Pulsed Field Magnetization for GdBaCuO Bulk With Stronger Pinning Characteristics
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Abstract—The GdBaCuO superconducting bulk with stronger pinning characteristics ($B_T = 1.8 \text{T at } 77 \text{K}) by the field cooled magnetization (FCM) has been magnetized at $T_s = 70 - 20 \text{K}$ by the pulsed field magnetization (PFM) techniques; a sequential pulsed-field application (SPA) and a modified multi pulse technique with stepwise cooling (MMPSC). With decreasing $T_s$, the pinning force $F_p$ increases especially at the growth sector boundaries (GSBs), and then the nonuniformity of the trapped field profile becomes more and more conspicuous on the bulk surface. At low $T_s$, the SPA technique is not necessarily a suitable technique to enhance the trapped field $B_T$ and the total trapped flux $\Phi_T$. However, these values can be enhanced by the MMPSC method. The properties of the bulk with stronger pinning characteristics during PFM are discussed.

Index Terms—MMPSC method, pinning force, pulsed field magnetization, trapped field.

I. INTRODUCTION

For the practical application of superconducting bulks as a strong quasi-permanent magnet such as a magnetic separation for environmental cleaning [1] and a drug delivery system (DDS) for medical applications [2], the magnetizing technique is very important. Recently, a pulsed field magnetization (PFM) has been developed instead of a conventional field-cooled magnetization (FCM) because of a compact, mobile and inexpensive setup. The trapped field $B_T^{FC}$ by PFM was, however, pretty small, compared with the trapped field $B_T^{FC}$ by FCM due to the large temperature rise by the dynamical motion of the magnetic fluxes. The maximum $B_T^{FC}$ ever reported had been as low as 3.8 T at 30 K by an iteratively magnetizing-pulsed field method with reducing amplitude (IMRA) [3]. We have systematically studied the time and spatial dependences of the temperature $T(t,x)$, local field $B_L(t)$ and the trapped field $B_T^{PF}$ on the surface of cryo-cooled REBaCuO (RE: rare earth element) bulks during PFM for various starting temperatures $T_s$ and applied fields $B_{ext}$ and have suggested the importance of the precise measurements of $T(t,x)$ on the bulk surface [4], [5].

To enhance $B_T^{PF}$, the reduction in temperature rise $\Delta T$ is an indispensable issue. The lowering of $T_s$ to 10–20 K, which is effective for FCM due to the enhancement of the critical current density $J_c$, is not necessarily effective for PFM because of the large heat generation due to the increase of pinning loss and the decrease in the heat capacity of the bulk. Taking the obtained experimental results into consideration, we proposed a new PFM technique named a modified multi pulse technique with stepwise cooling (MMPSC) [6], and have succeeded the highest field trapping of $B_T^{PF} = 5.20 \text{T}$ on the GdBaCuO bulk 45 mm in diameter, on which only 3.6 T was trapped by a single pulse application at 40 K [7]. $B_T^{PF} = 5.20 \text{T}$ is a record-high value by PFM to date. We applied the technique to other bulks with different pinning ability and confirmed that the MMPSC was a universal and effective method to enhance $B_T^{PF}$ [8].

Another approach to enhance $B_T^{PF}$ is to use the bulk with higher $J_c$. Nariki et al. have fabricated the high-performance GdBaCuO bulks, on which trapped fields $B_T^{EC}$ were as high as 2.1–2.2 T (48 mm in diameter) [9] and 3.05 T (65 mm in diameter) at 77 K [10]. If the bulk with higher $J_c$ and higher $B_T^{EC}$ is magnetized by PFM such as the MMPSC method, higher $B_T^{PF}$ value is expected. In this paper, we applied the PFM techniques to the GdBaCuO bulk with higher trapped field characteristics ($B_T^{EC} = 1.8 \text{T at } 77 \text{K}$). The trapped field $B_T^{PF}$, the total trapped flux $\Phi_T$, and the temperature rise $\Delta T$ are investigated for the sequential pulsed field application (SPA) and MMPSC methods.

II. EXPERIMENTAL PROCEDURE

The GdBaCuO superconducting bulk disk (45 mm in diameter and 18 mm in thickness) used in this study was fabricated by SRL-ISTEC, Japan. The melt processing was performed under controlled oxygen partial pressure of 1% O$_2$ in Ar [9]. The trapped field $B_T^{EC}$ was as high as 1.8 T at 77 K. The bulk was mounted on soft iron yoke cylinder and tightly anchored onto the cold stage of a Gifford-McMahon (GM) cycle helium refrigerator. The experimental setup around the bulk was described elsewhere [8]. The magnetizing solenoid coil, which generated the pulse field up to $B_{ext} = 6.4 \text{T}$ with a rise time of 12 ms and a duration of 100 ms, was placed outside the vacuum chamber, in which the central axis of the resulting field coincides with that of the bulk. The starting temperature $T_s$ of the bulk was controlled over the range from 70 K to 20 K. Three magnetic pulses (Nos. 1–3) with the same amplitude $B_{ext}$ were applied sequentially after re-cooling to $T_s$. We abbreviate this technique as a sequential pulsed-field application (SPA) method. The time
dependence of the local field \( B_C^L(t) \) was measured at the bulk center 0.5 mm above the bulk surface; the temperature \( T(t) \) on the bulk surface was also measured using a fine thermocouple during PFM. The trapped field profile \( B_C^T(0.5 \text{ mm}) \) was mapped 0.5 mm above the bulk surface, stepwise with a pitch of 1.2 mm by scanning an axial-type Hall sensor (F.W. Bell, BHA 921) inside the vacuum chamber using an \( x \to y \) stage controller with a flexible bellows. The total amount of the trapped magnetic flux density \( \Phi_T = \Phi_T(0.5 \text{ mm}) \) was calculated by integrating the magnetic flux density \( B_C^T(0.5 \text{ mm}) \) over the region where it was positive. The MMPS method was also applied to the bulk. The detailed sequence of the method was described in Section 3.3.

III. RESULTS AND DISCUSSION

A. Sequential Pulsed-Field Application (SPA)

Fig. 1 shows the trapped field \( B_C^T \) at the bulk center for the No. 1 and No. 3 pulses in SPA, as a function of the applied pulsed field \( B_{\text{ex}} \) for various starting temperatures \( T_0 \). For the No. 1 pulse, \( B_C^T \) at \( T_0 = 70 \) K starts to increase for \( B_{\text{ex}} \geq 3 \) T, takes a maximum at \( B_{\text{ex}} = 4.5 \) T and then decreases with increasing \( B_{\text{ex}} \). The \( B_C^T = B_{\text{ex}} \) curve can be usually observed for the PFM technique, which is attributed to a temperature rise in the bulk due to the heat generated by the fast motion of flux lines in the presence of resistive forces; the pinning force and the viscous force. The applied pulse field, at which the magnetic flux starts to be trapped at the bulk center, increases to 4.5 T at \( T_0 = 50 \) K and further increases with decreasing \( T_0 \). This comes from the increase of the shielding current in the superconductor with decreasing \( T_0 \). The peak in the \( B_C^T = B_{\text{ex}} \) curve cannot be confirmed at \( T_0 \leq 50 \) K because of the experimental limit of \( B_{\text{ex}} \) = 6.4 T. For the No. 3 pulse, \( B_C^T \) slightly increases as shown in the dotted lines.

Fig. 2 shows the total trapped flux \( \Phi_T \) after the No. 1 and No. 3 pulse as a function of the applied field \( B_{\text{ex}} \) for various starting temperatures \( T_0 \). All the \( \Phi_T = B_{\text{ex}} \) curves take a maximum. The maximum \( \Phi_T \) value increases and the \( B_{\text{ex}} \) value, at which \( \Phi_T \) takes a maximum, shifts to the higher value with decreasing \( T_0 \). It should be noted that the \( \Phi_T \) value fairly increases for the SPA technique; the \( \Phi_T \) value for the No. 3 pulse is 20~40% larger than that for the No. 1 pulse, and that the increment rate increases with decreasing \( T_0 \). In this way, the SPA technique is effective for the enhancement of \( \Phi_T \) rather than that of \( B_C^T \).

Fig. 3 shows the time evolution of the applied field \( \mu_0 H_{\text{ex}}(t) \) and the local fields \( B_C^L(t) \) after applying the magnetic pulse of \( B_{\text{ex}} = 6.25 \) T at \( T_0 = 50 \), 30 and 20 K.

Fig. 4(a) shows the time dependence of the temperature change \( T(t) \) on the bulk surface after applying the pulse fields from 5.00 T to 6.32 T at 30 K. \( T(t) \) sharply rises up, takes a maximum at 5 s and then gradually decreases. It should be noticed that the time, at which \( T(t) \) takes a maximum, is in the order of seconds, which is clear contrast with the local field \( B_C^L(t) \) shown in Fig. 3; the time, at which \( B_C^L(t) \) takes a maximum, is in the order of milliseconds. The maximum temperature \( T_{\text{max}} \) increases with increasing \( B_{\text{ex}} \) due to the increase of pinning loss and viscous loss. \( T_{\text{max}} \) reaches 70 K.
for $B_{\text{ex}} = 6.32$ T. The maximum temperature rise $\Delta T_{\text{max}}$ increased with decreasing $T_s$ (not shown) due to the enhancement of pinning loss and the decrease in the heat capacity of the bulk. Fig. 4(b) shows the pulse number dependence of $T(t)$ in the SPA method on the bulk surface for $B_{\text{ex}} = 6.32$ T at $T_s = 30$ K. $T_{\text{max}}$ gradually decreases with increasing pulse number and then saturates due to the decrease of the pinning loss of the already trapped fluxes. The decrease of the $T_{\text{max}}$ enhances the $\Phi_T$ and $B_T^2$ values as shown in Figs. 1 and 2.

Figs. 5(a) and 5(b) show the trapped field profiles $B_T$ (0.5 mm) after applying the No. 1 pulse field of $B_{\text{ex}} = 3.4$ T at $T_s = 70$ K and $B_{\text{ex}} = 5.2$ T at $T_s = 30$ K, respectively. For relatively higher $T_s$ and lower $B_{\text{ex}}$, as shown in Fig. 5(a), the nonuniformity of the trapped field profile is not so large, except for the region near the position A. The result roughly suggests that the distribution of $J_e$ in the bulk is relatively small at higher $T_s$. On the other hand, at lower $T_s$ and relatively lower $B_{\text{ex}}$, as shown in Fig. 5(b), the position dependence of the trapped field is quite remarkable; $B_T$ at the positions B, C and D increases over 1.5 T. However, $B_T$ at the position A (bulk center) remains 0.5 T. The positions B, C and D are not in the growth sector boundaries (GSBs) but in the growth sector regions (GSRs). The pinning force in the GSBs is usually stronger than that in the GSRs due to the large number of crystal defects. The nonuniformity of the trapped field might be a characteristic feature for the bulk with strong pinning force. Figs. 5(c) and 5(d) show the cross sections of the trapped field profiles for typical conditions along the $x$- and $y$-axes, respectively, in which the characteristic positions from A to D are indicated. $B_T$ at the positions B, D and around C increases with decreasing $T_s$. For the lower $B_{\text{ex}}$, the magnetic fluxes can be preferentially trapped at the weak pinning centers in the GSRs.

Figs. 6(a) and 6(b) show the $B_T$ (0.5 mm) profile after applying the higher pulse field (No. 1 pulse) of $B_{\text{ex}} = 6.2$ T at $T_s = 50$ K and 30 K, respectively. In Fig. 6(a), the $B_T$ shows nearly the cone-shaped profile and the magnetic fluxes are preferentially trapped along the GSBs rather than the positions B, C and D. As a result, the center of the trapped field shifts toward the bulk center (position A). In this way, for the higher $B_{\text{ex}}$, the magnetic fluxes can be preferentially trapped at the strong pinning centers in the GSBs due to the large temperature rise. Figs. 6(c) and 6(d) show the cross section of the $B_T$ profile along the $x$-axis for No. 1 and No. 3 pulses of $B_{\text{ex}} = 6.2$ T at $T_s = 50$ K and 30 K, respectively. It should be noted that the trapped fields are enhanced especially at the bulk periphery by the SPA method.
magnetization (FCM)) has been magnetized by a sequential pulsed-field application (SPA) and a modified multi pulse technique with stepwise cooling (MMPSC). With decreasing temperature, the pinning force $F_p$ increases especially at the growth sector boundaries (GSBs) rather than the growth sector regions (GSRs), and then the nonuniformity of the trapped field distribution becomes more and more conspicuous on the bulk surface. It was found that the MMPSC method was valuable technique to enhance the trapped field $B_{T2}$ and the total trapped fluxes $\Phi_T$ also for the bulk with stronger pinning characteristics. However, since the optimum condition for the MMPSC method strongly depends on the used bulk crystal and the experimental apparatus, it is not easy to apply the MMPSC method. The advent of a new PFM technique is anticipated to magnetize sufficiently the superconducting bulks with stronger pinning characteristics.

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REFERENCES


