RECEIVED
AUG 04 1997
OSTI

ANL/ET/CP-94032
CONF-970758--

**Critical Current Density and Dissipation
in Sintered YBCO Filaments**

by

Y. S. Cha¹, S. Y. Seol², and J. R. Hull¹

**¹Argonne National Laboratory
Argonne, Illinois 60439**

**²Chonnam National University
Kwangju 500-757, Korea**

The submitted manuscript has been created by the University of Chicago as Operator of Argonne National Laboratory ("Argonne") under Contract No. W-31-109-ENG-38 with the U.S. Department of Energy. The U.S. Government retains for itself, and others acting on its behalf, a paid-up, nonexclusive, irrevocable worldwide license in said article to reproduce, prepare derivative works, distribute copies to the public, and perform publicly and display publicly, by or on behalf of the Government.

Distribution

R. W. Weeks
R. B. Poeppel
U. Balachandran
R. A. Valentin

Authors
ESA Section
B. Baudino
F. Y. Fradin
H. Drucker
S. Lake

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Submitted to CEC/ICMC Conference, Portland, Oregon, July 28-Aug. 1, 1997.

*Work supported by the U.S. Department of Energy, Energy Efficiency and Renewable Energy, as part of a program to develop electric power technology, under Contract W-31-109-Eng-38.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible electronic image products. Images are produced from the best available original document.

**Critical Current Density and Dissipation
in Sintered YBCO Filaments**

by

Y. S. Cha¹, S. Y. Seol², and J. R. Hull¹

**¹Argonne National laboratory
Argonne, Illinois 60439**

**²Chonnam National University
Kwangju 500-757, Korea**

Abstract

Critical current density and dissipation of four sintered YBCO filaments were measured using a continuous DC power supply. Each sample exhibited somewhat different characteristics from the others even though 3 of the 4 samples are from the same batch. The data suggest that it is possible for the YBCO filament to be in a state of stable equilibrium when part of the filament is in the flux-flow state and part of the filament is in the normal state (local hot spots). This behavior may be advantageous for resistive fault current limiters because the intermediate state (partly flux-flow and partly normal) has an overall resistance much higher than that of the flux-flow state but it does not lead to thermal runaway (burnout) or excessive heating compared to a YBCO filament driven into normal state over its entire length. Two of the samples were broken as a result of local burnout.

Introduction

In practical applications of high-temperature superconductors, it may be necessary to determine the dissipation characteristics of the superconductors beyond the critical current density usually defined by the $1 \mu\text{V}/\text{cm}$ criterion. For example, In the prediction of burnout of high-temperature superconductor current leads, the information on flux-flow resistivity is needed [1]. In the design of a resistive fault current limiter, it is important to understand how the high-temperature superconductor responds to current above its critical current density [2]. In general, in the calculation of transient temperature fields in a conductor, the electrical resistivity of the superconductor in all of the thermodynamic states is required in order to determine the heat generation rate [3]. There are relatively few reported data on dissipation (flux-flow) of various high-temperature superconductors well above its critical current density [4-6] because majority of reported data are focused on critical current density. Data on burnout is even more scarce because it destroys the sample.

In this paper, we describe the results of measurements of the critical current density and dissipation (up to local burnout) of four sintered YBCO filaments in liquid nitrogen. Implications of the results for application in resistive fault current limiter are discussed.

Experimental Set Up

The standard four points technique is employed in the measurements. The current leads are made of copper braids which are silver soldered to the ends of the YBCO filaments. Relatively large contact areas exist between the YBCO

filament and the copper braids because the former was inserted into the braid. This help to reduce the contact resistances between the YBCO filament and the current leads. Dissipation in the YBCO filaments was measured over a wide range of current far beyond the critical current density ($1 \mu\text{V}/\text{cm}$ criterion). All the tests were conducted at 77 K by using a continuous DC power supply. A total of four YBCO filaments were tested (sample 1 through 4) and their dimensions and conditions are summarized in Table 1. The length of each YBCO filament is approximately 77 mm. The diameter in Table 1 is an approximate value because it is not uniform and may vary slightly along the length of the YBCO filament.

Sample No. 1 is one of the filaments received more than 6 months ago before the testing date and was stored in the laboratory without any special attention such as in a desiccant chamber. Samples No. 2 to 4 are tested shortly after they were received and are also stored in the laboratory environment. All the data reported here are under steady-state conditions.

Experimental Results

Figure 1 shows the E/J data for sample No. 1. This sample had a critical current density of $1,000 \text{ A}/\text{cm}^2$ (the critical current is 4.6 A) which is the highest among all the samples tested so far even though the sample had been left in the laboratory for more than six months. As the current density was increased beyond $1,425 \text{ A}/\text{cm}^2$, which corresponds to a current of 6.5 A) the measured voltage suddenly jumped and then dropped, showing some kind of instability. The test was then stopped and an attempt was made to remove the sample from the sample holder for visual examination. However, during the process of removing the sample, the filament was broken. Visual examination under a magnifying

lens showed that the filament was broken as a result of mechanical stress (bending), not as a result of burnout, because both ends of the break showed that the filament structure (or texture) was not different from the bulk material (similar to that shown in Fig. 4). This is supported by evidence that the current density was increased to a maximum of only 1.43 times the critical current density, and burnout is not likely to have occurred at this relatively small ratio of J/J_c .

Figure 2 shows the E/J data for sample No. 2. The critical current density of sample No. 2 was 370 A/cm^2 ($I_c = 2.3 \text{ A}$) which is considerably less than that of sample No. 1. The data points shown in Fig. 2 are average values because at currents greater than 4 A, the voltage (electric potential) showed fairly large fluctuations ($\pm 10\%$). The test ended at $I = 5.1 \text{ A}$ because at this current, the electric circuit was suddenly open indicating that the loop was broken. Post-test examination showed that the YBCO filament was indeed broken near the solder joint of one of the braided current leads. Further examination under a magnifying lens revealed that the color of the YBCO filament on both sides of the break changed from black to gray as shown in Fig. 3. This change in color at the break is quite different from a break due to bending which exhibited no change in color as shown in Fig. 4. The grayish film-like texture on the surfaces of the YBCO filament near the break is probably the result of local heating which eventually led to burnout. Local heating could be caused by inhomogeneity of material properties. A current of 5.1 A corresponds to a current density of 820 A/cm^2 and a ratio of $J/J_c = 2.2$, which is higher than the ratio achieved for sample No. 1.

Figure 5 shows the E/J data for sample No. 3. The critical current density of sample No. 3 is 875 A/cm^2 . The numbers in Fig. 5 serve to indicate the order in which these data points were taken. For example, the experiment starts with point 1 and progresses to points 2, 3, etc., and finally it ends with point 21. By following the number, one can determine whether the data were taken in the direction of increasing or decreasing current. The arrows in the figure also help to indicate the direction of increasing or decreasing current. Figure 5 exhibits several interesting behaviors for sample No. 3 that were not observed for samples No. 1 and 2. First, there is apparently a bi-stable region for current density between approximately $1,080\text{-}1,550 \text{ A/cm}^2$. Within this range, the electric potential can have two different values. When the electric potential of the YBCO filament is on the upper curve, we have observed a relatively large volume of vapor continuously rising towards the liquid/air interface from a location near one of voltage taps, indicating large heat generation locally. When the YBCO filament is on the lower curve, boiling is fairly uniform and there is no local concentration of boiling. Thus, the lower curve may correspond to the flux-flow state and the upper curve may correspond to partially normal state when local hot spots become normal (near one of the voltage taps). Whether the electric potential will remain on the upper or the lower curve depends on the magnitude of ΔJ . For example, at point 8, a large increase in J ($\Delta J \approx 100 \text{ A/cm}^2$) caused E to jump from 7 to $3000 \text{ } \mu\text{V/cm}$ (point 9). However, by using smaller ΔJ , the data points move along the lower curve as shown in Fig. 5. The jump from lower to upper curve is likely due to a sudden large increase in resistive heating as a result of large current increase. The YBCO heats up almost adiabatically in such a short period and local temperature may exceed the critical temperature and become normal which results in the voltage jump shown in Fig. 5. The YBCO turns normal only locally at the hot spot (near one of the voltage taps) which may be present because

the material is not homogeneous. Once part of the YBCO becomes normal, it remains in the normal state indefinitely and locally it does not come back to the flux-flow state. For smaller ΔJ , local temperature anywhere never exceeded the critical temperature and the entire YBCO filament is still in flux-flow state and remains on the lower curve. It appears that for $J < 1,050 \text{ A/cm}^2$, the YBCO filament is stable only in the flux-flow state and for $J > 1,550 \text{ A/cm}^2$, the YBCO filament is only stable in the partially normal state. As J increases near or slightly above $1,550 \text{ A/cm}^2$, the state of the YBCO filament becomes quite unstable and the voltage reading fluctuates up and down as shown by data points 15, 16, and 17 in Fig. 5.

The tests of sample No. 3 were carried out up to a current ratio of $J/J_c \cong 1.8$. Even though part of the YBCO filament might have been in the normal state, equilibrium could still be achieved without experiencing thermal runaway up to $J/J_c = 1.8$. Sample No. 3 is intact after the tests and can be used again if necessary.

Figure 6 shows the E/J data for sample No. 4. Sample No. 4 had a critical current density of only 18 A/cm^2 ($1 \mu\text{V/cm}$ criterion). Flux-flow state existed over a wide range of current density up to $J \cong 1,400 \text{ A/cm}^2$ ($J/J_c \cong 78$). Between $J = 1,400$ and $1,900 \text{ A/cm}^2$, the YBCO is in some kind of intermediate state which appears to be quite unstable and can jump up and down as shown by the data points at $J \cong 1,630 \text{ A/cm}^2$. This intermediate state could correspond to a partially normal state as a result of a local hot spot similar to that of sample No. 3. As the current density is increased beyond $1,630 \text{ A/cm}^2$, there is another jump in voltage which could mean that another part of the YBCO also becomes normal. However, unlike sample No. 3, boiling appears to be fairly uniform and no local

concentration of boiling was observed for sample No. 4 even though boiling intensity increases with current density. Further increase in current density to $J = 2,100 \text{ A/cm}^2$ leads to thermal runaway and burnout because more and more parts of the YBCO become normal. The first evidence of burnout is, of course, the detection of an open circuit. Post-test examination shows that the YBCO filament is broken and the break is approximately 4-5 mm from one of the voltage taps. Figure 7 shows the photograph on one side of the break (the diameter of the YBCO filament is 0.84 mm). A large crack is clearly visible near the break. Similar to sample No. 2, the color of the YBCO changed from black to gray, indicating that the break is due to burnout and is not due to mechanical stress.

Summary

We have tested four YBCO filaments (samples No. 1 through 4) at 77 K and each sample exhibited somewhat different characteristics from the others even though samples 2, 3, and 4 are from the same batch. Samples 2 and 4 ended up broken as a result of burnout at a local hot spot. The data from sample No. 3 seem to suggest that it is possible for the YBCO filament to be in a state of stable equilibrium when part of the filament is in the flux-flow state and part of the filament is in the normal state (local hot spots). As long as the number of local hot spots is limited, thermal runaway did not occur and the superconducting state could be recovered when the current is reduced. This behavior may be advantageous for resistive fault current limiters because the intermediate state (partly flux-flow and partly normal) has an overall resistance much higher than that of the flux-flow state but it does not lead to thermal runaway (burnout) or excessive heating compared to a YBCO filament driven into normal state over its

entire length. The question of recovery time needs to be addressed which requires further experiment under transient conditions.

Acknowledgments

This work has been supported by the U.S. Department of Energy, Energy Efficiency and Renewable Energy, as part of a program to develop electric power technology, under Contract W-31-109-Eng-38. The authors would like to thank Henry Muller of Illinois Superconductor Corp. for providing the YBCO samples.

References

1. S. Y. Seol, Y. S. Cha, R. C. Niemann, and J. R. Hull, "Prediction of Burnout of a Conduction-Cooled BSCCO Current Lead", IEEE Trans. on Applied Superconductivity, Vol. 7, No. 2, pp. 696-699, June 1997.
2. J. D. Hodge, H. Muller, D. S. Applegate, and Q. Huang, "A Resistive Fault Current Limiter Based on High Temperature Superconductors", Applied Superconductivity, Vol. 3, No. 7-10, pp. 469-482, 1995.
3. A. Abeln, E. Klemt, and H. Reiss, "Stability Considerations for Design of a High Temperature Superconductor," Cryogenics, 32, 269-278, 1992.
4. Y. S. Cha, S. Y. Seol, D. J. Evans, and J. R. Hull, "Flux-Flow Resistivity of Three High-Temperature Superconductors", IEEE Trans. on Applied Superconductivity, Vol. 7, No. 2, pp. 2122-2125, June 1997.

5. Y. S. Hascieck and L. R. Testardi, "Constant E-J Relation in the Current Induced Resistive State of $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$," IEEE Trans. Magn., 27, 1186-1189, 1991.
6. T. R. Askew, J. G. Nestell, R. B. Flippen, D. M. Groski, and N. McN. Alford, "Dynamic Measurement of Flux Flow Resistivity in $\text{YBa}_2\text{Cu}_3\text{O}_7$ Wires," IEEE Trans. Appl. Superconductivity, 3, 1398-1401, 1993.

Table 1. 77 K Test of YBCO Filament

	<u>Sample #1</u>	<u>Sample #2</u>	<u>Sample #3</u>	<u>Sample #4</u>
Diameter (mm)	0.76	0.89	0.76	0.84
Distance between voltage taps (mm)	19	30	26	26
Critical current (A)	4.6	2.3	4.0	0.1
Critical current density (1 μ V/cm criterion) (A/cm^2)	1000	370	875	18
Date received	12/16/94	7/10/95	7/10/95	7/10/95
Pre-test condition	Stored in the lab environ- ment	Stored in the lab environ- ment	Stored in the lab environ- ment	Stored in the lab environ- ment
Post-test condition	Broken mecha- nically	Broken due to burnout	intact	Broken due to burnout
Burnout current density (A/cm^2)	>1,425	820	>1,575	2,100
Burnout current density ratio (J/J_c)	>1.4	2.2	>1.8	116.6

Fig. 1. E versus J for sample No. 1

Fig. 2. E versus J for sample No. 2

(a)

Fig. 3. Photographic picture near the break (due to burnout) of sample No. 2. (a) on one side of the break. (b) on the other side of the break

(b)

Fig. 3. Photographic picture near the break (due to burnout) of sample No. 2. (a) on one side of the break. (b) on the other side of the break

Fig. 4. Photographic picture near a break (due to bending) of sample No. 2

Fig. 5. E versus J for sample No. 3

Fig. 6. E versus J for sample No. 4

Fig. 7 Photographic picture near a break (due to bending) of sample No. 4