BREAKDOWN CHARACTERISTICS IN DC SPARK EXPERIMENTS OF COPPER FOCUSING ON PURITY AND HARDNESS

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Abstract

The breakdown characteristics related to the differences in purity and hardness were investigated for several types of copper using a DC spark test system. Three types of oxygen-free copper (OFC) materials, usual class 1 OFC 7-nine large-grain copper and 6-nine hot-isotropic-pressed (HIP) copper with/without diamond finish, were tested with the DC spark test system. The measurements of the beta, breakdown fields, and breakdown probability are presented and discussed in this paper.

INTRODUCTION

High-gradient RF breakdown studies are one of the fundamental methods for developing normal-conducting high-energy accelerators, as breakdowns could deteriorate beam quality and cause significant damage to the surface of the structures. High-gradient experiments on prototype structures for the X-band linear collider have been conducted at NLCTA of SLAC and Nextef of KEK [1, 2]. Another experiment has been initiated at Nextef using simpler geometry, narrow waveguides, a power of 50 MW, and an electric field of around 140 MV/m [3]. The motivation of the present experiment is to investigate the DC breakdown characteristics of different materials in order to estimate the attainable acceleration field and the breakdown rate and to help us understand the breakdown phenomena in RF structures through an experiment using the simpler system. We evaluate the experimental results by comparing the breakdown rate to material properties such as grain size, purity, hardness, and crystal structure. DC breakdown studies have been conducted for many years at Saitama University and recently by the European Organization for Nuclear Research (CERN) [4, 5]. Among the breakdown studies stated above, the DC experiment is the fastest, most convenient way to determine the differences in material properties as compared to the RF experiment. Thus, we investigated the breakdown characteristics to evaluate the different effects of purity and hardness using the DC spark system at CERN.

DC SPARK EXPERIMENT

Experimental Setup and Samples

The schematic of the DC experimental setup is shown in Fig. 1 (see reference [5] for more information). The anode is a hemispherical rounded tip and the cathode (sample) is a grounded rectangular plane. The positioning accuracy of this system is around 1 μm and the gap distance is set at around 20 μm. The discharge energy, i.e., the energy that is available to produce a spark, is approximately 220 mJ with an applied voltage of 4 kV. This corresponds to a field of 200 MV/m. This system can measure the field enhancement factor (β), the subsequent breakdown field (E_M), and the breakdown rate (BDR). Figure 2 shows the setup of the DC spark test in a vacuum chamber. We tested the three samples listed in Table 1. The OFC_Class1 sample is the OFC that is commonly used for the accelerating structure. The 7N_LG sample is OFC with a very high purity (99.99999%) and large grain size, of the order of a few centimetres. The 6N_HIP sample is also a high purity (99.9999%) OFC, but it is hardened by HIP. The surface of all samples were finished by diamond turning; however half of the 6N_HIP sample was also chemically etched in order to compare the effect of difference surface finishes.

Table 1: Sample List.

sample name		OFC_Class1	7N_LG	6N_HIP
purity [%]		99.996	99.99999	99.9999
impurity (ppm)	Bi	3	<0.001	<0.001
	Pb	3	0.002	0.001
	O	3	0.5	<2
	P	<3	0.001	0.003
	S	10	0.05	0.045
	Zn	<1	<0.01	<0.01
grain size [mm]		<1	10~30	<1
hardness [Hv]		30~40 (assume)	30~40 (assume)	80~90
material treatment		650 C, 2 hr anneal	650 C, 2 hr anneal	HIP inAr 800 degC, 1200 kg/cm^2, 2 hr
shaping		wire cut	wire cut	wire cut
surface finish		diamond turning	diamond turning	diamond turning, etching (2 μm)
point of interest		reference material	purity, grain size	surface finish, hardness

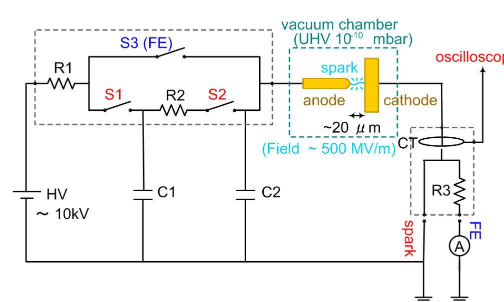

Figure 1: Schematic drawing of the DC spark system.

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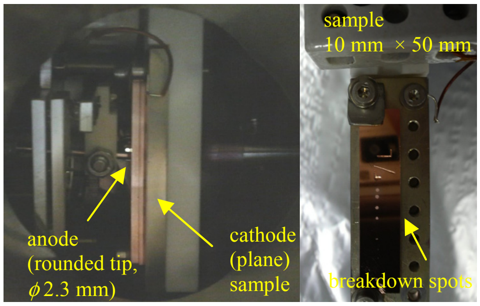

Figure 2: Left: DC spark setup in a vacuum chamber and right: tested sample.

RESULT AND DISCUSSION

Experimental Method and Analysis

β and E_M are measured alternately during the first process of conditioning. The first value of β, before any breakdowns, is generally low. In contrast, the first values of E_M are generally higher than the average breakdown field (E_a) during a typical conditioning. After a few breakdowns, the product of β and E_M, which is called local breakdown field (E_m), tends to approach a constant value. The BDR is the ratio of the number of breakdowns to the number of field applications. The β and E_M were measured at three spots on the sample, and the BDRs were measured at two spots after the conditioning. BDR measurement data are fitted with power curves of the electric field E as BDR ~ E^{α}. A similar power law is observed in RF experiments as well, but they have a different α value than that of the DC experiments [6, 7].

OFC_Class1

Examples of measured β and E_M are shown in Fig. 3 for the three spots from the OFC_Class1 sample, where the surface was finished by diamond turning, also called a mirrored surface. The first β was around 40 with an E_M of around 100 MV/m, for all samples except those shown in Fig. 3b. Figure 5a shows E_m corresponding to Fig.3 and each E_m is estimated to be around 15 GV/m by using after the 10 breakdowns. It was estimated from these results that the E_m converges to a constant value of around 15 GV/m after several breakdowns regardless of the different initial behaviour of β and E_M. More than 200 breakdowns occurred during a typical conditioning process, and E_a is around 175 MV/m for two spots. After many breakdowns, E_a did not vary substantially, although its value did depend on the spots. Figure 6a shows the BDR measured after conditioning. The fitted exponential (α) is estimated to be 20-25 from this data. The measured data are summarized in Table 2. The reference [7] says that E_m is estimated as 10.8 ± 1.7 GV/m, E_a is 159 ± 51 MV/m and α is estimated to be ~10–15 for OFC Class1 copper. One possible cause for the difference in values could be the different fabrication methods. In addition, the variation in the mean values of E_m in both experiments is fairly large and it is considered that the number of samples is less and this gives poor statistics in this experiment.

7N_LG

The 7N_LG sample was tested to determine the effect of purity on the breakdown characteristics. The surface was finished by diamond turning, the same as that used for OFC_Class1. The results in Table 2 show that the first β was much lower than that for the OFC_Class1, However, the E_m and E_a are almost the same. The value of α, shown in Fig. 6a, followed the same trend. It was also found that, except for the first processing, shown in Figs. 3 and 4a, OFC_Class1 and 7N_LG show similar trends in E_m, as shown in Fig. 5a&b. Thus it is not clearly found that DC spark data shows dependence of the breakdown characteristics on the purity.

6N-HIP

The half of the surface on the sample 6N_HIP is finished by etching following diamond turning to compare the breakdown characteristics depending on the surface difference. Figures 4b and c show the measured history of β and E_M with the mirrored surface and the etched surface, respectively. The measured value of the first β was much lower and that of E_M was much higher for the mirrored surface than that for the etched surface. This trend is similar to that of the OFC_Class1 sample. In contrast, the early process of E_m with the etched surface seems to vary moderately as shown in Fig. 5c. The E_m and E_a values are 11±1 GV/m and 195±58 MV/m, respectively, for the mirrored surface, whereas they are 14±3 GV/m and 181±51 MV/m, respectively, for the etched surface. As shown in Fig. 6b, the value of α is also different. Therefore it was found from the DC breakdown experiment that the performance was affected by the surface finish. The mirrored surface seems to be more quickly conditioned than etched surface.

The sample of 6N_HIP was processed by HIP to harden it in order to study the effect of hardness. Fig. 5c shows that the conditioning speed of 6N_HIP is faster, and Fig. 6 shows that its α value is smaller than that of OFC_Class1 and 7N_LG. The data is listed in Table 2. The results of this experiment show that the sample with HIP and a mirrored surface seems to be more quickly processed and have a higher E_a.

SUMMARY

The dependence of the breakdown characteristics on purity is not clearly found in this DC spark test. The sample of 6N_HIP has a lower E_m (=βE_M) and α than the OFC and the high purity material. The HIP material had good electrical discharge endurance. Thus it was found from this DC spark test that the breakdown characteristics are affected by the surface quality such as mirror finish and possibly hardness. Among variable samples, 6N_HIP with a mirrored surface showed higher discharge durability than the other samples. It is interesting that the first β tended to be extremely low with 7N_LG although the breakdown characteristics are similar to that of OFC_Class1 after conditioning. The BD spots on the surface will be observed microscopically to better understand and compare the OFC_Class1 and 7N_LG since they have different grain-size.

Future work includes testing the effect of hardness using a narrow waveguide which is processed by HIP to investigate whether similar electrical discharge endurances to those found in the RF breakdown study are obtained.

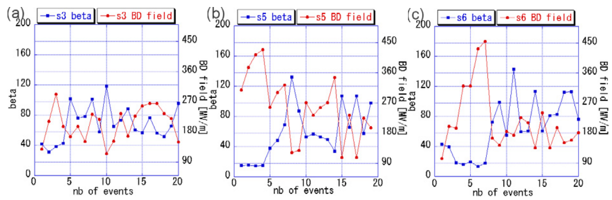

Figure 3: Processing examples of β and E_M with the sample of OFC_Class1 with mirrored surface.

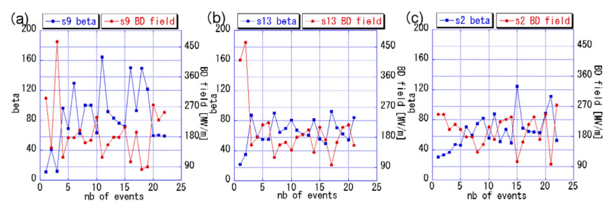

Figure 4: Processing examples of β and E_M with the sample. (a) 7N_LG with mirrored surface, (b) and (c) are 6N_HIP with mirrored surface and etched surface, respectively.

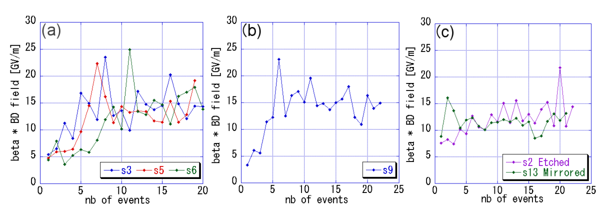

Figure 5: Local breakdown field E_m (the product of β and E_M) corresponding to (a): fig.3 with OFC_Class1, (b): fig. 4 (a) with 7N_LG, (c): fig.4 (b) (c) with 6N_HIP.

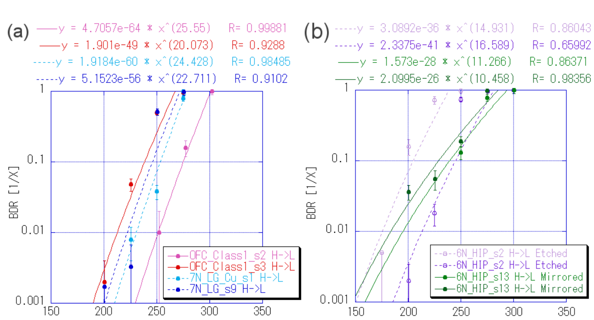

Figure 6: BDR corresponding to the applied field. (a) OFC_Class1 and 7N_LG, (b) 6N_HIP with etched surface and mirrored surface.

Table 2: Summary of the Measured Data.

sample name	OFC_Class1	7N_LG	6N_HIP	
surface condition	mirrored **(spot3)**	mirrored **(spot9)**	mirrored **(spot13)**	etched **(spot2)**
β before 1st BD	**42,** *43, 15*	**11,** *22*	**22,** *21, 24*	**30,** *42, 33*
1st BD field [MV/m]	**129,** *104, 309*	**296,** *262*	**412,** *315, 317*	**246,** *296, 302*
Max. E_M [MV/m] (event number)	**292 (3rd),** *455 (7th), 429 (4th)*	**466 (3rd),** *546 (3rd)*	**464 (2nd),** *315 (1st), 369 (2nd)*	**246 (1st),** *406 (2nd), 302 (1st)*
average β after few BDs (±1σ) (~10 sparks)	**73±20,** *87±29, 68±26*	**94±35**	**68±13**	**73±23**
average E_M after few BDs [MV/m] (~10 sparks)	**208±53,** *182±35, 225±74*	**178±58**	**173±36**	**199±54**
average E_m after few BDs [GV/m] (~10 sparks)	**15±3,** *15±4, 14±2*	**15±5**	**11±1**	**14±3**
E_a: average BD field during conditioning (~100 sparks) [MV/m]	**176±49** *178±65*	**175±57**	**195±58**	**181±51**
α (BDR~E^{α})	**20,** *26*	**24,** *23*	**11, 11**	**17, 15**

*The bold type data were measured at the same spot which is indicated in the bracket.

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