Local Measurements of the Magnetization Process of Bulk Superconductors induced by a Pulsed Magnetic Field

Hiroshi Ikuta¹, Masahiro Tokuyama¹, Yousuke Yanagi²

¹ Department of Crystalline Materials Science, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8603
² IMRA Material R&D Co., Ltd., Hachiken-cho 5-50, Kariya 448-0021, Japan
E-mail: ikuta@nuap.nagoya-u.ac.jp

Abstract. We investigated the magnetization process of a Sm-Ba-Cu-O bulk superconductor induced by a pulsed magnetic field at 40 K by measuring the local magnetic flux density using several small Hall sensors that were mounted on the sample surface. We observed that the penetration of flux lines along the growth sector boundary (GSB) is more difficult than along the growth sector (GS) region. This can be attributed to the difference in the pinning strength of the two regions. When a relatively large magnetic pulse was applied, we found that the flux lines that penetrated along a weak region can reach the center of the sample first, and magnetize then the GSB region from inside. The reason of this interesting reversal in the magnetizing order can be attributed to the strong pinning effect of Sm-Ba-Cu-O.

1. Introduction
Melt-processed bulk RE-Ba-Cu-O (RE = rare earth) high temperature superconductors are capable of trapping a large amount of magnetic flux [1], which underlies their outstanding potential for permanent magnet type applications. For such applications, it is necessary to magnetize the superconductor. The field-cooling (FC) method is usually used for magnetizing a bulk superconductor, which however, requires a large superconducting coil. From application perspective, pulse field magnetization (PFM) is more feasible because a large current has to be fed only for a very short time and the magnetizing coil can be made small [2; 3]. PFM is, however, less effective than the FC method because of the heat that is generated by the dissipative motion of flux lines [2–6]. Most significantly, the difference in the trapped field with the FC method tends to escalate when the ability of trapping flux lines increases by improving the material characteristic or by decreasing the temperature. Therefore, many efforts have been devoted to overcome this problem and to increase the trapped field by the PFM method [7–11]. Fujishiro et al have achieved a record high trapped field of 5.2 T by PFM for a 46 mm diameter Gd-Ba-Cu-O bulk superconductor that was cooled by a cryogenic refrigerator, which is however still lower than the trapped field achieved by FC magnetization [11].

It is important to elucidate the dynamics of the flux lines during PFM for a further progress of this method. Our group has therefore studied the PFM process by employing two local probe methods based on small Hall sensors and pickup coils [12–15]. In particular, the small Hall sensor method has elucidated that the penetration of the flux lines into the sample is anisotropic [14; 15].
A seeded melt-grown bulk superconductor exhibits faceted growth morphology and the boundary between two growth sectors forms a characteristic facet line. We observed that the penetration of flux lines along this growth sector boundary (GSB) is more difficult than the growth sector (GS) region. This result can be attributed to the difference in the pinning strength of the two regions and shows that the microstructure strongly influences the magnetization process by PFM.

In the present work, we studied the PFM process of a Sm-Ba-Cu-O bulk superconductor at 40 K. The critical current density of a Sm-based bulk superconductor is in general larger than Gd-Ba-Cu-O, which we had studied in a previous work [15]. In fact, the sample of the present study showed a larger trapped field when magnetized by the FC method at 77 K than the Gd-Ba-Cu-O sample of the preceding work. We studied the difference in the magnetization process by PFM in the GS and GSB regions, and found an interesting reversal phenomenon of the magnetizing order that can be attributed to the strong pinning effect of Sm-Ba-Cu-O.

2. Experimental

The sample was prepared from commercially available mixed powders that consist of SmBa$_2$Cu$_3$O$_y$ (Sm123) and Sm$_2$BaCuO$_5$ (Sm211) phase powders mixed with a molar ratio of Sm123:Sm211 = 2:1, 0.5 wt% Pt and 15 wt% Ag$_2$O powders. The melt-process was performed in a 1%O$_2$/99% Ar atmosphere. The sample was oxygenated by slow cooling from 400°C to 300°C in 350 h under flowing pure oxygen gas. The finished sample was 36 mm in diameter.

For the PFM experiments, the sample was mounted on the cold head of a Gifford-McMahon refrigerator and was cooled to 40 K. Magnetic pulses with various magnitudes were applied by discharging currents from a condenser bank. The waveform of the magnetic pulse was similar to that of our previous studies [9; 10; 13; 14] but the rise-time was approximately 14 ms. The current flowing through a shunt resistor was monitored by an oscilloscope, and the external field was calculated by multiplying the current by the coil constant. The coil constant was determined by measuring the magnetic flux density at the center of the magnetizing coil in the absence of a sample. We define the applied field $\mu_0H_a$ as the peak value of the external field.

We used six small Hall sensors (Asahi Kasei Electronics, HG-106C) to measure the local magnetization, each of which is 1.5 mm×2.5 mm in size. One of the sensors was put at the center of the sample surface (position P1), and the other sensors were aligned with an interval of 3.6 mm (positions P2-P6 from inside out). Note that the interval is smaller than our preceding study on Gd-Ba-Cu-O [15], giving a better spatial resolution. Position P6 corresponds almost to the periphery of the sample. Measurements along the GSB and GS regions could not be performed simultaneously, and the two data sets were taken in a separate experiment.

3. Results and Discussion

Figure 1(a) shows the trapped field distribution at liquid nitrogen temperatures measured by scanning a Hall sensor about 0.5 mm above the sample surface after FC magnetization. The trapped field shows a non-circular distribution, which can be correlated with the presence of GSBs and indicates that the microstructural difference between the growth sectors and the boundaries brings about an inhomogeneity in the trapped field distribution. Measurements along the GSB and GS regions were made by aligning the Hall sensors along the thick lines of the schematic drawing shown in Fig. 1(b).

Figure 2(a) shows the time dependence of the local magnetic flux density of the GS region with an applied field of $\mu_0H_a=3.3$ T. Because flux lines penetrate from the periphery of the sample, the local magnetic flux density started to increase first at the most outside position, position P6. The increase in the magnetic flux density at position P5 follows, which was first gradual, but then exhibited a rather steep increase. Similarly, the magnetic flux density at position P4 showed a sudden increase as well. However, only a small amount of magnetic flux could penetrate beyond position P4, and the magnetic flux density at positions P1-P3 was small.
Figure 1. (a) The trapped field distribution measured after field-cooling the Sm-Ba-Cu-O sample used for the PFM experiments to liquid nitrogen temperatures. The GSBs are running parallel to the horizontal and vertical axes of this figure. (b) A schematic drawing indicating where the Hall sensors were mounted on the sample.

for the entire duration of the magnetic pulse. During the field descending branch, the magnetic flux density at positions P4 and P5 decreased much slower than position P6, indicating that the flux lines were strongly pinned.

With an only small increase in the pulse intensity, however, the flux lines reached the central region of the sample. Figure 2(b) shows the time evolution of the local magnetic flux density for $\mu_0H_a=3.4$ T. As can be seen, the local magnetic flux density at the center of the sample, position P1, showed a quite abrupt increase, and the peak value of the magnetic flux density was almost as large as that of position P6. In fact, the maximum flux density of the magnetic field penetrated to the center of the sample was larger than that of positions P2-P5. The reason of this peculiar behavior will be discussed below. For a magnetic pulse of $\mu_0H_a=5.1$ T, the local magnetic flux density showed a rather weak position dependence as shown in Fig. 2(c). The start of the increase of magnetic flux density depended on the position, but once the flux lines had penetrated to the center of the sample, the local magnetic flux density changed almost identically thereafter. This means that the field gradient is very small, and the flux lines can move very easily.

Figure 3 shows the results of a similar experiment along the growth sector boundary. When

Figure 2. The time dependence of the local magnetic flux density measured by the small Hall sensors mounted along the growth sector region during pulse field magnetization; (a) $\mu_0H_a=3.3$ T, (b) $\mu_0H_a=3.4$ T, and (c) $\mu_0H_a=5.1$ T.
the magnetic pulse was rather small, $\mu_0 H_a=3.3$ T, the change in the local magnetic flux density was similar to the GS region as shown in Fig. 3(a). However, the penetration into the sample along this direction is obviously more difficult than the GS region, because the magnetic flux density of positions P4 and P5 were systematically smaller than the corresponding data of the GS region (Fig. 2(a)).

When the pulse intensity was increased to $\mu_0 H_a=3.4$ T, the local magnetic flux density showed a drastically different behavior as shown in Fig. 3(b). The magnetic flux density increased first at position P6, and then at position P5. The amount of flux lines that reached position P4 was very small as shown in the figure. In fact, the data of positions P4, P5, and P6 are very similar to the corresponding data of Fig. 3(a), which is quite natural because the intensity of the magnetic pulse differs only a little. Surprisingly, however, we observed a large increase in the magnetic flux density at position P1. The magnetic flux density at positions P2 and P3 also exceeded that of position P4, and decreased in this order. The reversal in the local magnetic flux density along the GSB region was more evident when the pulse intensity was further increased. As shown in Fig. 3(c), the local magnetic flux density of positions P1-P4 tended to be larger than that of position P5.

These observations suggest that it is difficult for the flux lines to penetrate the sample along the GSB region beyond position P4, but they can reach the center from a different direction, and magnetize the GSB region from inside. In fact, as the data of Fig. 2 show, the flux lines can more easily penetrate along the GS region. We note however, that the peak of the magnetic flux density at position P1 of Fig. 2(b) was larger than that of positions P2-P5 as mentioned above. This means that it was not exactly the same GS region that we had measured along which the flux lines reached the center of the sample first. Probably one of the other three GS regions is the weakest region, along which the flux lines can penetrate the sample most easily.

Figure 4 shows the time evolution of the magnetic flux density at the GS region, which corresponds to the data shown in Fig. 2. Field distributions with a time interval of 1 ms are plotted, and the left-half of each figure is for the external field increasing branch, while the right-half for the decreasing branch. The evolution of the magnetic flux density inside the sample was similar to our previous studies when the pulse intensity was $\mu_0 H_a=3.3$ T as shown in Fig. 4(a) [12; 13; 15]. During the field ascending branch, the flux gradient was very steep and only a small amount of magnetic flux penetrated to the center of the sample. This steep flux gradient can be understood by noting that a viscous force is exerted on moving flux lines in addition to the pinning force [3; 12]. At the early stage of the field descending branch, there was a flux flow toward the center of the sample, as was also observed in our earlier studies [12; 13; 15]. This is because the viscous force, which is proportional to the velocity of the flux line, decreases and
Figure 4. Evolution of the local magnetic flux density at the GS region during pulse field magnetization: (a) $\mu_0 H_a = 3.3$ T, (b) $\mu_0 H_a = 3.4$ T, and (c) $\mu_0 H_a = 5.1$ T. The field distribution is plotted with a time interval of 1 ms, and the left-half of each figure is for the external field increasing branch, while the right-half for the decreasing branch. The flux distribution is shown in green when a flux flow toward the center of the sample was observed. The thick blue line on the right-half shows the remnant magnetic flux density measured after the duration of the magnetic pulse.

the pinning force alone cannot sustain the steep flux gradient. However, the amount of flux lines that penetrated the center of the sample was still small, and the remnant magnetic field plotted by the thick blue line on the right-half of the figure, exhibited a peak at position P5.

When the external field was increased to $\mu_0 H_a = 3.4$ T, the flux lines suddenly started to penetrate into the sample. This can be attributed to a local temperature increase due to the heat generated by the flux motion in the presence of resistive forces. Because a large amount of flux lines reached the center, the remnant field was large, the peak of which located at the center of the sample. Figure 4(c) shows the results when the intensity of the magnetic pulse was further increased to $\mu_0 H_a = 5.1$ T. With this strong magnetic pulse, the field gradient during the PFM process was very small and the local magnetic flux density showed only a weak position dependence except for the early stage of the field ascending branch. More interestingly, the remnant magnetic flux density was negative in this case. We think that this can be explained as follows: a significant amount of heat was generated by the flux motion along the GS region that degraded the superconducting properties in this region, and practically no flux lines could be pinned. It is as if there were no superconductor in this region. The GSB region, on the other hand, could trap flux lines even with this strength of magnetic pulse as we will see below. The magnetic force lines of the pinned vortices circulate around the superconductor, but because the GS region can not shield the magnetic field until it is sufficiently cooled again, the circulation of the force lines went through the GS region. As a result, a negative remnant field was observed for the GS region.

Figure 5 shows the evolution of the magnetic flux density at the GSB region. When the applied magnetic pulse was small, $\mu_0 H_a = 3.3$ T, the magnetic flux penetration along the GSB
Figure 5. A similar plot as Fig. 4 for the growth sector boundary; (a) $\mu_0H_a=3.3$ T, (b) $\mu_0H_a=3.4$ T, and (c) $\mu_0H_a=5.1$ T.

region was restricted to the periphery region, similarly to the GS region, but the penetration of flux lines along GSB was more difficult than the GS region as shown in Fig. 5(a). Accordingly, the remnant field was smaller than that shown in Fig. 4(a). With increasing the intensity of the magnetic pulse to $\mu_0H_a=3.4$ T, the flux lines suddenly started to penetrate to the center of the sample. As shown in Fig. 5(b), however, the magnetic flux density at positions P3 and P4 remained rather small, and the flux gradient was not monotous during the field descending branch as well as in the remnant state. This is difficult to understand if we assume that flux lines move only along one direction. As we have discussed above, we think instead that the penetration of flux lines is anisotropic, and the flux lines penetrated to the center along a different region and then magnetized the GSB region from inside.

With further increasing the pulse intensity to $\mu_0H_a=5.1$ T, the amount of flux lines that flow to the GSB region from the other regions increased, and the remnant field at positions P3-P5 increased as shown in Fig. 5(c). A distinctive difference from the data of Fig. 5(b) is that the remnant field at the center, position P1, was virtually zero. This is because the GS region exhibited practically no flux pinning ability, and the flux lines easily escaped from the sample through that region when a strong magnetic pulse was applied as discussed above. Only the flux lines that were pinned in the GSB region remained, and the remnant magnetic field along the GSB region showed a peak at position P4.

The results of the present study show that the penetration of the magnetic flux lines is anisotropic, and they can move more easily along the GS region. In a preceding work, we studied the PFM process of a Gd-Ba-Cu-O bulk superconductor at 40 K and made a similar observation [15]. However, the results of the present study are much more striking, namely, we have observed that flux line may penetrate to the center of the sample through the GS region and then magnetize the GSB region from inside. We think that the reason why this observation was made so far only for the Sm-Ba-Cu-O sample is because of the difference in the pinning strength. In general, a bulk superconductor with a lighter rare earth element has a larger critical current density. In fact, the trapped field of our Sm- and Gd-based bulk superconductors were 1.23 T and 1.11 T respectively at liquid nitrogen temperatures when magnetized by the FC method.
Therefore, we think that the pinning strength of the Sm-Ba-Cu-O sample is larger than that of the Gd-based one, and the penetration of flux lines into the former sample is more difficult. This means that more flux lines pile up at the periphery region during the early stage of PFM. Once the field gradient exceeds what the pinning and viscous forces can sustain, the flux lines start to penetrate through the weakest region of the sample. The larger the amount of flux lines that were blocked during the early stage of PFM is, the larger is the heat generated along the path of flux motion. Accordingly, a larger increase in the local temperature is expected that makes the penetration of flux lines along that region even more easier, escalating the difference with the other region. We think that this explains why the anisotropy in the penetration of flux lines was more drastic for the Sm-Ba-Cu-O sample.

4. Conclusions
We studied the flux motion during pulsed field magnetization of a Sm-Ba-Cu-O bulk superconductor at 40 K by measuring the local magnetic flux density using small Hall sensors. We observed a large anisotropy in the flux penetration behavior during PFM and that the flux lines can move more easily along the GS region. More surprisingly, the flux lines penetrated to the center of the sample through the GS region and then magnetized the GSB region from inside when a large magnetic pulse was applied. We think that the reason why this behavior was not observed in our preceding work on Gd-Ba-Cu-O at the same temperature is because of the difference in the pinning strength between the two samples. The penetration into the Sm-Ba-Cu-O sample is more difficult for the flux lines, but once the large amount of blocked flux lines starts to penetrate the sample, a significant amount of heat is generated that escalates the difference between the GS and GSB regions.

References
[1] Ikuta H 2003 High Temperature Superconductivity 1 Materials ed Narlikar A V (Berlin: Springer-Verlag) p 79
[2] Itoh Y and Mizutani U 1996 Jpn. J. Appl. Phys. 35 2114
[3] Itoh Y, Yanagi Y and Mizutani U 1997 J. Appl. Phys. 82 5600
[4] Tsuchimoto M and Morikawa K 1999 IEEE Trans. Appl. Supercond. 9 66
[5] Braeck S, Shantsev D V, Johansen T H and Galperin Y M 2002 J. Appl. Phys. 92 6235
[6] Fujishiro H, Oka T, Yokoyama K and Noto K 2003 Supercond. Sci. Technol. 16 809
[7] Mizutani U, Oka T, Itoh Y, Yanagi Y, Yoshikawa M and Ikuta H 1998 Appl. Supercond. 6 235
[8] Sandar M, Suter U, Koch R and Klaser M 2000 Supercond. Sci. Technol. 13 841
[9] Yanagi Y, Itoh Y, Yoshikawa M, Oka T, Ikuta H and Mizutani U 2005 Supercond. Sci. Technol. 18 839
[10] Ikuta H, Ishihara H, Yanagi Y, Itoh Y and Mizutani U 2002 Supercond. Sci. Technol. 15 606
[11] Fujishiro H, Tateiwa T, Fujiwara A, Oka T and Hayashi H 2006 Physica C 445-448 334
[12] Terasaki A, Yanagi Y, Itoh Y, Yoshikawa M, Oka T, Ikuta H and Mizutani U 1998 Advances in Superconductivity X ed Osamura K and Hirabayashi I (Tokyo: Springer) p 945
[13] Ikuta H, Ishihara H, Yanagi Y, Itoh Y and Mizutani U 2000 Supercond. Sci. Technol. 13 846
[14] Ishihara H, Ikuta H, Itoh Y, Yanagi Y, Yoshikawa M, Oka T and Mizutani U 2001 Physica C 357-360 763
[15] Tokuyama M, Yanagi Y and Ikuta H 2007 Physica C, in press doi:10.1016/j.physc.2007.03.444