Temperature rise and trapped field in a GdBaCuO bulk superconductor cooled down to 10 K after applying pulsed magnetic field

K. Yokoyama a,*, M. Kaneyama b, H. Fujishiro b, T. Oka c, K. Noto d

a National Institute for Materials Science, 3-13 Sakura, Tsukuba, Ibaraki 305-0003, Japan
b Iwate University, 3-4-5 Ueda, Morioka, Iwate 020-8551, Japan
c IMRA Material R&D Co., Ltd., 3-50 Hachiken-cho, Kariya, Aichi 448-0021, Japan
d Iwate Industrial Promotion Center, 3-33-2 Iioka-shinden, Morioka, Iwate 020-0852, Japan

Received 23 November 2004; accepted 22 February 2005

Abstract

In order to magnetize the bulk superconductors more strongly by pulsed-field magnetization (PFM), the temperature rise $\Delta T(t)$ and the trapped field $B_T$ of the GdBaCuO bulk cooled down to 10 K have been investigated after applying the five successive (No1–No5) pulsed-field ranging from 4.70 T to 6.04 T. $\Delta T$ increased linearly with lowering initial bulk temperature $T_s$ and with increasing strength of the applied field $B_{ex}$. From the generated heat $Q$ estimation, the difference $Q$ value, $\Delta Q = Q(\text{No1}) - Q(\text{No5})$ which suggests that the $\Delta Q$ nearly stands for the flux pinning loss $Q_p$ shows the similar $B_{ex}$ dependence to the $B_T$ value.

© 2005 Elsevier B.V. All rights reserved.

PACS: 74.72.−h; 74.25.H

Keywords: GdBaCuO bulk superconductor; Temperature measurement; Pulsed-field magnetization; Heat generation

1. Introduction

Recently, the performance of REBaCuO (RE = Y, Sm, Gd, etc.) bulk superconductors such as a critical current density $J_c$ and the mechanical strength has been remarkably improved. As a result, the bulk can trap an extremely high magnetic field of up to 17 T at 29 K [1]. The bulk,
cooled down to lower temperatures by a cryo-cooled refrigerator, can be realized as a stronger magnet than a permanent magnet and an electromagnet and various kinds of applications such as magnetic separation and magnetron sputtering have been considered [2–4]. Bulk superconductors are usually magnetized by field-cooled magnetization (FCM). However, there are some difficulties due to the use of an expensive superconducting magnet with a higher field and a larger bore size, although higher trapped fields as high as the maximum ability of the bulk can be realized. Pulsed-field magnetization (PFM) has been recently investigated because the magnetizing equipment is rather simple and inexpensive by use of a conventional power supply and a copper coil. The trapped field obtained by PFM is, however, generally about half of that obtained by FCM at lower temperatures which results from the heat generation caused by the pinning loss and the viscous loss due to the flux motion such as flux jump and flux flow.

We have investigated the time evolution and spatial distribution of the temperature rise $\Delta T(t)$ on the surface of bulk superconductors after applying a pulsed field at an initial bulk temperature from $T_s = 70$ K down to 40 K [5–8]. The trapped field $B_T$ obtained by PFM increases with increasing strengths of the pulse field but decreases for a higher pulse field application due to the large heat generation. It can be clearly seen that $B_T$ increases with decreasing $T_s$ for a fixed $B_{ex}$. The monitoring of temperature and the estimation of the generated heat $Q$ enabled us to elucidate the mechanisms of PFM and to enhance $B_T$ [7]. In order to magnetize bulk superconductors more strongly by PFM, it is desirable to lower the temperature $T_s$. In this paper, we investigate $\Delta T(t)$ and $B_T$ for a GdBaCuO bulk superconductor cooled down to 10 K after applying a pulsed field. We discuss the possibility of the $B_T$ enhancement by PFM at lower temperatures.

2. Experimental

Fig. 1 illustrates the experimental equipment. A highly $c$-axis oriented GdBaCuO bulk superconductor, 46 mm in diameter and 15 mm in thickness, was set on the cold stage of a GM-cycle helium refrigerator (Sumitomo Heavy Industries, Ltd, SRDK-408D) with a cooling ability of down to ~4 K. The bulk fabricated by Nippon Steel Co., Ltd. consists of GdBa$_2$Cu$_3$O$_y$ (Gd123), Gd$_5$Ba$_2$Cu$_5$O$_{21}$ with a molar ratio of 1.0:0.4, 0.5 wt.% Pt powder and 10 wt.% Ag$_2$O. The epoxy resin layers impregnated upper and bottom surfaces of the bulk were removed in order to measure the surface temperature precisely and to reduce thermal contact resistance to the cold stage. The SUS304 ring was set onto the bulk disk for mechanical reinforcement and for $\Delta T(t)$ reduction [8]. The bulk was cooled down to 10 K with a radiation shield set on the first stage of the refrigerator. A Teflon-coated chromel–constantan thermocouple, 76 $\mu$m in diameter, was adhered to the center of the bulk surface using the GE7031 varnish and the time dependence of temperature $T(t)$ was measured. A Hall sensor (F.W. Bell, BHT-921) was also adhered near the bulk center in order to measure the trapped field $B_T$. A magnetizing copper coil dipped in liquid nitrogen was set outside the vacuum vessel and an exciting pulse current was supplied from a condenser bank of 60 mF. After the GdBaCuO bulk was cooled down to the initial temperature $T_s = 10$, 20, 30, 40 and 60 K, five successive pulsed fields (No1–No5) of 4.70, 5.53 and 6.04 T with a rise time of 12 ms were applied and the time dependence of temperature $T(t)$ and $B_T$ were measured at each stage.

3. Results and discussion

Fig. 2 shows the time responses of temperature $T(t)$ for various initial temperatures $T_s$ after apply-
ing the first (No1) pulse of 5.53 T. \( T(t) \) for each \( T_s \) rises up, takes a maximum within 5 s and then slowly recovered to the initial \( T_s \) for 15–20 min. In order to enhance the \( B_T \) value by PFM, the reduction of \( T_{\text{max}} \) is an indispensable issue. The maximum temperature \( T_{\text{max}} \) reaches 62 K for \( T_s = 20 \text{ K} \) and \( T_{\text{max}} \) is 60 K for \( T_s = 10 \text{ K} \). \( T_{\text{max}} \) slightly decreases and shows a saturation tendency with decreasing \( T_s \). \( T_{\text{max}} \) of the bulk is expected to decrease with decreasing \( T_s \) for the same input heat generation. However, the effect was very small, even if \( T_s \) decreased down to 10 K. Because the specific heat \( C \) of the bulk decreases and approaches zero with decreasing temperatures and/or the cooling power of the GM refrigerator becomes small in this lower temperature region.

Fig. 3 displays the \( T_s \) dependence of the temperature rise \( \Delta T \) after applying the No1 and No5 magnetic pulses for each applied field \( B_{\text{ex}} \). For all the \( T_s \) and \( B_{\text{ex}} \), the \( \Delta T \) is the largest for the No1 pulse, and decreases with increasing pulse numbers, approaching a fixed ultimate behavior for the No4 and No5 pulses. This behavior is quite reasonable because the largest amount of the flux penetrates into the virgin state bulk and further flux penetration for the succeeding pulses should be limited due to the presence of the already trapped flux. These saturation tendencies in \( T(t) \) are closely related with those of the trapped field \( B_T \). For the No1 pulse, \( \Delta T \) increases with an increase in \( B_{\text{ex}} \) and monotonically decreases with increasing \( T_s \). The \( \Delta T \) values seem to approach zero at the superconducting transition temperature \( T_c \). For the No5 pulse application, the magnetic flux previously intrudes into the bulk and the \( \Delta T \) values are smaller than those for the No1 pulse. It should be noticed that the \( \Delta T - T_s \) curve is not a straight line, contrary to that of the No1 pulse.

The heat generation \( Q \) in PFM can be estimated by the following equation:

\[
Q = \int_{T_s}^{T_s + \Delta T_{\text{max}}} C(T) V \, dT = Q_p + Q_v,
\]

where \( C(T) \) is the specific heat and \( V \) is the volume of the bulk. \( Q \) is regarded as the sum of the pinning loss \( Q_p \), which is closely related with the flux trapping, and the viscous loss \( Q_v \), which is related with the flux flow \( (Q = Q_p + Q_v) \). Since no additional flux trapping takes place for the No5 pulse, it is reasonable to assume that \( Q(\text{No5}) \) for the No5 pulse mainly consists of \( Q_v \). The difference \( \Delta Q (= Q(\text{No1}) - Q(\text{No5})) \) roughly stands for the pinning loss correlated with the flux trapping for the No1 pulse [7].

Fig. 4(a) shows the generated heat \( Q(\text{No1}) \) and \( Q(\text{No5}) \) for various \( T_s \) after applying the No1 and No5 pulsed fields as a function of \( B_{\text{ex}} \). The \( Q \) values were calculated using Eq. (1). The \( Q(\text{No1}) \) values at all the \( T_s \) are nearly equal for \( B_{\text{ex}} = 4.70 \text{ T} \), and the values increase linearly with increasing \( B_{\text{ex}} \).
and the $Q_{\text{No1}}$ increases with lowering $T_s$. On the other hand, the $Q_{\text{No5}}$ values are almost equal independently of $B_{\text{ex}}$ except for the value at $T_s = 60$ K and are always smaller than $Q_{\text{No1}}$.

Fig. 4(b) presents the $B_{\text{ex}}$ dependence of $\Delta Q = Q_{\text{No1}} - Q_{\text{No5}}$ at $T_s = 10–60$ K as a function of $B_{\text{ex}}$.

Fig. 5 shows the $B_{\text{ex}}$ dependence of the trapped field $B_T$ for each $T_s$. The $B_{\text{ex}} = 4.70$ T and 6.04 T, which stands for $Q_p$, decreases with increasing $T_s$. However, it can be seen that the $\Delta Q$ for $B_{\text{ex}} = 4.70$ T slightly increases with increasing $T_s$, except for $T_s = 60$ K. The $\Delta Q$ increases with increasing $B_{\text{ex}}$ at $T_s = 10$ K, but it changes moderately for a higher $B_{\text{ex}}$ at other temperatures.

4. Conclusions

We investigated the possibility of the $B_T$ enhancement in the GdBaCuO bulk by PFM at lower temperatures down to 10 K. The temperature rise ($\Delta T$) increased linearly with a lowering initial bulk temperature $T_s$ and with increasing strengths of the applied field $B_{\text{ex}}$. From the generated heat estimation, the $\Delta Q = Q_{\text{No1}} - Q_{\text{No5}}$ value which could be confirmed that the $\Delta Q$ value nearly stood for the flux pinning loss $Q_p$ showed the similar $B_{\text{ex}}$ dependence of the $B_T$ value. Furthermore, from the $B_{\text{ex}}$ dependence of the $B_T$, it was clarified that there was an optimal applied field $B_{\text{ex}}(\text{opt})$ for $B_T$ becoming maximum for each $T_s$. 

Fig. 5. The $B_{\text{ex}}$ dependence of the trapped field $B_T$ for each $T_s$. 

These results support the fact that the $\Delta Q$ value should be closely related with the flux trapping. For a lower $B_{\text{ex}} = 4.70$ T, $B_T$ is the smallest for $T_s = 10$ K because the magnetic flux can hardly intrude into the bulk due to the strong pinning potential. On the other hand, for a higher $B_{\text{ex}} = 6.04$ T, $B_T$ decreases with increasing $T_s$. The $B_{\text{ex}} = 6.04$ T value for the bulk cooled to $T_s = 60$ K is too high to trap the magnetic flux. These results suggest that there may be an optimal applied field $B_{\text{ex}}(\text{opt})$ for each $T_s$. If we apply a magnetic field $B_{\text{ex}}$ higher than 6.04 T at $T_s = 10$ K, the $B_T$ value may enhance. The maximum $B_T$ value was 1.6 T at $T_s = 10$ K after applying $B_{\text{ex}} = 6.04$ T in this study.
Acknowledgment

This work is partially supported by the IWATE CREAT project (October 1999–September 2004) by the Japan Science and Technology Agency.

References