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Theoretical analysis and numerical calculation of 3D trapped field distribution of single domain SmBCO bulks by Sm+011 TSIG methods

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A B S T R A C T

The lower critical temperature *Tc* and critical current density J_c are serious weaknesses of SmBCO bulk superconductors fabricated in air for practical applications, because of the Sm^{3+}/Ba^{2+} solid solution in $Sm_{1+x}Ba_{2-x}Cu_3O_y$ crystals. In this paper, high quality single domain SmBCO bulk samples S1 (ϕ20 mm) and S2 (ϕ32 mm) have been fabricated in air by a new Sm+011 TSIG method. The trapped field of the samples is 0.8 T and 1.15 T at liquid nitrogen temperature for the samples S1 and S2 respectively, which is the strongest trapped field of the SmBCO samples fabricated in air today. The theoretical formula for 3D trapped field distribution have been derived for a cylindrical model with uniformly distributed critical current density J_c based on the Biot Savart law; the cylindrical sample is divided into a series of concentric rings with the same width and thickness, the trapped field of the samples is the summation of magnetic field produced by all the rings, while the magnetic field generated by each ring was worked out by trapezoidal numerical integration based on the Biot Savart law with the critical current density J_c of the samples. It is found that the calculated field of the samples is well in agreement with the experimental results if the reasonable J_c of the samples is adopted. The theoretical calculation result also indicates that the larger the diameter and the thickness of the samples, the stronger the trapped flux density, but the optimal diameter/thickness ratio should be of a reasonable value around one, and it is not so good to fabricated samples with too larger diameter or thickness for practical applications.

1. Introduction

The ability to trap high magnetic flux, generate larger levitation force and self stable levitation, makes the single domain REBCO bulk superconductors to be of widely applications in many fields, such as high field permanent magnets [1–3], superconducting magnetic bearings [4] and flywheel energy storage system [5,6], motors and generators [7,8], and maglev systems [9–14].

The trapped field is one of the most important and useful method to measure the quality of the REBCO bulk superconductors, no matter it is fabricated by Top Seeded Melt Textured Growth (TSMTG) [15–19] and Top Seeded Infiltration and Growth (TSIG) [20–25] process. But the trapped field is weak for the SmBCO bulk superconductors fabricated in air, because the critical temperature *Tc* and critical current density J_c are lower, which is caused by the substitution of Ba^{2+} on Sm^{3+} site in $Sm_{1+x}Ba_{2-x}Cu_3O_y$ solid solution due to the minor size difference between Sm and Ba atom [26]. It is reported that both of the Oxygen Controlled Melt Growth (OCMG) method [27] and enriched Ba content [28,29] can reduce the Sm^{3+}/Ba^{2+} solid solution in the $Sm_{1+x}Ba_{2-x}Cu_3O_y$ (Sm123) crystals, and obtain high quality and nearly stoichiometric $Sm_1Ba_2Cu_3O_y$ samples. More recently, we have developed a new RE+011 SIG method, which is not only effective to fabricate high quality single domain YBCO and GdBCO bulks [20,22–24], but also effective to fabricate high quality single domain SmBCO bulks with less or no substitution of Sm^{3+} on Ba^{2+} site in the Sm123 systems [25].

The magnetic flux is generated and maintained by the macroscopic electrical currents circulating in the samples, which is also closely related with the geometry size of the REBCO bulk superconductors, such as the radius and thickness. How to predict the trapped field of these materials and make reasonable suggestion of the samples size for practical application is a very important key crucial problem. A number of analytical and numerical models have been proposed for simulating and modeling the physical properties of REBCO bulk superconductors, such as the trapped fields of YBCO bulk superconductors can be simulated based on the sand-pile model [30,31] and finite element methods [32–35] characterized by the *E–J* power law and *H*-formulations etc., these kinds of numerical simulations are very useful to predict the trapped fields of samples with different geometry, which

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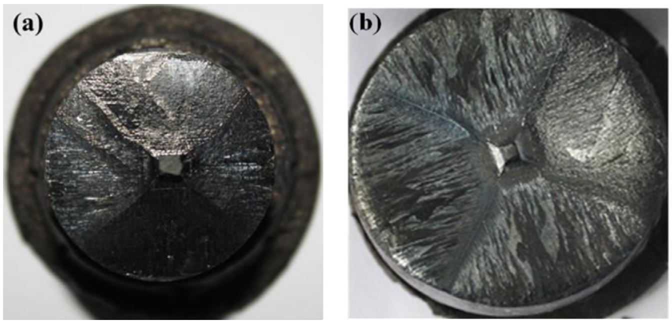

Fig. 1. Single domain SmBCO bulks fabricated in air by the new RE+011 TSIG method, (a) sample S1, 20 mm in the diameter and 10 mm in thickness, (b) sample S2, 32 mm in the diameter and 8.4 mm in thickness.

are more difficult to achieve experimentally. But most of the commercial software can not give the 3D trapped field distributions.

In this paper, the theoretical formula of 3D trapped field distribution was derived for a cylindrical models, the magnetic field is worked out by trapezoidal numerical integration based on the Biot Savart law with reasonable fitting critical current density J_c for the samples. In addition, two high quality single domain SmBCO bulks with different size have been fabricated by the new RE+011 SIG methods [23,25] and used for the trapped fields measurement and 3D numerical simulation, the trapped fields calculated by this 3D model are compared with the experimental results and well agreed with the experimental one.

2. Experimental

2.1. Sample preparation

Two single domain SmBCO bulks have been fabricated in air by the new Top Seeded Infiltration and Growth (TSIG), named as RE+011 TSIG method [23,25], the solid phase is composed of 99 wt.% [(Sm_2O_3 + 1.2$BaCuO_2$) + 1 wt.% CeO_2] and liquid phase is composed of (Y_2O_3 + 6CuO + 10$BaCuO_2$) respectively. The as pressed samples was heated up to 800 °C and held for 10 h, then heated up to 1070 °C and held for 1–2 h, then rapidly cooled to 1055 °C, after that, the samples were cooled to 1028 °C at a rate of 0.3 °C/h, and finally cooled to room temperature at a rate of 102.8°C/h. The as grown samples were oxygenized at 270 °C for 200 h in flowing oxygen, so that the as grown single domain SmBCO bulks could be of superconducting properties. One of the samples S1 is of 20 mm in the diameter and 10 mm in thickness, the other sample S2 is of 32 mm in the diameter and 8.4 mm in thickness, as shown in Fig. 1.

2.2. Trapped field measurements

The samples S1 and S2 were first magnetized in field cooled state with an electromagnet around 1.2 T to 1.4 T at 77 K, and then the trapped fields were measured at a distance of 0.5 mm above the surface of the samples at 77 K by a self made system using Hall probes [36]. Figs. 2 and 3 show the trapped field distributions of the samples S1 and S2, respectively. As we can see from these figures, the trapped field are all of conical envelope surface and there is only one peak value around the center of the corresponding samples, which means that both of samples S1 and S2 are not only of single domain in crystal morphology, but also of the single domain nature in magnetic properties. The maximum trapped fields are of about 0.804 T and 1.15 T for the samples S1 and S2 respectively.

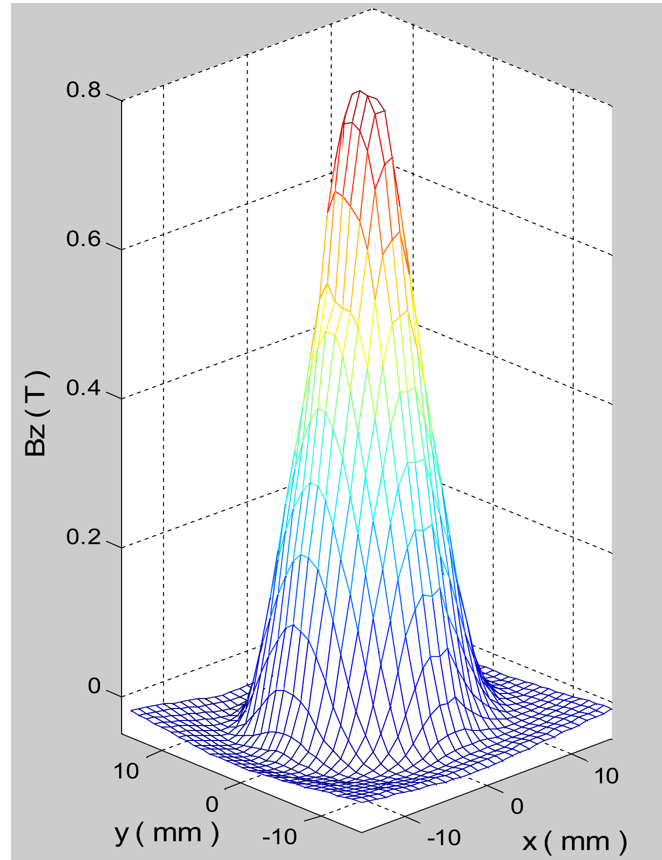

Fig. 2. The trapped field distribution of the samples S1 after magnetization at 77 K in field cooled state with applied field of 1.4 T.

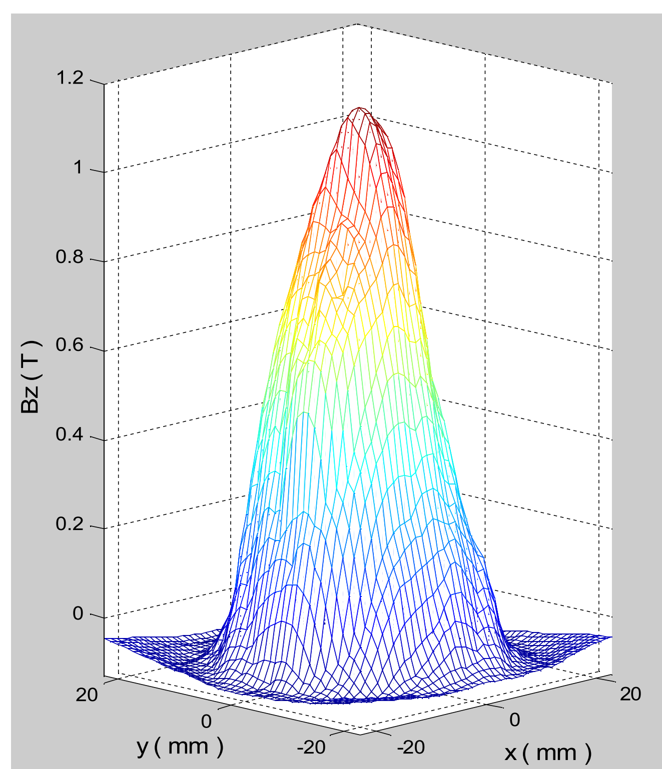

Fig. 3. The trapped field distribution of the samples S2 after magnetization at 77 K in field cooled state with applied field of 1.2 T.