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Increase in Transient Resistance of Bi2223 Superconducting Bulk by Applying External Magnetic Field

K. Kato, T. Noda, H. Shimizu, Y. Yokomizu, T. Matsumura and N. Murayama

***Abstract*— The critical current and the transient change of resistance in a Bi2223 bulk applied dc magnetic field were experimentally investigated. Taking account of the decreasing rate of critical current and the increasing rate of resistance obtained from the measurement, we estimated the condition under which the gross resistance of the bulk rises while maintaining the critical current and bulk volume. Furthermore, it is discussed whether the bulk should be used with the applied magnetic field or not from the viewpoint of the bulk volume required to obtain the critical current and resistance designated.**

Index Terms— **Bi2223 bulk, critical current, magnetic field, resistance**

I. INTRODUCTION

SUPERCONDUCTING fault current limiters based on the superconducting/normal (S/N) transition of high T_c superconductor (HTS) are expected to be introduced into electric power systems, so many studies have been carried out [1]-[7]. One of the problems for the actual application of the fault current limiter is that the magnitude of the resistance generated in the HTS immediately after the normal transition is too small to significantly limit a fault current. To increase the transient resistance, the application of external magnetic field to the HTS element may be effective [3]-[5]. However, the magnetic field may bring about not only the resistance rise but also the reduction of the critical current. Hence, it is important to understand the influence of the magnetic field on the critical current as well as the resistance.

In this paper, the critical current and the transient resistance of a Bi2223 bulk exposed to the external magnetic field were experimentally investigated. In the experiments, a dc magnetic field of up to about 80 mT was applied to the sample conductor in the longitudinal or transverse direction to the sample current. We supplied the sinusoidal overcurrent of 60 Hz to the sample for only a half cycle. Furthermore, taking into consideration both the critical current degradation and the increase in the resistance due to the magnetic field, we discuss the condition under which the application of the magnetic field has the advantage to use the Bi2223 bulk for the fault current limiter.

II. EXPERIMENTAL SET-UP AND PROCEDURE

The Bi2223 bulk sintered at 860°C for 20 hours under 300 kg/cm^2 pressure was adopted as a sample conductor [8]. Fig. 1 shows the XRD pattern for the Bi2223 bulk. X-ray was irradiated to the surface of the bulk, which was perpendicular to the pressing direction. As shown in Fig. 1, the bulk has a highly grain-aligned microstructure.

Fig. 2 illustrates the shape of the sample. The length and cross-sectional area of the sample are 105 mm and 2.25 mm×1.35 mm, respectively. Copper plates were soldered at both ends of the sample as the electrodes. To measure the voltage generated in the sample, the voltage taps were attached in the middle part of the sample at an interval of 54.9 mm where the external magnetic field was applied. The critical current without magnetic field I_{C0} was measured to be 120 A (defined by the criterion of 0.1 mV/cm). This value corresponds to the current density of 3 950 A/cm^2.

We measured the critical current and transient resistance of the sample conductor exposed to a dc external field. We applied the dc field to the sample in the longitudinal or transverse direction to the sample current. Fig. 3 (a) and (b) indicate the experimental set-ups for applying the longitudinal and transverse magnetic field, respectively. To apply the longitudinal magnetic field, the sample was arranged along the center axis of the magnet coil. In the case of the transverse field application, the sample was inserted into the air gap of the iron core with magnetizing winding. We applied the longitudinal flux density of 0 to 85.5 mT. For the transverse flux density, we adjusted within the range of 0 to 79.2 mT.

We suddenly supplied ac (60 Hz) overcurrent having the peak value of 189 A that was 158% of I_{C0} for only half cycle.

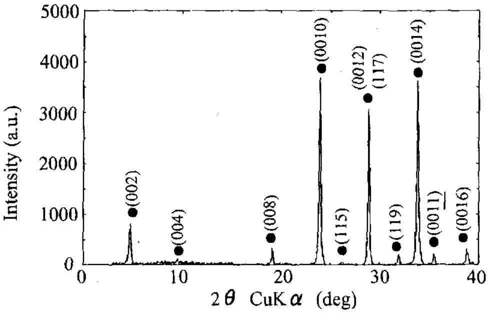

Fig. 1. XRD pattern for the sinter-forged sample.

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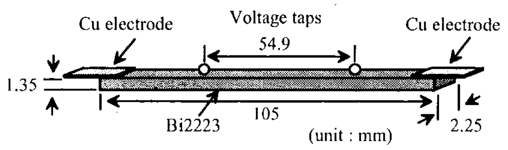
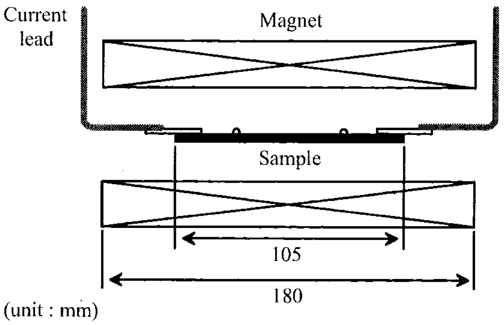
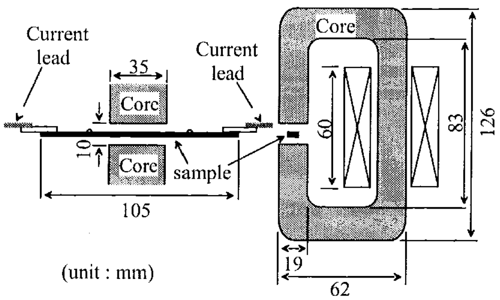


Fig. 2. Configuration of Bi2223 sample conductor.



(a) Longitudinal magnetic field



(b) Transverse magnetic field

Fig. 3. Experimental set-up for applying external magnetic field.

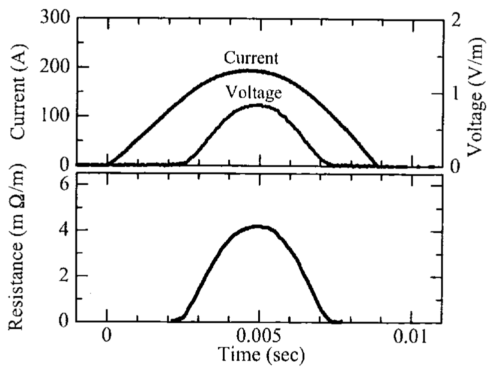


Fig. 4. Measured waveforms of current, voltage and resistance. (no magnetic field)

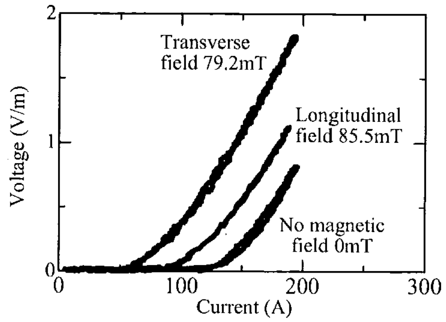


Fig. 5. Voltage-current characteristics.

III. MEASURED CURRENT, VOLTAGE AND RESISTANCE

Fig. 4 shows the waveforms of current, voltage and resistance measured under the condition of no magnetic field. We obtained the resistance by dividing the instantaneous value of the voltage by that of the current. The voltage and resistance in this figure were indicated in the magnitude per unit length of the sample.

The resistance is zero immediately after the beginning of current supplying, since the sample was superconducting. When the transport current reached the critical current of 120 A, the sample began to exhibit resistance. At the current peak, the resistance is also maximized. After that, the resistance decreases with the sample current and the sample recovers to the superconducting state with no resistance when the sample current is lower than the critical current.

Fig. 5 shows the voltage-current characteristics obtained by the waveforms of current and voltage in Fig. 4. This figure also indicates the results measured under the conditions that the longitudinal magnetic flux density of 85.5 mT and the transverse one of 79.2 mT were applied. It is found that the critical current, which is the current level at the beginning to generate the voltage, decreases by application of the magnetic field. The critical current degradation by the transverse field is greater than that by the longitudinal one because of the magnetic anisotropy of the sample conductor.

By application of the magnetic field, the voltage for the same current level goes up. This means that the resistance generated in the sample rises by the magnetic field. The increase in the voltage or resistance due to the transverse field is also larger than that of the longitudinal one.

IV. CRITICAL CURRENT DEGRADATION DUE TO MAGNETIC FIELD

Fig. 6 indicates the dependence of the critical current on the flux density which is externally applied. In the case of the longitudinal magnetic field, the critical current linearly declines at a rate of 0.55 A/mT. The application of transverse magnetic field causes a more drastic degradation of critical current than that of the longitudinal one. For example, the critical current is reduced to 76 A by the longitudinal magnetic flux density of 80 mT. On the other hand, the transverse flux density of 80 mT decreases the critical current to 51 A. These values correspond to 66% and 43% of I_{C0}.

V. RESISTANCE RISE AFTER S/N TRANSITION

Fig. 7 shows the sample resistance per unit length as a function of the magnetic flux density for some different instantaneous values of the sample current i. The resistance rises not only with the current but also linearly with the magnetic field.

The increase in resistance for the transverse field is greater than that for longitudinal one. For example, the

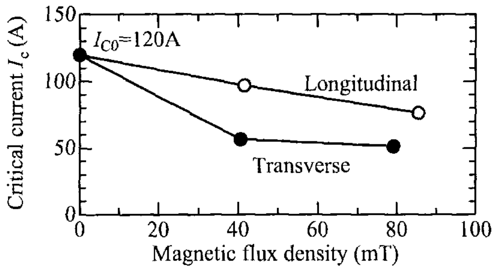


Fig. 6. Dependence of critical current on magnetic flux density.

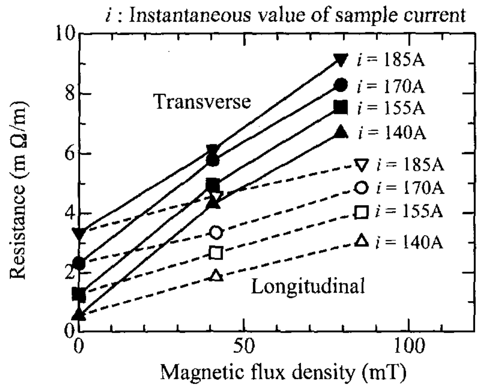


Fig. 7. Resistance as a function of magnetic flux density.

increments of resistance caused by the magnetic flux density of 80 mT are 2.5 mΩ/m and 6.0 mΩ/m for the longitudinal and transverse magnetic field, respectively. These values are independent of the magnitude of the current.

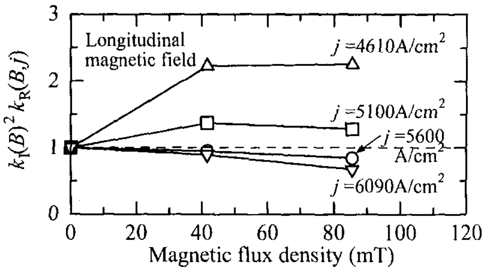
VI. RISE OF GROSS RESISTANCE DUE TO APPLIED MAGNETIC FIELD

Since the resistance increase due to the magnetic field is brought about in compensation for the degradation of the critical current, we may get no merit due to the application of the external magnetic field if the effect of the increase in the resistance is not sufficiently higher than that of the decrease in the critical current. To clarify the effective condition of application of magnetic field, we define the decreasing rate of critical current k_I and the increasing rate of resistance k_R as follows.

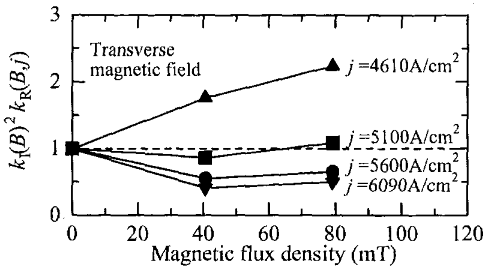
$$k_I(B) = \frac{I_C(B)}{I_{C0}} \quad (< 1) \tag{1}$$

$$k_R(B,j) = \frac{R(B,j)}{R_0(j)} \quad (> 1) \tag{2}$$

where $I_C(B)$ is the critical current of the sample exposed to the flux density B, $R(B,j)$ is the resistance of the sample applied flux density B at current density j, $R_0(j)$ is the resistance under the condition of no magnetic field at current density j. The resistance of the sample grows to $R(B,j) = k_R(B,j)R_0(j)$ by the magnetic field. On the other hand, the critical current becomes $I_c(B) = k_I(B)I_{C0}$. To keep the critical current in I_{C0}, the cross section of the sample must be $1/k_I(B)$ times as large as the original one. If the volume of the sample does not change, the sample length becomes $k_I(B)$ times as long as the original one. In this case, the resistance $R'(B,j)$ is written as follows.



(a) Longitudinal magnetic field



(b) Transverse magnetic field

Fig. 8. Influence of magnetic flux density on $k_I(B)^2k_R(B,j)$.

$$\begin{aligned} R'(B,j) &= \frac{k_I(B)}{1/k_I(B)} k_R(B,j)R_0(j) \\ &= k_I(B)^2 k_R(B,j)R_0(j) \end{aligned} \tag{3}$$

The value of $k_I(B)^2k_R(B,j)$ corresponds to the increasing rate of the gross resistance due to the magnetic field application under the condition that the critical current I_{C0} is maintained without altering the element volume. If $k_I(B)^2k_R(B,j) > 1$, we can increase the resistance by applying the magnetic field. In the case of $k_I(B)^2k_R(B,j) \leq 1$, the resistance reduces by the magnetic field.

Fig. 8 shows the magnitude of $k_I(B)^2k_R(B,j)$ as a function of the external magnetic flux density. Fig. 8 (a) and (b) correspond to the conditions of the longitudinal and transverse magnetic field, respectively. In the case of j=4610 A/cm^2 (i=140 A), $k_I(B)^2k_R(B,j)$ is greater than unity, i.e., the larger resistance can be obtained by the applying the magnetic field than $R_0(j)$ under the same critical current and the same volume conditions. The magnitude of $k_I(B)^2k_R(B,j)$ decreases with an increase in current density j. For $j \geq 5600$ A/cm^2 (i=170 A), $k_I(B)^2k_R(B,j)$ is lower than unity. Hence, there is no advantage to apply the magnetic field in such case.

VII. REQUIRED VOLUME OF HTS ELEMENT

From the discussions in the preceding chapter, it is found that we can get the effect of the applied magnetic field for the resistance rise only for the relatively small current density. On the other hand, the large resistance may be obtained by carrying at high current density without the application of the magnetic field, where the critical current degradation does not occur. In this section, we discuss whether we should use the HTS element at high current density without the magnetic field or at low current density with the magnetic field from the viewpoint of the required volume of the HTS element having certain critical current and resistance. We now consider the condition that the current i_1 (current density j_1) flows in the HTS element having the shape shown in Fig. 2 under B=0 as a basis and define the element volume in this case as 1 pu. The critical current and resistance of this element are I_{C0} and $R_0(j_1)$, respectively. To realize the element resistance $R_0(j_1)$ and total element current i_1 at the current density j_2 ($j_2 < j_1$) and $B = 0$, the cross section of the element must be enlarged by a factor j_1/j_2 and the length of the element is simultaneously increased by a factor $(R_0(j_1)/R_0(j_2)) \cdot (j_1/j_2)$. Then, the element volume V_0 is given as follows.

$$V_0 = \frac{R_0(j_1)}{R_0(j_2)}\left(\frac{j_1}{j_2}\right)^2 \tag{4}$$

In this case, the critical current is j_1/j_2 times as high as I_{C0}. We can obtain the same critical current as I_{C0} by applying the magnetic field B' satisfying the condition as follows.

$$\frac{j_1}{j_2}k_{\rm I}(B') = 1 \tag{5}$$

Since the resistance is $k_{\rm R}(B', j_2)$ times as large as $R_0(j_1)$ by the application of magnetic field B', the element length must be reduced by a factor $1/k_{\rm R}(B', j_2)$ to get the resistance $R_0(j_1)$. Considering $j_2/j_1 = k_{\rm I}(B')$, we can express the required volume V of the element as

$$V = \frac{V_0}{k_{\rm R}(B', j_2)} = \frac{R_0(j_1)/R_0(j_2)}{k_{\rm I}(B')^2 k_{\rm R}(B', j_2)}. \tag{6}$$

If $V < 1$, we can reduce the volume of HTS element by the application of the external magnetic field.

Fig. 9 shows V calculated using (6) as a function of the current density j_2 for j_1=6090 A/cm^2, where the critical current is 120 A, the resistance is 3.35 mΩ/m at the current 185 A. The magnitude of this current density j_1 corresponds to i_1 of 185 A. The values of B' and $k_{\rm R}(B', j)$ were derived using linear interpolation in Fig. 6 and Fig. 7, respectively. As seen from this figure, V is beyond unity for all conditions, i.e., there are no conditions that the required volume of the element can decrease by the application of magnetic field for the sample adopted in this paper. If the HTS element having the property that the flux flow resistance (dv/di) considerably increase by the magnetic field application is used, however, $k_{\rm I}(B')^2 k_{\rm R}(B', j_2)$ may be larger than $R_0(j_1)/R_0(j_2)$, i.e., V may lessen.

In the discussion above, it is assumed that the external magnetic field is constantly applied to the HTS element. We can get the effects of the application of the magnetic field by using the techniques which require application of an external magnetic field to the HTS element only during the current limiting operation as shown in Flux-Lock type fault current limiter [3] and magnetic shield type fault current limiter with active control coil [4].

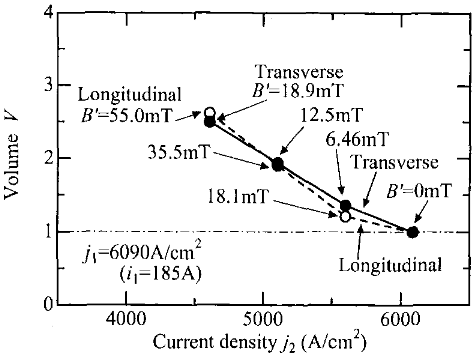


Fig. 9. Required volume V of element as a function of j_2.

VIII. CONCLUSIONS

The critical current degradation and the resistance rise were measured in Bi2223 bulk exposed to a dc magnetic field. It was found that we can have the advantage in the gross resistance rise by the magnetic field application using the bulk at the relatively small current density under the same critical current and bulk volume conditions. Furthermore, it was discussed whether the volume of the bulk having the same critical current and gross resistance can be reduced by the magnetic field application or not. As a result, it became clear that a larger amount of bulk was required in the case of applying the magnetic field than that of no magnetic field as long as the adopted Bi2223 bulk was used.

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