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Investigation of the flux flow–inhibiting effect of a hole-opened superconducting bulk magnet

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Abstract

A hole-opened bulk material has been proposed to supply magnetic flux into the large-size and high-performance bulk efficiently because superconductivity is intentionally lowered in the portion with holes. We were anxious about the flux flow in a high applied field, while it was confirmed that the flux flow was suppressed in a high applied field at a low temperature. To examine the flux flow-inhibiting effect in detail, in this paper, the time response of flux density in four portions, between the holes, the inside of the inner holes, the side opposite the holes, and the center, was measured. Although small holes served as a channel and magnetic flux flew out through a channel just after applying a pulsed field, a channel closed for up to 0.2 seconds, flux flow was disturbed, and then the magnetic flux was trapped. As J_c increased with a decrease in temperature, a channel closed more quickly, and a trapped field was enhanced.

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Keywords: superconducting bulk magnet; small hole; pulsed field magnetization; flux flow

1. Introduction

A strong magnetic field generation by a $REBa_2Cu_3O_{7-x}$ superconducting bulk magnet and its industrial application have been intensively studied. A pulsed field magnetization (PFM), which is one of the major magnetization methods, has the advantages of time and cost; therefore, it is an important technique for industrial applications.

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However, there is a problem in that the strength of the trapped field is lower than that of a field-cooling method. To improve the trapped field, several advanced PFMs have been developed [1-3], and these are magnetizing methods in which several pulsed fields are applied with varying amplitudes of magnetic fields and cooled down temperatures based on the idea of controlling heat generation of the bulk during the magnetization. Fujishiro et al. [3] achieved a value in excess of 5 T. However, recent enhancement of the performance of bulk material and enlargement of the size tend to increase the amplitude of the applied field because the magnetic flux does not penetrate the bulk easily due to the strong magnetic shield. If a very strong magnetic field is applied to overcome the shield, a large amount of heat occurs, and accordingly, the trapped field is decreased.

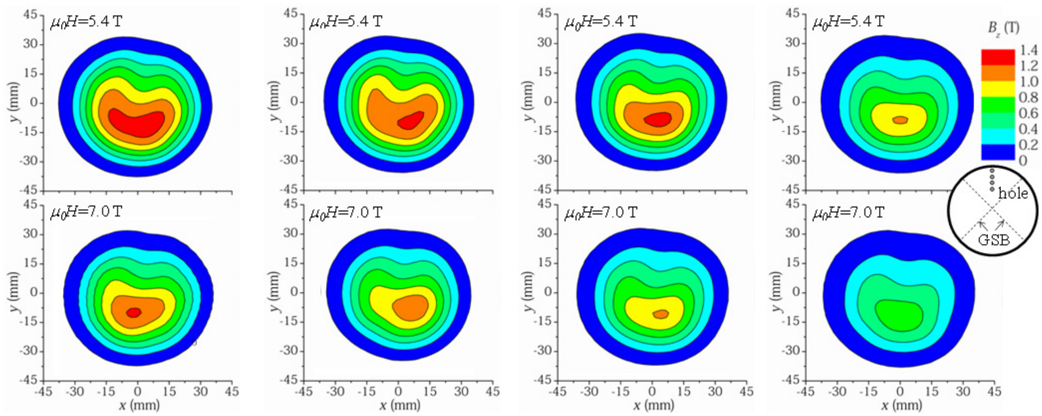
We have proposed a hole-opened bulk material, in which the holes play the role of an artificial magnetic flux path to supply it in the bulk-reducing heat generation [4]. When the basic experiment of applying a single pulsed field with various amplitudes was carried out at 20-50 K, magnetic flux penetrated the bulk in a low applied field. In a high applied field, a trapped field was decreased by flux flow at a high temperature, but the reduction in magnetic flux was slight at a low temperature. This paper measures the magnetic flux density near the hole on the bulk surface and investigates the inhibiting effect of the flux reduction.

2. Experimental

A hole-opened sample is made by drilling four holes of 2 mm diameter in a growth sector region (GSR) of a $GdBa_2Cu_3O_{7-x}$ bulk material of 60 mm diameter and 20 mm thickness. The bulk is cooled by a 2-stage-type GM refrigerator and the temperature is adjusted to 20-50 K with a thermo-controller. A pulsed field of $\mu_0 H$=3.1-7.0 T with a rising time of 10 ms is applied, and the magnetic flux density in four portions, between the holes, the inside of the inner holes, the side opposite the holes, and the center, is measured with a sampling rate of 100 μs by Hall sensors (BHT-921, F. W. BELL) during magnetization. Thereafter, the trapped field distribution at 4 mm above the bulk surface is measured by a Hall sensor (HGT-3030, Lake Shore Cryotronics, Inc.) with respect to elements along the pole axis B_z. The sensor is scanned with a pitch of 2 mm in *x* and *y* directions.

3. Results and discussion

Fig. 1 shows the magnetic field distributions after applying pulsed fields of 5.4 and 7.0 T at (a)20 K, (b)30 K, (c)40 K, and (d)50 K. In all figures, distortion by flux flow appears at the holed portion. When magnetic field distribution of 7.0 T of the applied field is compared with that of 5.4 T, the reduction of the trapped field is not significant at a low temperature, and distortion is minimal. However, the trapped field decreases greatly at a high temperature.



(a) 20 K (b) 30 K (c) 40 K (d) 50 K

Fig. 1. Trapped field distributions for the applied fields of 5.4 and 7.0 T at (a)20 K, (b)30 K, (c)40 K, and (d)50 K.

Fig. 2 shows the total magnetic flux, Φ, which is calculated from the magnetic field distribution of Fig. 1. For comparison, the results of a holeless $GdBa_2Cu_3O_{7-x}$ bulk of the same size are illustrated. For an applied field below 4.6 T, the Φ value of the hole-opened bulk is larger than that of the holeless bulk at all temperatures, which means that magnetic flux easily penetrates the small holes. Although the Φ values are reduced for an applied field above 5.4 T at 20 and 30 K and above 4.6 T at 40 and 50 K, the decrease of the hole-opened bulk is less than that of the holeless bulk at 20 and 30 K. This result is suggestive of a flux flow-inhibiting effect by the holes. On the other hand, both curves overlap mostly at 40 K, and the value of the hole-opened bulk decreases greatly at 50 K. This result implies that the above-mentioned effect is lost at a high temperature.

Fig. 3 shows time responses of the magnetic flux density of H1 (between holes), H2 (inside of the inner hole), H3 (opposite side), and H4 (center) for 0.3 seconds in $\mu_0 H$=6.2 T. The B_z of H1, H2, and H3 rises similarly just after applying a pulsed field. Thereafter, the B_z value of H3 is almost constant at 1 to 2 T in 0.15 seconds because magnetic flux is trapped, while the values of H1 and H2 decrease to zero for 0.1 seconds due to a still larger flux flow. For H4, the trapped flux decreases due to low J_c though much magnetic flux penetrates to a central portion, as the temperature is higher.

In the results shown in Fig. 3, there is a tendency for the values of H1 and H2 to increase gradually after decreasing to zero. Fig. 4 shows time responses of the magnetic flux density of H1 and H2 for 1.5 seconds in $\mu_0 H$ =5.4, 6.2, and 7.0 T. For $\mu_0 H$=5.4 T, the B_z of H1 and H2 decreases sharply to almost zero, followed by a rapid rise. Time until the value changes from decrease to increase is shorter, and the value is larger, as the temperature is lower. For $\mu_0 H$=6.2 T, the difference in B_z of H1 is large at each temperature. Although the difference in rise time is small at all temperatures in H2, that at 20 K is a little early. For $\mu_0 H$=7.0 T, the B_z value of H1 still decreases at all temperatures, and that at 50 K is quite small.

From these results, the B_z of H3 and H4 decreases due to a decrease in J_c caused by large heat generation after applying a pulsed field. As J_c is improved with a decrease in temperature, flux flow stops, and the B_z remains

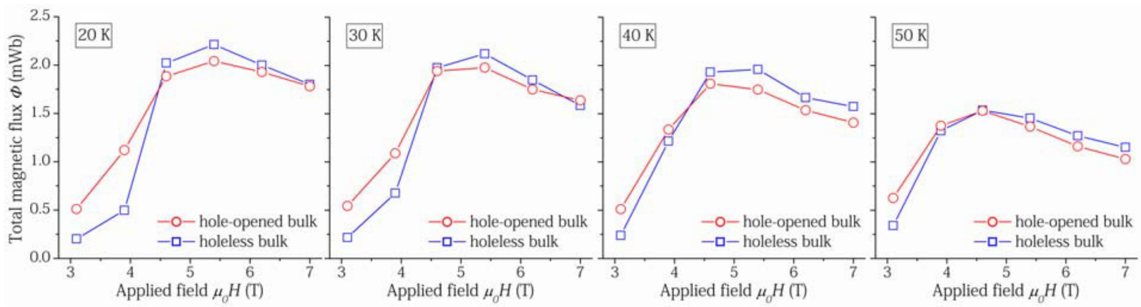


Fig. 2. Comparisons of total magnetic flux Φ between the hole-opened bulk (circle) and the holeless bulk (square) at 20, 30, 40, and 50 K.

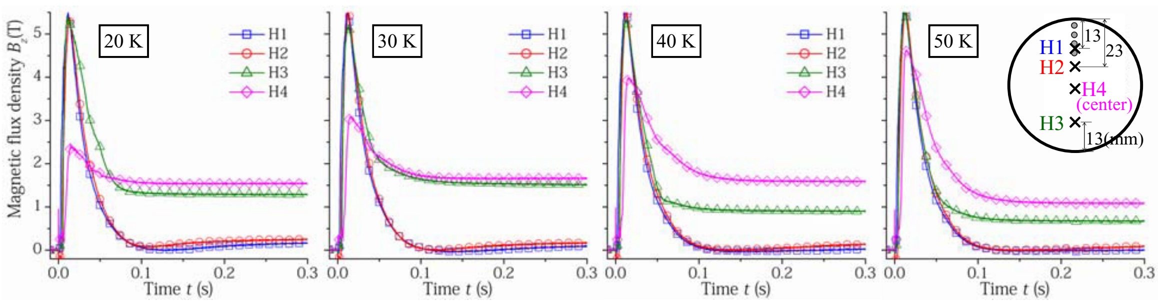
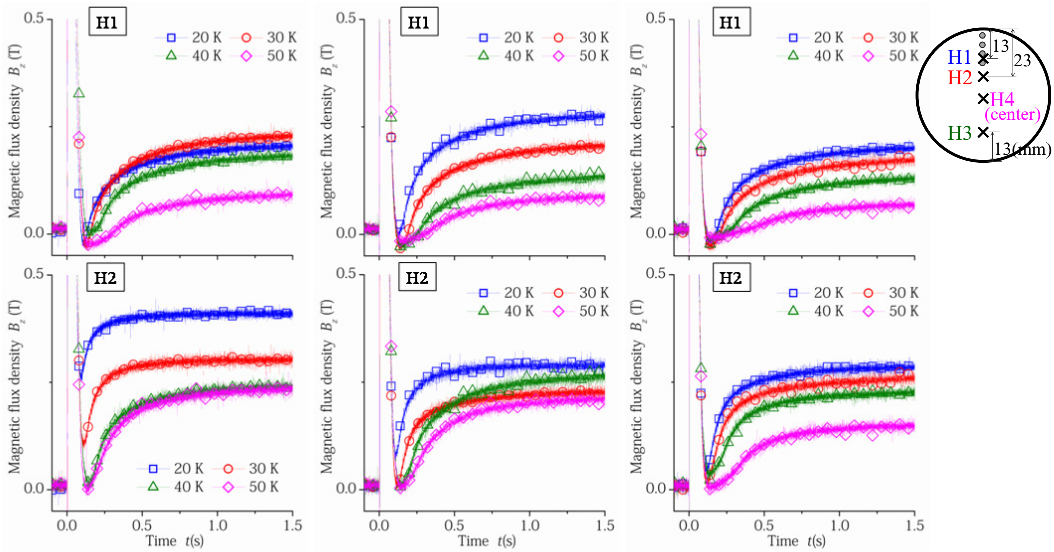


Fig. 3. Time responses of the magnetic flux density of H1 (between holes; symbol: square), H2 (inside of holes; symbol: circle), H3 (opposite side; symbol: triangle), and H4 (center; symbol: diamond) in $\mu_0 H$=6.2 T at 20, 30, 40, and 50 K.



(a) $\mu_0 H = 5.4$ T (b) $\mu_0 H = 6.2$ T (c) $\mu_0 H = 7.0$ T

Fig. 4. Time responses of magnetic flux density at a temperature of 20 K (symbol: square), 30 K (symbol: circle), 40 K (symbol: triangle), and 50 K (symbol: diamond) for (a) $\mu_0 H = 5.4$ T, (b) 6.2 T, and (c) 7.0 T.

practically constant. On the other hand, the B_z of H1 and H2 decreases sharply to almost zero, followed by a rapid rise. Although magnetic flux flows out from small holes due to large heat generation just after applying a pulsed field, J_c is improved due to a decrease in temperature, and consequently, magnetic flux that is going to flow out through the holes is trapped.

4. Conclusion

We have proposed a hole-opened bulk material to trap magnetic flux efficiently. When a basic experiment was carried out using a φ60 mm $GdBa_2Cu_3O_{7-x}$ bulk material with four φ2 mm holes, it was confirmed that the magnetic flux penetrated at a lower applied field, and moreover, the flux flow was suppressed in a high applied field at a low temperature. In this paper, the flux flow-inhibiting effect was investigated in detail by measuring the time response of magnetic flux density on the bulk surface during application of a pulsed field. The experimental results suggested that small holes served as a channel, and magnetic flux flew out through a channel just after applying a pulsed field. However, a channel closed for up to 0.2 seconds, flux flow was disturbed, and then the magnetic flux was trapped. In addition, as J_c increased with a decrease in temperature, a channel closed more quickly, and a trapped field was enhanced. To verify the consideration, a detailed temperature measurement will be carried out in the next study.

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