Field trapping property of HTS bulk magnet with reduced voids in pulsed field magnetizing process

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Abstract. The field trapping ability of melt-textured bulk superconductors is usually restricted by the mechanical properties because of the magnetic stress induced in the samples during the activation processes which give them intense magnetic fields of several T. Therefore it is of crucial importance to enhance the toughness of the materials by means of reinforcing techniques. In this experiment, we adopted a dense Dy-based HTS bulk sample fabricated by means of controlling the concentration of voids inside during the heat treatment. A single magnetic pulse fields up to 7.66 T have been applied in the temperature range down to 30.6 K with use of GM refrigerator, and the profiles of pulsed fields and the resultant trapped fields are discussed with respect to their performances. It was found that the trapped field grows as elongating rise time of the pulsed field and lowering initial temperature. The densely fabricated Dy123 sample was activated up to 1.98 T at 31 K in the same manner with no substantial difference from the porous Gd123 samples when the magnetic pulse field of 7.66 T was applied. The temperature rises up to 20 K are not substantial in comparison to those of the Gd123 compounds which exhibit the temperature rises more than 30 K at 40 K by applying 4.64 T. This is attributed to the fact that the \( J \) value of the dense Dy123 are inferior to that of Gd123, which reflectes the field trapping ability.

1. Introduction

RE-Ba-Cu-O (RE=Y, Sm, Dy, Gd, abbreviated as RE123) melt-textured bulk superconducting compounds which includes RE211 inclusions perform the excellent magnetic property as quasi-permanent magnets when they capture the applied magnetic fields [1, 2]. The maximum magnetic performance has reached 16 T at 24 K by doping Zn element, as reported by Gruss et al. [3]. The highest value of 17.24 T has been reported by Tomita et al. [4] by reinforcing Y123 bulk magnet by the resin impregnation method. These data of the field trapping ability are commonly achieved in the field cooling process (hereafter abbreviated as FC) with use of superconducting solenoid magnets. On the other hand, in the pulsed field magnetizing process (PFM), one knows that the flux motion causes local heating in the sample, raises the temperature, lowers the critical current density, and subsequently degrades the trapped field ability [5]. A smart process called MMPSC as a kind of PFM processes, which was conduct by Fujishiro et al. [6, 7], has recently recorded the maximum trapped
field of 5.2 T in the way which suppresses the heat generation by means of applying iterative pulsed fields at two temperature stages. The sweep rates of applied fields must be carefully chosen to be slow in the FC process so as to suppress the temperature rise even during the FC process [8, 9].

Since the trapped field in the bulk sample yields intense stress inside and give the sample serious damages, the field trapping performances are regulated by the mechanical strength of the material. Therefore it is of crucial importance to enhance the mechanical strength of the materials. Recently, Teshima et al. has developed a novel fabrication process to reduce the voids in the Dy-based 123 materials and succeeded in strengthening their mechanical properties [10]. Since it must be undoubtedly important for us to use tough materials when we utilize the bulk materials as the field trapping magnets, in the study, we aim to activate the mechanically strengthened magnets by the intense fields over 7 T, and estimate the flux motion and heat generation during the PFM process.

2. Experimental procedures

A schematic view of the experimental setup is shown in Fig. 1. A melt-processed dense Dy123 bulk sample was manufactured by Nippon Steel Co. LTD., and adapted to the PFM operation. The dimensions of the sample were 30 mm in diameter and 15 mm in thickness. The mechanical strength of the sample was substantially enhanced by reducing internal voids [10]. A Hall sensor (Bell BHT 921) was attached just at the centre of the sample surface so as to measure the flux motion during the PFM operation. A fine Cu-Co thermocouple, the size of which is 0.07 mm diameter, was glued on it at the position in the growth sector region, as Fig. 1 shows. The HTS sample was cooled to the lowest temperature of 30.6 K by a Gifford-McMahon refrigerator (AISIN SEIKI Co., GR-103). Intense magnetic fields were generated by feeding currents to the pulsed coil from the condenser bank (SBV-10124, manufactured by Nihon Denji Sokki Co). In the PFM process, we applied various magnitudes of the single pulsed fields ranging from 4.4 to 7.66 T. The pulsed field coil is cooled in the liquid nitrogen vessel to reduce its resistivity. We varied the values of condenser bank in the range from 40 – 120 mF to give the sample various rise times of the pulse fields. Then the changes of the temperature and the trapped magnetic flux density were measured during whole the magnetizing procedure.
3. Results and Discussions

3.1. Flux motion measured at the bulk sample surface in PFM activation processes

Figure 2 shows the time evolution profiles of measured data of trapped magnetic fields as a function of applied fields when the magnetizing currents were fed from 120 mF condenser bank at 30.6 K. One can obviously see that the magnetic flux does not penetrate enough into the center of the sample when the applied field is lower than 5 T. On the other, the heat generation due to the flux motion causes substantial decay of the trapped field in the field application more than 7 T.

Figure 3 shows the time profiles of trapped magnetic fields as a function of condenser capacitance $C$ which corresponds to the rise time of pulse field. When the applied field is 5 T (Fig. 3a) the rise time directly affects to the delay of the field penetration and resultant trapped field performances. And the trapped fields gradually increase with increasing $C$. When the field grows to 6 T the rise times are elongated and the peaks of the external field are delayed. When the applied field is 6 T (Fig. 3b) the magnetic flux deeply steps into the sample with increasing the rise time. The flux behavior drastically changes when we give the sample the magnetic field of 6 T. And the trapped field has jumped up to 1.98 when we apply the current from 120 mF. It is notable the field penetration is drastically enhanced when we elongate the rise time a little.

3.2 Trapped field and temperature rises due to heat generation

Figure 4 shows the temperature dependence of trapped fields when the applied fields changes from 4.44 to 7.66 T at 120 mF. The trapped field clearly shows us the different behaviour when the starting

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**Figure 2.** Magnetic flux density of penetrating into the bulk sample surface centre measured at 30.6 K with various magnetic field applications

**Figure 3.** Evolutions of magnetic field application $B_{ex}$ and penetrating magnetic flux density $B_t$ for applied field of 5 T (a) and 6 T (b) with varying capacitances of the condenser bank
temperature is below 50 K. Although the flux penetration follows the applied fields in the temperature range over 50 K, the applied weak fields less than 6 T are strongly repelled below 50 K. This phenomenon causes the heat generation that corresponds to the temperature rises, as shown in Fig. 5. The flux penetration behavior is quite different between higher and lower temperature regions separated at 50 K. Both the trapped field and the temperature rise linearly change with changing temperature, as shown in Figs 4 and 5. In contrast, one can see the decay of trapped field at 30 K and 7.66 T in Fig. 4, which reasonably corresponds to the highest temperature rise of 20 K, as shown in Fig. 5. The temperature rises of 20 K is not substantial in comparison to that of Gd 123 compounds which exhibit the temperature rises more than 30 K at 40 K by applying 4.64 T [11]. This is attributed to the fact that the $J_c$ values are inferior to those of Gd123, which reflects the field trapping ability.

4. Conclusions

We investigated the flux penetration and field trapping behaviours of densely fabricated Dy123 HTS bulk material with use of PFM technique which generates strong field over 7 T. As well as the porous bulk samples, the rise time of the pulsed field strongly affected to the heat generation during the pulse application and the resultant field trapping ability. The field trapping behaviour drastically changed between higher and lower temperatures than 50 K. The heat generation is not substantial for Dy123 in comparison with Gd123. It is ascribed to the inferiority in $J_c$ values of Dy123 to Gd123 system.

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