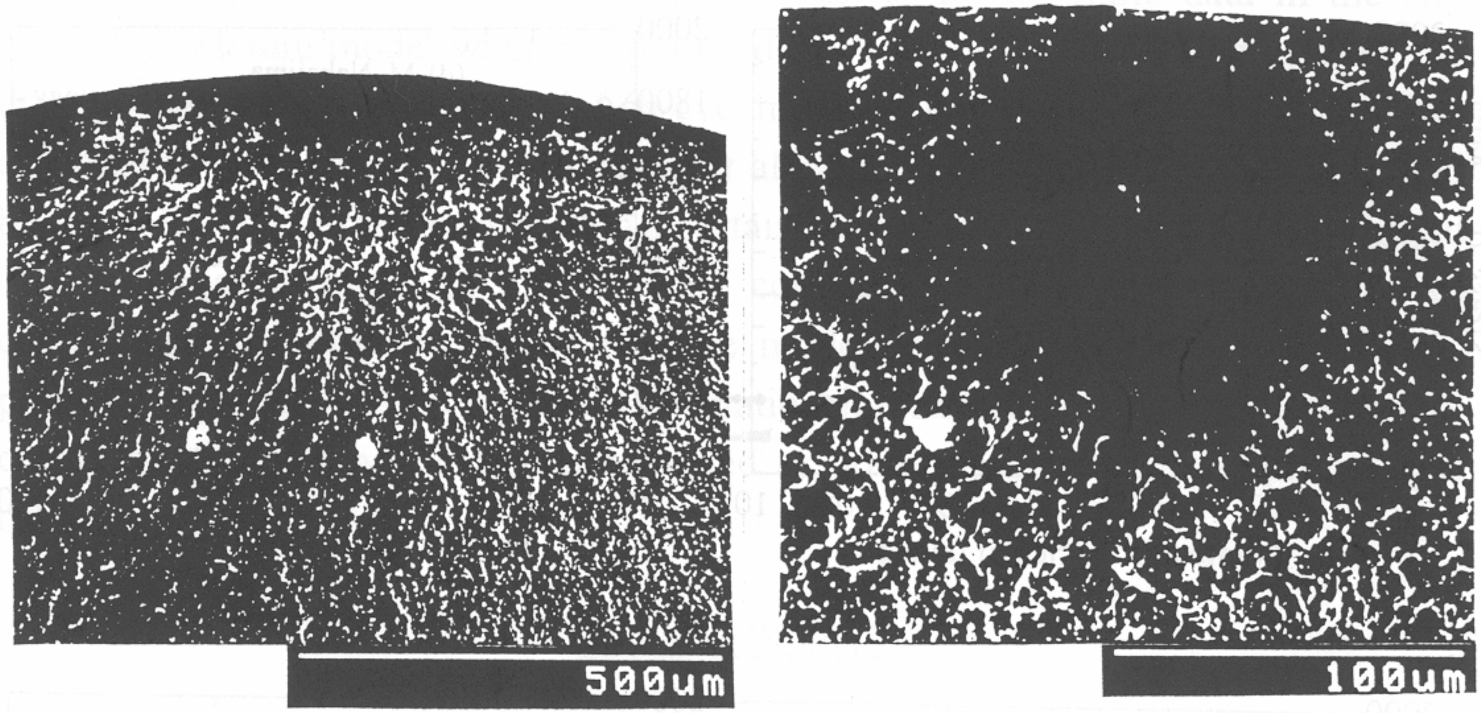


(T. Sakai et al., 1999)

Surface Failure versus Internal „Fish-Eye“ Failure

(T. Sakai et al., 1999)

HCF: Surface failure	UHCF: Internal failure



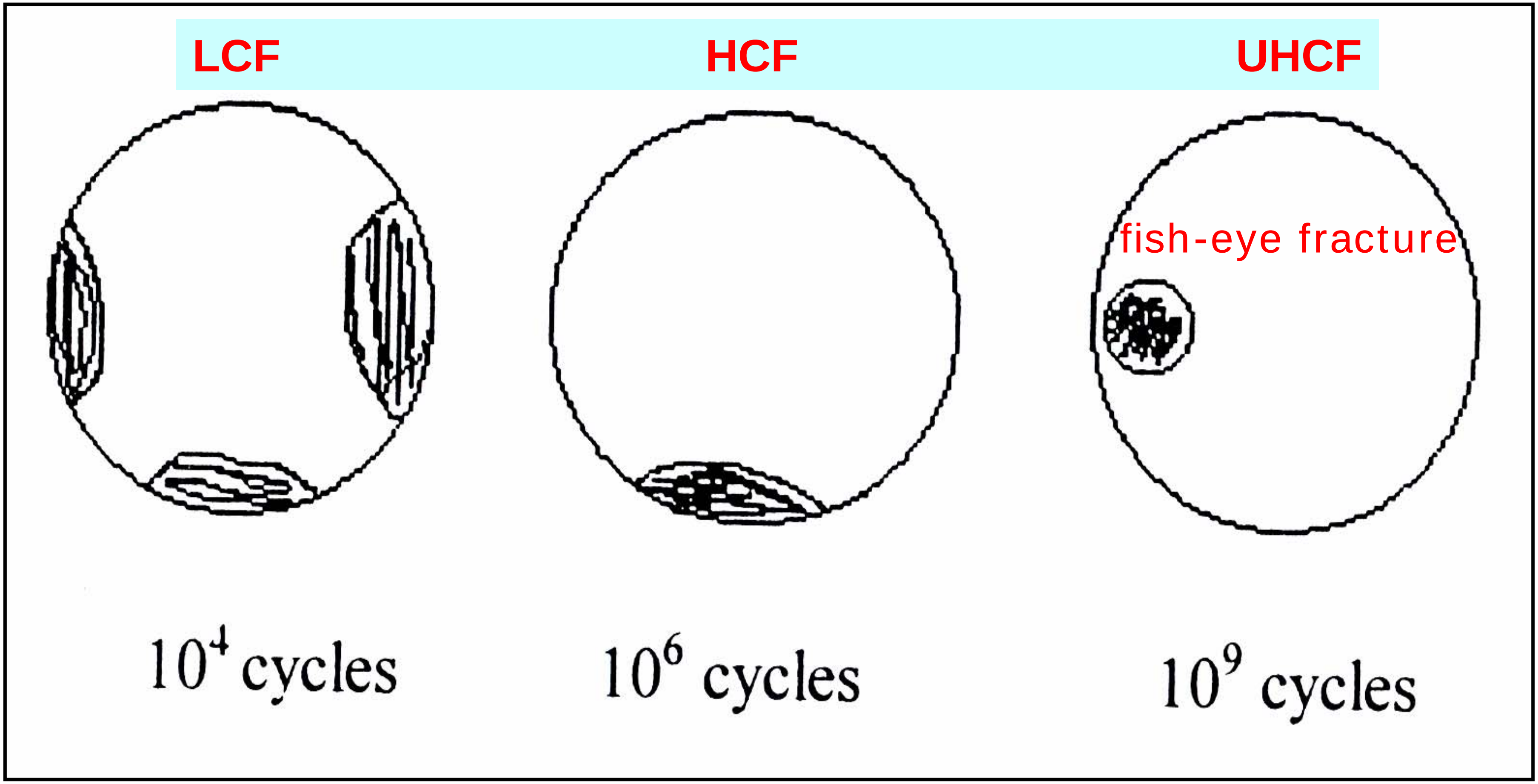
σ =1500MPa, N=30700

(a) Fracture surface in slip governed mode

σ =1300MPa, N=24376900

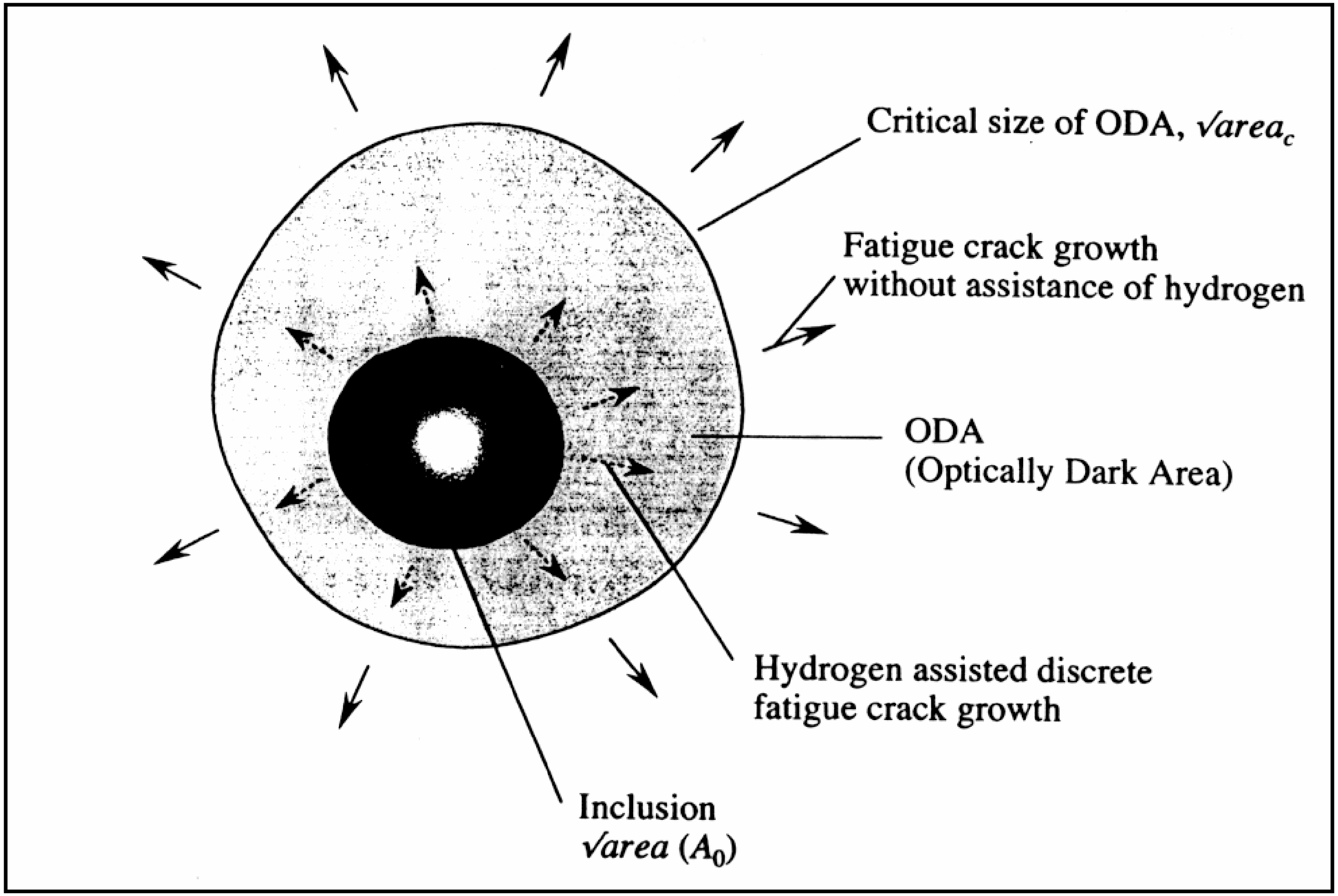
(b) Fracture surface in fish-eye mode

Fatigue Crack Initiation Sites in LCF, HCF and UHCF



Schematic after C. Bathias et al., 2000

Details of „Fish-eye Fracture“



(Y. Murakami et al., 2000)

Proposed Multi-Stage Fatigue Life Diagrams of Type II Materials

S. Nishijima and K. Kanazawa, 1999

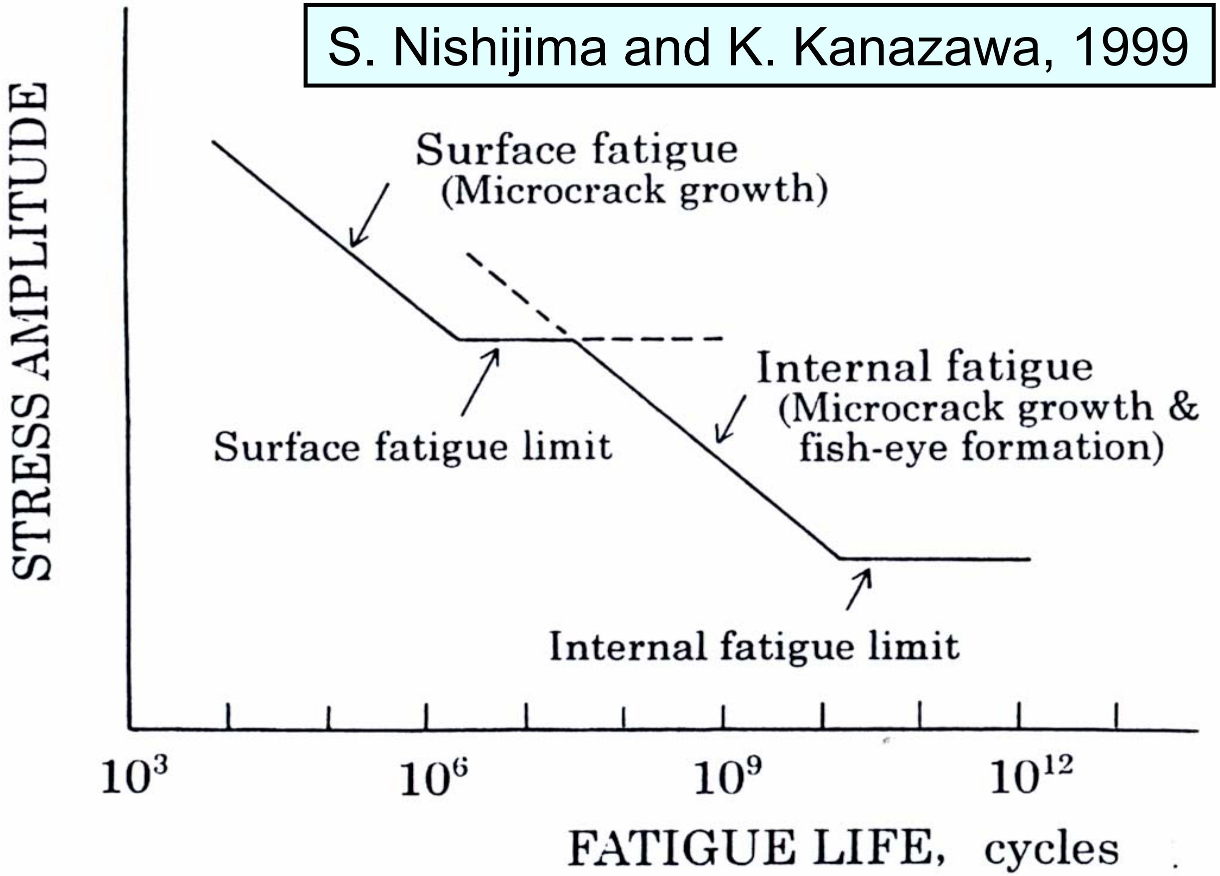
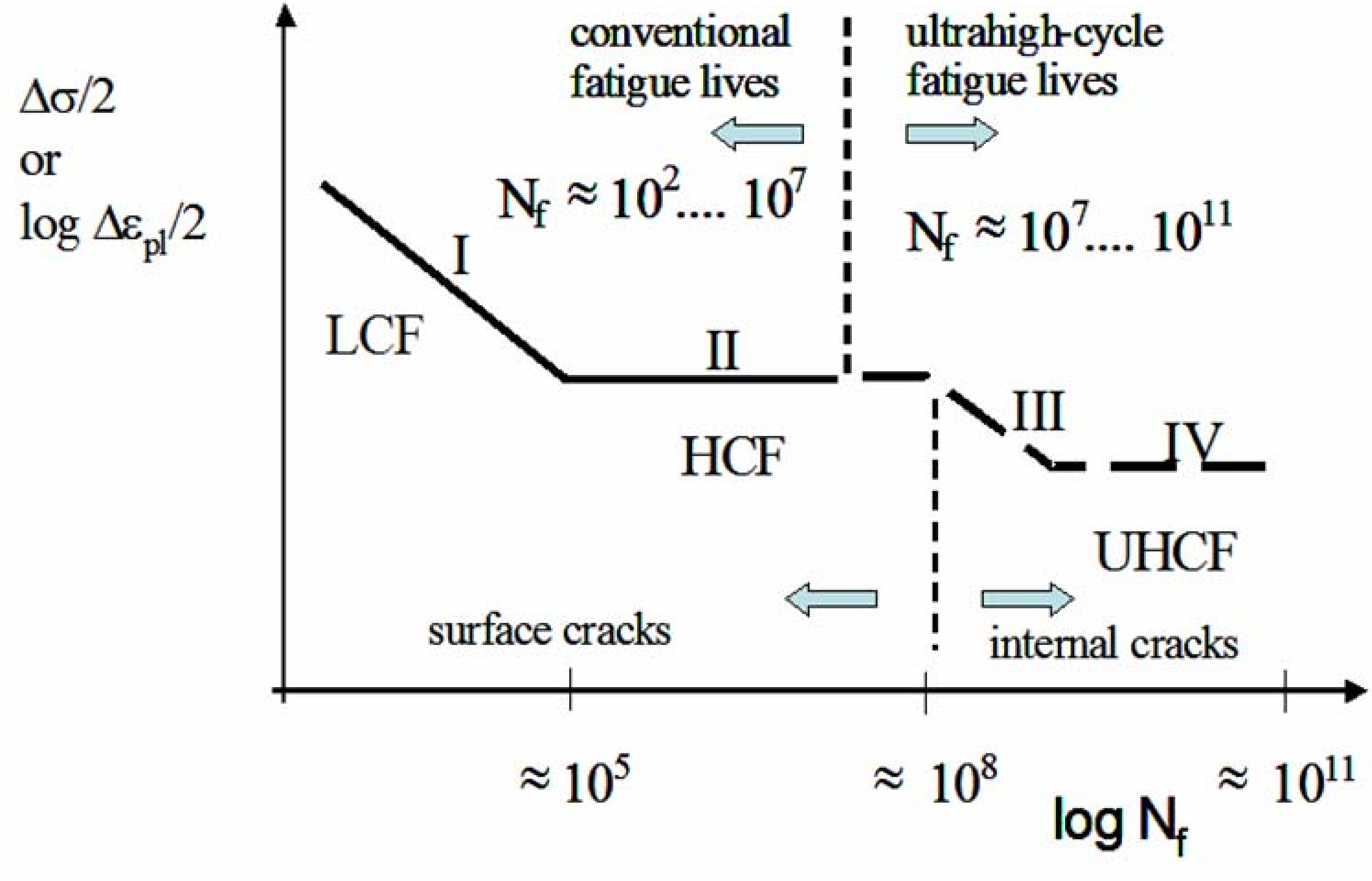


Fig. 12 The concept of a twofold *S–N* curve.

Multistage Fatigue Life Diagram of Type II Materials



Onset of Fatigue Damage in Type II Materials

LCF,HCF

At the surface:

- cracking caused by surface roughening?
- cracking caused by surface inclusions?

UHCF

At interior inclusions:

- cracking of inclusions?
- debonding?
- cracking in emanating slip bands?
- importance of ODA (optically dark area) and effect of hydrogen (Y. Murakami et al.)

Dominance of Fatigue Crack Initiation in UHCF Range

Fatigue crack initiation versus **propagation in UHCF**

Fatigue life in the UHCF regime of type II materials has often been described in terms of **fatigue crack propagation**, e.g.

$$\Delta K = \frac{2}{\pi} \Delta\sigma \sqrt{\pi d_i / 2}$$

(e.g. Murakami et al., 2000)

Increasing evidence (compare Bathias et al. (2002) and P.C. Paris et al. (2004)), shows that fatigue life in UHCF is controlled by

fatigue crack initiation and slow growth

until fatigue crack growth can be described by LEFM.

Details of Subsurface Fish-eye Fracture

Effect of surface roughness

Depth and diameter of fatal inclusions

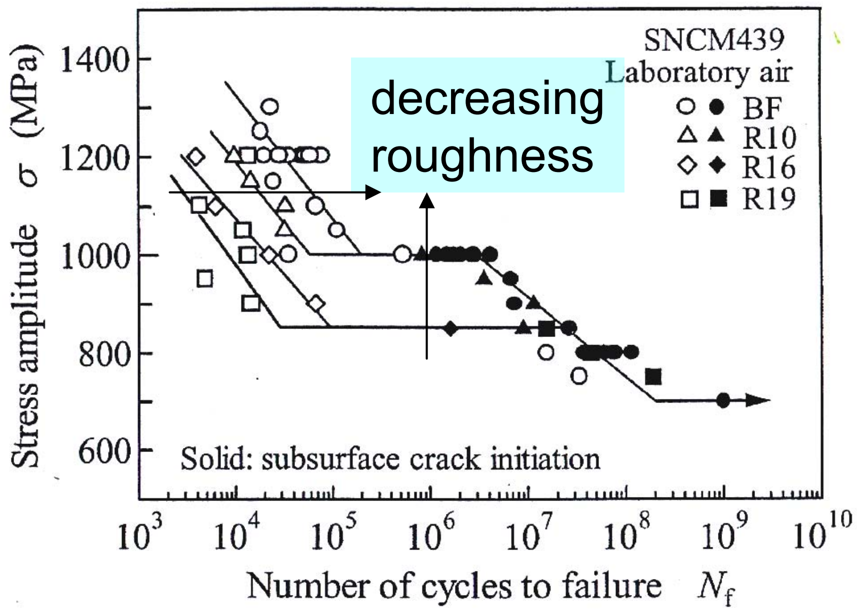


Fig. 5. S–N diagram.

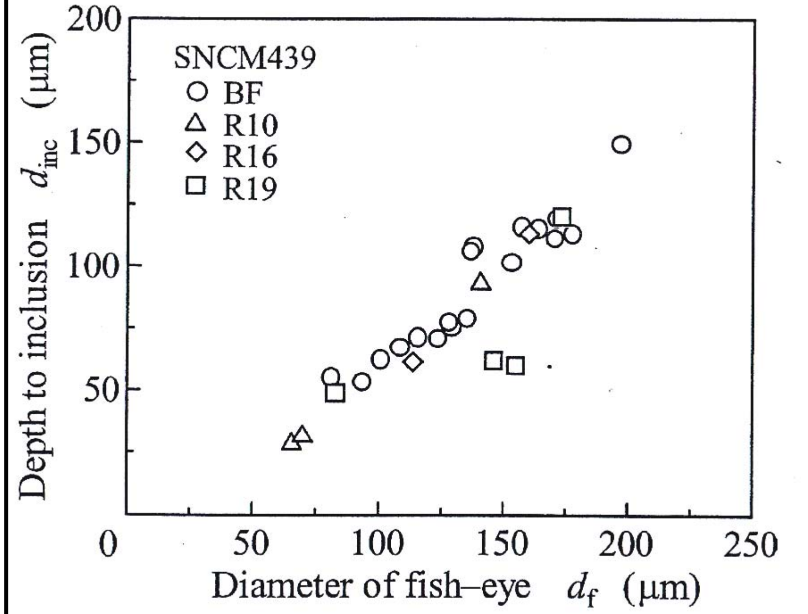


Fig. 8. Relationships between depth to inclusion from surface and diameter of fish-eye.

H. Itoga et al.: International Journal of Fatigue 25(2003)379-385

Fatigue Life and Location of Inclusions

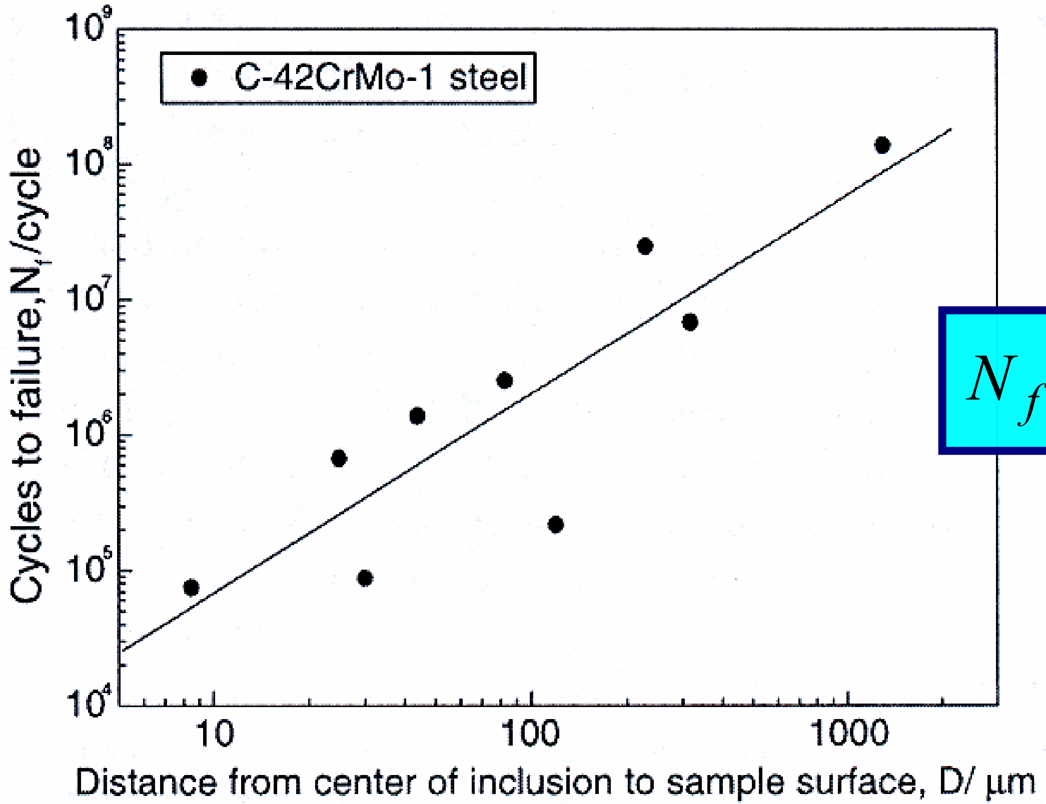


Fig. 6. Relationship between fatigue life N_f and position D of inclusion.

$$N_f = 2.32 \times 10^3 D^{1.47}$$

Z.G. Yang et al., 2004

Critical Inclusion Density in Type II Materials

For a specimen of diameter *d* and length *l*, containing inclusions of diameter d_i, there is a **critical inclusion density:**

$$n_{i,crit} = \frac{1}{d_i \, \pi \, d \, l}$$

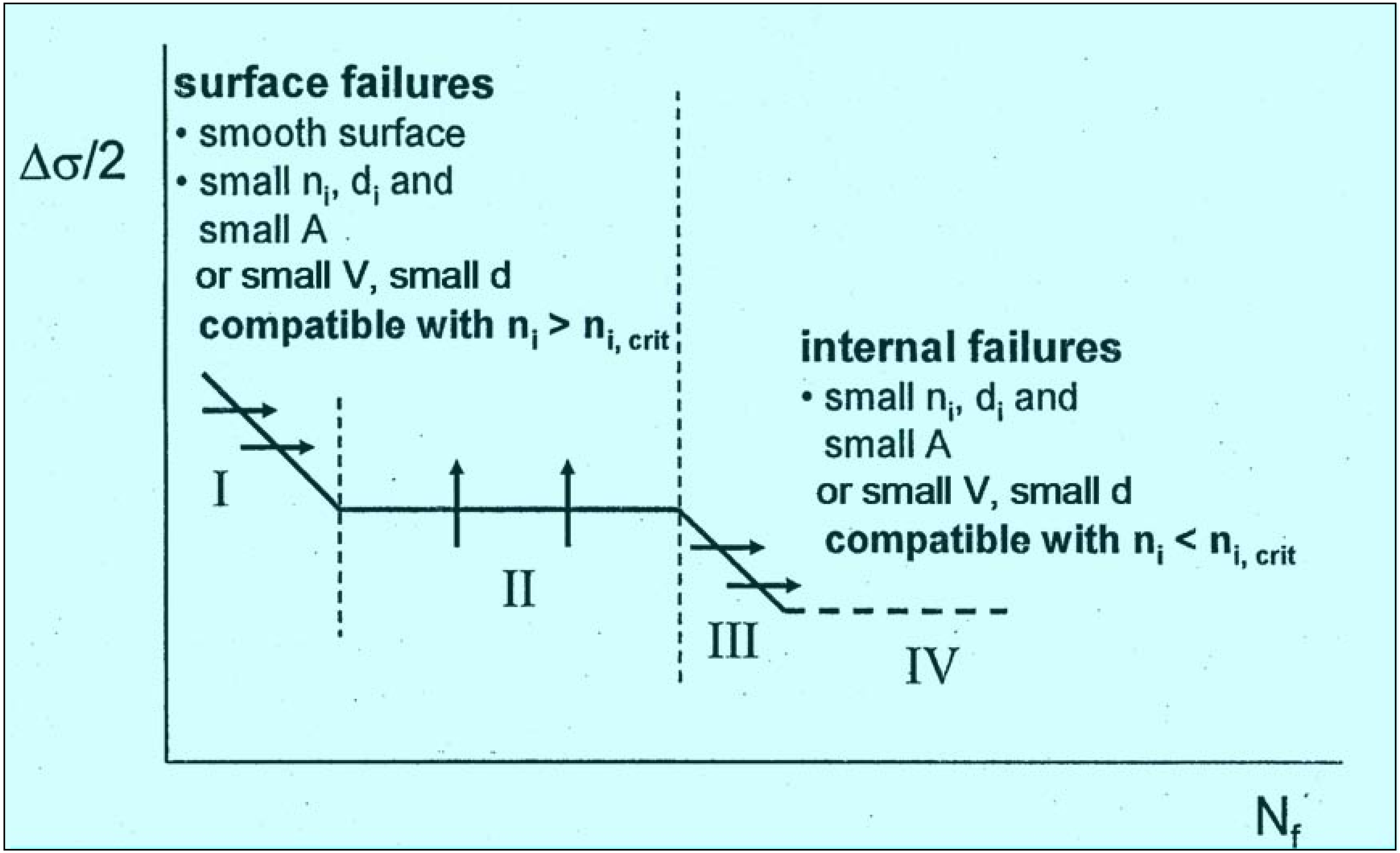
(Mughrabi, VHCF-2, 2001)

$$n_{i,crit} = \frac{1}{d_i A} = \frac{d}{4 V d_i}$$

(*V*: volume, *A*: surface area of specimen)

When $n_i < n_{i,crit}$, surface failure at an inclusion at/near the surface is improbable!

Factors which enhance fatigue life

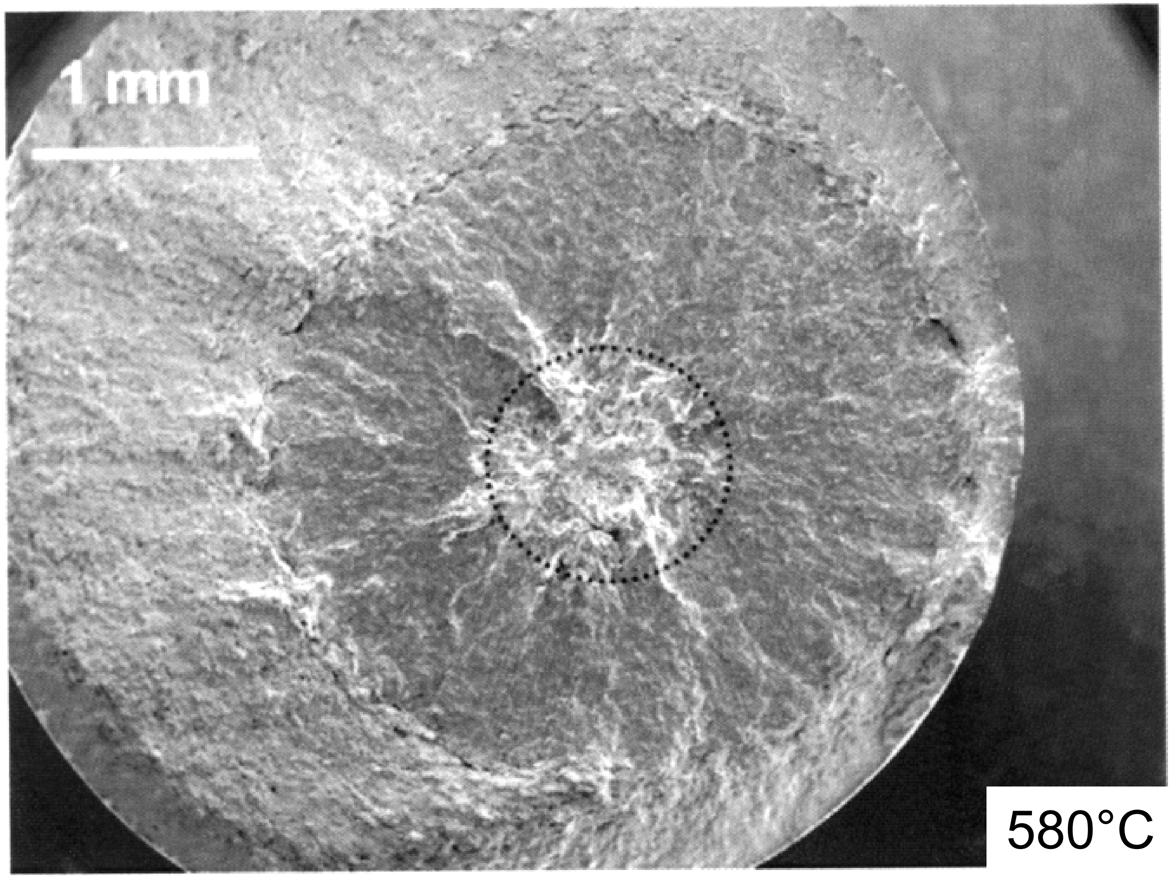


Other subsurface fatigue failures

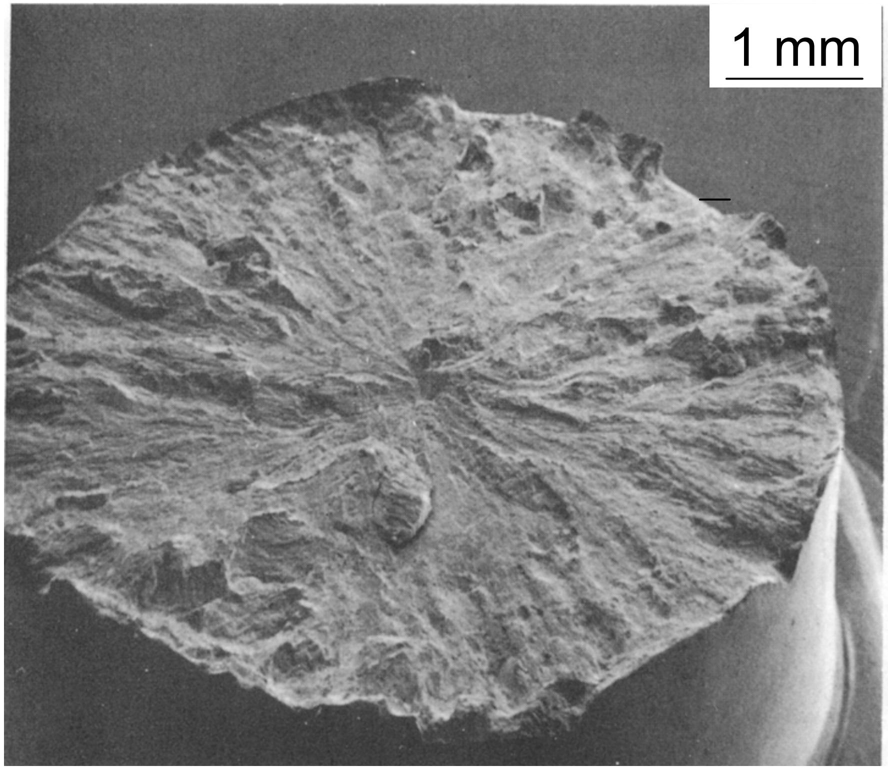
Examples of other subsurface failures:

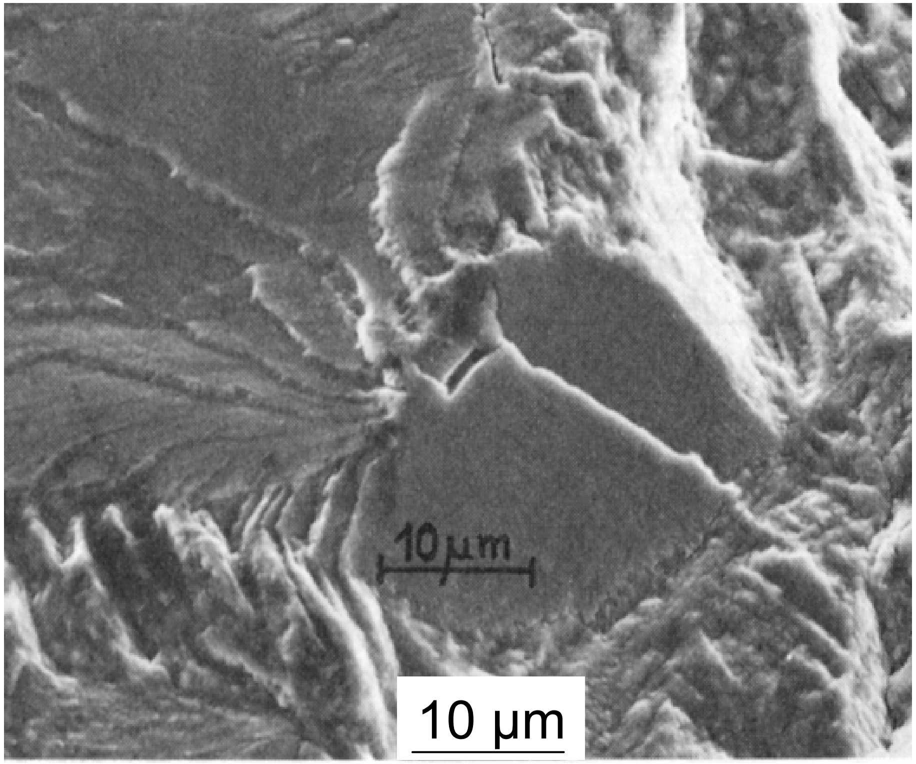
- in nickel-base superalloys
- in titanium alloys
- At casting pores

Internal Fatigue Failure in René 88 at Elevated Temperatures



Internal Failures in Fatigued Titanium Alloys

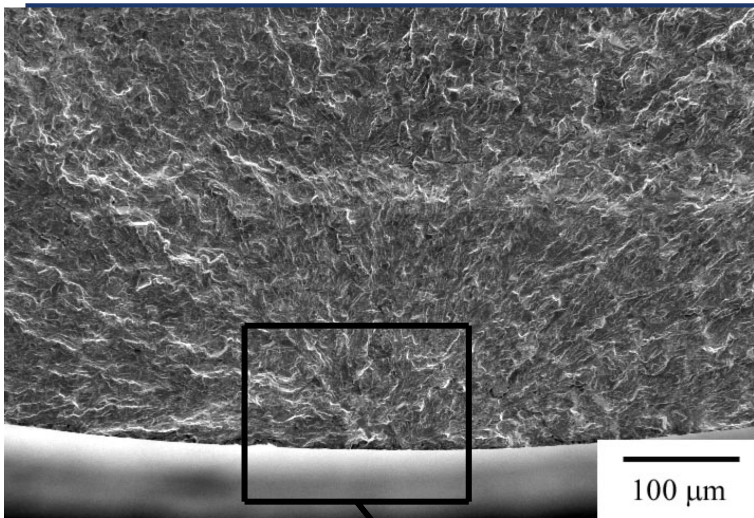




Ti6242
J.U. Specht (1992)

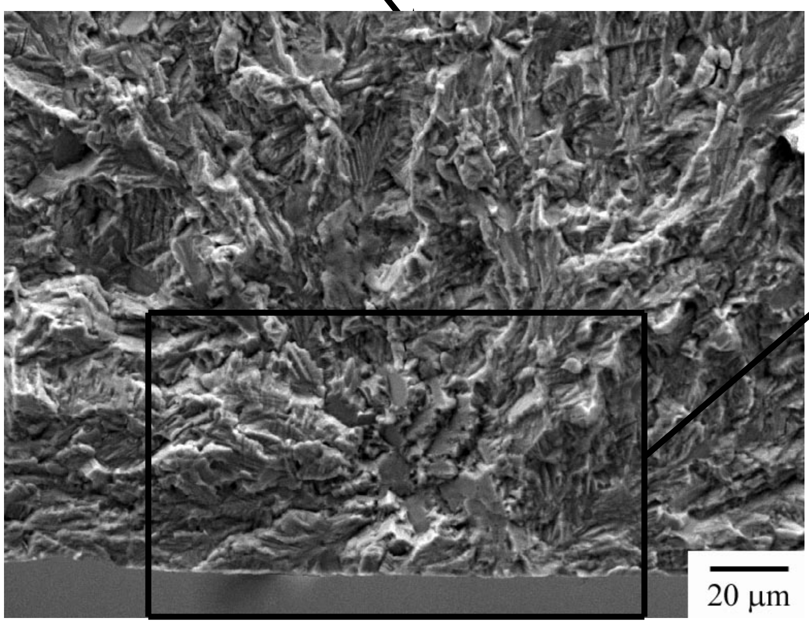
Ti-6Al-4V
J. Ruppen et al. (1979)

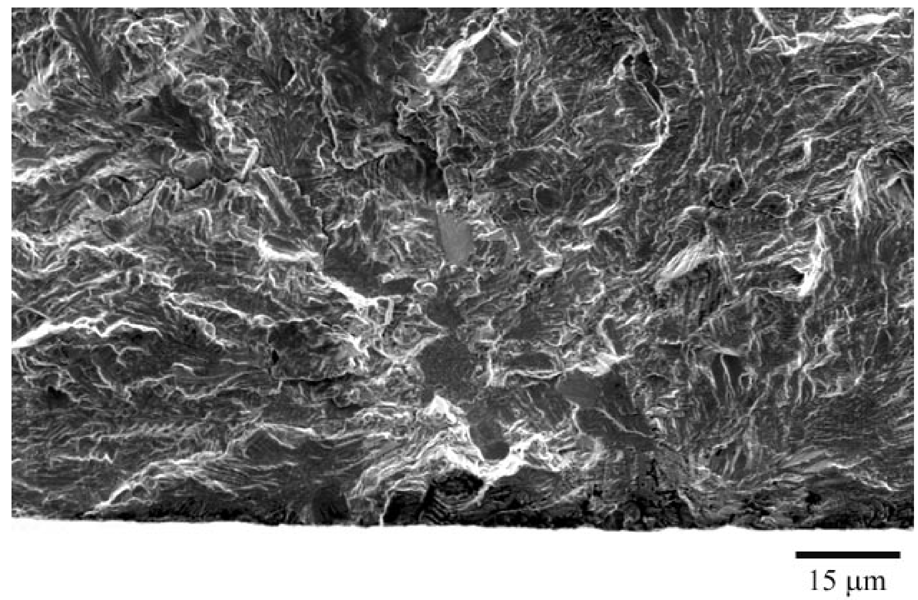
Ti-6246, σ_{max}= 700 MPa, R=0.05, RT



Wayne Jones, private communication, 2005

- Crack initiation and early stage propagation along primary α grains in a near surface failure
- Crack initiation sites are 20-25 µm

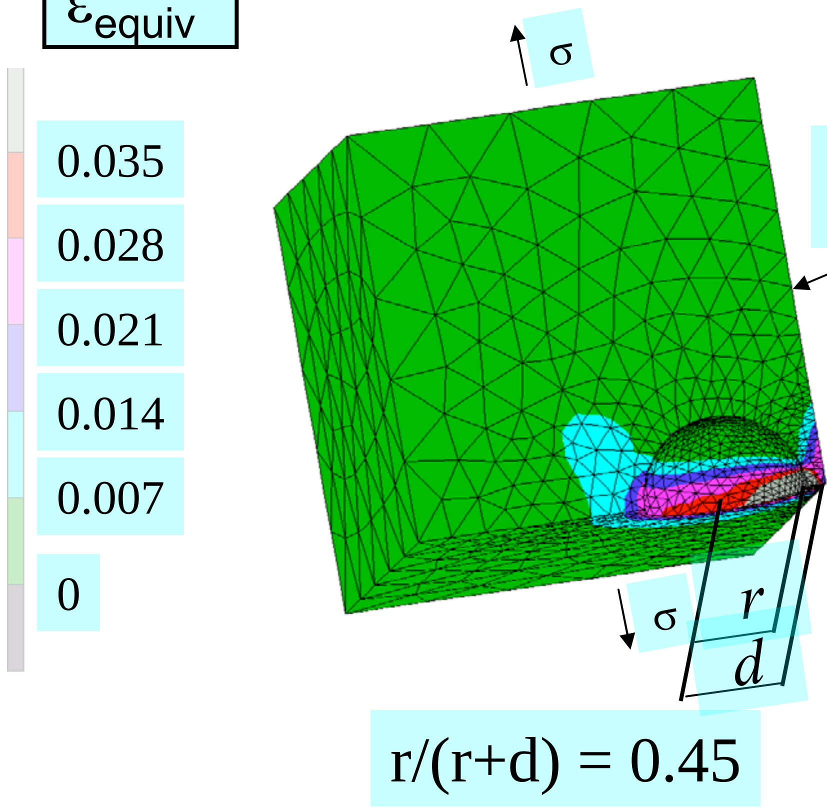


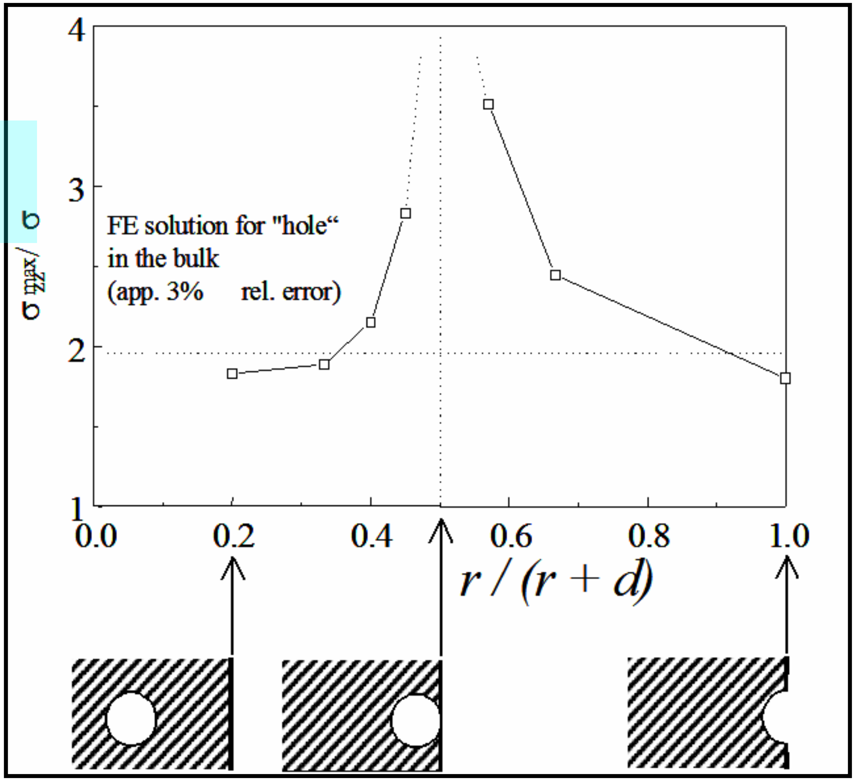


FEM calculation of local stresses/strains near internal cavities (e.g. casting pores)

local strains

local stresses





A. Borbély et al., 2002

Type I and Type II Materials

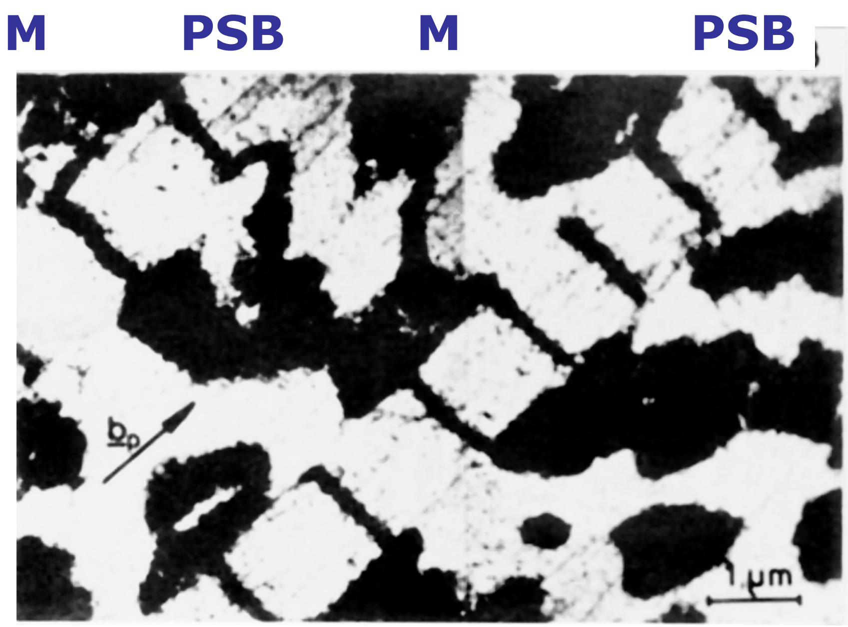
It is expedient to distinguish between

- **Type I materials (such as Cu, Ni, Al)**:
  ductile, single-phase, no heterogeneities such as inclusions, pores, etc.

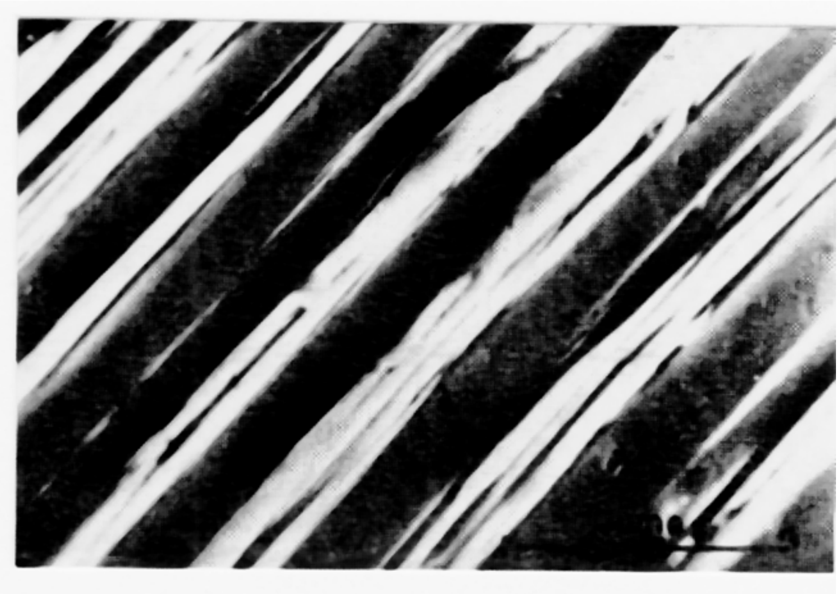
and

- **Type II materials (such as HSLA-steel or cast materials)**:
  high-strength, containing heterogeneities such as inclusions and pores

Type I Materials: Persistent Slip Bands in Fatigued Copper



TEM



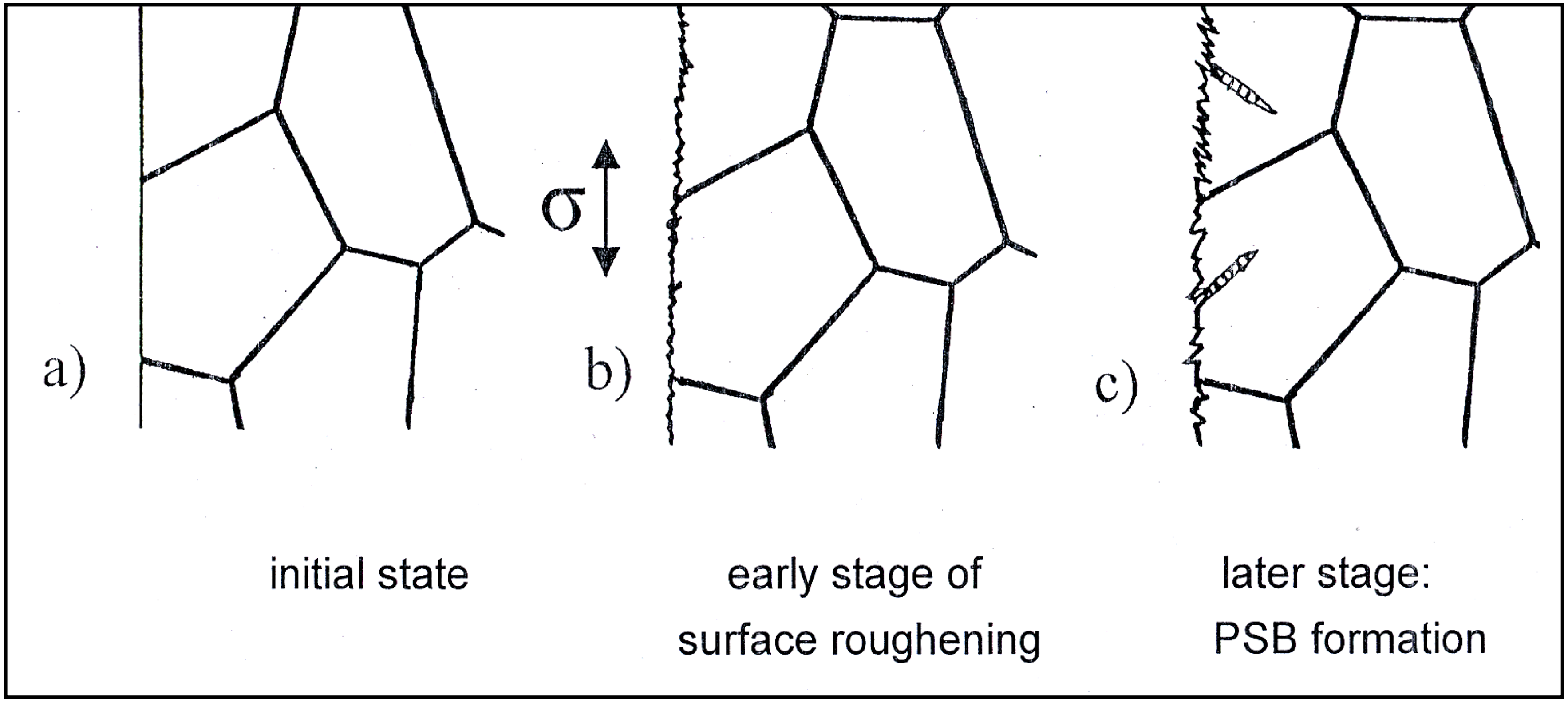
SEM

$\gamma_{\mathbf{pl,PSB}} \approx 10^2\ \gamma_{\mathbf{pl,M}}$!!

PROBLEM: Can PSBs develop below the PSB threshold during fatigue in the UHCF regime ? ?

Surface Roughening, Stage I Crack Initiation Below PSB Threshold

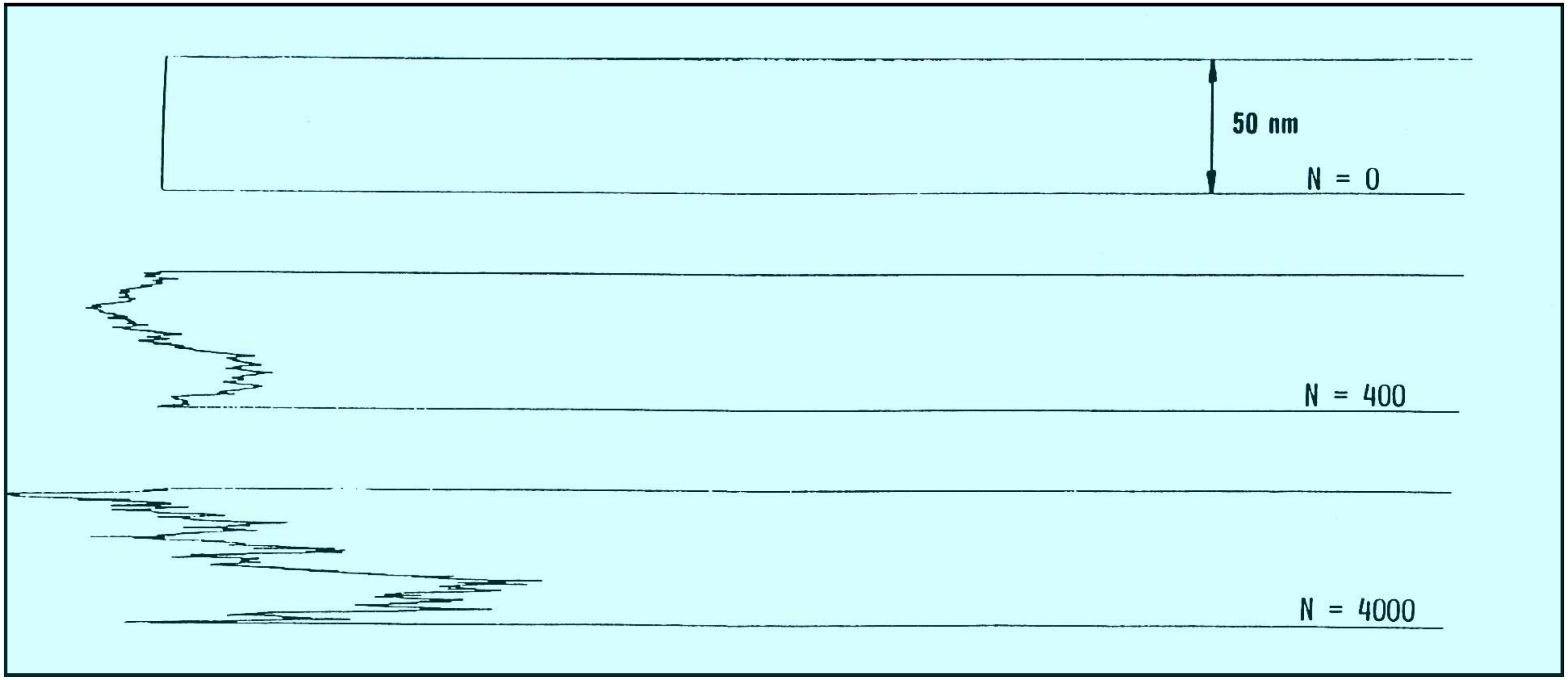
Stages of fatigue damage evolution



$$\sqrt{< x^2 >} = \sqrt{4 N \gamma_{\mathrm{pl,loc}} \, p \, b \, h} = (rms)$$

p: slip irreversibility

Surface roughening by random irreversible cyclic slip



Measure for surface roughness:

$$\sqrt{< x^2 >} \approx \sqrt{4 \cdot p \cdot N \cdot \gamma_{pl,loc} \cdot b \cdot h}$$

Below PSB-threshold:

$$\gamma_{pl,loc} \equiv \gamma_{pl,M} \approx 10^{-2} \gamma_{pl,PSB}$$

Surface Roughening by Random Slip

Meaningful measure of surface roughening:

r.m.s. displacement $\sqrt{<x^2>}$ between two neighbouring atomic glide planes:

$$\sqrt{<x^2>} = \sqrt{4 N \gamma_{pl,loc}\, p\, b\, h} = (rms)$$

local shear strain amplitude $\gamma_{pl,loc} = M\, \Delta\varepsilon_{pl,loc}/2$
(at very low amplitudes, $M = 2.24$ = Sachs orientation factor)

local shear strain amplitude in PSBs: $\gamma_{pl,loc} = \gamma_{pl,PSB} \approx 10^{-2}$

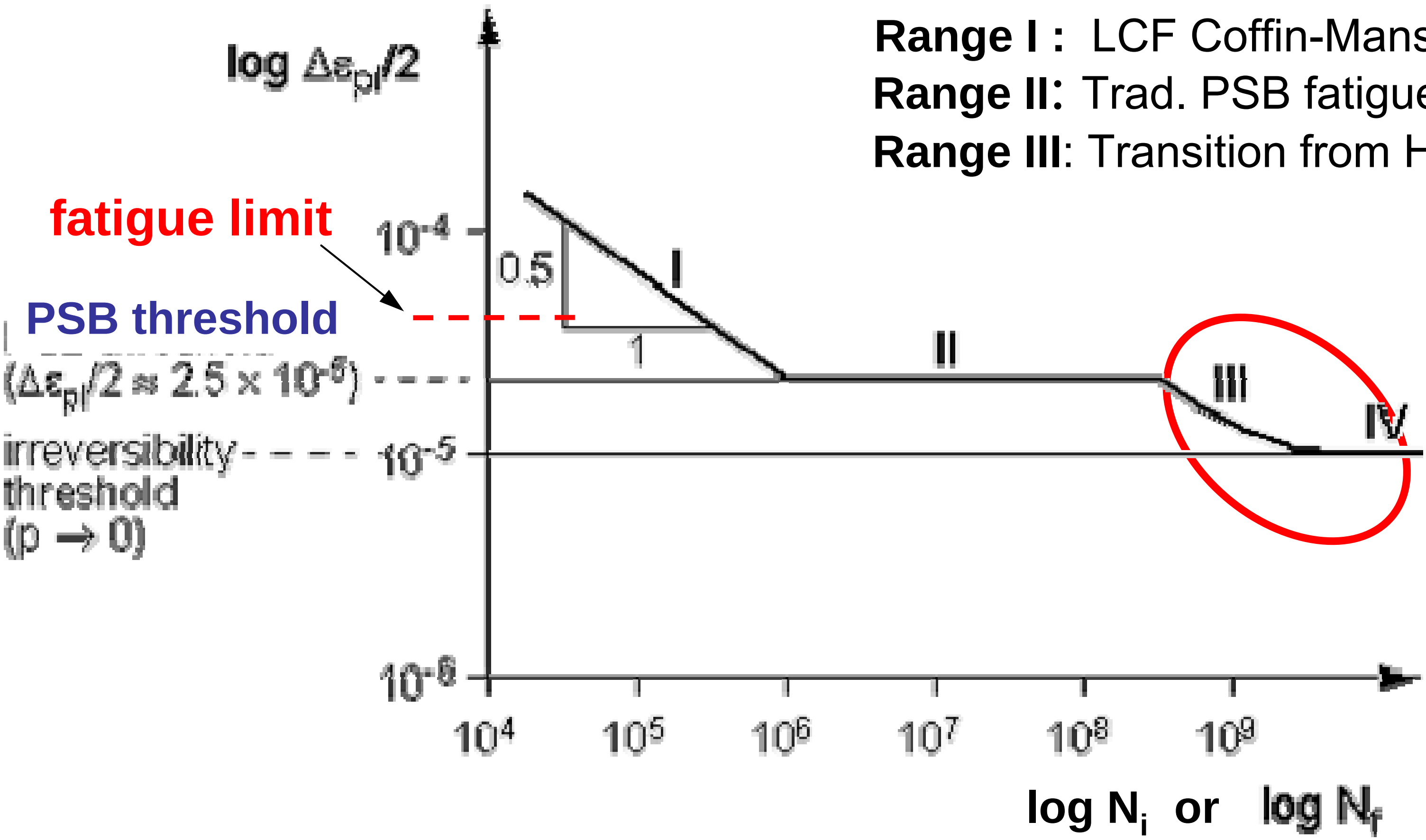
local shear strain amplitude in matrix: $\gamma_{pl,loc} = \gamma_{pl,M} \approx 10^{-4}$

i.e. $\gamma_{pl,PSB} >> \gamma_{pl,M}$!!

cyclic slip irreversibility $p = p(\Delta\varepsilon_{pl}/2)$, becoming smaller as $\Delta\varepsilon_{pl}/2$ decreases.

Fatigue Life/Crack Initiation Diagram of Fcc Metals

(H. Mughrabi, 1999)



Range I : LCF Coffin-Manson regime

Range II: Trad. PSB fatigue limit (HCF)

Range III: Transition from HCF to UHCF

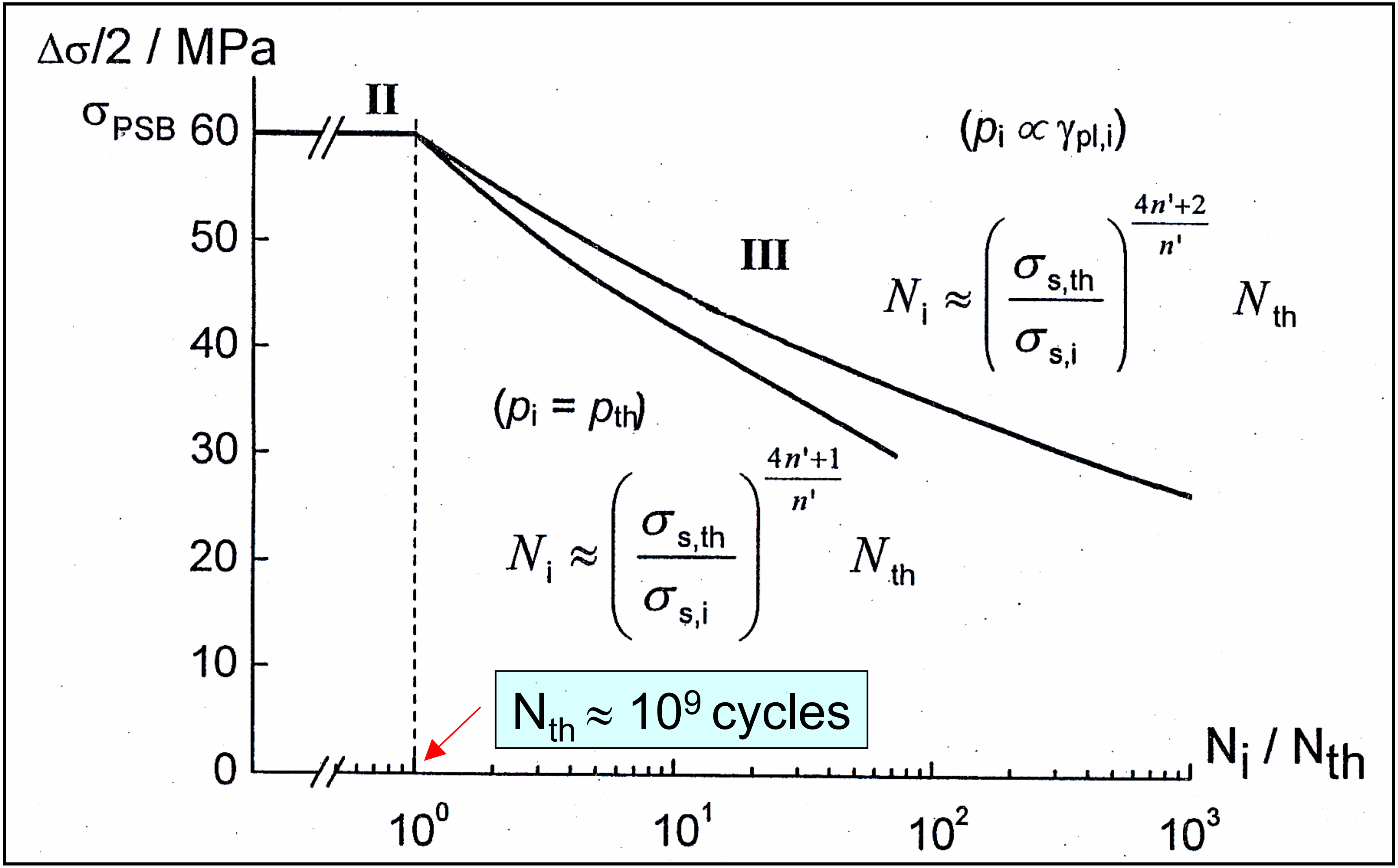
Physical origin of range III: gradual surface roughening by random slip:

$$\sqrt{< x^2 >} = \sqrt{6\, N\, \gamma_{pl,loc}\, p\, b\, h} = (rms)$$

p: slip irreversibility

$0 < p < 1$

Predicted UHCF Fatigue Crack Initiation Lives (example: copper)



UltraHigh-Cycle Fatigue of Copper

High Cycle Fatigue (HCF):

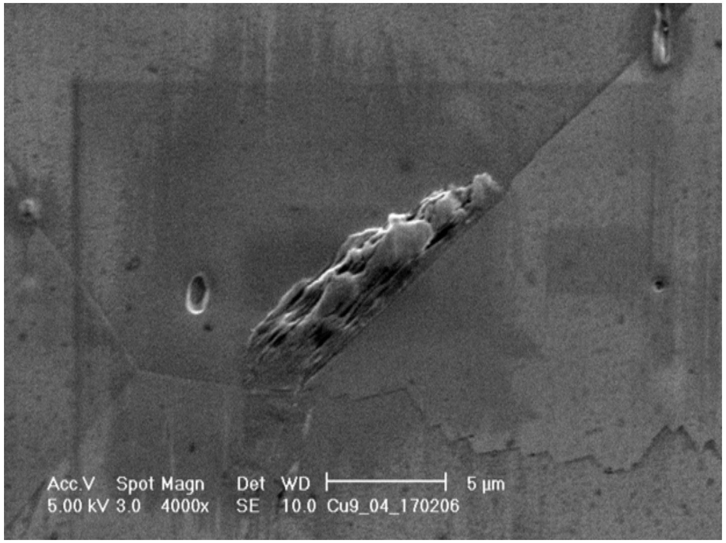
typically $N_f \leq 10^6 - 10^7$ cycles to failure

UltraHigh-Cycle Fatigue (UHCF) or Very High Cycle Fatigue (VHCF):

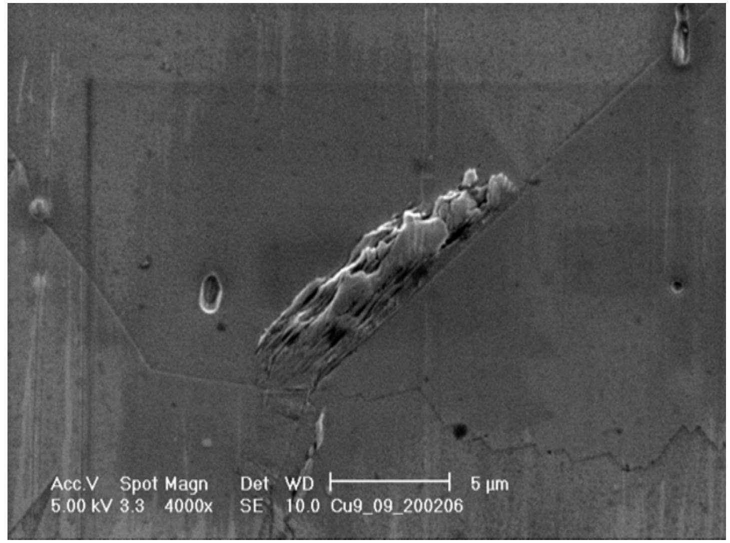
typically: $N_f \geq 10^8 - 10^9$ cycles to failure

(Collaboration with S. Stanzl/Tschegg, B. Schönbauer, A. Weidner, D. Amberger & F. Pyczak)

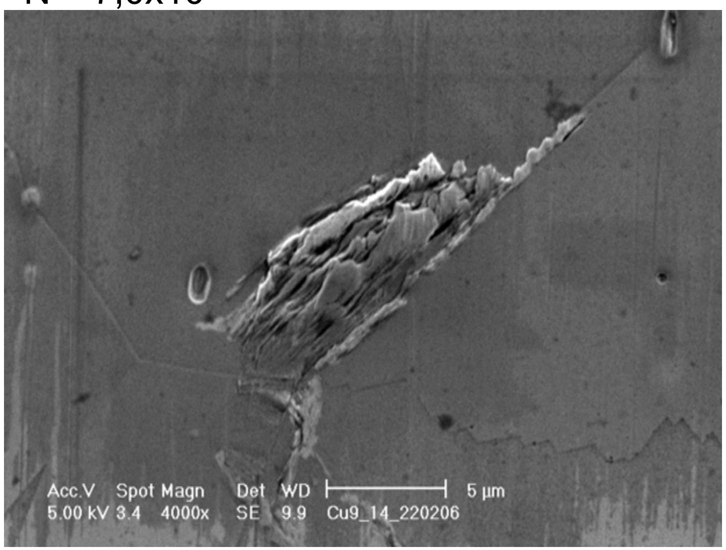
Evolution of Slip Band Structure at High N



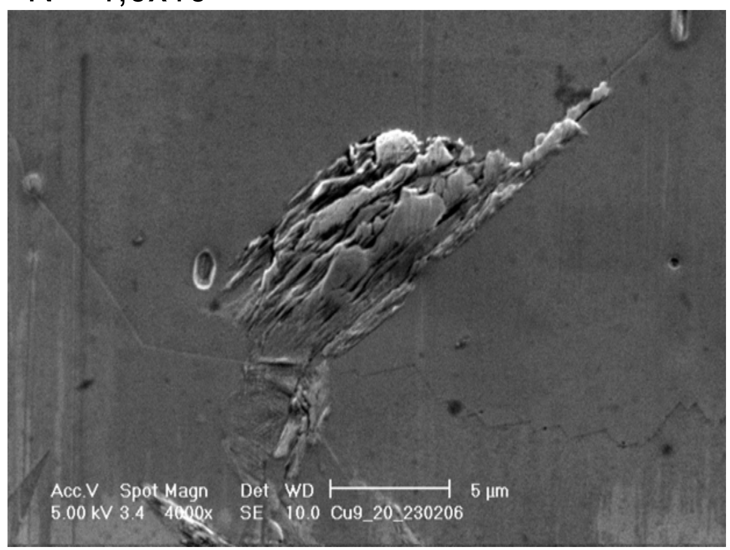
N = 7,0x10^{6}



N = 1,0x10^{7}



N = 5,0x10^{7}



N = 1,0x10^{8}

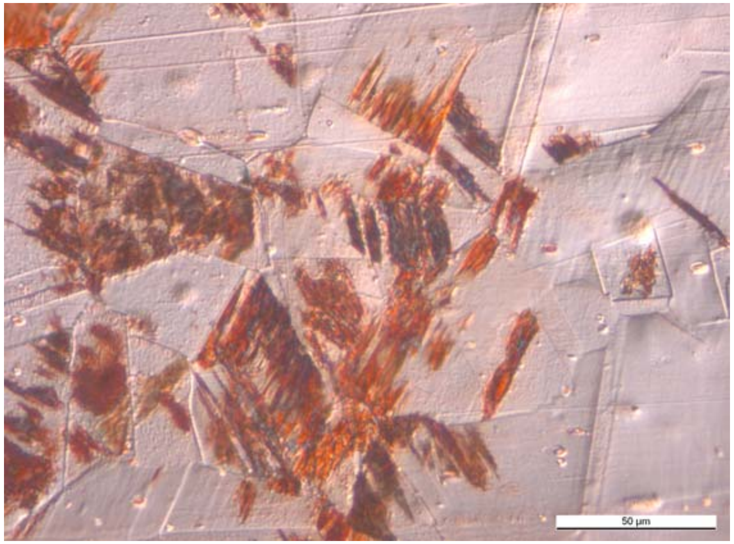
PSB threshold
$\Delta\sigma/2 \approx$ 63 MPa

Loading below PSB threshold

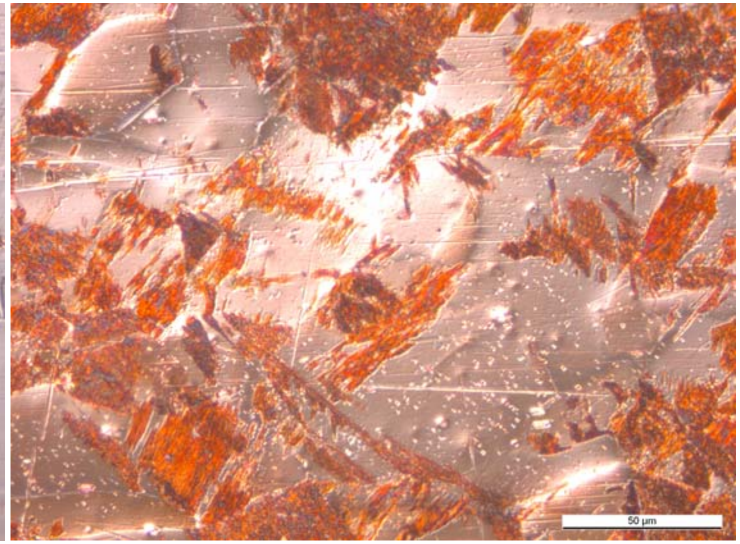
$\Delta\sigma/2$ = 52.2 MPa

S. Stanzl-Tschegg and H. Mughrabi, 2006

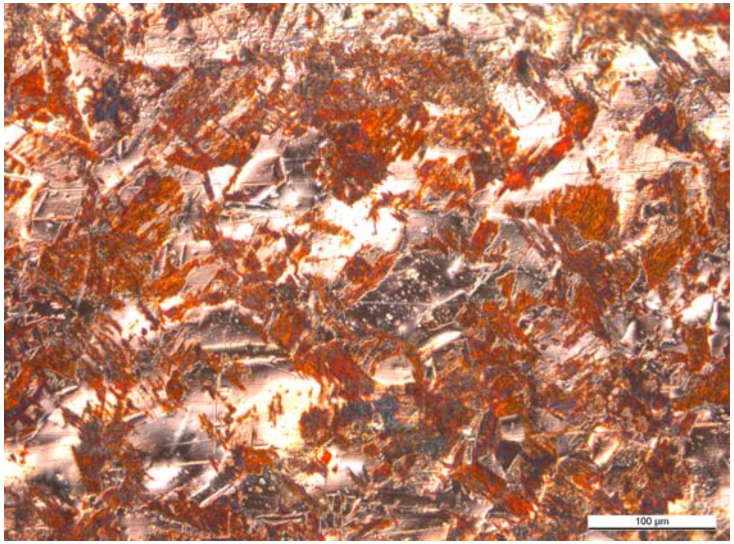
Irreversible Slip Below PSB Threshold at Very High N



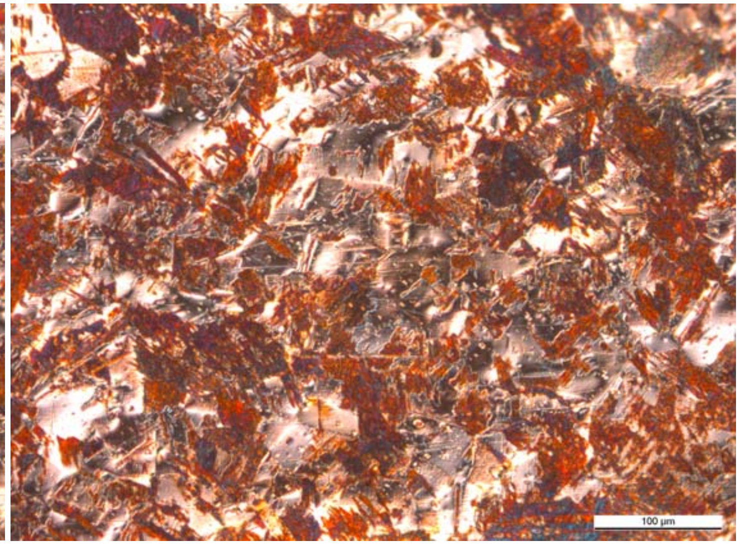
$\Delta\sigma/2$ = 30 MPa



$\Delta\sigma/2$ = 42 MPa



$\Delta\sigma/2$ = 48 MPa



$\Delta\sigma/2$ = 54 MPa

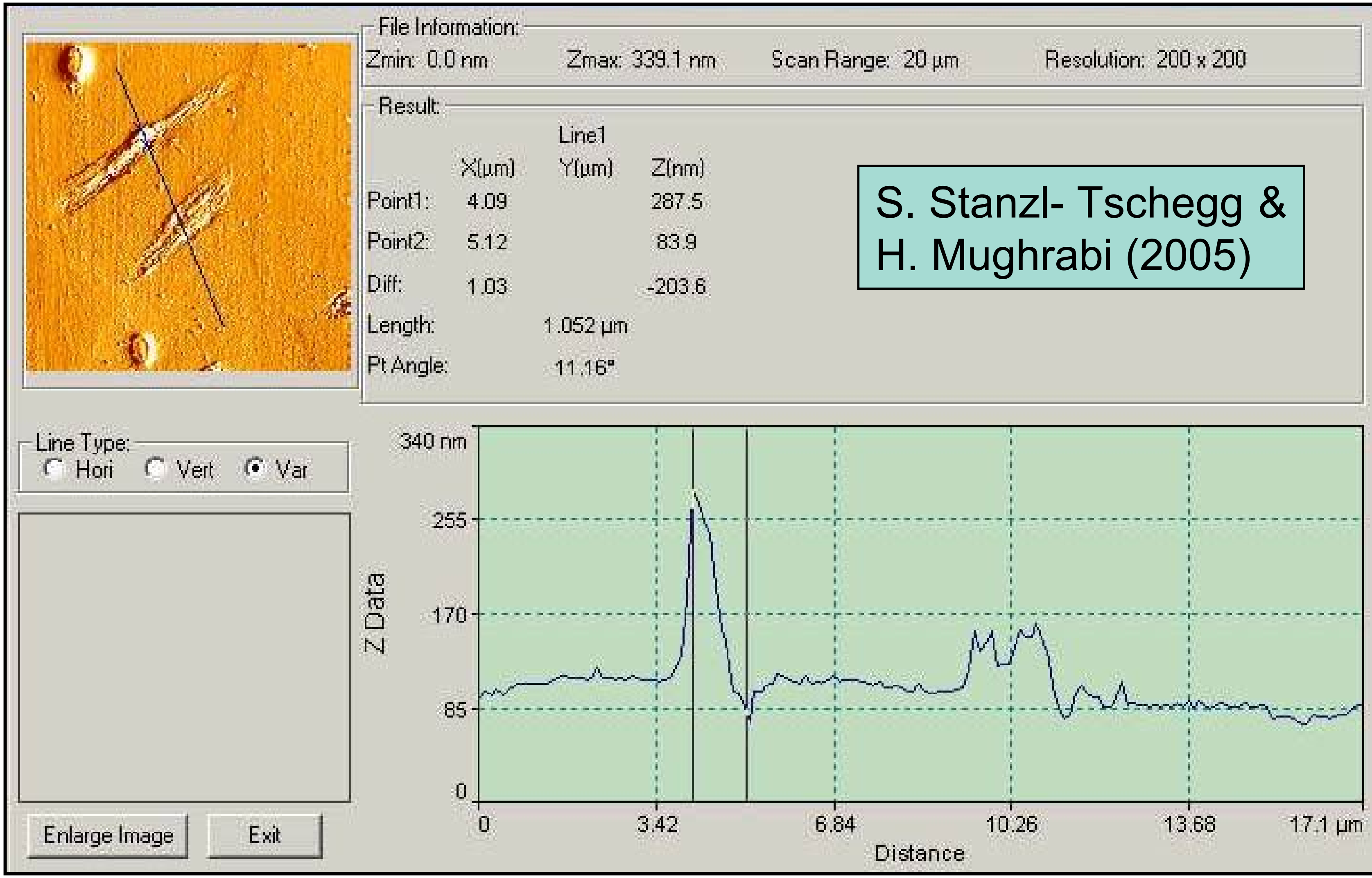
PSB threshold $\Delta\sigma/2 \approx$ 63 MPa

Increase of irreversible slip (slip band density) with stress

N = 1.3x10^{10} cycles

S. Stanzl-Tschegg and H. Mughrabi, 2006

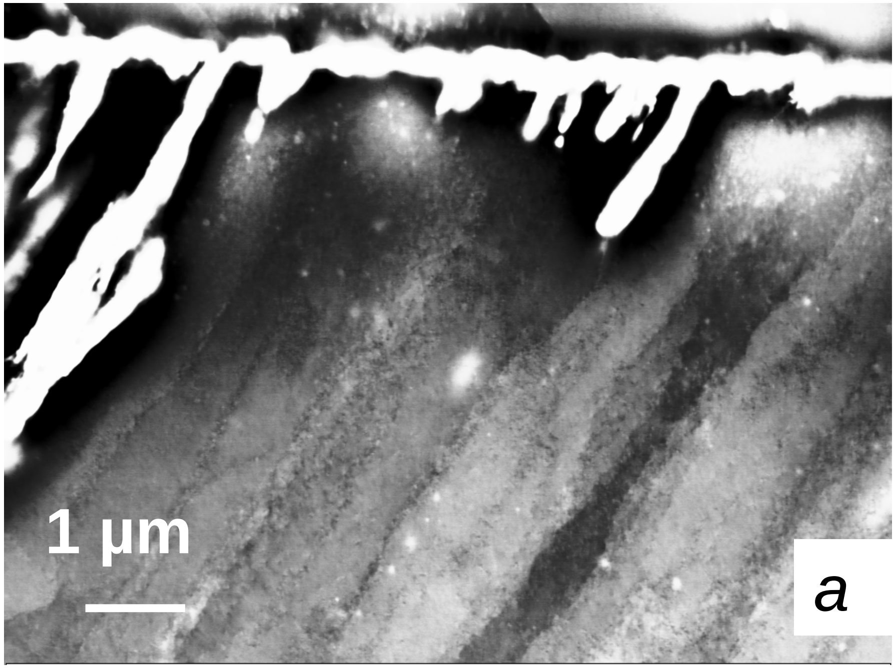
PSBs (?) in Cu below PSB Threshold, after N = 1.3×10^9 Cycles

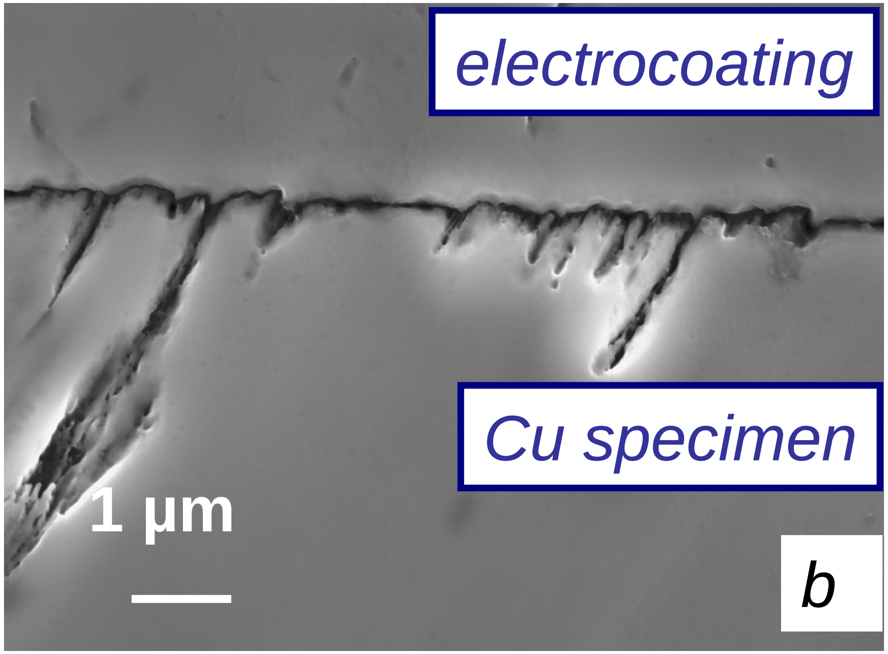


Fatigue-induced surface roughness, localized slip and stage I cracks in UHCF of copper

N =1.59×**10^{10}** cycles, $\Delta\sigma/2$ = 57 MPa.

i.e. ca. 6 MPa below PSB threshold (63 MPa)



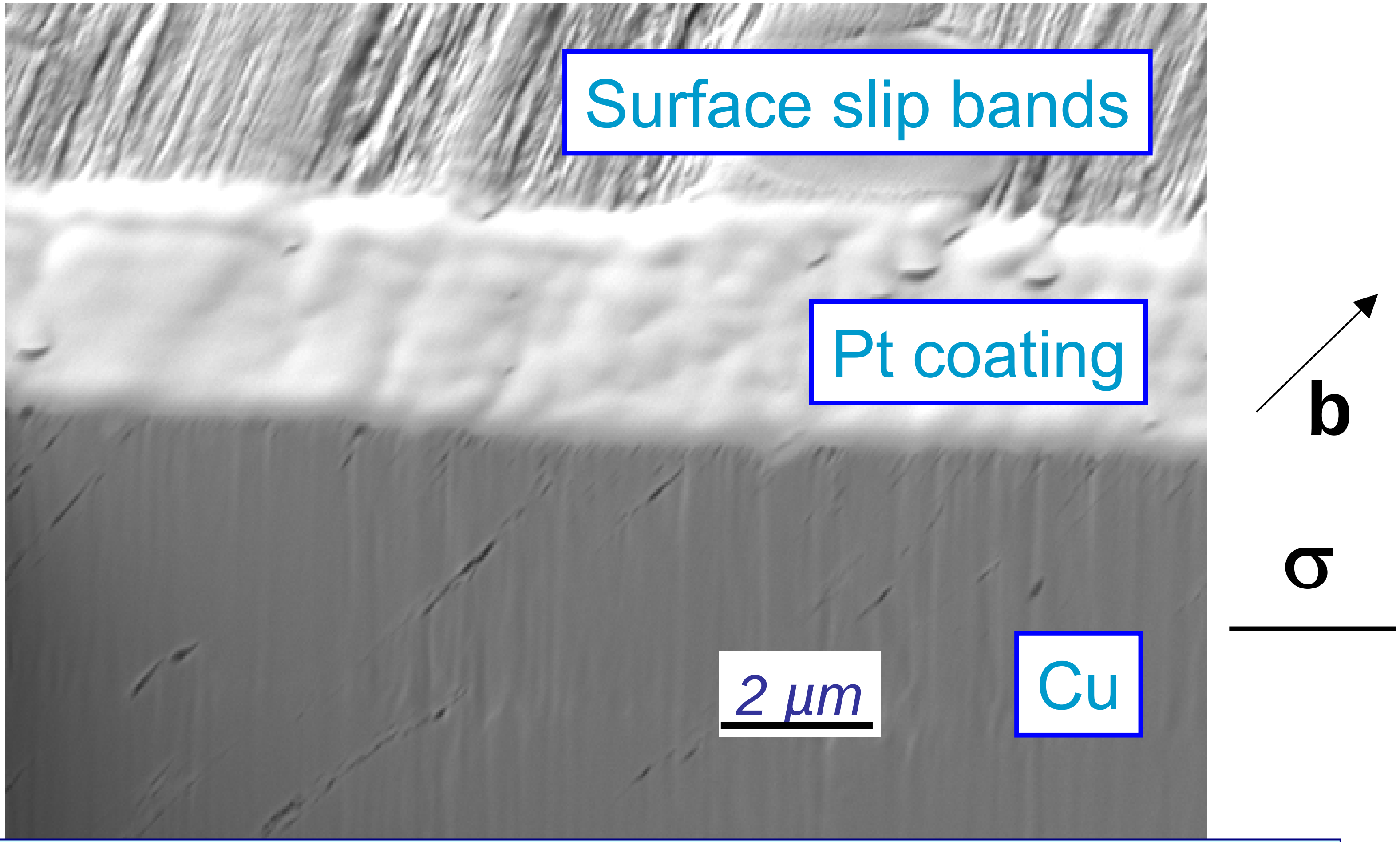


BSE detector

σ

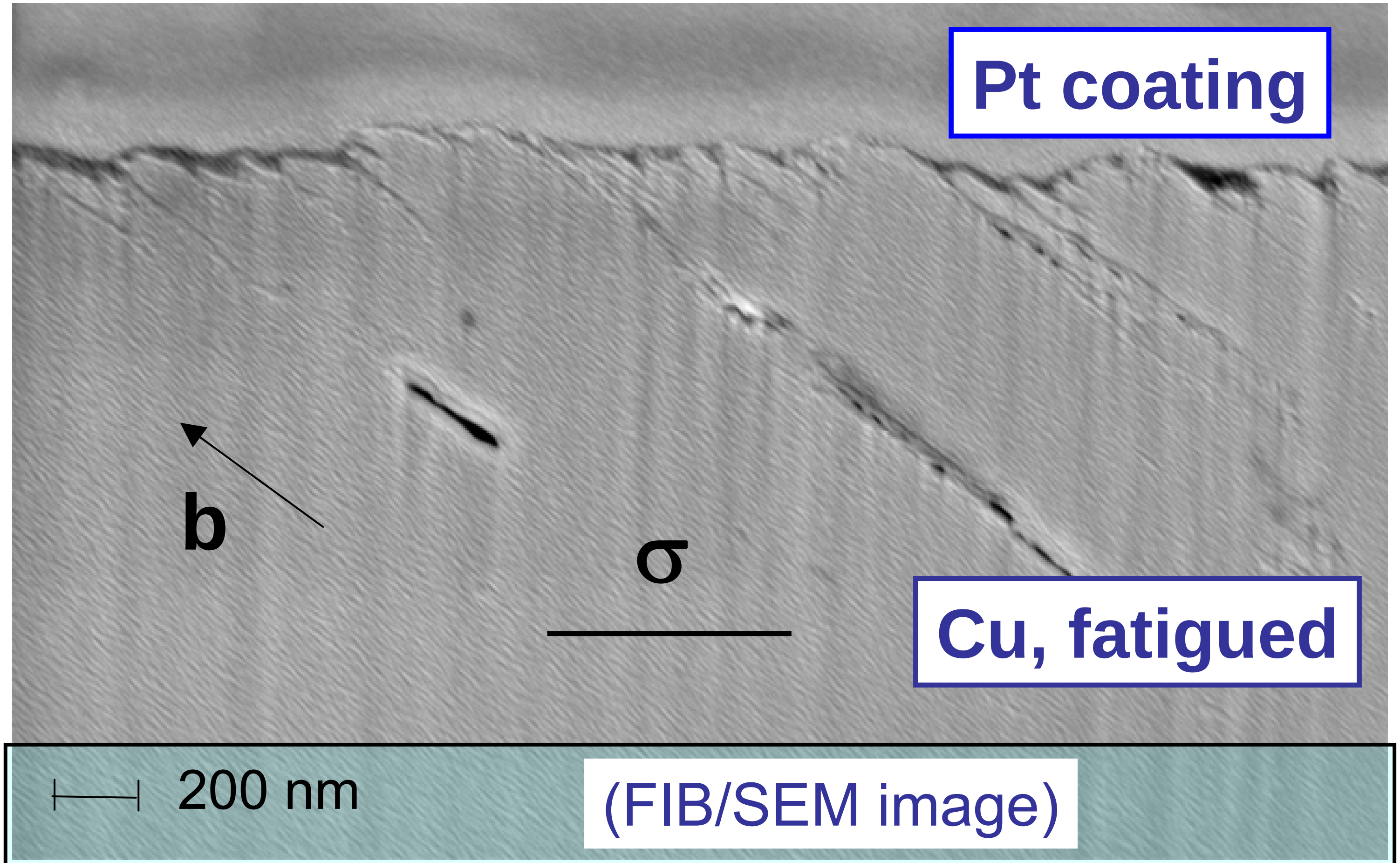
In-Lens SE detector

Stage I mode II shear cracks evolving from roughened surface



Cu fatigued, 1.59×10^{10} cycles (20 kHz) , FIB/SEM image
ca. 6 MPa below PSB threshold

Stage I mode II shear cracks evolving from roughened surface



Cu, fatigued for 1.59×10^{10} cycles (20 kHz)

ca. 2 MPa below PSB threshold

UHCF: Assessment of surface roughness

„rms roughness“: $\sqrt{<x^2>} \approx \sqrt{6N\gamma_{pl,loc}pbh} = (rms)$

From experiment: $\sqrt{<x^2>} \approx$ *150 nm (parallel to **b**)*

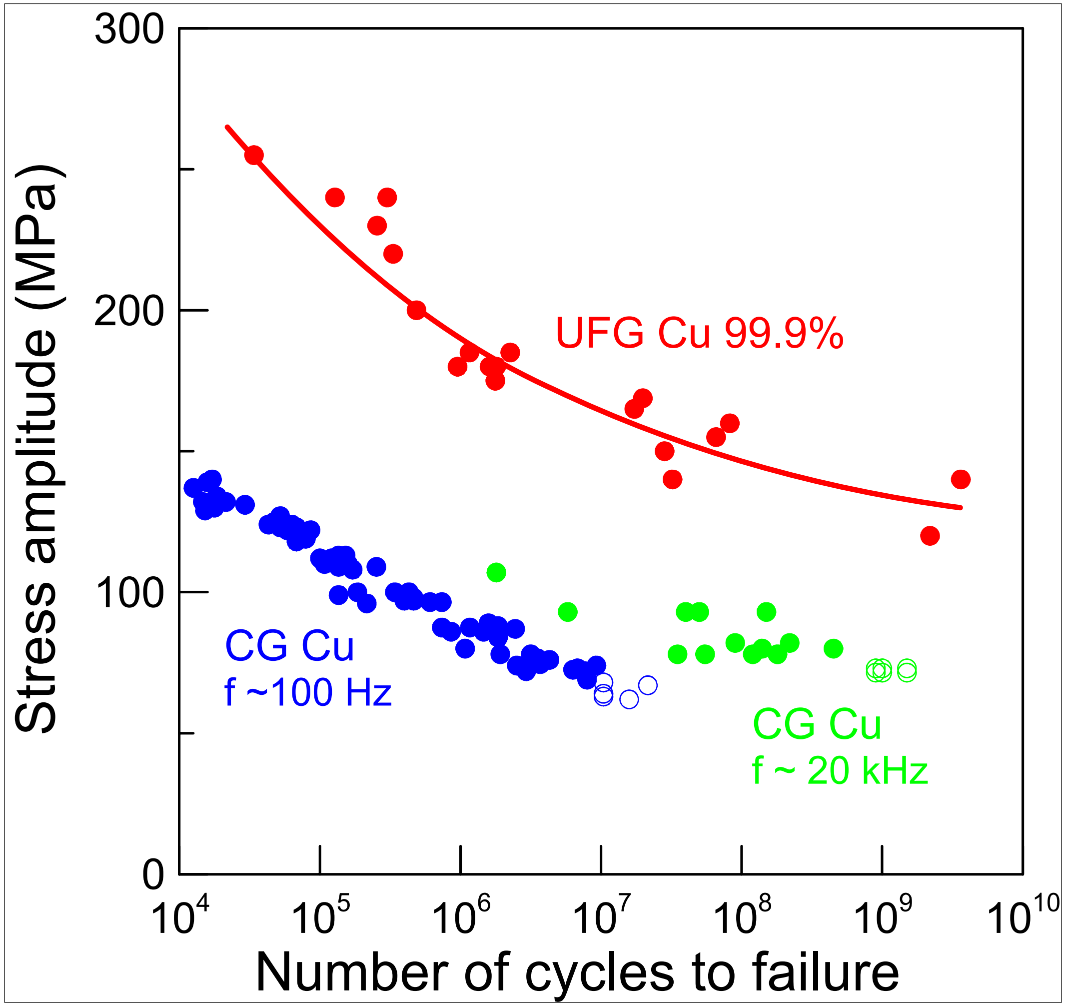
Inserting: b ≈ 2.5×10^{-10} m, h ≈ 2.0×10^{-6} m, N ≈ 1.6×10^{10} cycles and $\gamma_{pl.loc} \approx 1.37 \times 10^{-5}$, we obtain an estimate for the previously unknown **cyclic slip irreversibility** in surface grains:

$$p \approx 0.000034$$

This value is indeed very small but leads to significant irreversibilities in the UHCF-regime, resulting in $\gamma_{pl,loc,cum} = 4N \cdot \gamma_{pl.loc} \cdot p \approx$ **34 !!!!!**

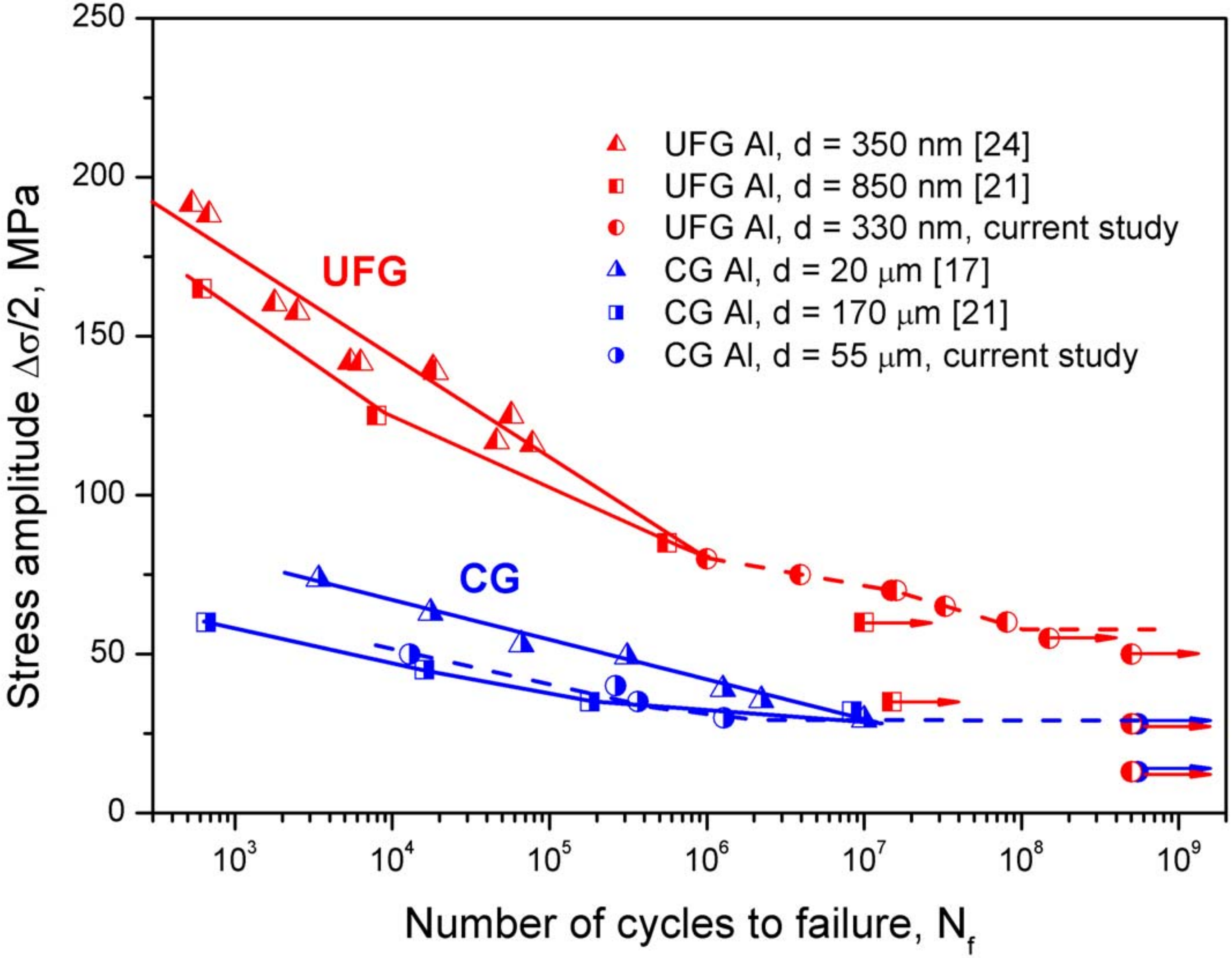
Comparison of S-N curves of UFG copper and CG copper

After P. Lukáš, L. Kunz and M. Svoboda, 2006



S-N (Wöhler) diagram of CG and UFG aluminium

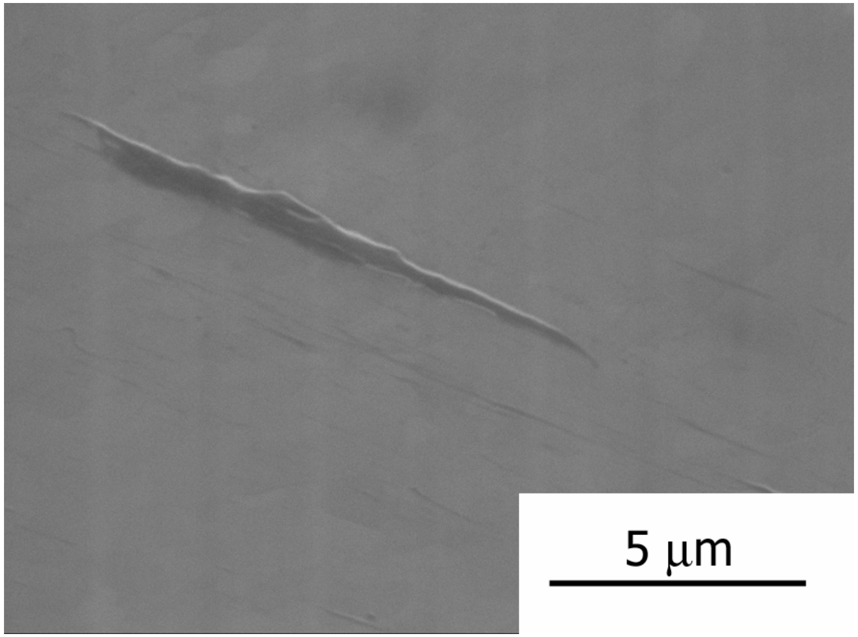
(H.W. Höppel et al., 2007)

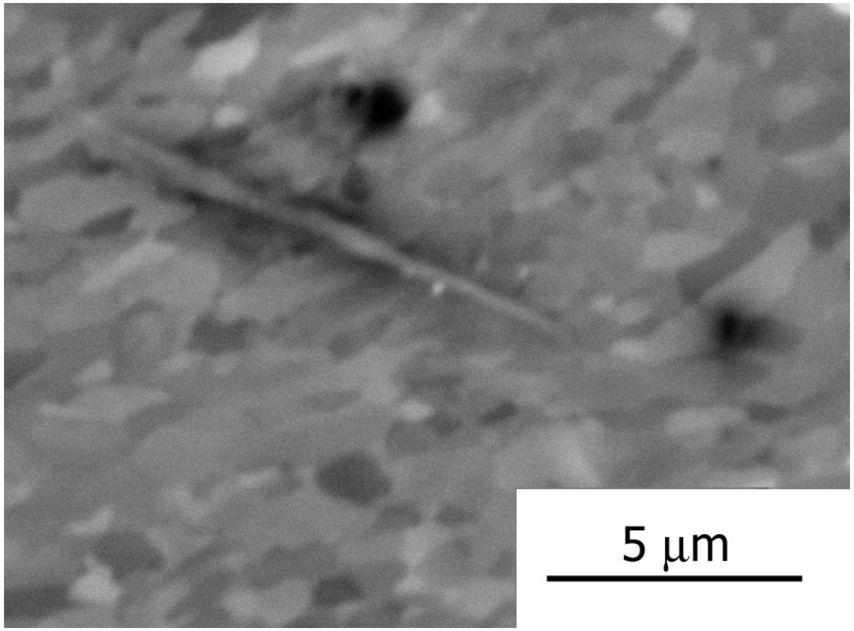


Extrusions in Al fatigued at $\Delta\sigma/2$ = 13 MPa

(H.W. Höppel et al., 2007)

loading axis





secondary electron contrast **electron channeling contrast**

PSB thresholds in UHCF (Type I Materials)

LCF/HCF range:

- PSBs appear as cyclic saturation is approached
- PSB thresholds: the amplitudes of stress and plastic strain, above which PSBs appear in the LCF/HCF range.

UHCF range:

- PSBs appear at amplitudes below PSB threshold after sufficiently large number of cyles.
- **i.e. PSB threshold is cycle-dependent !!!**

CONCLUSIONS

- **Fatigue life** in UHCF regime is controlled by **fatigue crack initiation.**
- **Multistage fatigue life diagrams** must be expected for type I materials (no inclusions) and for high-strength type II materials (with inclusions), albeit for very different reasons.
- The existence of a **fatigue limit** is questionable.
- In **type II materials**, the sites of crack initiation change from the surface to internal inclusions in the transition from HCF to UHCF.
- **Details of UHCF behaviour of type II materials** depend on type, density and size of the inclusions and on specimen geometry.

CONCLUSIONS, cont‘d

- **Details of UHCF behaviour of type II materials** depend on type, density and size of the inclusions and on specimen geometry.
- The **mechanisms of UHCF fatigue crack initiation** at subsurface (and surface) sites must be studied in much more detail.
- In **some other materials**, subsurface failures also occur, for not well understood reasons.
- In **type I materials**, stage I fatigue cracks are initiated **below the PSB threshold** in UHCF, since the accumulation of very small cyclic slip irreversibilities can lead to a **critical surface roughness** and, subsequently, to PSB formation.

THE END

THANK YOU FOR YOUR ATTENTION

Condition for crack initiation at site of maximum stress concentration:

$\sigma_{i,loc} = \sigma_{s,th} = \sigma_{PSB}$. Assume $\rho_{th} \approx \rho_i$, crack depths $a \propto rms$.

Then we obtain:

$$\frac{K_{t,i}}{K_{t,th}} = \sqrt{\frac{a_i \rho_{th}}{a_{th} \rho_i}} \approx \sqrt{\frac{(rms)_i}{(rms)_{th}}} \text{ and, after replacing (rms): } \frac{K_{t,i}}{K_{t,th}} \approx \sqrt[4]{\frac{N_i \gamma_{pl,i} p_i bh}{N_{th} \gamma_{pl,th} p_{th} bh}}$$

Multiply by $\sigma_{s,i}$, equate to $\sigma_{s,th}$, then with c.s.s. curve and $\gamma_{pl} = M \cdot \Delta\varepsilon_{pl}/2$, and resolving for number of cycles N_i at which a crack would initiate at the stress level $\sigma_{s,i}$, one obtains:

$$N_i = \frac{p_{th}}{p_i} \left(\frac{\sigma_{s,th}}{\sigma_{s,i}} \right)^{\frac{4n'+1}{n'}} N_{th}.$$

Variant 1: $p \neq p(\Delta\varepsilon_{pl}/2)$.

$$N_i \approx \left(\frac{\sigma_{s,th}}{\sigma_{s,i}} \right)^{\frac{4n'+1}{n'}} N_{th}.$$

and

Variant 2: $p \propto 1/\Delta\varepsilon_{pl}/2$

$$N_i \approx \left(\frac{\sigma_{s,th}}{\sigma_{s,i}} \right)^{\frac{4n'+2}{n'}} N_{th}.$$

Number of cycles till fatigue crack initiation in range III

$$\frac{K_{t,i}}{K_{t,th}} = \sqrt{\frac{a_i \rho_{th}}{a_{th} \rho_i}} \approx \sqrt{\frac{(rms)_i}{(rms)_{th}}}$$

. Assuming $\rho_{th} \approx \rho_i$ and $a_i \propto (rms)_i$, replacing (rms):

$$\frac{K_{t,i}}{K_{t,th}} \approx \sqrt[4]{\frac{N_i \gamma_{pl,i} p_i \mathrm{bh}}{N_{th} \gamma_{pl,th} p_{th} \mathrm{bh}}} .$$

Multiplying by $\sigma_{s,i}$, equating to $\sigma_{s,th}$, replacing γ_{pl} by $\Delta\varepsilon_{pl}/2$ via the cssc,

Condition for crack initiation: $\sigma_{i,loc} = K_{t,i}\sigma_{s,i} \geq \sigma_{s,th} = \sigma_{PSB}$

→ **number of cycles N_i till fatigue crack initiation at the stress level $\sigma_{s,i}$:**

$$N_i = \frac{p_{th}}{p_i} \left(\frac{\sigma_{s,th}}{\sigma_{s,i}} \right)^{\frac{4n'+1}{n'}} N_{th} .$$

Ti 6246 Fatigue Data Room Temperature, R=0.05

Wayne Jones, personal communication, 2005