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Pulsed Magnetization for Gd-Ba-Cu-O Bulk with a Couple of Vortex-type Coils

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Pulsed magnetization was studied for field-free cooled high-temperature superconductor (HTS) bulk cylindrical disks of melt-textured Gd-Ba-Cu-O. The HTS bulk was placed in between a pair of pulsed vortex-type copper coils and immersed in liq. N_2. The pulsed field is trapped to the centre at the sample surface for low pulsed peak field. In a subsequent magnetization with increasing the applied field, the trapped peak field increases monotonously close to the peak field observed in the field cooling process down to liq. N_2 temperature. The electric energy necessary to magnetize the sample up to 1 T is smaller than the energy consumed with a conventional solenoid. Thanks to employing a couple of vortex-type coils, the HTS bulk cryo-magnets are effectively magnetized.

Key words: Gd-Ba-Cu-O, pulsed magnetization, vortex-type coils

1. INTRODUCTION

Enhancement of the magnitude of the trapped field in large-grain high-temperature superconductors (HTS) of the form RE-Ba-Cu-O (RE is a rare-earth element) is enabling potential applications to a variety of industries [1,2]. In-situ magnetization technique with a pulsed copper coil is a prerequisite for the rotating electrical machinery use of HTS bulk as cryo-permanent magnets [3-4]. To have enough magnetization in utilisation, the shielding characteristics associated with the transient heat due to the flux motion have to be overcome [5], where the temperature increase is coming from a transient flux flow upon pulsed magnetization [6]. In the previous works, most of the pulsed Cu coils have been solenoid-type and the sample of bulk HTS was placed inside the air-core of the solenoid [3,6,7]. The transient magnetization process of the bulk HTS has been interpreted based on a conventional Bean model qualitatively. A variety of ways for utilisation of the pulsed Cu solenoid were reported, however there was no work employing either the pulsed Cu coil other than solenoids or inhomogeneous pulsed field distribution upon magnetization of HTS bulk samples.

Presently we studied the magnetization of a field-free cooled HTS bulk disk of a melt-textured Gd-Ba-Cu-O which was inserted in between a couple of pulsed vortex-type Cu coils at liq. N_2 temperature. It is worth to note that the applied magnetic field distribution generated with a vortex-type coil is not homogeneous as in the use of a solenoid. The vortex-type coil applies the conical field distribution. The maximum field density is along the center axis of the HTS bulk disk and the direction of the field is almost parallel to the c-axis of the bulk. The magnetic field penetrates into the centre of the sample when small pulsed field was applied. With increasing the applied field, the trapped flux increases monotonously up to at least 1.32 T at liq. N_2 temperature as 1.4 T for field cooling(FC) down to liq. N_2 temperature. We discuss the merit of the present pulsed magnetization technique employing a pair of vortex-type coils and show a comparative result of the pulsed magnetization employing a conventional solenoid coil.

2. EXPERIMENTS

Melt-textured Gd-Ba-Cu-O bulk samples ($GdBa_2Cu_3O_{6.9}$ 70.9wt.%, $Gd_2BaCuO_{5.0}$ 19.2 wt.%, Pt

0.5 wt.%, Ag 9.4 wt.% in composition, Nippon Steel Co. Ltd., QMG) were magnetized by using a couple of vortex-type coils. Separately Gd-Ba-Cu-O bulk samples ($GdBa_2Cu_3O_y$ 59.5wt%, Gd_2BaCuO_5 24.4wt%, Pt 0.5wt%, Ag 15.6wt%) with different sizes were prepared [8]. For a comparative study of the pulsed magnetization with the present vortex-type coils, we prepared solenoid coil which possesses almost equivalent inductance as 11.1 mH with those of vortex-type ones of 9.8 mH. The geometry of the pulsed magnetization measurements is shown in Fig. 1. The magnetization geometry is applied to the design of rotating synchronous machines of axial-gap type, where the armarures play the role of pulsed Cu coils upon magnetization of HTS bulk [9].

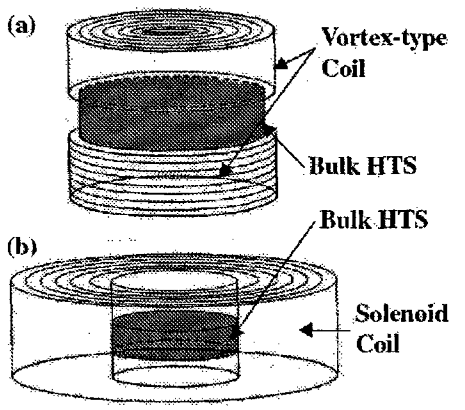

Fig. 1. Illustration of pulsed copper coils and superconducting bulk samples: a couple of vortex-type coils (a), a conventional solenoid-type coil (b).

Both types of coils generate 0.002 T at the centre of the bulk samples when the current flow of 1 A is applied. The rise time of the pulsed field was typically around 6-10 ms. The dimension of the vortex-type coil was 84 mm in diameter and 19 mm thick, 10 layers of 20 turn windings with a ϕ2 mm copper wire. The HTS bulk sample QMG with a diameter of 48 mm and a thickness of 19 mm (Sample **A**) was placed in between a pair of vortex-type coils together with a pulsed power circuit. To observe the trapped field distribution at the surface of the samples, we employed a large QMG with the dimension of 60 mm in diameter with 19 mm thick (Sample **B**) and another Ag rich HTS bulk with 33 mm in diameter with 24 mm thick (Sample **C**). The maximum trapped fields at liq. N_2 temperature upon field-cooled magnetization for these samples yield 1.4 T, 1.8 T and 2.0 T for the samples A, B and C, respectively. The pulsed current generator was designed and the detailed description and its performance will be reported elsewhere [10].

Successive pulse magnetization associated with different peak fields was tested to optimize the way to obtain high trapped magnetic field with a few number of pulsed current excitations from the condensor bank. Demagnetization was not performed between pulsed magnetizations. The intervals between triggering pulses were typically 15 min-30 min to get an enough thermal equilibrium. Both sample and coils were immersed in liq. N_2. The remanent magnetization was measured with a Hall probe scanned without taking out the samples. The acquisition was in two-dimension above the sample surface in a distance ranging 1mm- 2mm depending on the size of samples.

3. RESULTS AND DISCUSSIONS

Figure 2 shows the applied field dependence of the trapped field at the centre of the surface of the sample **A** after the pulsed external field was triggered. Comparatively, we employed a conventional solenoid in addition to a pair of vortex-type coils.

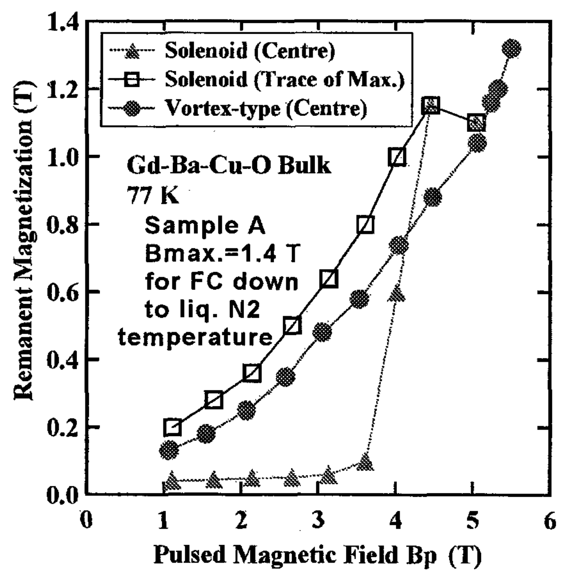

Fig. 2. The applied peak field (B_P) dependence of the trapped field in the centre of the surface. The data was taken after the pulsed field was applied with employing a pair of vortex-type coils and conventional solenoid. Additionally, the trace of the trapped maximum peak field is shown in case of magnetization with the solenoid.

In the case of the pulsed magnetization with a solenoid, when the applied field was small, shielding currents remain flowing and produce a hump in the remanent flux profile at the centre of the sample surface after the decay of the pulse. The magnetic flux is predominantly trapped in the periphery of the sample [7]. Therefore, the maximum peak field was observed in the periphery. With increasing the applied field, the magnetic field penetrates inside and we observe 1.18 T as the maximum trapped flux in the centre of the sample surface. The position of the peak of the trapped flux distribution displaces from periphery toward the inner centre core region with increasing the applied field in case of the conventional solenoid as shown in Fig. 3. In the process, there is a tendency to have a field distribution profile with multi-peaks coming from the flux motion upon multi-pulse process. Eventually, the trapped field tends to saturate or decrease upon increase the applied peak field.

In contrast, the trapped flux at the centre of the sample increases monotonically with increasing the applied field from the pulsed vortex-type coils as shown in Fig. 3. The initial flux penetration in the periphery with employing the solenoid was not observed. It seems that the flux penetrates into the centre of the surface even when we apply small pulsed field. No remarkable trace of saturation of the trapped field was observed up to at least 1.3 T. To verify the flux penetration, we measured the flux distribution of the surface of the samples **B** and **C** with different diameters than the sample **A**.

Figure 3 exhibits the trapped flux distribution in the surface area of the sample **C** centre after we applied a series of small pulsed field with 5.8 T, 7.3 T and 7.7 T peak field with a pair of vortex-type coils.

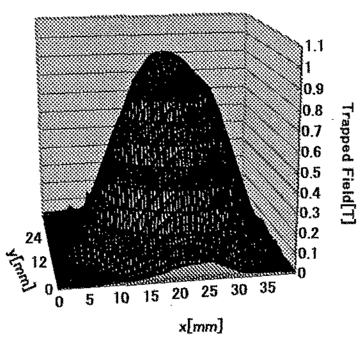

Fig. 3. The trapped magnetic field distributions for sample **C** after we applied the successive peak pulse fields B_P of 5.8 T, 7.3 T and 7.7 T. Each interval time between triggering pulsed currents was 30 min. The data was taken after the pulsed field was applied with employing a pair of vortex-type coils at liq. N_2 temperature.

The rise time was 5.8 ms. With increasing applied field, the cone-shape flux distribution appears and shows the peak around the centre. In the case of the sample B, the trapped flux distribution shows a hump [11] due to relativaly low thermal conductance possibly coming from smaller content of Ag than in sample C. The similar result has been observed in the pulsed magnetization of Sm-Ba-Cu-O bulk below 70 K [6]. The area of the flux hump corresponds to one of the four a-axis growth sectors composed of sub-grains during the melt-growth process. In addition, some asymmetry remains in the flux distribution except for high peak fields.

In the present pulsed magnetization, the electric energy charged in the capacitor is transformed into the magnetic energy thanks to the pulsed current which can be monitored as the voltage drop through a shunt resistance of 0.1 m ohm. A coupled of vortex-type coils are associated with the pulsed current leading to the energy with $(1/2)LI^2$, where L and I are the inductance of the coil and the transient pulsed current. This energy, magnetization energy, is eventually converted to the integrated energy of the magnetic field which appeared transiently as a function of time.

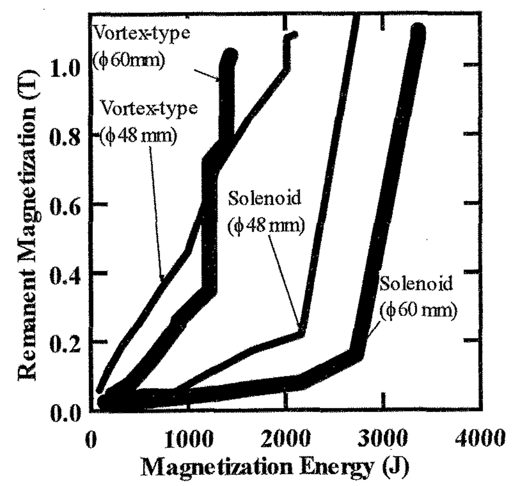

Fig. 4. The trapped peak fields for applied electric energy calculated based on the charged electric energy in the condensers of the high voltage pulse current generator in the pulsed magnetization on the samples A with ϕ48mm and B with ϕ60mm. The calculated values were compensated with electric losses through inductive coils and shunt resistance.

Figure 4 exhibits the observed centre magnetic field trapped in a successive pulsed magnetization process in relation to the magnetization energy which is calculated from the charged electric energy corrected for the energy loss through the shunt resistance. Apparently, when we magnetize up to 1 T as the centre field which is above a half of the maximum trapped field 1.8 T observed in the FC process, the magnetization energy up to 1300 J per pulse is sufficient with employing a couple of vortex-type coils for the sample B with ϕ60 mm.

Contrary, the magnetization energy at least over 3300 J per pulse is necessary to reach to 1 T when we use the solenoid. In case of the sample A, the pulsed electric energy value required to reach >1 T with a pair of vortex type coils becomes close to the pulsed energy necessary by using the solenoid. It is not surprising, since the maximum trapped field in case of FC was 1.4 T which is lower than that of the sample A. Thus, a couple of vortex-type coils provide us an effective way to magnetize HTS bulk cryo-magnets up to at least over a half of the maximum trapped peak field. The obtained trapped density profile is together with sufficient homogeneity.

With employing a pair of vortex-type coils, the shielding permits a significant flux penetration and rather sufficient high values of trapped peak flux. It is worth to note that the applied magnetic field distribution with a vortex-type coil is not homogeneous as in the use of the solenoid. The vortex-type coil applies the field with conical distribution profile with the maximum value along the centre axis of the HTS bulk disk and the direction of the field is almost parallel to the c-axis of the bulk. The present field distribution is similar to the well-dressed trapped field distribution with field cooling process. On the other hand, when the magnetic field penetrates inside the bulk disk sample, the excess flux tends to occupy in the periphery region by employing the conventional solenoid. The excess flux penetration around the periphery area in case of the applied field with solenoid may cause an excess flux motion associated with increase of the local temperature, which leads to the undesirable decrease of the maximum field, distortion of flux patterns. These results suggest that the utilisation of vortex-type coils leads to high efficiency of magnetization of HTS bulk materials.

4. CONCLUSIONS

We studied the magnetization of a field-free cooled HTS bulk disk of a melt-textured Gd-Ba-Cu-O sandwiched in between a couple of pulsed vortex-type Cu coils at liq. N_2 temperature. The vortex-type coil applies the field with conical distribution profile associated with the maximum flux density along the center axis of the HTS bulk. Magnetic field penetrates to the centre at the surface of the sample and the flux trapping is rather homogeneous under small applied peak field. The trapped flux increases monotonically with increasing the applied field from the vortex-type coil without any trace of saturation of the trapped field up to at least 1.32 T as 1.4 T upon FC down to liq. N_2 temperature.

In contrast, the magnetic flux is predominantly trapped in the periphery of the sample under small applied field when we use the conventional pulsed Cu solenoid. The excess flux penetration around the periphery area may cause an excess flux motion associated with increase of the local temperature, which leads to undesirable loss of magnetization energy, i.e., decrease of the maximum field and/or deviation from a well-dressed flux distribution.

The pulsed magnetization with a pair of vortex-type coils is a candidate for a magnetization way to obtain a sufficient trapped field distribution with smaller magnetization energy loss. Further extensive study including flux penetration mechanism is under progress, which leads to the optimization of magnetization process with employing a pair of vortex-type coils for near-future application to synchronous rotating machines. We note that the present magnetization geometry is applied to an axial gap-type rotating machine in which the pulsed magnetization is provided with a pulsed armature coil.

5. ACKNOWLEDGEMENTS

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