Pulsed surface heating:
Ultrasonic and Laser fatigue experiments

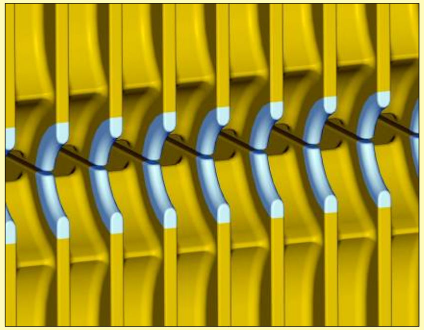
Contents:

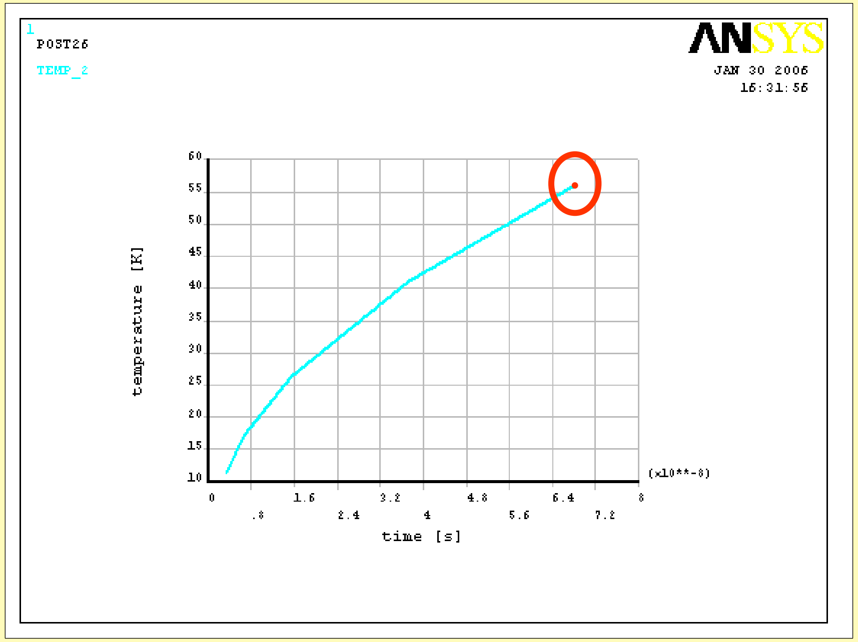
- CLIC Fatigue issues
- Materials & Preparation
- Pulsed laser fatigue testing (Sergio Calatroni & Holger Neupert)
- Ultrasonic fatigue testing
- Up-to-date results
- Conclusions & Future plans

CLIC Fatigue issues

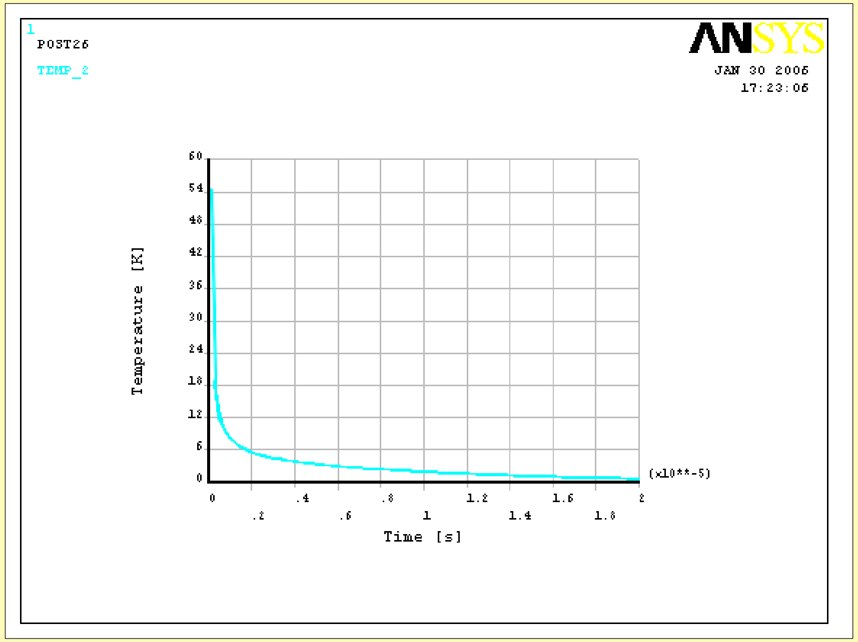
CLIC Fatigue issues

- The instantaneous surface temperature rise due to 68 ns long pulsed RF currents in the outer wall of the cavities is 56 °C for Copper Zirconium C15000 alloy at cold worked temper state having the electrical conductivity of 92% IACS.
- Between the pulses all the heat is rapidly conducted via the bulk leading to stress relaxation and thus to cyclic thermal stresses.

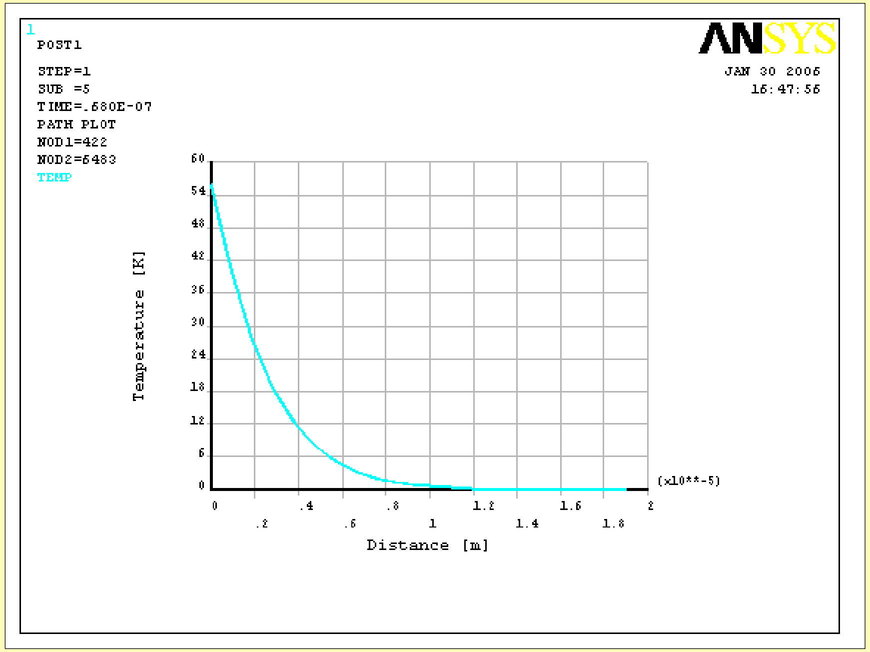


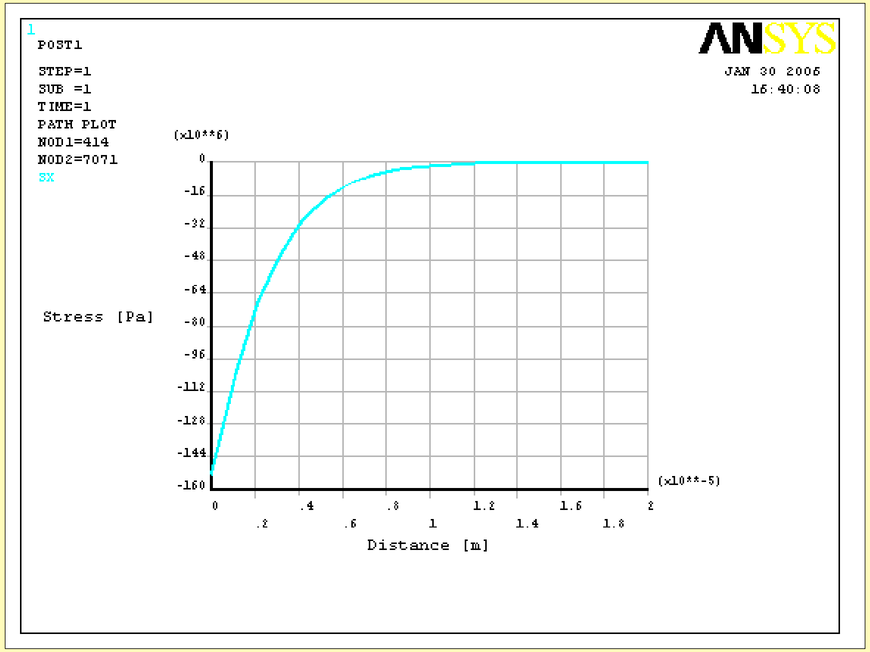


Surface heating during 68 ns pulse



Surface cooling between the pulses
(Idle time 6.7 ms)





Max Temperature- and Stress profiles of 68 ns pulse

CLIC Fatigue issues

Thermal Fatigue Problem

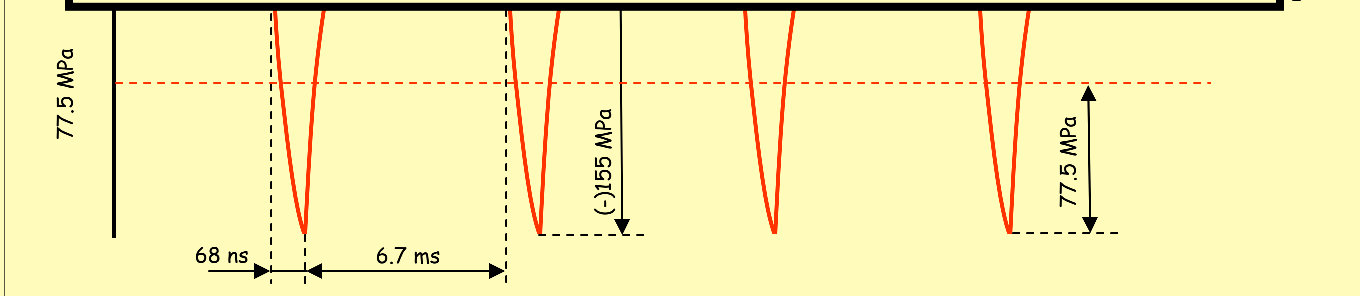
Stress Amplitude 77.5 Mpa
Mean stress -77.5 Mpa

or

Stress amplitude 77.5 Mpa
Stress Ratio R=-∞ *

N = $7x10^{10}$

*(R = Stress min / Stress max)



CLIC Fatigue issues

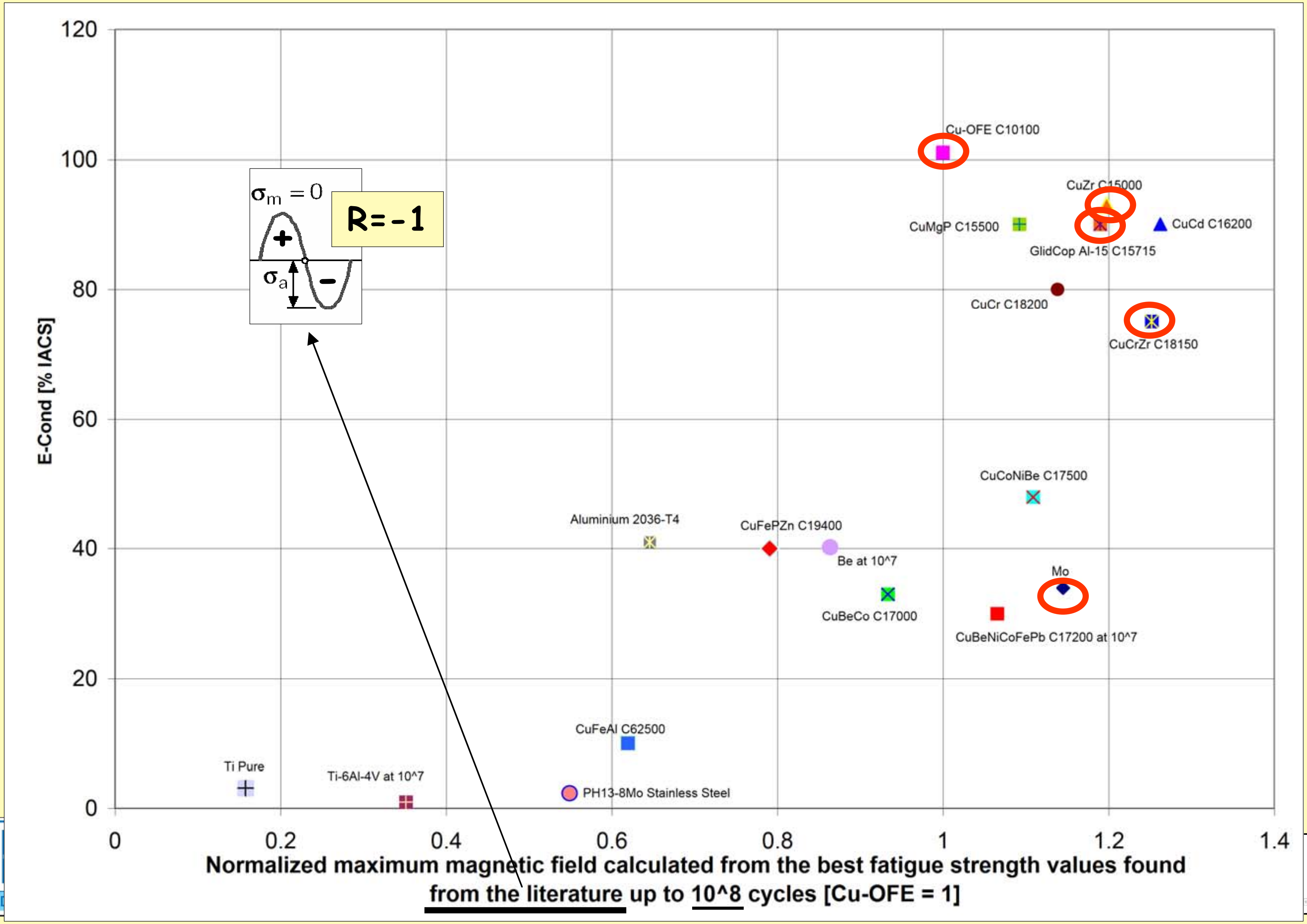
CLIC

+ Vacuum
+ Compressive mean stress
+ Smooth surfaces
+ "Room" temperature
+ "Fast" stress cycle

- Copper alloys are non-ferrous metals, no fatigue limit
- High criteria due to surface currents. Already a small change in surface roughness is crucial.
- Required bi-metallic structure might limit the achievable material state
- Extremely high number of cycles
- Extremely high number of parts, the probability of a failure arises
- The "RF-fatigue" life is expensive and time consuming to test.

Materials & Preparation

Materials & Preparation



Materials & Preparation

Table: Selected materials for the fatigue testing

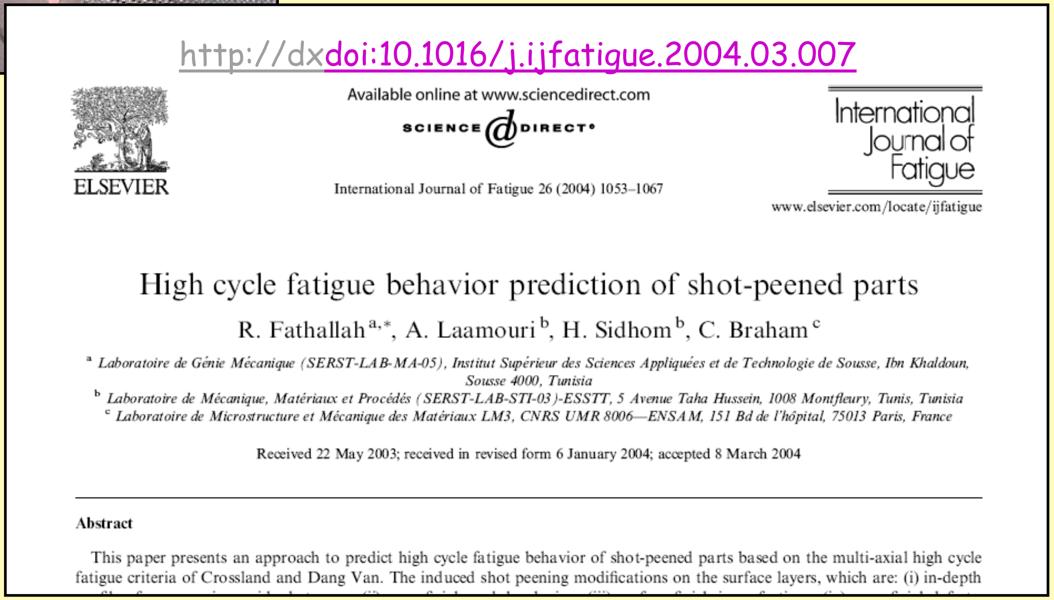
Material	UNS	Electrical conductivity [%IACS]	Cold-Working Ratio [%]	Treatment	Supplier
CuZr	C15000	92	39[1], 40[2], 80[1]	as machined, shot peened, cavitation shot-less peened, ultra burnished, as HIPed	[1]Hitachi Cable Corp., [2]Luvata Oy
CuZr	C15100	94	39, 80	as machined	Hitachi Cable Corp.
CuZr	C15150	97	39, 80	as machined	Hitachi Cable Corp.
CuCrZr	C18150	75	20	as machined	Luvata Oy
Cu-OFE	C10100	101	50	as machined	Luvata Oy
GlidCop® Al-15	C15715	90	0	as machined, as HIPped	SCM Metal Products, Inc
Molybdenum	-	33	?	as machined	Plansee

Materials & Preparation

http://www.rosler.com/www_roesler2004/roesler_shotpeening_628_99_0_f.htm

"Classical" Shot Peening

- Blasting of metal or glass balls against materials surface
- Hardens the surface and introduces a compressive residual stress
- Long history of improving fatigue strength of parts of machines
- Applicable to complex geometries
- Increases the surface roughness



http://dxdoi:10.1016/j.ijfatigue.2004.03.007

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High cycle fatigue behavior prediction of shot-peened parts

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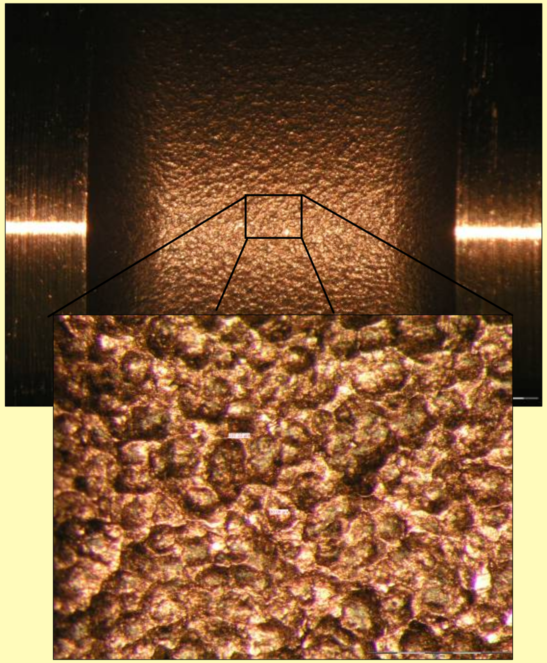
Abstract

This paper presents an approach to predict high cycle fatigue behavior of shot-peened parts based on the multi-axial high cycle fatigue criteria of Crossland and Dang Van. The induced shot peening modifications on the surface layers, which are: (i) in-depth



Shot peened surface of fatigue test sample in C15000

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Materials & Preparation

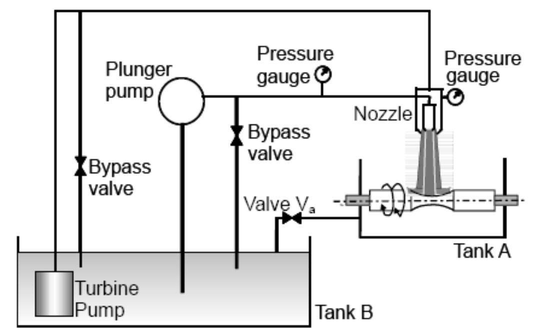

Fig. 2 Cavitating jet apparatus

Cavitation Shot-less Peening

- Forging of a material by cavitating bubbles
- Hardens the surface and introduces a compressive residual stress
- Applicable to complex geometries
- Good surface roughness could be preserved
- Tests in collaboration with Tohoku University (Japan) under way

http://cav2003.me.es.osaka-u.ac.jp/Cav2003/Papers/Cav03-OS-2-3-002.pdf

Cav03-OS-2-3-002

Fifth International Symposium on Cavitation (CAV2003)
Osaka, Japan, November 1-4, 2003

IMPROVEMENT OF FATIGUE STRENGTH ON STAINLESS STEEL BY CAVITATING JET IN AIR

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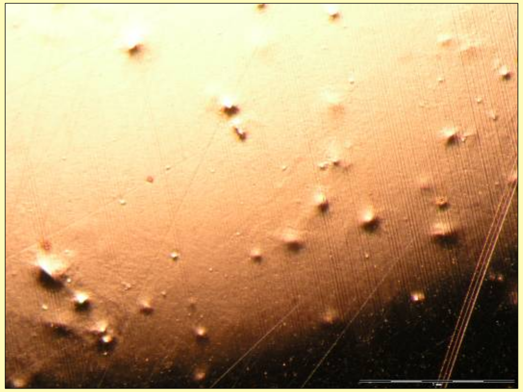
ABSTRACT

Beneficial residual stresses can be introduced on the surface of materials thereby impeding the initiation and/or development ...

quiescent media due to interfacial instabilities caused by density differences, rupture when subjected to large velocity gradients, deform and disintegrate due to turbulent flow conditions, ...



Cavitation Shot-less Peened surface of fatigue test sample in C15000

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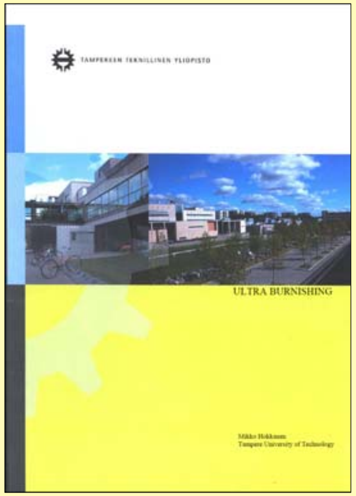
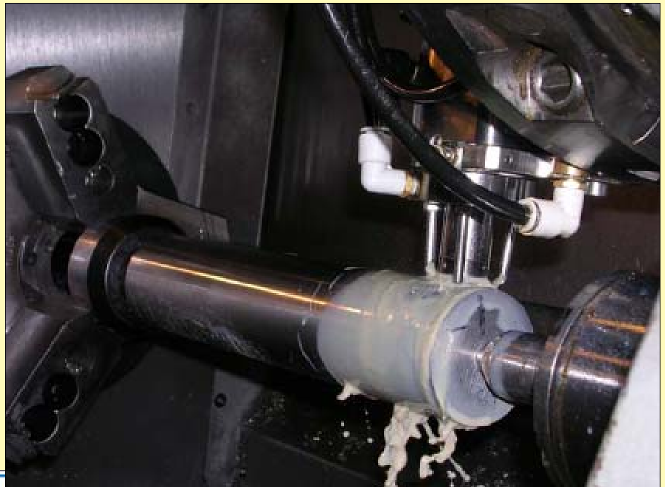
Materials & Preparation



http://www.hiqusa.com/hiqusa_report.pdf

Ultra Burnishing

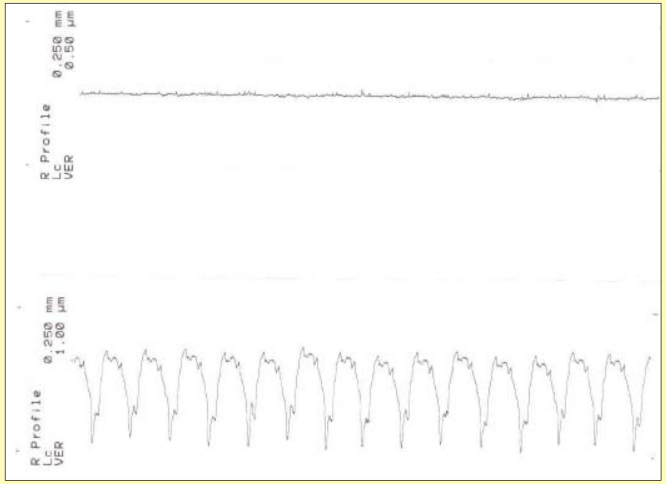
- Forging of material by ultrasonic excitation
- Hardens the surface and introduces a compressive residual stress
- Applicable to complex geometries
- Smoothens the surface



Ultra Burnishing in NC lathe

Ultra Burnished surface of fatigue test sample in C15000

The forging tool tip used in Ultra Burnishing



Surface profiles of turned (below) and ultra burnished (above) tempering steel surfaces.

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Pulsed laser fatigue testing

Sergio Calatroni and Holger Neupert, CERN TS-MME

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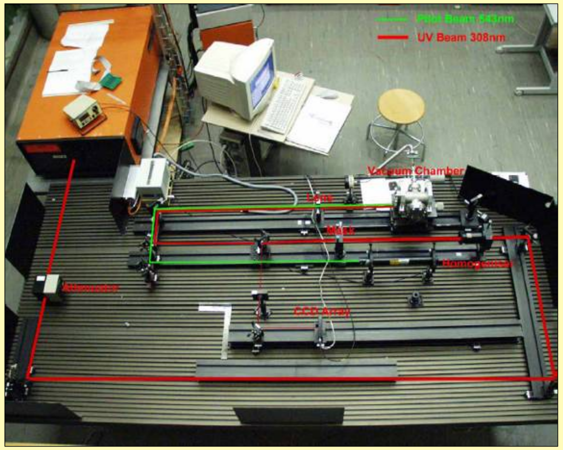
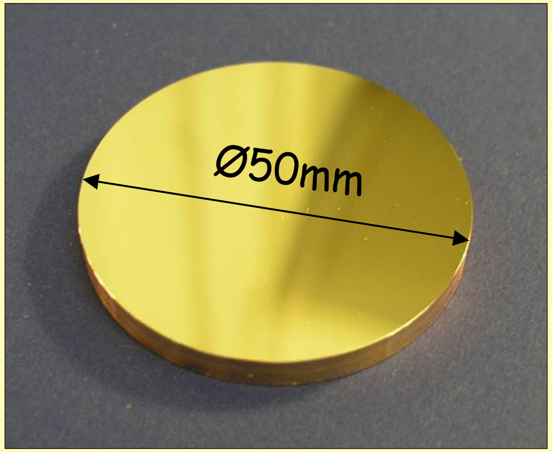
Pulsed laser fatigue testing

- Surface of test sample is heated with pulsed laser. Between the pulses the heat will be conducted into the bulk.
- The Laser fatigue phenomenon is close to RF fatigue.
- The operating frequency of the pulsed laser is 20-200 Hz -> only low cycle tests, up to 10^8.
- Observation of surface damage with electron microscope.



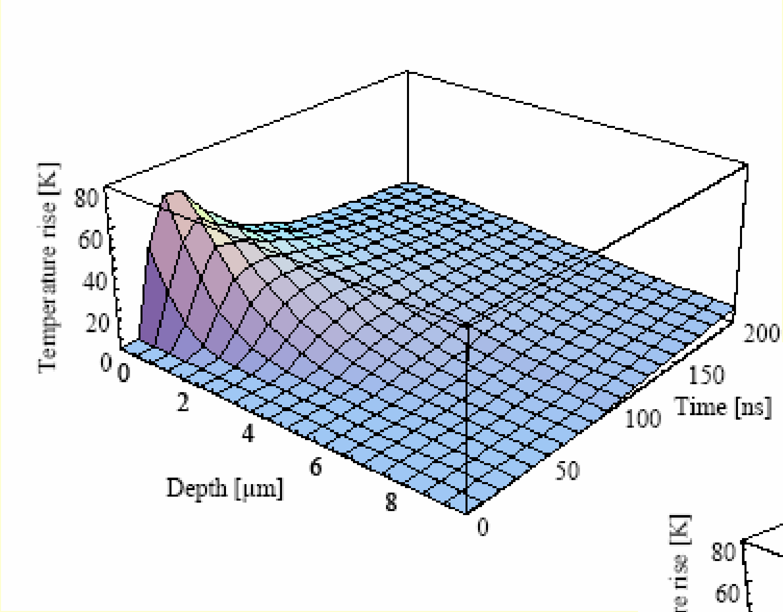
"Old" laser test setup



Diamond turned test sample

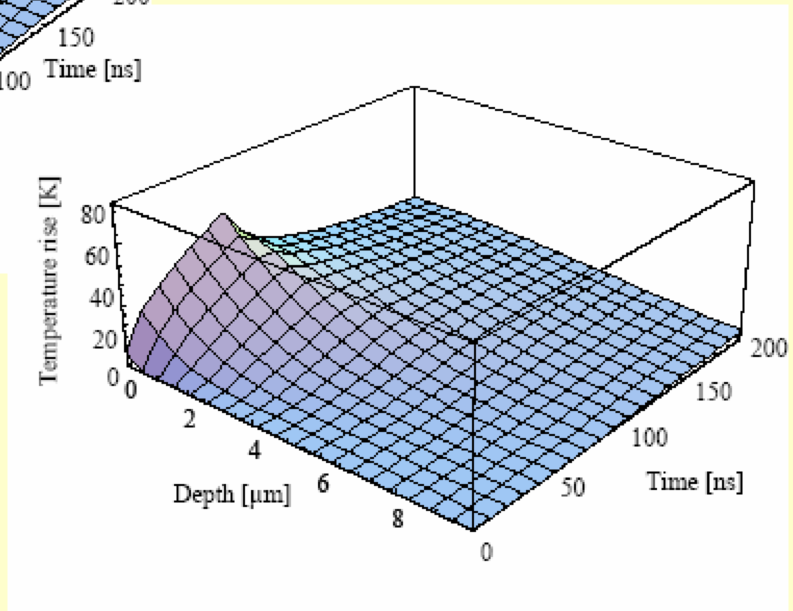
Pulsed laser fatigue testing

Comparison of heating profiles



← Laser pulse

RF pulse ↓



The pulse shapes correspond. In particular the temperature profile at the peak is very similar, and results in similar stress level.

$$\sigma = \frac{\Delta T * E * \lambda}{(1-\nu)}$$

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http://clic-meeting.web.cern.ch/clic-meeting/2006/02_17min.html

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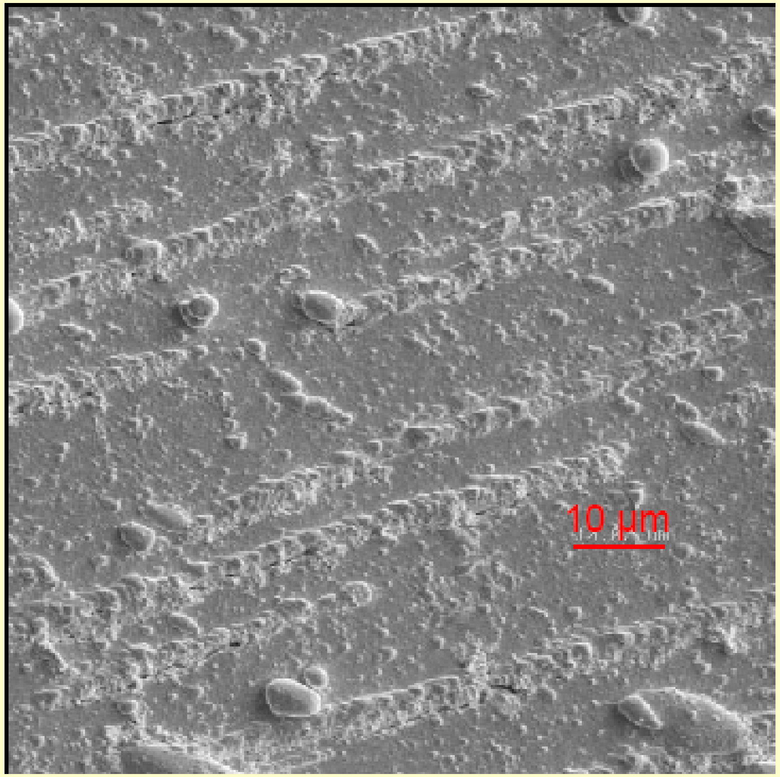
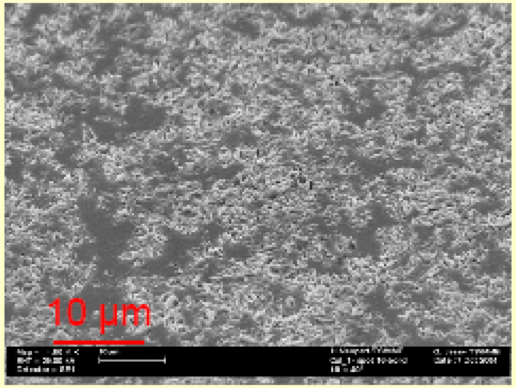
Pulsed laser fatigue testing

Comparison of surface damage: RF & laser



Cu, 56 Mpulses, ΔT = 120 K, σ = 170 MPa
[D.P. Pritzkau and R.H. Siemann, PRST-AB 5, 112002 (2002)]



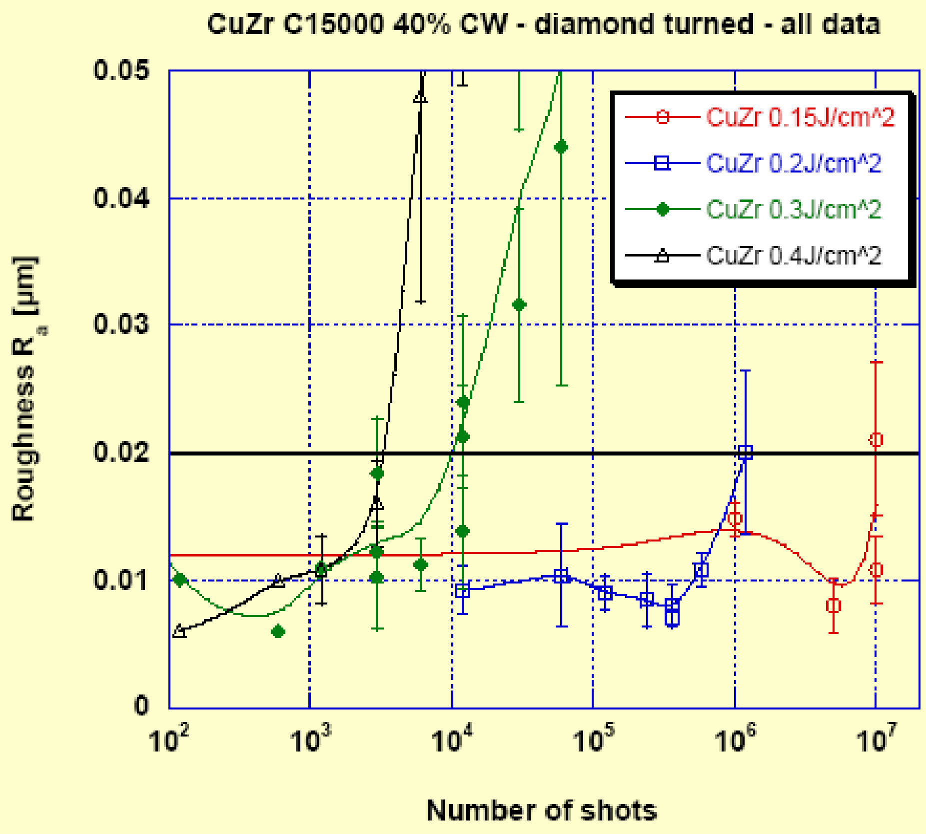
Cu, 1 Mshots, 0.1 J/cm^2,
ΔT = 80K, σ = 115 MPa

There is only one known RF experiment that allows comparing RF-induced surface damage and laser-induced surface damage.
It seems logical to assume that the physical mechanisms behind fatigue are the same in both cases

http://clic-meeting.web.cern.ch/clic-meeting/2006/02_17min.html

Pulsed laser fatigue testing

Surface roughness as a function of fluence and number of shots: CuZr



The value of 0.02 µm has been chosen as the first measurable departure from the reference surface (flat, diamond turned).

This is thought being the most important phenomenon. The further increase of roughness is only crack propagation.

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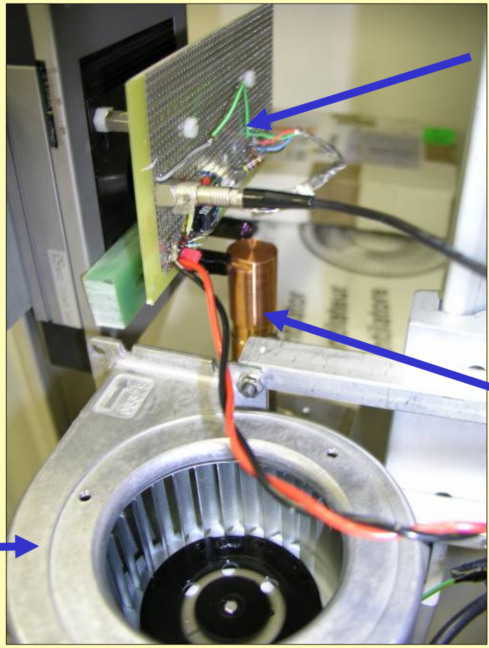
http://clic-meeting.web.cern.ch/clic-meeting/2006/02_17min.html

Ultrasonic fatigue testing

Ultrasonic fatigue testing

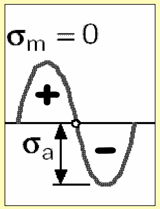
- Cyclic mechanical stressing of material at frequency of 24 kHz.
- High cycle fatigue data within a reasonable testing time. CLIC lifetime 7×10^{10} cycles in 30 days.
- Will be used to extend the laser fatigue data up to high cycle region.

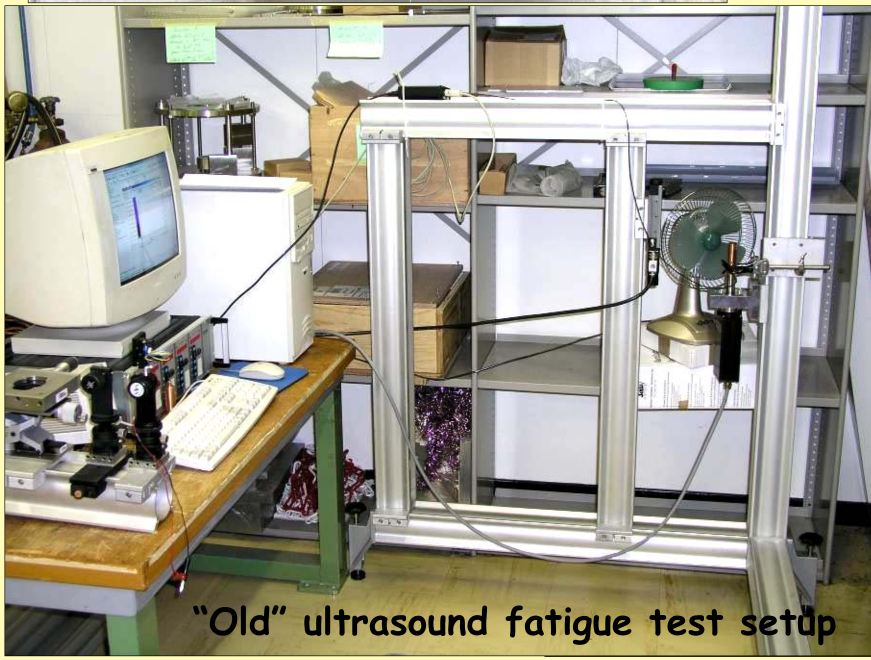


Amplitude measurement system

Fatigue test specimen

Air Cooling

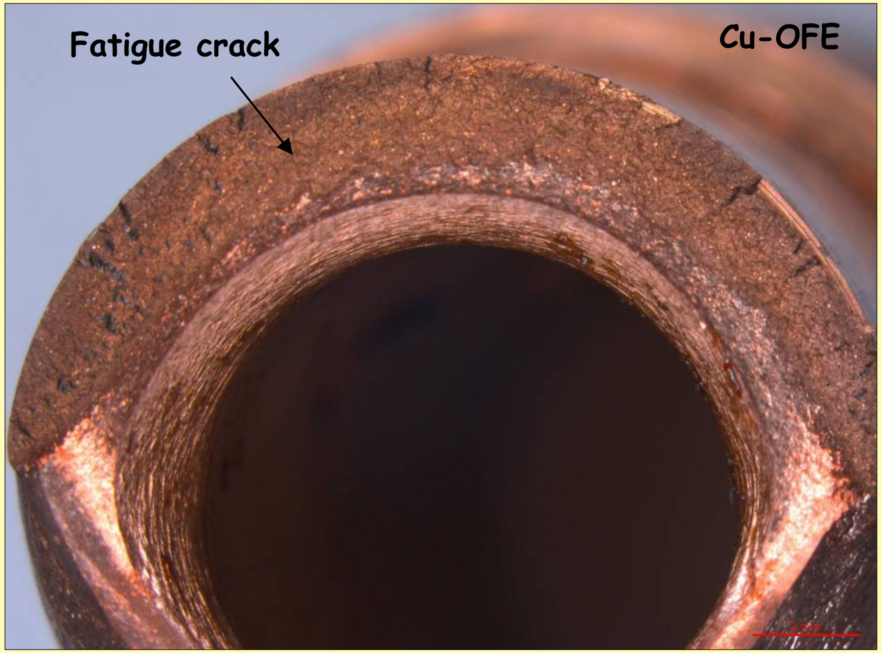


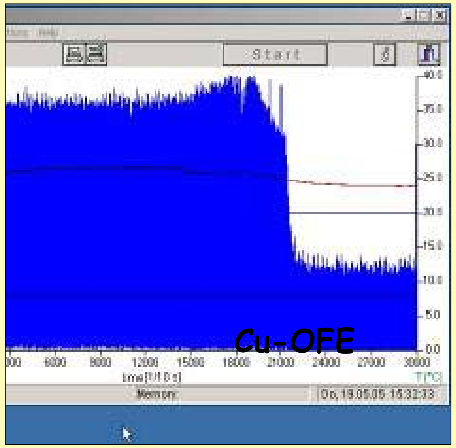


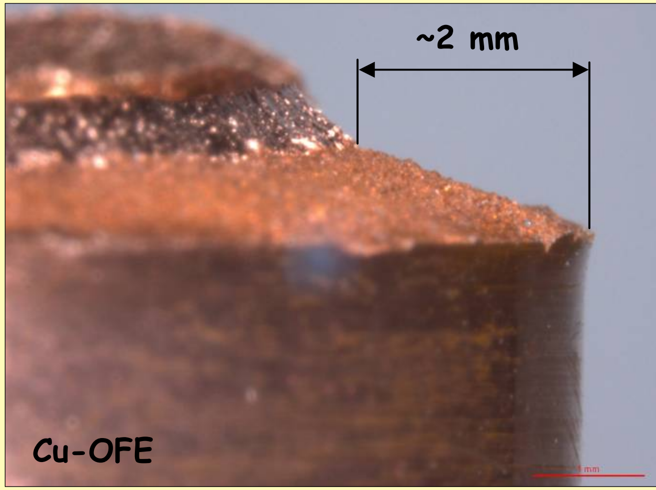
Ultrasonic fatigue testing

- The operating frequency of the Ultrasound unit is 24 kHz ± 1 kHz.
- A crack changes the resonant frequency of the sample.
- When the crack is about 2 mm deep, the sample is 1 kHz off the resonance and the device stops the "normal" operation.
- "Traceability" of crack initiation point is of the order of 10^5-10^6 cycles depending on the material.

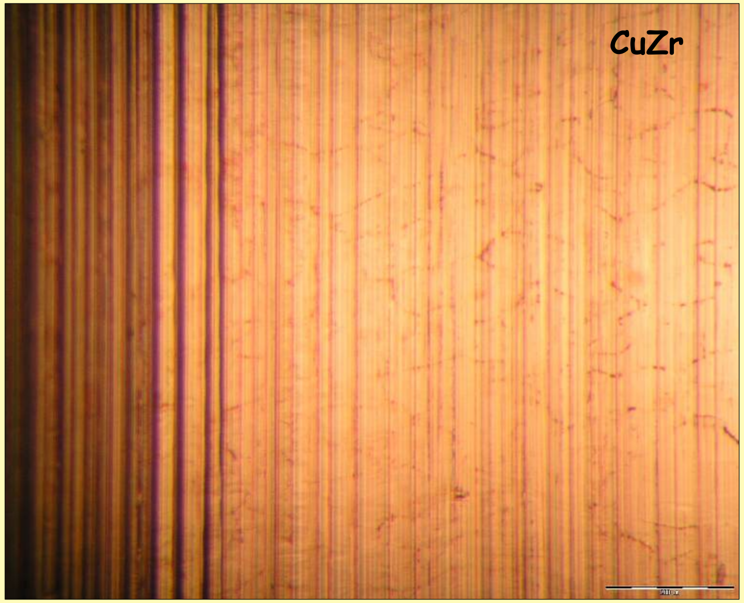
=> No low cycle tests



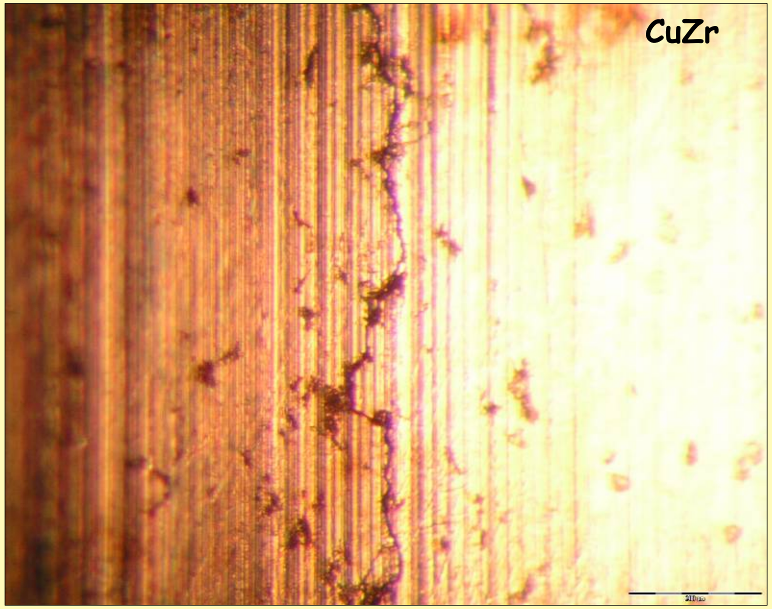




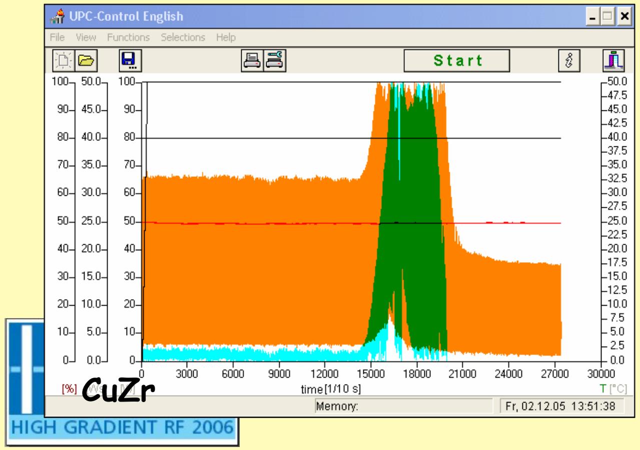
Ultrasonic fatigue testing

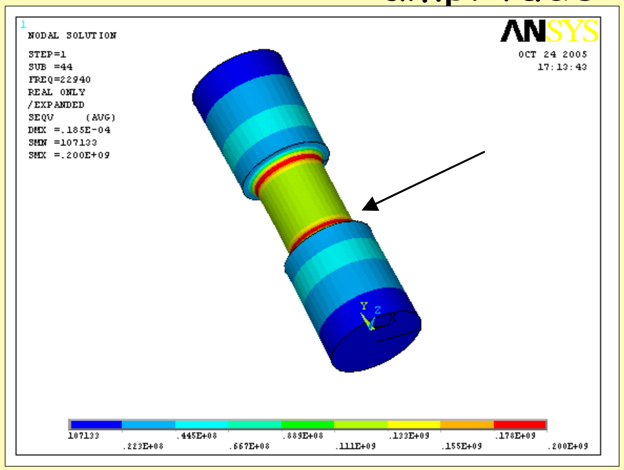


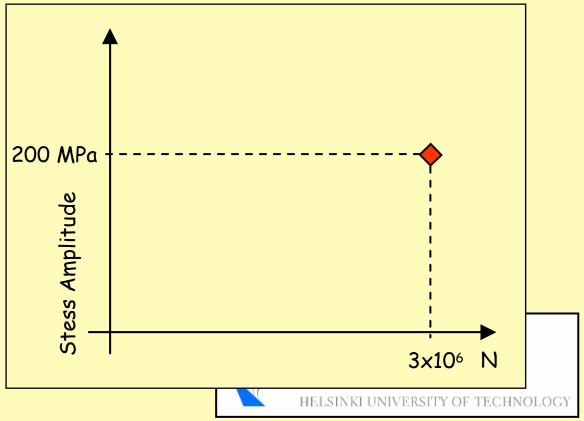
Diamond turned specimen before



After $3*10^6$ cycles at stress amplitude 200 MPa

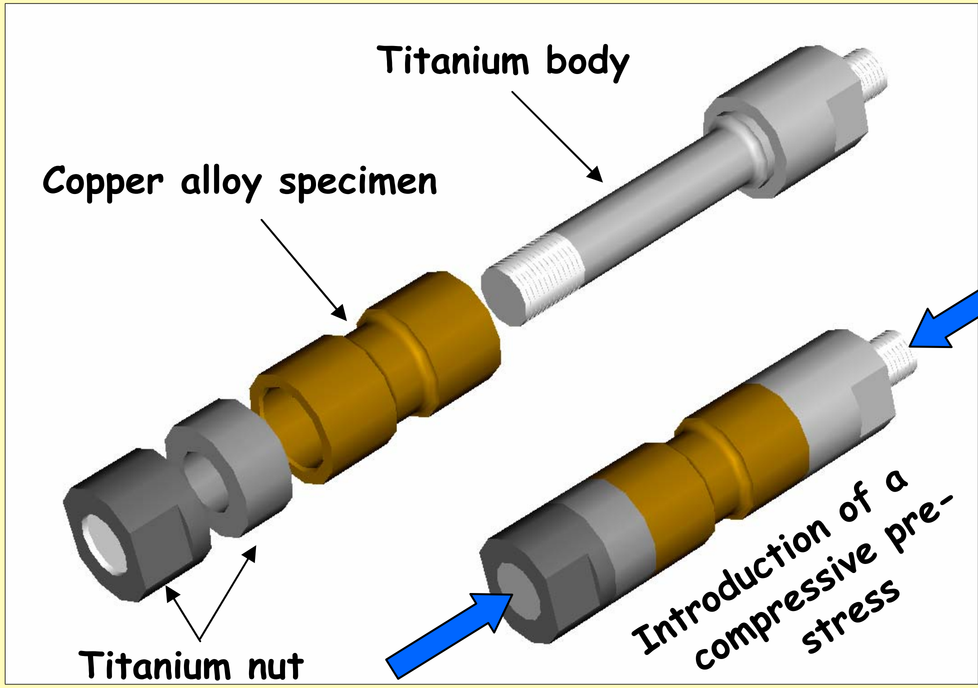




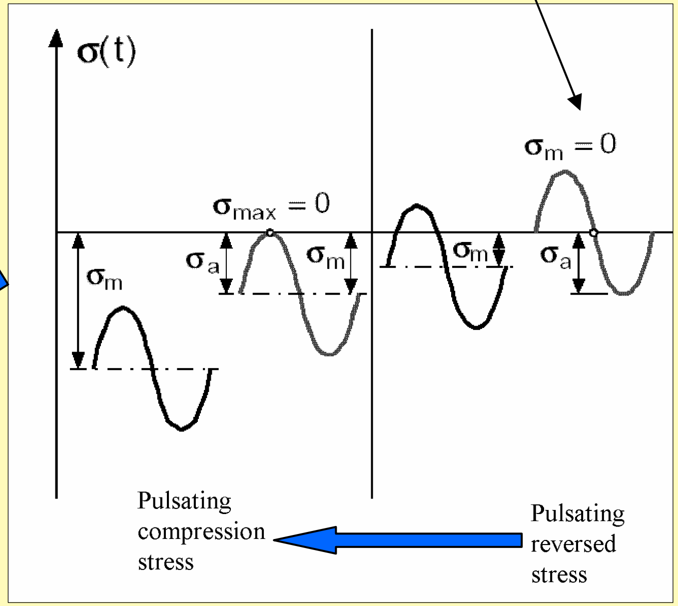


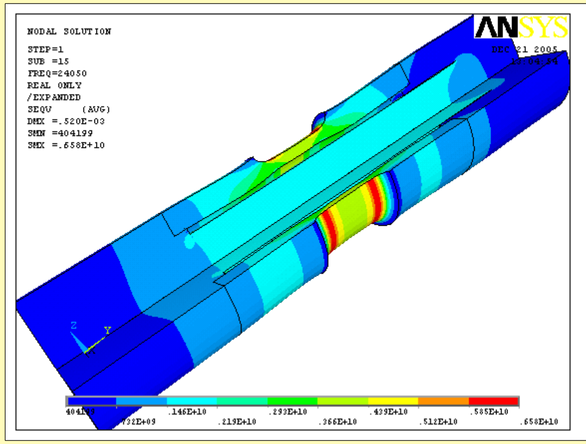
Ultrasonic fatigue testing

Varying the stress condition by a special pre-stressed specimen



Default ultrasound stress condition

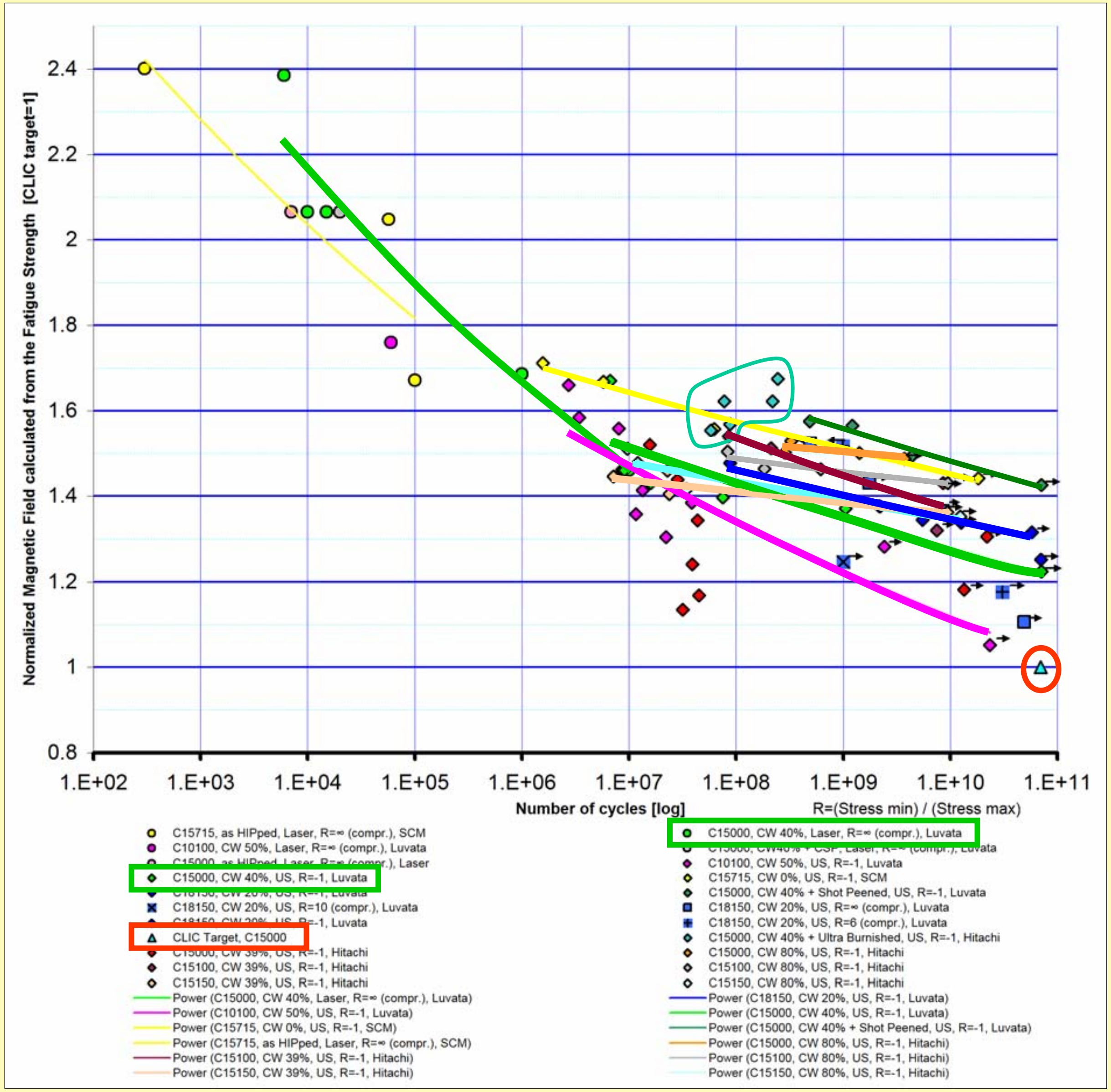




Up-to-date results

Up-to-date results

- ◇ Ultrasound
- □ Ultrasound pre-stressed
- ○ Laser
- △ CLIC Target
- → Run-out



Alloy

$CuAl_2O_3$

C15715

↑

CuZr / CuCrZr

C15000, C15100, C15150, C18150

Cold Working Ratio

80 %

⇕ ?

Alloying Ratio

(40% cw)

Peened

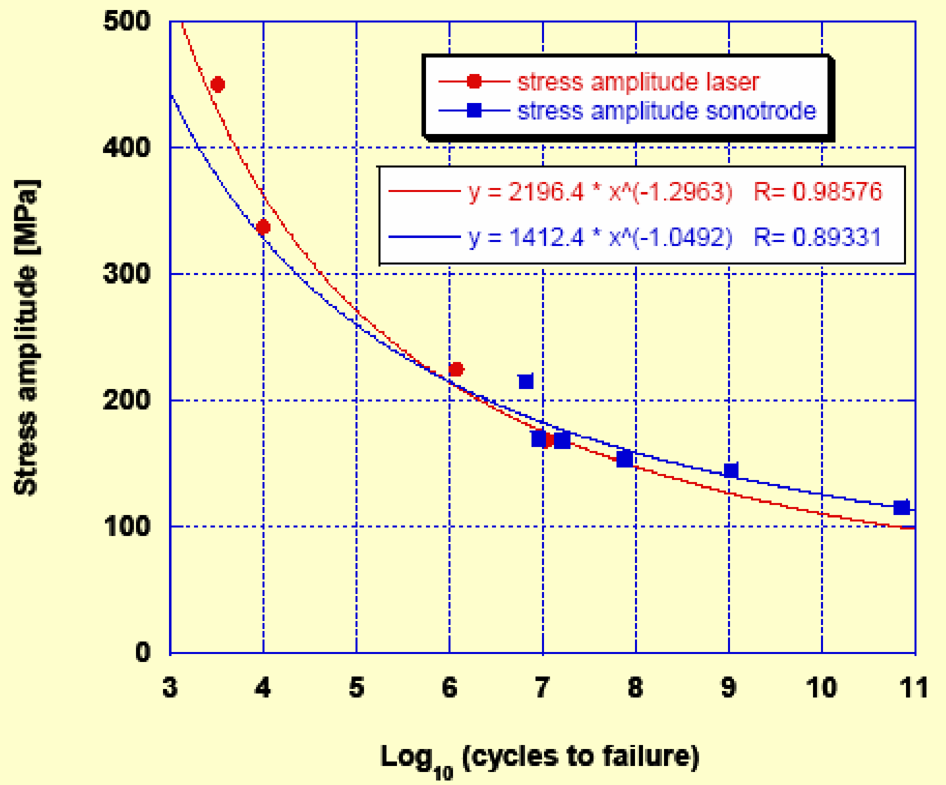
↑

Non peened

C15000 ?

Up-to-date results

Fatigue limit: laser & ultrasound



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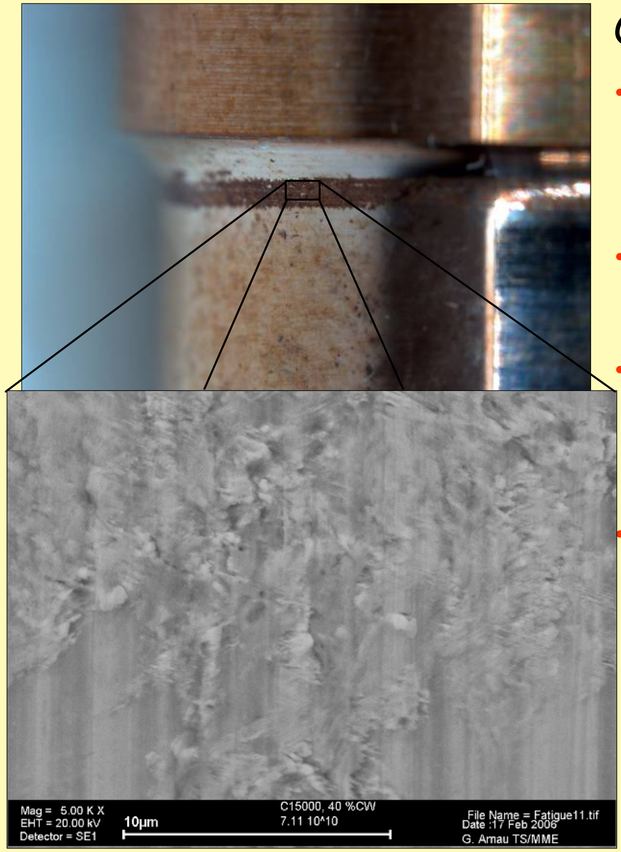
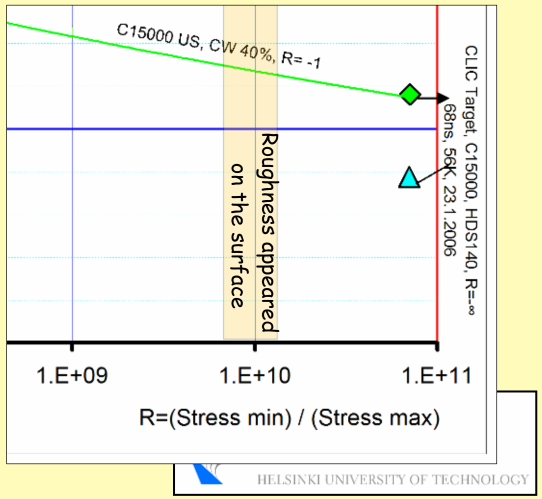
http://clic-meeting.web.cern.ch/clic-meeting/2006/02_17min.html

Up-to-date results

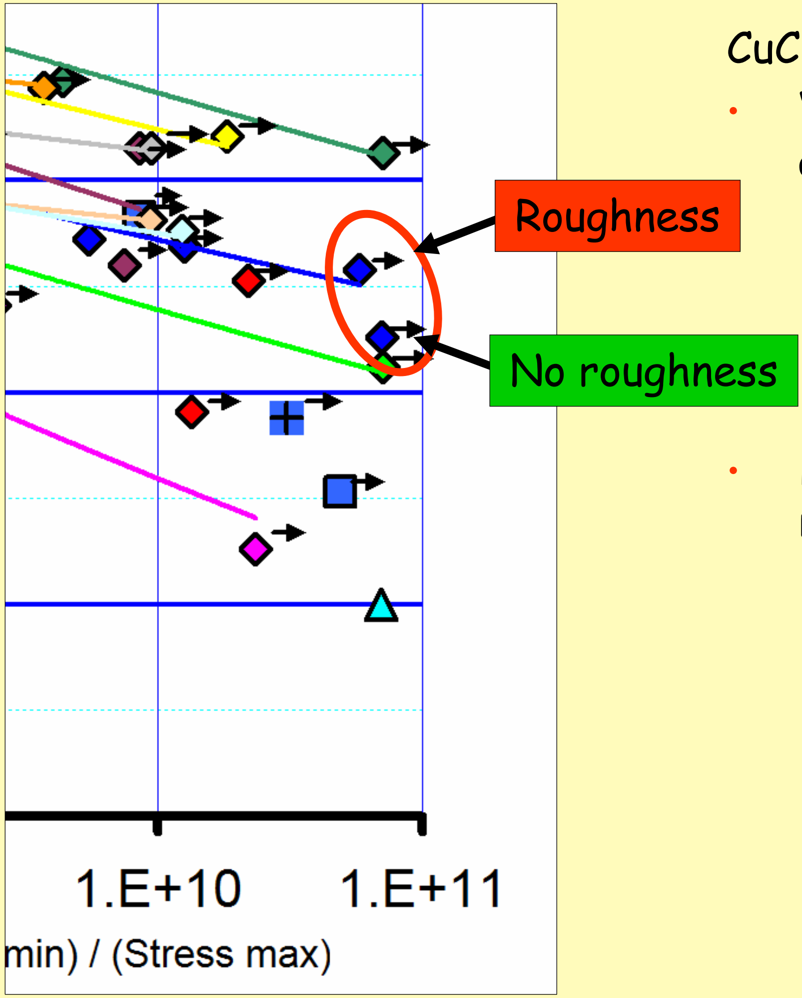


Observation:

- Most of the ultrasound specimens that survived the CLIC lifetime without a fracture experienced surface roughening at the point of maximum stress.
- This is likely to be an early stage of fatigue before the crack initiates.
- The RF induced stress in the CLIC accelerating cavities increases with the surface roughness due to the surface electrical resistance increase.
- The surface roughening under cyclic deformation is likely unacceptable for CLIC.



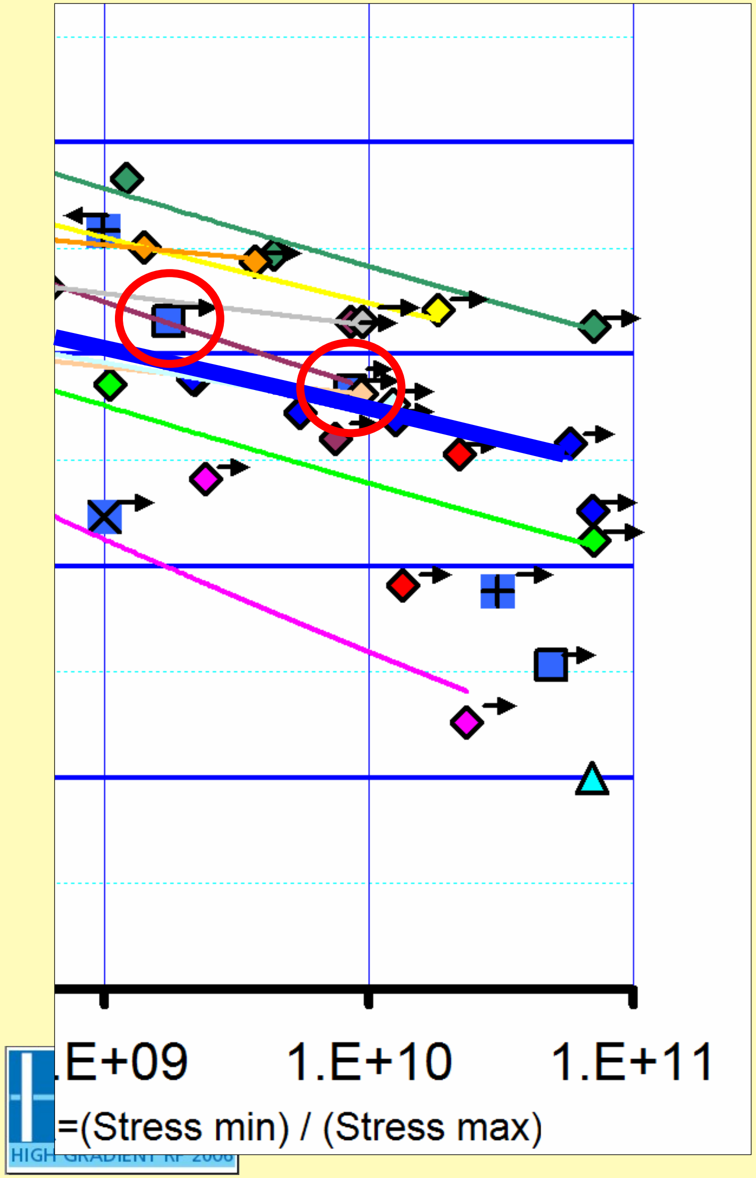
Up-to-date results



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}.

Up-to-date results

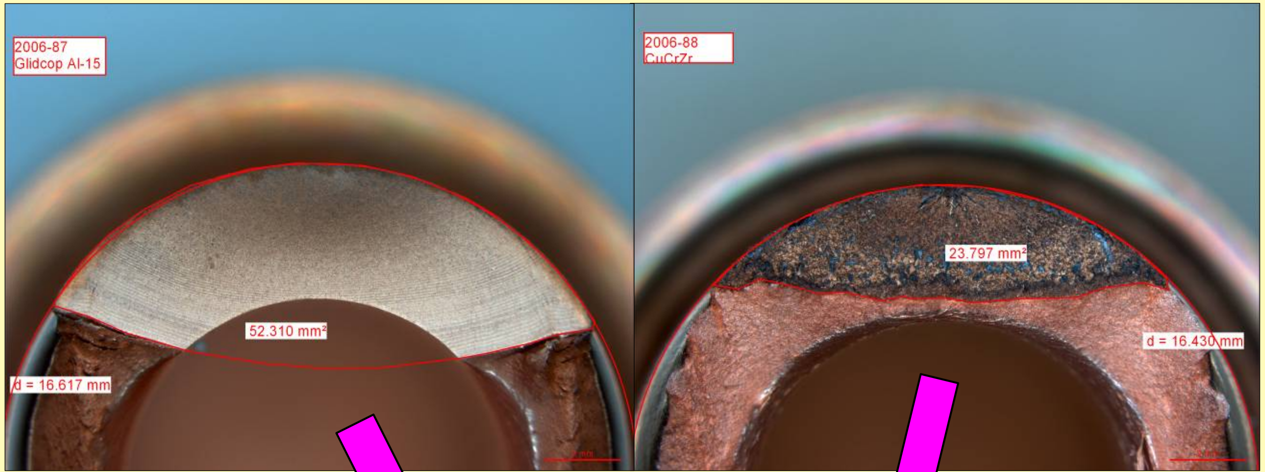


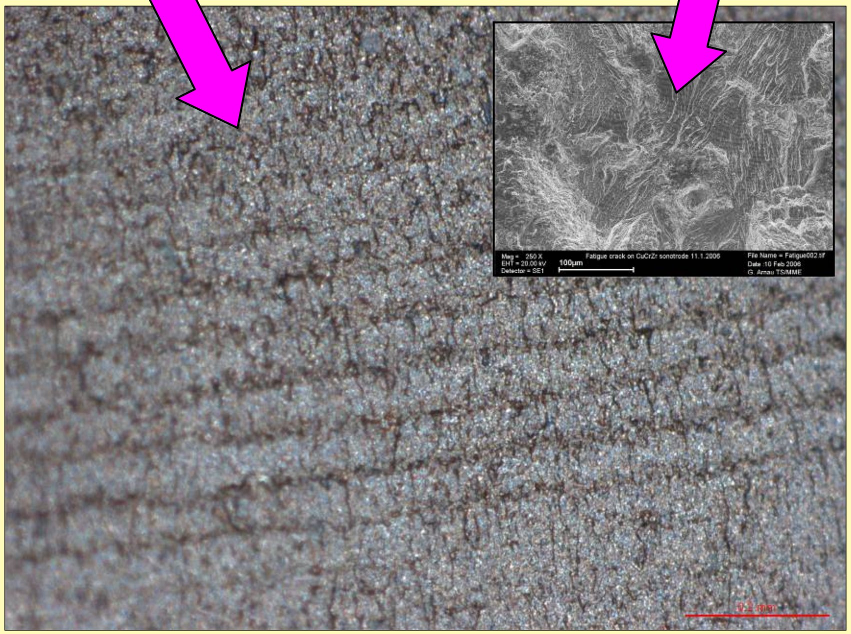
C18150 fully reversed conditions R=-1

C18150 fully compressive conditions R=∞

Based on the few experiments with pre-stressed C18150 specimens it looks like that the compressive mean stress does not change the fatigue strength from the fully reversed conditions (at least when the absolute maximum stress value does not exceed the yield strength).

Up-to-date results





Observation: After the crack has initiated, the crack development behavior is fastest in GlidCop® Al-15 (C15715), while for the others it has more stable behavior. The crack propagation speed was measured to be 10 times higher for GlidCop® (C15715) than for CuCrZr (C18150).

Gonzalo Arnau Izquierdo

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Conclusions & Future plans

Conclusions & Future plans

Looks like that CLIC parameters could be achieved with existing materials with a reasonable safety margin (More studies are needed for the final conclusion).

The alloying rate of CuZr seems to have an effect on the fatigue strength. Conclusions cannot be drawn from the current few data (more experiments foreseen). In general smaller zirconium quantity is beneficial for the CLIC cavities (the overall efficiency).

In the CLIC RF cavities the crack propagation rate is probably not as critical issue as the resistance against the fatigue crack initiation, because a small crack already causes a rapid failure of the structure.

Ultrasonic experiments for CuZr alloys at soft "as HIPped" state is missing (experiment underway).

The surface roughening is probably a critical issue for the RF cavities. The RF induced stress in the CLIC accelerating cavities increases with the surface roughness due to the surface electrical resistance increase.

A 10 - 20 % drop from the threshold stress values is probably required to keep the surface smooth up to 7×10^{10} number of cycles range.

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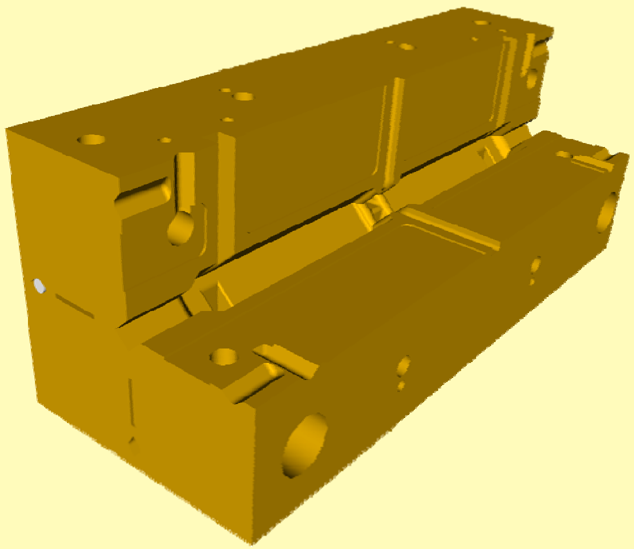
Conclusions & Future plans

The peening techniques are interesting methods for increasing the fatigue resistance, especially if the manufacturing process of the cavities leads to a soft material state. The high strength is required only near the surface.

RF fatigue experiments are under way, which will eventually provide cross checks whether the ultrasonic and pulsed laser fatigue data are usable for the accelerating cavities.



30 GHz pulsed heating cavity

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