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Temperature changes in a melt-processed YBCO superconductor activated by field cooling magnetizing process

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Abstract

The temperature rise during the field cooling (FC) magnetizing process with various sweep rates by using a 10 T superconducting solenoid magnet was systematically evaluated with respect to an YBCO single domain trapped-field magnet cooled to 57–75 K by a GM refrigerator. The maximum temperature change has reached 6 K when the sweep rate was −11.3 mT/s and initial temperature of 57 K. The recent elevation of the sweep rate of superconducting magnet and the critical current density of bulk samples have made the heat generation serious even in the FC operation by quasi-static magnetic field.

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Keywords: Melt-process; Bulk superconductor; Trapped field magnet; Field cooling

1. Introduction

It is well-known that the melt-processed $REBa_2Cu_3O_y$ (RE = Y, Sm, Gd, abbreviated as RE123) bulk superconductors including RE_2BaCuO_5 (RE211) precipitates act as permanent magnets when they capture the magnetic field [1,2]. As was reported by Gruss et al. [3], the performances of the field-trapping ability of a Y123 compound has been greatly improved by doping Zn to it. The maximum trapped field has reached 16 T at 24 K. Recently, 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

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technique. The data thus referred as the trapping ability of bulk magnets are generally obtained by the field cooling method (hereafter abbreviated as FC).

Some experimental results on the heat generation due to the flux penetration during the pulsed field magnetization process (PFM) have been reported elsewhere [5]. The flux motion causes local heating in the sample, raises the temperature, lowers the critical current density, and subsequently degrades the field trapping ability. Ikuta et al. [6] reported that the temperature rise during the PFM at 77 K reaches up to 5 K. On the other hand, Yanagi et al. [7] reported they reached 17 K when the PFM was operated at 35 K. Various efforts such as "IMRA" method [8] or magnetizing method on the way of cooling the sample [9] have been made to suppress the heat generation. Fujishiro et al. [10,11] reported on the relationship between temperature-rises during the PFM process and suggested the possible improvement with respect to the field-trapping ability of the bulk materials.

We have considered it very important to suppress the temperature rise even during the FC process as well as the PFM. The sweep rates of applied fields are chosen to be sufficiently slow in the FC process. However, since the sweep rates of superconducting solenoid magnets have been improved to be faster, in conjunction with the enhancement of the critical current density of the bulk samples, the heat generation is no longer negligible even in the process. Tomita et al. have succeeded to suppress the temperature rise less than 1 K by slowing the field descending speed less than −5.8 mT/s. In the report, the temperature changes during the FC process as functions of the temperatures and the sweep rates on the reducing field are estimated for an YBCO bulk superconductor cooled around 57 K by the GM refrigerator.

2. Experimental details

Fig. 1 shows the schematic views of the experimental setup. A melt-processed Y–Ba–Cu–O bulk sample manufactured by Dowa Mining Co. consisted of $YBa_2Cu_3O_y$ (abbreviated as Y123) and Y_2BaCuO_5 (Y211) by a molar ratio of 5:2 with addition of 0.5 wt.% Pt. The dimensions of the sample were 45 mm in diameter and 15 mm in thickness. The sample was impregnated by epoxy resin reinforced by glass fibers. The trapped field distribution measured at 77 K showed a single domain shape with the maximum value of 0.9 T at the center of the bulk surface. The top resin layer was carefully removed as to measure the accurate thermal data by the thermocouples attached on the sample surface, and the bottom layer was also removed to improve the thermal conduction from the cold head of refrigerator.

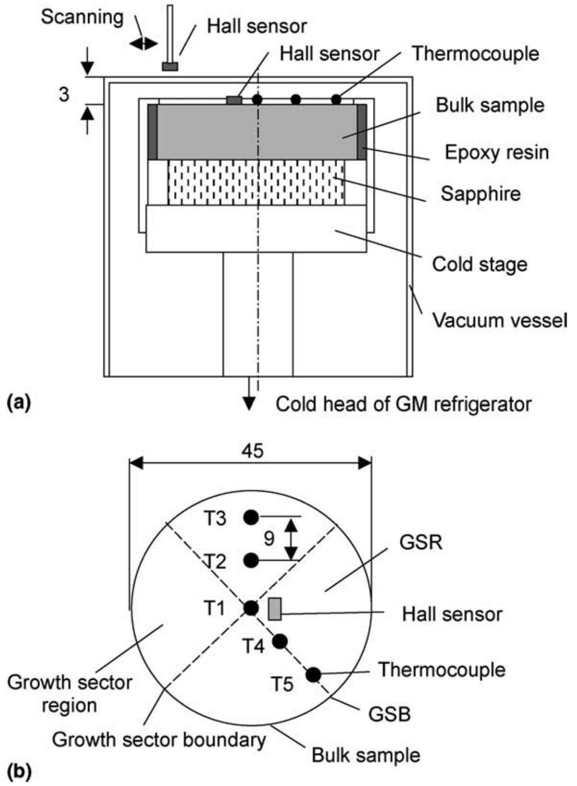

Fig. 1. Experimental setup for the temperature measurement for the Y-system bulk sample sustained on the cold stage of the cryostat (a) and positions of the temperature sensors on the sample surface (b).

The sample was placed on the cold stage with a sapphire plate, as shown in Fig. 1(a). Five pairs of chromel–constantan thermocouples (T1–T5) with a size of 0.76 mm in diameter for the shielded lines were glued on the positions shown in Fig. 1(b) by

GE 7031 varnish. A Hall sensor (Bell, BHT 921) was attached just near the center of the sample to monitor the applied magnetic field. A Pt–Co thermometer embedded in the cold head of the refrigerator controlled the temperatures of the cold stage.

The FC process was operated after setting the equipment in the room temperature bore of a 10 T superconducting solenoid magnet, which was manufactured by Japan Superconductor Technology Company. In the FC process, a static field of 5 T was applied in the higher temperature ranges than T_c, and the sample was cooled to the lowest temperature by a Gifford-McMahon type refrigerator (AISIN Seiki Co., GR-103). Then the magnetic field is reduced to zero with various descending rates that do not lead to quench the superconducting coil. The sweep rates of magnetic field on the descending stage were −2.53, −5.06, and −11.3 mT/s.

The trapped field distribution after the FC process was measured by scanning an axial-type Hall sensor just above the vacuum chamber. The direction of measurement was parallel to the bulk axis. The distance between the sensor and the bulk sample surface was 3.5 mm.

3. Results and discussions

3.1. Temperature changes after FC magnetization process

Fig. 2 shows the temperature changes of the sample for various descending rates of the magnetic field, −11.3, −5.06 and −2.53 mT/s. The data were measured by the thermocouple T1 at the surface center during FC magnetization process. The magnetic fields started decreasing from 5 T at $t = 0$ and arrived at 0 T showing their steep peaks of maximum temperatures. One can obviously see that the faster the speed of descending field the higher the temperature rises. The maximum temperature raise was observed as 5.9 K when the sweep rate was −11.3 mT/s.

The curves shown in Fig. 2 appear to consist of two changing rates in each rate. According to the critical state model, the magnetic fluxes start to scatter from the brink of the sample at the very beginning of the field reducing. The heat generation starts in the periphery region and gradually penetrates into the central portion. It arrives to the maximum value when the field change reaches the center of the sample.

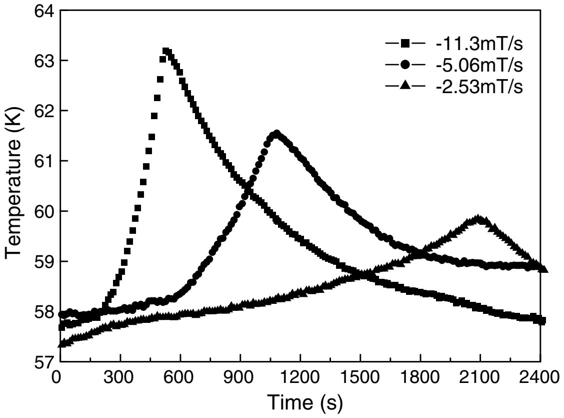

Fig. 2. Time evolutions of the temperatures measured at the center of the bulk sample surface (T1) with various sweep rates during the FC process operated form 5 to 0 T.

Fig. 3 indicates the temperature changes measured in the FC at various temperatures as a function of field descending rates. All of the

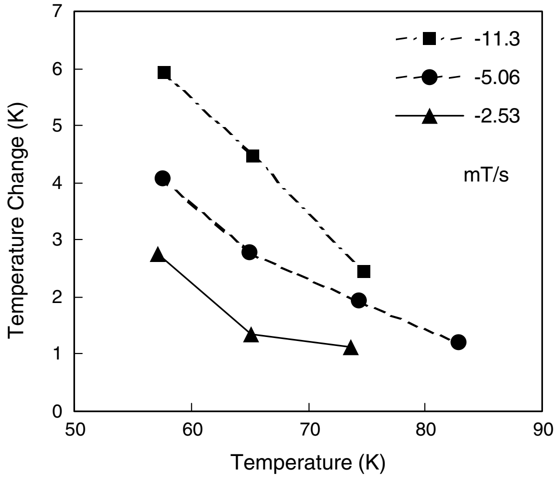

Fig. 3. The temperature changes at the bulk magnet surface for the initial temperatures before lowering fields as a function of sweep rates of the reducing magnetic field. The averaged temperature data derived from T1 to T5 were used.

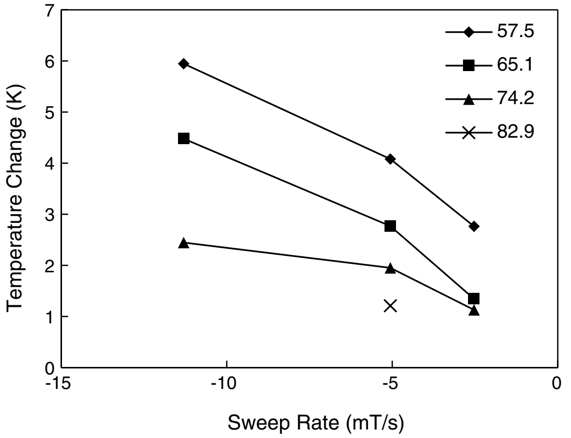

Fig. 4. The temperature rise measured on the bulk magnet surface as a function of sweep rates of reducing magnetic field. The averaged temperature data (derived from T1 to T5) were cited in the figure.

temperature data plotted in Fig. 3 were averaged T1–T5 before and after FC. One can see the apparent dependency of temperature rise on the initial temperature before FC. The lower the initial temperature, the higher the maximum temperature rises. It is attributed to the facts that the specific heat of the sample decreases whereas the pinning force increases when it is cooled to the lower temperatures [10]. The maximum temperature rise of 6 K was observed when the FC was operated with the sweeping rate of −11.3 mT/s at the initial temperature of 57 K.

The sweep rate dependent of temperature rise is shown in Fig. 4. The faster descend on the applied field causes the faster motion of fluxes. As was reported by Ikuta et al. [6]., the heat generation is proportion to the flux speed, viscous force is proportion to the square of that. Hence the pinning force is strongly responsible to the heat generation.

3.2. Trapped magnetic field

Trapped magnetic flux density is plotted as a function of sweep rates in Fig. 5. As the position of Hall sensor is slightly put aside from the center of sample surface, the plotted points do not represent the field trapping ability of each FC operation, however they have exhibited the superior values of over 3 T. An apparent scatter of data was observed

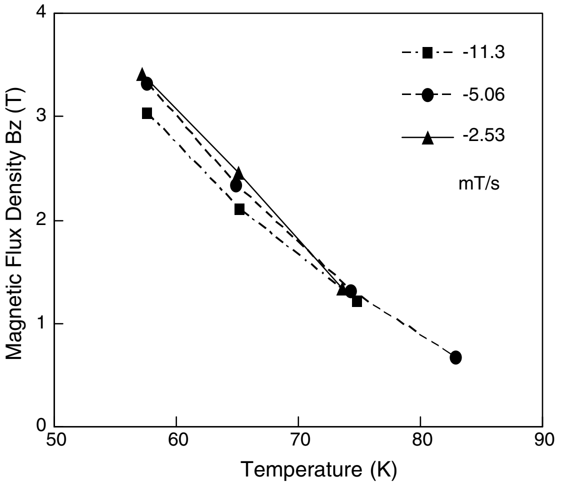

Fig. 5. Trapped magnetic flux density measured on the surface of the bulk magnet for the temperature as a function of sweep rates of the reducing magnetic field. The position of the Hall sensor is shown in the Fig. 1.

at 57 K. It suggests that the trapped field is strongly influenced by the sweeping rate during FC. The decline was estimated to be 11.7% of the maximum data 3.415 T. As shown in Fig. 6, the sweep rate dependency is quite clear at every temperature. That implies that the sweeping rate is really necessary to be carefully controlled so as to suppress the

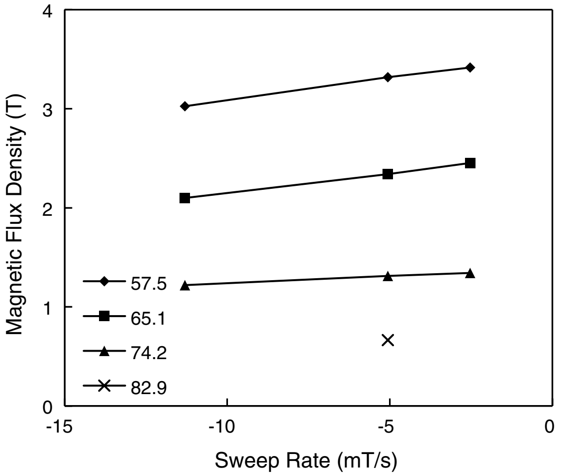

Fig. 6. Sweep rate dependent for the trapped magnetic flux density as a function of the averaged temperatures.

heat generation due to the flux motion in the high field trapping bulk sample.

3.3. Position dependence of temperature change

Fig. 7 shows the temperature development measured at every thermocouple T1–T5. The sweep rate was −11.3 mT/s at 57 K. The profiles reach the maximum values at the same time. It indicates that the generating heat diffuses in a short time to all the portions of the sample. The fact that the temperatures at T4 and T5 are slightly higher than the rests may possibly suggest that the heat generation does not uniformly occurs and that is responsible for the variety of critical current density that is originated from the microstructure, such as the dispersion of pinning centers. It is not clear at present because of the variation of the initial temperatures on the surface and further investigation is necessary to clarify the phenomena.

3.4. Trapped field distribution

Fig. 8 shows a trapped field distribution map magnetized with a reducing rate of −11.3 mT/s at 57 K, and the temperature rise during FC was 6 K. The map was measured in the horizontal plane 3.5 mm above the bulk surface. The distribution indicates concentric round contour lines of magnetic field and that no serious cracks exist in the sample. One can note that the circles on the dashed-lines which corresponds to the growth sector boundaries (GSB) slightly deviates outside. It shows that the critical current density on the GSBs is rather superior to that in the growth sector regions. The inhomogeneous heat generation is regard to be less influential to the whole trapped field distribution map that was measured above 3.5 mm from the surface, in spite of the temperature rise of 6 K. All the data were listed in Table 1. It is worthwhile mentioning that even the slowest sweeping rate of −2.53 mT/s results in the temperature rise of 3 K at 57 K.

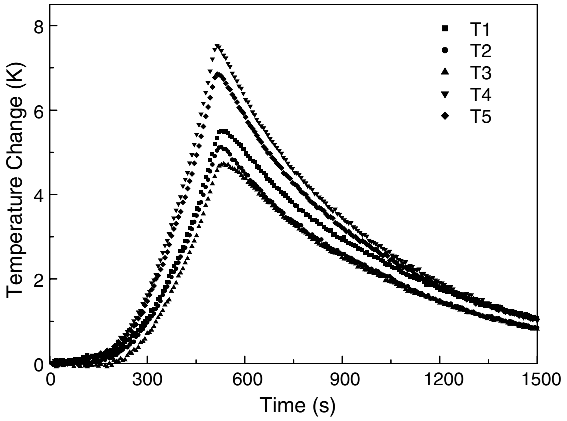

Fig. 7. Normalized temperature changes of various positions on the bulk sample.

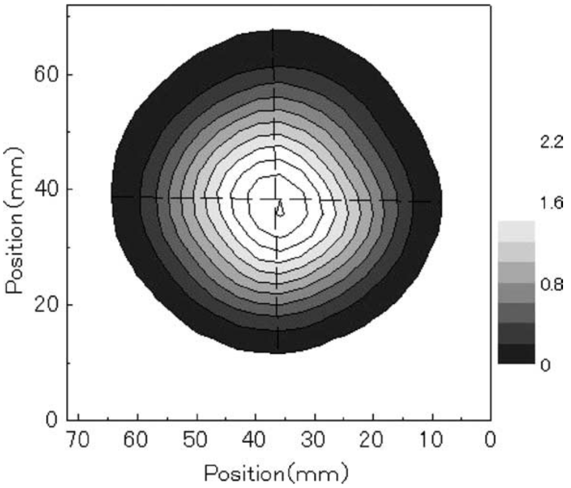

Fig. 8. Trapped field distribution map of bulk sample measured by a scanning Hall probe 5 mm above the vacuum surface. Dashed lines show the growth sector boundaries.

Table 1
Temperature and trapped filed data for the field cooling process

Sweep rate (mT/s)	Initial averaged temperature (K)	Averaged temperature change δT (K)	Trapped field B_z (T)
−2.53	57.2	2.8	3.415
	65.1	1.3	2.453
	73.6	1.1	1.341
−5.06	57.6	4.1	3.319
	64.9	2.8	2.340
	74.3	1.9	1.313
	82.9	1.2	0.665
−11.3	57.6	5.9	3.025
	65.2	4.5	2.098
	74.8	2.4	1.219

4. Conclusions

The temperature rise of a YBCO single domain bulk superconductor in FC process has reached 6 K when the sample was magnetized with the fastest descending speed of −11.3 mT/s. Strong dependency on the resultant trapped magnetic field and sweep rate during FC operation was certified. It was found that the planar variation of the critical current density on the sample surface has an effect on the performance as a trapped-field magnet. We have so far emphasized that the temperature change is never a negligible phenomena even in the FC magnetizing operation using quasi-static magnetic field.

Acknowledgement

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