The Effect of Mechanical Hardness on RF Breakdown

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Stanford, CA 94305

August 19, 2003

Prepared in partial fulfillment of the requirement of the Office of Science, DOE SULI under the direction of Stefanie Harvey in the Physical Electronics Group at the Stanford Linear Accelerator Center.

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Abstract

The Effects of Mechanical Hardness of RF Breakdown. KRISTI ADAMSON (Brigham Young University, Provo, UT 84604), STEFANIE HARVEY (Stanford Linear Accelerator Center, Palo Alto, CA 94305).

Preliminary high-energy tests have been performed on the next linear collider test accelerator and the traveling wave structures have been examined with a scanning electron microscope. This has yielded the locations of radio frequency breakdowns, characterized by surface craters, occurring on the oxygen-free electric copper traveling wave structure. It has been proposed that the occurrence of high voltage breakdown may be related to material hardness. We have examined this possibility by measuring the hardness of various crystal grains within the copper structure and searching for any correlations to the breakdown events. The hardness of various copper crystals grains has been measured with a nano-indenter and the crystal grains have subsequently been analyzed for breakdown damage. This preliminary analysis does not show any explicit indications that mechanical hardness may be related on the occurrence of RF breakdown. Further research is suggested to verify these initial results.

Introduction

The Next Linear Collider Test Accelerator (NLCTA) has undergone some preliminary high-energy tests, and autopsies have been performed on the traveling wave structure. This wave structure, composed of oxygen-free electric (OFE) copper, has been found to experience radio frequency (RF) breakdown in the high-voltage testing environment. With a scanning electron microscope (SEM), the locations of these breakdown events have been determined by the presence of visible craters in the copper structure.

There are several factors that may contribute to RF breakdown. It is thought to be affected by the strength of the electric and magnetic fields, stray particles, grain boundaries and basic material properties. This paper will address the possibility that the amount of RF breakdown may be connected to the mechanical hardness of the copper.

It has previously been suggested that the hardness of the traveling wave structure may be inversely related to RF breakdown. The hardness of the OFE copper has been ascertained through both micro- and nano-indentation methods. The locations of RF breakdown events have been compared to the hardness of individual crystal grains in order to determine what, if any, correlations are present.

Background

RF Breakdown

The purpose of the Next Linear Collider will be to produce particles of previously unreached high energies. In order to accelerate these particles, the use of radio frequency high electric (on the order of MV/m) and magnetic (A/m) fields is required. One objective of the NLCTA is to determine how well the copper traveling wave structure

holds up under such extreme conditions. Tests have resulted in instances where the RF power does not transmit nor reflect, but rather is absorbed by the wave structure. Such a collapse of the RF field within the cavity is termed as RF breakdown and is accompanied by a surge of current [1] as well as visible craters on the structure.

One theory that has been put forth is that RF breakdown occurs when the metal melts and subsequently vaporizes. The high pressure caused by the expanding plasma causes the metal to splash and a crater forms. [2] As shown in Figure 1, these craters can be viewed with SEM and measured.

Hardness

Hardness is a quality of a material that describes its resistance to deformation. It is not a universal quality such as mass or volume – its value depends on the particular method of measurement. Hardness is generally defined as

$$H = P/A, \quad (1)$$

where P is the force load being placed on the material, and A is the contact area between the material and the indenter.

Micro-hardness testing is becoming more and more common in the laboratory as an important material characterization. Micro-hardness typically refers to testing methods that involve small indentations, with dimensions on the order of 10-100's of microns. This allows for a localized measure of the material's hardness and also causes less damage to the test sample. A pyramidal-shaped diamond produces the indentations, which are then viewed and measured through an optical microscope. The hardness is determined by:

$$H = P/CL^2 \quad (2)$$

where L is the length of the long diagonal and C is a constant, based on the indenter's geometry, which relates the diagonal to the contact area.

The process of manually measuring microscopic indentations can be time-consuming and limited in accuracy as technology advances and indentation size continues to decrease. In response to these problems, a method of nano-indentation has been developed. [3] Small indentations are produced at depths up to 1 micron by a pyramidal diamond indenter. The contact area is found by the total penetration depth of the indenter. From this information as well as knowledge of the indenter load, the hardness of the material can be determined.

Methods

The cells suggested for this study are titled T53VG3R 89 and T53VG3RA 89. These cells are taken from the same location in two similar wave structures. T53VG3R and T53VG3RA are both composed of 53 cells, and the title cell 89 refers to the 30th cell within the structure. This cell was chosen due both to the fact that previous studies had been performed on it, such as SEM imaging and electric field modeling, and to its location. A cell towards either end of the wave structure encounters a significant amount of breakdown, so much that it would prove difficult to characterize any undamaged parts of the sample. Thus a cell in the middle has been chosen, as it will have less damage and more area to study.

The copper cells undergo an extensive firing and cleaning process before being used in the test accelerator. Cells are chemically cleaned before and after rough and fine machining. Before the cells are bonded together through diffusion, they are chemically etched – T53VG3R is cleaned for 60 seconds, while T53VG3RA is cleaned for 30

seconds. Etching effectively removes material from the surface of the sample, and studies have not yet been performed to determine how this difference in etching time affects the behavior of the wave structures. After the brazing, the wave structure is placed in wet H₂ fire at 950°C and then goes through two or three cycles in dry H₂ fire. The cells are then vacuum baked at 650°C, installed in the test accelerator and have a final 140°C bake. [4]

Hardness testing was performed with both a micro-indenter and a nano-indenter. A Rockwell micro-indenter was used with a Knoop diamond indenter. The hardness was determined by measurements on this system, using equation (2), where $C=0.07052$, P is measured in kilograms and L has units of millimeters. These units are typical of hardness testing [5].

The micro-indenter was used with a load of 200 grams to determine the hardness of copper coupons. Three copper coupons were measured and resulted were averaged. Twenty-four indentations were taken on each coupon at periodically spaced distances from the center to acquire an average hardness value.

A Nano-Indenter XP was used for nano-indentation with a Berkovich diamond tip. A series of 25 indentations were made to a depth of 1 micron for an average reported hardness value. Ascertaining a hardness value is more involved and complex in nano-indentation than in micro-indentation and will not be addressed in this paper. For a more thorough understanding of this method, the reader is referred to Nix and Doerner [3].

Magnified images of the cells are taken with SEM and the craters are subsequently analyzed as a function of position with the aid of the program Scion Image TM. It is believed that the relative strength of an RF breakdown is indicated by the size

of a crater. Thus rather than count the number of craters, the percentage area covered by craters is measured.

Results

The damage due to RF breakdown on cell T53VG3RA 89 was studied and produced somewhat noisy results as can be seen from Figure 2. The raw data was averaged and a 15-point smooth plot was produced on Figure 3. The amount of damaged area (shown as a percentage) is plotted as a function of the distance from the center of the cell iris.

At the time of this paper, only 5 crystal grains had been analyzed. The damage attained on each grain was compared to the average results from Figure 3. Figure 4 shows a comparison between the five crystals and the average.

Hardness measurements were made of OFE copper coupons, material similar to that used in the copper wave structure. Coupons that have been machined, but not yet fired or etched, had a Knoop Hardness Number (KHN) of 70.6 ± 0.5 , as determined by the micro-indenter. After firing and chemical etching, the hardness of the coupons decreased to a KHN of 64.2 ± 2.1 .

Individual crystal grains of T53VG3RA 89 have been studied and their hardness results are listed on Chart 1. An average hardness number for the entire cell was obtained from 8 measured grains and yields a value of 1.0 GPa.

Grain	Hardness Value (GPa)	Standard Deviation
1	1.110	0.250
2	1.102	0.198
3	0.938	0.063
4	0.887	0.025
5	0.921	0.201

Chart 1. Hardness values, obtained through nano-indentation methods, for crystal grains chosen at random.

Discussion

The original hypothesis of this project was that softer crystals would be more susceptible to RF breakdown events; however, initial results suggest otherwise. One should note that the error calculated in each grain hardness measurement is great enough to include the hardness values of all five grains. At this point, no statistically significant differences are seen in the hardness measurements of individual grains. Yet the grains did show variances in the amount of damage received due to RF breakdown. Grain #2 showed an above-average amount of damage, while the other four grains received virtually no damage.

Measuring the hardness of a material is a very surface-sensitive technique. Values obtained are highly dependant on the method used, such as indenter shape, application of force load and surface roughness. Should the surface be damaged or altered in some way, it is possible that the hardness measurements will change. While the results of this paper imply that hardness does not affect RF breakdown, it is possible that the damaged grains were initially softer, yet through this damaging process they became hardened. It would be beneficial to study wave structure cells before RF processing. However, this would be a destructive procedure – to study the wave structure's hardness would make it unsuitable for NLCTA testing.

It is also important to note that nano-indentation may not be the most appropriate method for this study, as it is not sensitive enough to detect such small changes in hardness as are found in the copper wave structure. It is suggested that atomic force microscopy is investigated for this analysis.

Conclusions

Based on the initial data, it does not appear that the mechanical hardness of crystal grains and the occurrence of RF breakdown are correlated. However, at this point, only preliminary results have been analyzed and thus no firm conclusions can be made.

It is suggested that this relation is further examined and that more crystal grains are included in future studies. It would also be desirable to perform a more detailed study of copper that has not yet undergone RF processing for comparison.

Acknowledgements

I would like to thank the Department of Energy for providing me with the opportunity to work at the Stanford Linear Accelerator Center and allowing me such an outstanding learning experience. I also thank Stefanie Harvey for her patience, time and guidance, as well as all the members of the Physical Electronics Group at SLAC.

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Figure 1. SEM image of a crater produced by RF breakdown

Figure 2. Percentage of cell area damaged by RF breakdown as a function of position (distance from center).

Figure 3. Average percentage of area damaged by RF breakdown as a function of position.

Figure 4. Plot of average behavior and individual grain behavior.