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Pulsed Field Magnetization of GdBaCuO Superconducting Bulks with High Magnetization Efficiency Using a Split-Type Coil with Soft Iron Yoke

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***Abstract*—Pulsed field magnetization (PFM) and field-cooled magnetization (FCM) have been carried out for GdBaCuO disk-shaped bulks fabricated by two-step buffer-assisted (BA)-top seeded infiltration growth (TSIG) technique, and the results are compared with those of bulks fabricated by conventional top seeded melt growth (TSMG) technique. In both PFM and FCM experiments, the two-step BA-TSIG bulks showed higher trapped field properties than the TSMG bulks and, in particular, the maximum trapped field by PFM was over 3.5 T at 40 K using a split-type coil with soft iron yokes. The magnetization efficiency, B_T^{max}/B_{app}^*, was defined to evaluate the trapped field efficiency quantitatively, where B_T^{max} is the maximum trapped field and B_{app}^* is the optimum applied field to achieve B_T^{max} at each operating temperature. A high efficiency over 80% was achieved for the two-step BA-TSIG bulks at 40 K, which was nearly 10% higher than that for the TSMG bulks. These results were due to the high critical current density, J_c, and the thinness of the two-step BA-TSIG bulks, readily causing flux jumps to assist in achieving higher trapped fields.**

***Index Terms*—Bulk superconductor, magnetization efficiency, pulsed-field magnetization (PFM), two-step BA-TSIG bulk, trapped field magnet**

I. Introduction

Large, single-grain REBaCuO (RE = rear earth elements or Y) superconducting bulks can carry a large current density. They have a promising potential to be used in various engineering applications, such as magnetic resonance and imaging [1] and magnetic separation [2], as a strong and compact quasi-permanent magnet. The trapped magnetic field in the bulk is proportional to the diameter of the single grain and the critical current density, J_c, unlike conventional permanent magnets such as Sm-Co or Nd-Fe-B. There are several reports showing the significant trapped field potential of REBaCuO bulks, including 17.24 T at 29 K in a YBaCuO bulk-pair reinforced with epoxy resin and Wood's metal [3] and 17.6 T at 26 K in a Ag-doped GdBaCuO bulk-pair reinforced with shrink-fit stainless steel [4].

The top seeded melt growth (TSMG) technique is one of the most reliable and successful methods to fabricate the REBaCuO bulks [5], which have reliably shown high J_c values over 10 kAcm^{-2} at 77 K and a high trapped field potential. On the other hand, the top seeded infiltration growth (TSIG) technique has been developed to further improve the trapped field properties, since it enables a dense single-grain microstructure with near-net shape processing [6 - 8]. In recent significant improvements by TSIG, the superconducting properties have been greatly improved, leading to J_c values of ~ 20-50 kAcm^{-2} at 77 K, which exceeds conventional TSMG and TSIG bulks [9 - 13]. The advanced process is named the two-step buffer-assisted (BA)-TSIG process, and results in a success rate higher than 95% in fabricating single-grain REBaCuO bulks [14].

The pulsed field magnetization (PFM) technique is a compact, mobile and inexpensive way to magnetize the superconducting bulks, requiring a shorter magnetizing time (milliseconds order) compared to field-cooled magnetization (FCM). However, the trapped field by PFM is considerably lower than that by FCM, particularly at lower temperatures, due to the rapid movement of magnetic flux within the bulk. As a result, the maximum trapped field achieved by PFM is 5.2 T at 29 K for a GdBaCuO disk bulk to date [15]. There are various approaches to improve the trapped field by PFM. The use of a split-type coil with a pair of soft iron yokes inserted in its bore has effectively enhanced the trapped field [16]. A trapped field of 3.2 T has been achieved at 40 K by a single pulse for Ag-doped TSMG bulk using this coil fixture, which was 1.5 times higher than that using a conventional solenoid coil setup. This enhancement resulted from the easier occurrence of abrupt flux intrusion like a

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flux jump in the ascending stage and the considerable suppression of flux decay in the descending stage of the PFM process [17, 18].

In this study, single PFM experiments were performed for Ag-doped GdBaCuO bulks fabricated by two-step BA-TSIG using a split coil with soft iron yokes to achieve a higher trapped field. The experimental results were compared with those of the conventional TSMG bulks. The magnetizing efficiency for the two-step BA-TSIG bulk was considerably higher than that for the TSMG bulk. The difference in the magnetization properties is discussed, including FCM results.

TABLE I
SERIAL NUMBER (SN), FABRICATION METHOD, DIAMETER, *d*, AND THICKNESS, *t*, OF EACH AG-DOPED GDBACUO BULKS USED IN THIS STUDY.

Sample	SN	Fabrication method	*d* (mm)	*t* (mm)
GdBCO + Ag	#1246	Two-step BA-TSIG	29.9	9.2
	#1250		30.3	11.6
	#476	TSMG	30.0	15.0
	#477		30.0	15.0

II. EXPERIMENTAL

A. Sample Details and FCM Results

The bulk samples used in this study were fabricated by the two-step BA-TSIG technique, and the trapped field properties of the bulks magnetized by PFM and FCM were compared with those of the bulks fabricated by the conventional TSMG technique. The serial number (SN), fabrication method, diameter, *d*, and thickness, *t*, of each bulk are shown in Table 1. The thickness of two-step BA-TSIG bulks (#1246 and #1250) is about two-thirds of that of the TSMG bulks (#476 and #477). The experimental setup used in this study is shown in Fig. 1, which is the same as our previous study [16]. The bulks were tightly set in the sample holder made of brass using an indium sheet inserted between the bulk and sample holder to realize a good thermal connection. The sample holder was directly connected to the cold stage of a Gifford-McMahon cryocooler, and then the vacuum chamber was evacuated. Cernox[TM] thermometer was set on the side of the sample holder to control the initial temperature, T_s, at 40 K or 65 K. The split-type copper coil (72 mm in I.D., 124 mm in O.D., 65 mm in H) with a soft iron yoke pair was placed outside of the vacuum chamber and submerged in liquid nitrogen. The time evolution of the magnetic field during PFM was measured by a Hall sensor at the center of the bulk surface. Magnetic pulse ranging from B_{app} = 3 to 6 T with a rise time of 13 ms and duration of 200 ms was applied. FCM experiments were also performed for each bulk to confirm the maximum trapped field potential.

Fig. 2 shows the FCM results of the two-step BA-TSIG (#1250) and TSMG (#476 and #477) bulks. Comparing the results at the same temperature, the trapped field, B_T^{FCM}, of the #1250 bulk was higher than that of the #476 and #477 bulks. The B_T^{FCM} of #1250 was 6.8 T at 40 K, which was 1.2 times higher than that of #477. At 77 K, a higher B_T^{FCM} of 1.53 T was achieved, which suggests that the #1250 bulk (30 mm in diameter) has a higher potential than #477 and #476, even though the volume of the bulk is small. The #1250 bulk has a comparable potential to the bulk of Nariki *et al*. [19], for which a record high B_T^{FCM} value of 3.05 T was achieved at 77 K at the center of the GdBaCuO bulk surface (65 mm in diameter) fabricated by conventional melt-processing. According to the Bean model, the B_T^{FCM} value is proportional to the diameter, *d*, of the disk bulk and J_c , which is given by the following typical equation : $B_T = k\mu_0 J_c d$ [20]. The diameter of the #1250 bulk in this work (30 mm) is about half of the bulk in [19] (65 mm), i.e., suggesting the trapped field potential of #1250 is almost the same.

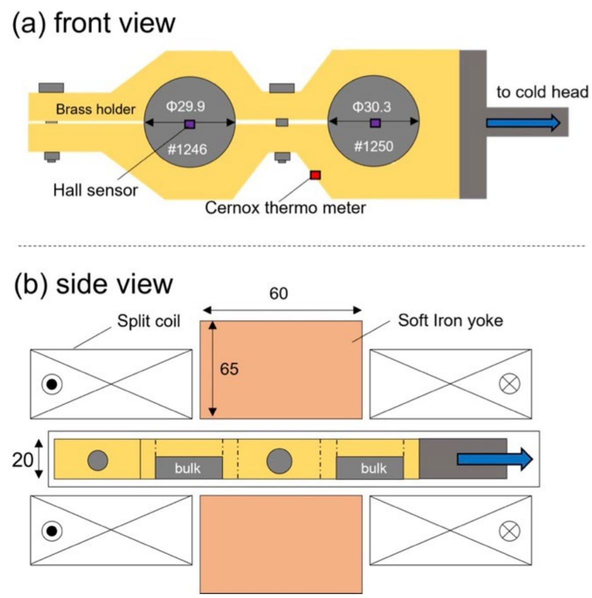

Fig. 1. Schematic view of the experimental setup, (a) front view and (b) side view.

III. RESULTS AND DISCUSSION

Fig. 3(a) shows the trapped field by PFM, B_T^{PFM}, for each bulk at *t* = 500 ms, as a function of applied field, B_{app}, at 65 K (the #477 bulk was measured at 67 K). It should be noted that soft iron yokes remained in the split coil fixture during the recording of B_T^{PFM}. There was no significant difference in the maximum trapped field, B_T^{max}, for each bulk, independent of the fabrication process. On the other hand, the penetration magnetic field, B_p, of #1250 and #1246 bulks, at which the magnetic field starts to penetrate to and trap at the center of the bulk surface, was around 1 T lower than that of the #476 bulk. This result may suggest that the magnetic shielding effect of the two-step BA-TSIG bulk was smaller, despite the higher J_c. However, the thickness of the two-step BA-TSIG bulks (#1250 and #1246) was about two-thirds of that of the TSMG bulks (#476 and #477). The effect of aspect ratio (height/diameter) of the bulk on the trapped field must be considered, although the aspect ratio dependence of the trapped field has been reported to

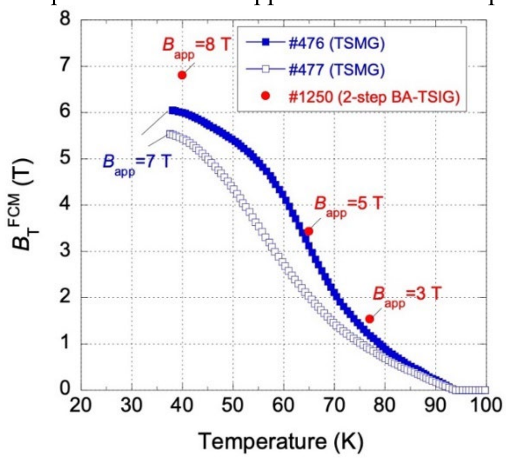

Fig. 2. The FCM results, B_T^{FCM}, for the bulks fabricated by the TSMG technique (#476 and #477) and those fabricated by the two-step BA-TSIG technique (#1250). #476 and #477 bulks were field-cooled at 40 K from 7 T, and then the external field was swept to zero and warmed to 100 K. FCM of the #1250 bulk was performed only by the external field sweeping, and three data points were obtained; from 3 T at 77 K, from 5 T at 65 K and from 8 T at 65 K.

be relatively small [21 - 22]. In general, both the B_p and B_T^{max} values increase with increasing J_c, but the two-step BA-TSIG bulks (#1250 and #1246) were thinner than the TSMG bulks (#476 and #477), leading to a reduction in magnetic shielding and flux jump occurred more readily. The B_p of #477 was also lower than that of the #476 bulk, which may come from the inhomogeneity of J_c. Fig. 3(b) shows a similar relationship at T_s = 40 K. The B_T^{max} values of the two-step BA-TSIG bulks were higher than those of the TSMG bulks, which is consistent with the FCM results. Similarly to the results for T_s = 65 K, the B_p value for the two-step BA-TSIG bulks was also lower than that for TSMG bulks.

It is difficult to qualitatively compare the PFM characteristics of bulks of different sizes using only the B_T^{PFM} obtained in Fig. 3. Figs. 4(a) and 4(c), respectively, show the trapped field distribution of the #1246 and #476 bulks measured at 2 mm above the bulk surface for a lower applied field (4.06 and 4.01 T, respectively) at T_s = 40 K. During the PFM process, the magnetic field generated from the external magnetizing coil intrudes from outer periphery of the bulk toward the center. When the external magnetic field is lower, the magnetic flux is trapped mainly in the outer peripheral region (thus, the bulk is not yet fully magnetized). Figs. 4(b) and 4(d), respectively, show the trapped field distribution for B_{app}^* at T_s = 40 K, at which the maximum trapped field was obtained. The magnetic field is clearly trapped at the bulk center. Comparing the trapped field distributions of #1246 and #476, the distribution of #1246 has a concentric circle shape, which indicates that the #1246 bulk has higher J_c uniformity over the entire bulk in comparison to the #476 bulk.

To evaluate the magnetizing properties further, we define the magnetization efficiency as B_T^{max}/B_{app}^*, in which the B_T^{max} is the maximum trapped field (introduced with Fig. 3) and B_{app}^* is the optimum applied field, at which B_T^{max} was achieved.

Fig. 5 shows the B_T^{max} value for each bulk at 40 K and 65 K, as a function of the magnetization efficiency. Regardless of the difference in T_s, the magnetization efficiency of the two-step BA-TSIG bulks (#1250 and #1246) was higher than that of the

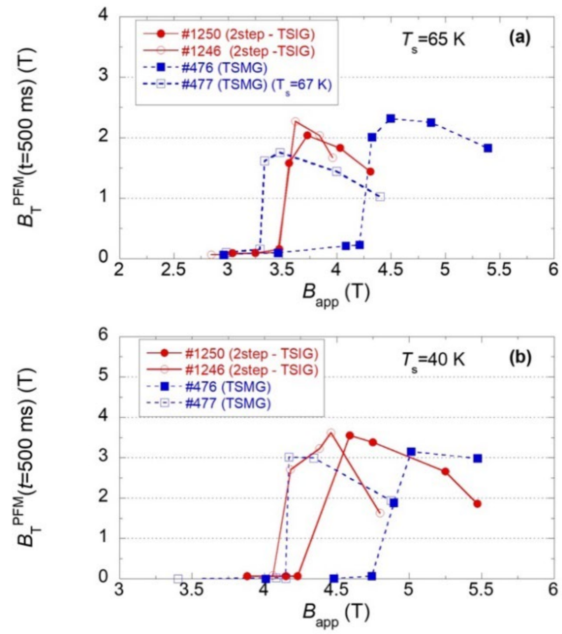

Fig. 3. The applied field, B_{app}, dependence of the trapped field, B_T^{PFM}, for each bulk at t = 500 ms, for (a) T_s = 65 K and (b) T_s = 40 K. The red symbols show B_T^{PFM} for the bulks fabricated by two-step BA-TSIG and the blue symbols show B_T^{PFM} for the TSMG bulks.

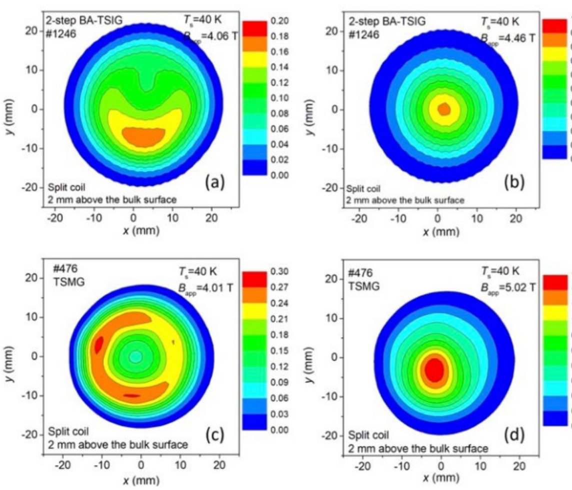

Fig. 4. Trapped field distributions measured 2 mm above the bulk surface at T_s=40 K. (a) and (c) show the distribution of #1246 and #476 for a lower applied field. (b) and (d) show the distribution for optimum applied field, at which the maximum trapped field was obtained

TSMG bulks (#476 and #477). The closer the magnetization efficiency is to 1, the smaller the influence of the J_c reduction due to heat generation during PFM, that is, the magnetization is closer to FCM. The difference in the magnetization efficiency became particularly large at T_s = 40 K, where the #1246 bulk exhibited the highest magnetization efficiency over 80% and B_T^{max} over 3.5 T by a single pulse. From the temperature measurements, the temperature rise of the two-step BA-TSIG bulks was larger than that of TSMG bulks for both T_s. At T_s = 40 K, the temperature rises of about 6 K and 4 K were observed for two-step BA-TSIG and TSMG bulks, respectively, for about

B_{app} = 4.5 T. Thus, the magnetization efficiency of the two-step BA-TSIG bulks is higher than that of TSMG bulks, in spite of

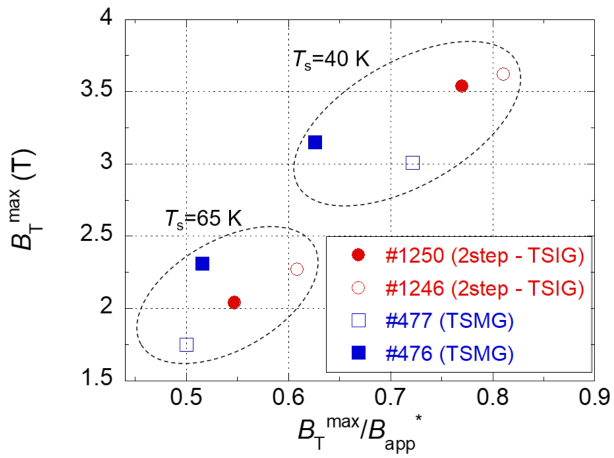

Fig. 5. The relationship between the maximum trapped field, B_T^{max}, and the magnetization efficiency, B_T^{max}/B_{app}^*, for each bulk at 40 K and 65 K.

the larger temperature rise. Therefore, it is considered that there is a strong relationship between the magnetizing efficiency and the heat generated – both in terms of its magnitude and uniformity – during the magnetizing process. In other words, since the ability to cool of the two-step BA-TSIG bulks with improved thermal properties was superior to that of the TSMG bulks , and high magnetizing efficiency was obtained.

Fig. 6 shows the time dependence of the local magnetic field at the center of the bulk surface, $B_L(t)$, and the external applied field, $B_{ex}(t)$, when optimum and high magnetic fields were applied to the #1250 ((a) and (b)) and #476 ((c) and (d)) bulks, respectively. Considering $B_L(t)$ in the case of applying the optimum field, shown in Figs. 6(a) and 6(c), the magnetic flux rapidly penetrated into the bulk center with a flux jump . In the case of the #1250 bulk fabricated by two-step BA-TSIG, interestingly, the peak field of $B_L(t)$ was higher, even though the magnitude of B_{app} was lower than that for the #476 bulk, which results from thinner thickness of the #1250 bulk. In addition, in the descending stage of the PFM process, the decay of $B_L(t)$ of the #1250 bulk was considerably small, which results from the attraction of magnetic flux by inserted yokes. As a result, a higher magnetization efficiency can be achieved. In the case of applying a higher (excessive) applied field, as shown in Figs. 6(b) and 6(d), the decay of $B_L(t)$ for the #1250 bulk in the descending stage was larger than that for the #476 bulk, despite the fact that the B_{app} value was almost the same. In these cases, the maximum temperature rise for #476 and #1250 bulks was about 8 K and 9 K, respectively. Generally speaking, the trapped field is drastically reduced after applying higher applied pulsed fields, since the dynamic flux movement generates a large amount of heat, Q, which is quantitatively defined as $Q = \boldsymbol{E} \cdot \boldsymbol{J}$, where E is the electric field and J is the current density. Furthermore, flux jumps can occur when the dynamical flux motion results in a thermomagnetic instability, which can drastically reduce the trapped field further. Considering the relationship between the heat generation and the decay of $B_L(t)$ for higher applied field, this result is consistent with the fact that the J_c of two-step BA-TSIG bulk is higher than that of the TSMG bulk.

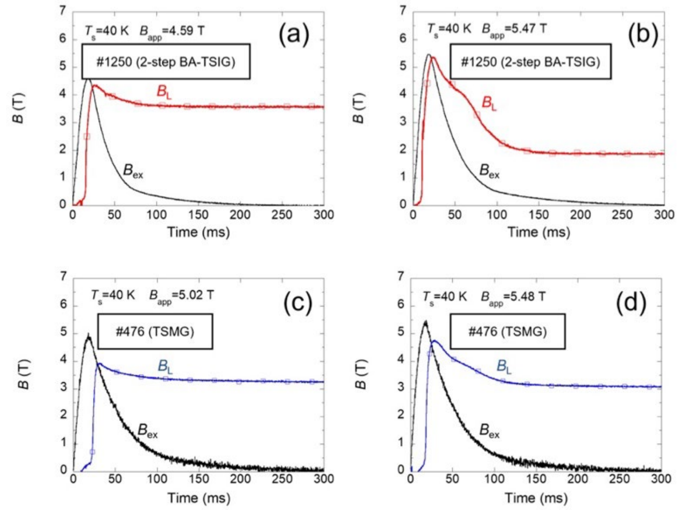

Fig. 6. The time dependence of the local magnetic field at the center of the bulk surface, $B_L(t)$, and the external applied field, $B_{ex}(t)$, estimated from the current flowing through a shunt resistor connected to the split coil. (a) and (b) show the cases of applying a optimum and high field for the #1250 (two-step BA-TSIG) bulk at 40 K, respectively. (c) and (d) show the same cases for the #476 (TSMG) bulk at 40 K, respectively.

IV. Summary

The trapped field properties for GdBaCuO bulks fabricated by the two-step buffer assisted (BA)-TSIG technique have been compared with those for conventional TSMG bulks. From the FCM results, J_c of the two-step BA-TSIG bulks was higher than that of the TSMG bulks, and a maximum trapped field of 1.53 T at 77 K for the two-step BA-TSIG bulk (30 mm in diameter) could be comparable to the world-record GdBaCuO bulk (65 mm in diameter) fabricated by conventional melt-processing. For PFM using a split-type coil with a soft iron yoke pair, a higher trapped field was achieved in the two-step BA-TSIG bulks in comparison to the TSMG bulks at T_s = 40 K, for which a high trapped field over 3.5 T was achieved using a single pulse. The magnetization efficiency, B_T^{max}/B_{app}^*, was defined to evaluate the performance under PFM. The magnetization efficiency for the two-step BA-TSIG bulks was higher than that for the TSMG bulks, which became particularly large (around 80%) at 40 K. The lower penetration field to achieve the maximum trapped field results from the thinness of the two-step BA-TSIG bulks, readily causes flux jumps to assist in enhancing the magnetization efficiency. These successful results provide further evidence that the two-step BA-TSIG bulk could be used as quasi-permanent magnets in various engineering applications more economically and efficiently.

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