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

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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. ΔT 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, $\Delta Q = Q(\mathrm{No1}) - Q(\mathrm{No5})$ which suggests that the ΔQ nearly stands for the flux pinning loss Q_p shows the similar B_{ex} dependence to the B_T value.

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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,

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cooled down to lower temperatures by a cryocooled 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 $GdBa_2Cu_3O_y$ (Gd123), Gd_2BaCuO_5 (Gd211) with a molar ratio of 1.0:0.4, 0.5 wt.% Pt powder and 10 wt.% Ag_2O. 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 μm 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.

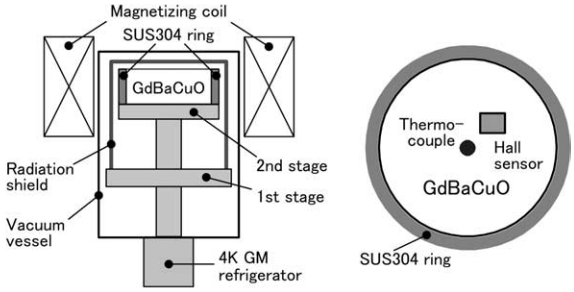

Fig. 1. Experimental equipment.

3. Results and discussion

Fig. 2 shows the time responses of temperature $T(t)$ for various initial temperatures T_s after apply-

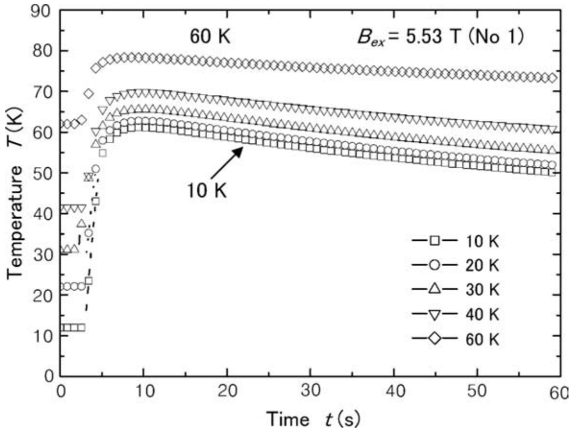

Fig. 2. The time responses of temperature $T(t)$ at the initial temperatures T_s ranging from 10 to 60 K after applying the first pulsed field of 5.53 T.

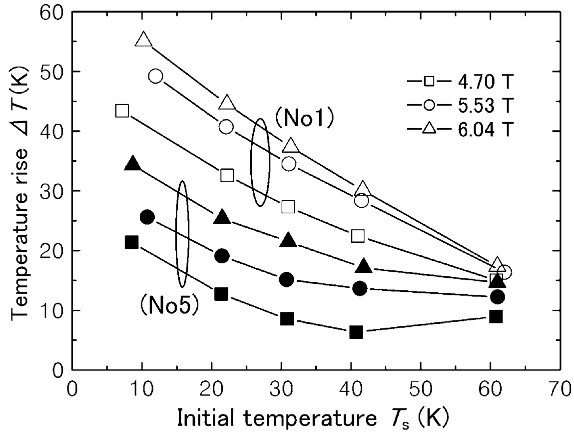

Fig. 3. The initial temperature T_s dependence of temperature rise ΔT after applying the first (No1) and the fifth (No5) pulsed field for various applied fields B_{ex}.

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_{max} is an indispensable issue. The maximum temperature T_{max} reaches 62 K for $T_s = 20$ K and T_{max} is 60 K for $T_s = 10$ K. T_{max} slightly decreases and shows a saturation tendency with decreasing T_s. T_{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 ΔT after applying the No1 and No5 magnetic pulses for each applied field B_{ex}. For all the T_s and B_{ex}, the ΔT 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, ΔT increases with an increase in B_{ex} and monotonically decreases with increasing T_s. The ΔT 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 ΔT 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:

$$Q = \int_{T_s}^{T_s+\Delta T_{max}} C(T)V\,\mathrm{d}T = Q_p + Q_v, \tag{1}$$

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(No5) for the No5 pulse mainly consists of Q_v. The difference ΔQ (=Q(No1) − Q(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(No1) and Q(No5) for various T_s after applying the No1 and No5 pulsed fields as a function of B_{ex}. The Q values were calculated using Eq. (1). The Q(No1) values at all the T_s are nearly equal for $B_{ex} = 4.70$ T, and the values increase linearly with increasing B_{ex}

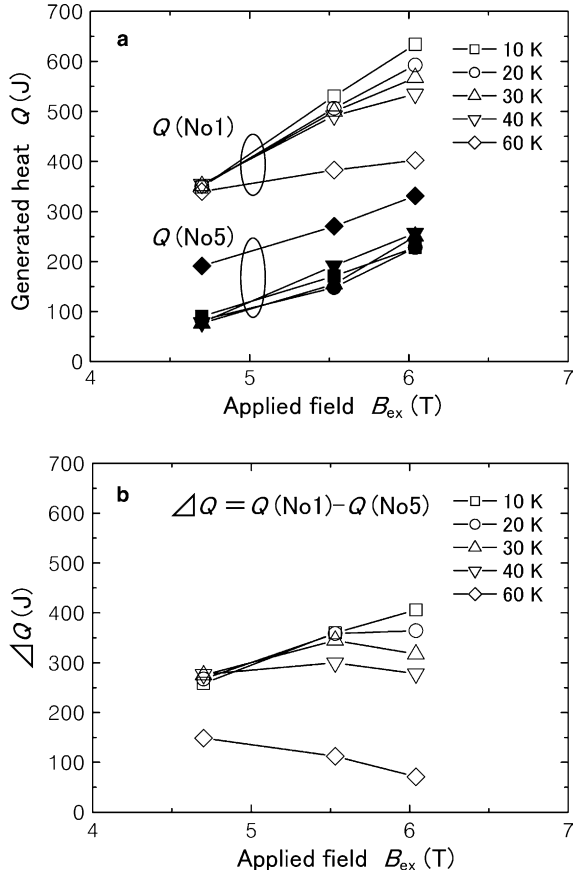

Fig. 4. (a) A generated heat Q(No1) and Q(No5), and (b) $\Delta Q = Q$(No1) − Q(No5) at T_s = 10–60 K as a function of B_{ex}.

and the Q(No1) increases with lowering T_s. On the other hand, the Q(No5) values are almost equal independently of B_{ex} except for the value at $T_s = 60$ K and are always smaller than Q(No1). Fig. 4(b) presents the B_{ex} dependence of ΔQ at each T_s. The ΔQ value for $B_{ex} = 5.53$ T and 6.04 T, which stands for Q_p decreases with increasing T_s. However, it can be seen that the ΔQ for $B_{ex} = 4.70$ T slightly increases with increasing T_s except for $T_s = 60$ K. The ΔQ increases with increasing B_{ex} at $T_s = 10$ K, but it changes moderately for a higher B_{ex} at other temperatures.

Fig. 5 shows the B_{ex} dependence of the trapped field B_T for each T_s. At $T_s = 10$ K, B_T increases linearly with increasing B_{ex}. On the other hand, for $T_s = 60$ K, B_T monotonically decreases with increasing B_{ex}. These B_{ex} dependences are similar to the ΔQ behaviors as shown in Fig. 4(b). These results support the fact that the ΔQ value should be closely related with the flux trapping. For a lower $B_{ex} = 4.70$ 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 $B_{ex} = 6.04$ T, B_T decreases with increasing T_s. The $B_{ex} = 6.04$ 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_{ex}(opt) for each T_s. If we apply a magnetic field B_{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 $B_{ex} = 6.04$ T in this study.

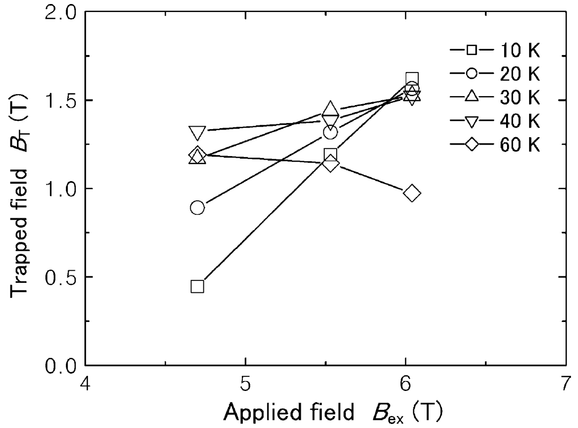

Fig. 5. The B_{ex} dependence of the trapped field B_T for each T_s.

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 (ΔT) increased linearly with a lowering initial bulk temperature T_s and with increasing strengths of the applied field B_{ex}. From the generated heat estimation, the $\Delta Q = Q$(No1) − Q(No5) value which could be confirmed that the ΔQ value nearly stood for the flux pinning loss Q_p showed the similar B_{ex} dependence of the B_T value. Furthermore, from the B_{ex} dependence of the B_T, it was clarified that there was an optimal applied field B_{ex}(opt) for B_T becoming maximum for each T_s.

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