

Improvement of the Flux Trapping in Gd-Ba-Cu-O Bulk Using Magnetic Particles

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Abstract. The trapped magnetic flux of Gd-bulks increases due to the improvement of its critical current density J_c . To obtain higher J_c , introduction of pinning centres is known as one of the effective methods. In a previous study, we have found that the doping by magnetic particles has a significant potential to increase the J_c under a magnetic field. From the viewpoint of magnetic pinning effect, several soft-ferromagnetic materials are thought to act as a positive reinforcement for pinning centres. In this paper, four kinds of alloy particles such as Fe-Si, Fe-Si-Al, Fe-Si-B-Cr-C and Fe-B-Si-Nb-Cr-Cu are independently introduced into the Gd-123 matrix. Various amounts of those particles, ranging from 0 to 0.6 mol% of Gd-123, were added into a Gd-123 matrix together with Gd-211 particles. Top-seeded melt growth process has been done. Samples with the size of 10 mm x 10 mm were annealed and polished to 7 mm in height. Trapped magnetic flux measurements have been conducted at 77 K after field cooling at 1 T. The result shows that the trapped flux of the Fe-B-Si-Nb-Cr-Cu doped and Fe-Si doped samples exceed considerably those of the undoped ones. A value of $B = 0.16$ T was obtained for the local maximum in the centre of the top surface in Fe-Si and Fe-B-Si-Nb-Cr-Cu doped samples. The results are discussed comparatively from the viewpoint of magnetic and flux trapping properties.

Keywords: Magnetic particle, Fe-Si addition, Gd-Ba-Cu-O system, Magnetic pinning

1. Introduction

The push for a higher trapped flux in LRE-Ba-Cu-O (where LRE = Light Rare Earth element such as Nd, Sm, Ru and Gd) high-temperature superconductors (HTS) bulk magnets has presented a significant challenge. In several kinds of LRE-Ba-Cu-O superconductors, single-grain Gd-Ba-Cu-O especially shows a high trapped field. For example, D.A. Cardwell et al., have reported they fabricated a Gd-Ba-Cu-O system bulk with 26 mm in diameter and recorded 0.91 T [1]. On a larger sized one, S. Nariki et al. reported a magnetic field up to 3 T with 67 mm in diameter [2].

The advantage of high flux trapping property can make the conventional industrial devices smaller. This characteristic proportionally affects both output power and torque density in the motor/generator applications. Thus, HTS rotational machines potentially provide a large torque thanks to compact and high magnetic flux density field-pole magnets [3,4,5]. Our group has constructed and tested a prototype of bulk HTS propulsion motor designed for a 30-kW output power. We have adopted Gd-

Ba-Cu-O HTS among several LRE-Ba-Cu-O systems as a mother material for further processing with an introduction of pinning centers.

In a previous study, it was found that doping by a little amount of Fe-B-Si-Nb-Cr-Cu particles enhances the J_c under magnetic fields, while T_c was not regarded significantly [6]. Many groups have reported that magnetic inclusions, such as magnetic diverters and effective pinning centers, can enhance the performance of HTS bulks [7,8,9]. From those studies, it was considered that magnetic particles remain without degrading the superconducting lattice. Thanks to those advantages, the improvement of trapped magnetic flux was corroborated by field cooling method [10]. The use of the soft magnetic particles as described above provides advantages such as possessing high coercive force and magnetic permeability over a wide frequency range. Although, it has not been made clear which magnetic property improves the superconducting properties dominantly. Then, the study has been particularly focusing on the magnetic properties of added magnetic particles.

In this paper, we have prepared four the bulk samples doped by four kinds of magnetic particles with different magnetic properties, in order to clarify which parameter affects the superconducting characteristic enhancement. Flux trapping property was measured and analyzed as a function of magnetic properties such as initial/maximum permeability, saturation magnetic flux density and coercivity.

2. Experimental preparation

2.1. Magnetic particles

Commercial magnetic particles, Fe-Si (Fe-3.5Si), Fe-Si-Al (Fe-9.5Si-5.5Al), Fe-Si-B-Cr-C (Fe-7Si-2.5B-2Cr-0.8C) and Fe-B-Si-Nb-Cr-Cu were prepared. The detailed magnetic properties of those particles are shown in table 1. For the Fe-B-Si-Nb-Cr-Cu particle, the component was identified as 68.7Fe-12.1B-13.8Si-3.34Nb-1.06Cr-1.02Cu by component analytical equipment.

Figure 1 shows photographs taken by scanning electron microscopy (SEM). The average sizes of Fe-Si, Fe-Si-Al, Fe-Si-B-Cr-C and Fe-B-Si-Nb-Cr-Cu particles are about 10 μm , 9 μm , 20 μm and 20 μm , respectively.

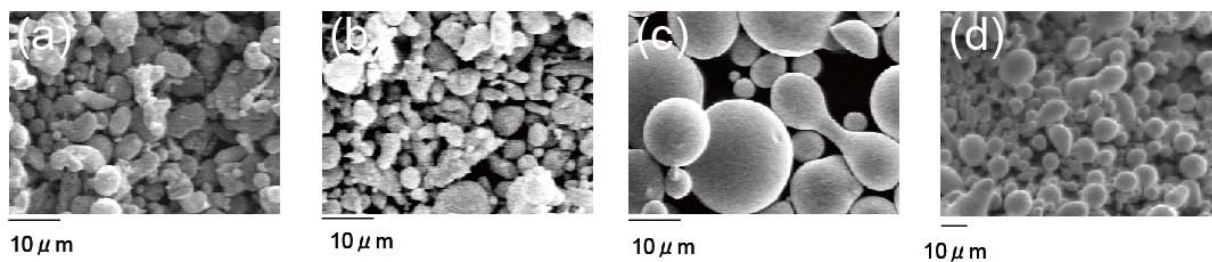


Figure 1. SEM observation of magnetic particles
(a) Fe-Si (b) Fe-Si-Al (c) Fe-Si-B-Cr-C (d) Fe-B-Si-Nb-Cr-Cu

Table 1. Properties of magnetic particles.

Composition of particles	Fe-Si	Fe-Si-Al	Fe-Si-B-Cr-C	Fe-B-Si-Nb-Cr-Cu
Average particle size (μm)	10	9	20	20
Initial permeability	1 000	30 000	5 000	-
Maximum permeability	30 000	120 000	50 000	80 000
Saturation magnetic flux density (T)	2	1.1	1.56	1.23
Coercivity (A/m)	24	1.6	2.4	40~80

2.2. Seed crystal

Nd-Ba-Cu-O seed crystals were fabricated by the conventional melt processing [11]. Commercially available $\text{NdBa}_2\text{Cu}_3\text{O}_{7-\sigma}$ (Nd-123, 3N) and $\text{Nd}_4\text{Ba}_2\text{Cu}_2\text{O}_{10}$ (Nd-422, 3N) precursors were first mixed together (Nd-123 + 20 mol% Nd-422), and uniaxially-compressed into pellets. Then, they were melt-processed in air using a certain temperature program.

2.3. Fabrication of Gd-Ba-Cu-O single grains in air with addition of magnetic particles

Commercial $\text{Gd}_2\text{BaCuO}_5$ (Gd-211, 3N) powder was introduced into the $\text{GdBa}_2\text{Cu}_3\text{O}_{7-\sigma}$ (Gd-123, 3N) system as the second phase to fabricate single-domain Gd-123 superconductivity bulks. In a previous study, we have found the optimum molar ratio of magnetic particles /Gd-123 is around 0.4 mol%. Therefore, precursor powders with the nominal composition of Gd-123 + 40 mol% Gd-211 + X mol % M, where X = 0.0, 0.2, 0.4 and 0.6, M = Fe-Si, Fe-Si-Al, Fe-Si-B-Cr-C, Fe-B-Si-Nb-Cr-Cu, were mixed thoroughly using Y_2O_3 - ZrO_2 balls. 10 wt% of Ag and 0.5 wt% of Pt were added and mixed together in order to enhance the mechanical stability and minimize the size of Gd-211, respectively. After being well mixed, powders were compressed into cylindrical pellets with 20 mm in diameter and 9 mm in thickness.

2.4. Melt process

Hot-seeding method in air was performed inside pellets. The pellets were heated to 1100 °C over 10 h, held at that temperature for 1 h, then cooled down to 1020 °C and subsequently held for 1 h. Before being cooled down to 1010 °C, a melt textured Nd-123 seed crystal was placed on the surface of the pellet to control the crystallization. During the growth, we followed with a slow cooling rate of 0.3 °C / h to 960 °C. After that, the samples were cooled down to the room temperature at a rate of 100°C / h.

Finally, the samples were further annealed for 200 hours from 450 °C to 300 °C by step cooling at the rate of 0.25 °C / h in flowing oxygen.

3. Results and Discussion

3.1. Fabrication of magnetic-particle-doped samples

Figure 2 shows the photographs of as-grown Gd-123 samples with different magnetic-particle additions. After the melting process, sample bulks have grown into a single domain with 17 mm in diameter and 8 mm in thickness. In each sample, facet grain boundaries clearly appeared on the surface of the bulks. The observation of the microstructure, including the doped particles distribution, may provide a supported evidence of the effective improvement of the pinning function in the present results.

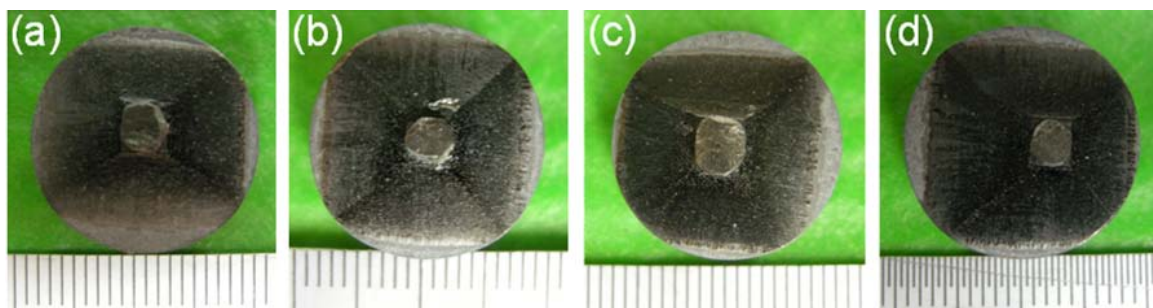


Figure 2. Top-view photographs of single grain fabricated from precursors with composition of Gd-123 + 0.4 mol% Gd-211 + 10 wt% Ag_2O + 0.5 wt% Pt + X mol% M. (a) 0.2 mol% Fe-Si (b) 0.6mol% Fe-Si-Al (c) 0.6mol% Fe-Si-B-Cr-C and (d) 0.4 mol% Fe-B-Si-Nb-Cr-Cu

3.2. Trapped flux measurement

Figure 3 shows the trapped field distribution of bulks (a) without magnetic particle addition, (b) with 0.2 mol% Fe-Si-Al and (c) 0.4 mol% Fe-B-Si-Nb-Cr-Cu. The trapped magnetic flux profile was measured at 77 K after field-cooled process with a uniform applied field of 1 T. Before the measurement, the samples were cut into 10 mm x 10 mm x 7.5 mm squares to obtain uniform grown sizes of HTS bulks. The single-grain bulks with both Fe-Si addition and Fe-B-Si-Nb-Cr-Cu addition exhibit a trapped field of over 0.16 T which is 10 % higher than the sample without addition. Also we can see that the integrated flux of the sample of Fe-B-Si-Nb-Cr-Cu addition is higher than the one with Fe-Si even though the maximum trapped field is almost the same.

Table 2 summarizes the results of flux trapping properties for different magnetic particles additions. The maximum trapped fields of non-doped, Fe-Si, Fe-Si-Al, Fe-Si-B-Cr-C and Fe-B-Si-Nb-Cr-Cu systems are 0.149 T, 0.165 T, 0.140 T, 0.135 T and 0.162 T, respectively. It can be seen that in a small amount range of magnetic particle doping, both maximum magnetic field and total flux increase. However, when the addition amount was more than 0.6 mol% of Gd-123, the trapped field decreased. This surely depresses the T_c due to the substitution of Cu element in the superconducting matrix, which follows a previous study

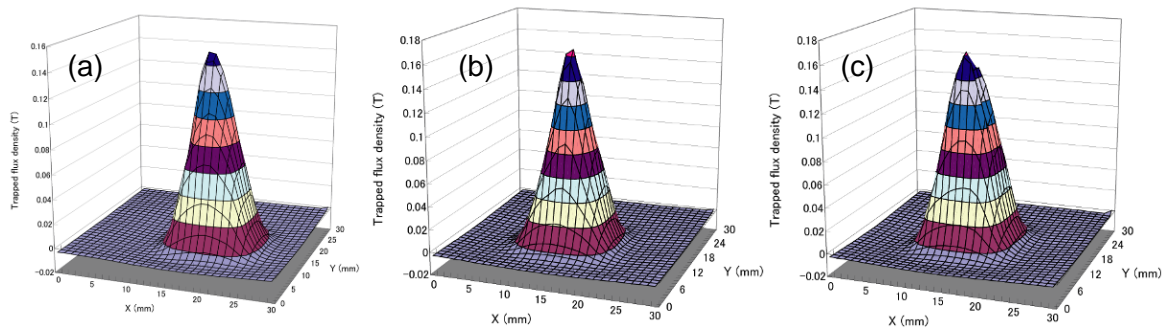


Figure 3. Trapped field distribution after the field cooling of the bulks (a) without magnetic particles addition (b) with 0.2mol% Fe-Si-Al (c) with 0.4 mol% Fe-B-Si-Nb-Cr-Cu

Table 2. Results of magnetic trapped flux properties.

	Maximum trapped magnetic field (T)				Magnetic flux (μ Wb)			
	0.0mol%	0.2mol%	0.4mol%	0.6mol%	0.0mol%	0.2mol%	0.4mol%	0.6mol%
Fe-Si		0.165	0.111	0.136	8.17	5.46	6.18	
Fe-Si-Al		0.140	0.085	0.090	7.22	5.24	5.35	
Fe-Si-B-Cr-C	0.149	0.070	0.135	0.122	7.75	4.94	7.58	7.53
Fe-B-Si-Nb-Cr-Cu		0.151	0.162	0.131	7.03	8.80	6.12	

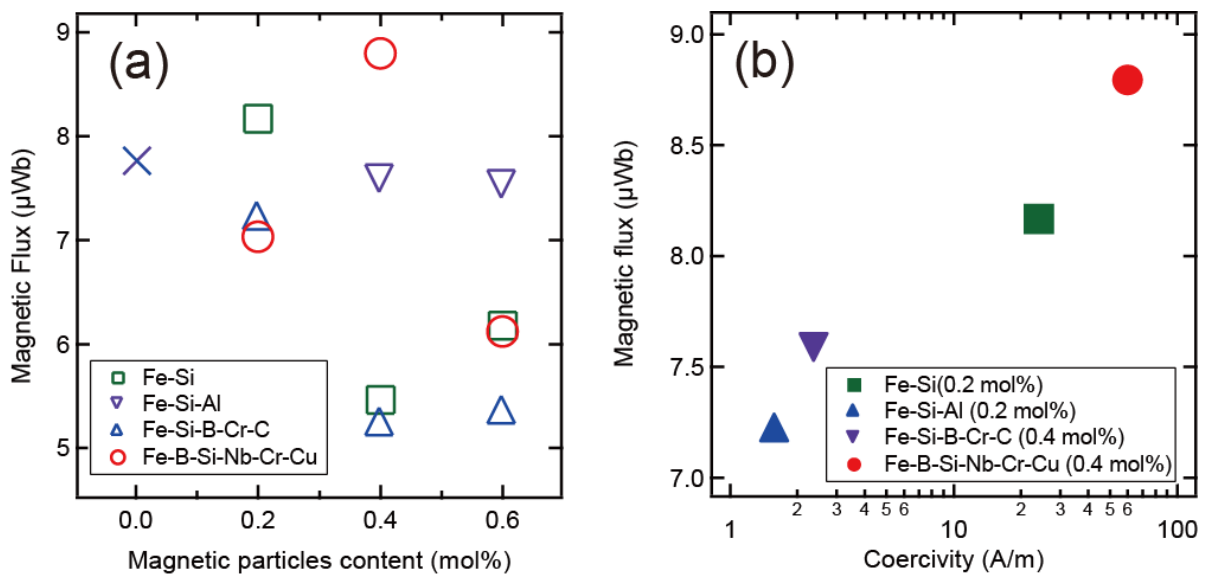


Figure 4. Trapped magnetic flux properties dependence (a) Total magnetic flux as a function of magnetic particle content (mol%) (b) The variation of maximum total magnetic flux for each magnetic dopant as a function of coercivity.

3.3. Variation of doping rate for different magnetic particles

Figure 4 (a) shows the results of the trapped magnetic flux as a function of the magnetic particles content for different magnetic particles. In the results of Fe-B-Si-Nb-Cr-Cu at 0.4 mol% doped samples, the value of the trapped magnetic flux is $8.80 \mu\text{Wb}$, which is 14 % higher than non-doped samples. Following this value, Fe-Si addition marked $8.17 \mu\text{Wb}$. These experimental results reveal that flux trapping properties of Gd-Ba-Cu-O bulks are enhanced by adding those magnetic particles. On the other hand, trapped magnetic flux results of Fe-Si-Al and Fe-Si-B-Cr-C doped samples are slightly decreased and no peak of total flux is observed.

Figure 4 (b) shows the plot of maximum trapped magnetic flux as a function of coercivity for each magnetic particle. A potential relationship of coercive force in doping particle with the trapped flux was observed. It implies that particles with higher coercivity affect the bulk to obtain better pinning stability in any way. Extensive study in the future is needed to prove this relationship, by measuring superconducting properties and investigating the microstructure. The trapped flux property has also been compared with other magnetic parameters such as permeability and saturation flux but no significant relation was observed.

4. Conclusions

Little amounts of magnetic particles of Fe-Si, Fe-Si-Al, Fe-Si-B-Cr-C and Fe-B-Si-Nb-Cr-Cu were introduced in a Gd-Ba-Cu-O bulk. The superconducting-bulk samples with 17-mm diameters were successfully obtained from precursor powders treated by melt process. We found an enhancement of the flux trapping property in the single grain with Fe-Si and Fe-B-Si-Nb-Cr-Cu additions. Both sample bulks exhibit the maximum trapped field of over 0.16 T, which is 10 % higher than the one without magnetic particles addition. The results of Fe-B-Si-Nb-Cr-Cu particles addition bulk marked the highest integrated flux of $8.80 \mu\text{Wb}$, and Fe-Si doped one followed it. The relationship between magnetic and trapped flux properties was studied. We concluded that the coercivity possess a significant effect on the trapped flux results. Further investigation is needed to determine the mechanism of the trapped flux enhancement.

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