# Progress report of CLIC fatigue studies

# Contents

- CLIC parameters vs. fatigue life
- Discussion on the latest ultrasonic (US) fatigue test results
- Usability of the test results
- Fatigue damage criteria of CLIC
- Near future plans
- Suggestions for future work
- Wild guess what can be achieved with existing material(s)

# Preface

Since January 2005

- 95 samples
- 12000 hours (500days) of non-stop ultrasound operation

W. Wünsch: Minutes of the CLIC Meeting - 27 April 2006

# CLIC parameters vs. fatigue life

Repetition rate → Number of cycles

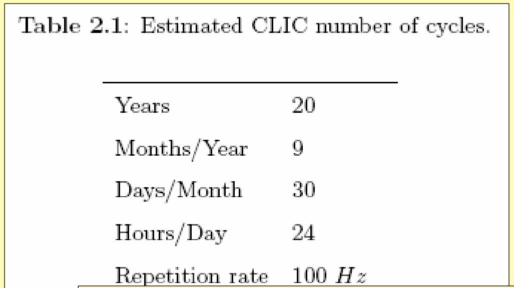
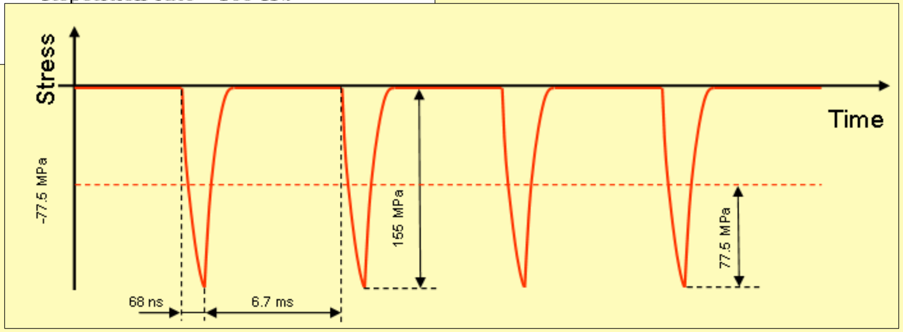


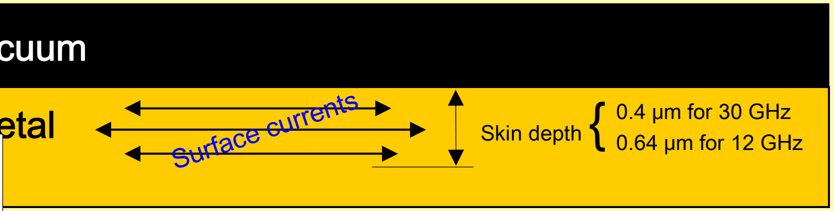
Table 2.1: Estimated CLIC number of cycles.

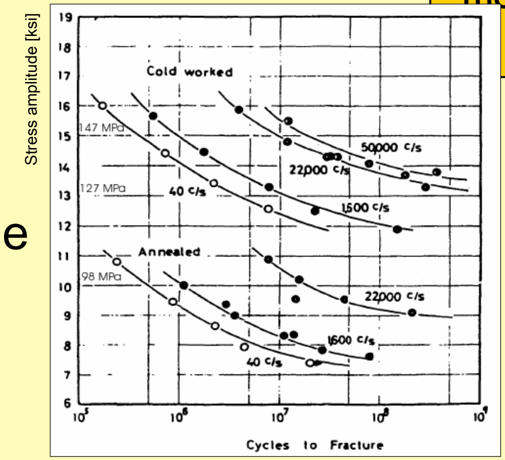
| | |
|---|---|
| Years | 20 |
| Months/Year | 9 |
| Days/Month | 30 |
| Hours/Day | 24 |
| Repetition rate | 100 $Hz$ |

ΔT → Stress amplitude and mean stress

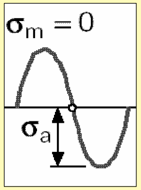


Frequency → Skin depth → Damage criteria

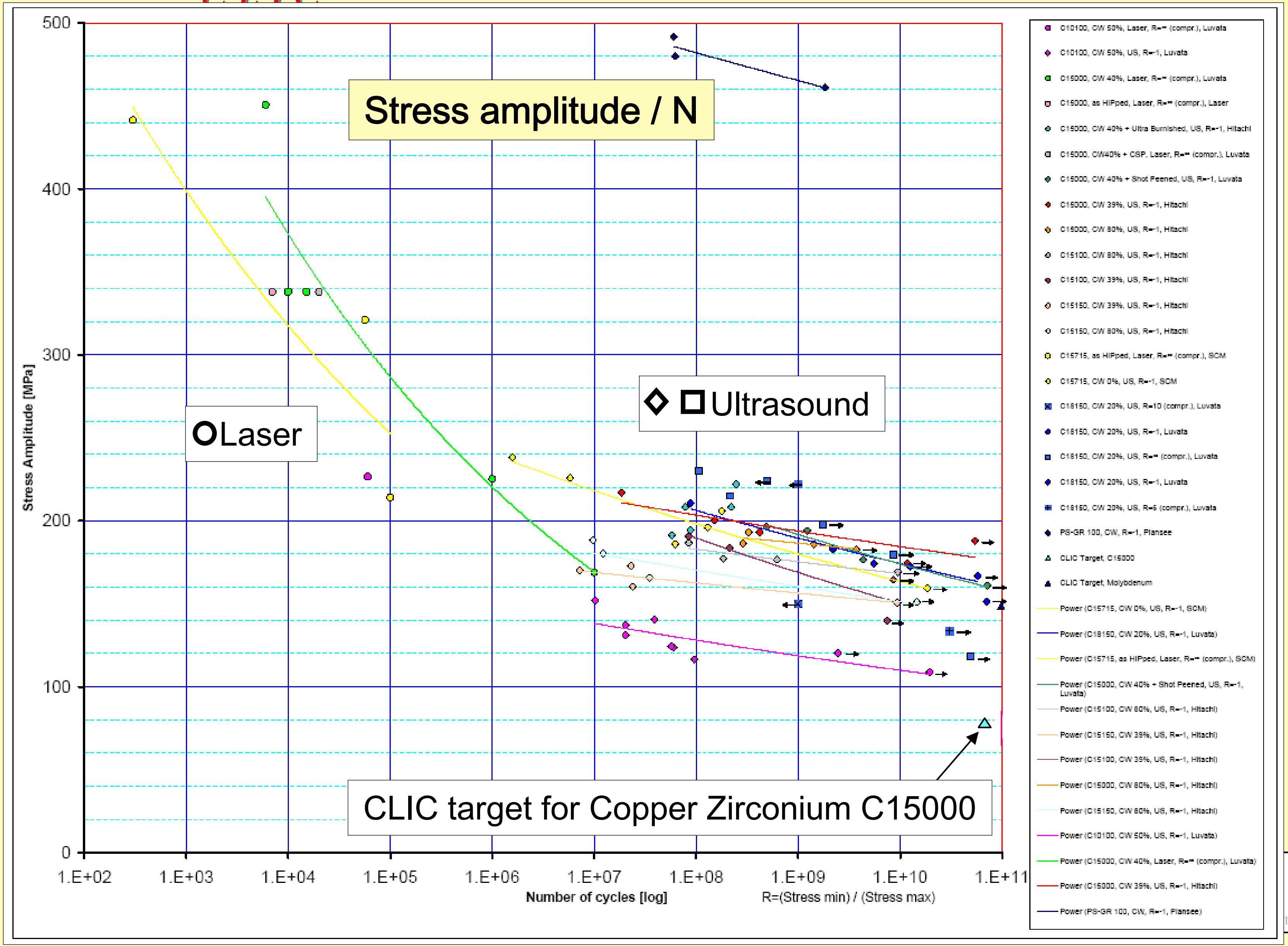




Pulse length → Hold-time



# Up-to-date Ultrasonic & Laser fatigue test results



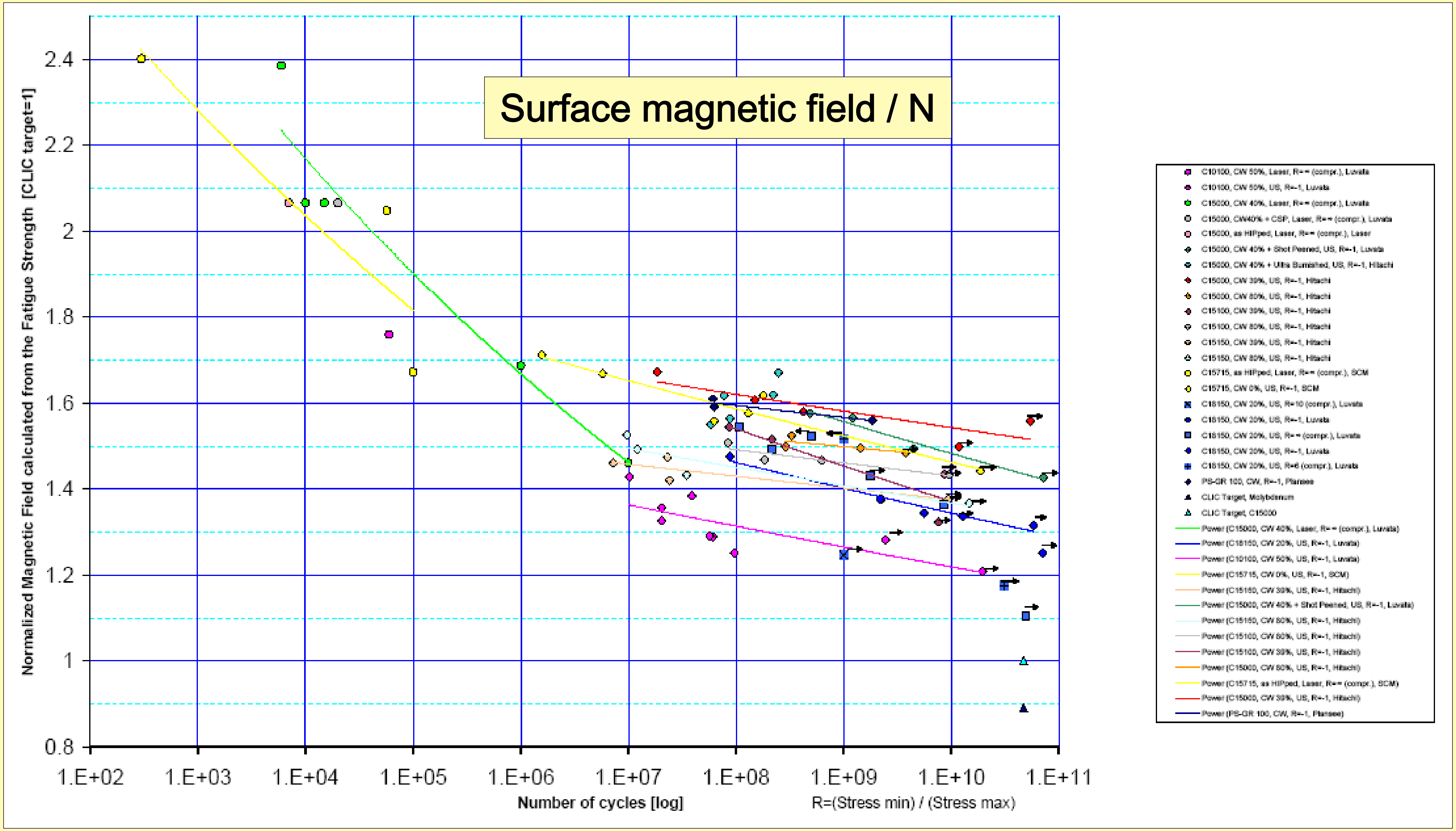
Stress amplitude / N

○Laser

◇ □Ultrasound

CLIC target for Copper Zirconium C15000

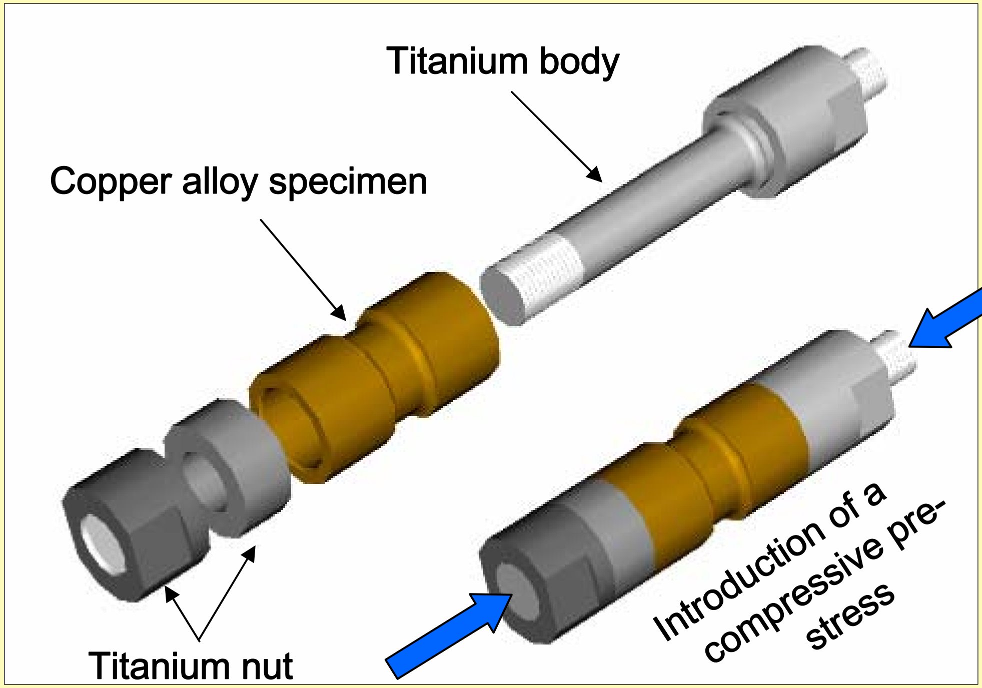
# Up-to-date Ultrasonic & Laser fatigue test results

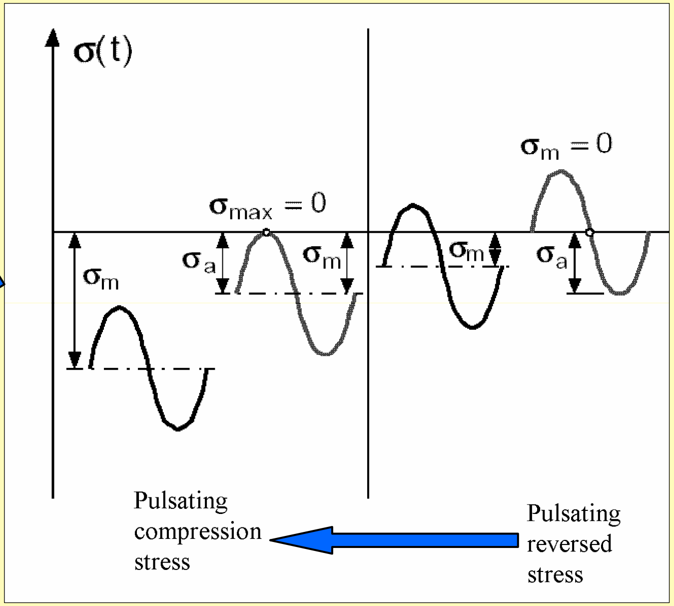

Surface magnetic field / N

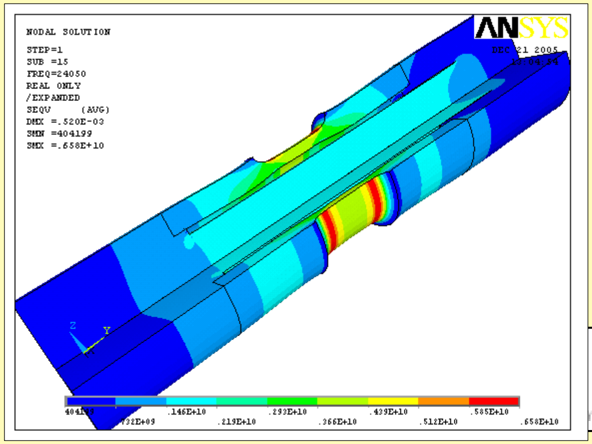
HELSINKI UNIVERSITY OF TECHNOLOGY

# Mean stress effects, US testing

## Special pre-stressed specimen to vary the stress condition (closer to RF fatigue)





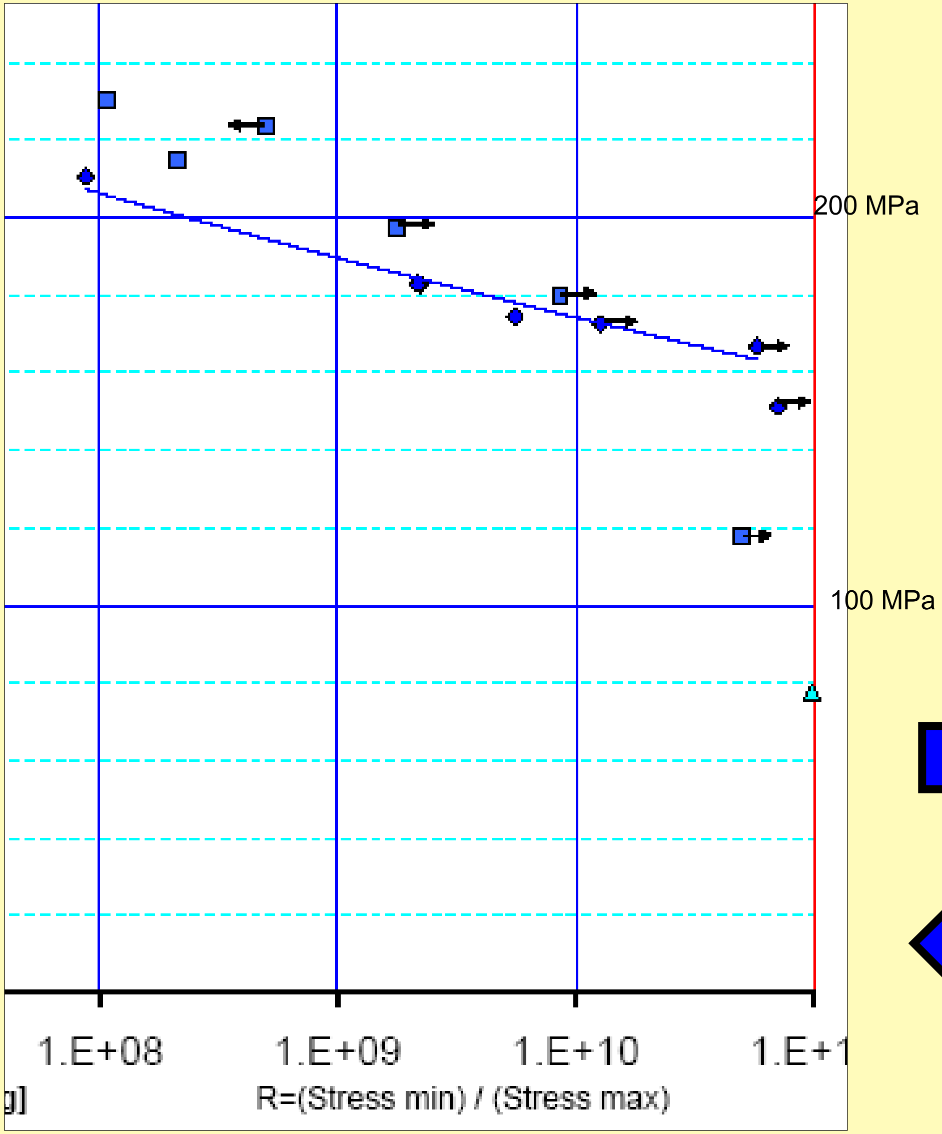


```
NODAL SOLUTION

STEP=1
SUB =15
FREQ=24050
REAL ONLY
/EXPANDED
SEQV     (AVG)
DMX =.520E-03
SMN =404199
SMX =.658E+10
```

Y OF TECHNOLOGY

# Mean stress effects, US testing



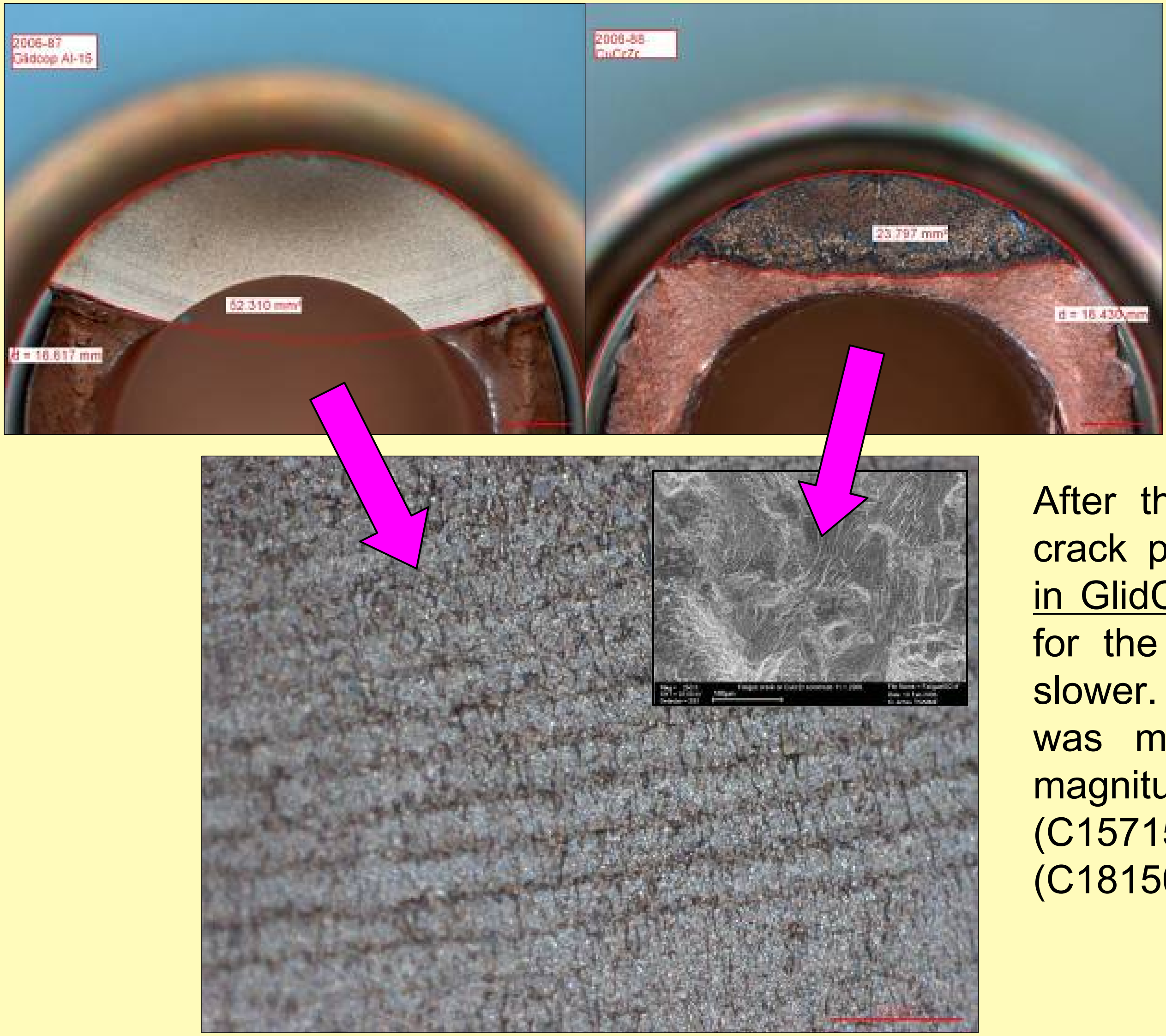
## Pre Stressed specimen

Experiments with pre-stressed C18150 specimens show that at these stress levels the <u>compressive mean stress does not have lower fatigue strength</u> compared to the fully reversed conditions.

■ C18150 fully compressive conditions R=∞

◆ C18150 fully reversed conditions R=-1

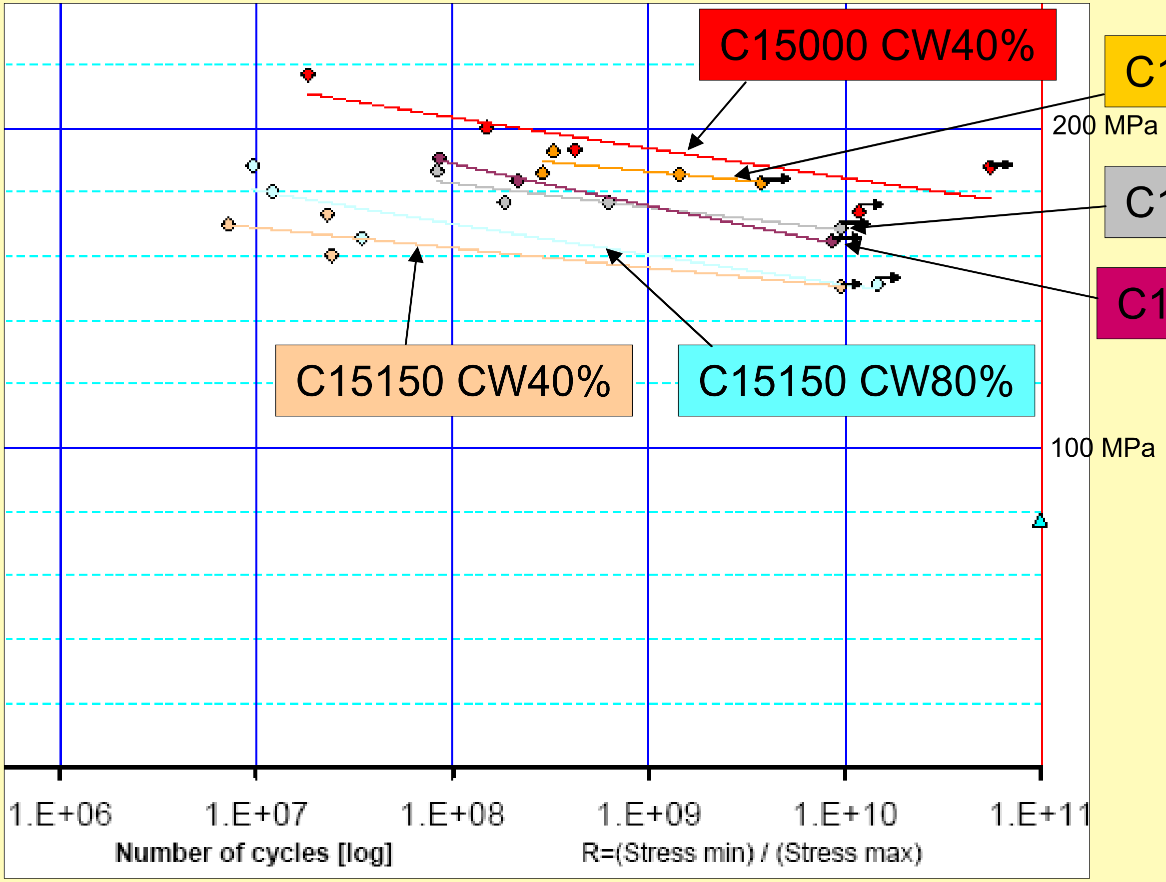
# Crack propagation rate, US testing



G. Arnau Izquierdo TS/MME

After the crack was initiated, the crack propagation was the fastest in GlidCop® Al-15 (C15715), while for the others it was significantly slower. The crack propagation rate was measured to be orders of magnitude higher for GlidCop® (C15715) than for CuCrZr (C18150).

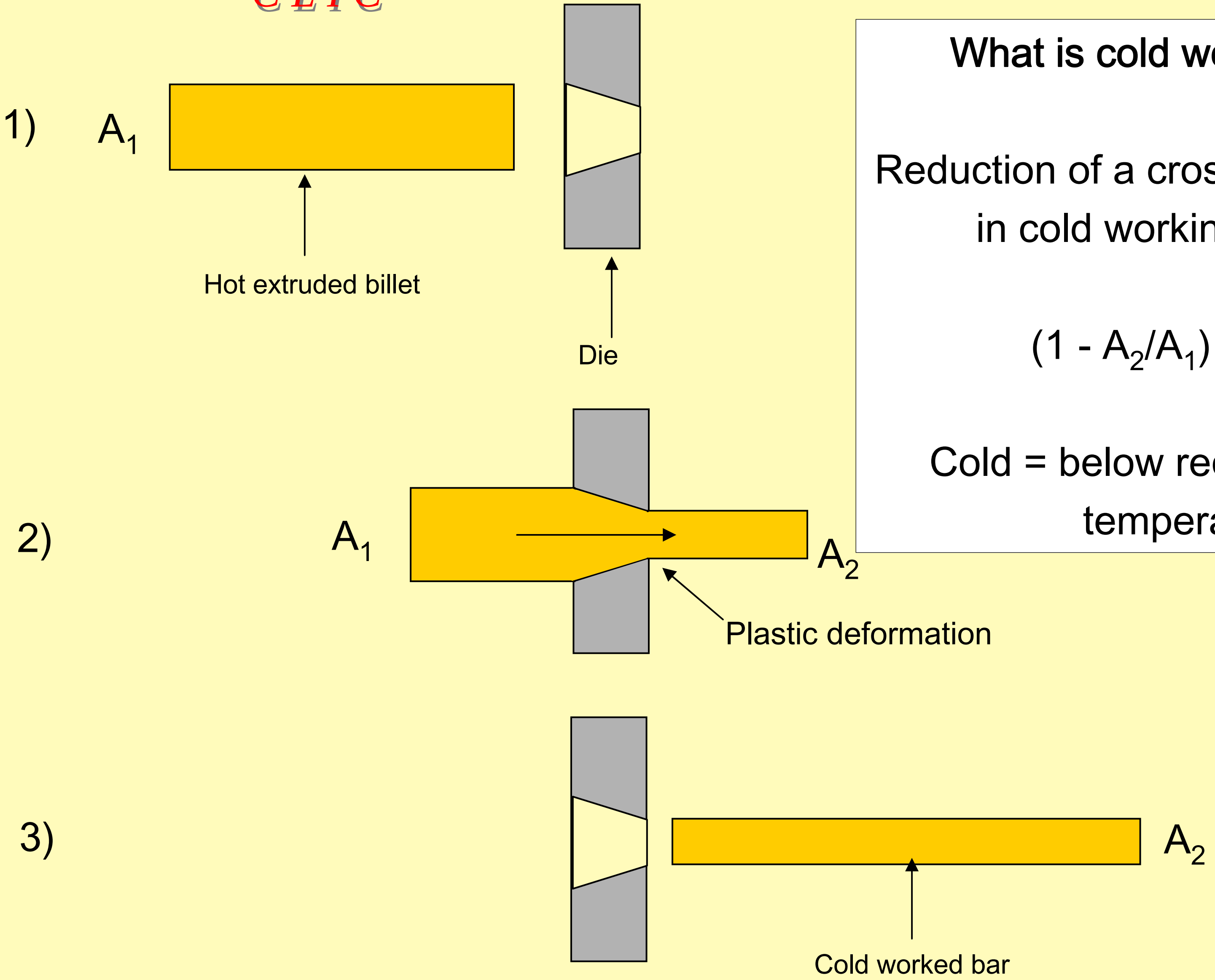
# Effect of cold working ratio, CuZr, US testing



It is not clear whether 40% or 80% cold worked state of Copper Zirconium alloys have better fatigue strength at high number of cycles.

At least the difference is small.

# Effect of cold working ratio, CuZr, US testing



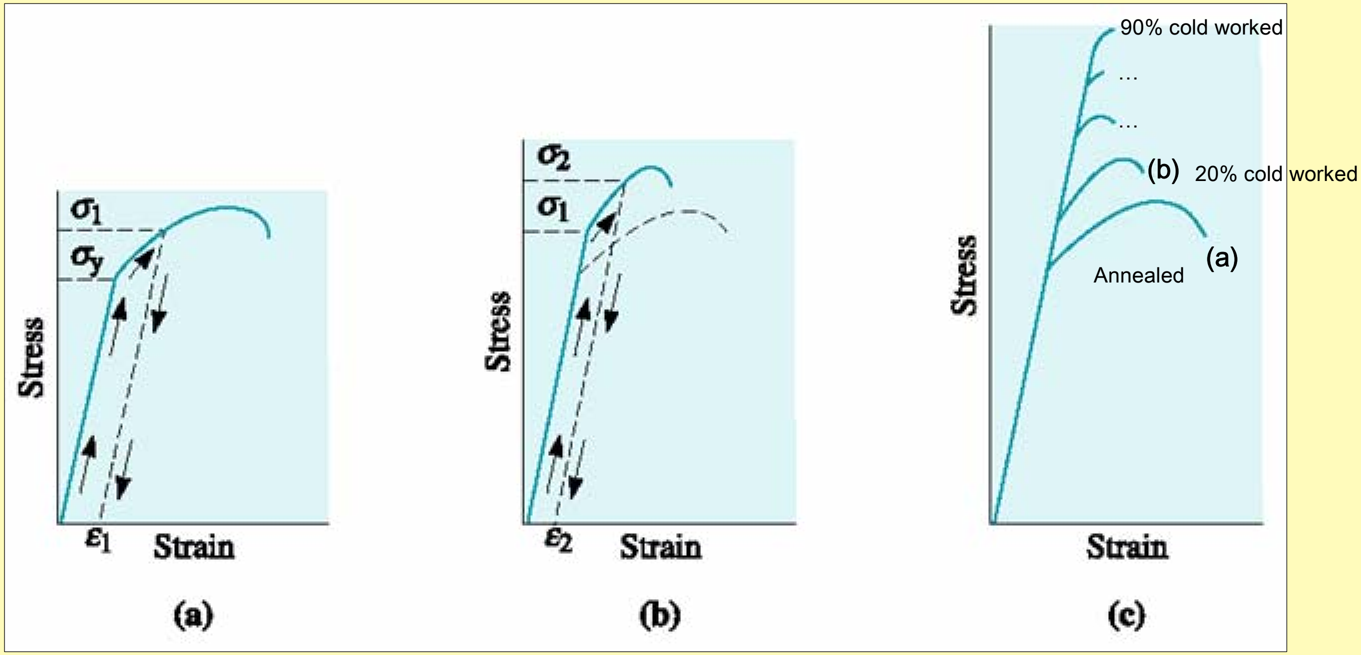
**What is cold working ratio?**

Reduction of a cross-sectional area in cold working process.

$(1 - A_2/A_1) * 100\%$

Cold = below recrystallization temperature

# Effect of cold working ratio, CuZr, US testing



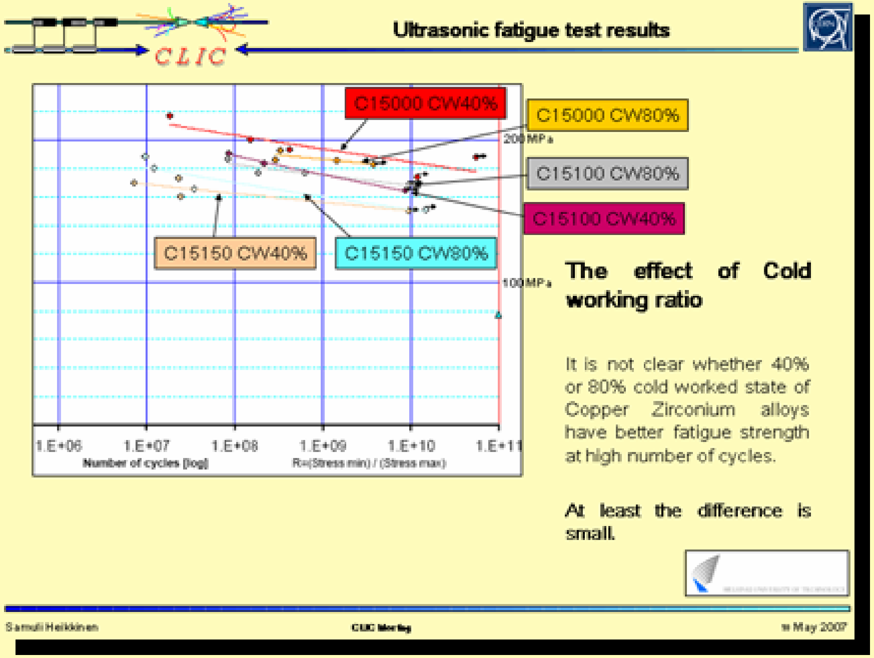
**Why Cold working?**

To increase strength by work hardening!

**Also Fatigue strength?**

I don’t know!

# Effect of cold working ratio, CuZr, US testing



**Ultrasonic fatigue test results**

**The effect of Cold working ratio**

It is not clear whether 40% or 80% cold worked state of Copper Zirconium alloys have better fatigue strength at high number of cycles.

**At least the difference is small.**

Samuli Heikkinen CLIC Meeting 11 May 2007

## 2 possible explanations:

1. Cyclic hardening! Material work hardens during the cyclic loading. → 0% cold worked material would not be too bad!

2. For CuZr, from 0% to 40% cold worked state the work hardening effect is big (already close to saturation). From 40% to 80% state the increase is small.

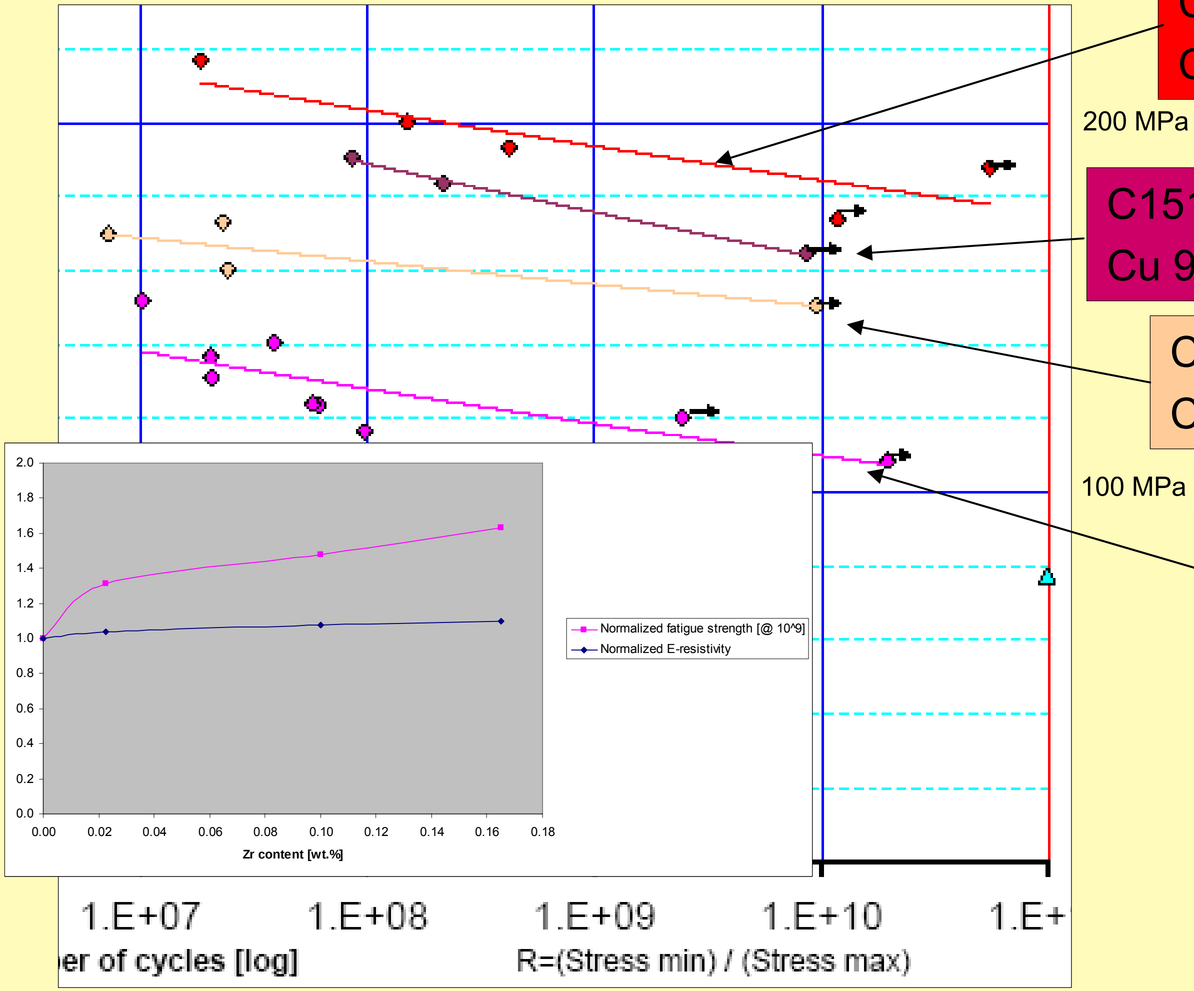
## How could it be confirmed?

Fatigue tests for 0% cold worked state.

↑

**Near future plan / Suggestion for future work**

# Effect of Zr content in CuZr, US testing



C15000 CW40% (high zirconium)
Cu 99.96 wt.%, Zr 0.13-0.2 wt.%

C15100 CW40% (medium zirconium)
Cu 99.96 wt.%, Zr 0.05-0.15 wt.%

C15150 CW40% (low zirconium)
Cu 99.96 wt.%, Zr 0.015-0.03 wt.%

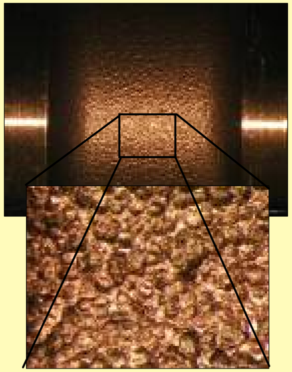
C10100 CW50% (pure copper)
Cu 99.99 wt.%, Zr 0 wt.%

The results show that increasing the zirconium content in Oxygen-free copper increases its fatigue strength.

# Compressive residual stress, US testing

## Classical Shot Peening

- Long history of improving fatigue strength of parts of machines
- Applicable to complex geometries
- Increases the surface roughness



## Cavitation Shot-less Peening (University of Tohoku, Japan)

- Forging of a material by cavitating bubbles
- Applicable to complex geometries
- Good surface roughness could be preserved

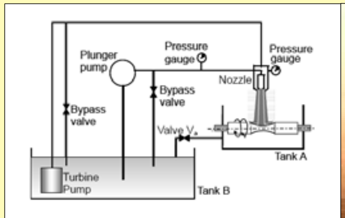
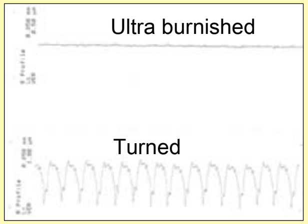
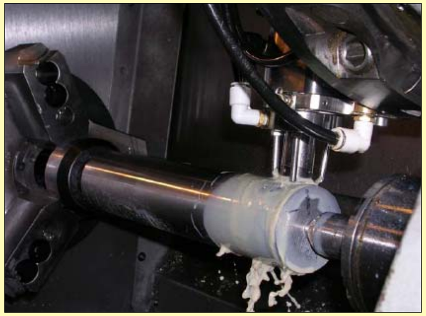


Fig. 2 Cavitating jet apparatus

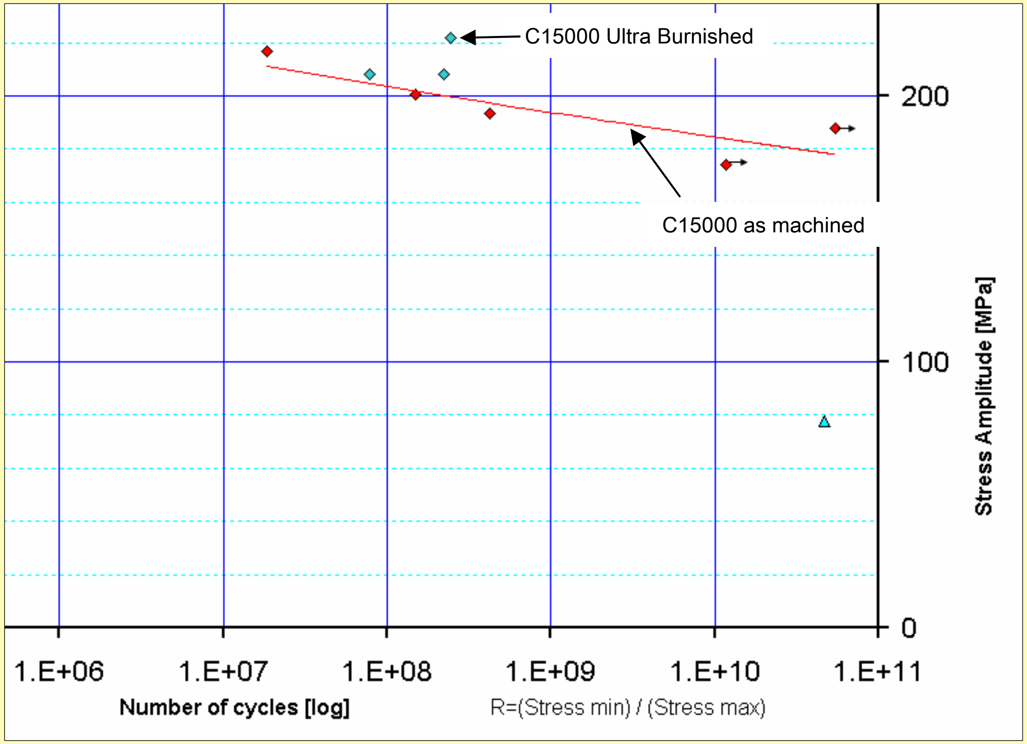
## Ultra Burnishing (Elpro Oy, Finland)

- Forging of material by ultrasonic excitation
- Applicable to complex geometries
- Smoothens the surface





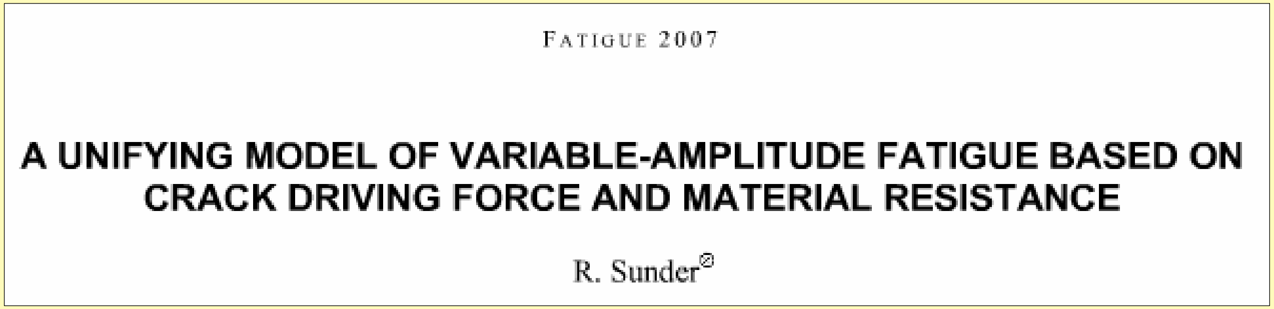
# Compressive residual stress, US testing



Peening might give small (<10%) increase in fatigue strength at these number of cycles due to compressive residual stresses.

but

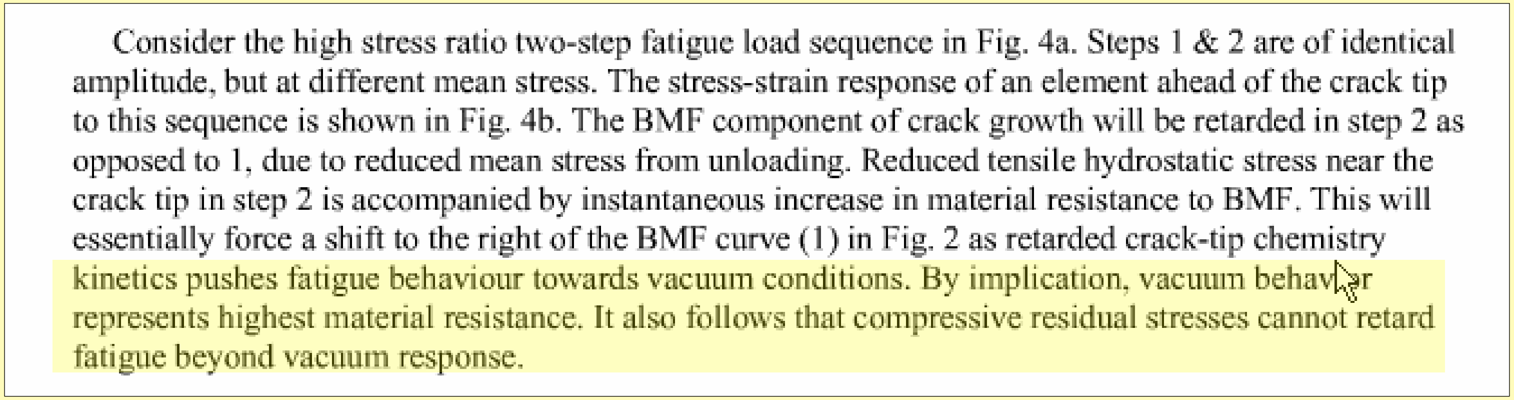
# Compressive residual stress, US testing



FATIGUE 2007

A UNIFYING MODEL OF VARIABLE-AMPLITUDE FATIGUE BASED ON CRACK DRIVING FORCE AND MATERIAL RESISTANCE

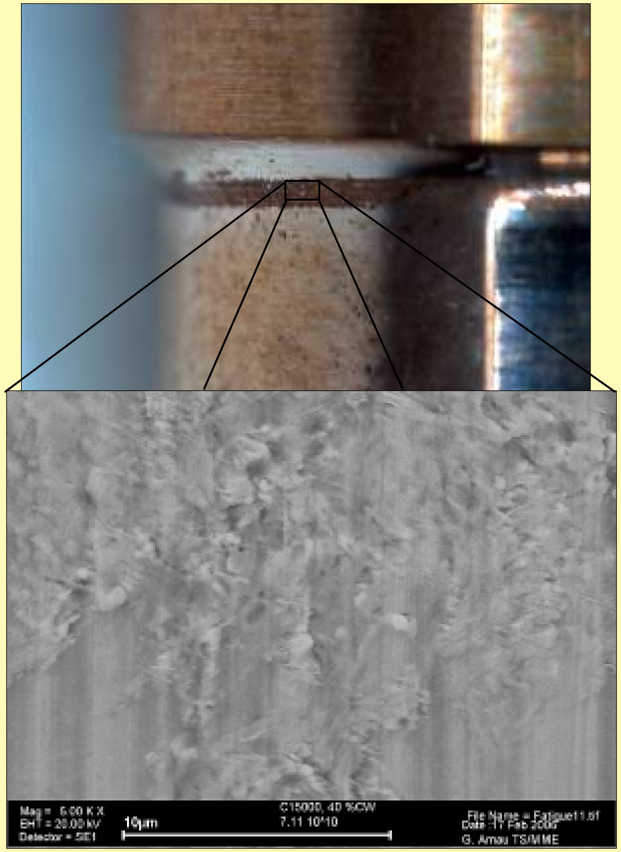
R. Sunder[⊗]



Consider the high stress ratio two-step fatigue load sequence in Fig. 4a. Steps 1 & 2 are of identical amplitude, but at different mean stress. The stress-strain response of an element ahead of the crack tip to this sequence is shown in Fig. 4b. The BMF component of crack growth will be retarded in step 2 as opposed to 1, due to reduced mean stress from unloading. Reduced tensile hydrostatic stress near the crack tip in step 2 is accompanied by instantaneous increase in material resistance to BMF. This will essentially force a shift to the right of the BMF curve (1) in Fig. 2 as retarded crack-tip chemistry kinetics pushes fatigue behaviour towards vacuum conditions. By implication, vacuum behaviour represents highest material resistance. It also follows that compressive residual stresses cannot retard fatigue beyond vacuum response.

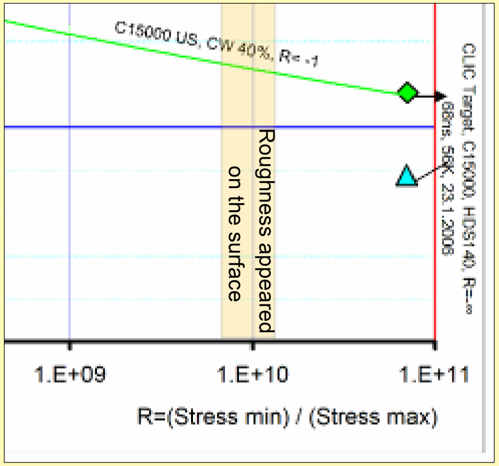
Suggestion for future work

# Roughening of the surface, US testing

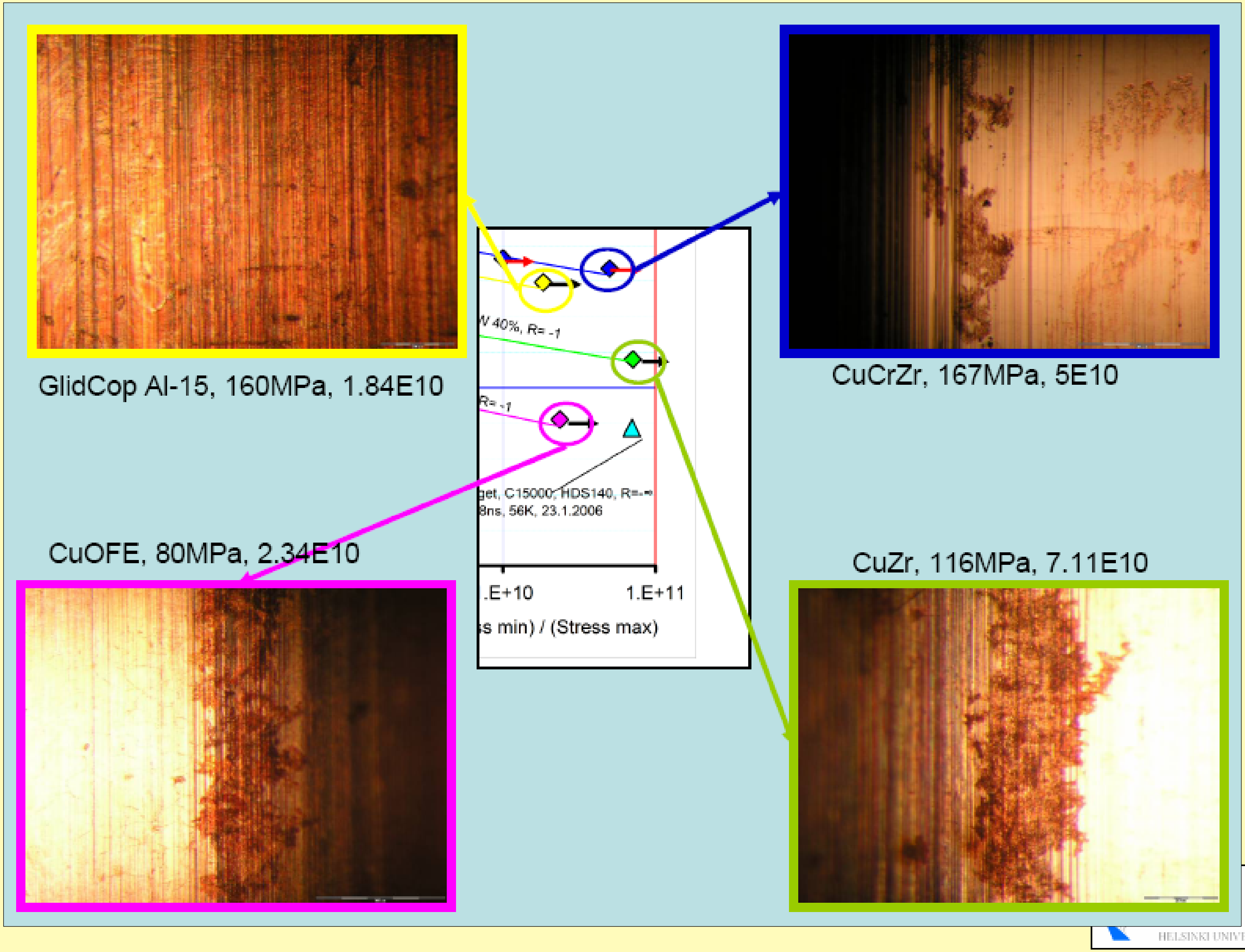


G. Arnau Izquierdo TS/MME

Most of the ultrasound specimens that survived the CLIC lifetime without a fracture experienced surface roughening at the point of maximum stress.



# Roughening of the surface, US testing



GlidCop Al-15, 160MPa, 1.84E10

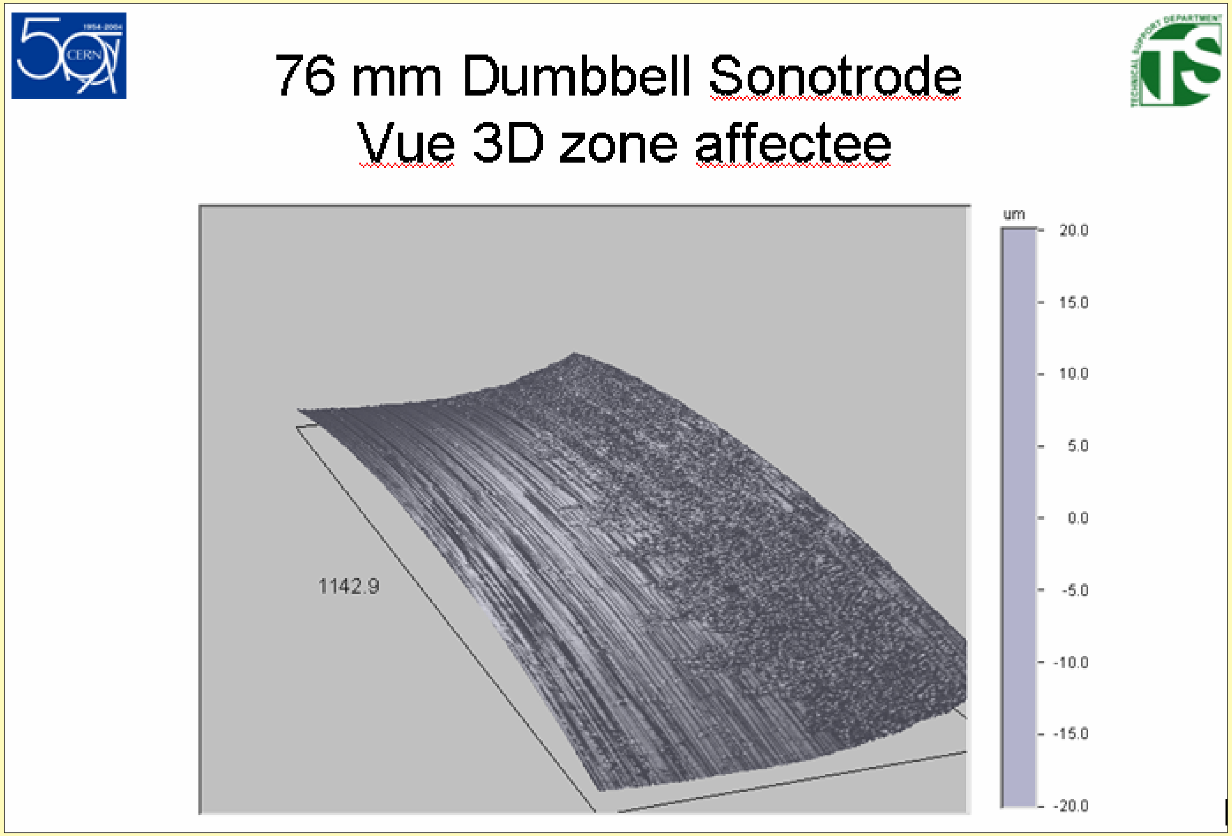
CuCrZr, 167MPa, 5E10

CuOFE, 80MPa, 2.34E10

CuZr, 116MPa, 7.11E10

# Roughening of the surface, US testing

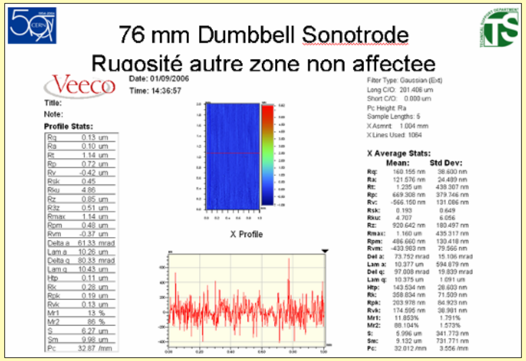
G. Arnau Izquierdo TS/MME



76 mm Dumbbell Sonotrode
Vue 3D zone affectee

A. Cherif TS/MME

# Roughening of the surface, US testing



76 mm Dumbbell Sonotrode
Rugosité autre zone non affectee

Date: 01/09/2006
Time: 14:36:57

Title:
Note:

**Profile Stats:**

| | |
|---|---|
| Rq | 0.13 um |
| Ra | 0.10 um |
| Rt | 1.14 um |
| Rp | 0.72 um |
| Rv | -0.42 um |
| Rsk | 0.45 |
| Rku | 4.86 |
| Rz | 0.85 um |
| R3z | 0.51 um |
| Rmax | 1.14 um |
| Rpm | 0.48 um |
| Rvm | -0.37 um |
| Delta a | 61.33 mrad |
| Lam a | 10.26 um |
| Delta q | 80.33 mrad |
| Lam q | 10.43 um |
| Htp | 0.11 um |
| Rk | 0.28 um |
| Rpk | 0.19 um |
| Rvk | 0.13 um |
| Mr1 | 13 % |
| Mr2 | 86 % |
| S | 6.27 um |
| Sm | 9.98 um |
| Pc | 32.87 /mm |

X Profile

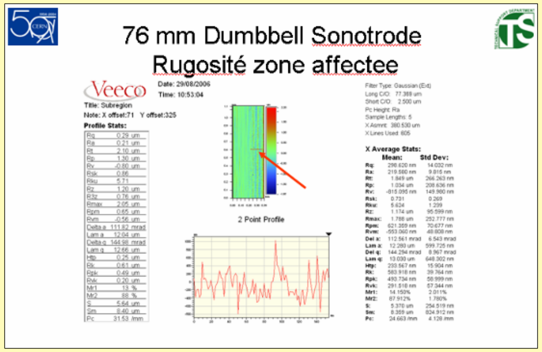
Filter Type: Gaussian (Ext)
Long C/O: 201.406 um
Short C/O: 0.000 um
Pc Height: Ra
Sample Lengths: 5
X Asmnt: 1.004 mm
X Lines Used: 1064

**X Average Stats:**

| | Mean: | Std Dev: |
|---|---|---|
| Rq: | 160.155 nm | 38.600 nm |
| Ra: | 121.576 nm | 24.489 nm |
| Rt: | 1.235 um | 438.307 nm |
| Rp: | 669.308 nm | 379.746 nm |
| Rv: | -566.150 nm | 131.086 nm |
| Rsk: | 0.193 | 0.649 |
| Rku: | 4.707 | 6.056 |
| Rz: | 920.642 nm | 180.497 nm |
| Rmax: | 1.160 um | 435.317 nm |
| Rpm: | 486.660 nm | 130.418 nm |
| Rvm: | -433.983 nm | 79.566 nm |
| Del a: | 73.752 mrad | 15.106 mrad |
| Lam a: | 10.377 um | 594.879 nm |
| Del q: | 97.008 mrad | 19.839 mrad |
| Lam q: | 10.375 um | 1.091 um |
| Htp: | 143.534 nm | 28.603 nm |
| Rk: | 358.834 nm | 71.509 nm |
| Rpk: | 203.978 nm | 84.923 nm |
| Rvk: | 174.595 nm | 38.981 nm |
| Mr1: | 11.853% | 1.791% |
| Mr2: | 88.104% | 1.573% |
| S: | 5.996 um | 341.773 nm |
| Sm: | 9.132 um | 731.771 nm |
| Pc: | 32.012 /mm | 3.556 /mm |

Roughness before:

Ra 0.1 µm



76 mm Dumbbell Sonotrode
Rugosité zone affectee

Date: 29/08/2006
Time: 10:53:04

Title: Subregion
Note: X offset:71 Y offset:325

**Profile Stats:**

| | |
|---|---|
| Rq | 0.29 um |
| Ra | 0.21 um |
| Rt | 2.10 um |
| Rp | 1.30 um |
| Rv | -0.80 um |
| Rsk | 0.86 |
| Rku | 5.71 |
| Rz | 1.20 um |
| R3z | 0.76 um |
| Rmax | 2.05 um |
| Rpm | 0.65 um |
| Rvm | -0.56 um |
| Delta a | 111.82 mrad |
| Lam a | 12.04 um |
| Delta q | 144.98 mrad |
| Lam q | 12.66 um |
| Htp | 0.25 um |
| Rk | 0.61 um |
| Rpk | 0.49 um |
| Rvk | 0.20 um |
| Mr1 | 13 % |
| Mr2 | 88 % |
| S | 5.64 um |
| Sm | 8.40 um |
| Pc | 31.53 /mm |

2 Point Profile

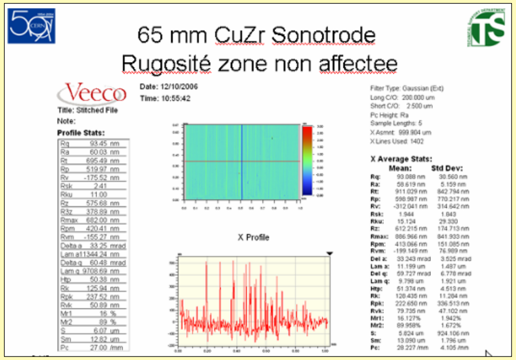
Filter Type: Gaussian (Ext)
Long C/O: 77.389 um
Short C/O: 2.500 um
Pc Height: Ra
Sample Lengths: 5
X Asmnt: 380.530 um
X Lines Used: 605

**X Average Stats:**

| | Mean: | Std Dev: |
|---|---|---|
| Rq: | 298.620 nm | 14.032 nm |
| Ra: | 219.580 nm | 9.815 nm |
| Rt: | 1.849 um | 266.263 nm |
| Rp: | 1.034 um | 208.636 nm |
| Rv: | -815.095 nm | 149.980 nm |
| Rsk: | 0.731 | 0.269 |
| Rku: | 5.634 | 1.239 |
| Rz: | 1.174 um | 95.599 nm |
| Rmax: | 1.788 um | 252.777 nm |
| Rpm: | 621.359 nm | 70.677 nm |
| Rvm: | -553.060 nm | 48.808 nm |
| Del a: | 112.561 mrad | 6.543 mrad |
| Lam a: | 12.280 um | 599.725 nm |
| Del q: | 144.294 mrad | 8.967 mrad |
| Lam q: | 13.030 um | 648.302 nm |
| Htp: | 233.567 nm | 15.904 nm |
| Rk: | 583.918 nm | 39.764 nm |
| Rpk: | 493.734 nm | 58.999 nm |
| Rvk: | 291.518 nm | 57.344 nm |
| Mr1: | 14.150% | 2.011% |
| Mr2: | 87.912% | 1.780% |
| S: | 5.370 um | 254.519 nm |
| Sm: | 8.359 um | 824.912 nm |
| Pc: | 24.663 /mm | 4.128 /mm |

Roughness after:

Ra 0.21 µm



65 mm CuZr Sonotrode
Rugosité zone non affectee

Date: 12/10/2006
Time: 10:55:42

Title: Stitched File
Note:

**Profile Stats:**

| | |
|---|---|
| Rq | 93.45 nm |
| Ra | 60.03 nm |
| Rt | 695.49 nm |
| Rp | 519.97 nm |
| Rv | -175.52 nm |
| Rsk | 2.41 |
| Rku | 11.00 |
| Rz | 575.68 nm |
| R3z | 378.89 nm |
| Rmax | 682.00 nm |
| Rpm | 420.41 nm |
| Rvm | -155.27 nm |
| Delta a | 33.25 mrad |
| Lam a | 11344.24 nm |
| Delta q | 60.48 mrad |
| Lam q | 9708.69 nm |
| Htp | 50.38 nm |
| Rk | 125.94 nm |
| Rpk | 237.52 nm |
| Rvk | 50.89 nm |
| Mr1 | 16 % |
| Mr2 | 89 % |
| S | 6.07 um |
| Sm | 12.82 um |
| Pc | 27.00 /mm |

X Profile

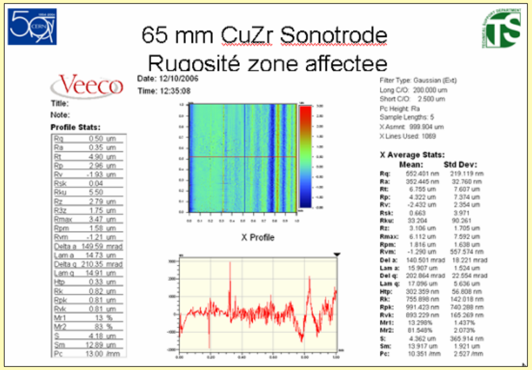
Filter Type: Gaussian (Ext)
Long C/O: 200.000 um
Short C/O: 2.500 um
Pc Height: Ra
Sample Lengths: 5
X Asmnt: 999.904 um
X Lines Used: 1402

**X Average Stats:**

| | Mean: | Std Dev: |
|---|---|---|
| Rq: | 93.088 nm | 30.560 nm |
| Ra: | 58.619 nm | 5.159 nm |
| Rt: | 911.029 nm | 842.794 nm |
| Rp: | 598.987 nm | 770.217 nm |
| Rv: | -312.041 nm | 314.642 nm |
| Rsk: | 1.944 | 1.843 |
| Rku: | 15.124 | 29.330 |
| Rz: | 612.215 nm | 174.713 nm |
| Rmax: | 886.966 nm | 841.933 nm |
| Rpm: | 413.066 nm | 151.085 nm |
| Rvm: | -199.149 nm | 76.989 nm |
| Del a: | 33.243 mrad | 3.525 mrad |
| Lam a: | 11.199 um | 1.487 um |
| Del q: | 59.727 mrad | 6.778 mrad |
| Lam q: | 9.798 um | 1.921 um |
| Htp: | 51.374 nm | 4.513 nm |
| Rk: | 128.435 nm | 11.284 nm |
| Rpk: | 222.650 nm | 336.513 nm |
| Rvk: | 79.735 nm | 47.102 nm |
| Mr1: | 16.127% | 1.942% |
| Mr2: | 89.958% | 1.672% |
| S: | 5.824 um | 924.106 nm |
| Sm: | 13.090 um | 1.796 um |
| Pc: | 28.227 /mm | 4.105 /mm |

Roughness before:

Ra 0.06 µm



65 mm CuZr Sonotrode
Rugosité zone affectee

Date: 12/10/2006
Time: 12:35:08

Title:
Note:

**Profile Stats:**

| | |
|---|---|
| Rq | 0.50 um |
| Ra | 0.35 um |
| Rt | 4.90 um |
| Rp | 2.96 um |
| Rv | -1.93 um |
| Rsk | 0.04 |
| Rku | 5.50 |
| Rz | 2.79 um |
| R3z | 1.75 um |
| Rmax | 3.47 um |
| Rpm | 1.58 um |
| Rvm | -1.21 um |
| Delta a | 149.59 mrad |
| Lam a | 14.73 um |
| Delta q | 210.35 mrad |
| Lam q | 14.91 um |
| Htp | 0.33 um |
| Rk | 0.82 um |
| Rpk | 0.81 um |
| Rvk | 0.81 um |
| Mr1 | 13 % |
| Mr2 | 83 % |
| S | 4.18 um |
| Sm | 12.89 um |
| Pc | 13.00 /mm |

X Profile

Filter Type: Gaussian (Ext)
Long C/O: 200.000 um
Short C/O: 2.500 um
Pc Height: Ra
Sample Lengths: 5
X Asmnt: 999.904 um
X Lines Used: 1069

**X Average Stats:**

| | Mean: | Std Dev: |
|---|---|---|
| Rq: | 552.401 nm | 219.119 nm |
| Ra: | 352.445 nm | 32.760 nm |
| Rt: | 6.755 um | 7.607 um |
| Rp: | 4.322 um | 7.374 um |
| Rv: | -2.432 um | 2.354 um |
| Rsk: | 0.663 | 3.971 |
| Rku: | 33.204 | 90.261 |
| Rz: | 3.106 um | 1.705 um |
| Rmax: | 6.112 um | 7.592 um |
| Rpm: | 1.816 um | 1.638 um |
| Rvm: | -1.290 um | 557.574 nm |
| Del a: | 140.501 mrad | 18.221 mrad |
| Lam a: | 15.907 um | 1.524 um |
| Del q: | 202.864 mrad | 22.554 mrad |
| Lam q: | 17.096 um | 5.636 um |
| Htp: | 302.359 nm | 56.808 nm |
| Rk: | 755.898 nm | 142.018 nm |
| Rpk: | 991.423 nm | 740.288 nm |
| Rvk: | 893.229 nm | 165.269 nm |
| Mr1: | 13.298% | 1.437% |
| Mr2: | 81.548% | 2.073% |
| S: | 4.362 um | 365.914 nm |
| Sm: | 13.917 um | 1.921 um |
| Pc: | 10.351 /mm | 2.527 /mm |

Roughness after:

Ra 0.35 µm

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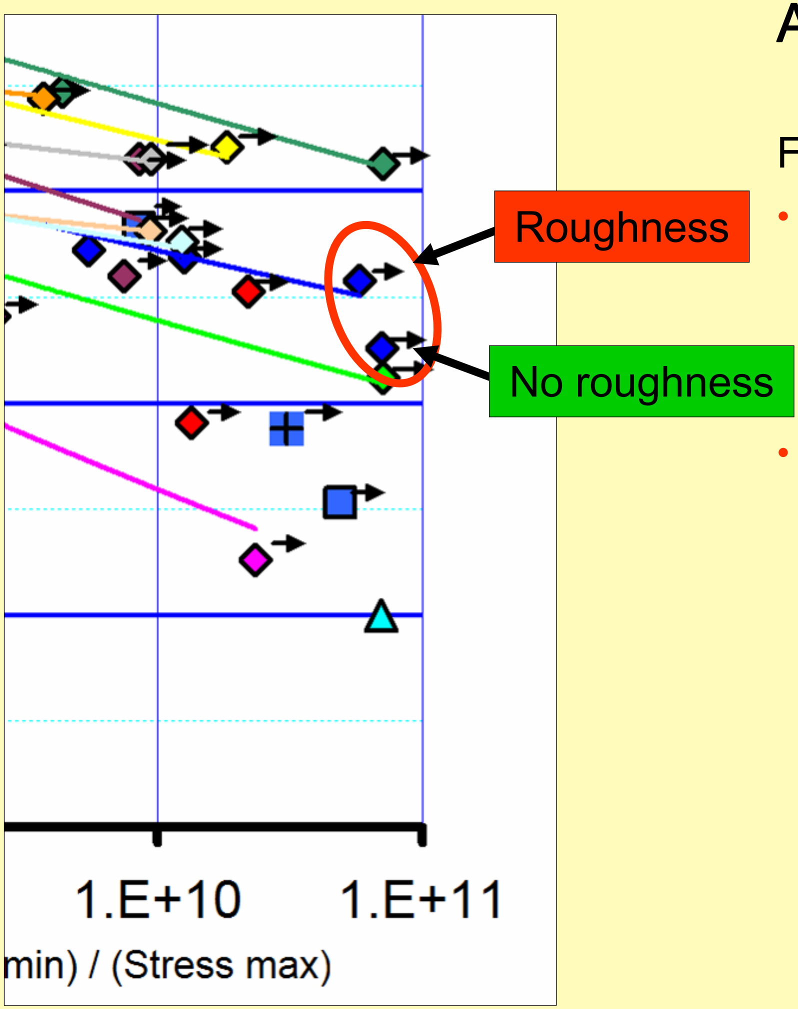
# Roughening of the surface, US testing



Roughness

No roughness

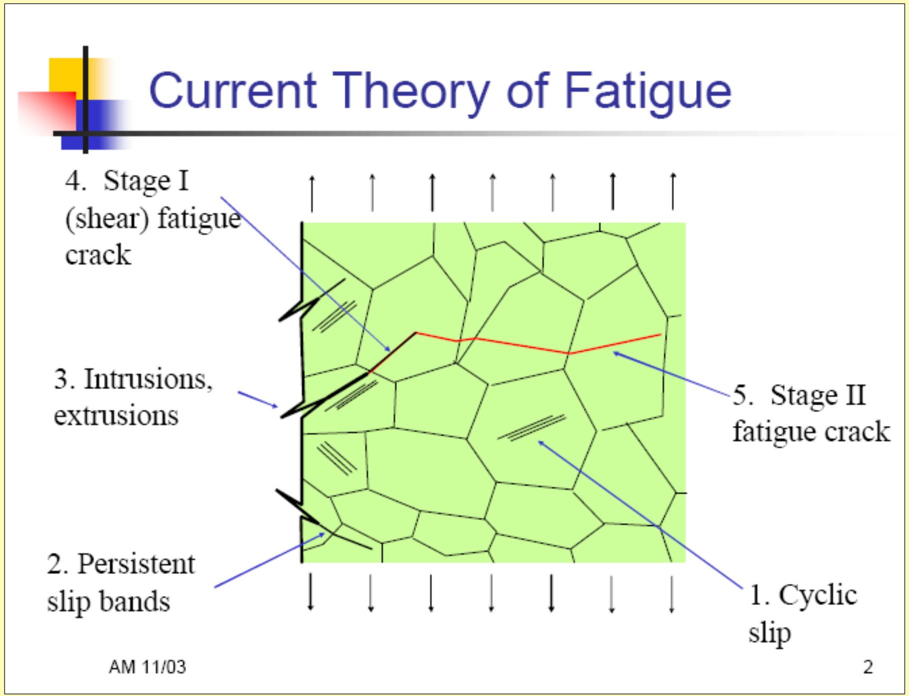
## Attempt to avoid surface roughening

For CuCrZr, C18150:

- “Near threshold conditions”, roughness appeared at N~2x10$^{10,}$ 167 MPa.
- For stress amplitude reduced by 10%, 151 MPa, roughness did not appear for N=7x10$^{10}$.

# Roughening of the surface

## What is this appeared roughness?



### Current Theory of Fatigue

4. Stage I (shear) fatigue crack

3. Intrusions, extrusions

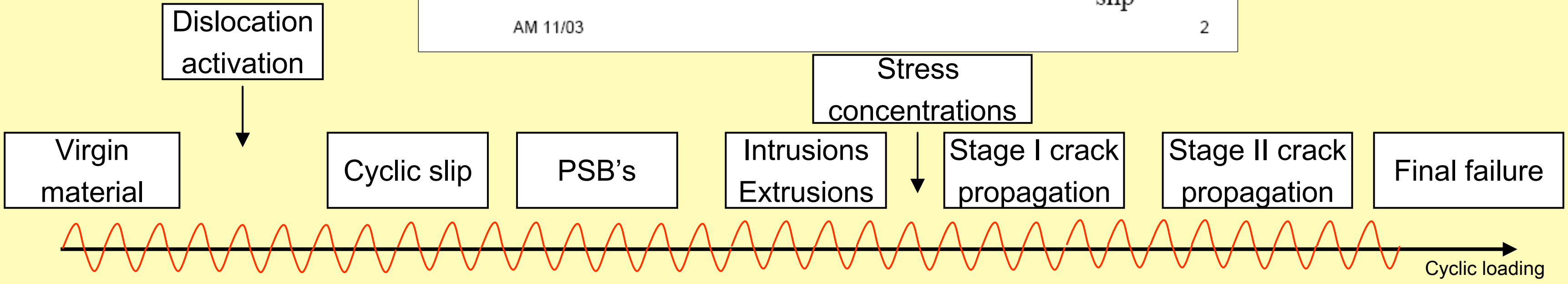
2. Persistent slip bands

5. Stage II fatigue crack

1. Cyclic slip

AM 11/03

2



Dislocation activation

Stress concentrations

Virgin material

Cyclic slip

PSB's

Intrusions Extrusions

Stage I crack propagation

Stage II crack propagation

Final failure

Cyclic loading

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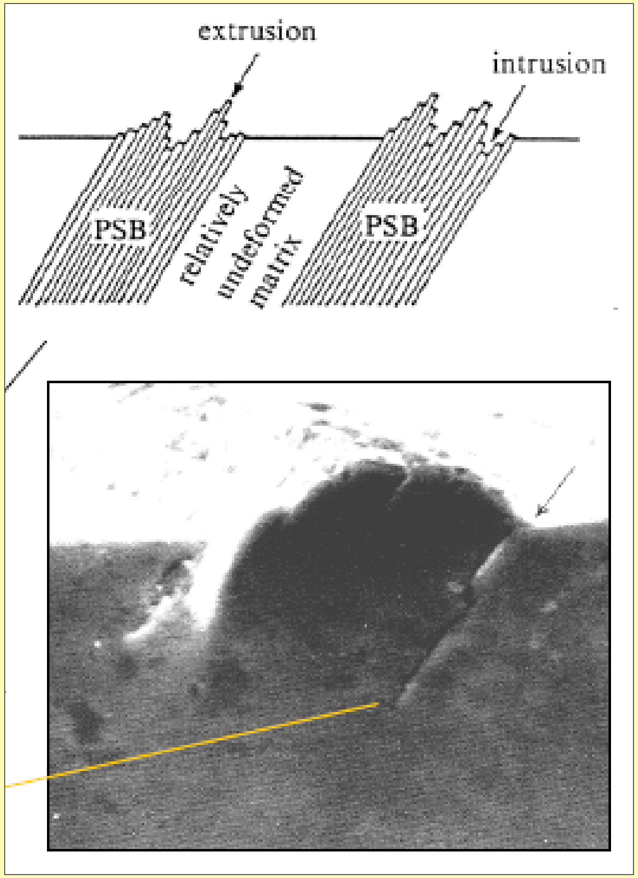
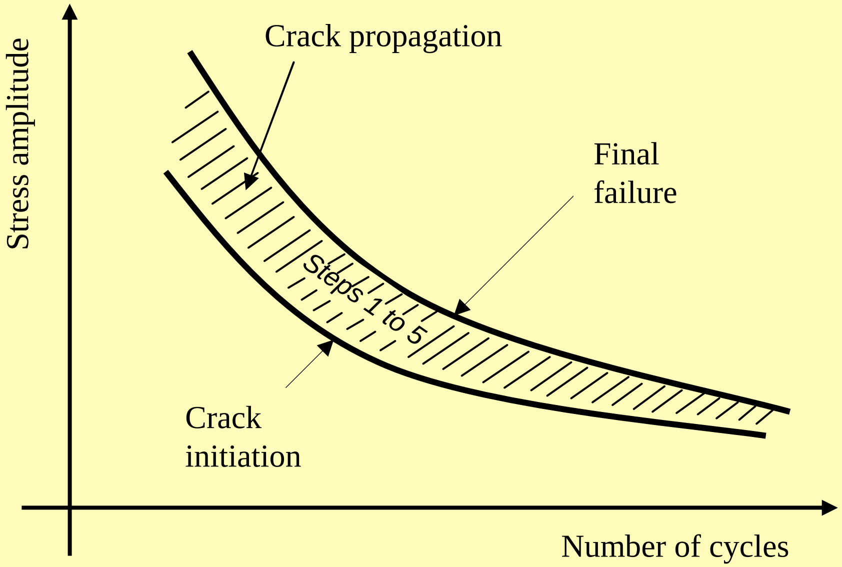
# Roughening of the surface

## Intrusions and extrusions

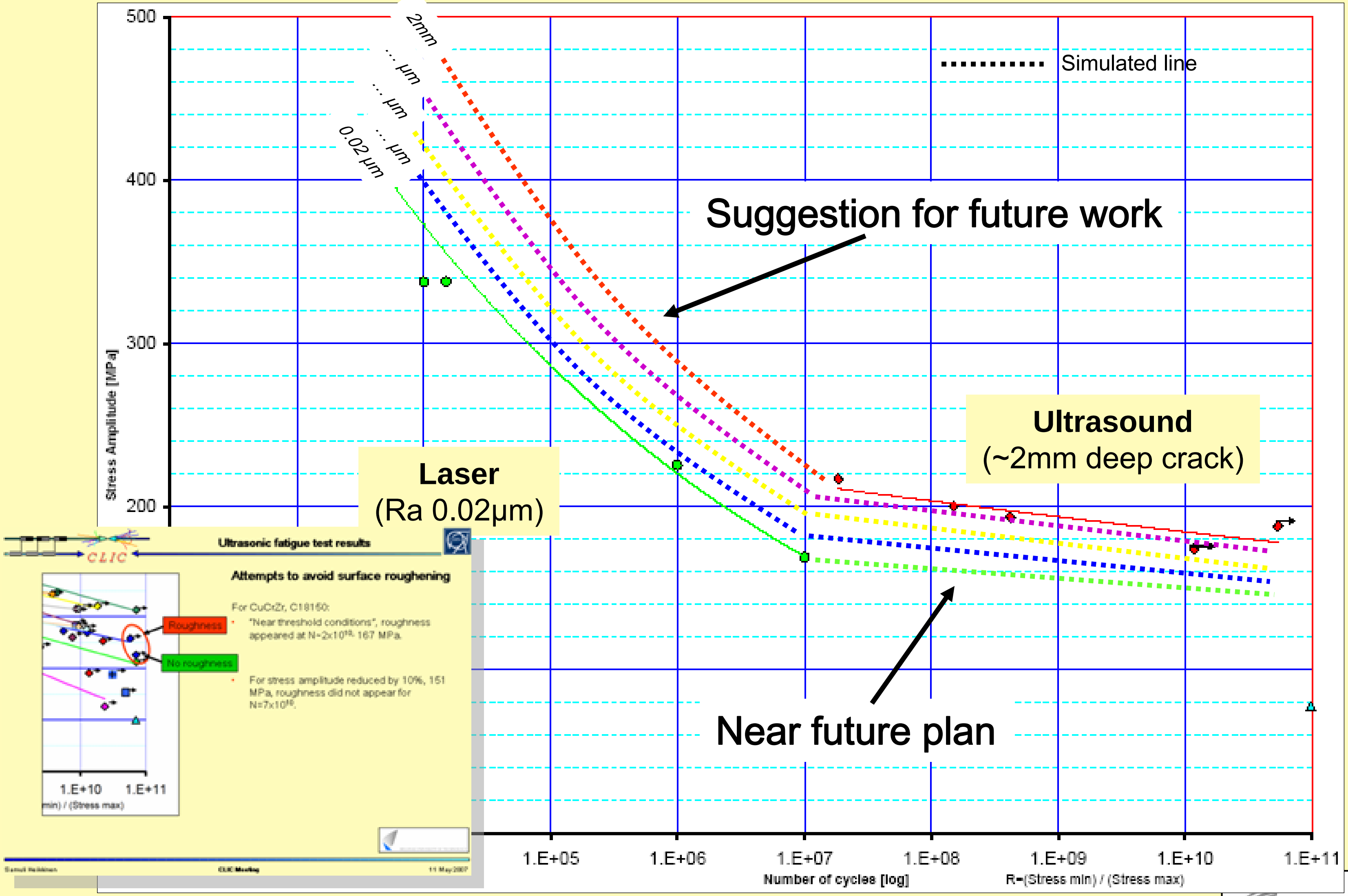


# Damage criteria



N(Final failure) = N(Crack initiation) + N(Crack propagation)

# Damage criteria



Suggestion for future work

**Ultrasound**
(~2mm deep crack)

**Laser**
(Ra 0.02µm)

Near future plan

**Ultrasonic fatigue test results**

**Attempts to avoid surface roughening**

For CuCrZr, C18150:

- "Near threshold conditions", roughness appeared at $N\sim2\times10^{10}$, 167 MPa.
- For stress amplitude reduced by 10%, 151 MPa, roughness did not appear for $N=7\times10^{10}$.

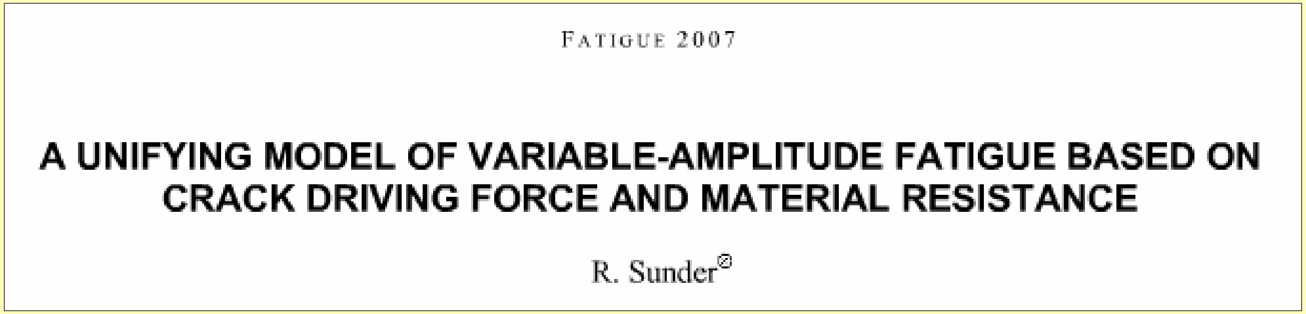
Skin depth

30 GHz ~ 0.4 µm

12 GHz ~ 0.64 µm

CLIC

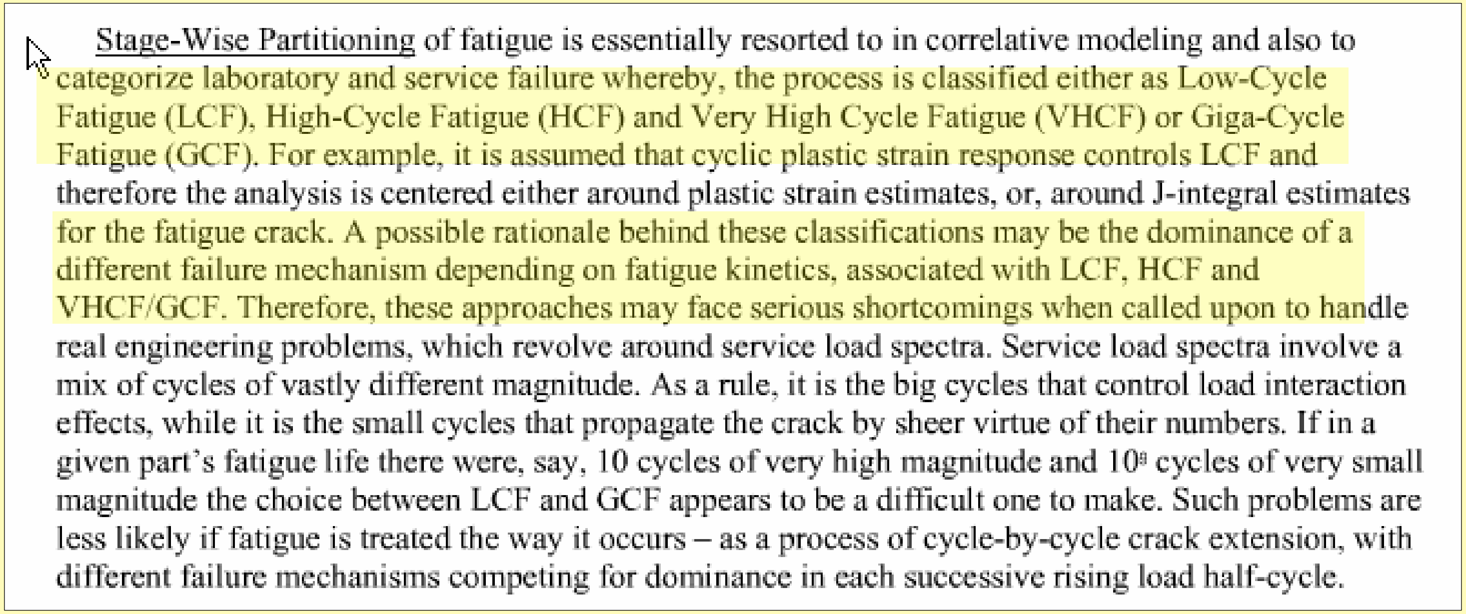
# Stage-Wise Partitioning



FATIGUE 2007

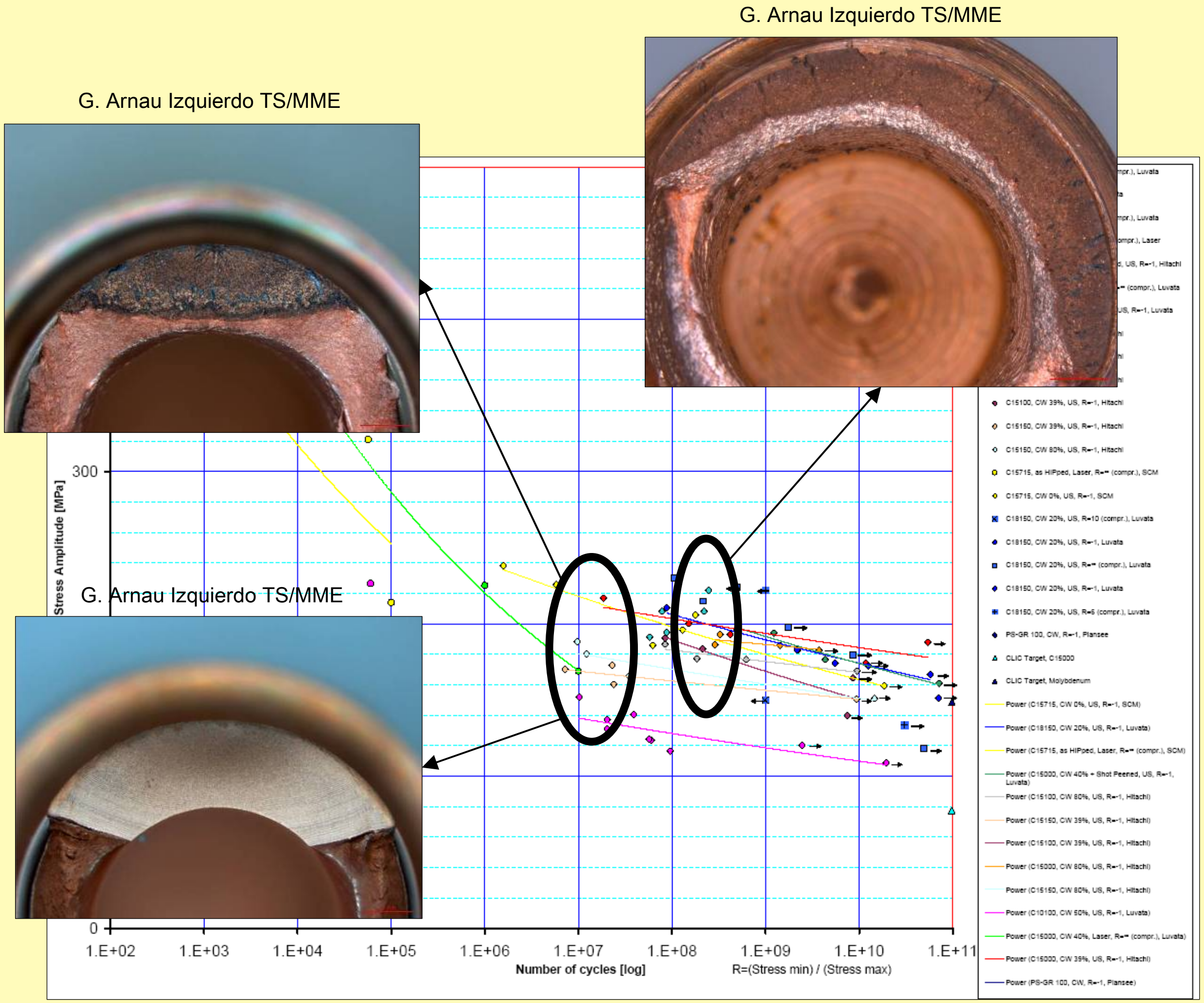
## A UNIFYING MODEL OF VARIABLE-AMPLITUDE FATIGUE BASED ON CRACK DRIVING FORCE AND MATERIAL RESISTANCE

R. Sunder



Stage-Wise Partitioning of fatigue is essentially resorted to in correlative modeling and also to categorize laboratory and service failure whereby, the process is classified either as Low-Cycle Fatigue (LCF), High-Cycle Fatigue (HCF) and Very High Cycle Fatigue (VHCF) or Giga-Cycle Fatigue (GCF). For example, it is assumed that cyclic plastic strain response controls LCF and therefore the analysis is centered either around plastic strain estimates, or, around J-integral estimates for the fatigue crack. A possible rationale behind these classifications may be the dominance of a different failure mechanism depending on fatigue kinetics, associated with LCF, HCF and VHCF/GCF. Therefore, these approaches may face serious shortcomings when called upon to handle real engineering problems, which revolve around service load spectra. Service load spectra involve a mix of cycles of vastly different magnitude. As a rule, it is the big cycles that control load interaction effects, while it is the small cycles that propagate the crack by sheer virtue of their numbers. If in a given part's fatigue life there were, say, 10 cycles of very high magnitude and $10^9$ cycles of very small magnitude the choice between LCF and GCF appears to be a difficult one to make. Such problems are less likely if fatigue is treated the way it occurs – as a process of cycle-by-cycle crack extension, with different failure mechanisms competing for dominance in each successive rising load half-cycle.

# Stage-Wise Partitioning, US testing

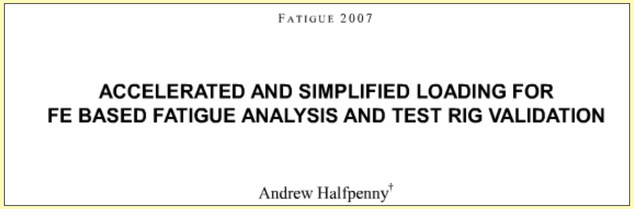

G. Arnau Izquierdo TS/MME

G. Arnau Izquierdo TS/MME

G. Arnau Izquierdo TS/MME

US test setup is needed also in the future

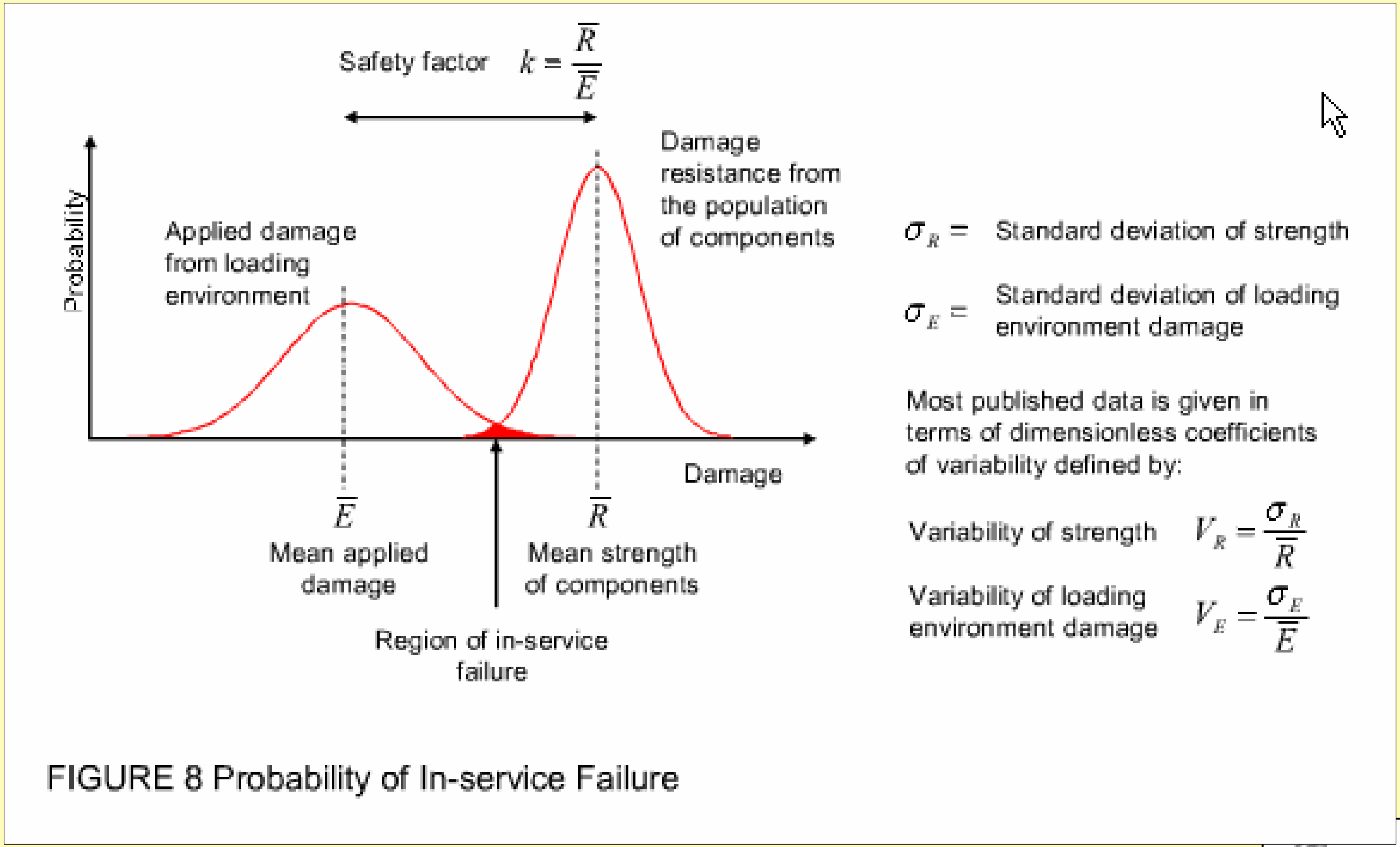
# Safety Factor



FATIGUE 2007

ACCELERATED AND SIMPLIFIED LOADING FOR FE BASED FATIGUE ANALYSIS AND TEST RIG VALIDATION

Andrew Halfpenny†



$\sigma_R$ = Standard deviation of strength

$\sigma_E$ = Standard deviation of loading environment damage

Most published data is given in terms of dimensionless coefficients of variability defined by:

Variability of strength $V_R = \frac{\sigma_R}{\bar{R}}$

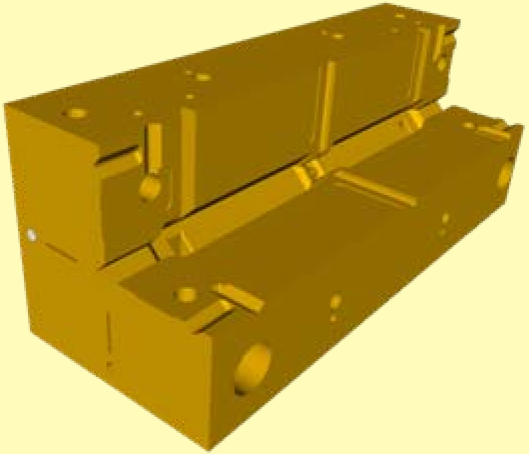
Variability of loading environment damage $V_E = \frac{\sigma_E}{\bar{E}}$

FIGURE 8 Probability of In-service Failure

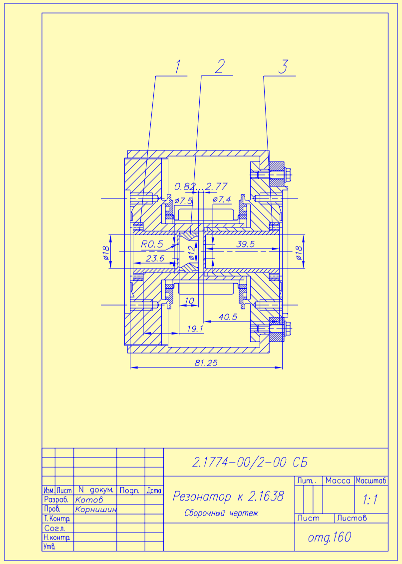
## Suggestion for future work

# Planned RF Fatigue Tests

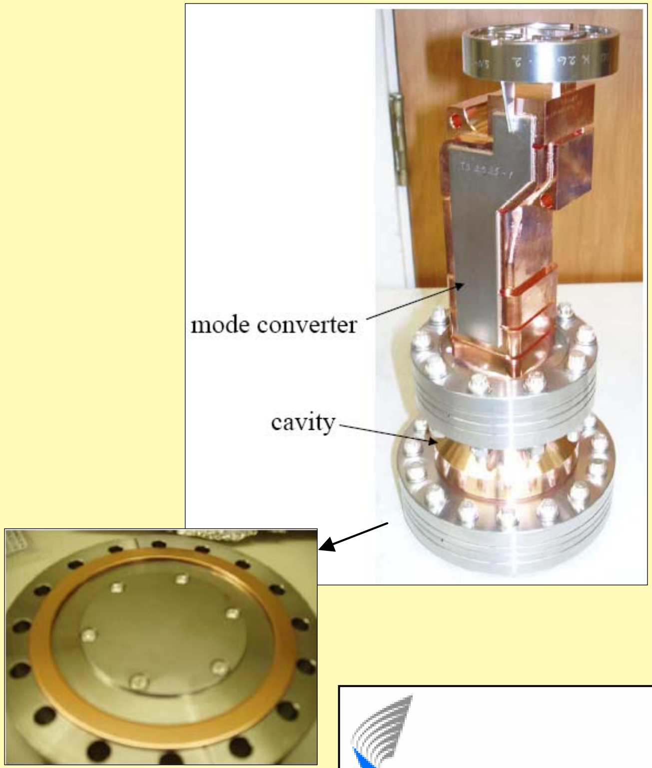
30 GHz pulsed heating cavity, CERN



30 GHz pulsed heating cavity, Dubna

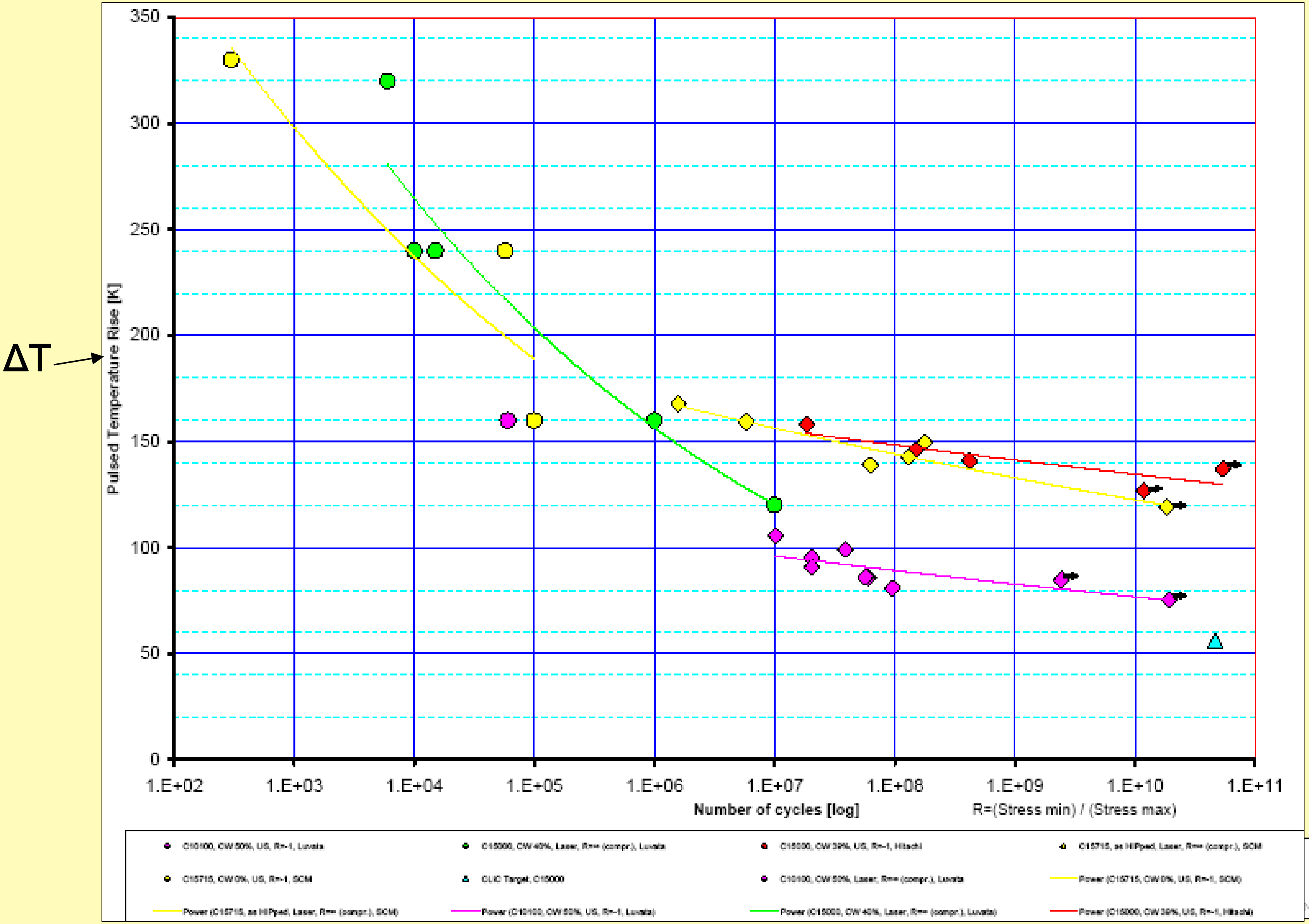


11.4 GHz pulsed heating cavity, SLAC

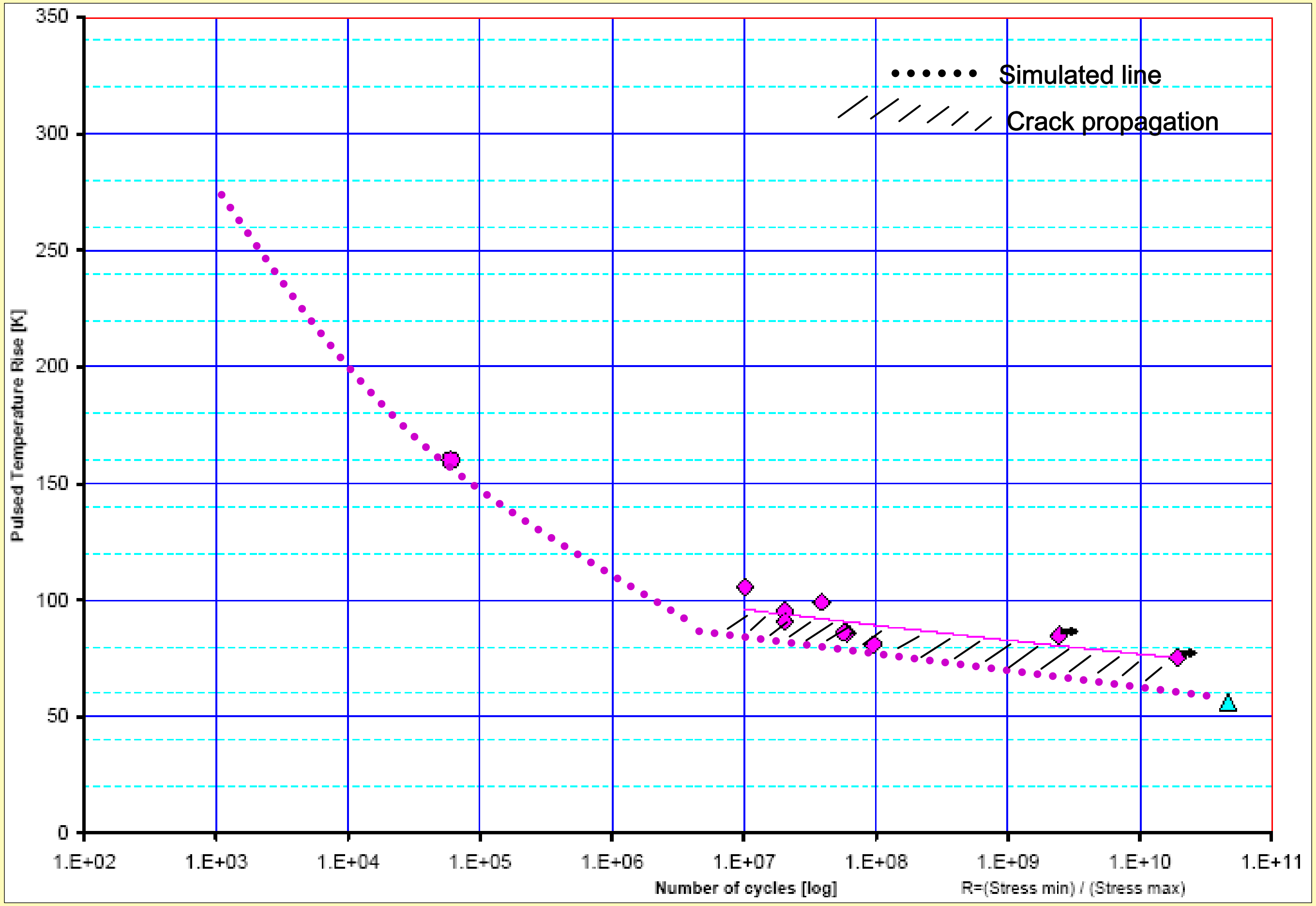


S. Tantawi, SLAC

# Wild guess what can be achieved with existing material(s)

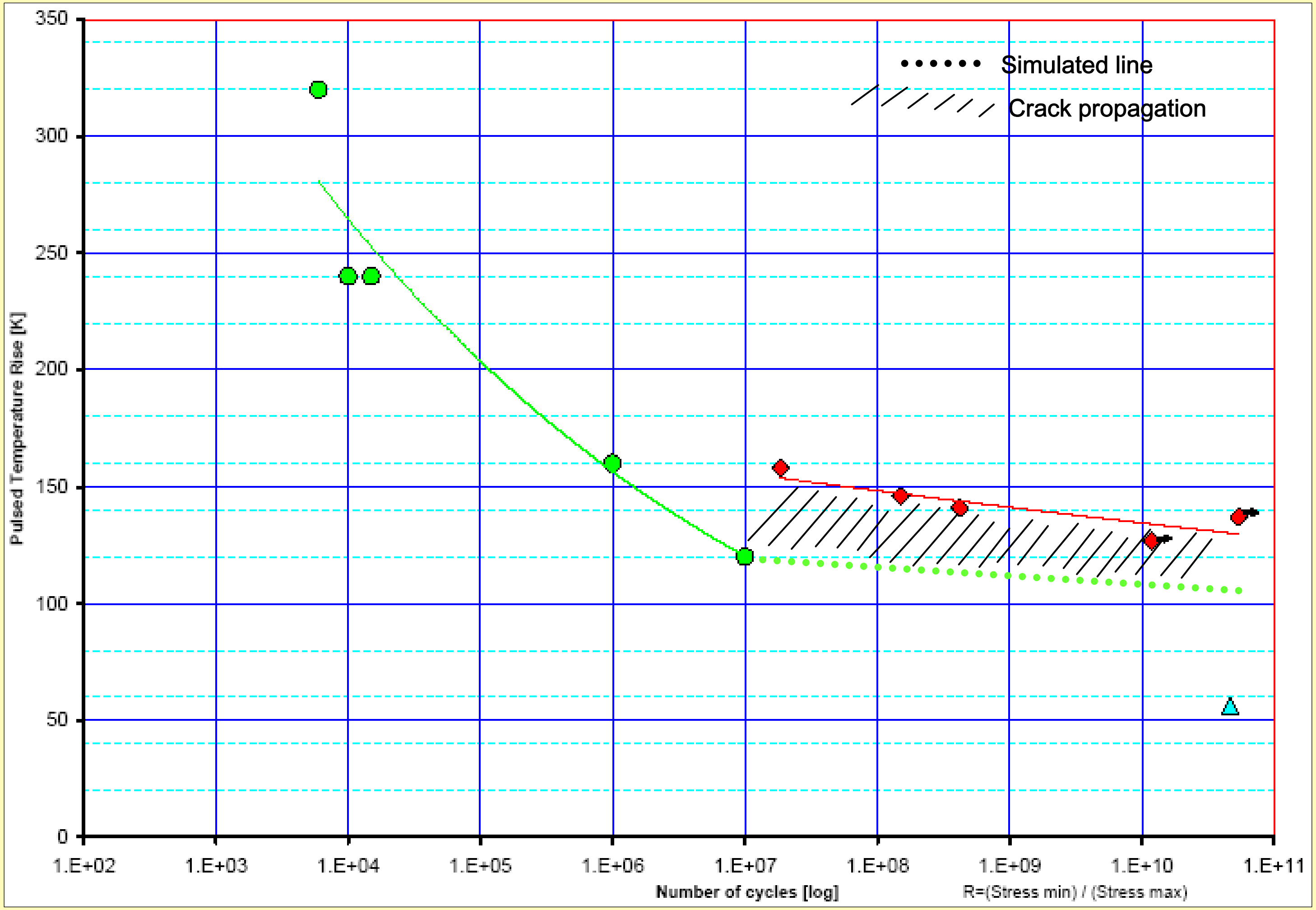


# Wild guess what can be achieved with existing material(s)



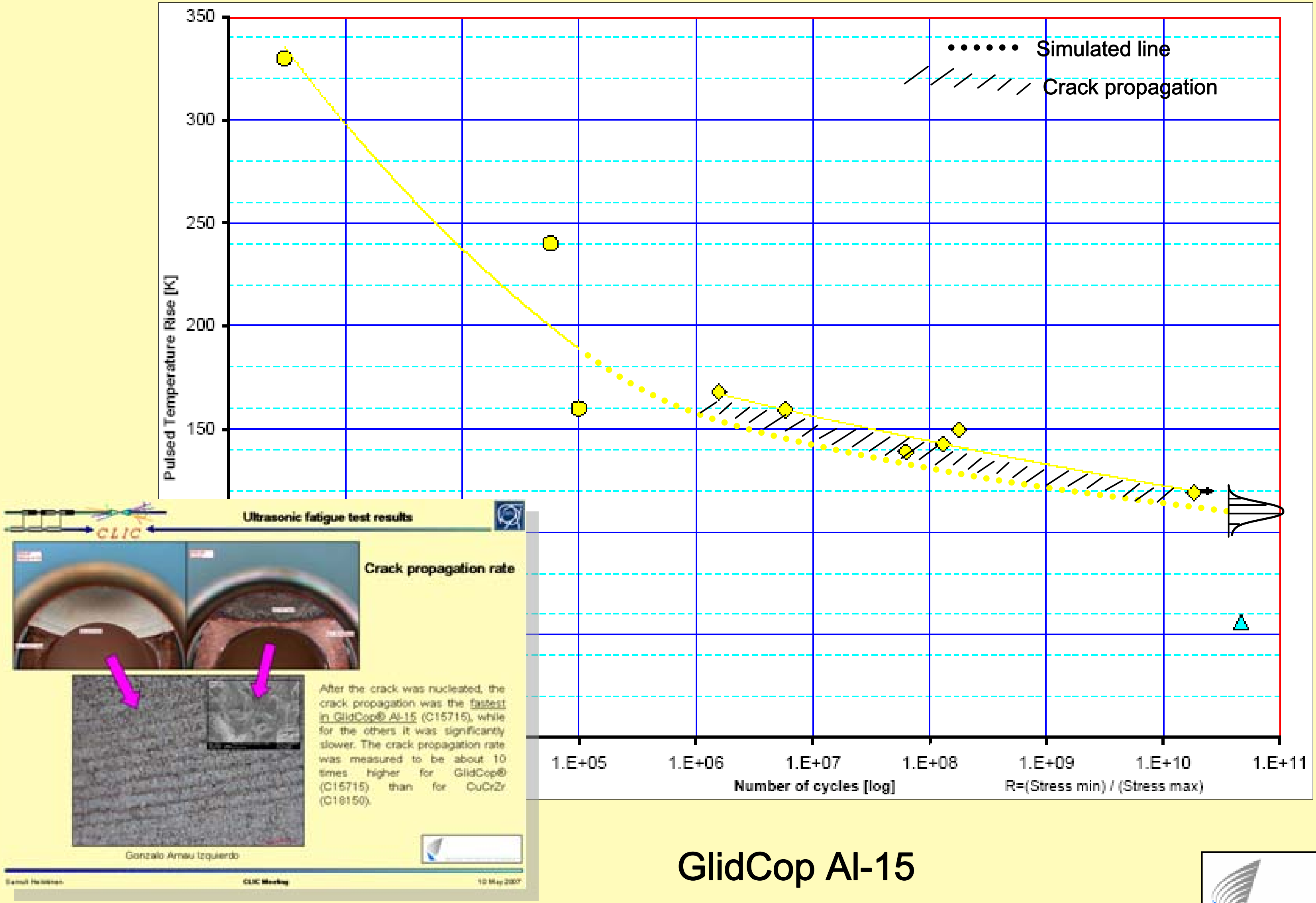
Cu-OFE C10100 (pure copper)

# Wild guess what can be achieved with existing material(s)



CuZr C15000, cold worked

# Wild guess what can be achieved with existing material(s)



**Ultrasonic fatigue test results**

**Crack propagation rate**

After the crack was nucleated, the crack propagation was the fastest in GlidCop® Al-15 (C15715), while for the others it was significantly slower. The crack propagation rate was measured to be about 10 times higher for GlidCop® (C15715) than for CuCrZr (C18150).

Gonzalo Arnau Izquierdo

Samuli Heikkinen CLIC Meeting 10 May 2007

## GlidCop Al-15

# Conclusions

- CLIC parameters: Repetition rate & ΔT have the biggest influence on fatigue
- Current US data classifies the materials
- The best commercially available candidates are tested, I guess!
- CLIC failure criteria have to be studied in detail
  - RF data is needed
  - Laser data needs more statistics and to go further than the Ra 0.02 μm limit
  - US data needs to be collected in similar way as laser (roughness vs. number of cycles)
- US test setup is still valuable tool, because neither laser nor RF can reasonably reach the CLIC number of cycle regime
- 0% cold worked material (CuZr) needs to be tested
- Compressive residual stress (peening, burnishing) might give small improvement (vacuum performance to be confirmed)
  - Could have extra value for soft material states (cold works the surface layer)
- In the end a statistical study of the strength should be done to define the safety factor