

CLIC Note 648

Thermal Fatigue Issues in High Gradient Particle Accelerators

S. T. Heikkinen, S. Calatroni, H. Neupert

Abstract

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 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 kilometers long and will be buried 100 meters underground. The main 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 kilometer length will be filled with main beam accelerating structures, which will require of the order of ten thousand tons of raw material and millions of individual parts. One of the main limiting factors of the main linac accelerating structures is the thermal fatigue due to the pulsed surface heating. The accelerating RF power pulses heat up repeatedly the surface of the structures by RF currents. These thermal stress cycles are expected to cause a surface break-up by fatigue.

Geneva, Switzerland

16/01/2006

THERMAL FATIGUE ISSUES IN HIGH GRADIENT PARTICLE ACCELERATORS

S. T. Heikkinen¹, S. Calatroni², H. Neupert³

^{1,2,3} CERN, Geneva Switzerland

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 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 kilometers long and will be buried 100 meters underground. The main 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 kilometer length will be filled with main beam accelerating structures, which will require of the order of ten thousand tons of raw material and millions of individual parts. One of the main limiting factors of the main linac accelerating structures is the thermal fatigue due to the pulsed surface heating. The accelerating RF-power pulses heat up repeatedly the surface of the structures by RF currents. These thermal stress cycles are expected to cause a surface break-up by fatigue.

Keywords: *Thermal Fatigue, Pulsed Surface Heating, Ultrasound Fatigue Testing, Laser Fatigue Testing, Fatigue Properties of Copper Alloys*

1 Introduction

Future high energy (TeV range) particle accelerators will require a high accelerating gradient to limit the total length to a reasonable value. In the CLIC study this accelerating gradient has been chosen to be 150 MV/m in order to fit a 3 TeV machine into a ~ 33 km long tunnel [1]. To achieve the required luminosity, the collider will operate at a repetition frequency of 200 Hz. This pulsed operation results in a pulsed surface heating phenomenon in the accelerating structures which is expected to cause a surface break up by fatigue.

2 Thermal fatigue of the accelerating structures

130 ns long RF pulses heat the surface of the structures at the machine repetition frequency of 200 Hz. The instantaneous maximum power density is about $5.6 \cdot 10^9 \text{ W/m}^2$ [2]. Between the RF-pulses there is a cooling time of about 3 ms. The pulse shape is shown in figure 1. The structures operate under vacuum so the cooling of the surface is mainly by heat conduction through bulk.

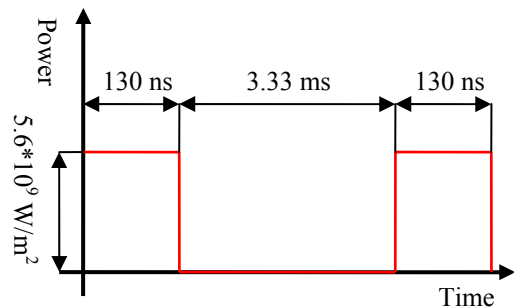


Figure 1: The time structure of deposited power from CLIC RF pulse.

The RF power deposits energy within a layer of $\sim 1/3 \mu\text{m}$ which then diffuses into the bulk. This surface layer heats up and cools down repeatedly. The expected instantaneous maximum temperature rise over the $2 \mu\text{m}$ layer is about 60 degrees while the bulk stays at constant temperature, see figures 2 and 3. This thermal loading has been simulated with the Ansys FEM code. This cyclic thermal gradient causes a pulsating compressive stress profile with maximum of about 200 MPa.

¹ Doctoral Student, Samuli.Heikkinen@cern.ch

² Research Scientist, Sergio.Calatroni@cern.ch

³ Technical Engineer, Holger.Neupert@cern.ch

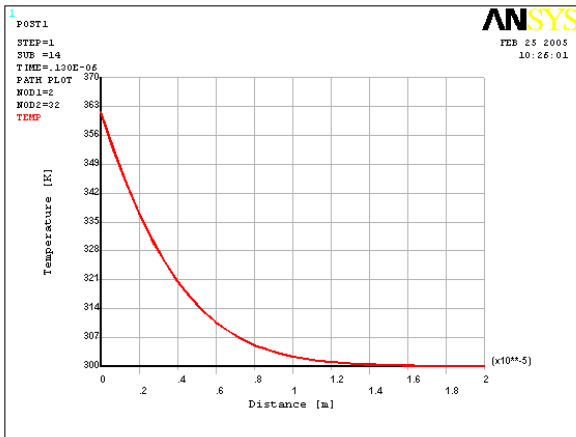


Figure 2: The temperature profile from the surface of the structure into the bulk at the point of maximum temperature difference.

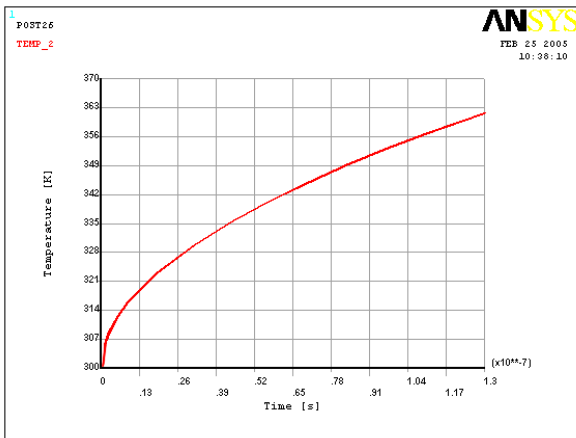


Figure 3: Surface temperature versus time during the 130 ns $5.6 \cdot 10^9$ W/m² pulse.

Due to the material's good thermal conductivity this heated layer cools down to its operating temperature in a few microseconds, see figure 4, this is well within the cooling time of 3 ms. So, the pulsed surface heating phenomenon does not affect the structure's average temperature.

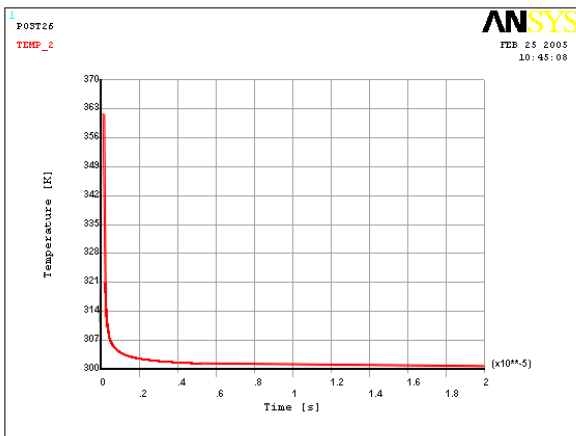


Figure 4: Surface temperature versus time during the "cooling" between the pulses.

The machine is estimated to operate 9 months per year 7 days a week and 24 hours per day over a period of 20 years. This lifetime corresponds to a total number of 10^{11} thermal cycles.

3 Materials

The main material requirements for the accelerating structures are good electrical and thermal conductivities, good machinability and good fatigue resistance. Over the years the material used for CLIC prototypes has been oxygen-free high conductivity copper Cu-OFE (C10200). The electrical conductivity of Cu-OFE is 101% IACS [3]. It has been used mainly due to its good electrical properties, relatively good machinability and good vacuum performance.

The fatigue strength for cold worked Cu-OFE is 117 MPa at 10^8 cycles [3]. This value is based on a reversed bending test which has an alternating ($R=-1$) sinusoidal stress cycle. Even though the characteristics of the RF induced thermal fatigue ($R=0$) and the reference mechanical fatigue are different it can be expected that the Cu-OFE's fatigue properties are insufficient. Given this fact a material survey was done in order to check whether a better material than Cu-OFE for the accelerating structures exists "off the shelf".

Driven by the efficiency requirement of the machine the electrical conductivity of the new material should be at least 90% IACS, a typical value for high conductivity copper alloys [3]. High cycle fatigue data for copper alloys is very limited. A good candidate appears to be precipitation hardened Copper Zirconium (C15000). It has 92-93% of the thermal- and electrical conductivities of Cu-OFE, but a factor of two better fatigue strength at 10^8 cycles [3]. Another candidate is GlidCop® AL-15 which has relatively good tensile strength properties [4] but whose fatigue data was not found.

Table 1: Material data comparison [3, 4]

Material	Electrical Conduct. [% IACS]	Thermal Conduct. [W/(m °K)]	Tensile Strength [MPa]	Fatigue Strength [MPa]
Cu-OFE	101	394	376 ¹	117 ³
CuZr	92	367	427 ¹	200 ³
GlidCop®	92	365	496 ²	-

¹ Cold Worked 84%

² Cold Worked 94%

³ At 10^8 cycles

4 Criteria

During the operation of the accelerator, high electric currents flow on a thin surface layer of the RF cavities. These currents are associated with the high electric field that accelerates the particles and also are the source of the pulsed surface heating. In the case of CLIC the particles are electrons and positrons. Due to these high surface currents even a small crack on the

surface may cause a deterioration of the operation. A crack interferes with the flow of the surface current and reduces the accelerating electric field. It also increases the electrical resistance of the surface thus it amplifies the surface heating and accelerates the fatigue.

The critical size of the crack has not yet been determined. It is clear that the parameter of interest is not the classical mechanical fatigue but the “crack formation fatigue” of the metal surface under pulsating compressive thermo-mechanical stress.

5 Experimental

For the fatigue study it is planned to carry out low cycle laser fatigue tests, high cycle ultrasonic fatigue tests and possibly in the near future low cycle RF fatigue tests.

The laser fatigue tests are based on a pulsed laser that heats a metal surface at 20 Hz. The shape of the heat cycle can be adjusted to be relatively close to the real case, so the thermal fatigue phenomenon of the accelerating structures can be simulated realistically. Unfortunately due to the equipment’s low frequency the tests are limited to the low cycle range.

The ultrasonic fatigue test specimen experiences a sinusoidal reversed ($R=-1$) tension-compression mechanical stress. The equipment works at the relatively high frequency of 24 kHz. It will be used to extend the generated laser test data up to high cycle range.

There is also a possibility that one of the CLIC collaborating laboratories will do RF fatigue experiments using a 30 GHz FEM as power source in the coming years. This equipment works at a repetition rate of 1 Hz, so it is limited to a very low cycle range, but it would consolidate the fatigue study.

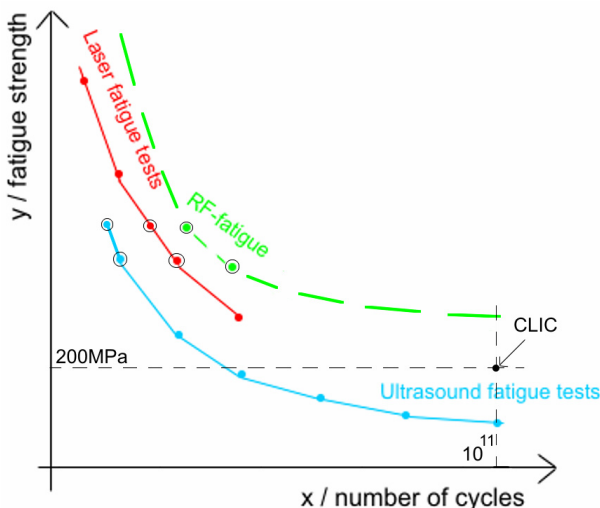


Figure 5: A schematic view of how the methods will be used together to provide a realistic estimate of the lifetime of CLIC (Simulated data). The circled dots represent the calibrated data points of different experiments.

The intention is to compare the results of these experiments using the same materials from the same batch, the same means of manufacturing, the same stress level and under the same conditions to predict the RF fatigue life of chosen materials, see figure 5.

5.1 Laser fatigue tests

UV-light is absorbed in the first few nm of copper surfaces very efficiently, reflectance being less than 0.2. The heat is thus deposited in the topmost surface layers, as opposed to the RF case which is $0.3 \mu\text{m}$. The excimer laser used produces a composite flash of two 20 ns UV-light (308 nm) pulses of a Gaussian shape at 20 ns intervals, as opposed to the rectangular shape of the RF pulse. The resulting temporal evolution of the temperature profile has been simulated by appropriate computer codes [5]. All relevant material properties are taken into account. Calculated temperature distributions for a RF pulse of 130 ns [6] and a laser light pulse of 0.1 J/cm^2 fluence are illustrated in Fig.6.

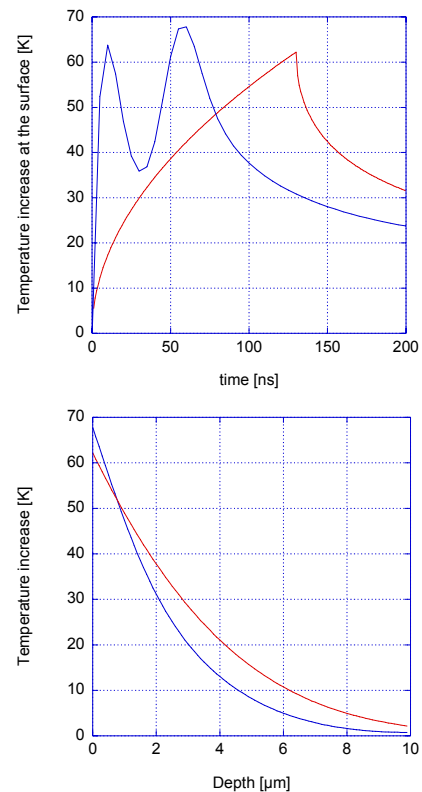


Figure 6: (a) Temperature variation at the surface of Cu for a CLIC 130 ns RF pulse (red curve) and induced by the XeCl excimer laser (blue curve) at 0.1 J/cm^2 fluence. (b) Temperature profile inside Cu when the surface reaches its peak temperature (after 130 ns for RF and 60 ns for the laser).

The Von Mises stress levels resulting from these distributions were calculated using a finite element analysis. Despite the fact that the temperature profile is steeper with the laser, stress levels on the surface are within 10% for the laser and RF cases for the same

surface temperature. A correlation can thus be established between the fluence of the laser and the RF-power density during the pulses. The temperature rise calculations have been validated by submitting pulses of increasing energy to the surfaces of Cu and CuZr alloy. The fluence at which surface melting starts is in excellent agreement with the calculated power density needed to heat the surface up to the melting point.

5.2 Ultrasonic fatigue tests

The method of ultrasonic fatigue testing has been described in detail in reference [7]. It involves cyclic stressing of materials at frequencies typically in the range of 15 to 25 kHz. The major advantage of the method is its ability to provide high cycle fatigue data within a reasonable testing time.

The equipment to be used for this study is Dr. Hielscher UIP250 ultrasonic processor which has an operating frequency of 24 kHz.

Due to the copper alloy's high internal friction at high frequencies a test sample will heat up dramatically even when cooling is introduced [8]. In this study it has been shown that for copper specimens a reasonable 12 degrees pulsed temperature rise can be achieved using a 1:5 duty cycle together with liquid cooling. This brings the effective frequency down to 3333 Hz, but is still competitive compared to conventional fatigue test equipments. At this effective frequency 10^{10} cycles can be obtained in 4-5 weeks depending on the operating frequency of the ultrasonic device. Reaching the level of 10^{11} cycles (CLIC parameter) in a reasonable time requires further studies.

6 Early stage laser test results

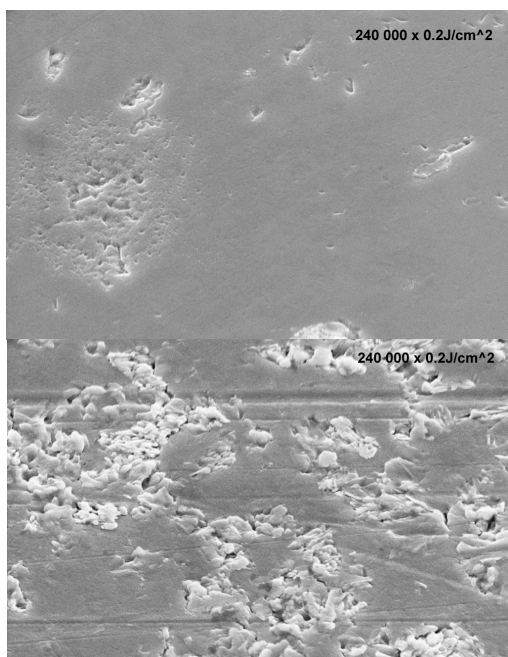


Figure 6: SEM images of laser-treated samples (240000 cycles). Top: CuZr, Bottom: Cu-OFE. For a description see the main text.

During first experiments, resistance to thermo-mechanical fatigue of Cu-OFE and a Copper Zirconium (15000) alloy has been compared. An example is given in Figure 6.

More severe damage was found on Cu than on CuZr for the same number of shots with the same fluence and hence the same temperature rise during each cycle. This qualitative result has been quantified by means of roughness measurements. More detailed results have been published in reference [9].

7 Conclusion

The early stage laser test results show that for materials having similar electrical properties there is a significant difference of the thermo-mechanical fatigue resistance. This is an encouragement to continue the fatigue studies further. The planned experiments using the laser, the ultrasound and the RF facilities, should give an answer for the CLIC pulsed surface heating problem.

References

- [1] Wilson, I., *The Compact Linear Collider CLIC*, CLIC Note 617, CERN-AB-2004-100, Geneva 2004. <http://cdsweb.cern.ch/search.py?recid=806280&ln=en>
- [2] Grudiev, A., Private communications.
- [3] Davis, J. R. (ed. et al.), *Metals Handbook*, Vol 2 Properties and selection: Nonferrous alloys and special purpose materials, Metals Park, OH: American Society of Metals 1990.
- [4] North American Höganäs, SCM Metal Products Inc., Technical data sheet, Glidcop® Dispersion Strengthened Copper, Glidcop® AL-15 (C15715).
- [5] CNR-LAMEL (Bologna, Italy).
- [6] Wilson, I., *Surface Heating of the CLIC Main Linac Structure*, CLIC Note 52, Geneva 1987.
- [7] Roth, L. D., *Ultrasonic Fatigue Testing*, *Metals Handbook 9th ed.*, Chapter 8: Mechanical Testing, p. 240-258, Metals Park 1978-1989.
- [8] Burghardt, H., Buschbeck, F., Kromp, W., *Ultrasonic Fatigue Tests with Stabilized Amplitude and Controlled Temperature*, *Ultrasonics*, Vol 14, Issue 3, p. 119-122, 1976 <http://www.sciencedirect.com/science/journal/0041624X>
- [9] Calatroni S., Neupert H., Taborrelli M., *Fatigue Testing of Materials by UV Pulsed Laser Irradiation*, Proc. of the 9th EPAC, Lucerne2004. <http://cdsweb.cern.ch/search.py?recid=801190&ln=en>