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10T class trapped field properties of a large Gd-Ba-Cu-O bulk superconductor

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Abstract

So far there have been few reports on high trapped fields for a large superconducting bulk because of large electromagnetic force and insufficient homogeneity. In this paper, the temperature dependence of trapped field for one large crystal of Gd-Ba-Cu-O 46 mm in diameter was empirically investigated. The sample was not broken even in the 10 T field-cooling, implying that the sample quality is excellent in spite of the large size. The trapped field measured at the sample surface was 9.1 T at 42 K, but it can be estimated approximately 13 T by extrapolating the experimental data over 60 K.

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1. Introduction

High temperature superconducting (HTS) bulks of RE-Ba-Cu-O (RE: Y or rare earth elements) are highly attractive for practical applications because of their excellent and unique features: 1) large current transport capacity in the presence of strong magnetic fields, 2) automatically stable levitation without active control systems and 3) extremely high trapped field ability in compact space. In addition, HTS bulks require no metal substrates like HTS tapes, leading to an effectively high value in critical current density (J_c). For these reasons, HTS bulks can be expected for various applications such as current leads, fault current limiters, frictionless bearings for flywheel energy storage or non-contact spinner, ship motors, wind or tidal power generators, desktop NMR/MRI, magnetic drag delivery systems, undulators and so on.

The trapped field ability of HTS bulks can be enhanced by cooling to lower temperatures and, in fact, there are several reports on high trapped fields over 10 T at 20 - 30 K for Y-Ba-Cu-O disks [1, 2]. However, they were for samples smaller than 30 mm, often measured in the gap between disk pair of HTS bulks, not at the surface of a single disk. There are few reports on high trapped fields for one crystal larger than 40 mm. This is primarily because the electromagnetic force induced inside the sample during high field activation is significantly increased with the sample size. As a result, larger samples were easier to fracture during high field activation. In addition to large electromagnetic stresses, sample homogeneity might be another factor. So far, it was difficult to produce a large single-grained sample with high uniformity.

Large HTS bulks with high trapped fields can significantly promote the development of bulk applications. In many HTS bulk applications, the total magnetic flux density, which is rapidly increased with the sample size, is more important than the peak height of the trapped field. In addition to the total flux density, the strength of magnetic fields at a certain distance from the bulk surface, not at the bulk surface, is also crucial from the practical viewpoint. The magnetic field of a larger and thicker bulk can reach a longer distance. We found that the careful control of heat

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treatment and the addition of Ag_2O enable to produce large crystals with high trapped fields in Ga-Ba-Cu-O even when they are melt-processed in air [3]. Gd-Ba-Cu-O is considered to be more suitable for large HTS bulks with high trapped fields. In this paper, the temperature dependence of trapped field for one large crystal of Gd-Ba-Cu-O 46 mm in diameter was empirically investigated and it was demonstrated that Gd-Ba-Cu-O bulks have the potential of trapped fields greater than 10 T at around 40 K.

2. Experimental

A large single-grained Gd-Ba-Cu-O bulk superconductor was produced by a melt and crystal-growth method [3, 4]. The precursor was prepared in a molar ration of $\text{GdBa}_2\text{Cu}_3\text{O}_{7-y}$ (Gd123) : $\text{Gd}_2\text{BaCuO}_5$ (Gd211) = 3:1 with 0.5 wt% Pt and 10 wt% Ag_2O . Pt was added for the refinement of Gd211 particles which act as an effective pinning center, leading to the enhancement of J_c . It is well-known that Ag addition is useful for improving the fracture strength properties of RE-Ba-Cu-O bulks. Next, the precursor was heated to 1443 K and then cooled to 1410 K. The seed crystal of (Nd, Sm)-Ba-Cu-O was placed on the top of the precursor and then gradually cooled to 1245 K for crystal growth in air. The as-grown sample was machined into a disk of 46 mm in diameter and 15 mm in thickness, and then annealed for 100 h at 673 K in flowing oxygen gas. Finally, the HTS bulk was reinforced with a stainless-steel ring 5 mm in wall thickness. Fig.1 shows the appearance of the HTS bulk used in this experiment and its trapped field distribution at 77 K. For comparison, a small HTS bulk 20 mm in diameter is also in Fig.1 (a). The trapped field exhibited a symmetrically concentric distribution, indicating that the sample homogeneity is very high.

Fig.2 displays the experimental setup for the trapped field measurement. The HTS bulk was mounted tightly on the cold stage of a Gifford–McMahon (GM) cycle helium refrigerator. A Hall sensor (F.W. Bell, BHT 921) and a Cernox thermometer were adhered on the center of the bulk surface. A magnetic field up to 10 T was applied to the sample using a cryo-cooled superconducting solenoid magnet (JASTEC JMTD-10T100) and the sample was field-cooled to temperatures of 40 - 80 K. The applied field was swept down to zero at a rate of 0.224 T/min. Two-dimensional trapped field profiles were measured by scanning an axial-type Hall sensor (F.W. Bell, BHA 921) on the vacuum chamber surface, at a distance of 6 mm above the bulk surface.

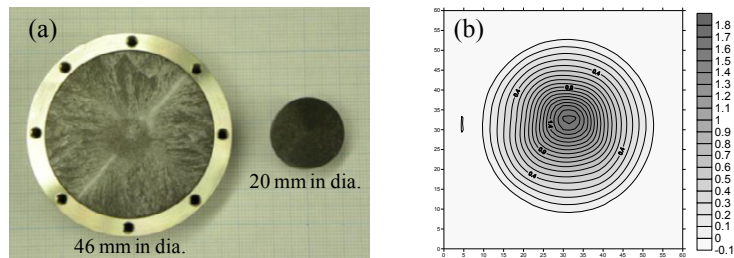


Fig. 1. (a) Ga-Ba-Cu-O bulk superconductor used in this experiment; (b) Its trapped field distribution at 77 K.

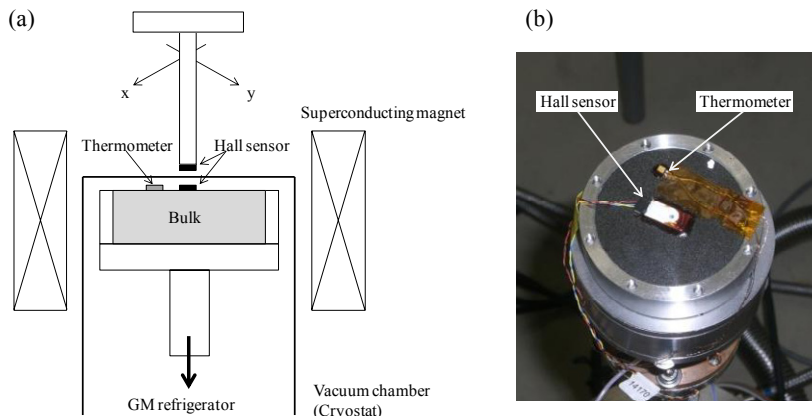


Fig. 2. (a) Experimental setup for the trapped field measurement; (b) Hall sensor and thermometer attached on the bulk surface.

3. Results and discussion

Fig.3 shows the two-dimensional trapped field distributions for one large crystal of Gd-Ba-Cu-O 46 mm in diameter at temperatures of 42 - 75 K. The trapped field reached 9.1 T at the bulk surface and 4.58 T at the cryostat surface. Ren et al. find that cracking is more likely during activation, and conclude that a trapped field of 10 T is achievable for Y-Ba-Cu-O with a fracture strength of 40 MPa [5]. However, so far in many cases, the samples fractured during the field-cooling process with a strong applied field of 10 T class for HTS bulks larger than 40 mm. This is probably because it is difficult to produce a large sample with high homogeneity and large samples are easy to contain parts with a fracture strength lower than 40 MPa. As shown in Fig.3, the trapped field exhibited a symmetric distribution with a single peak, indicating that the HTS bulk was not broken even in the field-cooling process with a strong applied field of 10 T. This result implies that the sample quality is excellent in spite of the large size. Fujimoto et al. reported that Gd-Ba-Cu-O bulks have an average fracture strength of about 97 MPa at 77 K and that its dispersion is relatively small [6]. Thus, the minimum value of the fracture strength inside the bulk in Gd-Ba-Cu-O tends to be higher than 40 MPa even if the sample size is larger than 40 mm. As a result, it was experimentally demonstrated that a Gd-Ba-Cu-O bulk as large as 46 mm was able to trap approximately 10 T. In order to enhance the trapped field properties for larger HTS bulks, it is more and more crucial to improve the sample uniformity.

Next, let us consider the temperature dependence of the trapped field. Fig.4 illustrates the temperature dependence of trapped field at the sample surface for the same HTS bulk. The trapped field ability of HTS bulks can be enhanced by cooling to lower temperatures. This behaviour was observed between 60 K and 80 K, as shown in Fig.4. However, below 60 K, the trapped field at the bulk surface was almost saturated. This is because the maximum applied field was 10 T in this experiment. Taking the experimental restrictions into consideration, a trapped field of 9.1 T is sufficiently high. If there is no experimental restrictions in the applied magnetic fields, a trapped field of approximately 13 T can be estimated at around 40 K by extrapolating the experimental data over 60 K. In RE-Ba-Cu-O bulk superconductors, RE211 particles are considered to work as an effective pinning center. Assuming that the RE211 phase is the main pinning center, it is well-known that the temperature dependence of J_c is to first approximation given by the following equation:

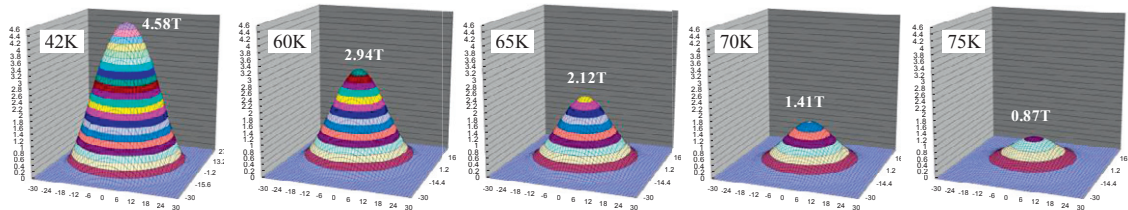


Fig. 3. Trapped field distributions measured at the cryostat surface.

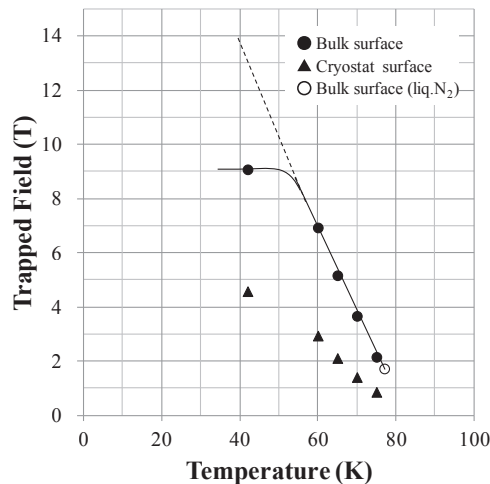


Fig. 4. Temperature dependence of the trapped field.

$$J_c \propto (1 - (T/T_c)^2)^{1.5}, \quad (1)$$

where T is the temperature and T_c the critical temperature. Compared with the expected value from the equation (1), the experimental data much more increased with decreasing the temperature, as shown in Fig.5. This result suggests that, besides the 211 phase, the contribution of different pinning centers to J_c or the trapped field is rapidly increased in lower temperatures. Some atomic-scaled defects intrinsically existed can be a candidate for such pinning centers.

The trapped magnetic field of a larger bulk can reach a longer distance. Thus, the magnetic field must be high even at the vacuum chamber surface when the HTS bulk is large. The magnetic field at the cryostat surface is also plotted in Fig.4 and reached 4.58 T at 42 K in this experiment. Since a high magnetic field of almost 5 T was achieved at the cryostat surface, what is called “Moses effect” can be easily observed, as shown in Fig.6. We tried the same experiment for a Gd-Ba-Cu-O bulk 64.5 mm in diameter and 20 mm in thickness. It is expected that the trapped field should start to saturate at higher temperatures for larger samples. However, the sample could not be cooled below 50 K in our experimental setup and the trapped field was extremely decreased while the applied field was being swept down. This phenomenon was not observed in the experiment for the sample 46 mm in diameter. As the cooling power in this experiment was not sufficient for the large sample 64.5 mm in diameter, the sample temperature was increased as the applied field was being ramped down, and consequently the trapped field became smaller than expected. Nevertheless, at around 50 K, the trapped field was 7 T at the bulk surface and 5 T at the vacuum chamber surface for the 64.5 mm HTS bulk. Compared with the experimental results for the Gd-Ba-Cu-O 46 mm in diameter, the magnetic field at the vacuum chamber surface was almost the same although the trapped field at the bulk surface was smaller. This is probably because of the sample size effect.

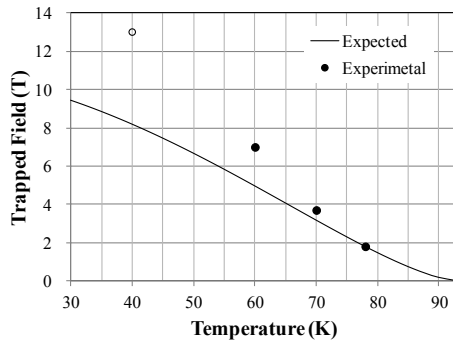


Fig. 5. Comparison between the experimental and the expected values.



Fig. 6. Demonstration of “Moses effect”

4. Summary

Large HTS bulks with high trapped fields can significantly promote the development of bulk applications. However, so far there have been few reports on high trapped fields for one crystal larger than 40 mm because of large electromagnetic force and insufficient homogeneity. Gd-Ba-Cu-O is considered to be more suitable for large HTS bulks with high trapped fields. In this paper, the temperature dependence of trapped field for one large crystal of Gd-Ba-Cu-O 46 mm in diameter was empirically investigated. Although the sample was simply reinforced by a stainless-steel ring, it was not broken even in the field cooling process with an applied field of 10 T, implying that the sample quality is excellent in spite of the large size. The trapped field measured at the sample surface was 9.1 T at 42 K, but it can be estimated approximately 13 T by extrapolating the experimental data over 60 K.

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