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# Thermal Behavior and Field-Trapping Property of Melt-Textured Superconducting Bulk Magnets Activated by Quasi-Static Magnetic Fields

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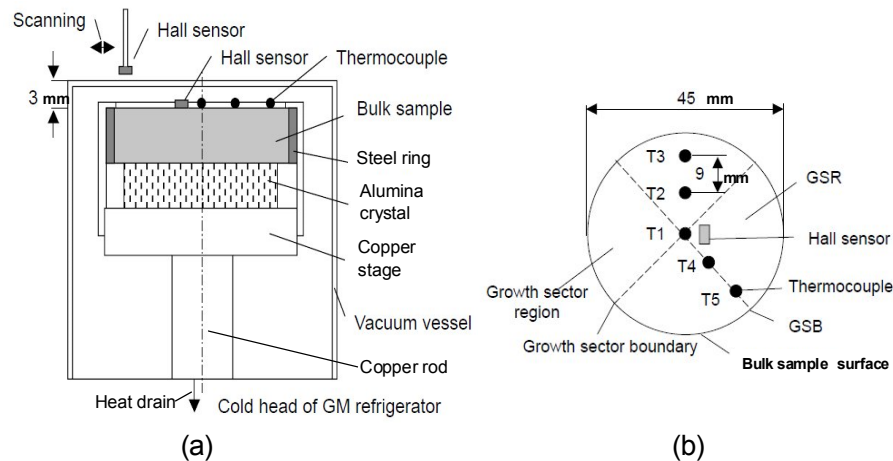
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**Abstract.** The thermal and field trapping behaviors of melt-processed RE-Ba-Cu-O (RE=Y, Sm) bulk superconductors during their magnetization processes conducted in the zero field cooling (ZFC) were investigated in comparison with the field cooling (FC) operations in the temperature range around 50 K. The temperature changes were precisely measured by five thermocouples attached on the sample surface. The authors discuss the relationship between the heat generation and resultant trapped magnetic field ability by means of the direct temperature measurement during these magnetizing processes. As the applied field is not satisfactorily given to the sample, the trapped field distributions activated in ZFC process show trapezoid shapes, whereas they show a corn shape without any strain when magnetized in FC process. The trapped magnetic field gradually increases even after when the applied magnetic fields reaches the highest value. According to the balance on the heat generation and drain, the temperature evolution shows us an almost stable state. These data suggest that the improvement with respect to the heat propagation of the bulk material must suppress the temperature rises and enhance the resultant flux trapping ability.

## 1. Introduction

The melt-textured large grain bulk superconductors composed of RE-Ba-Cu-O compounds (RE=Y, Sm, Gd, abbreviated as RE123) which includes RE211 particles perform the excellent property as quasi-permanent magnets when they trap the applied magnetic fields [1, 2]. The maximum trapped field has reached 16 T at 24 K by doping Zn to it, as reported by Gruss et al. [3]. The highest value of 17.24 T has been reported by Tomita et al. [4] by reinforcing the Y123 bulk sample by the resin impregnation technique. The data thus referred as the trapping ability of bulk magnets are generally obtained by the field cooling method (hereafter abbreviated as FC). In the magnetizing process using the pulsed fields (PFM), it is known that the flux motion causes local heating in the sample, raises the temperature, lowers the critical current density, and subsequently degrades the trapped field ability [5]. A smart process called MMPSC as a kind of PFM processes has recently derived the maximum performance of trapped field of 5.2 T, which was conducted by Fujishiro et al. [6, 7] in the way that



**Figure 1.** Experimental setup shown in (a) side view of magnetic pole and (b) top view showing the positions of thermocouples and a Hall sensor on the sample surface.

suppresses the heat generation by means of applying iterative pulsed fields at two temperatures. Since it must be undoubtedly important for us to suppress the temperature rise even during the FC process, the sweep rates of applied fields must be carefully chosen to be slow in the FC process [8, 9].

In the study, we aim the evaluation on the temperature rises due to the heat generation by flux motion in the bulk materials during the zero field cooling ZFC and FC processes for the Y-Ba-Cu-O and Sm-Ba-Cu-O bulk superconductors cooled at around 50 K.

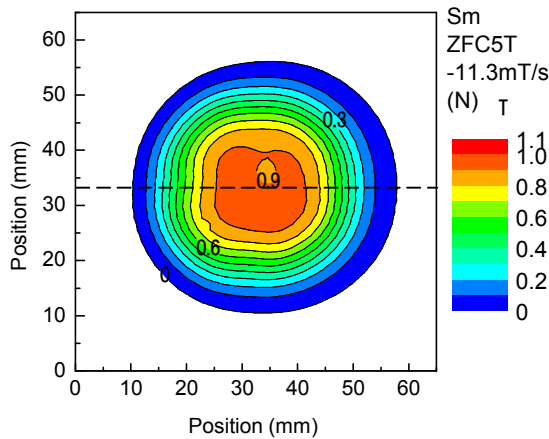
## 2. Experimental procedures

Schematic views of the experimental setup are shown in Fig. 1. A melt-processed Y123 bulk sample was manufactured by Dowa Mining Co., LTD. and adapted to the FC operation [8]. The dimensions of the sample were 45 mm in diameter and 15 mm in thickness. A same shape of Sm123 sample was adapted to the magnetization experiment by the ZFC process [9]. Five pairs of chromel-constantan thermocouples (T1-T5) were glued on both positions of a grain sector region and a grain sector boundary shown in Fig. 1(b). A Hall sensor (Bell, BHT 921) was also attached near the center of the bulk surface. In the FC process, a static field of 5 T was applied in the higher temperature ranges than  $T_c$ , and then the sample was cooled to the lowest temperature 50 K by a Gifford-McMahon refrigerator (AISIN SEIKI Co., GR-103). Then the magnetic field is gradually reduced to zero with descending rates of -2.53, -5.06 and -11.3 mT/s. In the ZFC process, the magnetic field of 5 T was also applied and then removed with the rates 5.06 and 11.3 mT/s at the temperature around 50 K. After the magnetization process, the trapped field distributions were measured by scanning an axial-type Hall sensor just above the vacuum chamber.

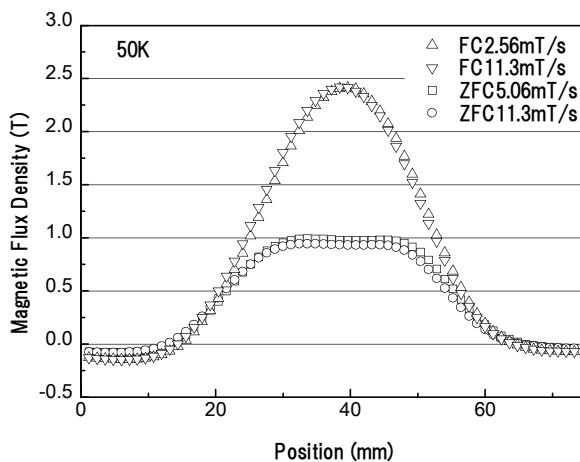
## 3. Results and Discussions

### 3.1. Trapped field distributions after ZFC and FC activation processes

The distribution of trapped magnetic flux density in ZFC process was measured by the scanning Hall probe outside the vacuum chamber, as shown in Fig. 2. One can obviously see that the distribution indicates concentric round contour lines of magnetic field and that the circles slightly deviate toward outside on the lines which correspond to the growth sector boundaries (GSB). This implies that the critical current density on GSB is rather superior to that in the growth sector regions.



**Figure 2.** Trapped field distribution after 5 T ZFC process at 50 K with a sweep rate of 11.3 mT/s.



**Figure 3.** Trapped field distributions after 5 T FC and ZFC processes with various sweep rates.

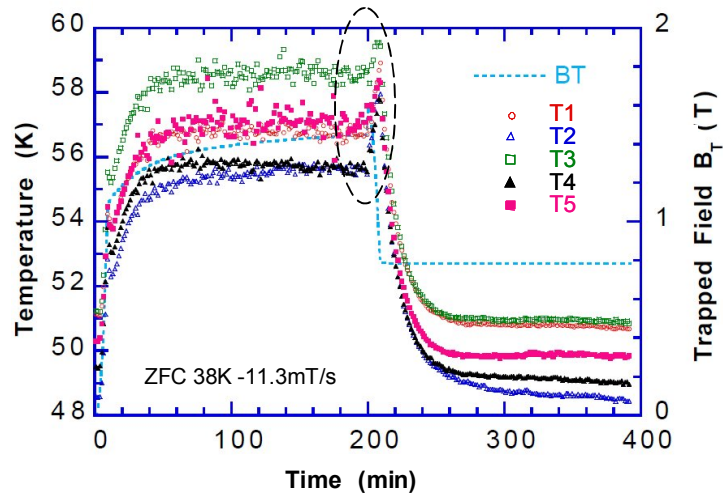
Figure 3 indicates the trapped field distribution along the dashed line in Fig. 2 with various sweeping rates of applied field in comparison with those in another ZFC and FC processes. As the applied field was not satisfactorily given to the sample, the trapped field distributions activated in ZFC process show a trapezoid shape, whereas they show a corn shape without any strain when the sample is magnetized in FC processes.

### 3.2 Temperature evolutions in the ZFC process

Figure 4 shows the temperature changes on its way of ZFC process with a sweep rate of 11.3 mT/s for Sm123 sample operated at initial temperatures around 50 K, whereas the cold head of the cooler was kept at 38 K. The profiles show that the temperatures began to rise immediately after when the magnetic field started rising at all the measured points. The temperature rises have soon saturated when the external field reached 5 T and stopped growing. The averaged temperature rise has reached 7.5 K until the field started decreasing. It is noted that the trapped field gradually keep increasing for about two hundred minutes even after the field stopped growing. This indicates that the flux distribution rearranges for a long time even in the static field and fluxes in the bulk sample still keep moving. The saturation of the temperatures implies that the heat generation and draining heat are almost balanced in the present condition. It is also suggested that the

improvement with respect to the heat propagation of the bulk material must suppress the temperature rises and enhance the resultant flux trapping ability.

According to the detailed thermal changes measured at the time of 200 minutes, as shown in the circle in Fig. 4, all the temperature data measured at all thermocouples rise together while the flux lines keep moving in the sample on the field descending stage. This is apparently attributed to the fact that the amount of generating heat is greater than draining one when the sweep rate is high. And the temperatures steeply start decreasing when the descending field reaches zero. The schematic illustration which explains the flux motion in the sample is shown in Fig. 5. The magnetic fluxes keep penetrating into the sample even after when the external field stops increasing, and fall into the central portion like a snow slide showing a flux creeping phenomenon.



**Figure 4.** Temperature and trapped field evolution in ZFC operation at around 50 K with a sweep rate of 11.3 mT/s. Cold head temperature was set at 38 K.

#### 4. Conclusions

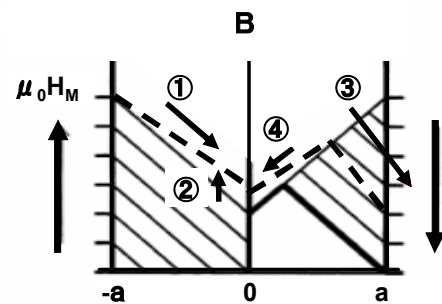
The temperature rises due to the heat generation of RE-Ba-Cu-O single domain bulk superconductors during the ZFC process have reached 7.5 K when the sample was magnetized with the sweeping rate of 11.3 mT/s. The invading flux exhibits the flux creeping due to the rearrangement of flux distribution even after when the external field stops increasing, and falls into the central portion like a snow slide. We have so far emphasized that the temperature change is never negligible even in the ZFC magnetizing operation as well as FC.

#### 5. Acknowledgement

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**Figure 5.** Illustration of invading flux in the Sm123 bulk sample in ZFC operation.