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Pulsed-field magnetization properties of bulk superconductors by employment of vortex-type coils

Z. Deng *, N. Shinoara, M. Miki, B. Felder, K. Tsuzuki, M. Watasaki, S. Kawabe, R. Taguchi, M. Izumi

Laboratory of Applied Physics, Tokyo University of Marine Science and Technology, Tokyo 135-8533, Japan

Abstract

Vortex-type magnetizing coils are gaining more and more attention to activate bulk superconductors in pulsed-field magnetization (PFM) studies, compared with solenoid-type ones. Following existing reports, we present experimental results of the different penetration patterns of magnetic flux between the two kinds of coils. It was found that the magnetic flux will primarily penetrate inside the bulk from the upper and lower surfaces by using vortex coils, rather than from the periphery in the case of solenoid coils. Moreover, the bulk submitted to a small pulsed-field excitation exhibits a similar field profile as the excitation field (convex or concave shape); a phenomenon named field memory effect. The use of vortex- or solenoid-type coils in PFM will pose an influence on the initial flux penetration patterns during the flux trapping processes, but both coils can finally excite the best conical trapped field shape of the bulk.

1. Introduction

As an inexpensive, small-volume and mobile experimental setup, pulsed-field magnetization (PFM) [1] is known as one of the practical activation techniques for bulk high-temperature superconductor (HTSC) applications, being widely used in various industrial fields like magnetic separation, motors/generators, drug delivery systems, magnetron sputtering, etc. [2]. To excite high potential of the trapped flux of bulk superconductors regarding the huge heat generation during the pulse application, much work has been done on studies of the pulse-applying method [3] and pulse-coil selection [4]. In that sense, the multi-

* Corresponding author. Tel/Fax: +81-3-5245-7466.
E-mail address: zgdeng@gmail.com.
pulse technique with stepwise cooling (MPSC) [5] is rather effective to excite the bulk performance and was the origin of a record of 5.2 T at 28 K [6]. Meanwhile, vortex-type magnetizing coils are attracting more and more attention compared with solenoid-type ones because the vortex coils can help to improve the trapped field and its distribution shape due to decreased heat generation [4].

In our previous work, the vortex-type magnetizing coils have been adopted in the prototype of a 10 kW bulk-type high-temperature superconducting (HTS) synchronous rotating machine [7], in view of realizing an in-situ magnetization with a compact configuration. The pulsed coils are one pair of vortex coils and form a sandwich structure with a bulk sample placed between the two coils. Each vortex coil is composed of an inner coil and outer coil, called controlled magnetic density distribution coil (CMDC) [8]. Three radial dimensions of the inner coil with a diameter of 84 mm, 60 mm and 44 mm were studied [8] and we found that the inner coil with a moderate diameter was effective in building a homogeneous conical-shape trapped flux density distribution. By applying the CMDC and MPSC techniques, a highest peak trapped field of 1.31 T was obtained for the motor operation [9]. Recently, Fujishiro et al [10] investigated the mechanism of the field trapping using vortex-type coils by numerical simulation and reported that for the vortex-type coil, the magnetic flux intrudes mainly into the bulk from the surfaces, while for the solenoid coil the magnetic flux intrudes into the bulk from the periphery. Following above reports, in this study, we will present the corresponding experimental results of the magnetic flux penetration patterns by employment of vortex-type coils and conduct a comparison with the solenoid-type coils.

2. Experimental

The PFM experiments were conducted by a homemade pulsed-field generator (Fig. 1(c)) together with a pair of vortex-type copper coils at 77 K. During the PFM, a GdBCO bulk sample of 60 mm in diameter and 20 mm in thickness, fabricated by Nippon Steel Corporation (NSC) in Japan, was sandwiched between two CMDC coils with a 7-mm gap on both sides (Fig. 1(a)). Each coil was 84 mm in outer diameter, 20 mm in height and wound by a 2 mm diameter copper wire. In addition, each vortex coil was composed of an inner coil and outer coil (Fig. 1(b)) which could be chosen to excite in different modes. The vortex coil can generate a conical-shape magnetic field and the effective magnetic field areas are dependent on the radial dimension of the coil (Fig. 1(d)). To compare the penetration patterns of magnetic flux, a solenoid-type coil with an outer diameter of 160 mm, inner diameter of 75 mm and height of 30 mm was also used, in which the bulk sample was placed just inside the center hole and the seed surface of the bulk sample was kept in the alignment of the upper surface of the coil. After the pulse, the
trapped flux distribution of the bulk was scanned by an axial Bell Hall sensor (BHT921, F.W. Bell) mounted on an $X$-$Y$ movable platform. The measurement gap was 4 mm for both excitation coils.

3. Results and discussion

3.1. Magnetic flux penetration patterns while employing vortex-type pulsed coils.

A small pulse field that can only partially penetrate inside the bulk sample was employed to investigate the flux penetration patterns by using the vortex coil and solenoid coil. Quite different features were observed in the 3D trapped flux distribution, as shown in Fig. 2. For the vortex coil, the bulk gained a relatively uniform flux distribution in the bulk central regions, as well as a flux gradient in the peripheries, which was reported as a quick intervention of the external magnetic flux into the bulk center [8]. On the contrary, for the solenoid coil, there is almost no trapped flux in the bulk center and the trapped flux is mainly accumulated at the periphery. These results clearly indicate different flux penetration patterns in the flux trapping process by using the two kinds of coils. For vortex coils, the flux is thought to penetrate inside the bulk primarily from the surface, which may be due to the parallel layout between the bulk and the coil. In this layout, the bulk upper and lower surfaces will mostly experience the applied field and the applied fields in the bulk center zones are larger than at the periphery due to the conical shape of the magnetic field generated by the vortex coil. While for solenoid coils, the flux will firstly penetrate inside the bulk from the periphery as usual, because the superconducting properties in these areas are relatively weaker, thus leading to a poor resisting ability to external flux intrusion. Another reason is that the generated field shape of solenoid coils is similar to the corresponding trapped flux profile shown in Fig. 2(c). The field is stronger in the bulk periphery but smaller in the bulk center.

3.2. Field memory effect in the beginning of the magnetization process

As shown in Fig. 2, the initial trapped flux distributions of the bulk after a small pulse-field excitation also show a close relationship to the shape of the excitation field. When employing the vortex-type coil, the bulk obtains a convex trapped field profile similar to the generated field shape of the vortex-type coil, while a concave trapped field distribution was obtained by using the solenoid-type coil. These results indicate the existence of a field memory effect in the beginning of the magnetization process. As a result, the use of the pulsed-coil types (vortex- or solenoid-type) in PFM will pose an influence on the initial flux penetration patterns due to the different external field configuration during the flux trapping processes.
3.3. Influence on the final trapped flux

It is worth noting that the different coil types may influence the initial flux penetration patterns during the flux trapping processes, but both vortex- and solenoid-type coils can work efficiently to excite the bulk performance by PFM. As an example, Fig. 3 presents the final trapped flux distribution of the bulk sample by employment of the two kinds of coils. After a multiple PFM with progressively increasing applied fields, the conical trapped field shape of the single-grain bulk could be excited by both kinds of coils. In Fig. 3(a), the bulk was only excited by the big 84 mm vortex coil; if the only inner coil was used to excite the center part of the bulk after the use of the big coil, a better conical field shape could be obtained [9]. At present, it is hard to say which coil is better for applications, because this is strongly dependent on the applied environments. However, in general, considering the size of vortex-type coils is smaller than the solenoid-type coils, a reduced heat generation and temperature rise can be obtained by vortex coils, which is quite important for PFM applications.

4. Conclusions

In this study, we presented the experimental results of the different penetration patterns of magnetic flux when employing vortex-type coils in PFM, that is, the magnetic flux will primarily penetrate inside the bulk from the upper and lower surfaces by using vortex coils, rather than from the periphery of the bulk pellet in the case of solenoid coils. Bulk superconductors also show a field memory effect in the beginning of the magnetization process. Different pulsed-coil types (vortex and solenoid) will pose an influence on the initial flux penetration patterns during the flux trapping processes, but both coils can work efficiently and finally excite the best conical trapped field shape of the bulk by PFM. The selection of the coil type is strongly dependent on the application environments. However, in general, the size of vortex-type coils is smaller than the solenoid-type coils, so a reduced heat generation and temperature rise can be obtained by vortex coils, which is very important for PFM applications.

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