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Direct J_c measurements and trapped field profiles using an identical superconducting bulk

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Abstract
We measured the trapped field profiles on a ⌀45 mm GdBCO superconducting bulk plate of 2 mm thickness magnetised using pulsed field magnetisation (PFM), zero-field-cooled magnetisation (ZFC) and field-cooled magnetisation (FCM). The profiles were compared with the distribution of the absolute value of the critical current density (J_c) estimated by the magnetisation measurements using small pieces cut from the bulk plate. The J_c value was enhanced about 20% below the seed crystal compared with that in the growth sector regions (GSRs). The J_c value was also slightly enhanced on the growth sector boundaries (GSBs). For a lower applied pulsed field than that for full magnetisation for PFM, a small amount of the magnetic flux was preferentially trapped at the lower J_c region around the bulk periphery, which was not necessarily similar to that by ZFC. For a higher applied pulsed field, the magnetic flux was finally trapped below the seed crystal and at the GSBs.

1. Introduction

Recently, pulsed field magnetisation (PFM) has been studied intensively as a convenient magnetising technique for superconducting bulk materials. The trapped field B_T^P by PFM was, however, small compared with the trapped field B_T^{FCM} by conventional field-cooled magnetisation (FCM) because of a large increase in temperature caused by the dynamical motion of the magnetic flux. The trapped field profile by FCM shows a symmetrical cone shape, even though a small fluctuation of the critical current density J_c exists in the bulk. However, the trapped field profile by PFM is very inhomogeneous in general [1] because the magnetic flux motion is as fast as 1–100 ms with a local and large temperature rise, which is thought to be highly sensitive to the inhomogeneous J_c distribution in the bulk. Yanagi *et al* reported that the magnetic flux was trapped in SmBCO bulk mainly around the growth sector region (GSR) for the lower magnetic pulse application; then the trapped flux region was inclined at 45° to the growth sector boundary (GSB) for the higher magnetic field [2]. These results suggest that the trapped field profile depends qualitatively on the J_c distribution and the strength of the applied pulsed field; J_c in the GSB is larger than that in the GSR. The J_c and the transition temperature T_c distributions using the magnetisation measurement were reported by Dewhurst *et al* for the YBCO bulk of 20 mm in diameter [3]. These values depended on the distance from the seed crystal along the radius and *c*-axis directions. However, the difference in the absolute value of J_c between GSB and GSR has not been reported. Eisterer *et al* measured the 'magnetoscan' profile at 77 K on the bulk, which was thought to represent the relative J_c distribution and investigated the relation between the magnetoscan profile and the trapped field one magnetised by FCM [4]. However, they did not report the absolute value of J_c on GSB and GSR, and there were no data on the position dependence of the absolute value of J_c.

Zero-field-cooled magnetisation (ZFC) is a magnetising technique using a superconducting coil, just as FCM does. Actually, ZFC can be regarded as a kind of PFM technique in which the duration of the applied magnetic pulse is as long as 100–1000 s. Consequently, the temperature rise for ZFC is fairly small because of the much lower velocity for the magnetic flux propagation than that for PFM [5]. The temperature rise for PFM also decreases concomitantly with decreasing strength of the pulsed field [6]. We can presume that the trapped field profile and the temperature rise for PFM with a lower pulse application than that for full magnetisation somewhat resembles those for ZFC. That is, the magnetic flux might be trapped around the lower J_c region for a lower pulsed field.

The superconducting bulk is commercially available as 30–60 mm in diameter, with 10–20 mm thickness. The inhomogeneity of the J_c might exist both in the *ab* plane and along the *c* axis in the bulk because of the characteristic mechanism of the crystal growth of bulk superconductors [7]. It is unsuitable to use the thick bulk to clarify the relation between the trapped field profile and the J_c distribution because of the inhomogeneity of J_c along the *c* axis. The penetration of the flux for the thin bulk occurs both from the side surface and from the top and bottom surfaces. The full penetration field for the thin bulk is much lower than that for the thick bulk and the flux dynamics may be different.

As described in this paper, we sliced the ⌀45 mm superconducting thick bulk to a thin plate of 2 mm thickness. We investigated the trapped field profiles on the thin bulk plate magnetised by PFM, ZFC and FCM under the lower applied field. The bulk plate was later cut into small pieces and the J_c distribution was estimated using the small pieces. The relation between the trapped field profiles and the distribution of the absolute value of J_c was investigated. The mechanism of the flux penetration and trap was also discussed during magnetising processes.

2. Experimental details

A ⌀45 mm GdBaCuO superconducting thin disc of 2 mm thickness (SRL/ISTEC, Japan) was sliced from the top surface of the 15 mm thick bulk disc [8], for which NdBaCuO single crystal was used as a seed crystal. Figure 1(a) presents the experimental set-up for PFM. The thin bulk disc was mounted tightly on the cold stage of a Gifford–McMahon (GM) cycle helium refrigerator with a 1 mm thick stainless steel cap. The magnetising solenoid copper coil, which was cooled using liquid nitrogen, was placed outside the vacuum chamber. The temperature T_s of the bulk was controlled to 40 or 60 K. A magnetic pulse B_{ex} with a rise time of 12 ms and duration of 100 ms was applied to the bulk plate. Two-dimensional trapped field profiles of B_T^P (1 mm) were mapped at a distance of $z = 1$ mm above the bulk surface, stepwise with a pitch of 1 mm by scanning an axial-type Hall sensor (BHA 921; F W Bell) inside the vacuum chamber using an x–y stage controller.

Figure 1(b) shows the experimental set-up for ZFC and FCM. The bulk plate was tightly anchored similarly on the refrigerator. The ZFC was performed at $T_s = 40$ K using a cryo-cooled superconducting solenoid magnet (JMTD-10T100, JASTEC. Inc.). During ZFC, the magnetic field was increased with 3 mT s^{-1}. Thereafter, it was kept at the maximum field for 10 min and then reduced to 0 T with -3 mT s^{-1}. For FCM, the magnetic field of 1.5 T was reduced

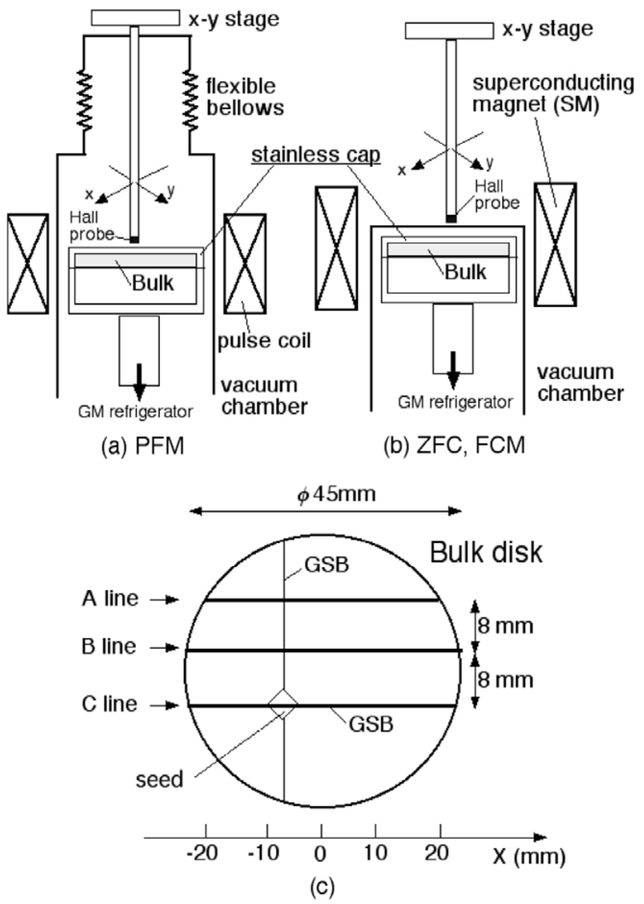

Figure 1. Experimental set-up for (a) PFM and (b) ZFC and FCM. (c) Position of the small pieces cut from the bulk plate. Using the pieces, the magnetisations, $M(H)$ and $M(T)$, were measured for the estimation of the critical current density J_c and the transition temperature T_c.

to zero with -3 mT s^{-1} at 40 K. Contrary to the trapped field profile for PFM measured at $z = 1$ mm, the trapped field profiles, B_T^{ZFC} (4 mm) and B_T^{FCM} (4 mm), were measured on the vacuum sheath surface at a distance of $z = 4$ mm from the bulk surface. We cannot measure the trapped field profiles for PFM and ZFC/FCM under an identical distance, z, from the top surface of the bulk because of the limitation of the experimental apparatus.

After measurements of the trapped field profiles magnetised by PFM, ZFC and FCM, the thin bulk was cut into small pieces. Figure 1(c) shows the positions of these small pieces. The 27, 30 and 33 small pieces were, respectively, cut along the A, B and C lines. The C line is just on the GSB. The position of $X = -7$ mm is the position at which the seed crystal was put during the crystal growth. The size of the small pieces was about $1 \times 1 \times 2$ mm^3. The magnetisation M was measured at 50 and 77 K under the magnetic field parallel to the *c* axis of the pieces up to $\mu_0 H = 5$ T using a commercial SQUID magnetometer (MPMS-5T; Quantum Design). The critical current density J_c was estimated from the $M(H)$ hysteresis loop using the extended Bean model, $J_c = 20\Delta M/a(1 - a/3b)$, where *a*

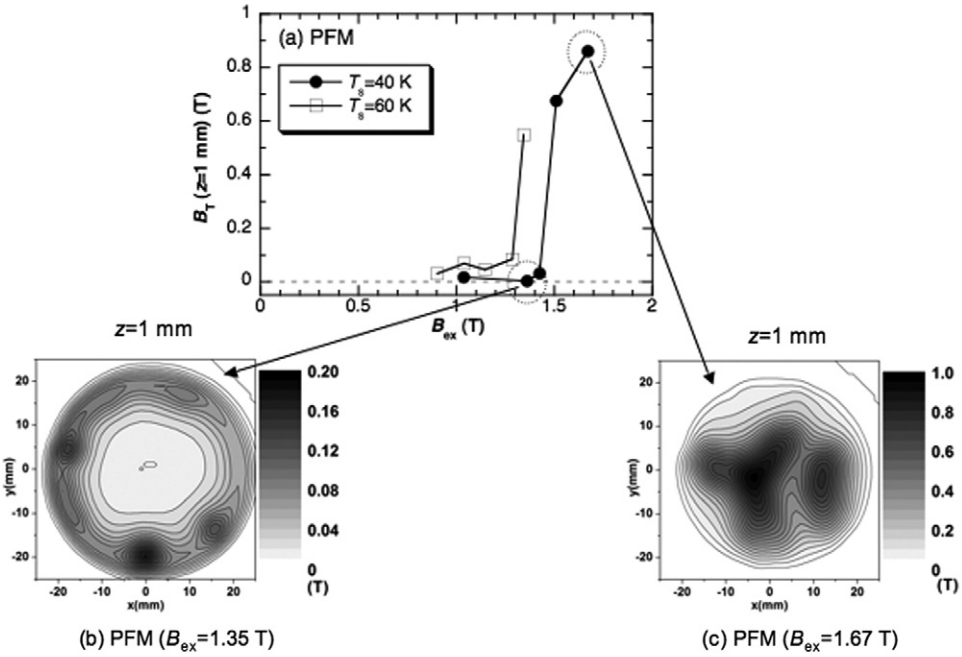

Figure 2. (a) Trapped field $B_T(z = 1$ mm) at the centre of the bulk magnetised by PFM ($T_s = 40$ and 60 K) as a function of the applied field B_{ex}. The trapped field profiles for (b) $B_{ex} = 1.35$ T and (c) $B_{ex} = 1.67$ T. The positions of the GSB and the seed are referred to in figure 1(c).

and b are the dimensions of the ab plane of the sample and ΔM is the width of the $M(H)$ loop. The superconducting transition temperature T_c of the samples was determined from the midpoint of the characteristically sharp transition using the temperature dependence of the magnetisation $M(T)$ under the magnetic field of $\mu_0 H = 0.4$ mT during ZFC.

3. Results and discussion

3.1. Trapped field profiles by PFM, ZFC and FCM

Figure 2(a) shows the trapped field B_T^P (1 mm) magnetised by PFM ($T_s = 40$ and 60 K) at the centre of the bulk as a function of the applied pulsed field B_{ex}. Figures 2(b) and (c) show the trapped field profiles at $z = 1$ mm for $B_{ex} = 1.35$ and 1.67 T. B_T^P (1 mm) was nearly zero for lower B_{ex} than 1.5 T at $T_s = 40$ K and a small amount of the magnetic flux was trapped only around the bulk periphery. For $B_{ex} = 1.35$ T shown in figure 2(b), the magnetic flux can be trapped mainly at the lower right and the upper left regions. However, the magnetic flux penetrated suddenly; it was trapped at the bulk centre for $B_{ex} \geqslant B_{ex}^*$(=1.5 T). For $B_{ex} = 1.67$ T shown in figure 2(c), the magnetic flux penetrated in the centre of the bulk and a large amount of magnetic flux was trapped mainly around the seed region and along the GSBs. The critical field B_{ex}^* decreased concomitantly with increasing T_s because of the decrease in the critical current density of the bulk. The B_T^P versus B_{ex} curves are popular for the ordinary bulk [6]. However, B_{ex}^* for a thin bulk plate is lower than that for ordinary bulks as thick as 10–15 mm in thickness.

Figure 3(a) shows the trapped field B_T^{ZFC} (4 mm) magnetised by ZFC at 40 K at the centre of the bulk as a function of the applied field B_{ex}. B_T^{ZFC} (4 mm) slowly increased concomitantly with increasing B_{ex}. It should be noticed that B_T^{ZFC} (4 mm) was larger than B_T^P (1 mm) as shown in figure 2(a) for $B_{ex} \leqslant 1.5$ T, even though the measuring distance of the trapped field by ZFC is further than that by PFM from the bulk surface. Because the magnetic flux penetrated gradually for ZFC it was trapped during the slow ascent and descent periods, with the long hold time. Using the analytical calculation presented by Chen *et al* [9], we calculated the $B_T(z)$ along the central axis. The $B_T(z)$ for $z = 4$ mm was about 57% as small as that for $z = 1$ mm for the bulk diameter of 45 mm and the thickness of 2 mm under an identical J_c. Figures 3(b) and (c) present the trapped field profiles at $z = 4$ mm magnetised by ZFC for $B_{ex} = 0.5$ T and 1.5 T. A small amount of magnetic flux was trapped mainly at the upper region of the figures and also at the right and lower regions of the bulk periphery. For lower B_{ex}, the region in which the magnetic flux was mainly trapped is presumed to be a low J_c region. The rise time of the applied field for ZFC at $B_{ex} = 1.5$ T was about 900 s, which was four orders of magnitude longer than that of the present PFM. The difference of the velocity of the magnetic flux results in the temperature rise in the bulk. Using our previous results [6], the temperature rise for PFM was estimated as 5 K for $B_{ex} = 1.5$ T at 40 K. The temperature rise for ZFC was reportedly as small as 1 K for $B_{ex} = 1.5$ T [5].

These results suggest a lack of interrelation between the trapped field profiles for ZFC and PFM. The mechanism of the magnetic flux penetration and trap for PFM was not necessarily the same as that for ZFC, even though the applied field B_{ex} was identical. In figure 3(a), B_T^{FCM} (4 mm) = 0.76 T magnetised by FCM ($T_s = 40$ K) was also shown. The trapped field profile B_T^{FCM} (4 mm) was shown in figure 3(d), which showed the concentric circular shape. The measurement of the trapped

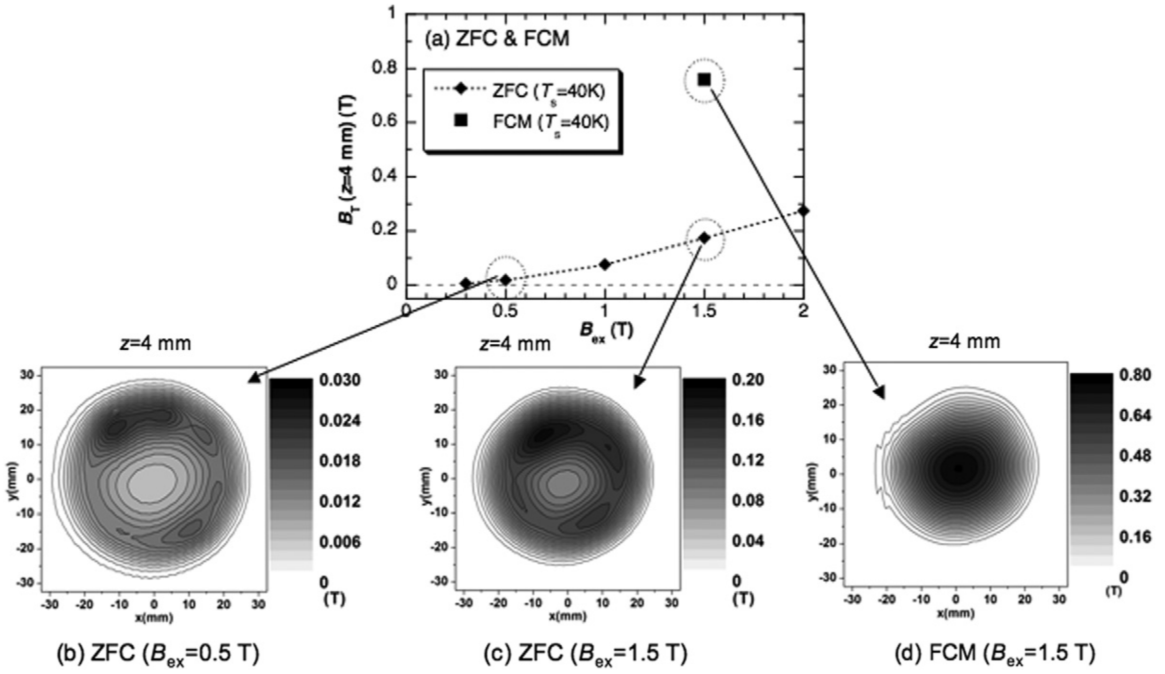

Figure 3. (a) Trapped field $B_T(z = 4$ mm) magnetised by ZFC and $B_T(z = 4$ mm) magnetised by FCM at the centre of the bulk ($T_s = 40$ K) as a function of the applied field B_{ex}. The trapped field profiles for (b) $B_{ex} = 0.5$ T by ZFC, (c) $B_{ex} = 1.5$ T by ZFC and (d) $B_{ex} = 1.5$ T by FCM. The positions of the GSB and the seed are referred in figure 1(c).

field profile magnetised by FCM was performed after the PFM and ZFC. No plausible crystal damage, introduced by the thermal and mechanical stresses, was observed by the B_T^{FCM} (4 mm) profile, as Tomita pointed out [10], which may result from the Ag addition in the bulk.

3.2. *T_c and J_c distributions estimated by the magnetisation measurements*

To estimate the T_c and J_c distributions in the bulk directly, the bulk disc was cut into small pieces along the three lines. Then the temperature and applied field dependences of magnetisation, $M(T)$ and $M(H)$, were measured. Figure 4 depicts the position dependences of T_c along three lines. Along A and B lines, T_c is nearly 93 K and the change of T_c is within 0.5 K, which is independent of the position X. However, it should be noticed that, along the C line, T_c around the seed position was relatively low, which may result from the Nd contamination from the seed crystal, as was seen in the YBCO bulk [3].

Figures 5(a) and (b) respectively depict the estimated J_c as a function of the applied field $\mu_0 H$ at 50 K for the small pieces along the B line and the C line. The J_c–$\mu_0 H$ curves do not show the monotonic decrease concomitantly with increasing the applied field, but show the so-called 'peak effect', which results from the existence of the field-induced pinning centre. The position, at which the peak effect took place, and the magnitude of the peak effect depended clearly on the position of the small pieces.

Figures 6(a) and (b) respectively show the position dependence of the J_c at 50 K and 77 K along the three lines.

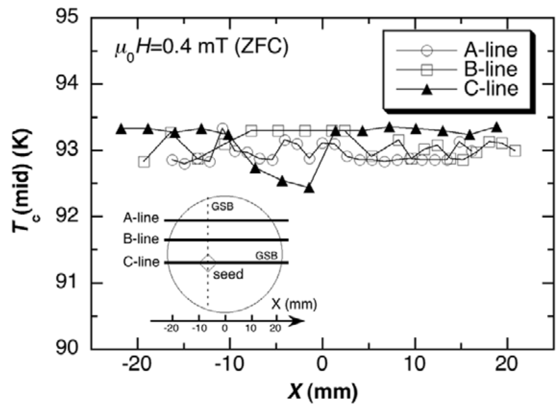

Figure 4. Position dependence of the T_c (mid) along the three lines, which was defined as half the value of the normalised magnetisation.

J_c was estimated at $\mu_0 H = 1.6$ T using the J_c–$\mu_0 H$ curves as depicted in figure 5. Because the maximum applied field was as low as 2 T for the present magnetisation procedures, it should be noted that the J_c values increase for the A, B and C lines in this order at each position because the C line is on the GSB and the pinning strength is greater than that on the GSR. The position dependence of J_c is not necessarily consistent with the trapped field profiles by ZFC and PFM for lower applied field.

In the C line, it is noteworthy that the J_c value was about 20% enhanced broadly at around the seed position ($X = -7$ mm), compared with other positions. Around the seed position, T_c decreased slightly as shown in figure 4. The enhancement of J_c comes from the increase in the

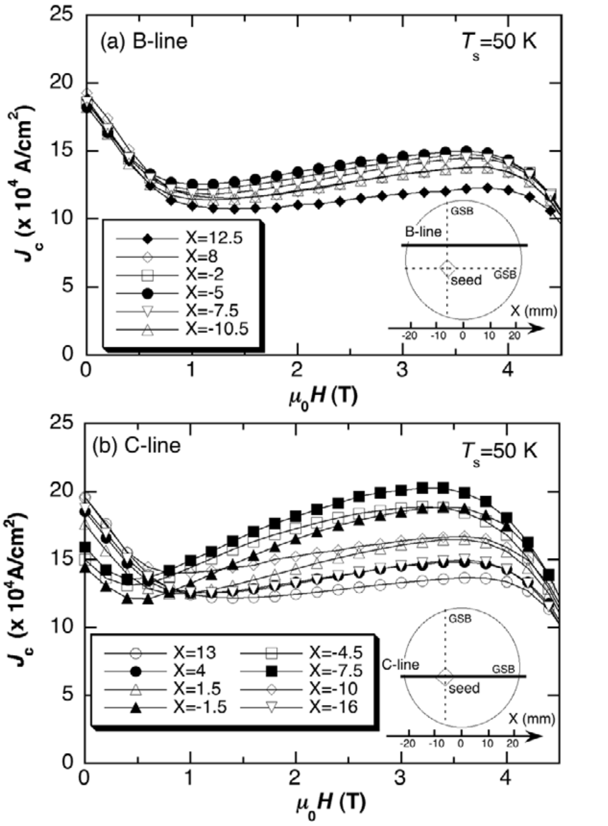

Figure 5. Estimated J_c as a function of the applied field $\mu_0 H$ at 50 K for small pieces along (a) the B line and (b) the C line.

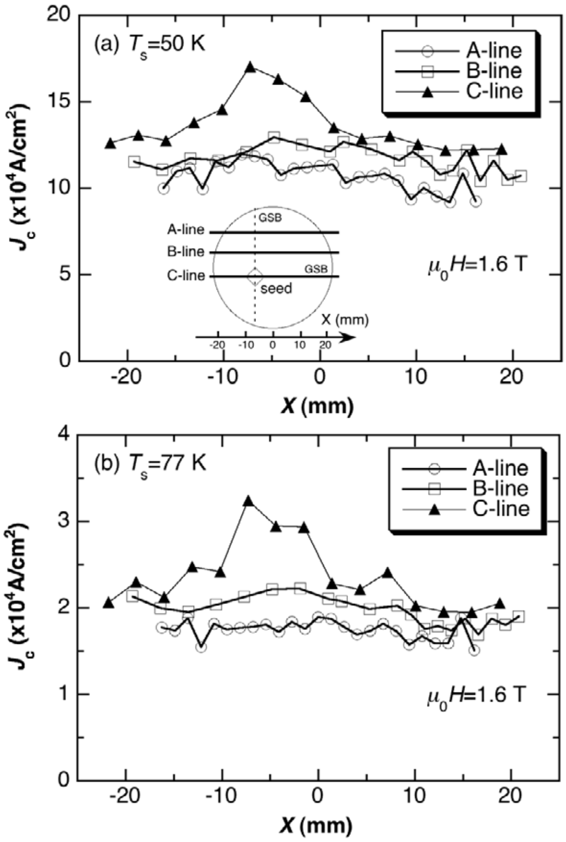

Figure 6. Position dependence of the J_c at (a) 50 K and (b) 77 K along the three lines.

field-induced pinning centres of the weak superconducting region such as the Nd-substitution region for the Ba site [8]. The J_c value was also enhanced slightly around the GSB in the B line. The enhancement of the J_c was confirmed experimentally around the GSB, which resulted from the increase of the crystal defect around the GSB and the seed position, and acted as strong pinning centres. Similar position dependences were confirmed at other magnetic fields. However, the inhomogeneity of the measured J_c was rather small. The inhomogeneity in the trapped field profile by PFM was rather large as shown, for example, in figure 2(c) for higher applied pulsed field. Because the magnetic flux penetrates in the bulk from the bulk periphery during PFM, the inhomogeneity of the trapped field profile results from the very small fluctuation of the J_c value around the outermost peripheral region. The trapped field of the bulk materials was reported to be much lower than that expected from the J_c values measured using small samples. It is difficult to correlate local J_c properties with trapped field behaviour on the bulk.

4. Summary

We have measured the trapped field profiles on a ⌀45 mm GdBCO superconducting bulk disc of 2 mm thickness magnetised using PFM, ZFC and FCM, and compared those with the transition temperature T_c and J_c distributions estimated using the magnetisation measurements. A summary of important results and conclusions obtained from this study is presented below.

(1) For a lower applied pulsed field than that for full magnetisation for PFM, a small amount of the magnetic flux was preferentially trapped at the lower J_c region around the bulk periphery, which was not necessarily similar to that by ZFC.

(2) For a higher applied pulsed field, the magnetic flux penetrated in the centre of the bulk and was mainly trapped below the seed crystal and at the growth sector boundaries (GSBs). The results were qualitatively consistent with those reported by Yanagi *et al*.

(3) The J_c value, as estimated using the magnetisation curves, was enhanced about 20% below the seed crystal, compared with that on the GSRs. The J_c value was also slightly enhanced on the GSBs.

(4) The trapped field profile for PFM depends mainly on the J_c distribution. The profile also depends on the applied field B_{ex} and the local temperature rise. The magnetic flux necessarily penetrates the bulk from the lower J_c region around the outermost periphery of the bulk. However, it is difficult to determine the intrusion position of the magnetic flux for a high-quality superconducting bulk and to correlate the local J_c properties with trapped field behaviour of the bulk.

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