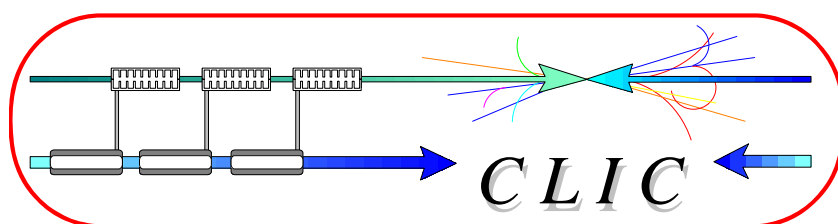


CERN – EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH



CERN-AB-2006-031

CLIC Note 678

STATUS OF THE FATIGUE STUDIES ON THE CLIC ACCELERATING STRUCTURES

S. Heikkinen¹⁾, S. Calatroni, H. Neupert, W. Wunsch

CERN, Geneva, Switzerland

Abstract

The need for high accelerating gradients for the future multi-TeV e^+e^- Compact Linear Collider (CLIC) imposes considerable constraints on the materials of the accelerating structures. The surfaces exposed to high pulsed RF (Radio Frequency) currents are subject to cyclic thermal stresses which are expected to induce surface break up by fatigue. 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 copper alloys in this parameter range has been initiated. Fatigue data for selected copper alloys in different states are presented.

¹⁾Helsinki University of Technology, Finland

Presented at
EPAC'06, Edinburgh, UK,
June 26-30, 2006

*Geneva, Switzerland
June 2006*

STATUS OF THE FATIGUE STUDIES OF THE CLIC ACCELERATING STRUCTURES

Samuli Heikkinen*, Sergio Calatroni, Holger Neupert, Walter Wünsch,
CERN, Geneva, Switzerland, *Helsinki University of Technology, Helsinki, Finland

Abstract

The need for high accelerating gradients for the future multi-TeV e^+e^- Compact Linear Collider (CLIC) imposes considerable constraints on the materials of the accelerating structures. The surfaces exposed to high pulsed RF (Radio Frequency) currents are subject to cyclic thermal stresses which are expected to induce surface break up by fatigue. 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 copper alloys in this parameter range has been initiated. Fatigue data for selected copper alloys in different states are presented.

INTRODUCTION

The current design of the 30 GHz CLIC accelerating structures is based on the HDS-type (Hybrid Damped Structure) geometry. The instantaneous surface temperature rise in the outer wall of the cavities due to 68 ns long RF pulses is 56°C for Copper Zirconium (C15000) alloy [1]. This sudden anisotropic temperature profile corresponds to 155 MPa compressive stress. Between the pulses all the heat is rapidly conducted via the bulk leading to stress relaxation and thus to thermal cycling. The fatigue loading is a cyclic compressive stress with stress amplitude of 77.5 MPa and mean stress of -77.5 MPa for C15000 [2]. 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 $7 \cdot 10^{10}$.

The experiments under way in order to qualify the material resistance to this stress pattern are based on high frequency ultrasonic excitation 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. A complete RF fatigue experiment of CLIC parameters is very expensive and time consuming to proceed. Only few low cycle RF experiments 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 of the high cycle and the low cycle experiments. The specimens for the different experiments are produced from same materials and go through the same manufacturing processes.

Materials and preparation

The induced thermal stress in 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 overall efficiency requirement of the CLIC machine, and a good fatigue performance is of course required. The candidate materials for the fatigue experiments have thus been selected from the group of high conductivity, high strength copper alloys, which are presented in Table 1 [2]. The state of the material plays a significant role on its mechanical properties, so a number of techniques to prepare the material have been investigated.

Table 1: Candidate alloys

Alloy	UNS C	Electrical conductivity [%IACS]	Cold-Working Ratio [%]
CuZr	C15000	93	40
CuCrZr	C18150	75	20
Cu-OFE	C10100	101	30
GlidCop® Al-15	C15715	90	0

Peening of the metallic material's surface is known to improve its fatigue strength [3]. It introduces a compressive residual stress over a thin surface layer which blocks the opening of cracks and it also work hardens the surface layer to be mechanically stronger. In the CLIC RF-cavities the critical area for the fatigue is a 10 μ m deep surface layer affected by the pulsed heating due to the surface magnetic fields. Different peening methods are considered to be interesting for the CLIC fatigue studies and here classical shot peening and new cavitation shot-less peening [4] techniques have been studied.

TEST SET-UPS

High cycle fatigue data, of up to $7 \cdot 10^{10}$ cycles, at various stress ratios have been collected in high frequency bulk fatigue tests using two commercial ultrasonic generators, which operate at 24 kHz. In this way the CLIC lifetime can be simulated in 30 days. The method has been presented in detail in references [2] and [5].

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. Only few fatigue data exist in the literature for compressive mean stresses, whose effect for copper alloys at high number of cycles is not well known. To study this issue a special pre-compressed test specimen has been designed.

*Samuli.Heikkinen@cern.ch

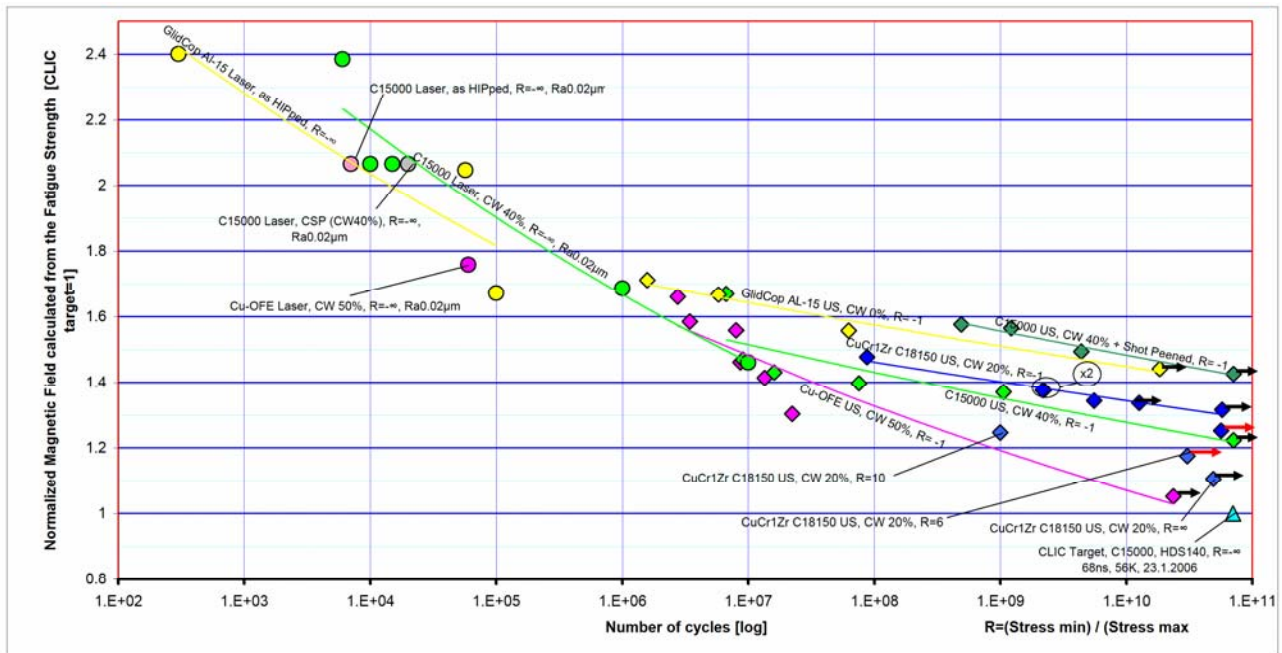


Figure 1: The fatigue data collected by the Ultrasonic- and Laser techniques. For ultrasound a data point is given by the number of cycles up to fracture and for laser it is up to an induced surface roughness R_a of $0.02 \mu\text{m}$. Incomplete ongoing experiments without a fracture are marked with an arrow. 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 based on the HDS140 accelerating structure design. The solid lines are fitted curves for the data points of the same colour and shape. The R parameter indicated close to the data points is equal to $(\text{Stress min}) / (\text{Stress max})$. $R=-1$ corresponds to fully alternating stress condition and $R=\infty$ corresponds to fully compressive stress condition.

Low to medium cycle fatigue data (up to 10^7 cycles) of fully compressive cyclic surface thermal stress 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 in reference [6].

EXPERIMENTAL RESULTS

Ultrasonic testing

US fatigue experiments up to high cycle regime have been made for all the candidate alloys: the results are presented in Figure 1. The data for commercially pure copper, Cu-OFE C10100, is not complete yet, but the early stage results show that the CLIC target value cannot be achieved with a proper safety margin. CuZr C15000, CuCrZr C18150 and shot peened CuZr C15000 reached the CLIC lifetime without crack initiation with the safety margins of 22%, 32% and 43% respectively. However these specimens did experience some unexpected fatigue effects. A significant development of surface roughness was observed on the surface at the point of maximum stress amplitude at a number of cycles of about $3 \cdot 10^{10}$ - $5 \cdot 10^{10}$. This is probably due to the Persistent Slip Band movement under cyclic loading. The irreversibility of shear displacements along the slip bands results in the

'roughening' of the surface where the persistent slip bands emerge from the surface causing intrusions and extrusions [6]. Unlike in the US tests, the RF induced stress in the CLIC accelerating cavities increases with the surface roughness. So the phenomenon of surface roughening under cyclic deformation is probably unacceptable for CLIC. To study this in more detail lower stress amplitude experiments need to be performed in order to find the thresholds for the surface roughness development.

The GlidCop[®] specimens show a high fatigue strength especially in the soft, non-cold worked, state. GlidCop[®]'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. It was observed that after the crack was initiated, the crack development behaviour is faster in GlidCop[®], while for the others it has more stable behaviour. The crack propagation speed was measured to be an order of magnitude higher for GlidCop[®] than for CuCrZr. The ITER R&D programme reported similar observations when they studied the physical and mechanical properties of copper alloys. For this reason GlidCop[®] was rejected as a candidate material for components of ITER [7].

The early stage of US experiments with pre-stressed specimens show that the mean stress has an effect on fatigue strength. A highly pre-stressed CuCrZr specimen

cracked at significantly lower stress amplitude than a specimen with a fully alternating stress. Pre-stressing is likely to limit the acceptable cyclic stress amplitude because the yield strength of a material is approached with lower stress amplitudes than under fully alternating loading conditions. This is an important issue for the CLIC RF cavities where the loading is fully compressive. On the other hand tensile mean stresses are known to decrease the fatigue strength of a material [6].

Classical shot-peening was studied as a surface hardening method. On 40% cold worked CuZr specimens shot peening increased significantly the fatigue strength. The surface quality after shot peening is not acceptable for the CLIC RF cavities, but a possible solution could be a re-machined shot peened surface.

Laser testing

It is expected that as soon as fatigue damage appears in RF, it leads to increased surface resistance and thus surface heating resulting very rapidly in a catastrophic effect. It seems thus logical to set the fatigue damage threshold at the first appearance of surface break-up. Laser testing was carried out on diamond machined specimens, having a surface roughness R_a of 10 nm (close to the sensitivity limit of the measuring device). The criterion for identifying the first fatigue damage induced by laser irradiation, i.e. deviation from flatness, is $R_a = 20$ nm. All data are reported in Figure 1. It is worth commenting that, for a given stress level, surface break-up appears first for C15000 in its softest state (HIP-treated), followed by 40% cold worked specimens and then by cavitation shot-less peened ones, with GlidCop[®] showing damage at the larger number of cycles. However upon further irradiation the roughness increases at a rate which ranks the materials in exactly the opposite order. This is in agreement with what was mentioned in the previous section.

Connectivity between the methods

From the data it is clear that surface fatigue thresholds, identified as when surface damage starts to appear in the laser experiments, and fatigue cracks appear in the bulk specimen, happen at similar stress levels for similar numbers of cycles [2]. This allows the two experimental techniques to be connected and to predict the surface damage at a high number of cycles. Fit to the data with the classic Woehler formula $\sigma = N^{-b}$ [3] where $N = \text{Log}_{10}$ (number of cycles) gives a similar exponent in both tests, with an average value, for example, for C15000 40% cold worked of $b = 1.2 \pm 0.1$.

CONCLUSIONS AND PERSPECTIVES

GlidCop[®] and Shot-Peened C15000 have given the best results so far. Compared with the CLIC design value they show that the current CLIC parameters could be achieved with existing materials with a reasonable safety margin, however more studies are needed for the final conclusion. In the CLIC RF cavities the fracture toughness is

probably not as critical as the crack initiation fatigue, because a small crack already causes a rapid failure of the structure. The GlidCop[®]'s fatigue experiments were interrupted due to parallel studies, aimed at assessing its resistance to electrical breakdown when exposed to high electric fields, of prime importance in the CLIC machine.

The manufacturing process of the CLIC accelerating cavities is not defined yet, so the final material state is still unknown. For this reason in the fatigue studies the whole range from annealed soft state to highly cold worked hard state plus the surface hardened alloys have to be taken into account. High cycle surface roughening is a critical issue and needs more studies. An RF fatigue experiment is under way.

Further pre-stressed US experiments are foreseen to study the effect of stress ratio in more detail. An experiment is under way to test whether the re-machining affects the fatigue performance achieved by shot peening. Different peening techniques are also foreseen in the test program.

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, M. Taborelli, CERN, for discussions and suggestions and G. Arnau Izquierdo, CERN, for the SEM analyses.

REFERENCES

- [1] I. Wilson, "A Summary of the Activities of the CLIC Study Team for the Year 2005", [CLIC Note 653](#), CERN, Geneva, March 2006.
- [2] S. Heikkinen and S. Calatroni, "Status of the Fatigue Studies of the CLIC Accelerating Structures", [Minutes of the CLIC Meeting 17.2.2006](#), CERN, Geneva, 17 February 2006.
- [3] Suresh, Subra, "Fatigue of Materials, 2nd ed.", 679 p., Cambridge University Press, Cambridge 1998.
- [4] H. Soyama, J.D. Park, M. Saka, "Use of Cavitating Jet for Introducing Compressive Residual Stress", *Journal of Manufacturing Science and Engineering*, Vol. 122, p. 83-89, ASME 2000.
- [5] L. D. Roth, "Ultrasonic Fatigue Testing, *Metals Handbook*, 9th ed.", Chapter 8: Mechanical Testing, p. 240-258, Metals Park 1978-1989.
- [6] S. Calatroni, M. Taborelli and H. Neupert, "Fatigue Testing of Materials by UV Pulsed Laser Irradiation", [CLIC Note 615](#) (EPAC 2004), CERN, Geneva, August 2004.
- [7] B. N. Singh, S. Tähtinen, "Final Report on Characterization of Physical and Mechanical Properties of Copper and Copper Alloys before and after Irradiation", [Risø-R-1276\(EN\)](#), Risø National Laboratory, Roskilde, December 2001.