Reinforcement of bulk Y-Ba-Cu-O superconductors by using Fe-Mn-Si-Ni shape memory alloy rings

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Abstract

Bulk Y-Ba-Cu-O superconductors are brittle ceramics and their tensile strengths are very low. Therefore, reinforcement of the bulk superconductor is needed for practical applications. Pre-compression load has been shown to be effective in enforcing the bulk superconductors. Fe-Mn-Si alloys exhibit shape-memory effects and the size change due to the shape recovery is large. Therefore, the Fe-Mn-Si shape memory alloy rings will function as effective reinforcement material for the bulk superconductors. We prepared Y-Ba-Cu-O bulk superconductors with top-seeded melt-growth process and the Ni added Fe-Mn-Si (Fe-Mn-Si-Ni) alloy ring which exhibited better shape memory performances than Ni-free Fe-Mn-Si alloys. The ring was extended by inserting a steel rod and heated to 623K. The amount of shape recovery strain was about 2%. Based on these results, the TSMG-processed bulk Y-Ba-Cu-O superconductor 39.0 mm in diameter was inserted into the Fe-Mn-Si-Ni ring whose inner diameter was 39.3 mm at room temperature. With heating to 623K, the Fe-Mn-Si-Ni ring shrank and firmly encapsulated the bulk Y-Ba-Cu-O superconductor. Cracking was not observed in the bulk superconductor. It was interesting to note that the trapped magnetic field of the Y-Ba-Cu-O superconductor at 77K was increased from 2,550 G to 3,795 G through Fe-Mn-Si-Ni ring reinforcement. These results clearly show that the reinforcement treatment with Fe-Mn-Si-Ni alloy ring or pre-compression load is effective in improving the field trapping ability in addition to the improvement of the mechanical properties.

Keywords: bulk superconductor; trapped magnetic field; reinforcement; YBaCuO; shape memory alloy

1. Introduction

Large single-domain bulk RE-Ba-Cu-O (RE: rare earth) superconductors can trap large magnetic fields much greater than those of conventional permanent magnets [1]. Therefore, the bulk superconductors can be used for various engineering applications such as a superconducting motor and a flywheel energy storage system.

When bulk superconductors trap magnetic fields, Lorentz forces are induced along a tensional direction, which sometimes leads to the fracture because the bulk superconductors are brittle ceramics. Therefore, the mechanical reinforcement is indispensable for engineering applications. It is common to use a metal ring to apply pre-compression load on the bulk superconductor by utilizing a difference in the thermal expansion coefficients between the bulk and the metal ring. For this purpose, stainless steel has been used as a metal ring [2]. However, the amount of thermal contraction of the stainless steel is very small and thus the reinforcement is not so large [3-5].

We noticed that higher compression forces can be applied to the bulk body if we use a Fe-Mn-Si shape memory alloy ring since it can exhibit much larger shape recovery strain than that of thermal contraction. Recently we have found that Ni-added Fe-Mn-Si (Fe-Mn-Si-Ni) alloys can recover at lower temperature than that of Ni-free sample.

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Therefore, it is expected that Fe-Mn-Si-Ni alloys show superior shape recovery strain. Hence we employed Fe-Mn-Si-Ni shape memory alloy rings for the reinforcement of bulk Y-Ba-Cu-O bulk superconductors. In the present study, we first characterized the deformation behavior of Fe-Mn-Si-Ni shape memory alloy ring, and then studied the effect of the shape recovery contraction on the field trapping abilities of bulk superconductors.

2. Experimental procedure

2.1. Sample preparation

Y-Ba-Cu-O bulk samples were synthesized using sintered YBa$_2$Cu$_3$O$_y$ (Y123) and Y$_2$BaCuO$_5$ (Y211) powders as starting materials. The Y123 and Y211 powders were prepared from commercial Y$_2$O$_3$, BaO$_2$ and CuO powders that were well mixed and calcined at 1173 K. We then mixed powders in a molar ratio of Y123: Y211 = 5:2, for which 1 wt% CeO$_2$ was added in order to lower the peritectic temperature and refine the Y211 second phase particles. We fabricated bulk Y-Ba-Cu-O superconductors with top-seeded melt-textured growth process using Nd123 crystal as a seed, the details of which are described elsewhere [6]. The melt-textured samples were annealed at 673 K for 100 h in flowing oxygen. The side-surfaces of all the samples were polished in order to firmly fit it into shape memory alloy rings.

2.2. Preparation of Fe-Mn-Si-Ni rings

It is known that the shape memory effect of Fe-Mn-Si alloys can be improved with a so-called training treatment, in that the alloys are deformed and heated several times [7]. In the present study, we used Fe-28Mn-6Si-5Cr-3Ni shape memory alloys for the reinforcement of bulk Y-Ba-Cu-O superconductors. The alloy rings were extended by inserting a steel rod with strains of about 7-7.5% at room temperature and heated to 923 K, which was repeated twice. Such a repeated deformation and heating process is called a training treatment. To check the final dimensions of a Fe-Mn-Si-Ni alloy ring, we deformed the ring and heated at 873 K for 30 min and measured the outer and inner diameters of the ring.

Finally, the side surfaces of the melt-textured Y-Ba-Cu-O bulk superconductors were polished mechanically to fit the inner diameter of the ring and inserted into the trained shape memory alloy ring that was expanded at room temperature. Then the Y-Ba-Cu-O bulk and the ring were annealed at 673 K for 6 h in air.

2.3. Trapped field measurements

We measured trapped field of single-domain Y-Ba-Cu-O bulk superconductors before and after the reinforcement with the Fe-Mn-Si-Ni alloy rings. For the magnetization of the superconductors, we used an electromagnet, which generates homogeneous fields up to 1T. The superconductors were cooled by liquid nitrogen in the presence of the field of the electromagnet. After removing the magnetic field, the trapped field was measured by scanning a Hall sensor in the area of 50×50 mm$^2$ at 1 mm above the sample surface.

3. Results and discussion

![Fig. 1. The change in the dimensions of a Fe-Mn-Si-Ni alloy ring at various processing steps.](image_url)
Figure 1 shows the change in the dimensions for a Fe-Mn-Si-Ni alloy ring at various processing stages. Here the samples are at 873 K for 30 minutes. Decreases in the inner and outer diameters are due to the shape recovery and the increases correspond to the expansion step with a steel rod at room temperature. One can notice that the change of lengths is small compared to those of the diameters, and reflects Poisson's ratio of Fe-Mn-Si-Ni alloy. The initial inner diameter of the extended alloy ring was 35.67 mm. The inner diameter of the shape memory alloy ring changed from 35.67 to 35.13 mm when heated at 873 K. Therefore the amount of strain due to the shape recovery was about above 1%. It is known that the amount of coefficient of linear thermal expansion of Fe-Mn-Si-Ni shape memory alloy is about $18 \times 10^{-6}$ K$^{-1}$, and hence the amount of shape recovery contraction of the alloy is much higher than that of thermal expansion. Thus one can conclude that the employment of the shape memory effect is useful for the reinforcement of bulk superconductors.

Based on the results presented in Fig. 1, we used a trained Fe-Mn-Si-Ni alloy ring for reinforcement of bulk Y-Ba-Cu-O. Figure 2 shows photos of (a) a Y-Ba-Cu-O sample without a metal ring and (b) the same Y-Ba-Cu-O sample reinforced with a Fe-Mn-Si-Ni shape memory alloy ring. The surface growth morphology shows that this sample is a single domain. One can also see that the fitting between the bulk superconductor and a Fe-Mn-Si-Ni ring is quite well after heating. We visually inspected the sample surface before and after the reinforcement with the Fe-Mn-Si-Ni ring, and could detect no appreciable change in the microstructure.

![Figure 2](image)

**Fig. 2.** Photos of (a) melt-textured Y-Ba-Cu-O bulk superconductor and (b) the same melt-textured Y-Ba-Cu-O bulk superconductor encapsulated in the Fe-Mn-Si-Ni ring.

Figure 3 shows trapped field distributions for (a) bulk Y-Ba-Cu-O sample without the ring and (b) Y-Ba-Cu-O sample reinforced with the Fe-Mn-Si-Ni ring at 77 K field-cooled in the magnetic field of electrical magnet. The sample without the ring exhibited the maximum trapped field of 2,555 G at 77 K, while that of the sample reinforced with the ring was 3,795 G. Considering the fact that the same Y-Ba-Cu-O sample was used to assess the effects of the reinforcement with the Fe-Mn-Si-Ni alloy ring, the present results may suggest that the reinforcement enhanced the field trapping capability. It is probable that pre-compression load on the bulk superconductors may lead to the alleviation of the reduction in the critical current density due to the tensile strain caused by the Lorentz force and thereby an enhancement of the field trapping ability, although a further study will be necessary to draw a definite conclusion.

![Figure 3](image)

**Fig. 3.** Trapped field profile for (a) melt-textured Y-Ba-Cu-O bulk superconductor and (b) the same melt-textured Y-Ba-Cu-O bulk superconductor reinforced with the Fe-Mn-Si-Ni ring.

4. **Summary**
We studied the reinforcement of bulk Y-Ba-Cu-O superconductors with Fe-Mn-Si-Ni shape memory alloy rings. We fabricated a single domain Y-Ba-Cu-O superconductor with the top-seeded melt-growth process. The sample was machined as to fit into a Fe-Mn-Si-Ni ring, and heated at 673 K for 6 hours in air. Through this treatment, the sample was encapsulated firmly into the ring. We also measured the trapped fields of the bulk Y-Ba-Cu-O sample before and after reinforcement with the Fe-Mn-Si-Ni ring. The results revealed that trapped magnetic fields were improved with Fe-Mn-Si-Ni ring reinforcement. Although it is still unclear that such an improvement is intrinsic or extrinsic, we can say that the reinforcement of bulk Y-Ba-Cu-O with Fe-Mn-Si-Ni shape memory alloy ring is effective in improving the mechanical properties of bulk Y-Ba-Cu-O without deterioration in superconducting properties.

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References