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Influence of Artificial Defects on Trapped Field Performance in a Superconducting Bulk Magnet

K Yokoyama[1], K Eranda[2], Y Zhao[2], A Katsuki[2], A Miura[2] and T Oka[3]

[1] Division of Mechanical and Electrical Engineering, Ashikaga Institute of Technology, 268-1 Omae-cho, Ashikaga, Tochigi 326-8558, Japan
[2] Department of Electrical and Electronic Engineering, Graduate School of Engineering, Ashikaga Institute of Technology, 268-1 Omae-cho, Ashikaga, Tochigi 326-8558, Japan
[3] Education Center for Engineering and Technology Faculty of Engineering. Niigata University, 2-8050, Ikarashi, Nishi-ku, Niigata 950-2181, Japan

E-mail: k-yokoyama@ashitech.ac.jp

Abstract. In this study, we attempt to improve the trapped magnetic field by pulsed-field magnetization using REBCO bulk with small holes processed artificially. In our previous study, a hole was opened in the growth sector region (GSR) in accordance with the idea that the performance of the growth sector boundary (GSB) was not reduced because the critical current density of the GSB was higher than that of the GSR. In the next study, a small hole was processed on the GSB to decrease the magnetic shield toward the magnetic flux that entered through the GSB. The experimental results suggested that placing a hole on the GSB was advantageous to trapped field performance as compared with placing a hole at the GSR. In this paper, three more holes were processed in the bulk with a single hole on the GSB, and trapped field performance was investigated. Although the performance was decreased overall in the bulk with four holes, we confirmed that the peak value of total magnetic flux shifted to the low applied magnetic field, although the maximum value was almost the same as that of the bulk with a single hole.

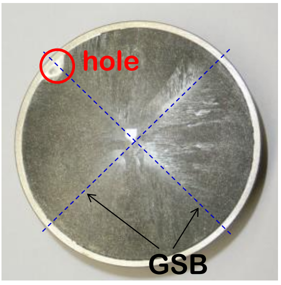
1. Introduction

We attempted to improve the magnetic field of REBCO bulk magnet by pulsed-field magnetization (PFM) and to develop an efficient magnetization method. PFM is a useful method for industrial applications because the bulk can be activated by a conventional copper coil and a condenser bank without an expensive superconducting magnet. However, there is a problem that a trapped field is small due to a decrease of J_c caused by large heat generation when a magnetic field is applied, because the magnetic flux penetrates by overcoming the magnetic shield. Then, several advanced PFM methods [1, 2], such as IMRA method [3, 4], were developed to improve the trapped field. In this method, the inhomogeneous characteristic of the bulk material was utilized. The magnetic flux was introduced from the low J_c part of the bulk at the first pulsed-field application; thereafter, that part was filled by applying low fields. In REBCO bulk superconductors, growth sector boundaries (GSBs) and growth sector regions (GSRs) are formed during the manufacturing process, and the J_c characteristic of the GSB is higher than that of the GSR because many RE211 particles, which are the pinning center, exist on the GSB. However, the quality of the bulk material has become uniform with advances in material fabrication techniques, and there is no difference in the J_c at both areas. Therefore, it becomes difficult to trap the high magnetic field by PFM due to the increase of the magnetic shield with the increase of J_c, although the trapped field activated by the field-cooling method is improved [5]. If a high magnetic field is applied to overcome the shield, a substantial amount of heat is generated, and, consequently, the trapped field is reduced. Therefore, it is necessary to supply the magnetic field to the bulk efficiently while restraining the generation of heat.

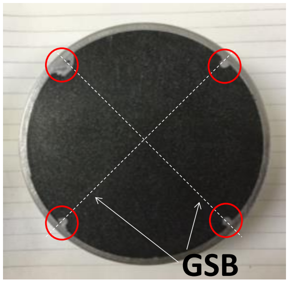
We have proposed artificially processing small holes in a part of the bulk material for the purpose of supplying the magnetic field to the bulk easily and estimated the magnetizing performance [6, 7]. A hole is not a superconductor; thus, it becomes easy for the magnetic flux to penetrate from the portion with the hole due to a decrease of the magnetic shield. In the first part of our study, a hole was opened at the GSR based on the idea that the magnetic flux was introduced from the GSR with the low J_c characteristic, and it was trapped on a GSB with a high J_c [6]. In the next step, the hole was processed on the GSB based on the concept that the magnetic flux penetrated from the GSB as well as the GSR [7]. When comparing the magnetizing performance of both bulks, it was confirmed that the magnetic flux could penetrate in a lower applied field in the case in which the hole existed on the GSB, although the amplitude of the trapped field was almost the same. Although the hole with a 2-mm diameter was drilled at one of four places on the GSB in our previous study, a hole of the same size was processed at all places on the GSB completely, as an extreme example in this paper, and the magnetizing performance was investigated by applying a single pulsed field while varying the amplitude and the temperature.

2. Experimental

The highly *c*-axis-oriented GdBCO bulk material with dimensions of 60 mm in diameter and 20 mm thick consisted of 75.0 wt.% Gd123, 24.5 wt.% Gd211, and 0.5 wt.% Pt powder (Nippon Steel & Sumitomo Metal Corporation), and it was reinforced mechanically with a 2-mm thick stainless steel ring (SUS316L). Figure 1(a) shows the bulk sample with a single hole 2 mm in diameter at the rim of the sample on the GSB that was used in our previous study. In this paper, each single hole was processed in three other places of the GSB in the same sample and filled with solder, as shown in Figure 1(b). Hereinafter, they are referred to as “single-hole bulk” and “four-hole bulk,” respectively. The sample was installed to the second stage of a two-stage GM refrigerator using a sample holder. The refrigerator had an ultimate temperature of 13 K and a cooling capacity of 5 W at 20 K. Four Hall sensors (BHT-921, F.W.BELL) were adhered on the sample surface, as shown in the inset of Figure 2, with Kapton tapes to investigate the behaviour of the magnetic flux during magnetization. After a vacuum vessel was attached and evacuated by a diffusion pump, the bulk was cooled to 20, 30, 40, and 50 K using a temperature controller. A single pulsed field was applied while varying the amplitudes of 3.1, 3.9, 4.6, 5.4, 6.2, and 7.0 T for each temperature, where the rising time of the pulse was 10 ms. The magnetic flux density was monitored with a sampling rate of 100 μs during magnetization, and the trapped field distribution at 7 mm above the bulk surface was measured by scanning the three-dimensional Hall sensor (BH-703, F.B.BELL) with a 2-mm pitch after magnetization. Moreover, the total magnetic flux was calculated using the distribution data.



(a) single-hole bulk



(b) four-hole bulk

Figure 1. Photographs of bulk superconductors with a single hole and four holes

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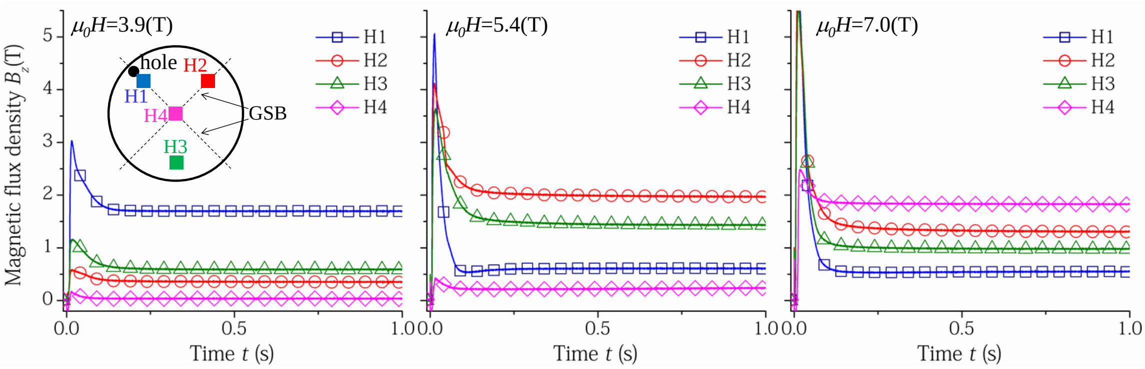
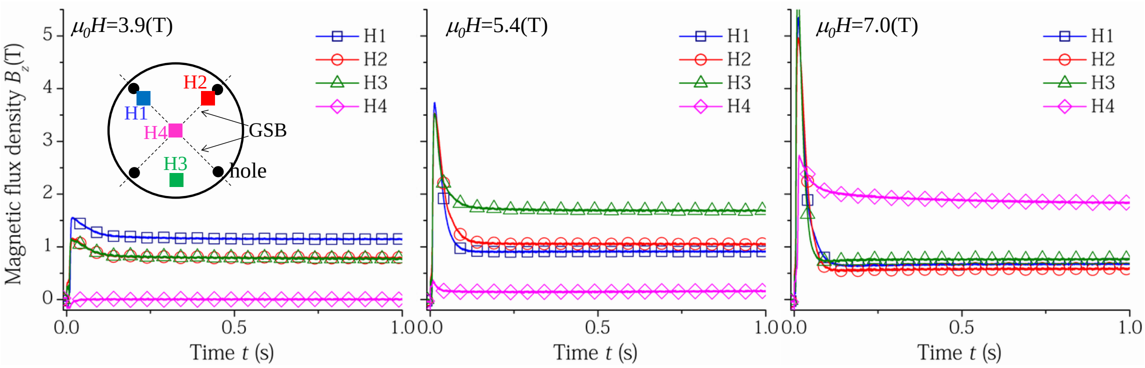
3. Results and discussion

3.1. Time responses of magnetic flux on the bulk surface

Figure 2 shows the time responses of the magnetic flux density on the bulk surface in (a) the single-hole bulk and (b) the four-hole bulk at 20 K. For the applied field $\mu_0 H$ = 3.9 T, only the value of H1 became large, indicating that the magnetic flux penetrated preferentially from the portion with the hole in the single-hole bulk. On the other hand, in the four-hole bulk, the value of H2 increased as compared with that of the single-hole bulk, indicating that the magnetic flux entered from the portion where other holes existed. There was no difference in the values of H3 and H4 in both bulks. For $\mu_0 H$ = 5.4 T, the value of H2 of the four-hole bulk decreased as compared with that of the single-hole bulk. It was considered that the magnetic flux was trapped on the GSB in the single-hole bulk, while the pinning center decreased by processing small holes in the four-hole bulk. The result of $\mu_0 H$ = 7.0 T had the same tendency as that of $\mu_0 H$ = 5.4 T.



(a) single-hole bulk

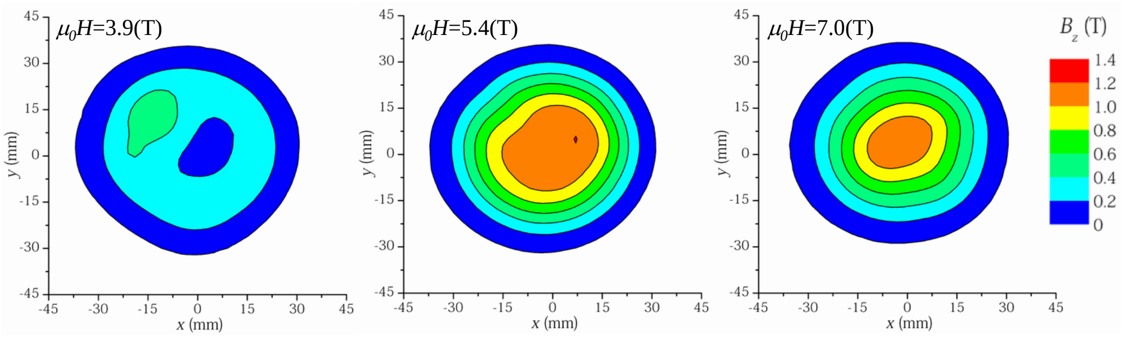


(b) four-hole bulk

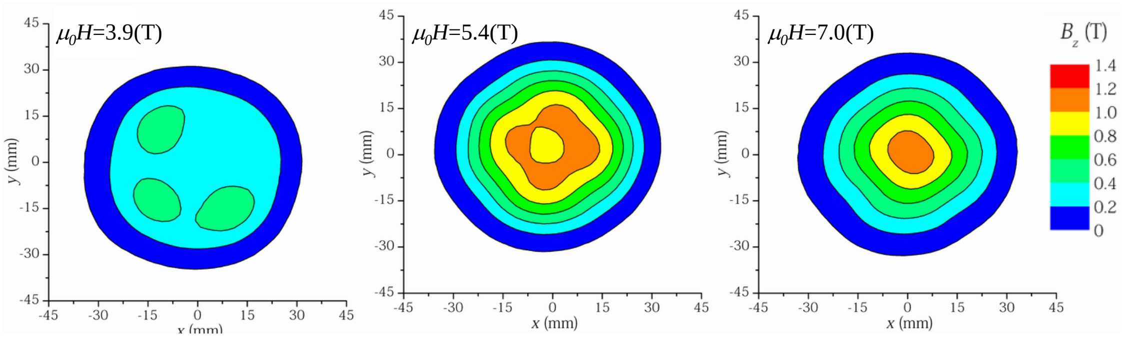
Figure 2. Time responses of magnetic flux density on the bulk surface at 20 K.

3.2. Trapped field distributions

Figure 3 shows trapped field distributions in (a) the single-hole bulk and (b) the four-hole bulk at 20 K. For $\mu_0 H$ = 3.9 T, small peaks existed in the portions with holes in both bulks, indicating that the magnetic flux penetrated from that portion, and they were trapped there. In the single-hole bulk, the distribution of $\mu_0 H$ = 5.4 T was mostly concentric; moreover, that of $\mu_0 H$ = 7.0 T changed to a square shape, indicating that the magnetic flux was trapped on the GSB. However, there was a small distortion in the portion with the hole (H1), namely, the influence of the small hole was somewhat apparent. In the four-hole bulk, the distributions of $\mu_0 H$ = 5.4 and 7.0 T were diamond shape, indicating that the magnetic flux on GSBs decreased conspicuously near the small hole.



(a) single-hole bulk



(b) four-hole bulk

Figure 3. Trapped field distributions at 20 K.

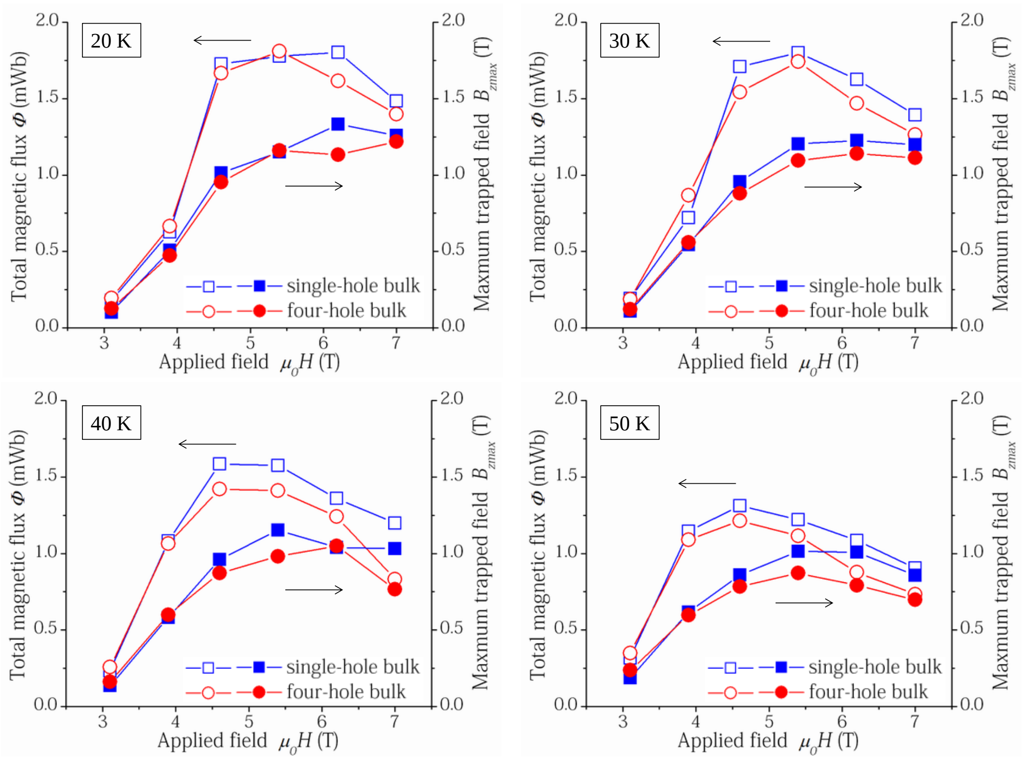


Figure 4. Comparisons of total magnetic flux (open symbols, left axis) and maximum trapped flux density (solid symbols, right axis) as a function of applied field between the single-hole bulk (blue and square symbols) and the four-hole bulk (red and circle symbols) at 20-50 K.

3.3. Total magnetic flux and maximum trapped field density

Figure 4 compares the total magnetic flux, Φ (open symbols, left axis), and the maximum trapped flux density, B_{zmax} (solid symbols, right axis), as functions of the applied field of the single-hole bulk (blue and square symbols) and the four-hole bulk (red and circle symbols) at 20-50 K, where the B_{zmax} was the maximum value in the trapped field distribution, as shown in Figure 3. Although there was almost no difference between the bulks in low applied fields, both the Φ and the B_{zmax} of the single-hole bulk were larger than those of the four-hole bulk, suggesting that four holes are too much because the flux flow was increased by decreasing the number of pinning centers. However, we can see that the peak value of the total magnetic flux shifted to the low applied magnetic field, although the maximum value did not change at 20 K. We will consider the number and the position of small holes aiming at a magnetizing method that can trap a high magnetic field with a low applied field.

4. Conclusions

We attempt to improve the trapped magnetic field by PFM using a REBCO bulk with small holes processed artificially. Since the trapped field performance when the hole was opened on the GSB was superior to the performance when the hole was existed at the GSR in our previous experiments, in this paper, we increased the number of holes opened on the GSB and estimated the trapped field property. As determined from the time responses of flux density during magnetization, the magnetic flux penetrated easily for low applied fields in the four-hole bulk, while the trapped field was decreased for high applied fields. A similar tendency was also seen in the magnetic field distribution results, and the magnetic flux was not trapped on the GSB, due to the flux flow in high applied fields. When comparing the total magnetic flux and the maximum flux density between the singe-hole bulk and the four-hole bulk, both values of the single-hole bulk were higher than those of the four-hole bulk in high applied fields. Surplus holes had a harmful influence on the trapped field characteristic; therefore, it is necessary to investigate the number and position of small holes most suited to trapping a high magnetic field by low applied field.

Acknowledgments

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