AN EXPERIMENTAL INVESTIGATION ON CAVITY PULSED HEATING*

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Abstract

Cyclic thermal stresses produced by rf pulsed heating can be the limiting factor on the attainable reliable gradients for room temperature linear accelerators. These limits could be pushed higher by using special types of copper, copper alloys, or other conducting metals in constructing partial or complete accelerator structures. Here we present an experimental study aimed at determining the potential of these materials for tolerating cyclic thermal fatigue due to rf magnetic fields.

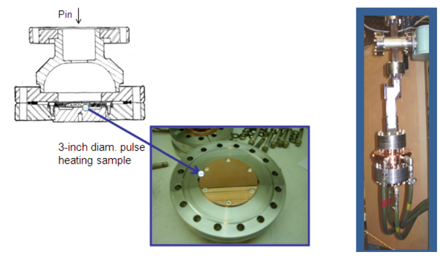
INTRODUCTION

Cyclic thermal stresses produced by rf pulsed heating was originally considered a limiting factor for linear accelerators at extremely high frequencies [1-2]. This motivated experimental studies of the phenomenon [3]. Design of future linear colliders demanded strong damping of wakefields caused by higher order modes [4]. Adding damping features to these structures typically enhances surface rf magnetic fields and hence thermal stresses. In these structures, thermal stresses could potentially limit the reliable operating gradient. Recent studies of breakdown rates in high gradient linear accelerators showed a direct correlation between these rates and pulsed heating[5]. Geometrical variations of structures aimed at reducing surface rf magnetic fields can only go so far. The only alternative after that is to totally or partially change the structure material.

EXPERIMENTAL SETUP

The experimental setup utilizes a special cavity that permits testing of the materials without damage to the cavity itself, which is made of OFHC copper. The cavity shape concentrates the magnetic field on one flat surface where the test material is placed. There is no electric fields on the cavity walls and the mode utilized is TE_{013}-like and has substantially reduced magnetic fields on all surfaces except that of the material under test[6]. The cavity includes one rf coupling slot through a centered circular aperture in the top.

The mechanical design of the cavity, a picture of the sample holder, and a picture of the cavity connected to the mode converter is shown in Figure 1. The cavity loaded quality factor is ~22,800. From the low power cavity parameters, the simulation field profile, and the measured amplitude of the high power input pulse, one can calculate the pulsed temperature rise pattern across the flat plate made of the material under test. A feedback loop is added to guarantee a constant temperature profile on the sample.



(a) (b)

Figure 1: (a) Pulsed heating cavity with 3” sample attached to cavity end cap and (b) connected to power source through a TE_{10} (WR90) to TE_{01} mode converter.

The high power tests are performed using a SLAC XL4 50MW, 11.42 GHz, X-band klystron. Because there is no circulator available at this frequency and power level, we use a long stainless steel waveguide with an attenuation of about 4 dB to provide 8 dB round trip isolation between the klystron and the cavity. The pulse length for these experiments is approximately 1.5μm’s at the input to the cavity at a pulse repetition rate of 60 Hz.

RF TEST RESULTS

The pulsed heating experiments were conducted at SLAC National Accelerator Laboratory in collaboration with CERN and KEK. The samples tested were exposed to different machining and heat treatment processes and the materials used in this study included OFE copper, copper zirconium, copper chromium, HIP copper, single crystal copper, electroplated copper, Glidcop®, copper silver, and silver plated copper.

The first two samples tested were Oxygen Free Electronic grade (OFE C10100) copper. The first sample was initially processed to a peak pulsed heating temperature of 70^{o}C for approximately 4x10^6 rf pulses. Thermal fatigue cracks were already evident at this temperature and was predominate along grain boundaries. Fatigue cracking results when a material is subjected to repeated cyclic stresses. Above a certain threshold, microscopic cracks will begin to form on the surface. An increase in the number of rf cycles during a 2nd similar 70^{o}C run showed many newly formed fatigue cracks and extrusions and propagation of sites that were initiated during the first run. A 2nd OFE Copper (Cu) sample was tested to a temperature of 110^{o}C. The surface damage

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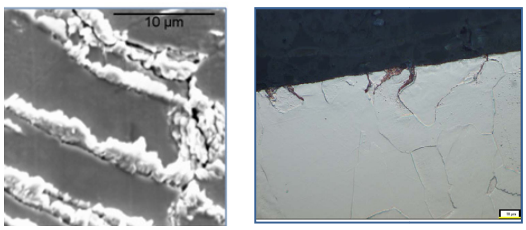
included both intergranular and transgranular fatigue cracks. Transgranular fatigue cracks occur on the face of the crystal and are a stochastic process that begins with dislocations that lead to slip lines and slip bands. Intergranular fatigue cracks are microfractures that occur along grain boundaries. An SEM image showing both types of fatigue cracks is shown in Figure 2a. The cyclic thermal fatigue stresses produced a very noticeable slip band extrusion in this sample and in all of the samples tested in this study. The surface damage observed at 110°C was significantly more severe compared to the first pulsed heating sample tested to 70°C.



(a) (b)

Figure 2. (a) SEM images showing surface extrusions on copper sample tested to 110°C. (b) Metallography showed subsurface damage along grain boundaries extending 20-40µms below the surface.

Metallography was conducted on the sample tested to 110°C to investigate subsurface damage (Fig. 2b). Grain boundary separation and damage were observed to form channels that widened near the surface creating a funnel appearance. The channels extended from depths of 20-40µm's below the surface. These results suggested only intergranular damage. Internal flaws, inclusions, and grains boundaries are sites where locally the crystal lattice is heavily disturbed. This may facilitate fatigue crack initiation and growth and be the reason why mainly intergranular fatigue cracks have been found.

The next two samples tested were C15000 Copper Zirconium (CuZr (0.13-0.2%)). At 70°C this sample had much less damage than the Cu sample. It wasn't until reaching a temperature of 100°C that the surface damage on the CuZr sample approached the level of damage observed on the Cu sample tested to 70°C.

The remaining samples tested in this study were processed with approximately 10^7 rf pulses at a peak pulsed heating temperature of 110°C. This required approximately one week of runtime at a pulse repetition rate of 60 Hz. These samples are shown in Figure 3 and are listed in order of their material hardness as measured by a Rockwell Superficial Hardness Tester. The hardness values (HR15T) are located in the top right corner of each photograph. The pulsed heating surface damage was significantly more pronounced on the softer materials that are shown on the top row of Figure 3. In contrast, the samples with hardness values >70 HR15T (bottom row) were minimally impacted by cyclic thermal fatigue.

The Single-Point Diamond Turned (SPDT) OFE Cu sample was chemically etched and hydrogen fired at 1000°C for 15 minutes. The heat treatment resulted in this

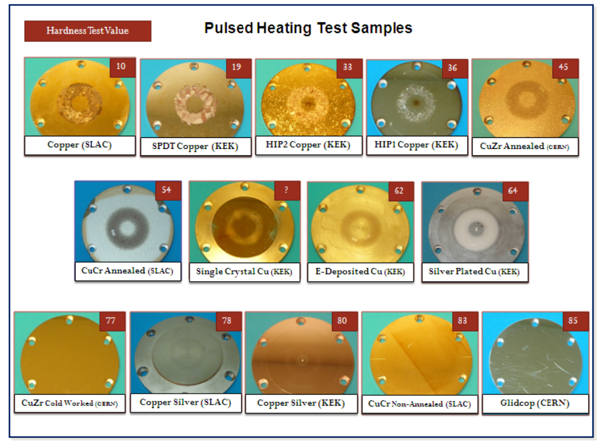
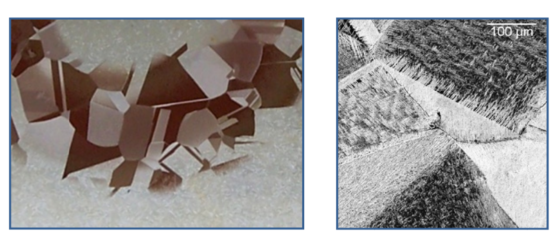


Figure 3: Pulsed heating samples that were tested to 110°C shown in order of their material hardness.

sample (Fig. 4) having a much larger grain size compared to the previous two copper samples tested. Examination of individual grains revealed that some grains were impacted more than other grains within the same radial distance (i.e. same pulsed heating temperature). Electron Back Scattered Diffraction has shown [7] that surface degradation arising from pulsed heating is dependent on the crystallographic orientation of the grains. The darker grains had the least amount of surface damage and from Ref. [7], would correspond to a [100] crystal orientation. The grain orientation with the most severe damage (lighter regions) would correspond to a [111] grain orientation.

A [100] single crystal copper sample was tested but this test did not suggest that grain orientation alone was sufficient to overcome surface fatigue issues at these temperatures. On the single crystal sample the lengths of the extrusions and fractures were much smaller (< 10 um) than in the previous samples tested. The material hardness was found to increase almost proportionally to the pulsed heating temperature. A radial distribution of hardness and cyclic temperature rise also showed that a threshold of approximately 60K has to be overcome in order to initiate surface hardening.

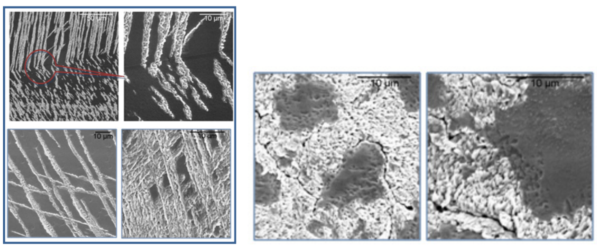
Two HIP Cu samples were tested but only one sample was chemically etched. Both had significant pulsed heating damage and there was no major difference observed between the etched and non-etched sample. In the softer large grain samples, the damage on some grains



(a) (b)

Figure 4: (a) SPDT Cu sample and (b) HIP Cu sample with neighboring grains having varying degrees of surface damage.

had a matted appearance while other grains had a weave-like appearance. The weave pattern is created by the crossing of transgranular fractures that terminate on grain boundaries (Fig. 5a). The grain with the matted surface is created by extrusions occurring through submicron size pits that form on the face of the crystal (Fig. 5b). It is speculated that the observed differences in types of grain damage may be due to a difference in crystallographic orientation. The outer edge and lower temperature region of the pulsed heating ring revealed that grain boundaries are typically the first location that is targeted.



(a) (b)

Figure 5: (a) Transgranular extrusions oriented in different directions and terminating along grain boundaries creating a weave-like pattern and (b) extrusions through micropits.

There were two Cu chromium (C18200) samples that were tested and one was subjected to a 988°C vacuum braze cycle. The softer heat treated sample had significantly more surface damage than the one without heat treatment and most of the damage on the harder sample occurred along grain boundaries. A cold worked copper zirconium (CuZr) and an annealed copper zirconium sample were also tested. Remarkably, at a pulsed heating temperature of 110°C, there was no clear evidence of surface damage on the cold worked sample. This sample was retested to 150°C which resulted in a faintly visible pulsed heating ring. The softer annealed sample had significantly more surface damage in contrast to the harder cold worked CuZr sample. From the experiments that contained both soft and hard materials, the harder non-annealed materials substantially outperformed the softer materials. Although this may have been a likely outcome, it is problematic in the development of high power rf components that typically require a high temperature brazing cycle.

Two copper silver (C10700) samples were tested and neither one of them were subjected to heat treatment. The hardness of the CuAg sample was similar to the CuCr sample and the experimental results were similar showing that the surface damage was dominant along grain boundaries. A 300µm silver plated Cu sample was also tested but the silver plating was severely damaged due to cracking and spalling.

The sample with the highest measured hardness value was Glidcop® Al-15 (C15715). Small striation lines of pulsed heating damage were observed around the pulsed heating ring that had the same orientation irrespective of location. The cause is unclear but may have been due to material defects, or surface imperfections created in the diamond fly-cutting process that was used. However, this process was also used on other samples and the striation pattern was not observed in any other experiment. Except for these small strips, the surface damage on the Glidcop® sample was minimal.

CONCLUSIONS

This study has shown the possibility of pushing the gradient limits due to cyclic thermal fatigue by the use of copper zirconium and copper chromium alloys. Intergranular and transgranular extrusions were observed to varying degrees on all the samples tested to 110°C except for the cold worked CuZr sample which wasn't observed until after the 150°C test run. At low cyclic temperatures, grain boundaries were observed to be the initial sites impacted by pulsed heating. At higher cyclic temperatures (110°C), metallography revealed subsurface intergranular damage that extended 20-40µm's below the surface on heat treated copper. A pulsed heating surface damage dependence on crystallographic orientation was determined using Electron Back Scattered Diffraction technology.

There were two types of surface damage observed on the grain surfaces. Transgranular surface extrusions oriented in different directions and terminating on grain boundaries which created a weave pattern appearance and the second type of damage observed was due to extrusions through micro-pits. It is speculated that the differences between these two may be due to a difference in crystallographic orientation.

In general, non-heat treated samples which had a higher material hardness and smaller grain size significantly outperformed the heat treated samples. This may be due to the small grain boundaries limiting the propagation of surface extrusions which terminated on grain boundaries.

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