CERN – EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CLIC-Note-708

HIGH POWER RF INDUCED THERMAL FATIGUE IN THE HIGH GRADIENT CLIC ACCELERATING STRUCTURES

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Abstract

The need for high accelerating gradients for the CLIC (Compact Linear Collider) imposes considerable constraints on the materials of the accelerating structures. The surfaces exposed to high pulsed RF (Radio Frequency) currents are subjected to cyclic thermal stresses possibly resulting in surface break up by fatigue. Various high strength alloys from the group of high conductivity copper alloys have been selected and have been tested in different states, with different surface treatments and in different stress ratios. Low to medium cycle fatigue data (up to 108 cycles) of fully compressive surface thermal stresses has been collected by means of a pulsed laser surface heating apparatus. The surface damage has been characterized by SEM observations and roughness measurements. High cycle fatigue data, up to 7x1010 cycles, of varying stress ratio has been collected in high frequency bulk fatigue tests using an ultrasonic apparatus. Up-to-date results from these experiments are presented.

Presented at: FATIGUE 2007 Conference, Cambridge, UK, 26-28 March 2007

Geneva, Switzerland
(04 April 2007)

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The need for high accelerating gradients for the CLIC (Compact LInear Collider) imposes considerable constraints on the materials of the accelerating structures. The surfaces exposed to high pulsed RF (Radio Frequency) currents are subjected to cyclic thermal stresses possibly resulting in surface break up by fatigue. Various high strength alloys from the group of high conductivity copper alloys have been selected and have been tested in different states, with different surface treatments and in different stress ratios. Low to medium cycle fatigue data (up to 10^8 cycles) of fully compressive surface thermal stresses has been collected by means of a pulsed laser surface heating apparatus. The surface damage has been characterized by SEM observations and roughness measurements. High cycle fatigue data, up to 7×10^{10} cycles, of varying stress ratio has been collected in high frequency bulk fatigue tests using an ultrasonic apparatus. Up-to-date results from these experiments are presented.

INTRODUCTION

The CLIC (Compact LInear Collider) is being studied at CERN (European Organization for Nuclear Research) as a possible future high-energy (0.5-5 TeV e^+e^- centre-of-mass) physics facility. The current aim of the CLIC Study Team is to demonstrate the key feasibility issues before 2010. CLIC will be about 33 kilometres long and will be placed 100 metres below ground. The main linear accelerator (linac) of CLIC consists of accelerating structures with the following demanding performance requirements: accelerating gradients of about 150 MV/m, power flows of about 200 MW, 1-2 µm dimensional tolerances, an optical-quality surface finish and ultimately a low mass production cost. About 80% of CLIC's 33 kilometre length will be filled with main beam accelerating structures, which will require of the order of thousands of tons of raw material and millions of individual parts.

CLIC FATIGUE ISSUES

Since no fatigue data exists in the literature up to very large numbers of cycles and for the particular stress pattern present in RF cavities, a comprehensive study of materials in this parameter range has been initiated. Due to efficiency requirements of CLIC a high electrical conductivity is needed for the material of the RF cavities. The induced thermal stress of the CLIC parameter range is inversely proportional to the electrical and thermal conductivities of the cavity material. High electrical conductivity is also important for the high overall efficiency requirement of the CLIC machine, and a good fatigue performance over the machine lifetime is of course

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required. This limits the material to be from the group of high conductivity coppers. Strengthening methods susceptible to increase fatigue resistance like alloying and cold working are generally accompanied by a decrease in electrical conductivity. An optimum compromise of those properties has to be obtained by the best choice of copper grade, temper state and surface treatment.

The current design of the 30 GHz CLIC accelerating cavities is based on the HDS-type (Hybrid Damped Structure) geometry, Figure 1. The instantaneous surface temperature rise due to 68 ns long pulsed RF currents in the outer wall of the cavities is 56 ºC for Copper Zirconium C15000 alloy at cold worked temper state having the electrical conductivity of 92% IACS, Braun et al. [1]. Thermo-mechanical finite element simulations (ANSYS software) of the CLIC cavities give a 155 MPa compressive stress for C15000, Figure 2. Between the pulses all the heat is rapidly conducted via the bulk leading to stress relaxation and thus to thermal cycling. The fatigue loading for C15000 is a cyclic compressive stress with stress amplitude of 77.5 MPa and mean stress of -77.5 MPa. The design lifetime of CLIC is 20 years and the pulse repetition rate is currently fixed to 150 Hz, which result in a total number of thermal cycles of 7×10^{10}.

The 68 ns long RF pulses induce also elastic shock waves which travel into the bulk as presented by Huopana and Heikkinen [2]. By ANSYS coupled field thermo-elastic simulations the maximum stress level of these waves is about 10 MPa for C15000, Figure 3. The stress level of these waves is low compared to the stress at the point of maximum magnetic field (155 MPa), so they do not affect the fatigue lifetime of the structure.

EXPERIMENTAL SETUPS

To perform a complete RF fatigue experiment with CLIC parameters would be very expensive and time consuming. Therefore the experiments under way in order to qualify the material resistance to this stress pattern and number of cycles are based on high frequency ultrasonic excitation and pulsed laser irradiation. The ultrasonic (US) experiment is used to study the bulk fatigue behaviour at the high cycle regime and pulsed laser irradiation to simulate the thermal surface fatigue phenomena at low cycle regime. Only few RF fatigue experiments with low number of cycles are foreseen to cross check the results of the other experiments.

In order to simulate the total CLIC lifetime it is important to find the connectivity between data from the high cycle and the low cycle experiments. The specimens for the different experiments are produced from identical materials and through the same manufacturing processes. Diamond turning was used as a fabrication technique of the specimens to produce reproducible surfaces for both experiments.

Ultrasonic fatigue testing

High cycle fatigue data, of up to 7×10^{10} cycles, at various stress ratios have been collected by high frequency bulk fatigue experiments using two commercial ultrasonic generators operating at 24 kHz. In this way the CLIC lifetime can be simulated in 30 days. The method has been presented in detail by Roth [3] and its application to CLIC by Heikkinen and Calatroni [4]. By default the loading condition in ultrasonic testing is fully reversed tension-compression with zero mean stress.

In the cavities the thermal cycling causes fully compressive loading. To study the effect of compressive mean stresses for copper alloys at high number of cycles a special pre-stressed test specimen has been designed. The pre-stressed specimen consists of a hollow copper alloy sample and a body made in Ti 6Al 4V alloy, Figure 4. The hollow sample is compressed by the body to a desired stress level which represents the mean stress of the cyclic loading applied by the ultrasonic generator, Figure 4.

Pulsed laser fatigue testing

Low to medium cycle fatigue data (up to 10^8 cycles) of fully compressive cyclic surface thermal stresses has been collected by means of a pulsed UV laser surface heating apparatus. The surface damage has been characterized by SEM observations and roughness measurements. The method has been presented in detail by Calatroni et al. [5].

MATERIALS AND PREPARATION

The candidate materials for the fatigue experiments presented in Table 1 have been selected from the group of high conductivity coppers. Included are commercially pure copper, precipitation hardenable grades with different Zr contents and with Cr, and finally an oxide dispersion strengthened grade.

TABLE 1 All the presented alloys have been tested by ultrasonic experiment and partially by laser experiment. Some of the candidate alloys have been selected in different temper states and surface treatments.

Alloy family	UNS	Electrical conductivity [%IACS]	Cold-Working Ratio [%]	Treatment	Supplier
CuZr	C15000	92	39[1], 40[2], 80[1]	as received, shot peened, cavitation shot-less peened, ultra burnished, as Hot Isostatic Pressed	[1]Hitachi Cable Crop., [2]Luvata Oy
CuZr	C15100	94	39, 80	as received	Hitachi Cable Corp.
CuZr	C15150	97	39, 80	as received	Hitachi Cable Corp.
CuCrZr	C18150	75	20	as received	Luvata Oy
Cu-OFE	C10100	101	50	as received	Luvata Oy
GlidCop® Al-15	C15715	90	0	as received, as Hot Isostatic Pressed	SCM Metal Products, Inc

The material's state and post manufacturing treatments have significant effects on its mechanical properties. A number of techniques to prepare the material have been investigated. Peening of the surface is known to improve its fatigue strength. It introduces a compressive residual stress over a thin surface layer which resists the opening of cracks and it also work hardens the surface layer [6]. In the CLIC RF-cavities the critical region for the fatigue is a 10 µm deep surface layer affected by the pulsed heating due to the surface magnetic fields. The rest of the structure practically just conducts heat away from the surface, so different peening methods are considered for the CLIC accelerating cavities. Here the classical shot peening and new techniques: ultra burnishing (UB) described by Hokkanen [7], and cavitation shot-less peening (CSP) by Soyama et al. [8] have been studied.

The achievable material state can be limited by the manufacturing techniques finally retained for the CLIC accelerating structures. Based on the current design copper has to be joined with refractory metal, for example molybdenum forming a bi-metallic structure, Figure 1. Prototypes of the bi-metal have been made by hot isostatic (HIP) diffusion bonding, and by explosion bonding described by Arnau Izquierdo [9]. This study states that obtainable mechanical strength after the required HIP cycle is higher on C15000 than on C10100. However the strength is still significantly less than obtained for temper states that include cold working and ageing of the same grade. Singh and Tähtinen [10] present similar behavior for the strength of the prime aged CuCrZr alloy, which is significantly reduced due to HIP thermal cycle. The as HIPed material state has, therefore, been included in the experiments. The technical data sheet of SCM Metal Products [11] shows that the mechanical strength of GlidCop® does not reduce as much as for CuZr alloys.

The explosion bonding technique, as an alternative to be applied for the bi-metal production, does not include high temperature cycles. If that technique is retained, any copper grade and temper state would retain mechanical strength after bonding.

EXPERIMENTAL RESULTS

Ultrasonic fatigue testing

US fatigue experiments up to high cycle regime have been made for all the candidate alloys: the results are presented in Figure 5. The data for commercially pure copper, C10100 50 % cold worked, show that the CLIC target value cannot be achieved with a proper safety margin. The alloyed coppers reached the target value with a safety margin of at least 20 %. The best results have been achieved by shot peened and ultra burnished C15000 specimens, where the initial material state was 40 % cold worked and aged temper. Non-cold worked C15715, 80 % cold worked C15000 and C15100 alloys achieved also good results.

A majority of the specimens that reached the CLIC lifetime without fracture did experience some unexpected fatigue effects. A significant development of surface roughness was observed on the surfaces at the point of maximum stress amplitude at a number of cycles of about 3×10^{10}-5×10^{10}, Figure 6. This is likely to be an early stage of fatigue before the crack has nucleated, i.e. persistent slip band movement under cyclic loading. The irreversibility of shear displacements along the slip bands results in the ‘roughening’ of the surface where these persistent slip bands emerge from the surface causing intrusions and extrusions [6]. An initial goal of the experiments was to find the thresholds for fatigue crack initiation. The phenomenon of surface roughening was observed during the study. A number of experiments were performed at 10 % - 20 % lower stress amplitudes than the near threshold values up to the 10^{10} cycles range.

Given this decrease in the stress level the surface roughening did not appear at this number of cycle range.

The C15715 specimens show high fatigue strength in the non cold worked state. C15715's clear advantage is that its strength does not decrease dramatically when reducing the cold-working ratio. However its fracture toughness is lower than for the other alloys as presented earlier by Heikkinen et al. [12], Figure 7, and Singh and Tähtinen [10].

Based on the experiments with pre-stressed C18150 specimens it appears that the compressive mean stress does not reduce the fatigue strength when the absolute maximum stress value does not exceed the yield strength values. This can also be stated from the fact that the results from the laser and ultrasonic experiments can be directly related. The stress condition for laser experiment is fully compressive and for the US experiment it is fully reversed. These results show that the conclusion concerning this subject by Heikkinen et al. [12] is invalid.

Classical shot-peening was studied as a surface hardening method. On 40 % cold worked C15000 specimens shot peening increased significantly the fatigue strength, but the surface quality after shot peening is not acceptable for the RF cavities, where a good surface quality is required. The shot-peened surface needs to be smoothed by re-machining for example. This material removal may reduce the near surface residual stress and thus cancel its beneficial effect for fatigue.

Ultra burnishing has the advantage that it increases the quality of a machined surface [7] and the surface is acceptable for the RF cavities. 40 % cold worked C15000 specimens were ultra burnished and the results show that it increases the fatigue strength of the material. The effect seems to be similar as for the classical shot-peening. There is some scatter in the data of ultra burnished specimens tested by the ultrasonic experiment. The used ultra burnishing apparatus was not optimized for the type of geometry of the specimens. This drawback caused some defects on the surfaces resulting in unwanted local stress concentrations and thus scatter in the data, Figure 5.

Pulsed laser fatigue testing

Laser testing was carried out on diamond machined specimens, having a surface roughness Ra of 10 nm (close to the sensitivity limit of the measuring device) in accordance with the present CLIC specifications. In the laser fatigue experiments, SEM observations indicate that surface delamination is the first phenomenon to occur. In order to quantify it, it has been decided to set the criterion for identifying the first fatigue damage induced by laser irradiation at Ra = 20 nm. All available data are reported in Figure 5. A complete set of experiments spanning different stress level is only available at present for C15000 40% cold worked and C15715 as HIPed, with a few scattered data points available for other materials. It is worth commenting that, for a given stress level, surface break-up appears first for softer materials. However upon further irradiation the roughness increases at a larger rate for the hardest materials.

From the data it is clear that surface fatigue thresholds, defined as the onset of surface damage in the laser experiments and the appearance of fatigue cracks in the bulk specimen, happen at similar stress levels for similar numbers of cycles as presented earlier by Heikkinen and Calatroni [4 and 12].

CONCLUSIONS AND FUTURE PLANS

Shot-peened and ultra burnished C15000 (40 % cold worked) have given the best results so far followed by C15715 and 80 % cold worked C15000. Compared with the CLIC design value the results show that the current CLIC parameters could be achieved with existing materials with a reasonable safety margin, however more studies are needed.

The Zr content in CuZr seems to have an effect on the fatigue strength, however further studies are needed to understand the phenomena. In general smaller zirconium quantity is beneficial for the RF cavities, because then the electrical conductivity of the alloy is higher and the power losses of the CLIC machine are smaller (the efficiency requirement).

In the CLIC RF cavities the fracture toughness is probably not as critical as the resistance against the fatigue crack initiation, because a small crack already causes a rapid failure of the structure. The manufacturing process of the CLIC accelerating cavities is not yet defined. The achievable temper state may vary from soft as HIPed to cold worked and aged, furthermore surface hardening techniques may also be applied. Ultrasonic experiments for C15000 in the soft as HIPed state are planned.

The early stage of fatigue within the high cycle regime, the surface roughening, is 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. So, the phenomenon of surface roughening under cyclic deformation is unacceptable for CLIC. Based on the ultrasonic experiments it appears that a safety margin of 10 - 20 % from the threshold stress values is required to keep the surface smooth up to $7*10^{10}$ number of cycles range.

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. The peening technique could still provide a good surface quality as in the case of ultra burnishing and be suitable for mass production and high geometrical tolerances. Laser shock peening is one candidate technique that will be studied in the near future. Cavitation shot-less peening was tested for one specimen by laser apparatus. The sample could sustain a larger number of cycles before damage than a non-peened sample. Again, more data are required on this technique.

RF fatigue experiments are under way to cross check whether the ultrasonic and pulsed laser fatigue data are usable for the accelerating cavities.

ACKNOWLEDGEMENTS

We acknowledge the effort from: Prof. Soyama, Tohoku University, Japan, for collaboration on CSP technique, Dr. Hielscher GmbH, Germany, for ultrasonic hardware, Luvata Oy, Finland, for copper products, Kazuo Sugaya and Takashi Araki, Hitachi Cable, Japan, for very fruitful collaboration on various copper alloys, Mauro Taborelli, CERN, for discussions and suggestions, Tylite International Oy and Elpro Oy, Finland, for the development on the ultra burnishing technique, and Jouni Huopana, University of Oulu, for Ansys FEM simulations.

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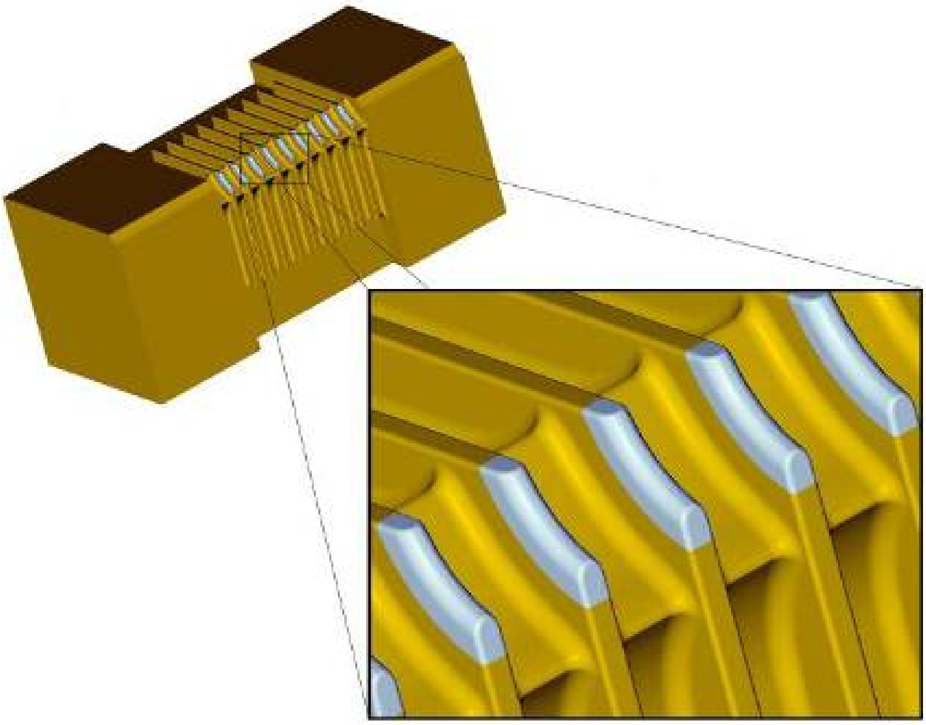

Figure 1 3D-CAD view of the HDS bi-metal structure.

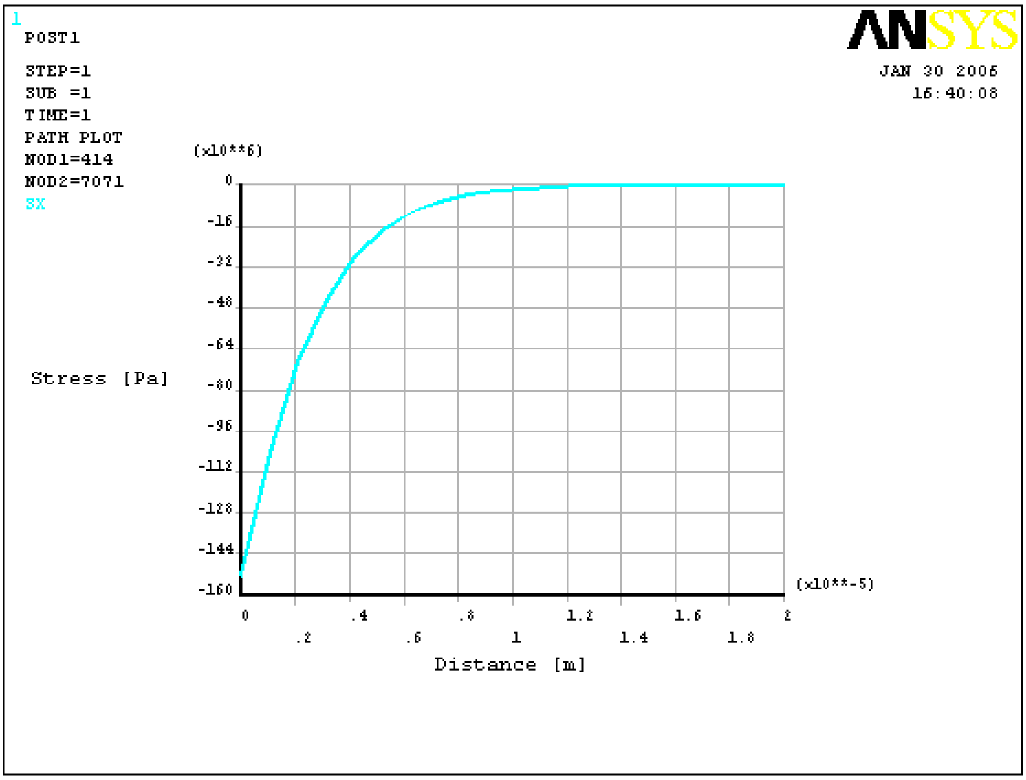

Figure 2 The stress profile for C15000 from the surface into the bulk, at the point of maximum magnetic field [4].

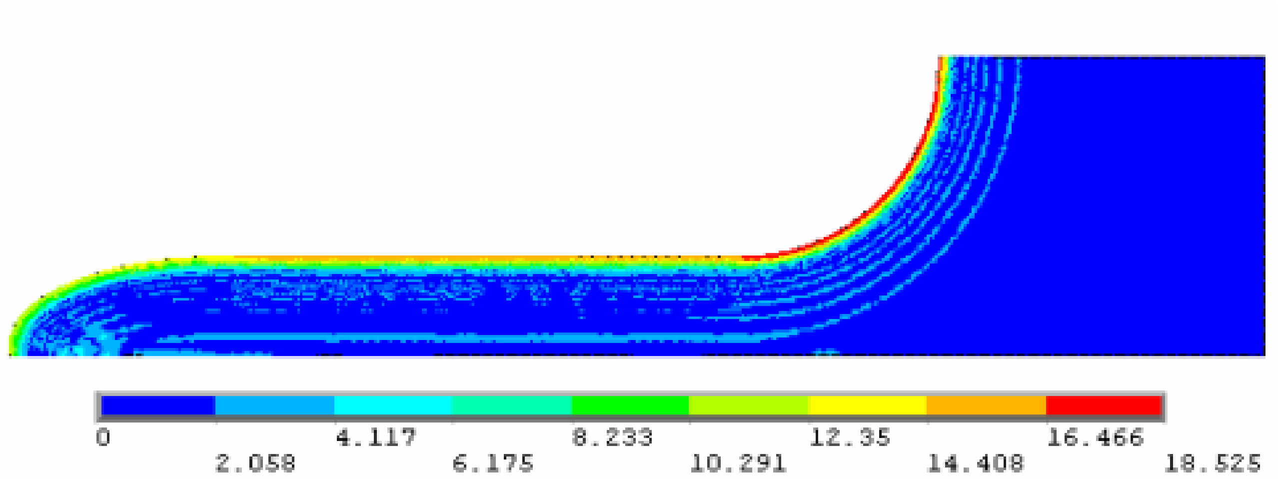

Figure 3 Simulated thermo-elastic waves which have initiated from the thermal shocks due to the pulsed RF currents on the surface [2].

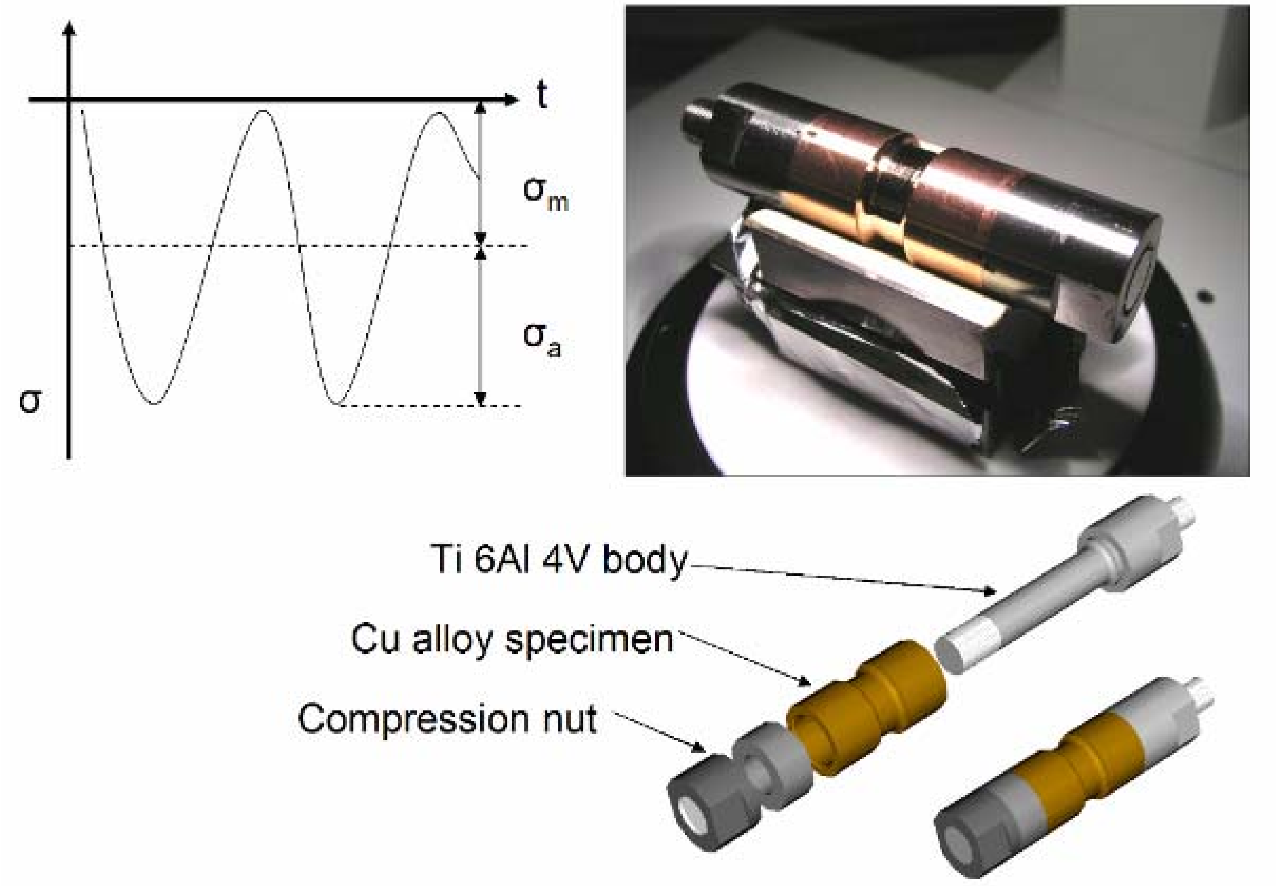

Figure 4 Pre-stressed specimen for the ultrasonic fatigue experiments and the loading pattern.

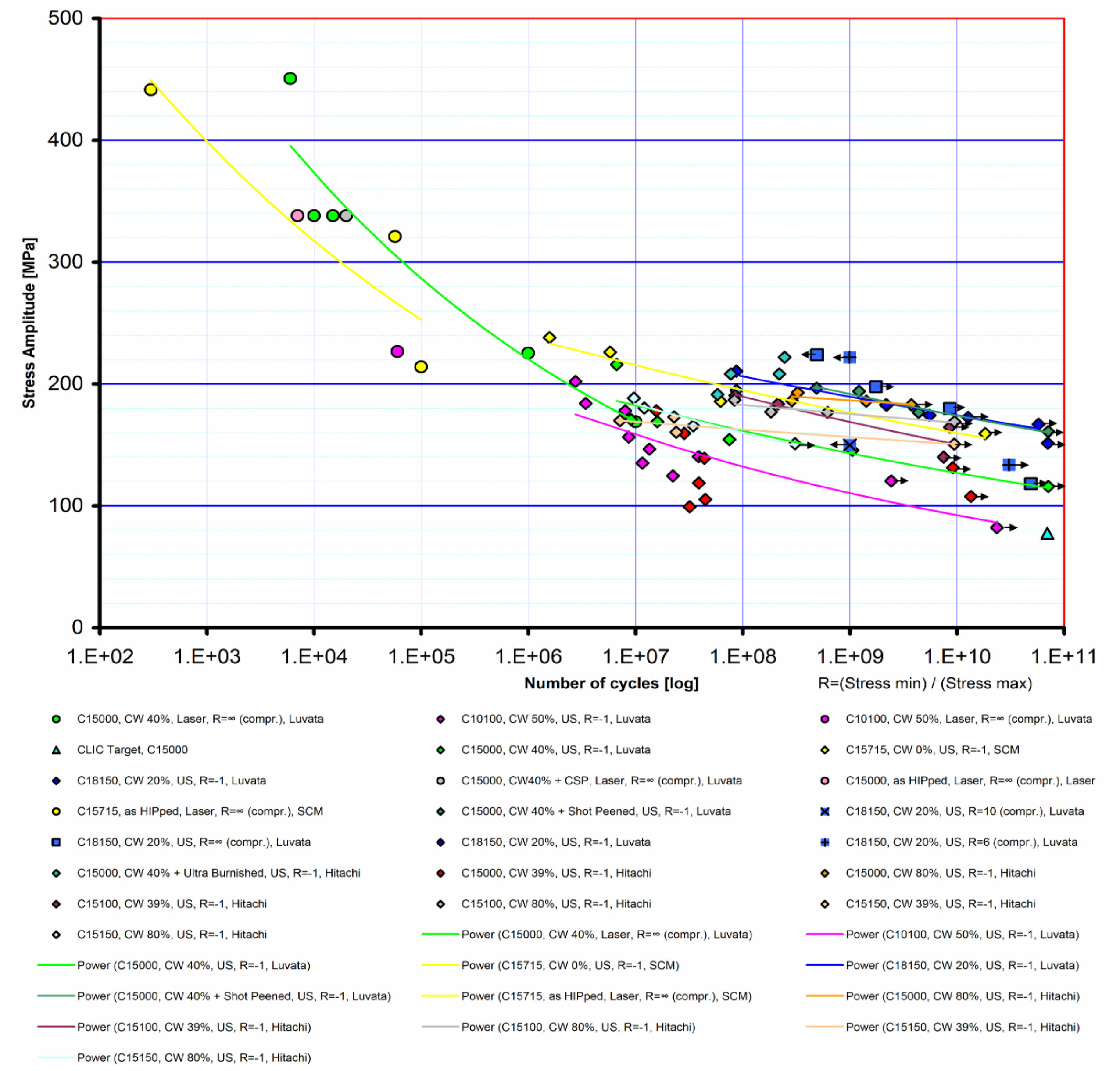

Figure 5 The fatigue data collected by the Ultrasonic- and Laser techniques. For ultrasound a data point is given by the number of cycles up to fracture and for laser it is up to an induced surface roughness Ra of 0.02 µm. Incomplete ongoing experiments without a fracture are marked with an arrow pointing to right. An arrow pointing to left means a fractured specimen, but where the time of fracture was earlier, i.e. was not detected at the correct time. The y-axis values represent the corresponding magnetic field on the surface based on the applied stress amplitude. In this way the mechanical stress amplitude is converted to surface magnetic field on a RF cavity's surface, which is then normalized to CLIC target value. The Circles are data points for Laser fatigue experiment and the diamonds are data points for Ultrasonic fatigue experiment. The triangle is the current CLIC target value. The solid lines are fitted curves for the data points of the same color and shape. The R parameter indicated close to the data points is equal to (Stress min)/ (Stress max). R=-1 corresponds to fully alternating stress condition and R=∞ corresponds to fully compressive stress condition with a zero maximum stress.

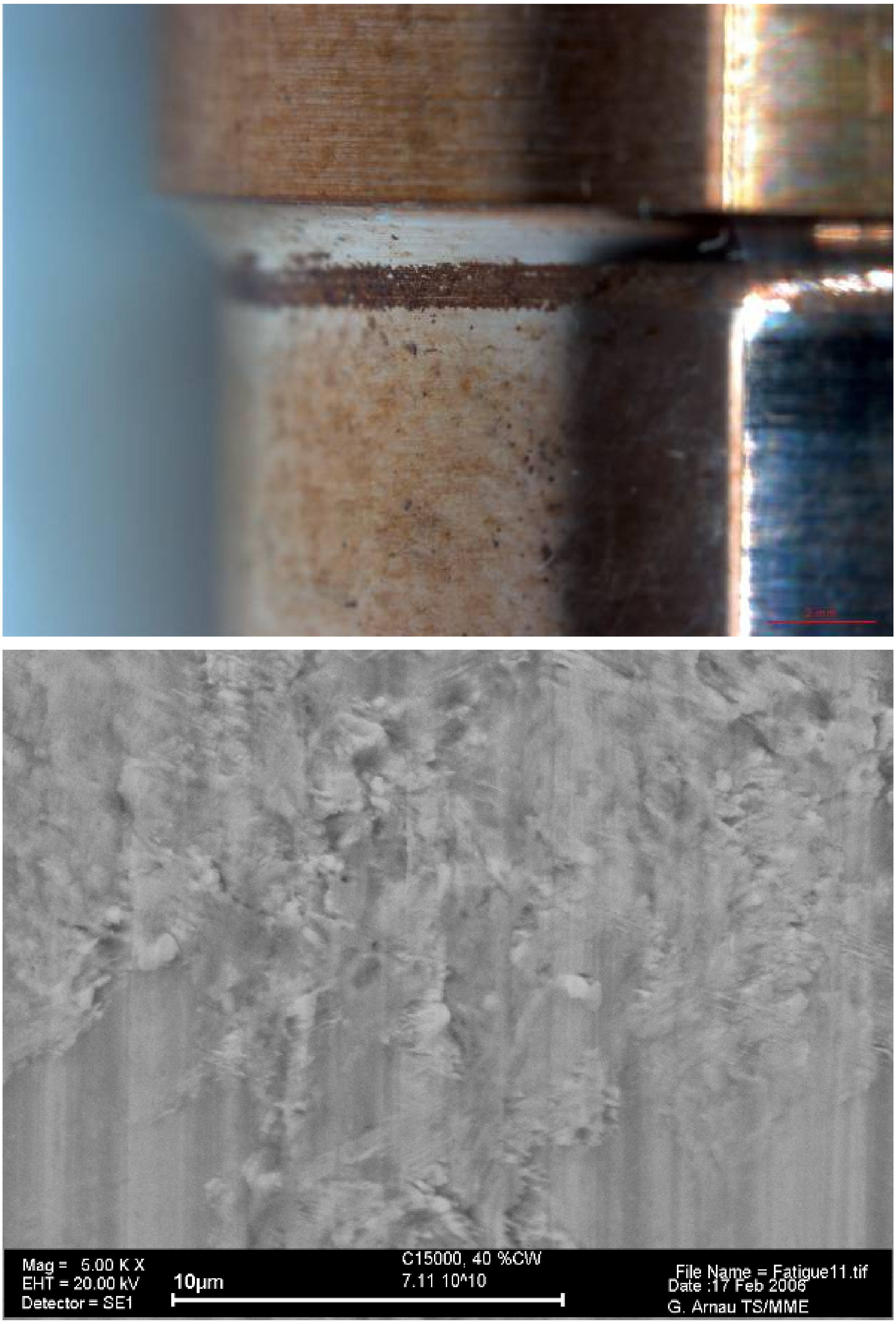

Figure 6 Optical microscope and SEM view of the surface roughening of C15000 specimen of the ultrasonic experiment.

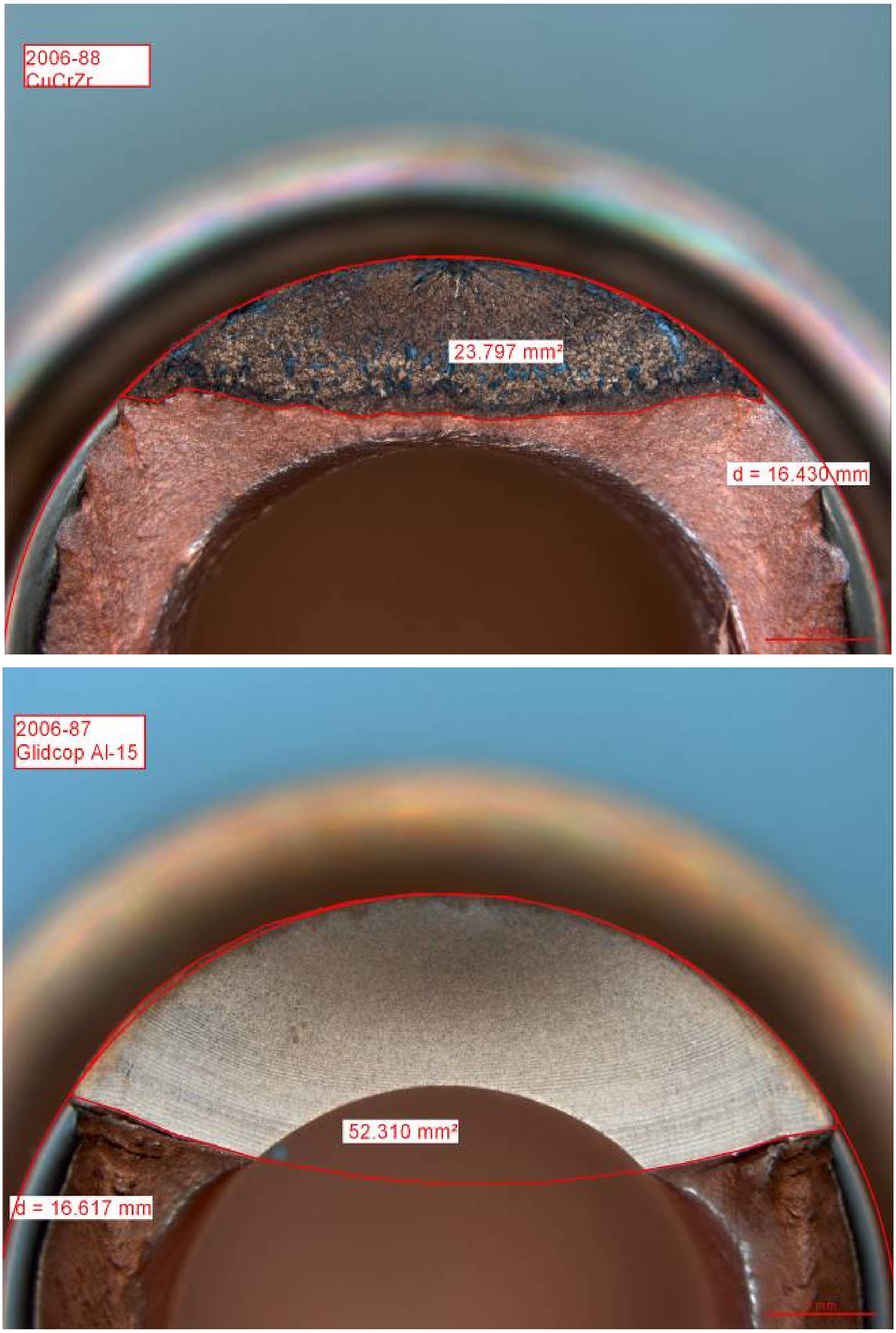

Figure 7 Front views of opened cracks of specimens of the ultrasonic experiment in CuCrZr and GlidCop® Al-15. Different crack propagation behaviors are visible, slow stable for CuCrZr and fast unstable for GlidCop® Al-15.