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Temperature measurements in small holes drilled in superconducting bulk during pulsed field magnetization

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ABSTRACT

The time dependence of the temperatures $T(z, t)$ has been measured along the thickness direction z in several drilled holes in a superconducting bulk during pulsed field magnetization (PFM) and the heat generation and heat transfer in the bulk have been discussed. In the previous paper [H. Fujishiro, S. Kawaguchi, K. Kakehata, A. Fujiwara, T. Tateiwa, T. Oka, Supercond. Sci. Technol. 19 (2006) S540], we calculated the $T(z, t)$ profiles in the bulk by solving a three-dimensional heat-diffusion equation to reproduce the measured $T(t)$ on the bulk surface; the heat generation took place adiabatically and the calculated $T(z, t)$ was isothermal along the z direction. In this study, the measured $T(z, t)$ at the top surface was higher than that at the bottom surface just after the pulse field application at $t < 0.5$ s, and then became isothermal with increasing time. These results suggest that the magnetic flux intrudes inhomogeneously into the bulk from the edge of the top surface and the periphery at the early stage. The inhomogeneous magnetic flux intrusion and the flux trap during PFM change depending on the strength of the pulsed field and the pulse number in the successive pulse field application.

1. Introduction

For practical applications of superconducting bulks as a quasi-permanent magnet, a pulsed field magnetization (PFM) is a suitable technique because of mobile and inexpensive experimental setups [1]. The trapped field B_T^P by PFM is, however, fairly smaller than the trapped field B_T^{FC} by a field-cooled magnetization (FCM) because of a large temperature rise by means of the dynamical motion of the magnetic flux. To clarify the magnetizing mechanism during PFM and to enhance B_T^P, the measurements and analyses of the temperature rise in the bulk are valuable. We have systematically investigated the time and spatial dependence of the temperatures $T(x, t)$, local fields $B_L(x, t)$ and the trapped field $B_T(x)$ on the surface of the cryo-cooled REBaCuO bulk during PFM, as functions of an initial temperature T_s and an applied field B_{ex} [2]. Furthermore, we estimated the generated heat Q during PFM by use of the temperature rise ΔT and the specific heat C of the bulk [3]. Taking these results into consideration, we proposed a new PFM method named a modified multi-pulse technique with stepwise cooling (MMPSC) and attained 5.2 T on the GdBaCuO bulk 45 mm in diameter at 30 K, which is a record high B_T^P value to date [4].

Furthermore, we estimated a temperature distribution in the bulk by solving a three-dimensional heat-diffusion equation. Fig. 1 shows the time evolution of the calculated temperature profile $T(z, t)$ along the thickness (z) direction for the YBaCuO bulk after applying the pulsed field of 3.83 T at 40 K [5]. The calculated profiles under an ideal condition are shown in Fig. 1a, where the thermal contact resistance R_c between the bottom of the bulk disk and the surface of the cold stage of the refrigerator was ignored. After the pulse field application, the temperature of the bottom surface of the bulk was fixed at 40 K and $T(z)$ increased with increasing z. The $T(z, t)$ took a peak at each z at as short as $t = 1$ s and then returned to 40 K only at 20 s, which were unrealistic estimation. Because the measured $T(t)$ on the bulk surface recovered to 40 K at about 900 s. The discrepancy comes from the magnitude of the generated heat Q, which was about two orders of magnitude larger than the cooling power Q_p of the used refrigerator. Fig. 1b shows the optimum estimation for $T(z, t)$, in which the calculated $T(t)$ well reproduced the measured $T(t)$ on the bulk surface. In this case, the calculated $T(z, t)$ might increase adiabatically and show no z dependence. However, we do not know whether the measured $T(z)$ shows z dependence in the bulk or not.

In this paper, we measured directly the time dependence of the temperatures $T(z, t)$ in several drilled holes in the bulk during PFM, and discussed the heat generation and heat transfer in the bulk. The temperature measurement in the hole was performed by other group [6], but the z dependence of temperature $T(z, t)$ has not been measured.

2. Experimental procedure

A c-axis oriented SmBaCuO bulk superconductor (Dowa Mining Corp.) of 45 mm in diameter and 15 mm in thickness was used. The

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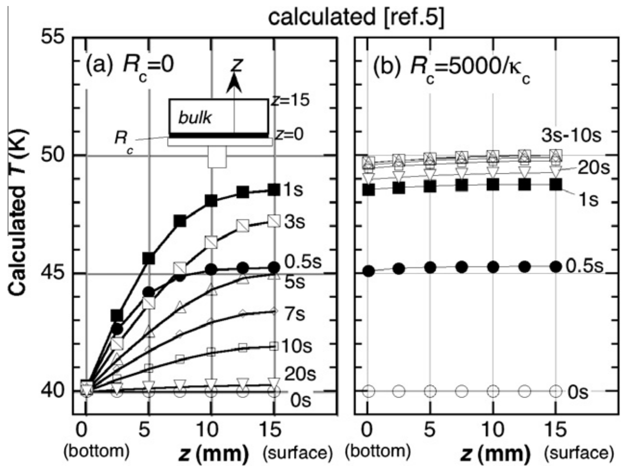

Fig. 1. Time dependence of calculated temperature changes $T(z, t)$ as a function of the distance z from the bottom of the YBCO bulk after the pulse field application, which were shown in Ref. [5]: (a) is for the ideal but unrealistic case with the contact thermal resistance of $R_c = 0$ and (b) is for the optimum case.

stainless steel (SUS304) ring with 2.0 mm in thickness and 15 mm in height was fixed onto the bulk disk using Stycast 2850GT. The bulk was tightly anchored onto the cold stage of a Gifford–McMahon (GM) cycle helium refrigerator and was cooled to $T_s = 40$ K in a vacuum chamber. In this study, two settings ("set A" and "set B") were performed for the temperature $T(z, t)$ and magnetic field $B_L(t)$ measurements as shown in Fig. 2. Several small holes 1 mm in diameter were drilled at the center and the periphery of the growth sector regions (GSRs) in the bulk, and $T(z, t)$ was measured using fine chromel-constantan thermocouples (76 μm in diameter). In "set A", a through hole was drilled at the bulk periphery and the time dependence of temperatures was measured at the surface ($T1(t)$), middle ($T2(t)$) and bottom ($T3(t)$). $T4(t)$ and $T5(t)$ were also measured at the bottoms of the holes 7.5 mm in depth. Two Hall sensors (F.W. Bell, model BHT 921) were adhered at the positions C (bulk center) and M (10 mm distant from the bulk center) in GSR and the time evolutions of the local fields $B_L(t)$ and the trapped fields $B_T = B_L(t \to \infty)$ were monitored by using a digital oscilloscope. In "set B", the temperatures at the surface ($T6(t)$), middle ($T7(t)$) and bottom ($T8(t)$) were measured. $T1(t)$ and $T4(t)$ were also measured for comparison. For both settings, the bulk was magnetized by pulsed fields using a solenoid-type copper coil dipped in liquid N_2. The detailed experimental setup for the coil and the bulk was described elsewhere [2]. Three magnetic pulses (Nos. 1–3) with nearly the same amplitude B_{ex} from 3 to 6.5 T were applied sequentially after re-cooling to 40 K.

3. Results and discussion

Fig. 3a shows the trapped fields B_T(C) and B_T(M) as a function of the applied field B_{ex} for the No. 1 pulse. The magnetic flux starts to intrude and to be trapped into the bulk for $B_{ex} > 3.5$ T. B_T(C) and B_T(M) took a maximum at $B_{ex} = 4.8$ T and then decreased with increasing B_{ex} because of a large heat generation. B_T(C) was larger than B_T(M) for $B_{ex} < 5$ T, but decreased drastically for $B_{ex} > 5.5$ T because of the flux jump. Fig. 3b shows the time evolution of the applied field $B_{ex}(t)$ and local fields ($B_L(C)(t)$ and $B_L(M)(t)$) after applying the pulsed field of $B_{ex} = 4.8$ T. The rise time and the duration of $B_{ex}(t)$ was 12 ms and 150 ms, respectively. $B_L(M)(t)$ rises up firstly and then $B_L(C)(t)$ rises up. $B_L(t)$ takes a maximum and then slowly decreases to the final value.

Figs. 4a and 4b depict respectively the time evolution of the temperatures $T(z, t)$ at each position in "set A", after applying the Nos. 1 and 3 pulses of $B_{ex} = 4.8$ T. For the No. 1 pulse, $T(t)$ shows a peak within 1 s at each position and decreases slowly to 40 K for about 600 s. Let us take notice of the temperature change along the z direction at the bulk periphery. $T1(t)$, $T2(t)$ and $T3(t)$ rise up in this order and take a peak. These results suggest that the larger heat generation took place firstly on the bulk surface. For the No. 3 pulse shown in Fig. 4b, a similar tendency in the temperature was observed at $T1(t)$, $T2(t)$ and $T3(t)$ with a slight decrease in temperature. It is noteworthy that $T4(t)$ and $T5(t)$ for the No. 3 pulse are clearly smaller than those for the No. 1 pulse. These results suggest that the magnetic flux does not move violently and is not trapped around these positions for the No. 3 pulse because of the existence of the already trapped flux for the Nos. 1 and 2 pulses.

Figs. 4c and 4d display the time evolution of temperature $T(z, t)$, as a function of the distance z from the bottom of the bulk, which are re-plotted using Figs. 4a and 4b, respectively. For $t < 0.5$ s, a large temperature gradient exists along the z direction and becomes isothermal with increasing time ($t > 1$ s). The measured $T(t)$ is quite contrast with the calculated $T(t)$ shown in Fig. 1b for $t < 0.5$ s. The experimental results suggest that the magnetic flux does not intrude into the bulk parallel to the z direction, but

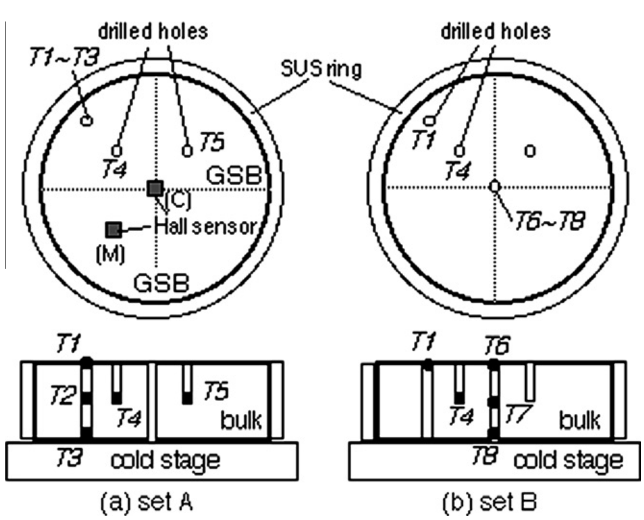

Fig. 2. The measuring position of temperatures $T(t)$ and magnetic fields $B_L(t)$ for (a) "set A" and (b) "set B".

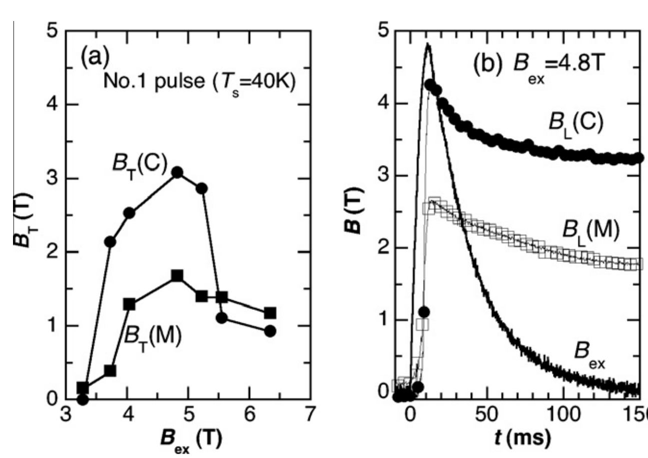

Fig. 3. (a) The trapped field B_T as a function of applied field B_{ex} at the center (C) and the middle (M) positions on the bulk. (b) The time evolution of the applied field $B_{ex}(t)$ and local fields ($B_L(C)(t)$ and $B_L(M)(t)$) after applying pulsed field of $B_{ex} = 4.8$ T at $T_s = 40$ K.

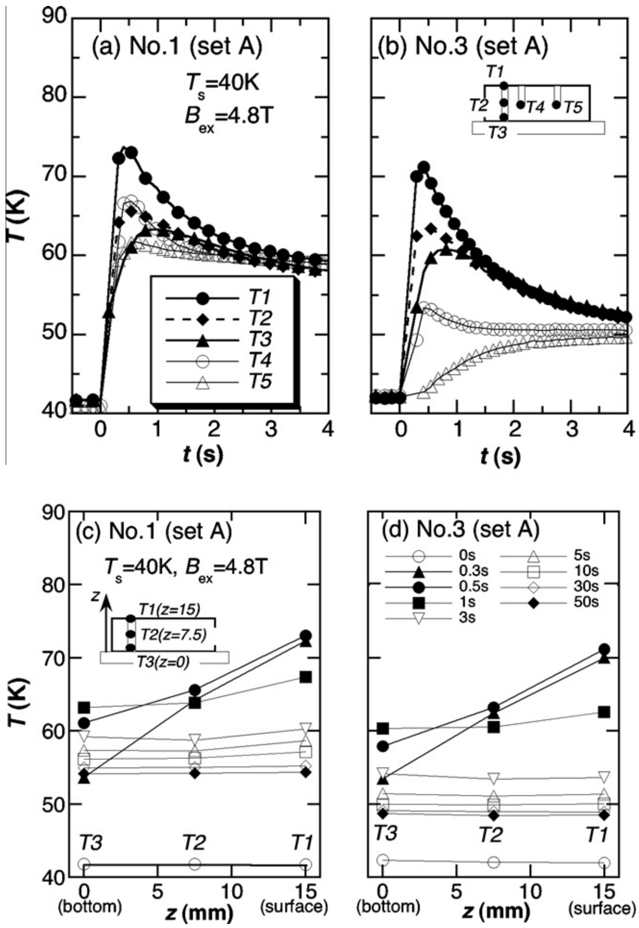

Fig. 4. Time evolution of temperatures ($T1(t)$–$T5(t)$) for "set A" after applying pulsed field of B_{ex} = 4.8 T of the (a) No. 1 and (b) No. 3 pulse. The temperature changes for the (c) No. 1 and (d) No. 3 pulse, as a function of the distance z from the bottom of the bulk, which were re-plotted using (a) and (b), respectively.

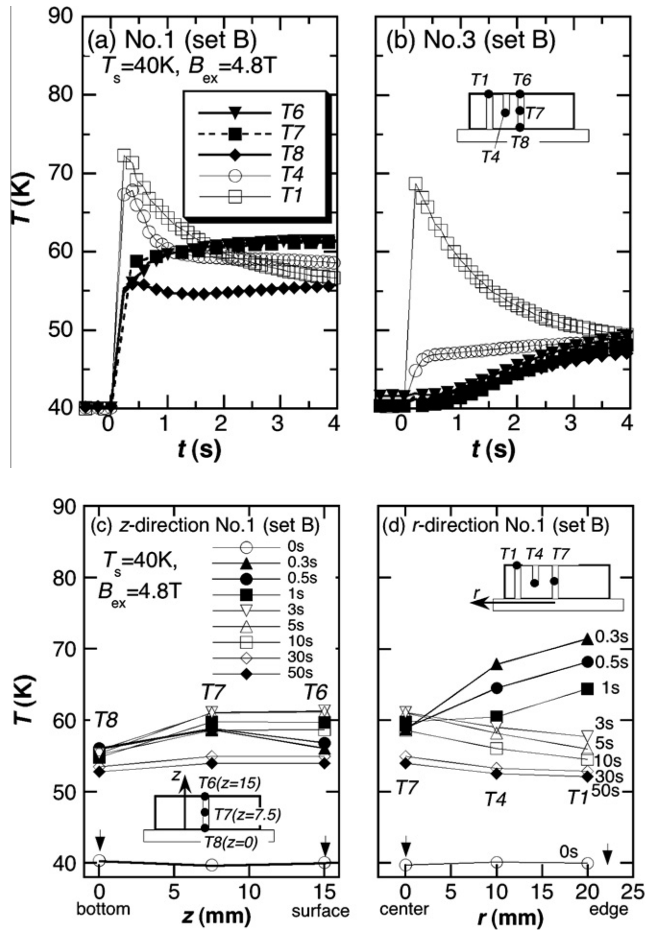

Fig. 5. Time evolution of temperatures ($T1(t)$, $T4(t)$, $T6(t)$–$T8(t)$) for "set B" after applying pulsed field of B_{ex} = 4.8 T of the (a) No. 1 and (b) No. 3 pulse. (c) The temperature changes for the No. 1 pulse, as a function of the distance z. (d) The temperature changes for the No. 1 pulse as a function of the distance r.

obliquely intrudes from the edge of the bulk at early stage of PFM. As a result, a large temperature gradient exists along the z direction.

Figs. 5a and 5b show respectively the time evolution of the temperatures $T(t)$ at each position in "set B", after applying the Nos. 1 and 3 pulses of B_{ex} = 4.8 T. $T1(t)$ and $T4(t)$, which were also measured similarly to "set A", show a similar time dependence and the maximum temperature rise. These results suggest that the experimental results can be reproduced by different experimental setups. It should be noted that the time dependence of temperatures ($T6$, $T7$, $T8$) at the bulk center was quite different from $T(t)$ in the bulk periphery ($T1$, $T2$, $T3$); for the No. 1 pulse, $T6(t)$ and $T7(t)$ reach 60 K at t = 1 s and then slowly increases up to 4 s. Furthermore, for the No. 3 pulse, the temperature rises of $T6$, $T7$ and $T8$ are very small and increases slightly with increasing time. Fig. 5c shows the temperature change along the thickness direction for the No. 1 pulse in "set B" for each t, which was re-plotted using Fig. 5a. The temperature at the bulk center is adiabatically and isothermally rises up along the z direction even at the early time, contrary to that in the bulk periphery. Fig. 5d shows the time dependence of temperature $T(r, t)$ along the radial (r) direction for the No. 1 pulse in "set B", in which the results of $T1(t)$, $T4(t)$ and $T7(t)$ were used. It is noteworthy that the temperature rise starts from the bulk periphery at the early stage ($t < 1$ s), and quickly decreased with increasing t. On the other hand, $T(t)$ at the bulk center, $T7(t)$ scarcely changes. As a result, the temperature gradient along the r direction exists oppositely for $t > 3$ s and gradually decreased because of the larger thermal diffusivity along the ab-plane than that along the c-axis in the bulk crystal.

Finally, we present the $T(z, t)$ for lower applied field. Figs. 6a and 6b display respectively the time evolution of the temperatures $T(z, t)$ as a function of the distance z in "set A", after applying the Nos. 1 and 3 pulses of B_{ex} = 3.7 T. The temperature rises were lower than

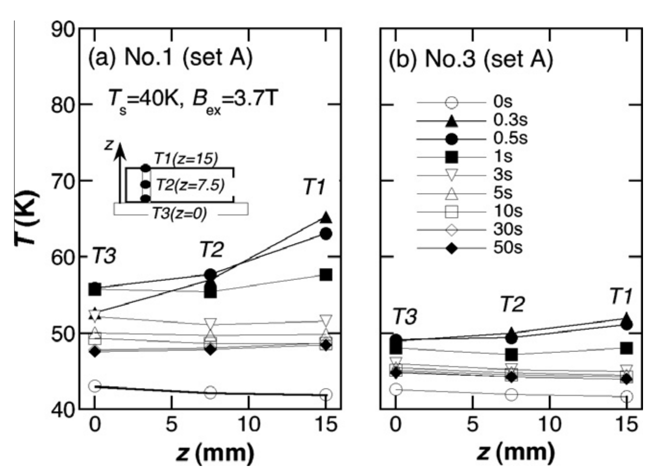

Fig. 6. The time evolution of the temperatures $T(t)$ as a function of the distance z in "set A", after applying the (a) No. 1 and (b) No. 3 pulses of B_{ex} = 3.7 T at T_s = 40 K.

those for $B_{ex} = 4.8$ T shown in Fig. 4c and d because of lower applied field. However, a smaller temperature gradient exists for $t < 0.5$ s along the z direction and becomes isothermal with increasing time ($t > 1$ s). For the No. 3 pulse, the temperature gradient scarcely exists along the z direction and the temperature rise was very small. These results resemble the calculated $T(z, t)$ as shown in Fig. 1b.

In summary, the time dependence of the temperatures $T(z, t)$ in several drilled holes in a superconducting bulk during pulsed field magnetization has been measured and compared with the calculated $T(z, t)$ by solving a three-dimensional heat-diffusion equation reported in the previous paper. The measured $T(t)$ at the top surface of the bulk was higher than that at the bottom surface and the temperature gradient exists along the thickness direction, just after the pulse field application of $t < 0.5$ s and then became isothermal with increasing time. In the simulation, $T(z, t)$ rises up adiabatically for $t > 0$ s and no temperature gradient exists along the thickness direction. The difference in $T(z, t)$ at the early stage suggests that the magnetic flux intrudes preferentially into the bulk from the edge of the top surface and the bulk periphery. The asymmetric cooling configuration of the bulk may be another reason; the bulk is cooled by conduction from the bottom surface on the cold stage of the refrigerator. The inhomogeneous magnetic flux intrusion and flux trap during PFM changed depending on the applied pulsed field B_{ex} and the pulse number.

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