Magnetic shielding properties of GdBCO bulks with different crystal orientation

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Abstract

High-temperature bulk superconductors have significant potential for superconductivity applications. For this paper, the magnetic shielding properties of GdBCO bulk with different crystal orientations were investigated at different temperatures for the purpose of determining its application as field concentrators. Four discs with a diameter of 20 mm and thickness of 5 mm were cut from the GdBCO single domain. In two discs, the c-axis of crystal was parallel to the disc radius, and, in the others, the c-axis was perpendicular to it. The magnetic shielding effects in a couple of bulks with a gap of 2 mm were measured in background fields up to 11 T. The magnetic fields were measured at the center and edge points between the two bulks at LN2, LHe, and temperatures controlled with a cryocooler. In LHe, the discs whose c-axes were parallel to the external magnetic fields maintained a zero field up to 11 T. Even in LN2, the field was shielded to 1 T. The results confirmed the strong magnetic shield effects of GdBCO bulk and can be used for the design of a field concentrator.

Keywords: GdBCO bulk; crystal orientation; shielding behavior

1. Introduction

Large-grain high-temperature superconductors (HTS) of the RE-Ba-Cu-O (where RE is a rare-earth element) bulk can trap magnetic fields of several Tesla at low temperature. The magnitude of the trapped field is proportional to the critical current density and the volume of the superconductor [1]. Many laboratory experiments regarding bulk HTS for compact magnets have been conducted. Nakamura et al. [2] reported the initial development of an HTS bulk magnet system for nuclear magnetic resonance (NMR). Shi et al. [3] reported that Y-Ba-Cu-O single-grain rings joined to form the geometry of a solenoid. Tomita et al. [4] developed a compact, lightweight, mobile permanent magnet system by stacking the Gd-Ba-Cu-O bulk annular. The results of such research show that bulk superconductors have great potential in compact magnet applications.

The concentration of the magnetic field by using a special machined GdBCO bulk is a novel application for constructing a compact high-field magnet system. Kiyoshi et al. [5] and Choi et al. [6] reported this magnetic field concentrator, which could doubled the applied field at 4.2 K. The field concentrator consisted of four pieces of
specially shaped bulks that were machined along the axial direction of the GdBCO single grain. Usually, a cylindrical bulk of GdBCO has crystal orientations and is used by applying a magnetic field in the axial direction and having the current flow in the radial direction. With the development of the synthesis process of the single grain bulk, larger dimensions of single grains with great performance could be achieved. With increasing dimensions, machining along the radial direction becomes feasible. It is, therefore, necessary to investigate the magnetic performance in the axial and radial crystal orientation. In this study, the magnetic shielding properties of GdBCO bulk with different crystal orientation were investigated at different temperatures for the purpose of determining its application as field concentrators.

2. Experiment

In the study, four discs with a diameter of 20 mm and thickness of 5 mm were cut from GdBCO produced by Nippon Steel. Fig. 1 is a schematic of the fabrication method of discs. Sample A was a couple of discs with a radius perpendicular to the c-axis of the single domain. Sample B, whose central axis was perpendicular to the c-axis of the single domain, was cut in the vicinity of the seed.

Experiments in magnetic fields were performed at different temperatures under the zero-field-cooling (ZFC) method. Fig. 2 is a schematic of the experimental setup. The two discs had a gap of 2 mm and were fixed in a copper support. The center between the discs coincided with the center of magnet. The magnetic flux density at the center ($B_{center}$) was measured by a transverse hall generator (HGCT-3020). Another hall generator was installed 8 mm away from the center to measure the magnetic field at the edge of the discs ($B_{edge}$). The thickness of the hall generator was 1.14 mm. Both hall generators were fixed in grooves in a copper support. The applied field ($B_{app}$) was provided by a 12 T cryocooler-cooled superconducting magnet with a room temperature bore of 100 mm‡. We used an FRP cryostat to measure in liquid helium (4.2 K) and liquid nitrogen (77 K). A cryostat with a single-stage Gifford-McMahon cryocooler was used to measure at temperatures of 30 K and 40 K. A temperature sensor was attached at the bottom of the discs. A 50 Ω heater was mounted on the probe in the cryocooler to adjust the temperature that was controlled by a temperature controller.

![Fig. 1 Schematics of samples A and B.](image1)

![Fig. 2 Schematic of the experimental setup.](image2)
3. Results and discussion

Fig. 3 (a) and (b) exhibit the internal magnetic flux density $B_{\text{center}}$ as a function of $B_{\text{app}}$ at different temperatures for samples A and B. The $B_{\text{app}}$ was excited with a sweep rate of 0.282 T/min and finally discharged to zero. For sample A, there is nearly perfect shielding at the center of the discs with the $B_{\text{app}}$ up to 11 T at 4.2 K. It could be inferred that the field would be further shielded with increasing $B_{\text{app}}$. Even in liquid nitrogen, $B_{\text{center}}$ remained about zero at $B_{\text{app}}$ of 1 T. On the contrary, the $B_{\text{center}}$ of sample B ascended at $B_{\text{app}}$ of 5 T and 4.2 K, and the shielded fields were much lower than those of sample A at other temperatures. Correspondingly, sample A had larger residual trapped fluxes after the magnetization. Furthermore, flux jumps occurred at 4.2 K due to the low thermal conductivity of GdBCO bulk in low temperature.

Fig. 3 $B_{\text{center}}$ as a function of $B_{\text{app}}$ at different temperatures for (a) sample A; (b) sample B.

Fig. 4 Simulation of the magnetic field distribution along radial direction.

Fig. 5 Shielding field as the functions of $B_{\text{app}}$ at 40 K.
A numerical simulation was carried out by using commercial finite-element-method software (OPERA-3D, Vector Fields). In the simulation, the materials were assumed to have perfect diamagnetism. A uniform external field of 1 T was applied perpendicularly to the discs. Fig. 4 shows the simulation of the magnetic flux density and its logarithm scale distribution along the radial direction between two discs.

The shielding fields ($\Delta B_{\text{center}}$) and ($\Delta B_{\text{edge}}$) were evaluated as $B_{\text{center}} - B_{\text{app}}$ and $B_{\text{edge}} - B_{\text{app}}$, respectively. Fig. 5 shows the $\Delta B_{\text{center}}$ and $\Delta B_{\text{edge}}$ as functions of $B_{\text{app}}$ at 40 K. The numerical calculation is plotted for comparison. The $B_{\text{app}}$ was excited to 10 T. For sample B, $\Delta B_{\text{edge}}$ gradually approached zero, which suggests that the bulk gradually penetrated from the edge with increasing external field. It is reasonable that the simulated result is higher than the experimental result because we assumed that the materials had perfect diamagnetism. The shielding field between the discs was generated by an induced shielding current flowing along the edge. According to the Bean model [7], the larger shielding field resulted from the larger critical current density $J_c$ of the bulk. It could be inferred that the $J_c$ flowing in the $ab$-plane of the GdBCO single domain is higher than that in the $c$-axis. This agreed well with magnetization $J_c$ of GdBCO reported by Cardwell et al. [8].

4. Conclusion

In this work, we have studied the magnetic shielding behavior of discs cut from a GdBCO single domain. A couple of discs were placed in an external field to measure the shielding fields at different temperatures. The magnetic field at the center of sample A was nearly perfectly shielded with $B_{\text{app}}$ up to 11 T at 4.2 K. The shielding fields of sample B were apparently lower than that of sample A at different temperatures. The performance of discs cut along the $ab$-plane is superior to that of discs cut from the $c$-axis. The results experimentally proved the strong magnetic shield effects of GdBCO bulk and can be used for the design of a field concentrator as well as other applications.

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