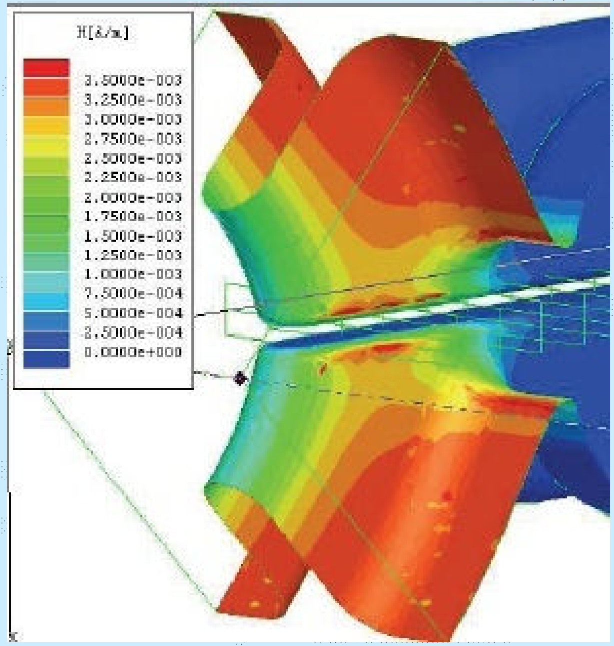
Markus Aicheler, Ruhr-University Bochum and CERN

Surface thermal fatigue in uniaxial and biaxial loading

Introduction: CLIC surface heating phenomenon



- Pulsed magnetic field induces currents
- Superficial Jule heating

⇒ cyclic heat-and cooling phases

⇒ thermal fatigue

For conductivity of copper: $\Delta T \approx 60$ K

⇒ $\sigma \approx 0$ MPa to 150 MPa (comp.)

⇒ Heated layer depth several µm

Surface magnetic field distribution in HDS cell

Estimated CLIC life time 2×10^{10} cycles @ 50Hz
(= 20 years of operation)

=> No mean to test a “real” structure under “real” conditions for whole life time!

Observation material

C10100 (OFE Copper)

- Reference material
- Well known
- Results comparable to other researchers
- Supplementary fatigue data needed (CuZr already well tested by Samuli)

40% cold worked

- as received
- Round bar cold rolled Ø 40 mm and Ø 100 mm
- Yield Strength: $R_{p0.2}$ = 316 MPa
- Ultimate tensile strength: R_m = 323 MPa
- Average grain size: Ø 110 um

Brazed

- Heat treatment in vacuum furnace:

300 K/h -> 795 °C; 60 min hold

100 K/h -> 825 °C; 6 min hold

Natural cooling in vacuum

- Yield Strength: $R_{p0.2}$ ≈ 72 MPa
- Ultimate tensile strength: R_m = 270 MPa
- Average grain size: Ø 400 um

2h@1000 °C

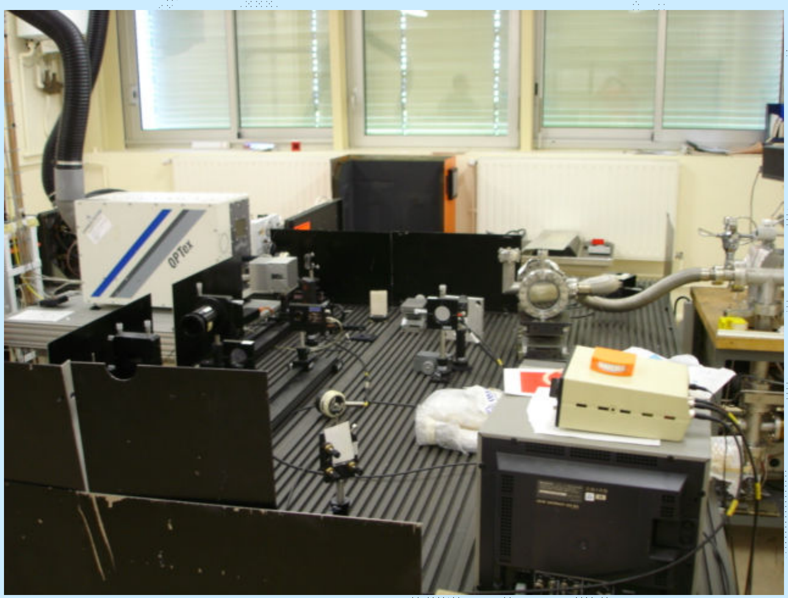
- Heat treatment in vacuum furnace:

300 K/h -> 1000 °C; 120 min hold

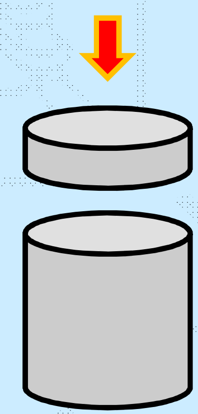
Natural cooling in vacuum

- Yield Strength: $R_{p0.2}$ ≈ 72 MPa
- Ultimate tensile strength: R_m = 257 MPa
- Average grain size: Ø 1400 um

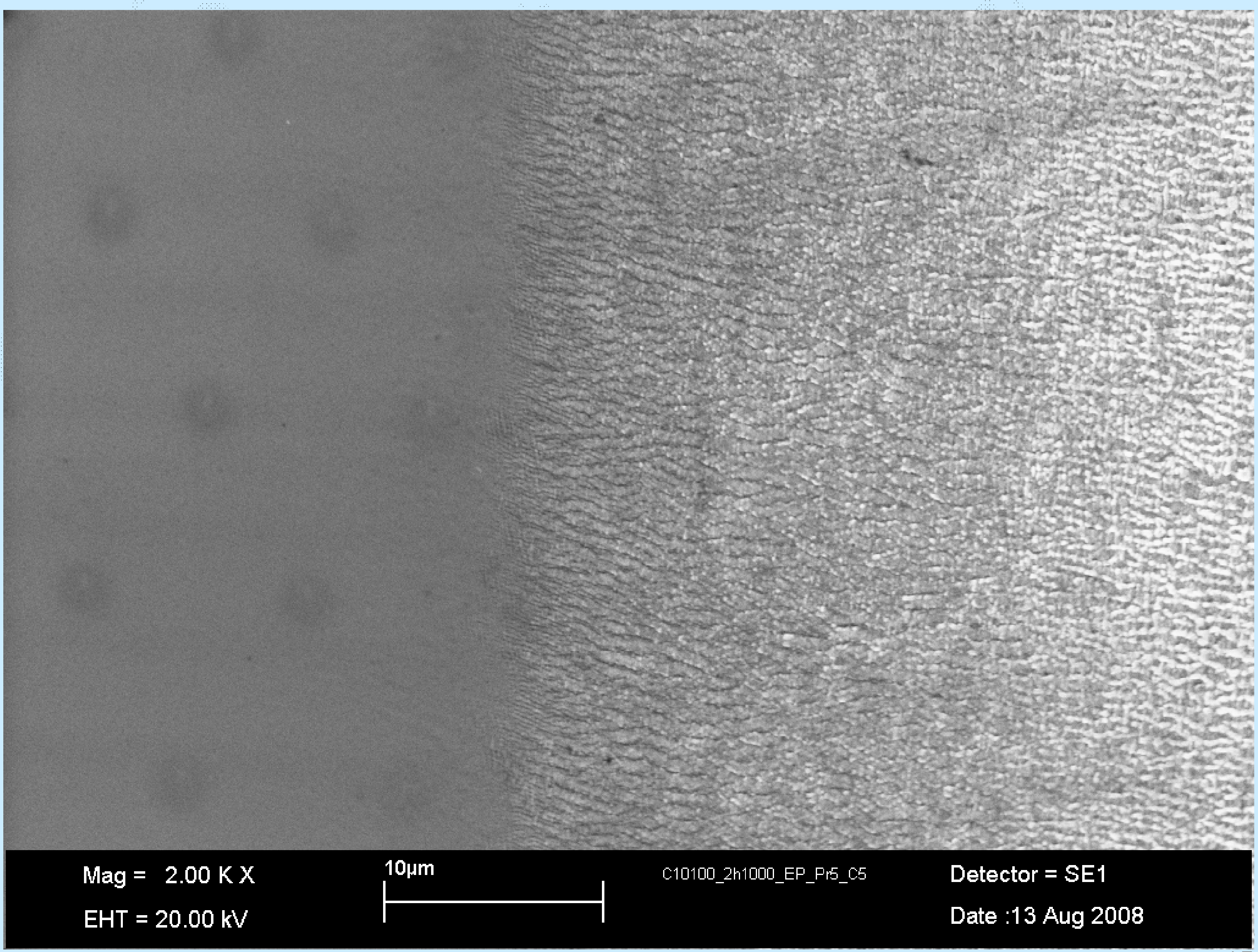
Laser fatigue device



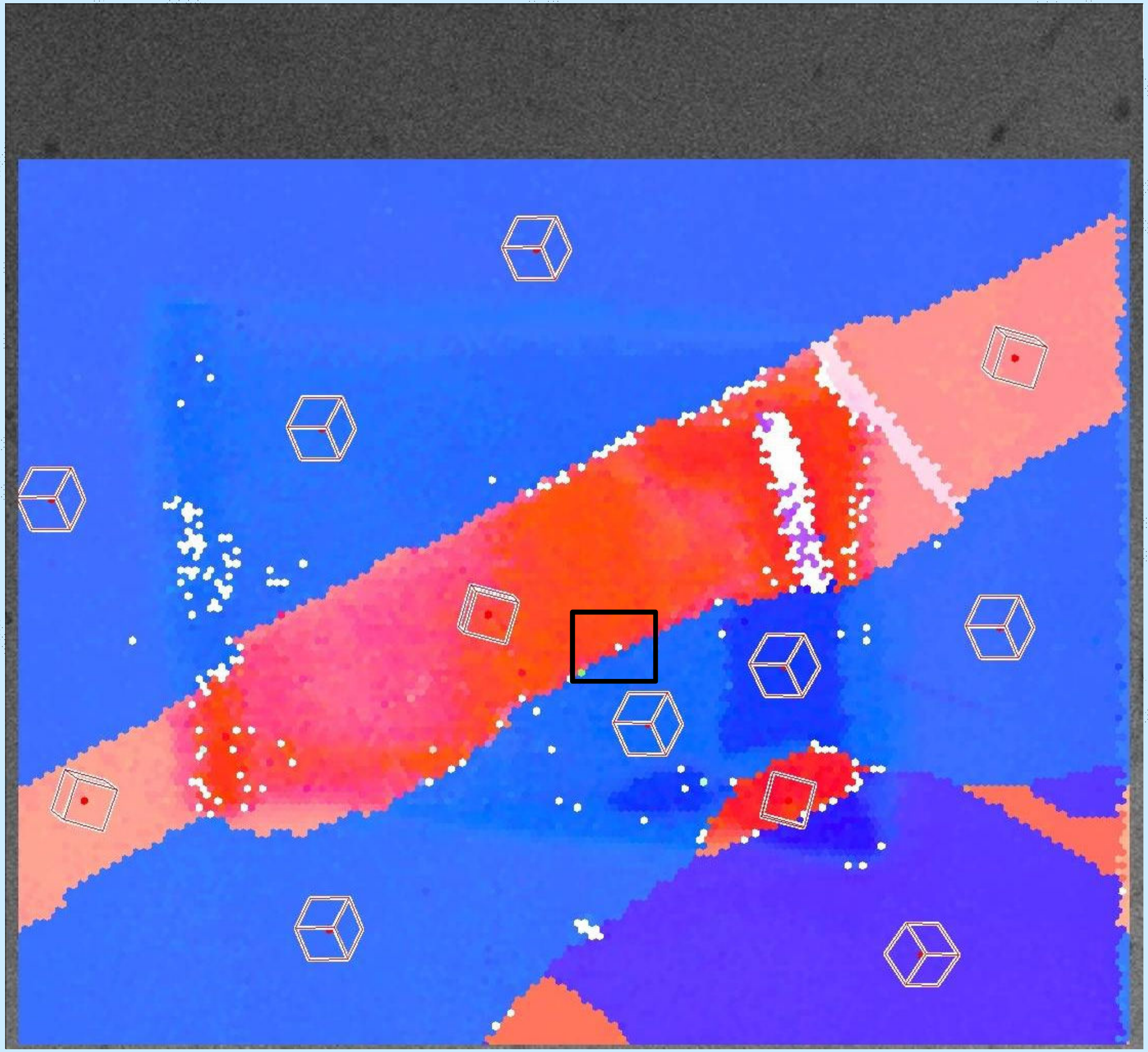
- Thermal fatigue through irradiation
- OPTEX Excimer Laser; λ = 248 nm
- Repetition rate 200 Hz
- Pulse length: 40 ns
- 5 x 10^4 shots @ 0.3 J/cm^2
- ΔT = 280 K ⇔ $\varepsilon = 7*10^{-3}$
- Round disc diameter 40 mm
- 25 discrete spots per disc

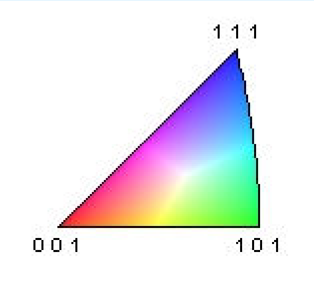


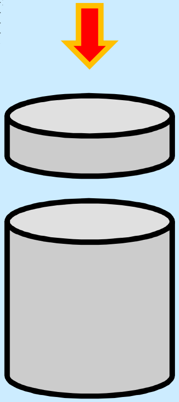
C10100_2h@1000_EP_Probe5_C5 Virgin Surface



C10100_2h@1000_EP_Probe5_C5







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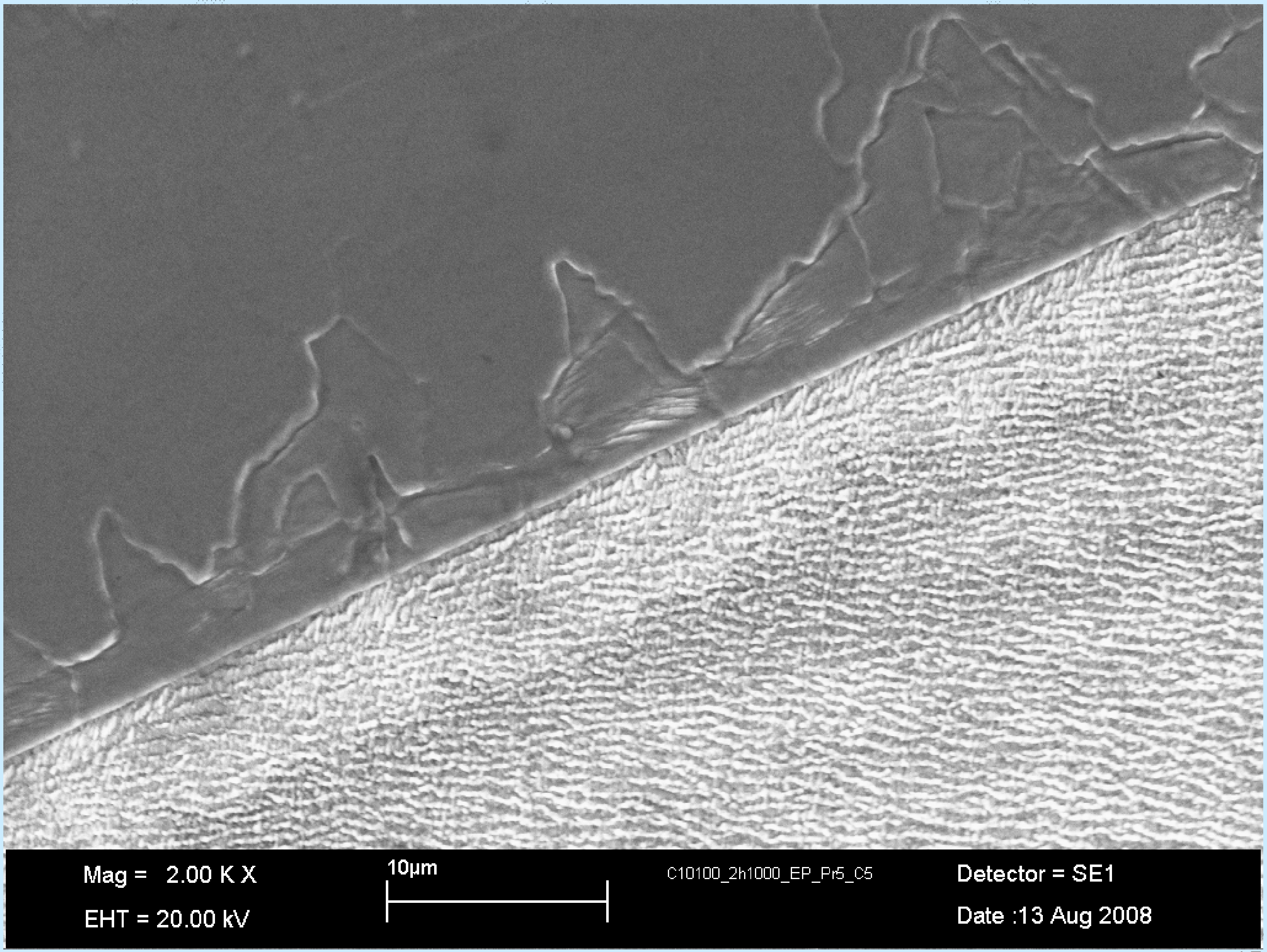
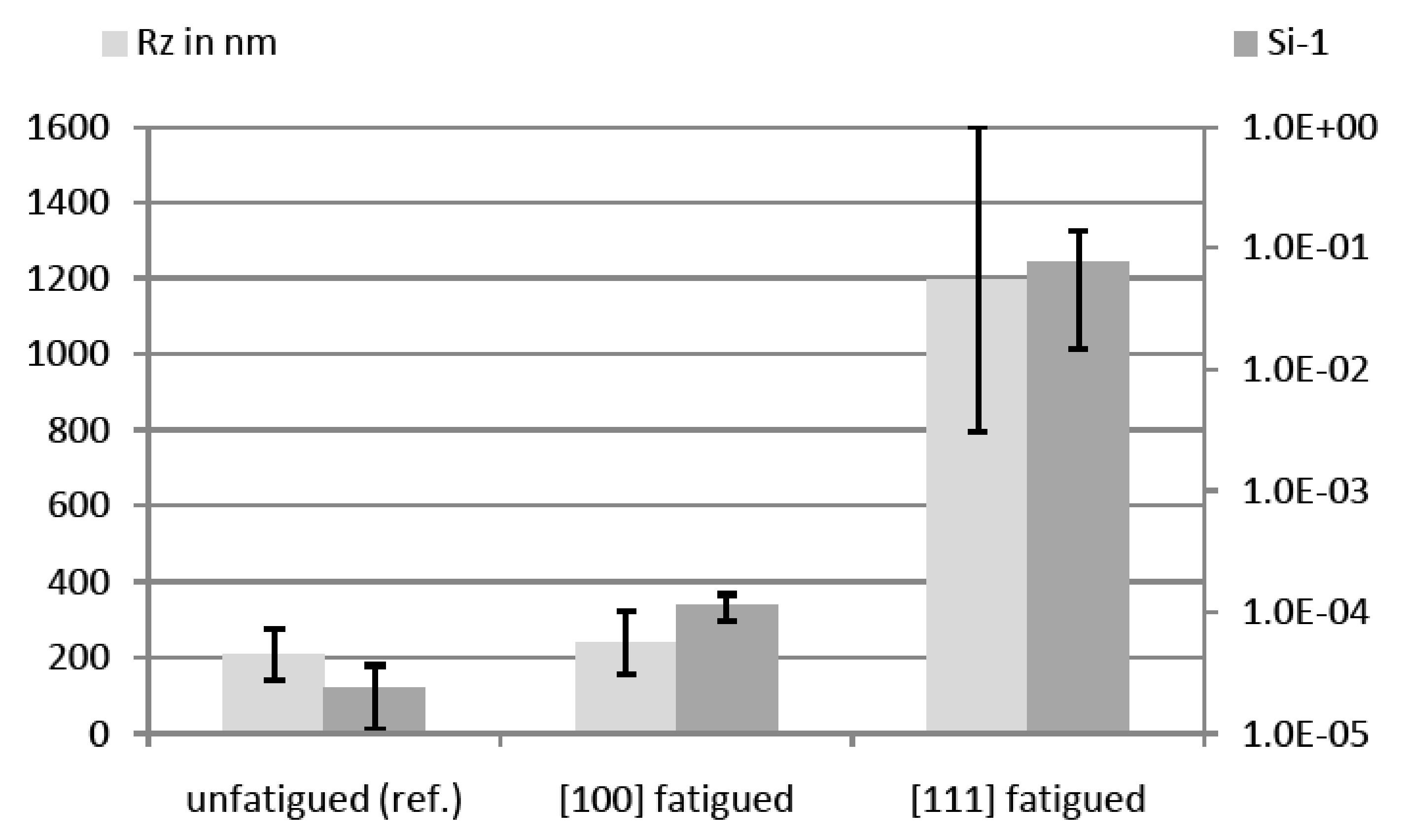
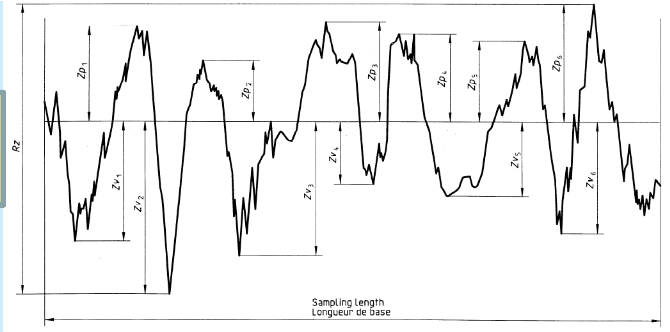
C10100_2h@1000_EP_Probe5_C5



C10100_2h@1000_EP_Probe5 Roughness Plot

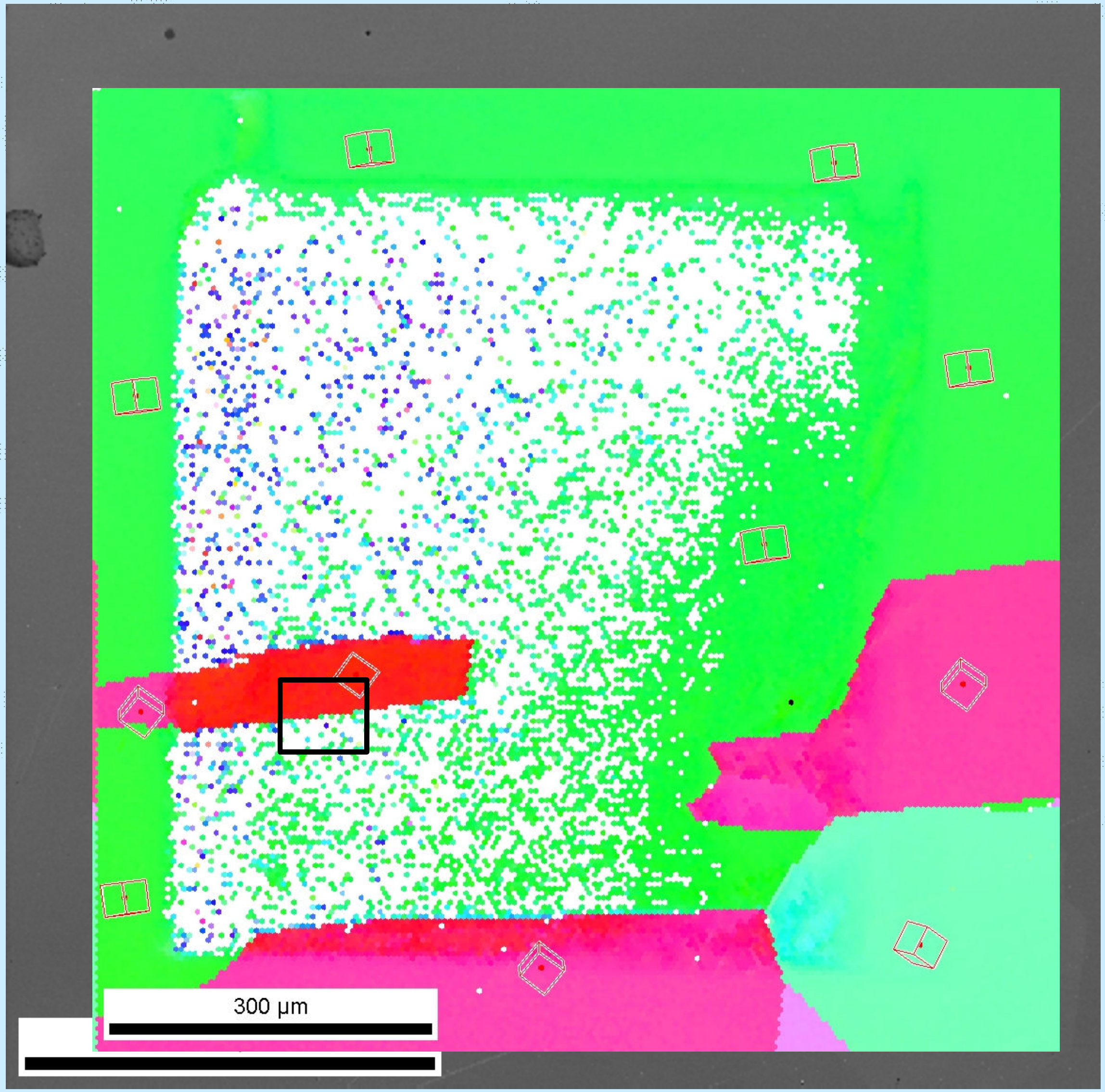


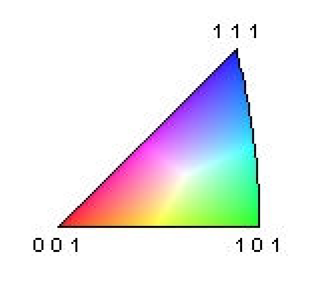
Rz



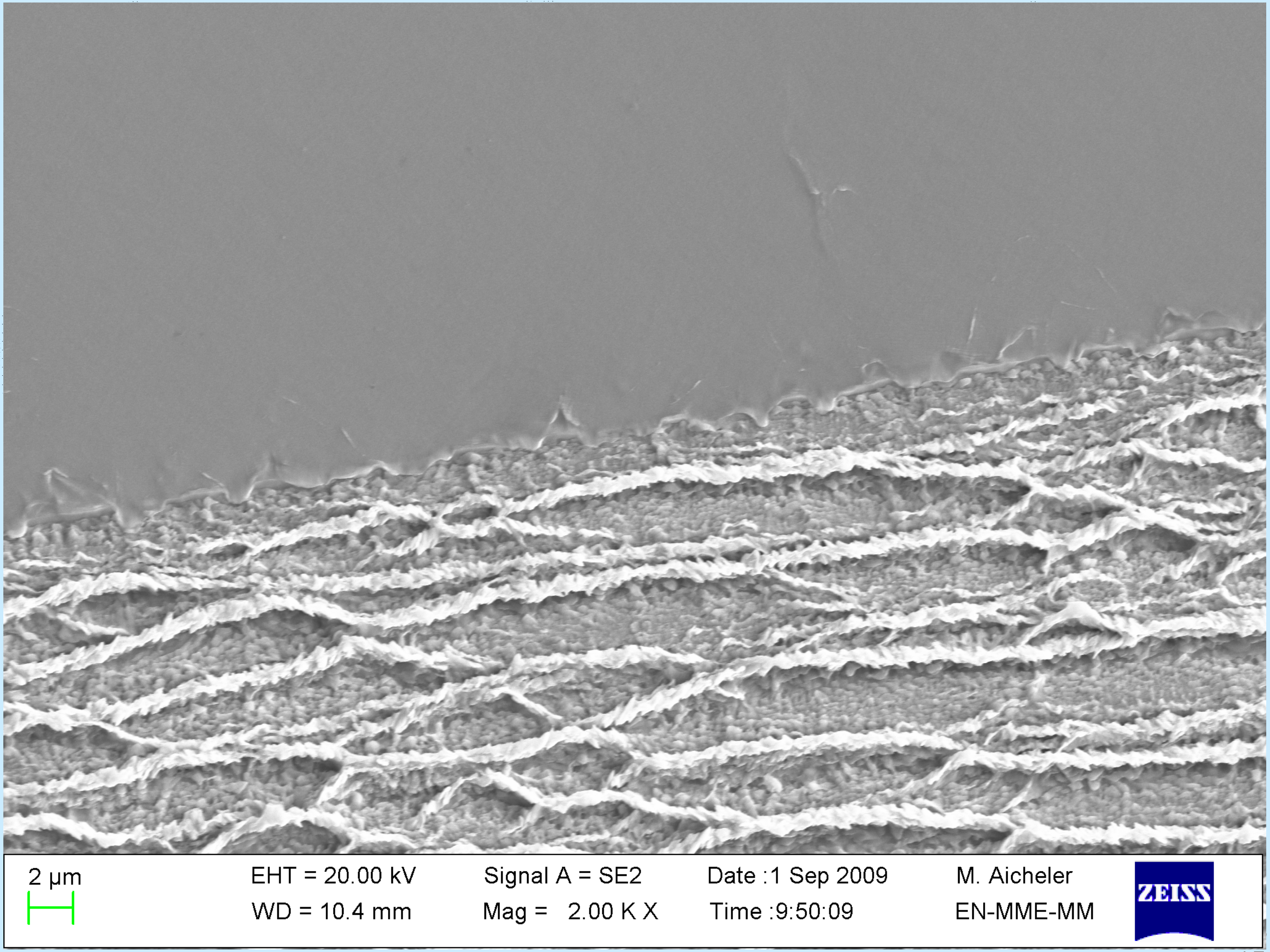
$$\text{Surface index} = \frac{\text{true surface}}{\text{projected surface}}$$

C10100_2h@1000_EP_45°Probe3_C1

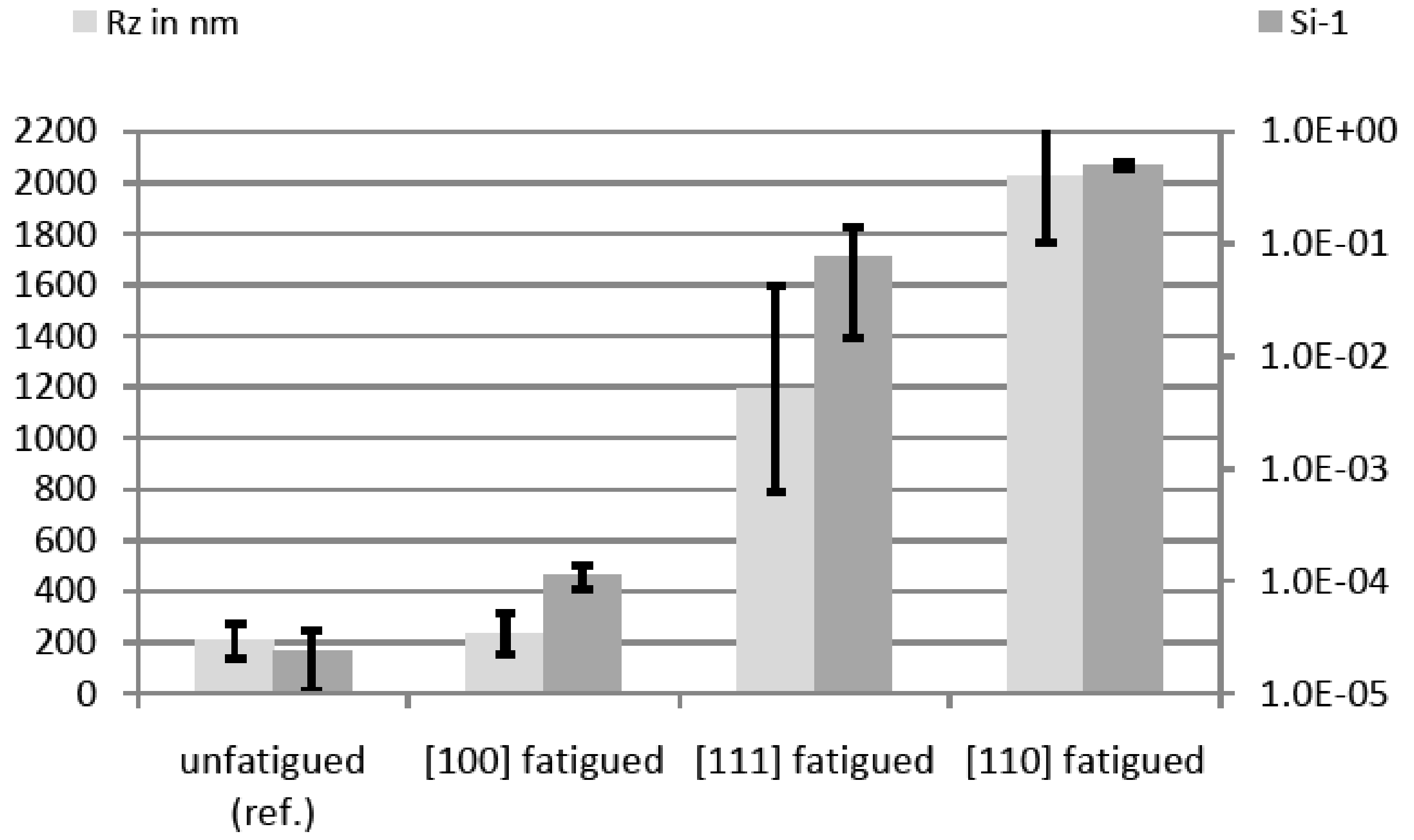




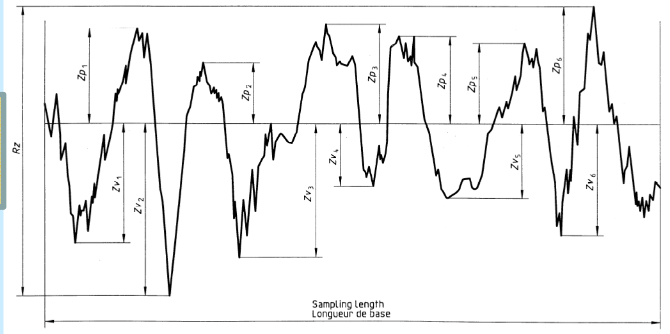
C10100_2h@1000_EP_45°Probe3_C1



C10100_2h@1000_EP_Probe5 Roughness Plot

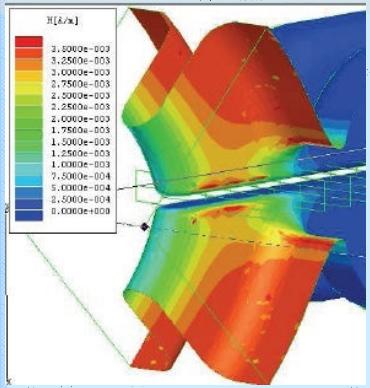


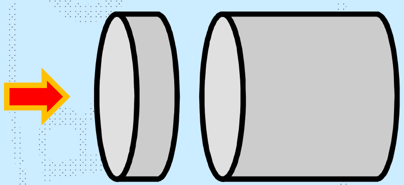
Rz

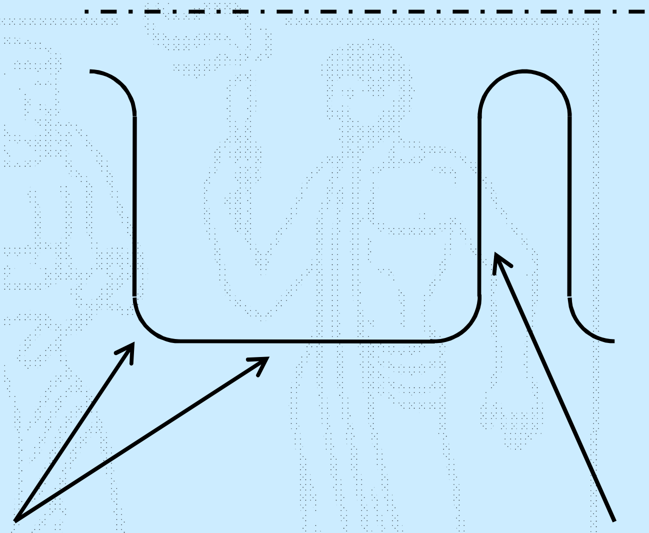


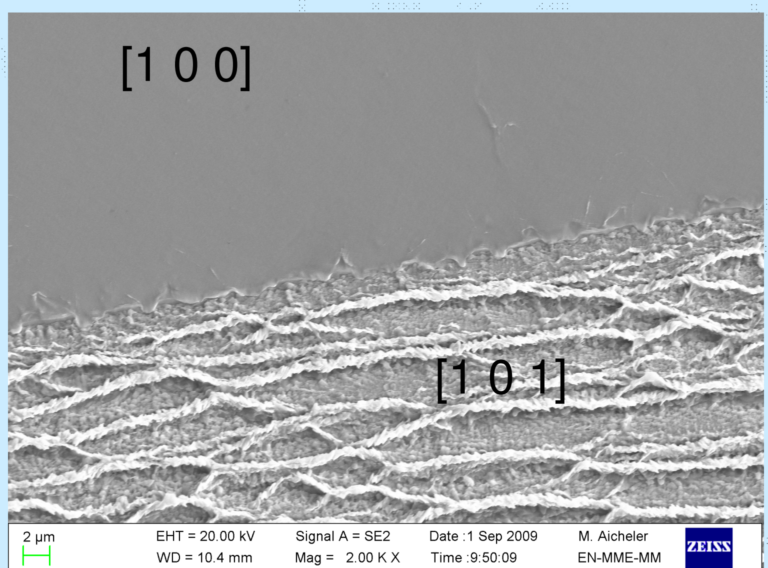
$$\text{Surface index} = \frac{\text{true surface}}{\text{projected surface}}$$

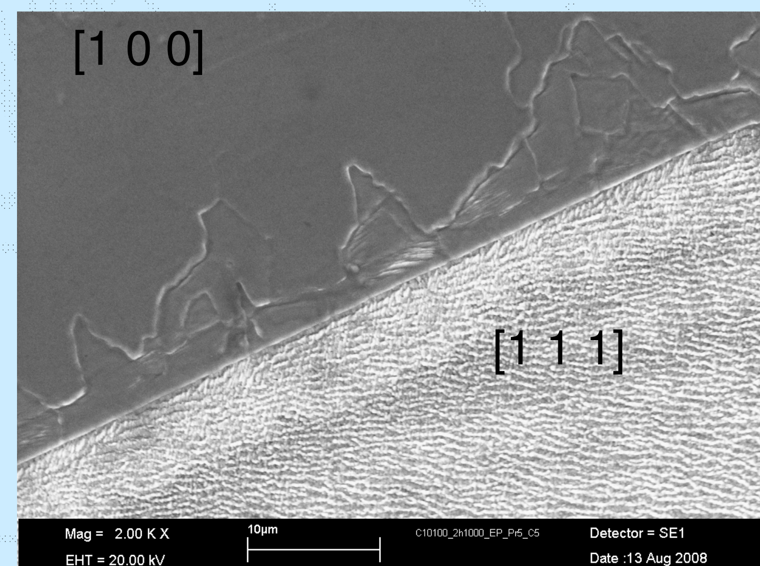
Real structure?







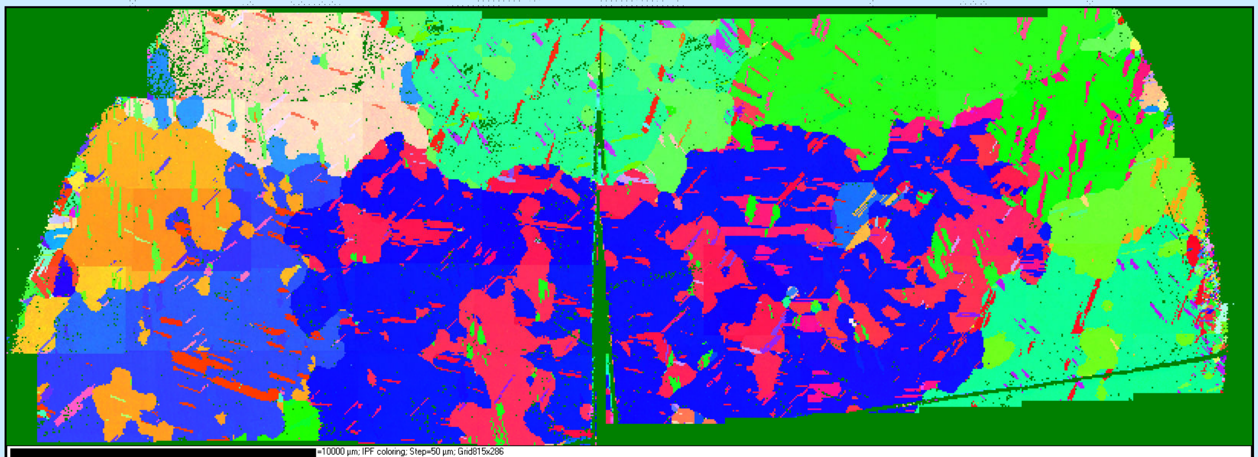




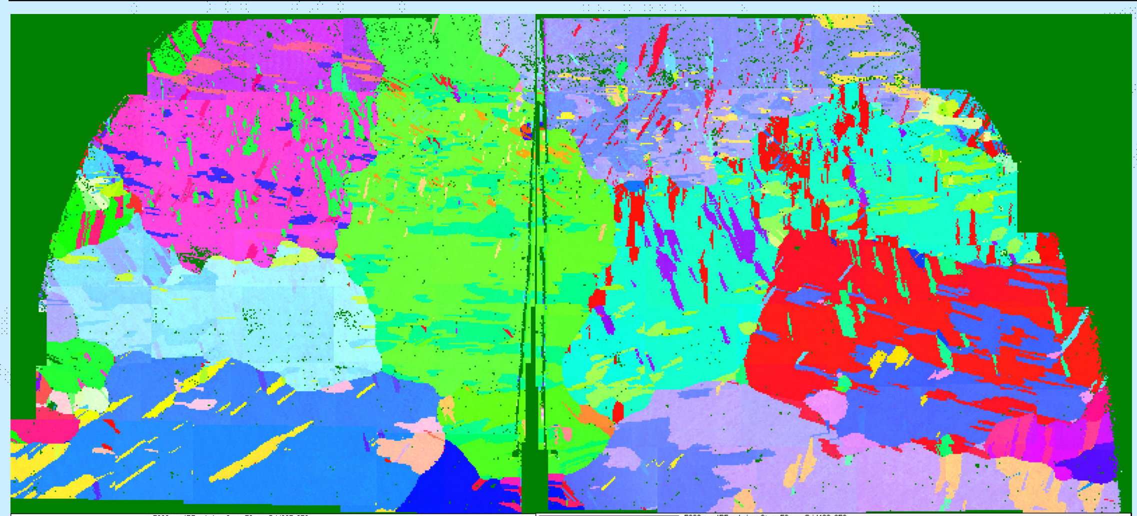
Real material…

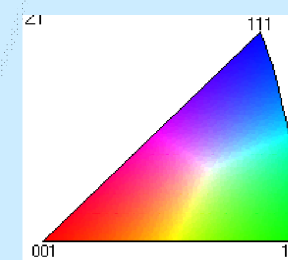
2h@1000°C

Cu 0°



Cu 45°

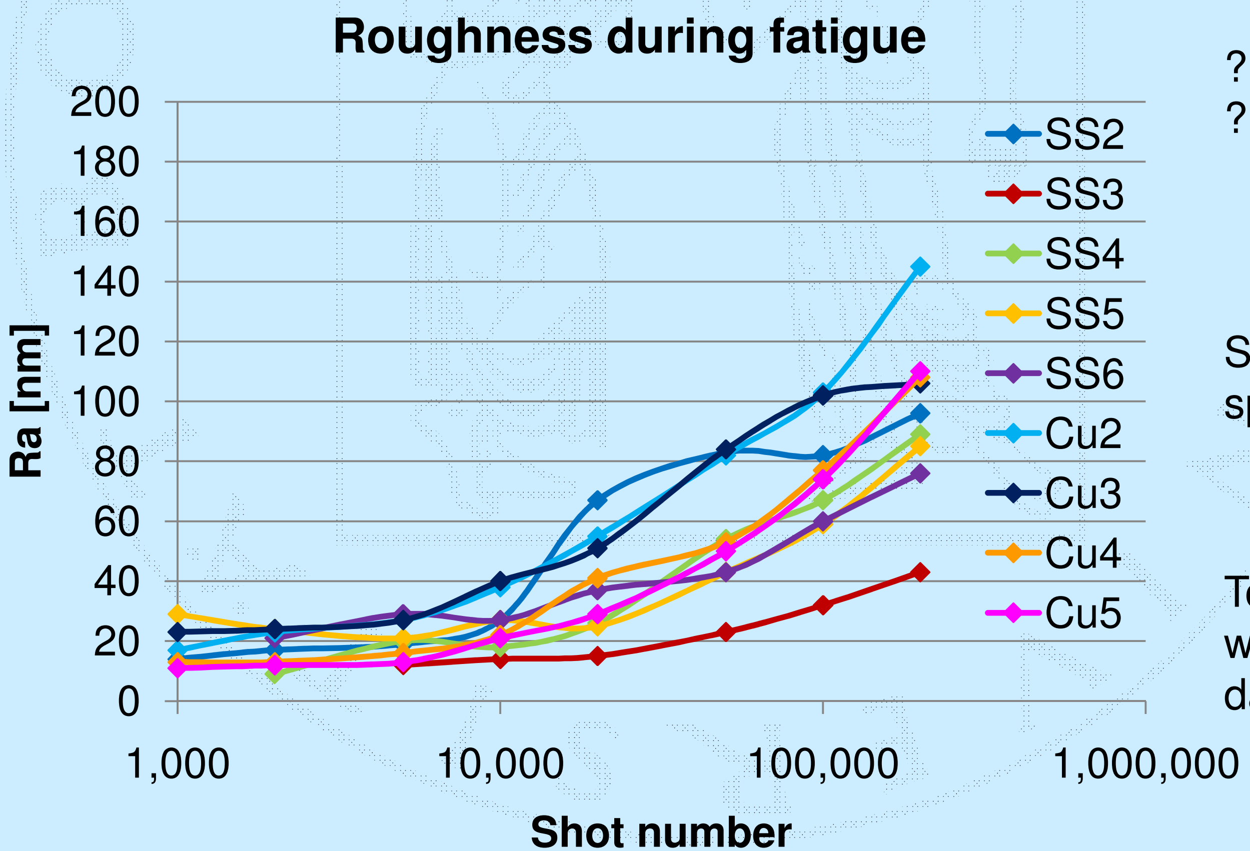




Courtesy of P.Alknes

Thin films

Substrate: Cu or SS ⇨ Ti bonding layer 250nm ⇨ Cu layer → Pressure / Thickness / Power



? Texture Index ?

? Reproducibility ?

SS3: 20µm no special texture…

To be compared with new bulk data…

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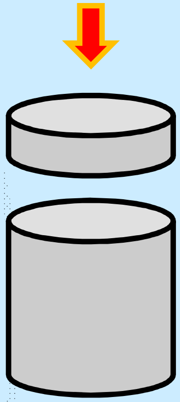
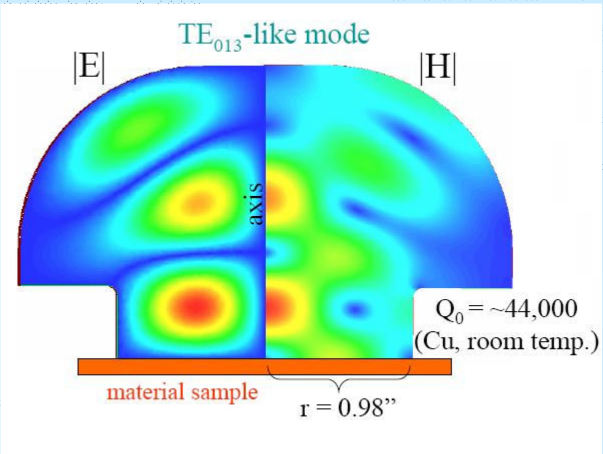
15.10.2009

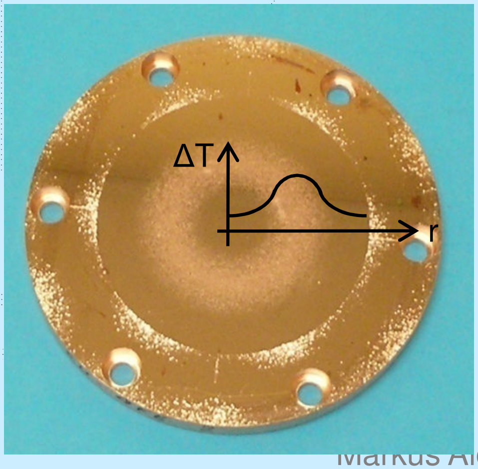
SLAC RF heating device (Stanford)

Photos: Sami Tantawi
Presentation 23 Jan. 2008

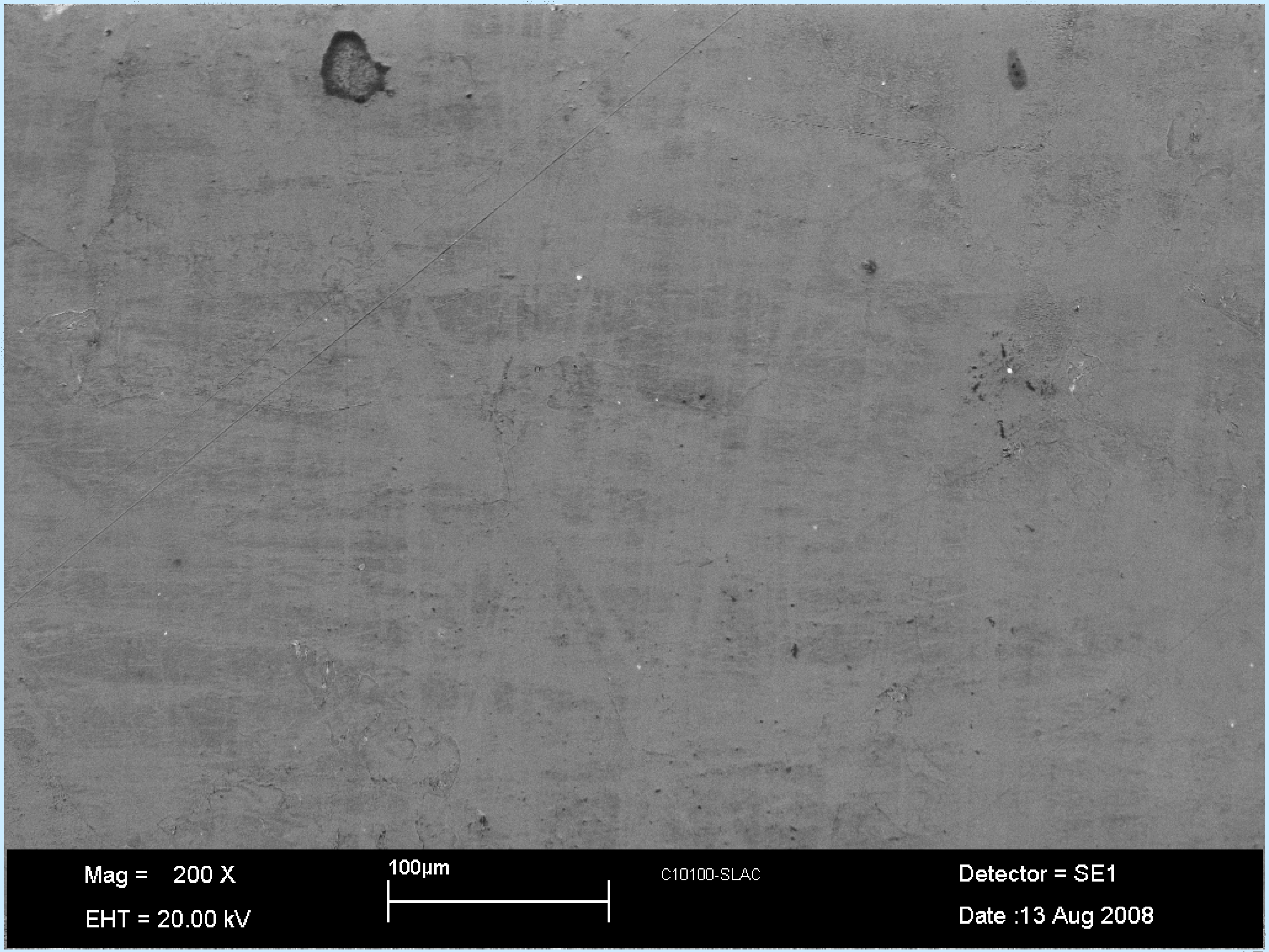
- Thermal fatigue due to RF heating
- Mushroom cavity @ 11,4 GHz
- Repetition rate 60 Hz
- Pulse length 1.5 µs
- 2 x 10^6 Pulses @ 50 MW
- ΔT_{max} = 110 K ⇔ ε = $1.8*10^{-3}$
- Round disc diameter 100 mm
- Continuous radial distribution of ΔT



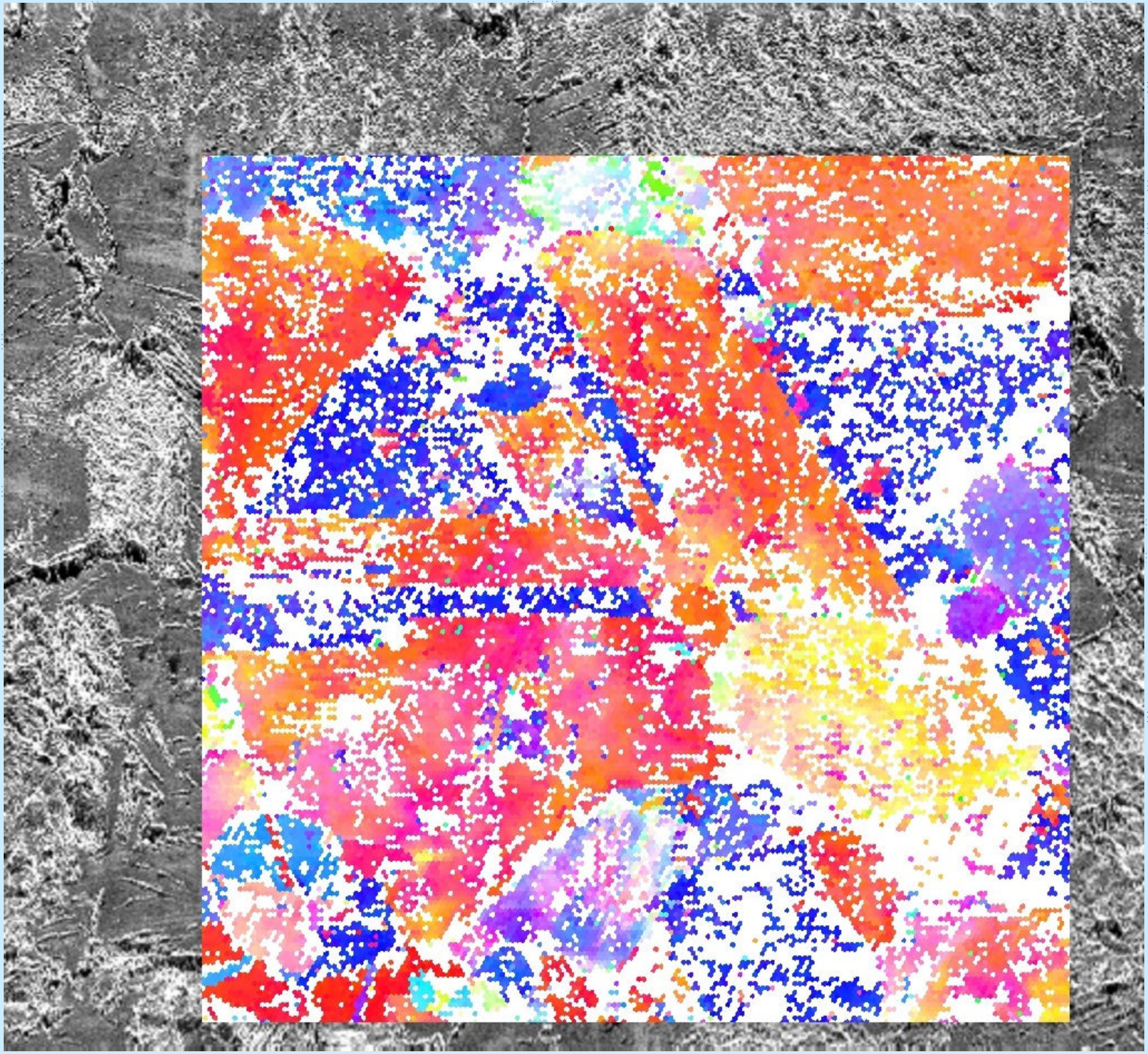


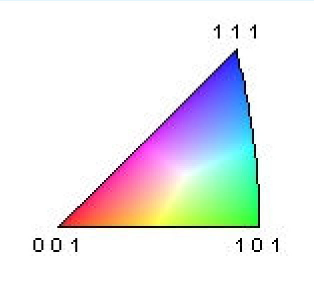


SLAC RF fatigue: Virgin Surface

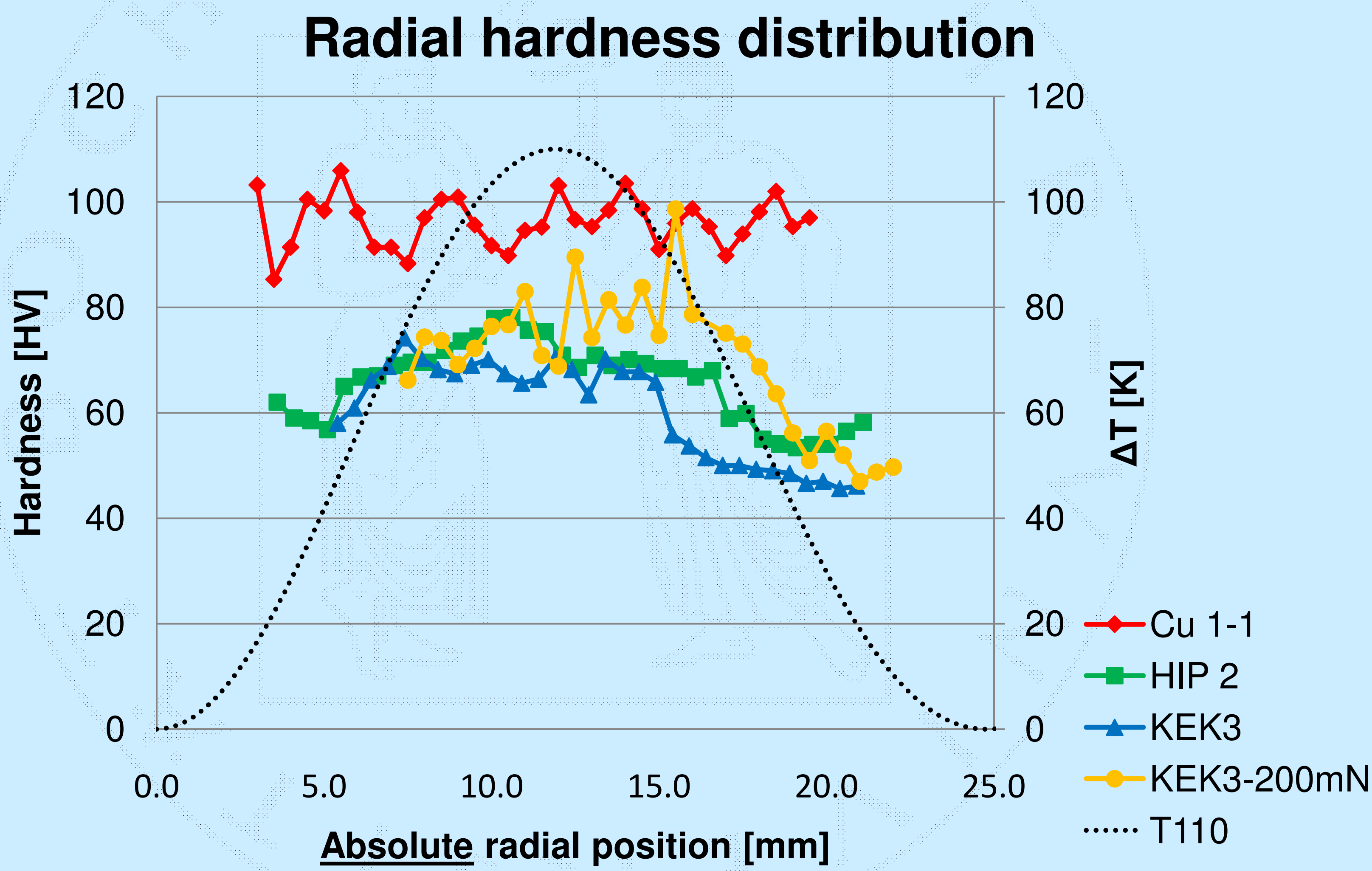


SLAC RF fatigue: Highest temp. load





SLAC RF fatigue: Highest temp. load



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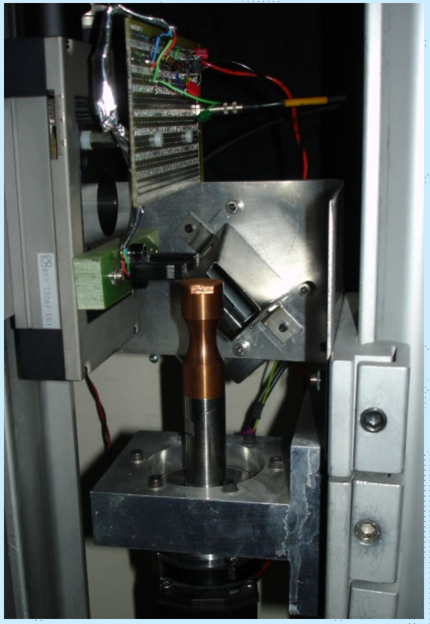
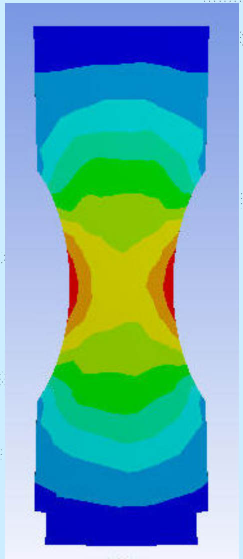
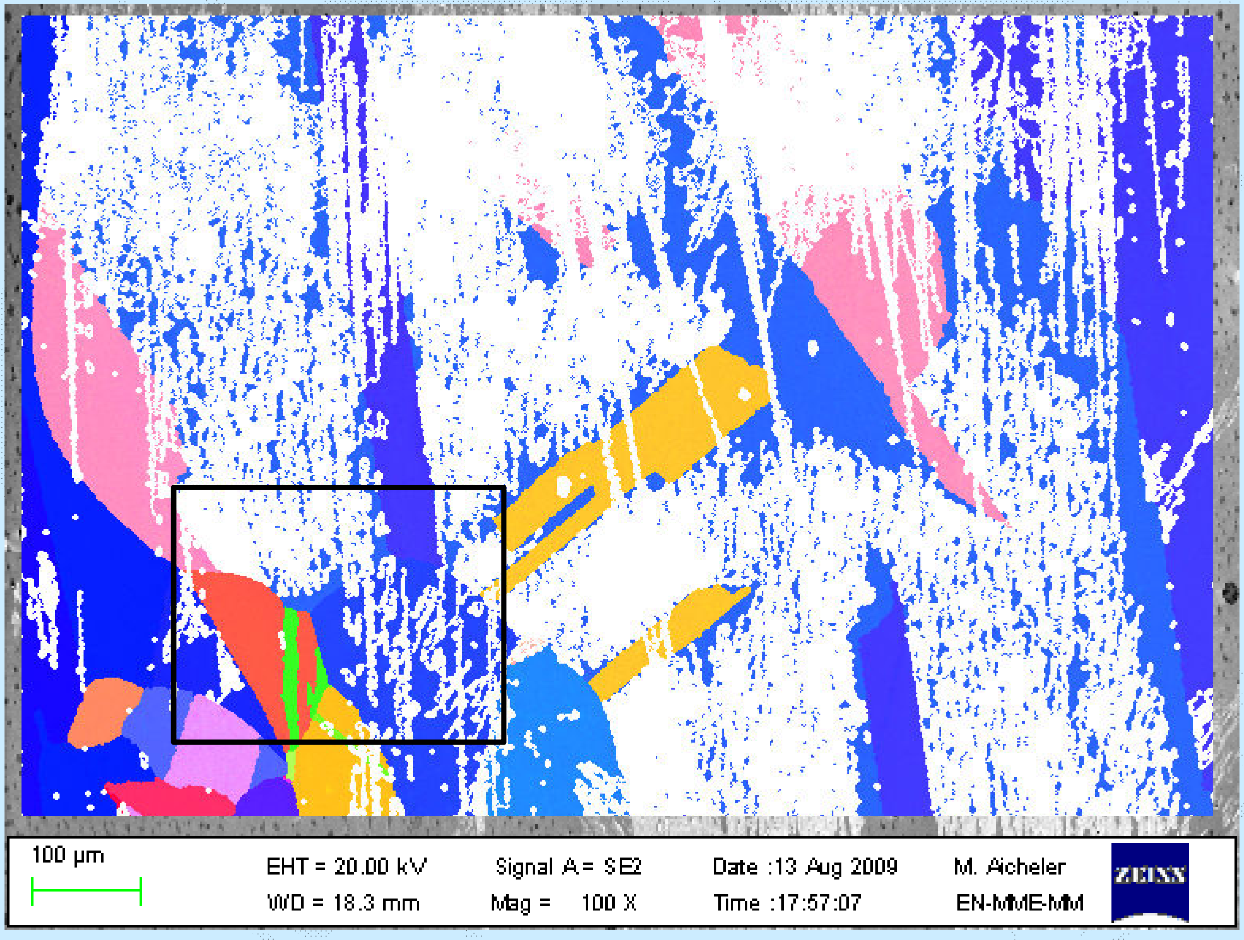
Ultrasound swinger device (USS)

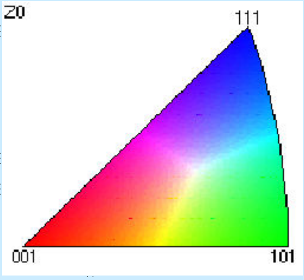


- Mechanical fatigue; R = -1 ($R = \sigma_{max} / \sigma_{min}$)
- Piezo electric resonant attenuator
- Repetition rate 24 kHz
- Cycles: $5*10^9$
- σ_{max} = +/-60 Mpa ⬄ $\varepsilon = 6*10^{-4}$
- Samples: special designed sonotrodes

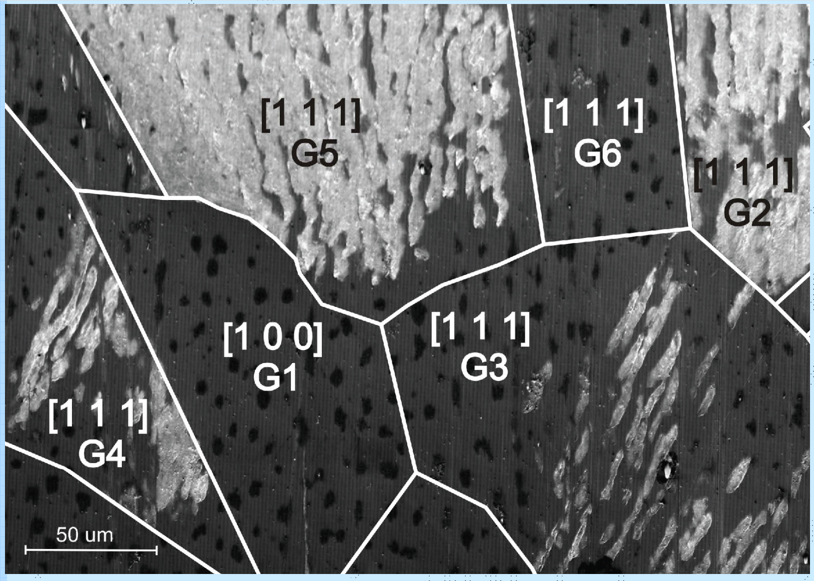


USS annealed sample



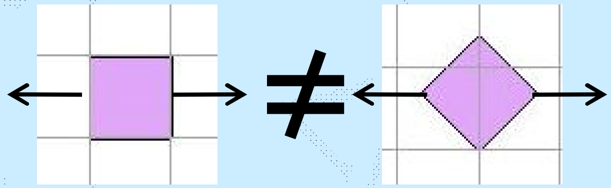


Discussion uniaxial fatigue results



Observation:

- only undamaged [1 0 0] grains observed so far
- [1 1 1] grains can appear also undamaged (G6) or partly damaged (G3 and G4)



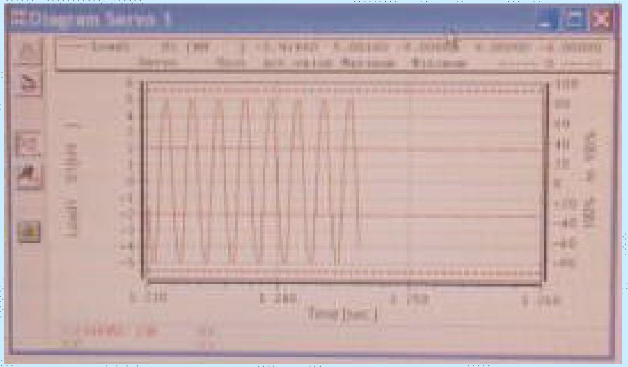
Analysis:

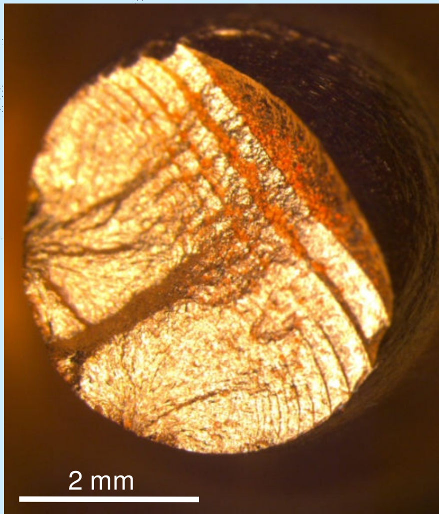
- In-plane orientation is very important in uniaxial loading
- The Euler1 angle of G6 differs significantly
  G3 and G4 do not differ in large amounts from G2 and G5
- Highest Schmid factor equal in G2-G6 and significantly lower in G6

Gradual degradation can therefore not be explained only by Euler1 and highest Schmid factor

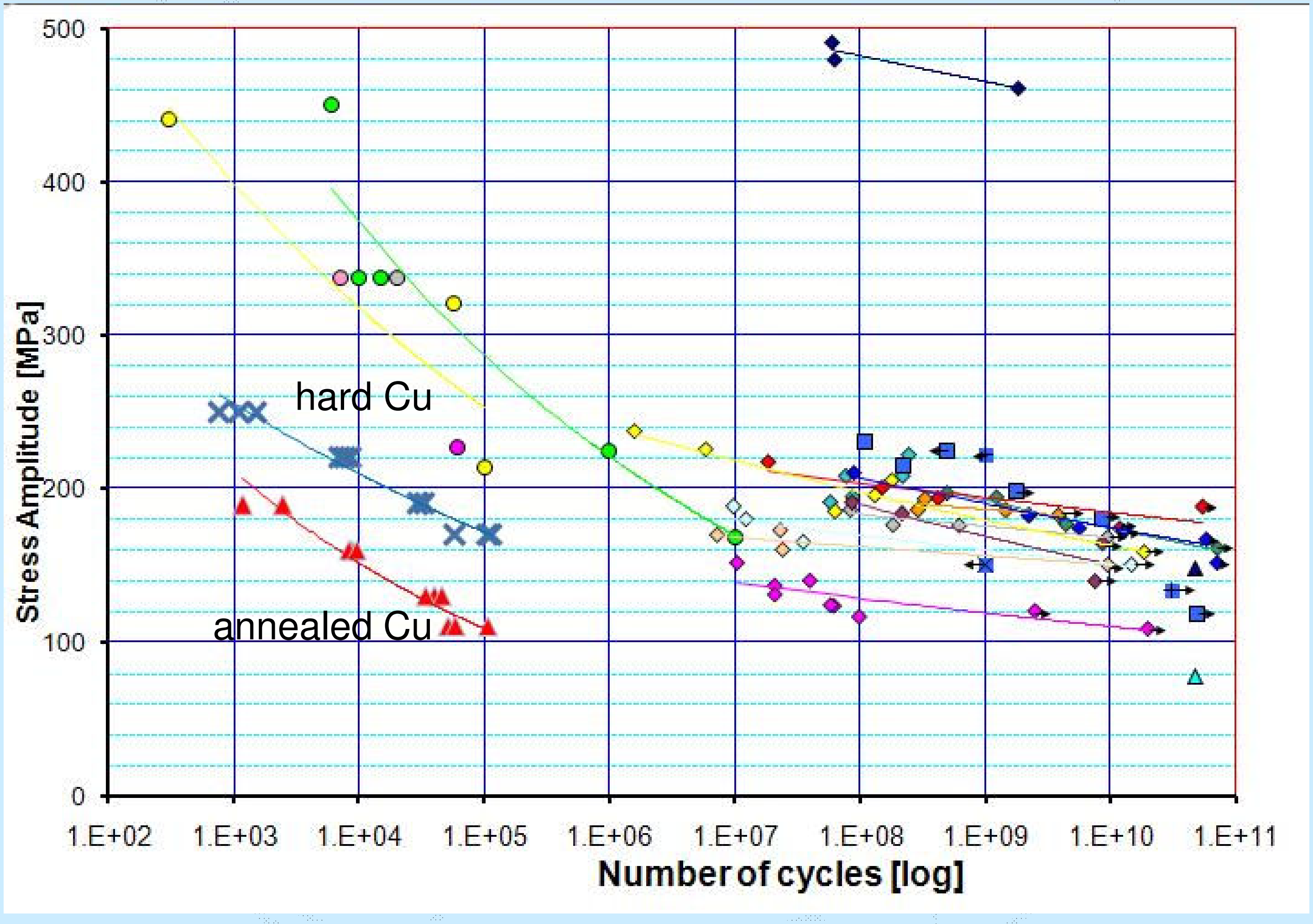
Conventional fatigue test

- Mechanical fatigue; R = -1 (R = σ_{max}/ σ_{min})
- UTS electro-mechanical universal-test machine
- Repetition rate 0.5 Hz
- Tested in loads up to +/-250 MPa; stress controlled
- Sample shape conform ISO 12106
- 3-5 samples for one data point
- Damage criterion: rupture





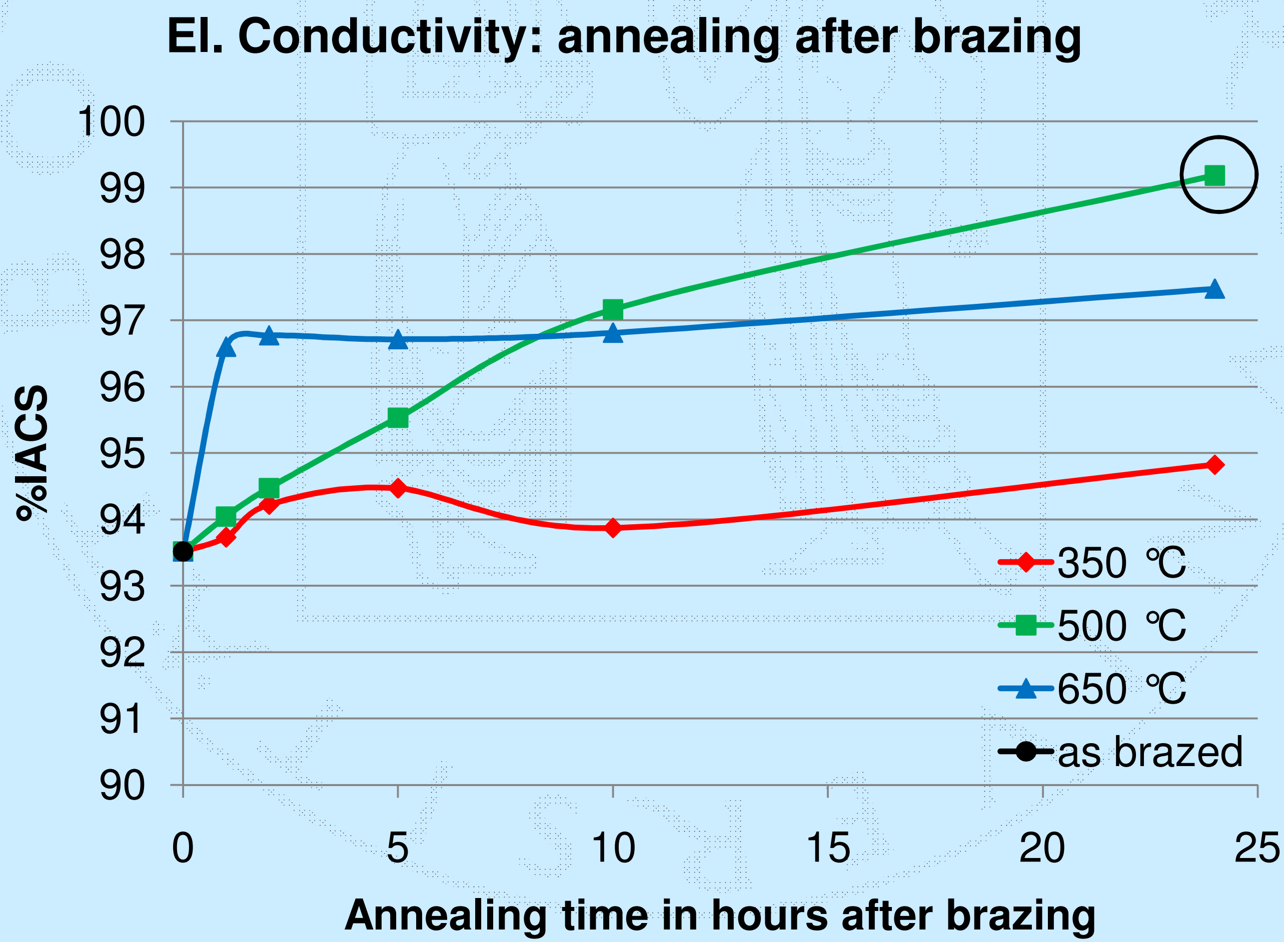
Conventional fatigue test



Conventional fatigue test

C15000 40%CW → Vacuum brazing → Annealing under Ar

300 K/h -> 795 ℃; 60 min hold
100 K/h -> 825 ℃; 6 min hold
Natural cooling in vacuum



All samples: 47±1 HV10

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Summary

- Laser experiments performed and full set of main orientations observed
=> Further understanding and attention focused on machining strategy for structure

- Tests with advanced textured copper films are ongoing
=> Possibility to enhance fatigue behavior of copper?!?

- Interpretation of uniaxial test results so far difficult
=> Ultimate comparison maybe not possible but ranking ok

- CuZr (C15000) introduced into test campaigns
=> "Best" state identified and under testing

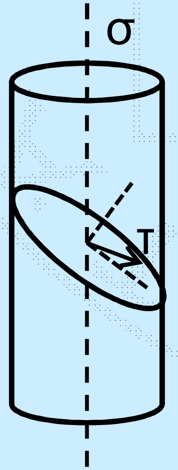
Thank you for
the attention!!!

Discussion thermal fatigue results

=> [1 1 1] (blue) direction high developed and [1 0 0] (red) direction less developed fatigue features

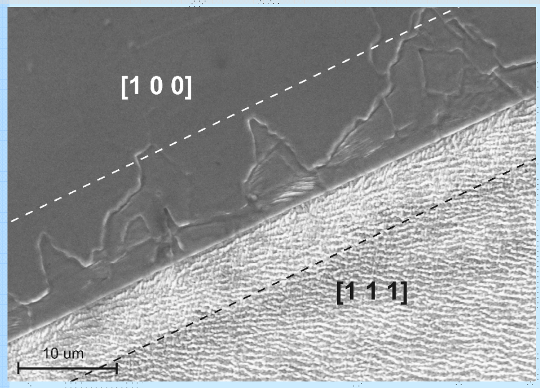
Possible explanations:

1. Isotropic thermal expansion causes due to anisotropic module different stresses ($\sigma_{[111]}/\sigma_{[100]}$ = 2.3 !!!) (Moenig)
2. Different Schmid factor configurations on slip systems
3. Different dislocation substructures form as a function of out-of-plane orientation (Zhang and Wang et al.)

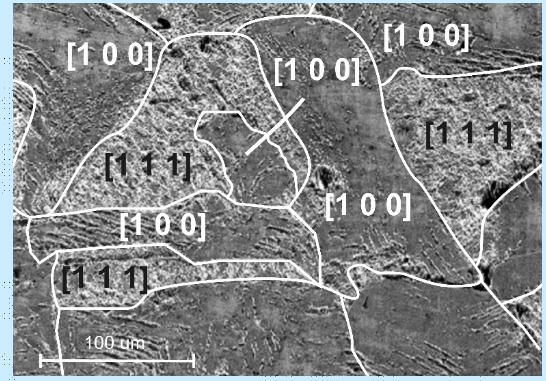


Schmid factor
$S=\tau/\sigma$

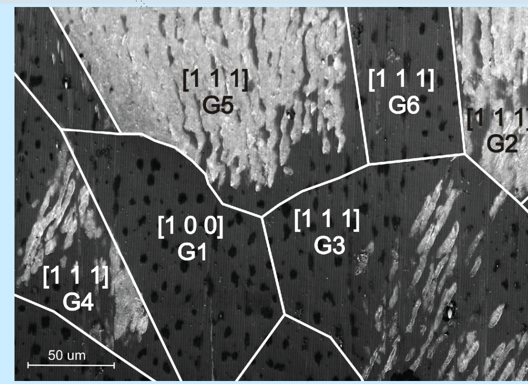
Conclusion and outlook



Laser fatigue



RF fatigue



USS fatigue

Conclusion

- **Features** look quite **similar** for thermal and mechanical uniaxial fatigue
- In thermal fatigue **easy** damage <=> orientation **assignment**.

  Uniaxial more **difficult**. (for once!!!)
- **Machining** strategy very **important!!!**

Outlook

- Further Schmid factor **analysis** and **statistics** needed to explain phenomena
- **Enhanced** fatigue life of strongly **textured** materials?