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# Temperature measurement of RE123 bulk superconductors on magnetizing process

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**Abstract**

We study on the magnetization behavior of to magnetize RE123 bulk superconductors to apply it as strong magnets. Through magnetizing process, the temperature of bulk superconductors is raised by pinning loss caused by the magnetic fluxes motion (e.g. flux jump of flux flow), and the trapped field is decreased. This paper presents the measurement of temperature changes of Sm123 bulk superconductors during the exciting process by iteratively magnetizing pulsed-field operation with reducing amplitudes (IMRA) method. Five thermocouples are put on the surface of Sm123 bulk superconductor of 46 mm in diameter. The temperatures at the center, on the growth sector boundary (GSB) line and in the sector region surrounded by GSB's line (inter-GSB region) are monitored. The temperature at a cold stage is also measured. A Hall sensor is attached near the center thermocouple to measure the trapped field. After a bulk superconductor is cooled by the GM type refrigerator until 40 K, iterative pulsed-fields of 2.32–5.42 T are applied by a magnetizing coil. When high magnetic field of 5.42 T is applied, a temperature of bulk superconductor reaches to 72.4 K and the magnetic field distribution has C form with which a part of circle is dented, and then, a trapped field is 2.28 T. When a lower magnetic field of 4.64 T is applied, a maximum temperature is 68.3 K and a trapped field is raised to 2.70 T, and moreover, the distribution becomes round shape like field-cooling method (FC). We showed clearly that heat generation by pinning loss was related to the mechanism of magnetic field capture.


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## 1. Introduction

The performance of high-$T_c$ REBaCuO (RE = Y, Sm, Gd, etc.) bulk superconductors has improved remarkably [1–3]. Since a critical current density, $J_c$, increased and the mechanical strength was improved, a bulk superconductor can trap a higher magnetic field. In addition, the use of the

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cryocooled refrigerators allowed us to easily generate the stronger magnetic field than permanent magnets and electromagnets. At the present, a magnetic field generation system in which a bulk superconductor is used as a permanent magnet is developed [4–6], and various applications of superconducting bulk magnets such as magnetic separation and magnetron spattering are considered [7–9].

Bulk superconductors are mostly magnetized by a field-cooling method (FC) and by a pulsed-field magnetization (PFM). In FC, although high magnetic field can be trapped, the place in which a magnetization is possible is restricted due to use of a superconducting magnet. In PFM, although a trapped field is lower than FC, magnetizing equipment is simple due to the use of a condenser bank and a copper coil. Therefore, PFM is an important magnetizing method towards the utilization of bulk superconductors. Since a trapped field of usual PFM generally is a half of that of FC, the development of magnetizing method to improve the trapped field in PFM has been considered. The iteratively magnetizing pulsed-field operation with reducing amplitudes (IMRA) method is to impress pulsed-fields several times changing strength of magnetic fields and higher magnetic field can be trapped than usual PFM [5,6].

During magnetization, bulk superconductors generate heat and thus the trapped field is decreased due to reduction in a critical current density $J_c$, where it is supposed that heat generation occurs by pinning loss when magnetic fluxes move into the bulk (e.g. flux jump and flux flow). For applying bulk superconductors as strong magnets, it is important to elucidate the magnetizing mechanism and to improve the magnetizing efficiency [5,10]. At present, various researches are done by experiments and simulations [11,12]. Ikuta et al. measured the time dependence of the magnetic flux density using pickup-coils in PFM of Sm123 bulk superconductor and clarified the motion of flux lines. Moreover, the velocity of flux lines is calculated using the experimental data and temperature changes are evaluated [11]. Ohsaki et al. studied PFM of a ring-shaped bulk superconductor and then estimated the current density distribution and temperature distribution by computer simulations using experimental results [12]. These reports are based on numerical analysis and those quantitative evaluations are not reported. We measure temperature changes of RE123 bulk superconductors using thermocouples directly and guess behavior of magnetic fluxes from experimental results [13,14].

This paper presents the measurement of temperature changes of Sm123 bulk superconductors during the magnetization process by IMRA method. Five thermocouples and a Hall sensor are attached on the surface of bulk superconductor, and temperatures and trapped fields are monitored on the each magnetizing process. Then motion of magnetic fluxes is discussed using the data of temperature rise and magnetic flux distribution.

## 2. Experimental

Fig. 1(a) shows a schematic of temperature measurement equipment. A Sm123 bulk superconductor of 46 mm in diameter and 15 mm in thickness with epoxy impregnation is set on a copper base connected to a cold head of GM refrigerator (AISIN SEIKI CO., LTD, GR301). The epoxy resin on both upper and lower sides of the bulk is however removed in order to measure the precise temperature and to reduce a thermal contact resistance to the cold head. The bulk superconductor is a highly *c*-axis oriented crystal and consists of $SmBa_2Cu_3O_y$ (Sm123), $Sm_2BaCuO_5$ (Sm211) with the molar ratio of 1.0:0.3, 0.5 wt% Pt powder and 1.5 wt% $Ag_2O$ addition (Dowa Mining Co., Ltd.). A heater coil is wound around a thermal conduction bar in order to adjust an initial temperature of bulk superconductor and it is controlled by a thermo-controller connected outside.

The surface of bulk crystal can be classified into two regions: One is the growth sector boundary (called as GSB) and another is sector region surrounded by GSB lines (called as inter-GSB region). The magnetic fluxes were confirmed more easily to move through inter-GSB regions than GSB lines [11] and we have also obtained the same

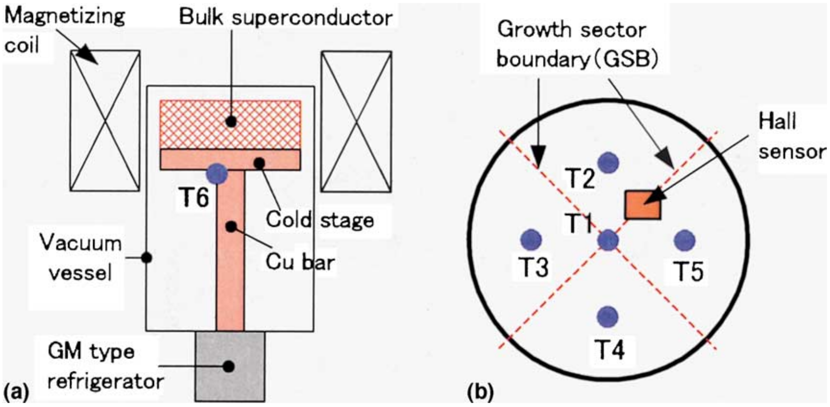


Fig. 1. Experimental equipment and arrangement of thermocouples. (a) A schematic of measurement equipment. SmBaCuO bulk superconductor is set on a copper base connected to a cold head of GM refrigerator and they are covered with a vacuum vessel. The bulk superconductor is magnetized by an inducting magnet. (b) Arrangement of thermocouples. T1 is put in the center and other thermocouples of T2–T4 are attached to each four inter-GSB regions, respectively.

results in the past experiment [13,14]. Teflon-coated chromel-constantan thermocouples of 76 μm in diameter are adhered on the surface of bulk superconductor using the GE7031 varnish. The arrangement of five thermocouples (T1, T2, ..., T5) is displayed in Fig. 1(b). T1 is put in the center where two GSB lines cross. Other thermocouples of T2–T5 are put in each four inter-GSB regions, respectively. Another thermocouple T6 is attached to the cold stage as shown in Fig. 1(a). A Hall sensor (F.W. Bell, BHT-921) is put near T1 to measure a magnetic flux density of trapped field. A superinsulation is wound around the bulk superconductor and they are covered with a vacuum vessel.

A magnetizing coil, which is solenoid coil winding copper wire and dips in liquid nitrogen, is arranged outside the vacuum vessel in Fig. 1(a) and exciting current is supplied by a condenser bank of 60 mF. A rising time of the pulsed-field is 10 ms and a maximum field of 7 T is generated. After a bulk superconductor is cooled down to 40 K, pulsed-fields of 2.32–5.42 T are applied. Each thermoelectric voltage of the thermocouples and a trapped field are measured about 7 times/s just before applying a pulsed-filed. After the magnetization, the magnetizing coil is removed and then the distribution of magnetic flux density at 3.5 mm above the bulk surface is scanned.

## 3. Results and discussion

Fig. 2 shows the relationship between applied fields $\mu_0 H$ and trapped fields $B_T$ in magnetizing process by IMRA method, where $B_T$ is the value measured by a Hall sensor on the surface of the bulk. Magnetic fields are impressed 14 times in order of 1, 2, ..., 14 changing strength of applied

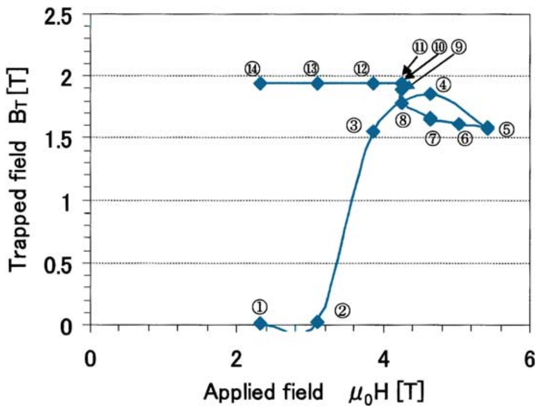


Fig. 2. The relationship between trapped field and applied field in the magnetizing process by the "IMRA" method. Trapped fields are measured with a Hall sensor attached at the center of the top surface of Sm123 bulk superconductors. Magnetic fields are impressed 14 times in order of 1, 2, ..., 14 changing strength of applied field, where it is increased from nos. 1–5 and decreased after no. 6.

field, where $\mu_0 H$ is increased from nos. 1 to 5 and decreased after no. 6. Temperatures and the magnetic field distributions are measured for every one excitation. Also, the following pulsed-field is excited after the temperature is stabilized at 40 K and then the interval is about 40–60 min.

In the increasing process of applied fields, $B_T$ increases with increase of $\mu_0 H$ and takes the local maximum of 1.86 T when $\mu_0 H = 4.64$ T. When a stronger magnetic field $\mu_0 H = 5.42$ T is impressed, it decreases to 1.58 T. Figs. 3 and 4 show (a) the time dependence of temperatures and (b) magnetic flux distribution when $\mu_0 H = 3.10$ T (no. 2) and 5.42 T (no. 5), respectively.

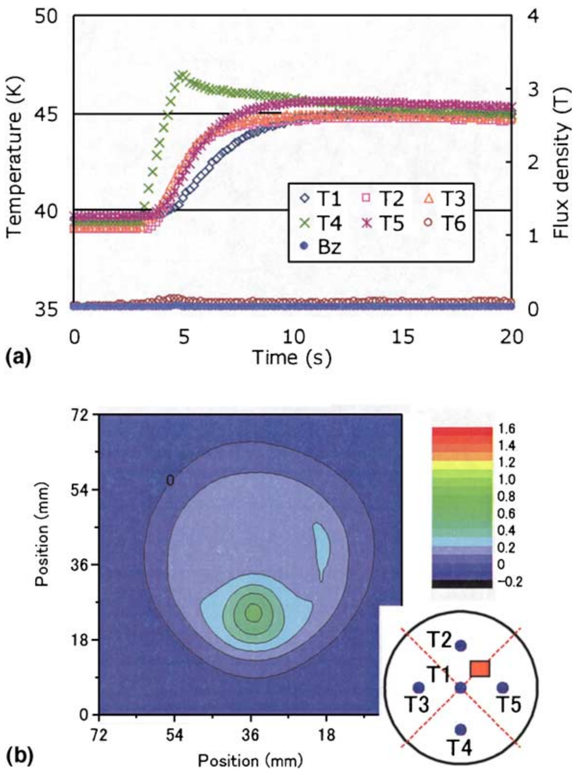


Fig. 3. Experimental results in the exciting field of 3.10 T. (a) Time responses of temperatures at T1–T6 and trapped filed. The left and right axes express the temperature and trapped field, respectively. The rising time of temperature change at T4 is the fastest of the other part and peak temperature is the highest, too. (b) Trapped field distribution 3.5 mm above the bulk surface. Magnetic fluxes are trapped only at the portion of T4.

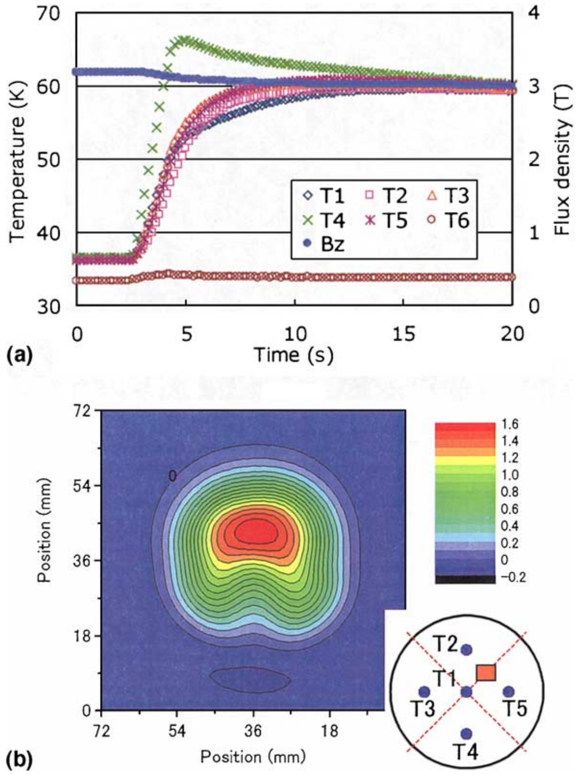


Fig. 4. Experimental results in the exciting field of 5.42 T. (a) Time responses of temperatures at T1–T6 and trapped filed. The left and right axes express the temperature and trapped field, respectively. A rising time of T4 is the fastest and maximum temperature reaches to 66 K. (b) Trapped field distribution 3.5 mm above the bulk surface. The distribution is indented at the portion of T4 and then it is the so-called C type distribution.

In Fig. 3(a), a rising time of T4 is the fastest and a maximum temperature is the highest of other parts. This shows that magnetic fluxes invade only from the portion of T4 though they are shielded inside the bulk superconductor since the applied field is weak. On the other hand, a temperature rise of T1 is the slowest and it is considered that a heat generation of T1 is caused by transmitting the heat generated on the perimeter. These results correspond well with the magnetic field distribution illustrated in Fig. 3(b) and magnetic fluxes are trapped only at the portion of T4 though they are small.

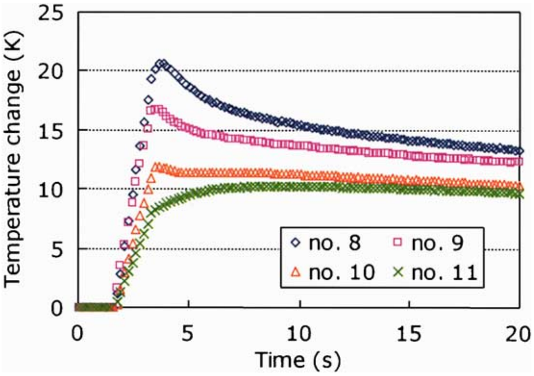


Fig. 5. Time dependence of temperature changes at T4 when magnetic field of 4.26 T is applied 4 times (pulse nos. 8–11). A temperature rise is about 21 K at no. 8 and it becomes small whenever a magnetic field is impressed and it is 10 K at no. 11. Also, the local maximum does not appear in no. 11 though it appears in nos. 8–10.

In Fig. 4(a), a rising time of T4 is the fastest and maximum temperature reaches to 66 K. Unlike $\mu_0 H = 3.10$ T, temperatures of the other parts including T1 are simultaneously rising and it means that magnetic fluxes invade to the center of the bulk since applied field is large. On the other hand, $B_T$ decreases after the excitation and the magnetic field distribution shown in Fig. 4(b) is indented at the portion of T4. It means that magnetic fluxes escape through T4.

From these results, it is considered that the place of low-$J_c$ is located locally in the portion of T4 and that becomes the channel along which magnetic fluxes pass. When applied field is weak, since pinning loss is small and heat generation also is little, magnetic fluxes invade from T4 and they are trapped there. When applied field is large, on the other hand, since pinning loss becomes large

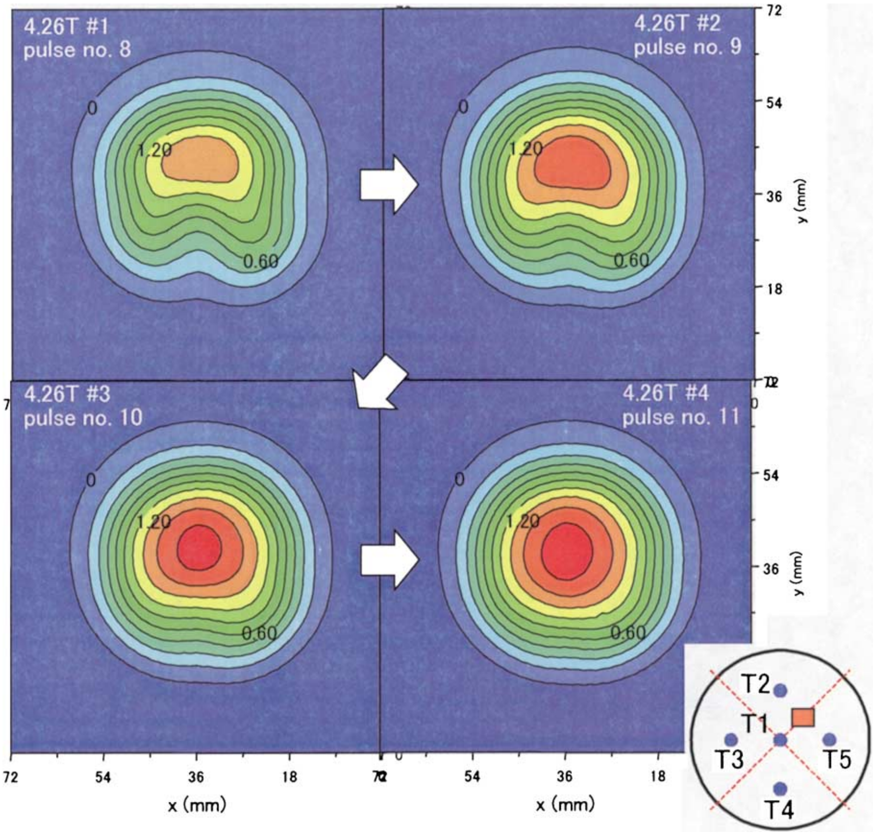


Fig. 6. Trapped field distributions when magnetic field of 4.26 T is applied 4 times (pulse nos. 8–11). Magnetic fluxes are gradually added for the dent portion of the portion of T4, and at last, it becomes the round distribution which is alike in FC.

and heat generation also is large, $J_c$ is lowered and magnetic fluxes go away.

In IMRA method, when a trapped field is decreased, the applied field is lowered. In Fig. 2, it lowers 0.39 T of applied fields at a time after pulse no. 6. Since heat generation also becomes little because the applied field is small, trapped field increases gradually. When the magnetic field of 4.26 T is impressed (pulse no. 8), $B_T$ increases greatly compared with pulse nos. 6 and 7. Then, the magnetic fields of the same strength are impressed iteratively.

Figs. 5 and 6 show the time dependence of temperature changes at T4 and the magnetic field distributions when magnetic field of 4.26 T is applied 4 times (pulse nos. 8–11), respectively. Although the magnetic field distribution has C form where the portion of T4 is dented in pulse no. 8, magnetic fluxes are gradually added for the dent portion, and at last, it becomes the round distribution which is alike in FC. In the time dependence of temperature change, on the other hand, a temperature rise is about 21 K at no. 8 and it becomes small whenever a magnetic field is impressed and it is 10 K at no. 11. Also, the local maximum of temperature does not appear in no. 11 though it appears in nos. 8–10. It is considered that pinning loss decreases since magnetic fluxes are trapped almost to the limit in bulk superconductors and thus the pinning center which participates in capture of a magnetic field is lost. From these results, a temperature rise is suppressed although magnetic fluxes invade the inside of bulk when the magnetic field of suitable strength is impressed. Therefore, heat generation is little after second excitation of 4.26 T and thus magnetic fluxes are able to be trapped at the position of T4.

Since a trapped field and temperature hardly change by pulse nos. 10 and 11 because magnetic fluxes are trapped in the bulk fully, strength of applied field is lowered. In pulse nos. 12–14, temperature changes are almost fixed and trapped fields do not increase, since applied field is weak and thus they cannot invade the inside of bulk. However, magnetic fluxes are added to the perimeter of bulk without heat generation, and therefore, total amount of magnetic fluxes increases and a strong magnetic field is formed.

## 4. Conclusions

We investigated temperature changes of Sm123 bulk superconductor on the magnetizing process by IMRA method and considered the magnetizing mechanism. Temperatures were monitored by thermocouples attached at four inter-GSB regions and at the center on the surface of the bulk, and the trapped field distributions were scanned.

When the applied field is large, pinning loss becomes large and heat generation also is large, and thus, $J_c$ is lowered. Moreover, the place of low-$J_c$ was located locally and that became the channel along which magnetic fluxes past. Thus, the magnetic field distribution had C form with which a part of circle was dented. Next, when a weak magnetic field was impressed, pinning loss became small and heat generation was little. Then, magnetic fluxes were gradually trapped for the dent portion and it became the round distribution which was alike in FC. That is, the IMRA method was the magnetizing process which utilized heterogeneity of bulk superconductors.

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