High performance of air-processed GdBa$_2$Cu$_3$O$_{7-\delta}$ superconductors with fined Gd$_2$BaCuO$_5$ and Gd$_2$Ba$_4$CuMoO$_x$ additions

C. Xu$^{1,2}$, A. Hu$^3$, N. Sakai$^2$, I. Hirabayashi$^2$ and M. Izumi$^1$

$^1$Department of Marine Electronics and Mechanical Engineering, Tokyo Univ. of Marine Sci. & Technol., 2-1-6, Etchujima, Koto-ku, Tokyo 135-8533, Japan

$^2$SRL, ISTEC, 1-10-13 Shinonome, Koto-ku, Tokyo 135-0062, Japan

$^3$Department of Physics, Univ. of Waterloo, Waterloo, Ontario, N2L 3G1, Canada

E-mail: cxu@e.kaiyodai.ac.jp

Abstract: We fabricated bulk GdBa$_2$Cu$_3$O$_{7-\delta}$ (Gd123) superconductors with additions of Gd$_2$BaCuO$_5$ (Gd211) and Gd$_2$Ba$_4$CuMoO$_x$ (Gd2411). We analyzed the relation between the addition amounts of Gd211 / Gd2411 particles and critical current $J_c$. We found Gd2411/Gd211 particles formed a band structure which resulted in the inhomogeneous distribution of $J_c$ in the Gd123 bulks. Gd2411 particles can stably exist in the vicinity of the seed site compared to Gd211 that is easy pushed out to edge area of single domain. This enhanced the critical current $J_c$ in the vicinity area of bulks.

1. Introduction

High-$T_c$ bulk superconductors LREBa$_2$Cu$_3$O$_{7-\delta}$ (LRE123, LRE: light rare earth, Nd, Gd, Sm, Eu) has been widely studied due to engineering applications [1, 2]. Second phase RE$_2$BaCuO$_5$ (RE211) particles, and associated defects are responsible for flux pinning. Since the optimized size of second phase particles for pinning should be typically twice the size of the coherence length (usually a few nano-meters in RE123), extensive efforts are carrying on the refinement of second phase RE211 particles [3, 4]. However, in the melt textured bulks RE123, refining the size of RE211 second phase...
inclusions to nano-scale is almost impossible due to the ripening and pushing out effects during peritectic solidification. Recently, Y$_2$Ba$_4$CuMO$_x$ (Y2411, M: Nb, Ta, W, Mo, Zr, Hf) has been reported to enhance the $J_c$ and trapped field in Y123 effectively [5].

In this paper, we synthesized sub-micrometer Gd211 particles as well as Gd$_2$Ba$_4$CuMO$_x$ (Gd2411, M: Zr and Mo) particles by solid reaction. We added Gd2411 particles into Gd123 bulks together with Gd211. We investigated the microstructure and superconducting properties for the bulks with Gd2411 and Gd211 additions.

2. Experimental

Commercial oxide powders were employed to synthesize Gd211 and Gd2411 single phase. For Gd2411, the mixing powder was pre-reacted at 950 °C for 10 hours in air twice and the single phase was obtained by calcining at 1400 °C twice in air, each time with 10 hours as duration time of calcinations. X-ray diffraction has been used to determine the single phase for both Gd211 and Gd2411. In order to get fine particles of Gd211, we employed ball-milling treatment for 1.5 hours, using Y$_2$O$_3$-ZrO$_2$ balls. BaO$_2$ compounds have been added into Gd123 bulks to suppress the solid solutions which have formed due to the substitution between Ba and Gd atoms [6, 7]. The nominal composition of the bulk was given as Gd123 + (0.4-y) Gd211 + yGd2411 + 0.1 BaO$_2$ with y = 0.2, 0.12, 0.08, 0.04, 0.02, 0.004 and 0.002 (labeled as y Gd2411), in a molar ratio. The growth processing was reported elsewhere [3, 8].

![Figure 1](image1.png)  
**Figure 1.** Applied magnetic field dependence of $J_c$ for samples with different Gd2411 additions

![Figure 2](image2.png)  
**Figure 2.** SEM Image of 0.2Gd2411 sample

In order to investigate the spatial distribution for both microstructure and superconducting properties, we cut a rectangular slab along a direction and c axis from each bulk. After observation of
microstructure by scanning electron microscopy (SEM), we continued to cut the rectangular slab into five slabs which were marked as ss1, ss2, ss3, ss4 and ss5, from the seed zone to the boundary of the single domain. The local composition was qualitatively identified with electron probe micro-area analysis (EPMA).

3. Results and discussions

3.1 Superconducting properties of Gd123 with different Gd2411 addition levels

The highest $J_c$ of each bulk was observed at different positions for different addition amounts. Figure 1 shows the highest $J_c$ for each composition as a function of applied fields while inset shows the according onset $T_c$ of all level Gd2411 additions. It is notable that when the additional amount $y \geq 0.02$, the $J_c$ below the seed position is higher than that near single domain edge position, while when $y < 0.02$ the higher $J_c$ located at the latter position. The highest $J_c$ of bulk samples dramatically decreases with increasing the Gd2411 additional amount. Meanwhile, the onset $T_c$ nearly keeps unchanged with the addition amount $y \leq 0.04$. There is a slight decrease of $T_c$ with a higher Gd2411 addition. Although a low $T_c$ value may partially result in suppression of $J_c$, the present result evidences that Gd2411 addition does not deteriorate superconductivity with a proper amount. Thus, a depression of $J_c$ values may arise from microstructure variation. The highest $J_c$ position dependence on the Gd2411 addition amount also indicates a spatial inhomogeneity of superconducting properties.

3.2 Gd211/Gd2411 distribution inside Gd123 bulks

The photo in figure 2 shows the microstructure image of a porous narrow layer in a-direction with a relatively rich concentration of the second phase in 0.2 Gd2411. The second phase rich and diluted bands alternatively distributed and this kind of band structure appeared in all the bulks with Gd2411 addition in our study, even 0.002 Gd2411 [9]. But this kind of band structure only appears within 5 mm from each side of the seed. In the last band, a rich second phase band, the distribution of second

![Figure 3. $J_c$ obtained from the different slabs cut from single domain bulk 0.02Gd2411. The inset shows $J_c$ values under self-field at different positions.](image-url)
phase is homogeneous.

3.3 Spatial variation of superconducting properties

\( J_c \) as a function of position away from the seeding site was illustrated in figure 3 for 0.02Gd2411. The variation tendency of \( J_c \) at zero field was shown in the inset of figure 3. The highest \( J_c \) appeared below the seed position, ss1, as we discussed in 3.2 while the lowest \( J_c \) located middle point of single domain, ss3, where should be the diluted second phase region before the last rich second phase band. Since there is almost no Gd211 inclusion below the seeding site, the present result strongly supports that Gd2411 enhances \( J_c \) values and demonstrates that \( J_c \) values follow the band structure of Gd211/Gd2411 distribution.

4. Conclusion

Gd2411/Gd211 second phase rich region and diluted second phase region alternatively appeared in the bulk samples for all the additional levels. \( J_c \) values were strongly dependent on the positions because of the inhomogeneous distribution of the second phase.

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