FATIGUE TESTING OF MATERIALS BY UV PULSED LASER IRRADIATION

S. Calatroni, H. Neupert, M. Taborelli, CERN, Geneva, Switzerland

Abstract

The energy dissipated by the RF currents in the cavities of pulsed high-power linacs induces cycles of the surface temperature. In the case of the CLIC main linac the expected amplitude of the thermal cycles is above fifty degrees, for a total number of pulses reaching 10^{11}. The differential thermal expansion due to the temperature gradient in the material creates a cyclic stress that can result in surface break-up by fatigue. The materials for cavity fabrication must therefore be selected in order to withstand such constraints whilst maintaining an acceptable surface state. The fatigue behaviour of Cu and CuZr alloy has been tested by inducing larger surface peak temperatures, thus reducing the number of cycles to failure, irradiating the surface with 40 ns pulses of UV light (308 nm) from an excimer laser. Surface break-up is observed after different number of laser shots as a function of the peak temperature. CuZr appears to withstand a much larger number of cycles than Cu, for equal peak temperature. The characterization of the surface states and possible means of extrapolating the measured behaviour to the expected number of pulses of CLIC are discussed in detail.

INTRODUCTION

The length of future TeV-range linear colliders will be determined by the final energy and the maximum accelerating field that can be obtained, therefore to restrict it to a reasonable size the field has been chosen in the CLIC study as high as 150 MV/m. As a consequence the peak surface electric field in the RF cavities of the main beam will be above 300 MV/m [1]. Such high electric and hence magnetic RF fields at the surface of the cavities will have two main consequences on the material surfaces. The high electric field regions are prone to breakdown that can be overcome only by an adequate choice of materials [2]. The high magnetic field regions are submitted to intense induced currents, which heat up abruptly the surface and induce thermo-mechanical stress because of the non-uniform thermal expansion. Such stress pulses may lead to fatigue deterioration of the surface, which will on the one hand worsen the surface conductivity thus increasing power losses and on the other hand initiate crack propagation leading to failure. Extensive investigations of thermo-mechanical fatigue induced by different processes have been performed on copper [3-5]. Material fatigue data are generally available only for about 10^8 cycles and for macroscopic stresses applied to the bulk of the material. In order to select and qualify materials for optimum fatigue strength for accelerator applications it is necessary to obtain data valid up to a number of cycles of the order of 10^{11} and this can be performed in a reasonable time span only by increasing the repetition rate at a given stress amplitude, or by inducing larger stresses and then extrapolating the measured fatigue strength to the requested number of cycles. This second road can be pursued by heating the surface of test specimens by short UV laser light pulses. The purpose of the present work is to explore the feasibility of this approach and to validate the laser tests as being relevant for the RF applications.

LASER HEATING AND RF HEATING

RF currents decay exponentially inside metal surfaces, the penetration depth in copper at the CLIC frequency of 30 GHz being about 0.38 µm. At the present level of optimization for the CLIC HDS accelerating structure, rectangular RF pulses of 60 ns duration are produced, dissipating on average a power of almost 6 GW/m^2. The power is dissipated inside a region extended over all the RF penetration depth inducing an increase of temperature, which then decays rapidly at the end of the pulse due to the thermal conduction of the material. In our experiment a pulsed XeCl excimer laser at 308 nm wavelength has been chosen to produce an accelerated ageing of materials by fatigue due to pulsed heating. The UV radiation is absorbed in the first nm of the material surface, a fraction of the order of 20% being reflected. The heat is thus deposited at the topmost surface, at variance from the RF case. The time shape of the pulse is also different, being in our case composed of two 20 ns Gaussian pulses peaking at 20 ns interval. The temporal evolution of the temperature profile in the material can be simulated through the use of appropriate computer codes [6] taking into account all the relevant material parameters. The temperature distributions produced by the two different processes are illustrated in Fig. 1, for a CLIC RF pulse of 130 ns duration [7] and for a laser pulse of 0.15 J/cm^2 fluence. The temperature profile inside the material is steeper with the laser but the associated Von Mises stress level at the surface, calculated with finite element analysis (ANSYS), and is similar within 10 % to the RF case for an equal surface temperature. A correlation can thus be established between the fluence of the laser and the resulting stress level, through the combined use of the two aforementioned computer codes. The validity of the laser simulation code has been checked by submitting both OFE Cu and CuZr to pulses of increasingly high energy up to the fusion temperature, condition that is in excellent agreement with the simulation. Cu is the usual material of choice for RF applications, while the CuZr dispersion strengthened alloy (UNS C15000) has been selected as an alternative candidate because of its well know fatigue strength properties, coupled with acceptable electrical and thermal conductivities.

The fatigue strength of metals is typically measured by submitting a test specimen to cyclic stress, the failure being identified by the rupture of the piece. The typical fatigue behaviour of a non-ferrous metal is well described by a power law of the type $\sigma \propto N^b$ where N is the number of cycles leading to failure at the applied stress level σ, the exponent b being -0.11 in the case of fully annealed OFE copper for example [8]. Even for very low applied stresses breakdown may occur for a sufficiently large number of cycles, provided that the stress exceeds the elastic limit. Breakdown is initiated by cracks produced by accumulation of dislocations, which then propagate inside the piece until complete break-up. The bulk fatigue strength tabulated for 10^8 cycles of Cu and CuZr is 117 MPa and 241 MPa respectively [9]. It should be underlined that the quoted values for fatigue strength are for low-frequency mechanical cycles, and can increase of at least 50 % when extrapolating to frequencies equivalent to the CLIC pulse duration [10]. Moreover these values are for complete break-up of test specimens, while a definition of break-up for a surface, as in the case of pulsed heating, is less straightforward and will be discussed below.

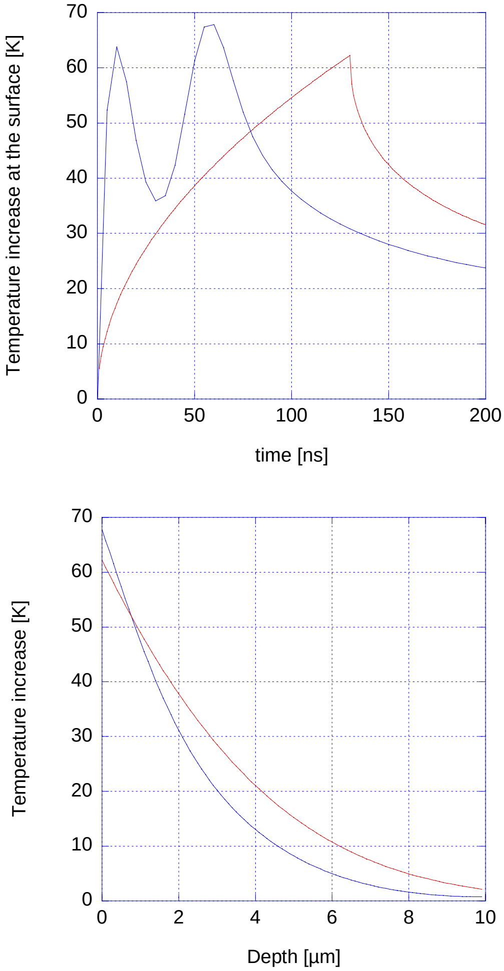

Figure 1: (a) Temperature variation at the surface of CuZr for a CLIC 130 ns RF pulse (red curve) and induced by the XeCl excimer laser (blue curve) at 0.1 J/cm^2 fluence. (b) Temperature profile inside CuZr when the surface reaches its peak temperature (after 130 ns for RF and 60 ns for the laser)

EXPERIMENTS AND DISCUSSION

The purpose of the experiment is to establish whether it is possible to extrapolate the results obtained applying high pulsed stresses for a rather low number of cycles to predict the fatigue strength at a number of cycles in excess of 10^{11}. OFE Cu and CuZr specimens, prepared by diamond turning slices cut from a forged rod, have been submitted to increasingly large number of laser shots under vacuum, at a repetition rate of 25 Hz. The fluencies applied are 0.15, 0.2, 0.3 and 0.4 J/cm^2, corresponding to temperature increases at the surface of 90, 120, 180 and 240 K respectively, or Von Mises stresses at the surface of 305, 410, 615 and 820 MPa for CuZr, the values for Cu being rather similar. The spatial uniformity of the laser beam and its stability in time are within ±10 %, and the size of the irradiated area is 0.5 mm^2. The samples produced have been characterised in several ways. Observations by Scanning Electron Microscope show clearly the degradation of surfaces depending on the irradiation conditions, with damages similar to those produced in RF tests [3]. Some examples are illustrated in Fig. 2. The first two pictures (from the top) illustrate the topography of the CuZr surface “as-machined” and after 240000 laser shots at 0.2 J/cm^2 showing a clear degradation. The same number of shots applied to Cu (third picture) resulted however in a much more degraded surface. Twenty times less shots were sufficient to produce on Cu a surface state visually similar to the one shown for CuZr (fourth picture). These considerations are qualitative and cannot lead to a quantitative prediction. Image analysis (standard deviation of the mean grey level of the pixels) has been attempted; however this method is too much dependent on the conditions on which the image is taken. Although corrections can be applied, it is reliable only for samples produced and analysed in the same batch. A more useful technique has been identified in the measurement of the average roughness by means of a non-contact dynamic-focussing laser surface profilometer. The results for all the samples are reported in Fig. 3. When decreasing the fluence, the same level of roughness is produced after a much larger number of laser shots. It is also apparent that the same level of roughness is developed much earlier on Cu than on CuZr, when treating with the same fluence. The acceptable level of damage produced by fatigue may then simply be quantified by an acceptable level of roughness. The plot in Fig. 3 leads in fact to a smooth dependence between the fluence (and thus the stress) and the number of shots required for achieving a given roughness, with an exponent surprisingly close to the value reported above.

However, it must be noted that the sample treated with the larger number of laser shots presented periodic features similar to what is commonly referred to in the literature as LIPSS [11], requiring further investigations.

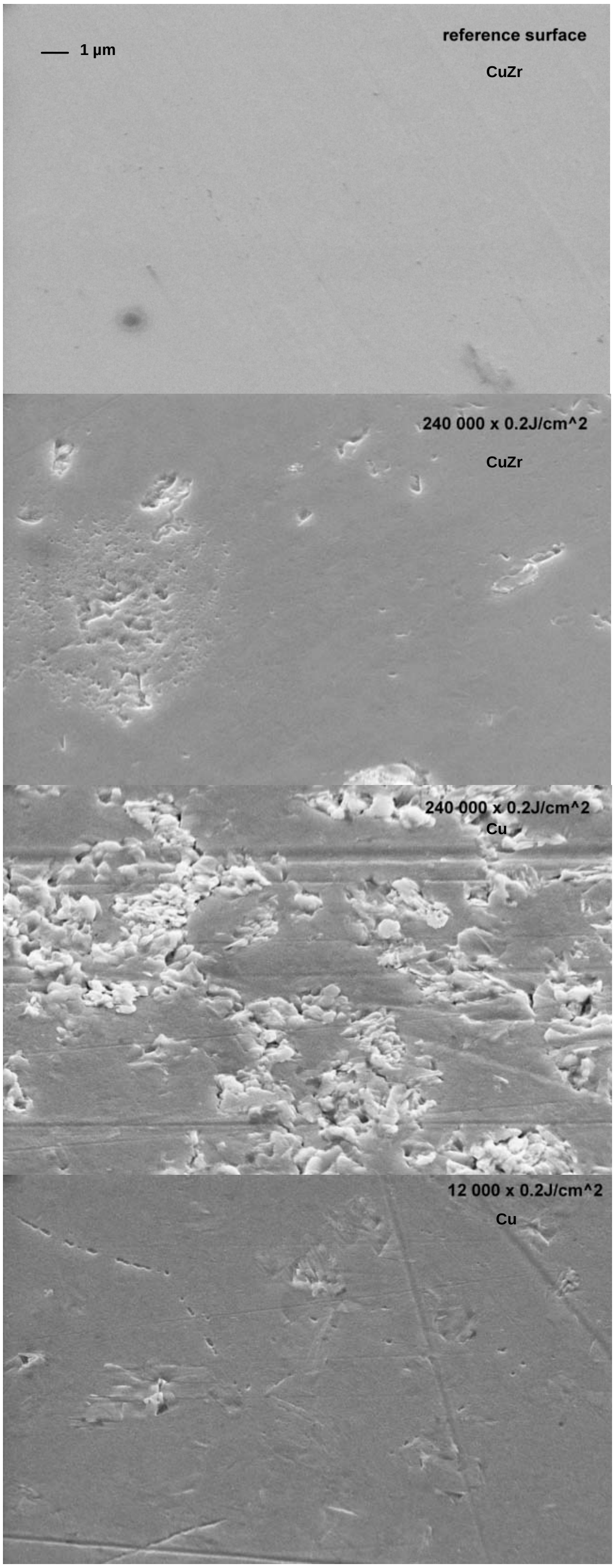

Figure 2: SEM images of laser-treated samples. For a description see the main text.

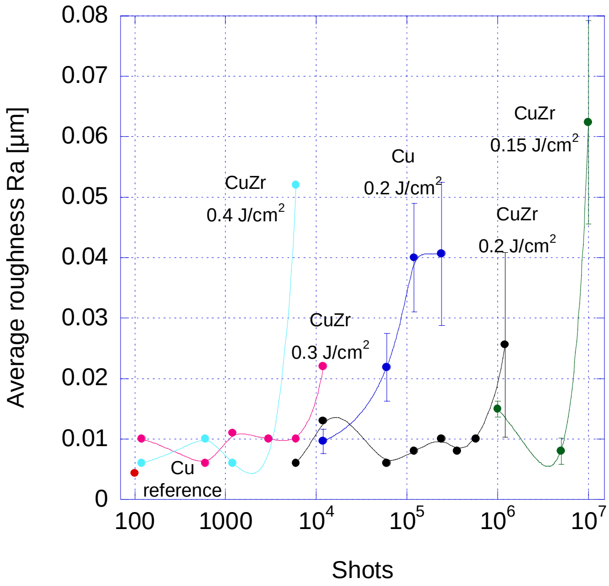

Figure 3: Average roughness for laser-treated samples. For a description see the main text

CONCLUSION

A method of inducing thermo-mechanical fatigue, with effects similar to those produced by RF pulses has been demonstrated by using an UV excimer laser. The measure of the surface damage by the average roughness allows extrapolating the results obtained for high stress / low number of cycles to a very large number of cycles. Further testing at a larger number of laser shots would obviously be useful, possibly by making use of a laser of faster repetition rate. The definition of an acceptable level of roughness for RF applications is also mandatory, and ad-hoc RF tests should be carried on in the near future.

ACKNOWLEDGEMENTS

The authors are deeply indebted to C. Benvenuti, who suggested the use of an UV laser for the tests, and to S.T. Heikkinen who carried out the stress calculations and provided several important data.

REFERENCES

[1] CLIC Design Report, CERN-2003-007
[2] M. Taborelli et al., Proc. of this Conference
[3] D.P. Pritzkau et al., PRST-AB 5 (2002) 112002
[4] H.M.Musal in: Laser induced damage in optical materials 1979 (ASTM, Washington, 1980) p. 159
[5] V.F. Kovalenko, Physics of Heat Transfer and Electrovacuum Devices (Sov. Radio, Moscow, 1975)
[6] CNR-LAMEL (Bologna, Italy).
[7] I. Wilson CLIC Note 52 (1987)
[8] D.P. Pritzkau, Ph.D. Thesis, SLAC-Report-577 (2001)
[9] S.Heikkinen private communication
[10] M. Kikukawa et al., JSME 1967 Semi-International Symposium, Tokyo.
[11] J.E. Sipe et al., Phys. Rev. B 27 (1987) 1141