Trapped Field Characteristics of Y-Ba-Cu-O Bulk in Time-Varying External Magnetic Field

著者	津田　理
journal or publication title	IEEE Transactions on Applied Superconductivity
volume	11
number	1
page range	1988-1991
year	2001
URL	http://hdl.handle.net/10097/46513

doi: 10.1109/77.920243

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 11, NO. 1, MARCH 2001

Trapped Field Characteristics of Y-Ba-Cu-O Bulk in Time-Varying External Magnetic Field

T. Ohyama, H. Shimizu, M. Tsuda, and A. Ishiyama

Abstract— **The trapped field characteristics of disk-shaped YBCO bulk exposed to external AC magnetic field are investigated experimentally. The magnetic flux density on the top surface of the disk, defined as "trapped flux" in this paper, was measured in both short and long terms as functions of amplitude and frequency of the AC external magnetic field. The observed trapped flux attenuation was obviously different from that of flux creep, i.e., with no external magnetic field; this implies that the trapped flux density within the YBCO disk is reduced by a temperature rise due to AC loss. The abrupt attenuation of trapped flux density in the first several cycles was observed at frequencies of 0.1 and 1 Hz, while not observed at 10 Hz. The attenuation rate after seven minutes of applying AC magnetic field, however, became almost the same regardless of frequency. The trapped flux attenuation in one cycle of AC magnetic field decreases with the frequency and increases with the amplitude of AC magnetic field. These results imply that the characteristic of trapped flux is closely related to AC loss, especially the hysteresis loss, and the AC loss depends on the frequency and the amplitude of the AC external magnetic field. It can be considered that transient electromagnetic behavior within HTS bulk, especially supercurrent distribution, is a key factor of the relationship between the trapped flux attenuation and the AC loss.**

Index Terms— **AC loss, AC magnetic field, trapped flux, YBCO bulk**

I. INTRODUCTION

The characteristic of trapped flux is one of the key factors in the application of high-temperature superconducting bulk, such as magnetic levitation system, rotor of motor, bulk magnet, and so on [1]-[3]. We have experimentally investigated the following effects on trapped flux density within YBCO bulk: 1) the changing rate of applied magnetic field in the field-cooling process; and 2) the frequency and the amplitude of external AC magnetic field after the field-cooling process. Electromagnetic behaviors within the bulk exposed to time-varying magnetic fields, especially supercurrent distribution, have also been investigated numerically using a developed simulation program based on the finite element method (FEM) considering voltage-current (E-J) characteristics. Although the characteristic of trapped flux in YBCO bulk was investigated and discussed in the previous paper [4], the long-term measurement of trapped flux attenuation could not be achieved because of a very small magnitude of DC magnetic field in the field-cooling process and AC magnetic field after the field-cooling process. This may be caused by the low critical current density of 4×10^7 A/m^2 in the bulk. For practical AC use, however, the long-term measurement of trapped flux density is required. Therefore, a new YBCO disk with a higher critical current density was prepared for the long-term measurement. The trapped flux characteristic in field-cooling process was evaluated and compared with that of the former sample disk to determine the magnitude of DC trapped field and the amplitude of AC magnetic field for the measurement. We measured trapped flux attenuation for several minutes as functions of the frequency and the amplitude of an AC external magnetic field.

II. EXPERIMENT

Using Hall probes, we measured magnetic flux density just above the top surface of the YBCO sample disk, defined as "trapped flux" in this paper, because it is impossible to measure the magnetic flux density within YBCO bulk directly. Fig. 1 is a schematic drawing of the experimental setup. We prepared a "new" YBCO disk, 45.2 mm in diameter and 3.0 mm thick, with the equivalent critical current density of 4×10^8 A/m^2 instead of an "old" YBCO disk, 45.6 mm in diameter and 3.3 mm thick, with the equivalent critical current density of 4×10^7 A/m^2. Note that the value in the new disk is measured using a rectangular-prism-shaped piece of the YBCO bulk, while the value in the old disk was estimated

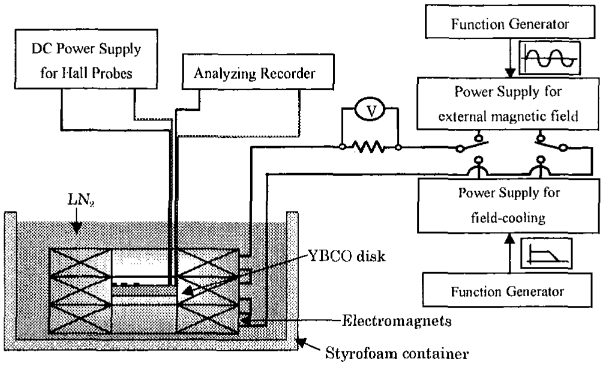


Fig. 1. Schematic drawing of experimental setup.

Manuscript received September 19, 2000.

T. Ohyama, H. Shimizu and A. Ishiyama are with Department of Electrical, Electronics and Computer Engineering, Waseda University 3-4-1 Ohkubo, Shinjuku-ku, Tokyo, Japan (telephone: +81-3-5286-3376, e-mail: atsushi@mn.waseda.ac.jp).

M.Tsuda was with the Department of Electrical, Electrical and Computer Engineering, Waseda University, Shinjuku-ku, Japan. He is now with the Department of Electrical and Electronic Engineering, Yamaguchi University, Ube, Japan (e-mail: tsuda@po.cc.yamaguchi-u.ac.jp).

by numerical simulation.

External magnetic field applied to the disk is generated by electromagnets composed of three solenoid coils wound with copper wires. The inner and outer diameter and the height of each coil are 62 mm, 120 mm and 21 mm, respectively. The three coils are piled up in the axial direction and the overall height is 69 mm. The disk, located at the center of the electromagnets, is fixed on a support and three sets of Hall probes, just above the top surface of the disk, are located at r=2.8 mm, r=14.8 mm and r=19.8 mm. The disk is exposed to the magnetic field of 0.21 T at the operating current of 15 A. All of the components for measurement are placed in a Styrofoam container filled with liquid nitrogen at 77 K. The experiment proceeds through the following steps.

1. Place the normal state disk at the center of the electromagnets and let it become superconducting in the presence of a DC magnetic field generated by electromagnets.
2. Reduce the magnetic field to zero at a constant reducing rate.
3. Apply an AC magnetic field to the disk ten seconds after the field-cooling process and measure trapped flux density by Hall probes both in the first ten cycles of the AC magnetic field and in the following seven minutes at intervals of one minute.

III. RESULTS AND DISCUSSION

A. Trapped Flux in Field-Cooling Process

In the previous old disk, the trapped rate, defined as the ratio of the magnetic flux density before field-cooling process to the trapped flux density, has conspicuously decreased with the magnitude of DC magnetic field in the field-cooling process; this implies that the characteristic of trapped flux might be affected by supercurrent saturation within the old disk. We measured the trapped rate in the new disk as a function of operating current of the electromagnet in the field-cooling process. Fig 2 shows the experimental result of trapped flux at the changing rate of DC magnetic field in the field-cooling process of -2.5 A/s (-0.035 T/s), where B_{init} and B_{final} are the measured magnetic flux density just before and after reducing the DC magnetic field for field-cooling. The result shows that the trapped rate in the new disk is still more than 90%, even at the field-cooling current of 25 A, while less than 90%, even at the current of 5 A. Based on this result, we chose a field-cooling current of 15 A, corresponding to 0.21 T, and the maximum operating current, generating the AC magnetic field, of 5, 7.5 and 10 A in r.m.s..

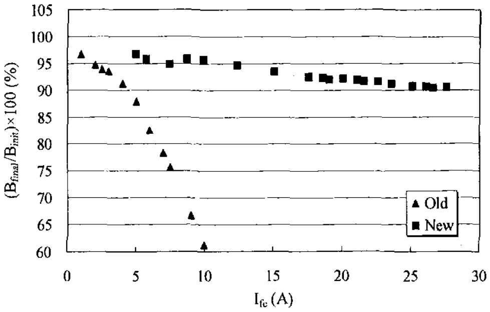
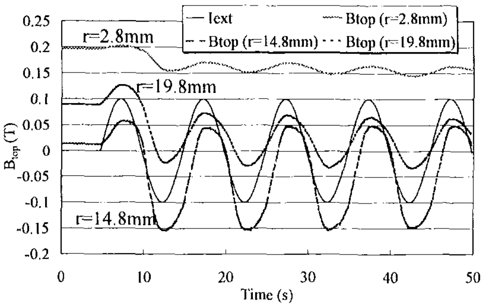


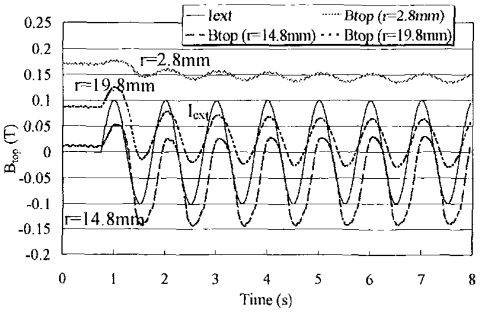
Fig. 2. Effect of magnitude of field-cooling process on magnetic field decay measured at the top surface of YBCO disk.

B. Influence of Frequency of AC Field on Trapped Flux

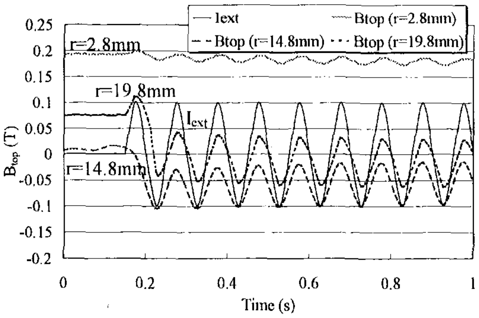
We measured trapped flux at the operating current of 10 A as a function of the frequency of external AC magnetic field. The observed waveforms of the first several cycles at the frequency of 0.1, 1, and 10 Hz are shown in Fig. 3. Although the trapped flux attenuation at r=14.8 mm and r=19.8 mm has a similar tendency regardless of the frequency, the trapped flux attenuation at r=2.8 mm decreases with the frequency; the abrupt attenuation in the first two cycles, as seen at 0.1 and 1 Hz, was not observed at the frequency of 10 Hz. This abrupt attenuation may be caused by the magnetic field with the opposite direction against that of trapped field [4]. According to the critical state model, the penetration depth of



(a) Frequency of external magnetic field is 0.1 Hz.



(b) Frequency of external magnetic field is 1.0 Hz.



(c) Frequency of external magnetic field is 10 Hz.

Fig. 3. Observed magnetic flux density traces.

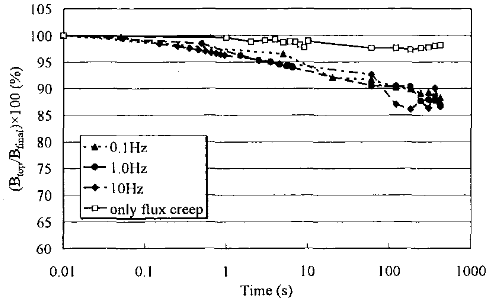
the supercurrent region becomes double when a magnetic field with opposite direction and the same amplitude is applied to the disk. It can be considered from the experimental result and the theoretical discussion that in the high frequency of 10 Hz, the magnetic flux cannot rapidly penetrate into the YBCO bulk according to the changing rate of AC magnetic field.

For AC applications of HTS bulk, the characteristics of trapped flux attenuation in the long term are much more important than that in the short term reported in the previous paper [4]. Therefore, we observed the trapped flux attenuation for seven minutes as a function of the frequency of AC external magnetic field. The maximum operating current for AC magnetic field was 5 and 10 A and the measurements was performed at the frequency of 0.1, 1 and 10 Hz. The experimental result of the trapped flux attenuation at r=2.8 mm, as a function of time, is shown in Fig. 4. The trapped flux attenuation in the case of zero external field, i.e., only flux creep, was also measured to investigate the influence of the flux creep on the trapped flux attenuation. The trapped flux attenuation with AC magnetic field is apparently different from that without AC magnetic field; this means that the trapped flux attenuation may be caused by a temperature rise due to AC loss, particularly hysteresis loss.

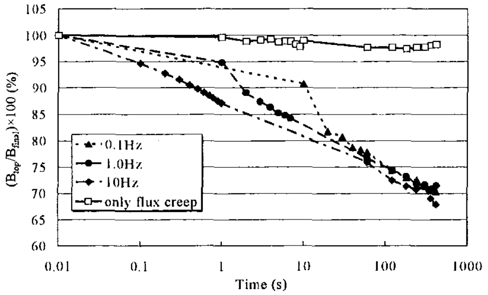
The frequency dependence of trapped flux attenuation is clearly observed in the case of the maximum operating current of 10 A, while not clear in the case of 5 A. In the case of 10 A, abrupt attenuation, as shown in Fig. 3, can be easily found in the case of 0.1 and 1 Hz. On the other hand, the trapped flux density attenuates gradually and almost linearly, i.e., with no abrupt attenuation, in the case of 10 Hz. Although the trapped flux attenuation at the beginning of the measurement depends on the frequency, the attenuation rate, defined as the ratio of the measured magnetic flux density, B_{top}, to that just before applying AC magnetic field, B_{final}, became almost the same at t=420 s regardless of frequency. The same results are re-presented in Fig. 5 as a function of the number of cycles of applied AC magnetic field. It can be considered that the magnitude of the slope in Fig. 5 is related to hysteresis loss within the disk, especially after the abrupt attenuation explained above. The slope of the trapped flux attenuation slightly decreases with the frequency; this means that the higher frequency, the less hysteresis loss. It can be considered as the reason that the penetration depth of magnetic flux decreases with the frequency because the changing rate of AC magnetic field increases with the frequency. The relationship between hysteresis loss and the slope of trapped flux attenuation may be related to the magnitude of supercurrent density; the supercurrent density has a tendency to increase with the frequency according to the E-J characteristic of YBCO bulk.

C. Influence of Amplitude of AC Field on Trapped Flux

The influence of amplitude of the AC external magnetic field on the trapped flux attenuation was investigated experimentally. The trapped flux attenuation at the frequency of 10 Hz was measured as a function of the amplitude of operating current for AC magnetic field. The experiment results were shown in Fig. 6. As seen in Fig. 6, the slope of attenuation was much larger than that of flux creep. Although the scattering in the measured value of attenuation rate is observed above t=100 s, the slope of attenuation rate increases with the amplitude of AC magnetic field. One of the

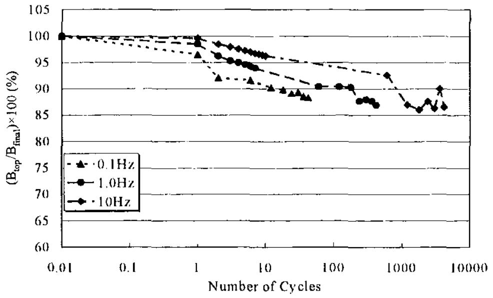


(a) Maximum operating current is 5 A.

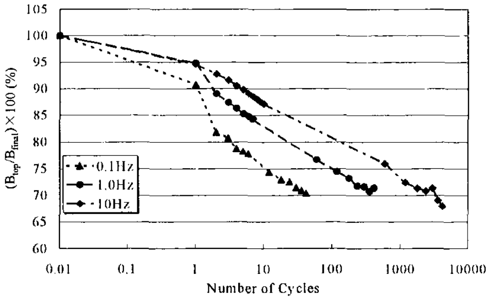


(b) Maximum operating current is 10 A.

Fig. 4. Trapped flux attenuation as a function of time.



(a) Maximum operating current is 5 A.



(b) Maximum operating current is 10 A.

Fig. 5. Trapped flux attenuation as a function of number of cycles of AC magnetic field.

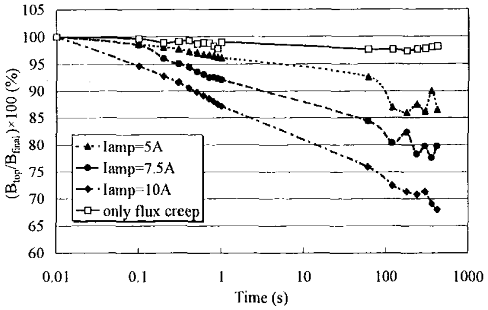


Fig. 6. Effect of amplitude of AC external magnetic field on trapped flux attenuation.

other noticeable results is that about thirty percent of trapped flux density was reduced due to AC magnetic field for seven minutes. These phenomena may depend on the relationship between the amplitude of external AC magnetic field and the hysteresis loss; the larger amplitude of AC magnetic field, the larger hysteresis loss. In Figs. 5 and 6, the fluctuations of the trapped field traces were observed in the long range of time. Further investigation of this amplitude dependence at different trapped field and frequency may be required to clarify the trapped flux characteristic of HTS bulk exposed to AC magnetic field.

IV. SUMMARY

We have investigated the characteristics of trapped flux in a YBCO disk exposed to an AC external magnetic field. The magnetic flux density on the top surface of the sample disk was measured in both short and long terms as functions of the amplitude and the frequency of AC magnetic field. The observed trapped flux attenuation was apparently different from that of flux creep; this implies that the trapped flux attenuation is caused by a temperature rise due to AC loss. The frequency dependence of AC magnetic field on trapped flux attenuation was investigated experimentally as functions of time and number of cycles in the AC magnetic field. Although the attenuation rate in the first several cycles depends on frequency, it became almost the same after a long term. The abrupt attenuation of trapped flux density in the first several cycles was observed more clearly at the lower frequency. The trapped flux attenuation in one cycle of AC magnetic field decreases with frequency and increases with the amplitude of AC magnetic field. The trapped flux density was reduced rapidly; about thirty percent of the trapped flux density was reduced against AC magnetic field for seven minutes. These results imply that the trapped flux attenuation is closely related to AC loss, especially hysteresis loss, and the characteristic of supercurrent distribution is a key parameter for evaluating the AC loss.

REFERENCES

[1] R. J. Storey, T. A. Coombs, A. M. Campbell, R. A. Weller and D. A. Cardwell, "Development of Superconducting DC machines using bulk YBCO", *IEEE Trans. On Applied Superconductivity*, vol.9, no.2, pp. 1253-1256, 1999.

[2] L. K. Kovale, K. V. Ilushin, S. M. A. Koneev, K. L. Kovalev, V. T. Penkin, V. N. Poltavets, W. Gawalek, T. Habisreuther, B. Oswald, and K. J. Best, "Hysteresis and Reluctance Machines with Bulk HTS Rotor Elements", *IEEE Trans. On Applied Superconductivity*, vol.9, no.2, pp. 1261-1264, 1999.

[3] R. Muramatsu, S. Sadakata, M. Tsuda, and A. Ishiyama, "Trial Production and Experiments of Linear Actuator with HTS Bulk Secondary", *Applied Superconduтivity Conference (ASC2000)*, 2LJ05, 2000.

[4] M. Tsuda, T. Ohyama, A. Ishiyama, "Electromagnetic behavior on high-temperature superconducting bulk YBCO exposed to time-varying magnetic field", *IEEE Trans. on Applied* Superconductivity, vol.10, No.1, 2000, pp 894-897, 1999.