Enhancement of superconducting properties of GdBCO bulk with the additives of Gd$_3$ZrO$_7$ particles

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Abstract. Due to the high performance in trapped magnetic field, critical current density, REBa$_2$Cu$_3$O$_{7-δ}$ (RE123 or REBCO, RE=rare earth elements, Gd, Y, Nd, etc.) bulk high temperature superconductors (HTS) have attracted lots of attentions. GdBCO superconductor bulk with 25 mm diameter and the additive of Gd$_3$ZrO$_7$ particles has been successfully fabricated by top-seeded infiltration and growth (TSIG) method. YBa$_2$Cu$_3$O$_{7-δ}$ (Y123) particles have been used as the liquid source, which provide enough the liquid source during the growth. The GdBCO bulk is a clear fourfold single domain with a four square around seed crystal, which is similar with the additive of the particles include Zr ions. The shape of the trapped field for the GdBCO bulk with 0.8%mol is a conical structure with 0.56T, which indicates the high performance of GdBCO bulk. The critical current density of B1 near the edge shows the maximum value. Gd$_3$ZrO$_7$ doping provides enough Gd ions to form Gd211 particles, which enhance $J_C$ near the edge of the bulks. The onset $T_c$ value increases to 95.5K and keeps the superconducting properties. The experimental data is useful for the industrial applications of the high-temperature superconductor bulk.

1. Introduction
The trapped magnetic field is 17T in YBa$_2$Cu$_3$O$_{7-δ}$ (Y123 or YBCO) superconducting bulks with a diameter of 26mm, which is higher than that in the traditional magnets [1]. The application of REBa$_2$Cu$_3$O$_{7-δ}$ (RE123 or REBCO, RE=rare earth elements, Gd, Y, Nd etc.) bulk high temperature superconductors (HTS) in power system, such as in magnetic separation systems and magnetic levitation [2-4], is attracting the researcher owing to its high critical density ($J_C$) and magnetic flux trapping performance. The top seeded melt growth (TSMG) is a conventional method to fabricate single-domain RE123 bulks. While the top seeded infiltration and growth (TSIG) process is popular recently [5-7], the TSIG method resolve the followed problems, such as shape distortion, shrinkage of the final sample and leakage of the Ba$_2$Cu$_3$O$_6$ (035) liquid phase etc.. Zhou et al. successfully processed GdBCO bulk of 32 mm in diameter by YBa$_2$Cu$_3$O$_7$ (Y123) liquid source through the modified TSMG method. The enough growth along the a-b plane has been allowed due to the Y123 liquid source, which depressed the
accumulation of Gd$_3$BaCuO$_5$ (Gd211) particles, so as to dramatically improve the properties of the GdBCO bulk. Nano-size Y211 additives enhance the critical current density and critical temperature of YBCO superconductor bulk [8-10]. The improvement of superconductivity properties have been found in the bulk with the doping of ZrO$_2$ particles [11-12].

In this article, we successfully fabricated the single domain GdBCO bulk of 25 mm in diameter with the additives of second phase Gd$_3$ZrO$_7$ particles and the Y123 liquid source of 3 mm thickness by the top-seeded infiltration and growth (TSIG) method. The enhancement of trapped field and critical current density of the GdBCO bulk have been analyzed.

2. Experimental

Powder Gd$_3$O$_3$ and ZrO$_2$ with high purity have been mixed to prepare single-phase Gd$_3$ZrO$_7$ powder by solid-state reaction. Commercial pure powders of Gd123, Gd211, Ag$_2$O and Pt with an initial composition of Gd123 + 40 mol% Gd211 + 10 wt% Ag$_2$O + 0.5 wt% Pt were mixed thoroughly and then made a cylinder pellet with the diameter of 25 mm and the thickness of 12 mm, with 0 and 0.8 mol% Gd$_3$ZrO$_7$. Commercially pure Y123 powders were chose to press into a pellet with the diameter of 25 mm and the thickness of 3 mm as the liquid source. The pellet of Y123 liquid source was put under the GdBCO precursor. Then the Y$_2$O$_3$ pellet of 3 mm in thickness was put under the Y123 pellet. The entire arrangement is onto the Al$_2$O$_3$ sheet into the box furnace. Y$_2$O$_3$ pellet avoids the reaction of the Al$_2$O$_3$ and the Y123 liquid source. The temperature profile is as followed. The maximum temperature ($T_{\text{max}}$) was set to 1079 °C, about 70 °C above the peritectic temperature ($T_p$). And the end of the reaction temperature was set to 987 °C, about 20°C below the $T_p$. We chose a cold Nd123/MgO thin film as a seed crystal to growth the bulk by a cooling rate of 0.3°C/h [13]. Subsequently, under the oxygen flowing, the annealing process was carried out. The pellet was firstly heated to 450°C in 5 h and hold for 40 h, then the temperature was slowly decreased to 350°C in 140 h, 300°C in 30 h. Finally it was cooled down to room temperature. The process method has been reported elsewhere [14].

For the trapped magnetic flux density, 1.0 T magnetic field was employed. The bulk was cooled down to liquid nitrogen temperature. After thirty minutes, the applied field was removed and the distribution of the trapped magnetic flux density was obtained by the Hall probe sensor. Thanks to Physical Property Measurement System (PPMS), DC magnetization measurements were measured. The small rectangular samples in a 2 mm×2mm×1 mm size were cut from the bulk to study the DC magnetization. There are two specimens under seed position, labeled as C1, C2, and the other specimens are under the boundary, labeled as B1, B2. $J_c$-$B$ curves were deduced under the extended Bean’s critical state model [15].

3. Results and discussion

Single domain GdBCO bulk with Y123 liquid source of 3 mm thickness and 0.8 mol% Gd$_3$ZrO$_7$ particles has been is successfully processed by TSIG as shown in Figure 1. As shown in this figure, the Nd123 seed keeps stable and there is no obvious melting phenomenon. The sample has a clear fourfold growth sector without other random nucleation of GdBCO grain. Compared with the undoped bulk, the bulk with the additives of 0.8 mol% Gd$_3$ZrO$_7$ has a square area with regular stripes around the Nd123 seed crystal. Similar phenomena were found in the bulk with the additive of ZrO$_2$ particles [11, 12], which may affect the superconducting properties of GdBCO bulk.
Figure 1. Top view of GdBCO bulk processed with the second-phase additives of 0.8 mol% Gd₃ZrO₇ particles.

Figure 2. Trapped flux density of GdBCO bulk with the second-phase additives of 0.8 mol% Gd₃ZrO₇ particles.

Figure 2 shows the distribution of the trapped magnetic flux density of the GdBCO bulk with the second-phase additives of 0.8 mol% Gd₃ZrO₇ particles. The results show that the trapping field curves of undoped and doped GdBCO superconductor bulk exhibit good symmetry and conical shape, which indicates that the single domain property of the sample is good [5, 6]. As one of the most important parameters for the practical application, the trapped field of the bulk with the second-phase additives of 0.8 mol% Gd₃ZrO₇ particles was measured and the maximum flux density value is 0.56T, which is higher than that of undoped bulk.
Figure 3. $J_C$-$B$ curves of the samples in the different positions of the GdBCO bulk with the second-phase additives of 0.8 mol\% Gd$_3$ZrO$_7$ particles at 77 K.

Figure 3 shows the $J_C$-$B$ curves of the bulk which located at different positions B1, B2, C1 and C2. It can be seen that the maximum critical current density value ($J_{\text{max}}$) is $4.9 \times 10^4$ A/cm$^2$ for the specimen taken from B1. The $J_C$-$B$ curves at different locations show that the $J_C$ values near the seed crystal are obviously lower than those at other locations. The $J_C$ values at the edge under low magnetic field are higher than those below the seed crystal. Gd$_3$ZrO$_7$ additive provides the enough Gd ion to form Gd211 particles. Due to push effect, the accumulation of more Gd211 particles at the edge of the sample in the suitable size and the number increase the $J_C$ of the specimen B1. So that the Gd211 phase at the edge increases, which provides more pinning centers for GdBCO single domain bulks, thus improving the magnetic flux pinning ability of the bulks.

Figure 4 shows the superconducting transition temperature, $T_C$, curves under the external magnetic field for the bulk with the second-phase additives of 0.8 mol\% Gd$_3$ZrO$_7$ particles in B1 position. The onset $T_C$ is around 95.5 K, which exhibits the high quality of the superconducting bulk. The narrow transition width about 1 K appears in the specimen, which shows the better superconducting properties. The result is corresponded with that of $J_C$. Gd$_3$ZrO$_7$ additive provide the enough Gd ion to form Gd123 particles, which are very essential for GdBCO superconducting phase. So that the critical current density and trapped field enhance [11, 13].

Figure 4. Superconducting transition temperature ($T_C$) curves of the GdBCO bulk in B1 position with the second-phase additives of 0.8 mol\% Gd$_3$ZrO$_7$ particles.
4. Conclusion
The single domain GdBCO superconductor with the diameter of 25 mm and the second-phase Gd$_x$ZrO$_y$ additive has been successfully growth by the TSIG technique. The Y123 pellet with 3mm thickness solves the leakage problem of liquid source and encourages the growth along a-b plane of GdBCO bulk. Gd$_x$ZrO$_y$ additive provide the enough Gd ion form Gd211 particle, which are very essential for the form of GdBCO superconducting phase. Thus, the properties of superconductor bulk have been improved. The trapped field for the GdBCO bulk with 0.8%mol is 0.56T, which indicate the high performance of GdBCO bulk. The critical current density value ($J_{c}$) is $4.9 \times 10^{4}$A/cm$^2$ of B1 near the edge. The Gd$_x$ZrO$_y$ doping provides enough Gd ions to form Gd211 particles, so that the $J_c$ enhances. $T_c$ value increase to 95.5K and keeps the superconducting properties. It can be concluded that the method can be effective to fabricate single domain GdBCO superconductor bulks with large scale in the future.

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