Pulsed Field Magnetization of Large MgB$_2$ Bulk Fabricated by Reactive Liquid Mg Infiltration

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1. Introduction

The superconducting bulk magnet using an REBaCuO (RE: rare earth element or Y) bulk can be used for practical applications such as sputtering cathodes, magnetic separation, and drug delivery systems. The REBaCuO bulks with 45–60 mm diameters are commercially available to produce tesla-order quasi-permanent magnets, which are fabricated by a melt textured method. Although a large single-domain bulk of over 100 mm in diameter is difficult to fabricate, large bulks have recently been realized only by a multiseeding technique.

MgB$_2$ bulk also has a promising potential as a quasi-permanent magnet because the problem of weak links at the grain boundaries can be ignored even in the polycrystalline samples owing to their long coherence length. The MgB$_2$ bulk enables us to realize better and larger polycrystalline bulk magnets below the transition temperature $T_c$. Several groups have already reported a trapped field on the MgB$_2$ bulk by field-cooled magnetization (FCM). A trapped field value of $B_t = 2.3$ T was obtained at 6 K on the MgB$_2$ bulk of 28 mm diameter and 11 mm thickness, which was sintered under a high pressure of 2 GPa. Yamamoto et al. reported a 1.2 T MgB$_2$ magnet (20 mm in diameter and 5 mm in thickness) magnetized by FCM at 17 K, and a 3 T-class magnet, which consists of doubly stacked MgB$_2$ bulks.

One of the authors (G. Giunchi) has developed MgB$_2$ bulks by the reactive Mg liquid infiltration (Mg-RLI) technique, which is preferable to fabricate dense and large MgB$_2$ bulk disks and cylinders, where the maximum $B_t$ value was about 1.3 T at 15 K by FCM on the Mg-RLI-MgB$_2$ bulk of 55 mm diameter and 15 mm thickness at the center hole of 6 mm.

Pulsed field magnetization (PFM) is an another technique to magnetize bulk superconductors. However, for the REBaCuO bulks, the trapped field $B_t$ achievable by PFM is nonetheless lower than that achievable by FCM because of the large temperature rise caused by the dynamical motion of the magnetic flux. Several approaches have been performed and succeeded in enhancing $B_t$ using multipulse techniques. We have experimentally examined the time and spatial dependences of the temperature $T(t, x)$, the local field $B_L(t, x)$, and the trapped field $B_t$ on the surface of cryocooled REBaCuO bulks during PFM for various starting temperatures $T_c$ and applied fields $B_{ex}$. To enhance $B_t$, the reduction in temperature rise and the lowering of $T_c$ are effective because of the enhancement of the critical current density $J_c$, similarly to the case for FCM. Considering the obtained experimental results, we proposed a new PFM technique named the modified multipulse technique with stepwise cooling (MMPSC) and successfully realized the highest field trap of $B_t = 5.20$ T on a GdBaCuO bulk of 45 mm diameter at 30 K, which is a record-high value achieved by PFM to date. Recently, we have demonstrated the numerical simulation of PFM for a cryocooled REBaCuO bulk disk, where the results of the simulation reproduced the experimental ones qualitatively. However, the PFM procedure for the MgB$_2$ bulk has not yet been reported.

In this study, we applied the PFM technique to a large MgB$_2$ bulk of 50 mm diameter for various applied fields $B_{ex}$ and temperatures $T_c$. The PFM procedure for the MgB$_2$ bulk is a first and systematic approach to enhance $B_t$. The numerical simulation for PFM was also performed for the MgB$_2$ bulk. Since the operation temperature of the MgB$_2$ bulk is fairly lower than that of REBaCuO, the thermal properties of the MgB$_2$ bulk such as the specific heat and the thermal conductivity are quite different. As a result, the PFM performance is expected to be quite different. We discuss the characteristics of PFM on the MgB$_2$ bulk, compared with those on the REBaCuO bulk.

2. Experimental Procedure

The MgB$_2$ bulk disk used in this study was 50 mm in diameter and 16 mm in thickness, which was fabricated by the Mg-RLI technique. The detailed fabrication process was described elsewhere. $T_c$ of the bulk was estimated to be 39 K using a small piece cut from a similar bulk fabricated by the Mg-RLI method. The bulk was tightly mounted in a stainless steel (SUS316L) ring of 8 mm thickness using a stycast 2850GT resin as a filling. Figure 1 shows the experimental setup around the bulk and the magnetizing pulse coil for PFM. The bulk was set on a soft iron yoke cylinder of 40 mm diameter and 20 mm thickness and tightly anchored onto the cold stage of a Gifford–McMahon (GM) cycle helium refrigerator. The initial temperature $T_c$ of the bulk was set from 18 to 33 K. A magnetizing solenoid coil (94 mm i.d., 153 mm o.d., and 67 mm height), which was dipped in liquid nitrogen, was placed outside the vacuum chamber. A magnetic pulse $B_{ex}$ with a rise time of 0.01 s

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and a duration of 0.1 s was applied to the bulk by flowing the pulsed current from a condenser bank. The time dependence of the applied pulsed field \(B_{ex}(t)\) was monitored from the current \(i(t)\) flowing in the shunt resistor. The time evolutions of the local field \(B_z^L(t)\) and the subsequent trapped field \(B_z\) at the center of the bulk surface were monitored inside the vacuum chamber by an axial-type Hall sensor (F W Bell, BHA 921), which touched the bulk surface, using a digital oscilloscope. Two-dimensional trapped field profiles of \(B_z\) (1 mm) were mapped at a distance of \(z = 1 \text{ mm}\) above the bulk surface, stepwise with a pitch of 1 mm by scanning the same Hall sensor using an \(x-y\) stage controller. During PFM, the time dependence of temperature \(T(t)\) was measured at the side surface of the SUS316L ring using a Cernox thermometer.

3. Model of Numerical Simulation for PFM

On the basis of the experimental setup around the MgB\(_2\) bulk for PFM, the framework of the numerical simulation was constructed using the axi-symmetric coordinate. The detailed procedure of the simulation was described elsewhere.\(^{17}\) The bulk was magnetized using a solenoid-type coil and the sizes of the bulk and the coil were the same as those of the experimental condition. Physical phenomena during PFM were described using electromagnetic and thermal fields, which were taken from ref. 21. The power-\(n\) model \((n = 5)\) was supposed to describe the nonlinear \(E-J\) characteristic in the superconducting bulk. The temperature and magnetic field dependences of the critical current density \(J_c(T, B)\) are described as

\[
J_c(T, B) = \alpha \left[ 1 - \left( \frac{T}{T_c} \right)^2 \right]^{3/2} \frac{B_0}{|B| + B_0},
\]

where \(T_c = 39 \text{ K}\) is the critical temperature at \(B = 0\), and \(B_0 = 1.3 \text{ T}\) is constant. In eq. (1), the simulation was performed for various \(\alpha\) values. As a result, the \(\alpha\) value of \(5 \times 10^7\) was best fitted to reproduce the experimental results, which corresponded to \(J_c\) (20 K, 0 T) of \(3.2 \times 10^7 \text{ Am}^{-2}\). This \(J_c\) value is two orders of magnitude smaller than that of the MgB\(_2\) bulks fabricated by an \textit{in-situ} method.\(^{6,22,23}\) This difference may come from the deterioration of \(J_c\) caused by the inhomogeneous Mg infiltration, as stated in a later section. The time dependence of the applied pulsed field \(B_{ex}(t)\) with the rise time of \(\tau = 0.01 \text{ s}\) was approximated in the following equation,

\[
B_{ex}(t) = B_{ex} \frac{t}{\tau} \exp\left(1 - \frac{t}{\tau}\right),
\]  

(2)

The numerical parameters used in the simulation are presented in Table I. The thermal conductivity \(\kappa\) and the specific heat \(C\) values of the MgB\(_2\) bulk were presumed to be temperature dependent, as referred from the literature.\(^{20,24}\) For simplicity, \(\kappa\) and \(C\) of the SUS316L ring and the mass densities \(\rho\) of MgB\(_2\) and the SUS316L ring were supposed to be constant. We set the spacing plate with a thermal conductivity \(\kappa_{\text{cont}}\) of \(0.5 \text{ W m}^{-1} \text{ K}^{-1}\) between the bulk and the cold stage (and SUS316L ring), which imaginarily represents both the cooling power of the refrigerator and the thermal contact. Commercial software, Photo-Eddy, combined with Photo-Thermo (Photon Ltd.), was used for analyses of the magnetic field and temperature distribution in the MgB\(_2\) bulk during PFM.

4. Experimental Results

Figure 2 depicts the trapped field \(B_z\) at the center of the bulk surface by PFM, as a function of applied pulsed field \(B_{ex}\). At \(T_c = 18 \text{ K}\), the magnetic flux intruded and was trapped at the center of the bulk surface at \(B_{ex} \geq 1 \text{ T}\), the trapped field \(B_z\) takes a maximum at \(B_{ex} = 1.7 \text{ T}\) and then decreased with increasing \(B_{ex}\). At \(T_c \geq 23 \text{ K}\), \(B_z\) showed a similar applied field dependence, and the applied field \(B_{ex}^0\), at which the magnetic flux starts to be trapped at the bulk center, decreases with increasing \(T_c\). The maximum \(B_z\) by PFM was 0.47 T at \(T_c = 23 \text{ K}\) in this study. These applied field and temperature dependences of \(B_z\) show similar characteristics to those for REBaCuO bulks.\(^{4}\) However, note that the steep \(B_{ex}\) dependence of \(B_z\) is a peculiar characteristic of the MgB\(_2\) bulk, compared with that for the REBaCuO bulk, which results from the large thermal conductivity \(\kappa\), small specific heat \(C\), and narrow temperature margin against the transition temperature \(T_c\) in the MgB\(_2\) bulk at \(T_c\). Detailed discussion is performed in §5.

Figure 3 shows the time dependence of the applied field \(B_{ex}(t)\) and the local field \(B_z^L(t)\) at the center of the bulk surface at \(T_c = 23 \text{ K}\) for various applied fields \(B_{ex}\). Each condition is indicated in Fig. 2, as the symbols of (a) to (d).
All the $B_{ex}(t)$ were noisy because of insufficient electrical shielding. For each condition, $B_{ex}(t)$ starts to increase for $t \geq 0.01$ s with a time delay, takes a maximum at 0.02 s, and then decreases to a final value due to the flux flow. It should be noted that, for $B_{ex}$ = 1.36 T as shown in Fig. 3(c), the abrupt $B_{ex}(t)$ drop was observed at $t$ = 0.08 s because of the flux jump.

Figure 4 presents the trapped field profiles $B_{z}$ (1 mm) on the surface of the MgB$_2$ bulk at $T_s$ = 23 K for various applied fields $B_{ex}$. For a lower applied field of $B_{ex}$ = 0.99 T shown in Fig. 4(a), a small amount of magnetic flux was mainly trapped at the coordinates of (−10, −10). For $B_{ex}$ = 1.06 T shown in Fig. 4(b), where the trapped field shows a maximum at $T_s$ = 23 K as shown in Fig. 2, the magnetic flux was trapped mainly on the oblique line (region A) together with several spots around the periphery. For $B_{ex}$ = 1.36 T shown in Fig. 4(c), the magnetic flux was trapped mainly around the bulk periphery, and for $B_{ex}$ = 1.69 T shown in Fig. 4(d), the magnetic flux escaped and was re-distributed owing to the temperature rise. These results indicate that region A has a lower $J_c$ and region B, as shown in Fig. 4(b), has a relatively higher $J_c$. Because, from the analogy in the REBaCuO bulks during PFM, the magnetic flux was trapped mainly around the growth sector region (GSR) with a lower $J_c$, for the lower magnetic pulse application, then the trapped flux region was inclined at 45° to the growth sector boundary (GSB) with a higher $J_c$ for the higher magnetic field. If the $J_c$ is ideally homogeneous in the bulk, the trapped field profile should show a concave profile for a lower $B_{ex}$ and a convex profile for a higher $B_{ex}$, according to the Bean model. These results shown in Fig. 4 suggest that the present MgB$_2$ bulk fabricated by the Mg-RLI method was inhomogeneous for the $J_c$ distribution, which may result from the inhomogeneous infiltration of the Mg liquid.

Figure 5 shows the total trapped flux $\Phi$ on the surface of the MgB$_2$ bulk at $T_s$ = 23 K for various applied fields $B_{ex}$, which was calculated by integrating the magnetic flux density $B_z$ (1 mm) over the region where it was positive. All the $\Phi$-$B_{ex}$ curves take a maximum and then decrease with increasing $B_{ex}$. The maximum $\Phi$ value increases and the $B_{ex}$...
value, at which $\Phi$ takes a maximum, shifts to a higher value with decreasing $T_s$.

5. Results of Numerical Simulation and Discussion

We present the results of the numerical simulation for a MgB$_2$ bulk during PFM. Figure 6(a) depicts the results of the simulation of the trapped field $B_t$ at the center of the bulk surface as a function of the applied field $B_{ax}$ for various $T_s$. In all the cases, $B_t (r=0)$ starts to increase concomitantly with increasing $B_{ax}$, becomes maximum, and then decreases with a further increase in $B_{ax}$. The critical applied field $B_{ax}^0$, at which the magnetic flux starts to trap at the bulk center, decreases concomitantly with increasing $T_s$. The results of the simulation reproduce qualitatively the experimental ones shown in Fig. 2.

Figure 6(b) presents cross sections of the trapped field profile $B_t (r)$ at $T_s = 23$ K for various $B_{ax}$. The positions of $r = 0$ and 25 mm are, respectively, the center and the edge of the bulk surface. The $B_t (r)$ profile changes from concave for a lower $B_{ax}$ to convex for a higher $B_{ax}$ and then the $B_t (r=0)$ value decreases with a further increase in $B_{ax}$. These behaviours are apparent for each $T_s$, but are not always strictly consistent with the experimental ones, as shown in Fig. 4, where region A was estimated to have a low $J_c$. In this study, the numerical simulation was performed under the ideal condition, in which the $J_c$ value was homogeneous in the bulk. However, the results of the numerical simulation roughly reproduced the experimental ones.

Figure 7 shows the results of the simulation of the applied field dependence of the total magnetic flux $\Phi$ for various $T_s$. All the $\Phi$–$B_{ax}$ curves take a maximum and then decrease with increasing $B_{ax}$. The maximum $\Phi$ value increases and the $B_{ax}^p$ value, at which $\Phi$ takes a maximum, shifts to a higher value with decreasing $T_s$. The $B_{ax}^p$ value for each $T_s$ is slightly lower than $B_{ax}^c$, at which $B_t^c$ takes a maximum. These behaviours are qualitatively consistent with the experimental ones, as shown in Fig. 5.

Figures 8(a) and 8(b) show, respectively, the time dependences of the local fields $B_t^c(t)$ and the temperatures $T(t)$ at the center of the bulk surface at $T_s = 23$ K for a typical applied field $B_{ax}$. The time dependence of the reduced magnetic pulse $B_{ax}(t)$ is also shown. In Fig. 8(a), the local field...
$B_C(t)$ starts to increase rapidly with a time lag for $B_{ex} = 1.1$ and 1.4 T and then decreases. In Fig. 8(b), the temperature $T(t)$ at the bulk center starts to rise rapidly and then decreases. The temperature starts to rise at $t = 0.01$ s, at which $B_{ex}(t)$ takes a maximum. $T(t)$ takes a maximum at $t = 0.07 - 0.1$ s, which becomes shorter with increasing $B_{ex}$. For $B_{ex} = 1.4$ T, a steep decrease in $B_C(t)$ results from the approach of the temperature to $T_c = 39$ K. In this case, the temperature at the bulk periphery exceeded $T_c$ and most of the trapped flux escaped from the bulk. The results of the simulation of the MgB$_2$ bulk were in clear contrast with those for REBaCuO bulks; the applied field dependence of the trapped field was broad and the temperature $T(t)$ takes a maximum at 7 s. The differences come from the large thermal conductivity, small specific heat, and narrow temperature margin against the transition temperature $T_c$ in the MgB$_2$ bulk. It is possible to add the secondary phases in the bulk to reduce the thermal conductivity and to enhance the specific heat. As a result, the temperature rise decreases during PFM and the trapped field will increase. The use of numerical simulation can optimize the operating parameters for PFM to enhance the trapped field. MgB$_2$ bulk magnets are expected to be applicable in magnetically levitated trains and so on using liquid H$_2$ or cryocooler cooling.

6. Conclusions

Pulsed field magnetization (PFM) was performed for the first time for a large MgB$_2$ bulk of 50 mm diameter fabricated by a reactive liquid Mg infiltration (Mg-RLI) method, and the trapped field properties were measured. Important results of experiment and simulation and conclusions obtained in this study are summarized as follows.

1) The maximum trapped field of $B_t = 0.47$ T was realized at the center of the bulk surface and the total trapped flux $\Phi = 0.5$ mWb was achieved at $T_c = 23$ K. Both values decreased with increasing temperature $T_c$.

2) The experimental results can be roughly reproduced by numerical simulation using electromagnetic and thermal fields, although inhomogeneous $J_c$ distribution exists in the present MgB$_2$ bulk fabricated by the Mg-RLI method from the trapped field profiles by PFM.

3) The flux dynamics and the heat generation/propagation of the MgB$_2$ bulk during PFM were in clear contrast with those for REBaCuO bulks because of the large thermal conductivity, small specific heat, and narrow temperature margin against the transition temperature $T_c$ in the MgB$_2$ bulk. In the future, using liquid H$_2$, high-strength MgB$_2$ bulk magnets are expected for practical applications.

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