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J_c distribution measurement and analysis on superconducting bulk using "Magnetoscan" method

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ABSTRACT

We have investigated the detection of the crystal defects and/or inhomogeneity of critical current density (J_c) in superconducting bulk experimentally and theoretically by the "Magnetoscan" technique. To detect them sensitively, the Hall probe located near the permanent magnet should be scanned as near as possible on the surface of the superconducting bulk. The scan of the permanent magnet causes the field trap on the bulk, which seriously influences the magnetoscan signal detected by Hall probe.

1. Introduction

The critical current density (J_c) is one of the most important parameters for high temperature superconducting bulks, tapes and thin films. The contact-less and non-destructive techniques to measure the J_c value and its distribution are desired for the practical application as a substitute for a direct measurement by a four-probe method. For example, a third harmonics method was developed for the superconductors to measure the J_c distribution [1]. When an ac magnetic field is applied to the superconductor by a multi-turn coil, the third harmonics generated by the shielding current are suddenly exited and the J_c distribution was detected. Ohshima et al. proposed the permanent magnet method for measurement of J_c distribution [2]. After approaching a permanent magnet closer to the superconductor, the maximum of the electromagnetic force is found to be approximately proportional to J_c. Eisterer et al. proposed a "Magnetoscan" technique to detect the local inhomogeneities directly without destroying the bulk crystal [3].

For a superconducting bulk, the J_c value cannot be measured directly using a conventional four-probe method because of large heat generation at the electric contacts. As a result, the J_c value is usually estimated by a magnetization method, that is *M-H* curve, using a small peace cut from the bulk crystal [4]. On the other hand, the J_c distribution for the whole bulk disk is commonly estimated by scanning the remnant magnetic flux profile after field-cooled magnetization (FCM), which is called "Hall scan". This technique is rather insensitive to the material inhomogeneity, since all parts of the sample volume contribute to the magnetic field at each measuring point, although the melt processed bulks are strongly inhomogeneous. We have investigated the enhancement of the trapped field B_T magnetized by pulsed field magnetization (PFM) and the relation between the trapped field profile and the J_c distribution [5]. The trapped field profile on the bulk magnetized by PFM was fairly inhomogeneous because of the complicated flux motion and the instantaneous and local temperature rise. The development of the measuring technique to connect the trapped field profile by PFM with the J_c distribution is desired.

In this paper, we constructed the apparatus of the "Magnetoscan" technique to detect the J_c distribution and/or crystal defects on the superconducting bulk. We investigated the optimum configuration between the permanent magnet, the Hall probe and the bulk surface experimentally and theoretically.

2. Experimental setup

Fig. 1a shows the experimental setup of the Magnetoscan method, which was proposed by Eisterer et al. [3]. A Hall probe (AREPOC, HHP-VP) with an active area of $0.05 \times 0.05\ mm^2$ was fixed on the edge of the small NdFeB permanent magnet (φ 6 mm, 20 mm in height; the surface magnetic field of 0.43 T). The permanent magnet and Hall probe were mounted in the GFRP holder in which the distance between the center of the permanent magnet and that of the active region of the Hall probe was fixed L_0 = 5.7 mm. The holder was scanned with a step of 0.5 mm along a "*meander line*" just above the bulk dipped in liquid nitrogen and the magnetoscan signal B_z along the *z*-direction, which was detected by the Hall probe, was recorded. The permanent magnet always follows the Hall probe. By scanning the Hall probe together with the magnet slightly above the bulk surface, local differences in J_c, associated with material inhomogeneity or crystal

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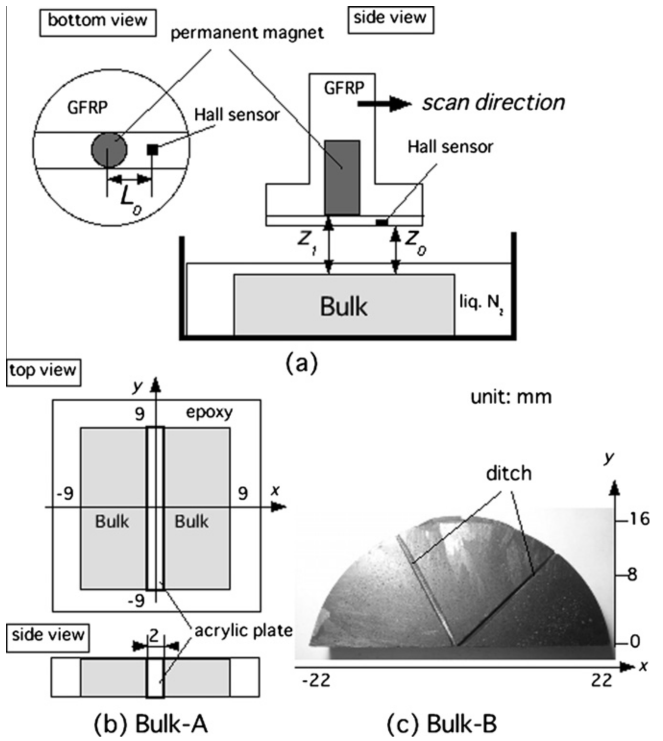

Fig. 1. (a) The experimental setup of the "Magnetoscan" method. The measured samples of (b) Bulk-A and (c) Bulk-B are indicated.

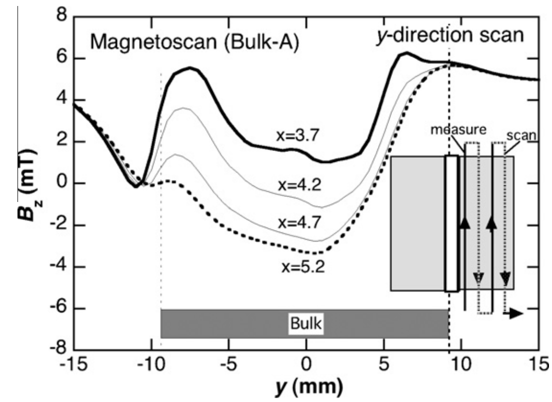

Fig. 2. The magnetoscan signals B_z for the Bulk-A at 77 K. The scan was performed along the y-direction.

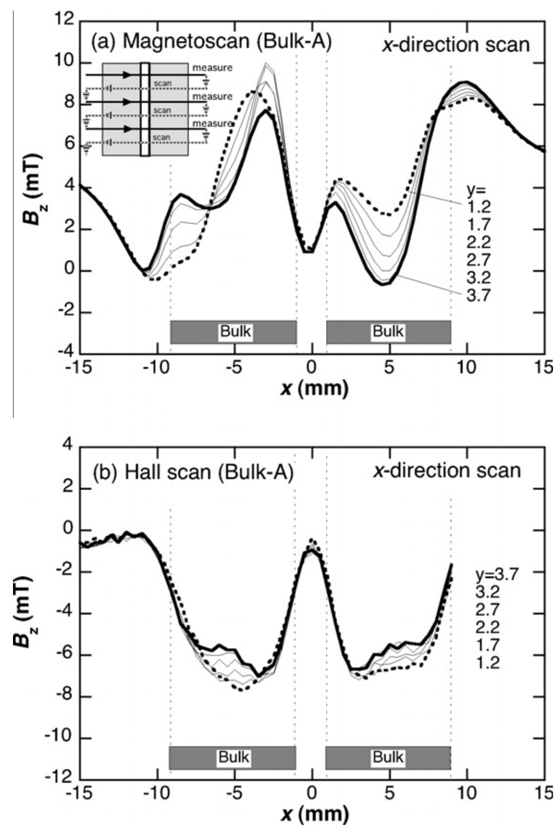

Fig. 3. The (a) "magnetoscan" signals B_z and the (b) "Hall scan" signals B_z for the Bulk-A at 77 K. The scan was performed along the x-direction across the acrylic plate.

defect, are detected. The gap between the Hall probe and the bulk surface was Z_0 = 0.25 mm and between the face of the permanent magnet and the bulk surface Z_1 = 1.5 mm.

We measured the bulk sample (Bulk-A) shown in Fig. 1b, in which the acrylic plate with 2 mm in thickness was sandwiched by two GdBaCuO bulk blocks ($9 \times 18 \times 3$ mm^3) using epoxy resin. After the "Magnetoscan", the remnant magnetic field B_z was measured along a same meander line using the another Hall sensor (Bell, BHA921; active area φ 0.51 mm) without magnet, which was named the "Hall scan". The "magnetoscan" signal was also measured using a half GdBaCuO disk (Bulk-B) (φ 45 mm and 5 mm in thickness) as shown in Fig. 1c, in which the two ditches (0.8 mm in width and 1.3 mm in depth) were scribed on the surface as quasi-crystal defects.

3. Results and discussion

3.1. Results of experiments

Fig. 2 depicts the magnetoscan signals B_z scanned along the y-direction for the Bulk-A at 77 K. At the edge of the bulk, the signal shows a dip for the scan from epoxy to bulk and shows a peak for the scan from bulk to epoxy. It should be noted that the shape of the magnetoscan signal changes with increasing the number of scanning; the depth of the dip and the peak height in the B_z–y profile become broad.

Fig. 3a presents the profiles of the magnetoscan signal B_z scanned along the x-direction across the acrylic plate for the Bulk-A at 77 K. The magnetoscan signal at the bulk edge shows a similar shape to the y-direction scan, and a new dip and peak profile can be seen around the acrylic plate, which suggests that the crystal defect or inhomogeneity of J_c as small as 2 mm in size can be detected by the magnetoscan signal. It should be noted that the shape of the magnetoscan signal around the acrylic plate changes with increasing number of scanning, similarly to that at the edge of the bulk. Fig. 3b shows the "Hall scan" profiles scanned along the x-direction after the magnetoscan for the Bulk-A. The Hall scan profiles suggest that the magnetic flux was not trapped on the acrylic plate, but on the superconducting bulk clearly during the magnetoscan process. This result suggests that the Hall scan after the scanning of the permanent magnet is a possible technique to detect the inhomogeneity of J_c and/or the crystal defect on the bulk surface.

Fig. 4 shows the magnetoscan signals B_z scanned along the x-direction for the Bulk-B. The anomaly of the magnetoscan signals can be detected both at the ditches 0.8 mm in width and at the edge of the bulk.

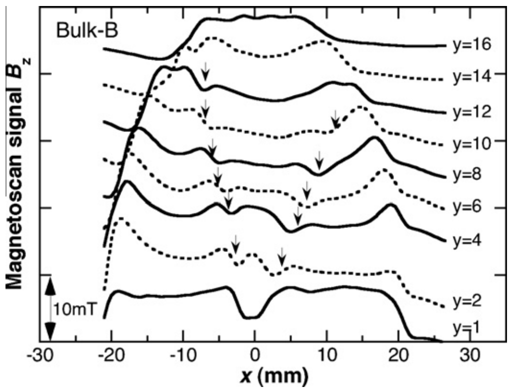

Fig. 4. The magnetoscan signals B_z for the Bulk-B at 77 K. The scan was performed along the x-direction.

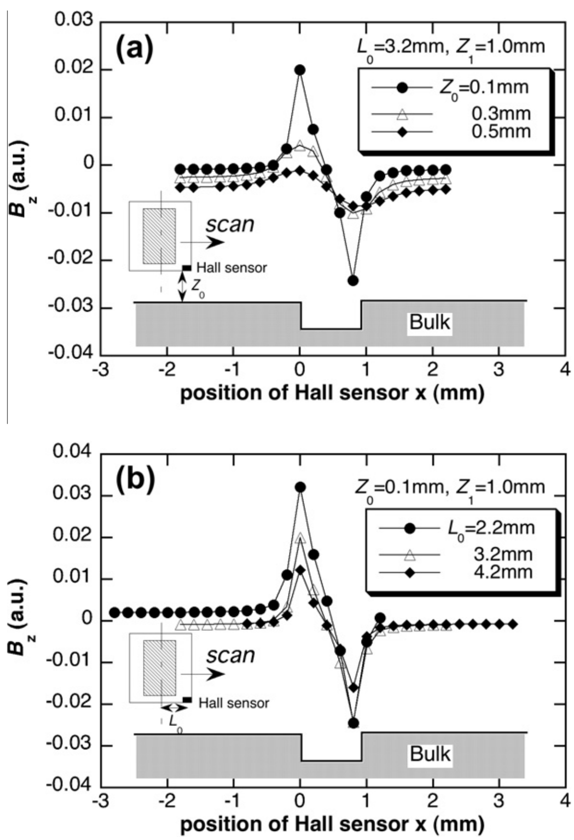

Fig. 5. (a) The simulated magnetoscan signal B_z as a function of Z_0 under the conditions of constant L_0 = 3.2 mm and Z_1 = 1.0 mm values. (b) The magnetoscan signal B_z as a function of L_0 under the conditions of constant Z_0 = 0.1 mm and Z_1 = 1.0 mm values.

3.2. Results of simulation

We have simulated the shape and the magnitude of the magnetoscan signal as parameters of the configurations between permanent magnet, Hall probe and surface of the bulk. Let us consider a superconducting bulk ($J_c = 1.0 \times 10^8$ A/m^2 at 77 K) with a ditch 1 mm in width and 0.5 mm in depth as a quasi-crystal defect on the bulk surface. In the simulation, a permanent magnet was replaced with a small coil equivalently and the current was induced in the coil. Physical phenomena during magnetoscan were described using electromagnetic equation [6], and the magnetic flux distribution and the magnetoscan signals (B_z, B_x) detected by the Hall probe were calculated in the gap between the coil and the bulk for each position.

Fig. 5a shows the simulated magnetoscan signal B_z as a function of Z_0 under the conditions of constant L_0 = 3.2 mm and Z_1 = 1.0 mm values. The simulated profile shows a peak for the scan from bulk to ditch (x = 0 mm) and shows a dip for the scan from ditch to bulk (x = 1 mm), which reproduce the experimental results as shown in Fig. 3a. The signal becomes sharp and large drastically with decreasing Z_0. Fig. 5b shows the magnetoscan signal B_z as a function of L_0 under the conditions of constant Z_0 = 0.1 mm and Z_1 = 1.0 mm values. The B_z value becomes sharp and large with decreasing L_0. However, the change in $B_z(L_0)$ is rather moderate compared with the Z_0 dependence of the B_z signal. The Z_0 and L_0 dependences of the magnetoscan signal were also confirmed experimentally (not shown).

Fig. 6 shows the simulated magnetoscan signal B_x along the x-direction as a function of L_0 under the conditions of constant Z_0 = 0.1 mm and Z_1 = 1.0 mm values. The magnitude of B_y decreases with increasing L_0, which is a similar behavior to B_z as shown in Fig. 5b. The results of the simulation are consistent with those reported by Zehetmayer et al. [7].

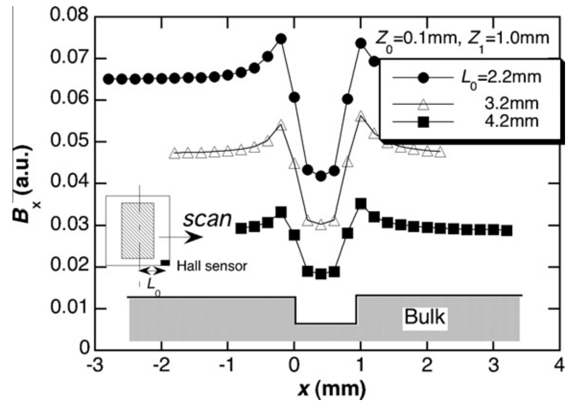

Fig. 6. The simulated magnetoscan signal B_x along the x-direction as a function of L_0 under the conditions of constant Z_0 = 0.1 mm and Z_1 = 1.0 mm values. The scan was also performed along the x-direction.

4. Summary

We have investigated the detection of the crystal defects and/or inhomogeneity of critical current density (J_c) in superconducting bulk experimentally and theoretically by the "Magnetoscan" technique. The important results and conclusions obtained from the study are summarized as follows,

(1) The quasi-crystal defects about 1–2 mm in size can be detected by the Magnetoscan technique experimentally.
(2) The magnitude of the magnetocan signal B_z increased sensitively with decreasing the gap Z_0 between the Hall probe and the surface of the bulk superconductor, which is also confirmed by the numerical simulation. The magnetoscan signal B_x parallel to the bulk surface is also sensitive to detect the quasi-crystal defect.
(3) The scan of the permanent magnet causes the field trap on the bulk surface, which seriously influences the magnetoscan signal detected by Hall probe. Therefore, the "Hall scan" after the scanning of the permanent magnet is a possible technique to detect the inhomogeneiety of J_c and/or the crystal defect on the bulk surface. The position and the magnitude of the permanent magnet must be optimized to enhance the sensitivity and the reliability of the magnetoscan signal.

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