Improvement of Thermal Stability with Alloy Impregnation in Gd-Ba-Cu-O Superconductors for Pulsed Field Magnetization

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Abstract. We present a post-fabrication treatment that improves thermal conductivity of bulk Gd-Ba-Cu-O magnets. A small hole about 1 mm in diameter was artificially drilled into the centre of bulk Gd-Ba-Cu-O 25 mm in diameter and 18 mm in thickness. An aluminium wire was inserted into the hole, and then the sample was subjected to the impregnation by using Bi-Su-Cd alloy. A pulsed-field magnetization was performed for Gd-Ba-Cu-O bulk with and without the alloy impregnation treatment. The temperature of samples was monitored with thermocouples and local magnetic field density was measured with a Hall sensor at several positions. The maximum temperature rise was depressed by 4 K and the trapped field was increased by 25 % at 44 K. The result shows that the alloy impregnation is very effective in enhancing the thermal conductivity and thereby improving the field trapping ability.

1. Introduction

Large-grain high temperature superconductors of RE-Ba-Cu-O (RE is rare-earth element) can trap magnetic flux of several tesla at low temperatures and can be used for quasi-permanent magnet applications. Potential applications to engineering concerning these cryo-magnets have emerged, some of them have already been commercialized [1,2]. However, the applicable range is limited by poor mechanical stability, low thermal conductivity of bulk superconductors and cost [3,4].

Pulsed-field magnetization (PFM) is practical method magnetizing bulk superconducting magnets installed in the rotating machines [5,6]. The magnitude of trapped magnetic field is, however, smaller than that with the field cooling technique (FC), which is primarily attributed to the temperature rise of the sample due to the flux motion during PFM [7]. Such a temperature rise is remarkable at low temperatures mainly due to two factors. First, thermal conductivity of bulk materials is low. Second, high magnetic field is needed to fully magnetize bulk superconductors. Therefore, the field-trapping capability during PFM is enhanced according to the suppression of heat generation and an increase in the thermal conductivity. In the present study, we focused on a technique to improve the thermal conductivity of bulk superconductor, based on the work by Tomita and Murakami [8] in that alloy impregnation into melt-textured Y-Ba-Cu-O improved trapped-fields over 17 T at 27 K in the FC magnetization.
2. Experimental details

2.1. Samples
Gd-Ba-Cu-O bulk sample (GdBa$_2$Cu$_3$O$_{6.9}$ 72.4 mol% Gd$_2$BaCuO 28.6 mol% Ag 10 wt.% Pt 0.5 wt.%) was manufactured by Dowa Mining Co.. The dimensions are 25 mm in diameter and 18 mm in thickness. The hole about 1 mm in diameter was artificially drilled into the center of bulk. A sample was initially characterized by measuring the trapped field profile at 77 K by cooling the sample with liquid nitrogen in an applied field of 2 T. After removal of the applied field, a Hall sensor (BHA921, Bell) was scanned over the entire surface, at a constant sensor-surface distance of 1.2 mm. The sample showed a maximum trapped field density of about 0.42 T with a single peak.

The bulk was embedded in a metal ring by epoxy resin to reinforce against the fracture due to the magnetic stress during the magnetization process. Then we inserted 0.9 mm diameter Al wire, of large thermal conductivity, into the hole for further enhancement of thermal conductivity. Al wire is bonded to the bulk with metal impregnation method. However, Gd-Ba-Cu-O bulk superconductor became non-superconductor at 523 K because oxygen was dissipated in the Gd-Ba-Cu-O bulk at 523 K. Therefore, the sample was subjected to the impregnation of Bi-Sn-Cd alloy (U-alloy102.5, melt point 375.5 K). Bi-Su-Cd was melted at 413 K and admitted to the mould, and hold 10 minutes; outgassing gases were evacuated with a rotary pump. Finally, the mould assembly was holed 20 minutes at 413 K in air and then was slowly cooled down to the room temperature.

2.2. Pulsed-field magnetization
We employed PFM for Gd-Ba-Cu-O bulk sample with and without the alloy impregnation treatment. Fig.1 (a) shows schematic illustration of the superconducting bulk magnet system (AISIN SEIKI Co., Ltd). The bulk sample is cooled to the superconducting state and then magnetized by pulsed current using magnetizing coil (solenoid type coil) dipped in liquid N$_2$. The yoke was removed in the magnetizing coil [9]. The rise time of a magnetic field was around 10 ms. The bulk magnet was stuck on cold stage of GM refrigerator by the insertion of an In-foil 0.5 mm in thickness. The temperature of samples was monitored with thermocouples and local magnetic field was measured with Hall sensor at several locations. A Hall sensor (Toshiba THS118) was attached to the location about 1 mm apart from the center. The thermocouples (IWATANI Au-0.07 %Fe, Normal Silver) were placed at the locations 1 mm apart from to the center and 1 mm apart from the periphery on the bulk surface using GE7031 varnish (Fig.1 (b)). The initial temperature of bulk surface was 44 K. The pulse field magnitudes were 4.8 T, 5.6 T and 6.3 T.

Figure 1. (a) Schematic illustration of superconducting bulk magnet system and (b) The configuration of Hall sensor and the thermocouples.

3. Results and discussion
3.1. Bulk impregnated with U-alloy

Figure 2 (a) is a picture of the top of surface. We note an Al wire and U-alloy in the center of bulk surface. Figure 2 (b) is an optical micrograph of cross-section along the hole for the alloy impregnated sample. We note that voids can be successfully fulfilled with Bi-Sn-Cd alloy through the hole drilled in the sample. Figure 2 (c) shows a secondary electron microscope image of boundary face for the alloy impregnated sample. We observed that U-alloy was impregnated µm order asperity. Therefore, the good interfacial bonding sample can be obtained.

![Figure 2](image)

**Figure 2.** (a) Picture of the top of surface (b) Cross-sectional view of a Bi-Sn-Cd alloy impregnated Gd-Ba-Cu-O disk. (c) SEM image of boundary zone for the alloy impregnated sample

3.2. Result of the pulsed-field magnetization at 44 K

Figure 3 shows trapped field density as a function of time for bulk Gd-Ba-Cu-O samples with and without alloy impregnation. The trapped field was increased when we applied a pulsed field with 5.6 T and 6.3 T peak field. In particular, trapped field was increased from 2 T to 2.5 T, when peak pulsed field was 5.6 T. However, trapped field was decrease when applied field was 4.8 T. Thanks to improvement of the thermal conductivity inside the sample, it became difficult for the external field to penetrate into the sample. Therefore, we think the initial temperature in the sample was decreased.

![Figure 3](image)

**Figure 3.** Trapped magnetic field density as a function of time for bulk Gd-Ba-Cu-O samples with and without alloy impregnation at the location 1 mm apart form the sample center when pulsed filed was applied.

Figure 4 indicates time dependence of temperature change at 44 K with pulsed field 5.6 T. The initial temperature was not changed for Gd-Ba-Cu-O bulk sample with and without the alloy impregnation treatment. The temperature change of periphery was lager than the center of the bulk. 3 seconds later, the temperature of the sample became rather uniform. The trapped field was decreased.
during the temperature increase. Then, the trapped field density became stable. In case of PFM with high pulsed magnetic field, the trapped field does not decay for a long time [10]. The maximum temperature rises for with and without impregnation were about 11 K and 15 K at the periphery of the bulk, respectively. Thereby, according to the U-alloy impregnation, the maximum temperature rise was depressed by 4 K.

![Temperature change as a function of time](image)

**Figure 4.** Temperature change as a function of time for bulk Gd-Ba-Cu-O samples with and without alloy impregnation when a pulsed field of 5.6 T was applied.

4. Conclusion
Upon U-alloy impregnation, the maximum temperature rise was depressed by 4 K and the trapped magnetic field density was increased by 25% at 44 K when we applied a pulsed field magnetization with the pulsed peak field of 5.6 T. The present result shows that the alloy impregnation is effective in enhancing thermal conductivity inside the bulk and thereby improving the field trapping function.

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