J. Plasma Fusion Res. SERIES, Vol. 5 (2002) 574–578

Improvement of Critical Current Density and Mechanical Properties of Bi-2223 HTS Bulk for Current Lead Application

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(Received: 11 December 2001 / Accepted: 4 June 2002)

Abstract

We have studied a $(Bi,Pb)_2Sr_2Ca_2Cu_3OX$ (Bi-2223)/Ag wires composite bulk to improve the mechanical and superconducting properties, a composite structure of Bi-2223 and Ag wires was newly developed for application to current leads. As the results, the maximum J_c value of the composite bulk which composed with twenty-four Ag wires of 0.4 mm in diameter was estimated to 1200 A/cm^2 (I_c = 150 A) at 4.2 K and 0 T. This J_c value was about three times higher than that of the oxide bulk without Ag wires. The mechanical property was estimated by a three point bending test, and the results show that the maximum bending stresses are about 60 MPa in Bi-2223 bulk without Ag wires and 70 MPa in the composite with forty-two Ag wires of 0.2 mm in diameter. Though Bi-2223 bulk without Ag wires fractured separately after the maximum bending stress, the composite by Ag wires did not fracture completely. The developed composite bulk must possess good mechanical properties as well as high J_c.

Keywords:

Bi-2223 sintered bulk, composite with Ag wires, highly oriented and dense structure, J_c value, mechanical strength

1. Introduction

It is known that free-oxygen copper is used to current lead for large-scaled application system, because it has high-current and low resistance properties. Typical problem when it used to current lead for large-scaled application system is high thermal conductivity. The other, Bi-2223 high critical temperature (T_c) superconductor (HTS) material is suitable to apply to the current lead for large-scaled application system such as a nuclear fusion reactor, because it has high critical current density (J_c) value of 10^4 A/cm^2 order at 77.3 K and lower thermal conductivity compared with free oxygen copper [1]. In fact, Bi-2223 oxide bulk material is used current lead for the liquid He-free cryocooler-cooled magnet system [2]. Bi-2223 bulk, however, has some problems to limit the application field. Typical problem is that J_c value of the bulk materials is much smaller than that of the wire and tape materials, and another is very brittleness and fragile mechanically because Bi-2223 oxide is ceramic material.

We thought that the improvement of the J_c value and mechanical strength is urgent for the nuclear fusion reactor application. Recently, several studies have been made on the improvement of J_c and/or mechanical property for Bi-2223 oxide bulk. Hishinuma et al. reported that J_c values of Bi-2223 bulks inserted with silver (Ag) sheet were improved with the number of Ag

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sheets [3-5]. Matsunaga et al. reported that mechanical property was improved by addition of ceramic fiber from results with a three point bending and tensile test [6]. Then, we prepared the Bi-2223 sintered bulk composed with fiber-shaped metal Ag wire, tried to improve J_c and mechanical property on the Bi-2223 bulk.

2. Sample Preparation

The nominal composition of calcined Bi-2223 powder was adjusted to be $Bi_{1.85}Pb_{0.35}Sr_{1.90}Ca_{2.05}Cu_{3.05}O_x$. The constant weight of 1.0 g was picked up. The Bi-2223/Ag wires composite bulk was prepared hand-made by stacking alternately the calcined powder and the Ag wires of 0.2 mm or 0.4 mm in diameter. The number of composed Ag wires of 0.2 mm in diameter was fourteen, twenty-eight and forty-two, and then the number of composed Ag wire of 0.4 mm in diameter was eight, sixteen and twenty-four. The stacked samples were molded with metal dies, and the sample size is about 5 mm in width, 22 mm in length and 2 mm in thickness. Figure 1 shows typical cross-sectional structure of the prepared sample composing with Ag wires of 0.2 mm diameter. The prepared samples were sintered at 840°C for 50 hours in air [2-4].

Microstructure of the interface region between the oxide and the Ag was observed using a Scanning Electron Microscope (SEM). In evaluation of superconducting property, the transport critical current (I_c) was measured at several conditions as follows; at 77.3 K and self-field, and at 4.2 K and magnetic field up to 5 tesla. Transport Ic was decided by using 1 μV/cm criterion. Critical current density (J_c) was obtained from transport I_c and cross-sectional area of Bi-2223 oxide expect for Ag wires. And then, engineering critical current density (J_e) was equal to over all J_c, and it was obtained from transport I_c and over all cross-sectional area of Bi-2223/Ag wire bulk. The other, mechanical property was measured by a three point bending test at room temperature. The span between the supporting points is adjusted to 15 mm. The load of 0.5 N was applied to the sample at the stroke ratio of 0.005 mm/sec. The loading was continued after the rupture.

3. Results and Discussions

3.1 Microstructure and Superconductivity

Crystalline characteristic of the Bi-2223/Ag wires composite bulks in the vicinity of interface between Bi-2223 oxide and Ag wire was studied. The results of SEM observation on the cross-section of Bi-2223 bulk composed with Ag wires of 0.2 mm in diameter sintered at 840°C for 50 hour are shown in Figs. 2(a) and 2(b). Figure 2(b) shows high magnification of Fig. 2(a). The upper black semicircular region in these Figs. 2(a) and 2(b) means porosity induced by hollowing out Ag wire. The highly c-axis oriented and densely structured Bi-2223 plate-like grains are formed along the circumference of the pore, and the other regions in the bulk are random and porous structure common in conventional Bi-2223 oxide bulk materials. In Fig. 2(b), it is noteworthy that good alignment and very dense structure occurred within 20 μm from the interface between Bi-2223 oxide and Ag wire. Similarly, this tendency was shown even in the sample composed with

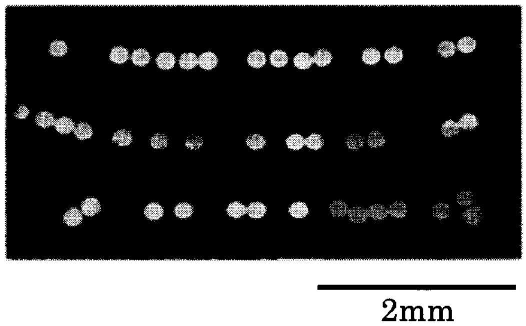

Fig. 1 Optical microscopic photograph of typical cross-sectional structure of Bi-2223/Ag wires composite bulk.

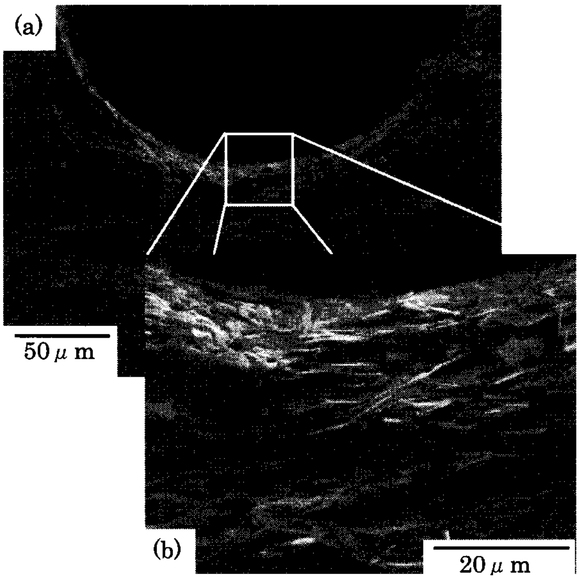

Fig. 2 SEM images of typical cross-sectional structure of Bi-2223/Ag wires composite bulk.

Ag wire of 0.4 mm in diameter. These suggest that highly oriented and densely structured Bi-2223 plate-like grains could be formed along surface of metal Ag wire in Bi-2223 oxide bulk. The Ag wires hollowed out forcibly from Bi-2223/Ag wires composite bulk, and the surface of Ag wire was observed using SEM-EDX. The large plate-like grain is observed along the surface of Ag wire, and the composition was estimated that indicated to be Bi-2223 phase. The element composition distribution on the Bi-2223/Ag wires composite bulk was studied using SEM-EDX. The composition estimated that single-phase of Bi-2223 grows at interface between the oxide and Ag, and mixture phase of Bi-2223 and Bi-2212 is present in the region far from Ag. The impurity phases contained in the two regions are Ca_2PbO_4 and $Ca_{2-X}Cu_XO_y$ ($X = 0 \sim 1$) compounds. Distribution of Ag element is concentrated in the Ag wires, and Ag does not diffuse into the oxide layer in the concentration range over the analytical limit.

In order to examine superconducting properties of Bi-2223 bulks when composed with Ag wire, the relationships between the number of Ag wires and transport I_c and J_c values at 4.2 K and self-field are shown in Fig. 3. The J_c value of Bi-2223 bulk without Ag wire was obtained less than 400 A/cm^2 (I_c = 50 A), and the J_c values of sample composed with forty-two Ag wires of 0.2 mm diameter and twenty-four Ag wires of 0.4 mm diameter were estimated to be about 800 A/cm^2 (I_c = 100 A) and 1200 A/cm^2 (I_c =150 A). Both transport I_c and J_c values are improved with increasing number of Ag wires. In similar to results of measurement at 4.2 K shown in Fig. 3, transport I_c and J_c values of samples at 77.3 K are improved by composing with Ag wires. All J_c values of the sample composed with Ag wires are higher than sample without Ag wire as measured at 77.3 K and 4.2 K. And then, engineering J_c (J_e) was also improved by composite of Ag wires. This means that improvement of transport I_c and J_c values at 4.2 K and 77.3 K is brought about by the effect of composing with Ag wires; highly oriented and densely structured Bi-2223 plate-like grains was formed on the circumference of Ag wires shown in Fig. 2(b).

One application for Bi-2223/Ag wires composite bulk is current lead, therefore it is necessary to check influence of magnetic field on the composite bulk. Figure 4 shows normalized J_c dependence of the magnetic field on the Bi-2223/Ag wires composite bulks. Normalized J_c values were obtained by dividing J_c values under several tesla of magnetic fields by J_c value at self-field. All J_c values of Bi-2223/Ag wires

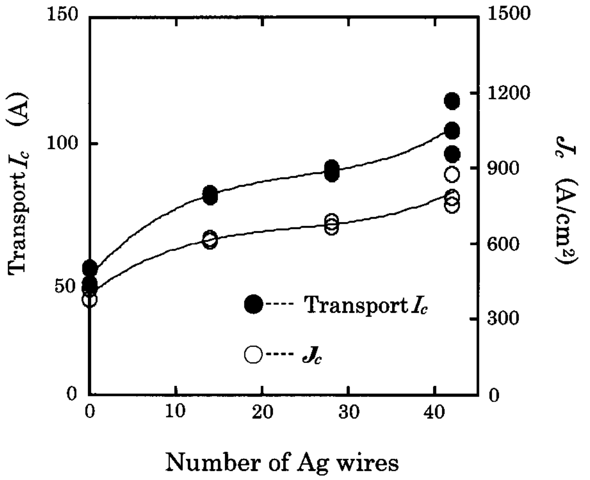

Fig. 3 The relationships between the number of Ag wires of 0.2 mm diameter and transport I_c and J_c values at 4.2 K and self-field.

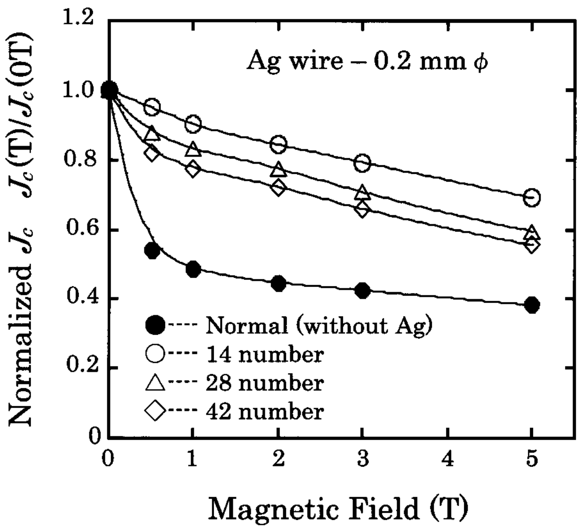

Fig. 4 The normalized J_c dependence of the magnetic field on the Bi-2223/Ag wires composite bulks.

composite bulks at every magnetic field are higher than that of Bi-2223 oxide bulks without Ag wires. J_c values of the samples composed with Ag wires are about twice as much as the sample without Ag wires on every magnetic field. And then, the decreasing of J_c value under magnetic field up to 5 tesla on the samples composed with Ag wires is restrained to half compared with that of the sample without Ag wires. It was noteworthy that J_c dependence of low magnetic field on the samples composed with Ag wires is much smaller than that of the sample without Ag wires. This is because highly c-axis oriented, homogeneous and densely structured Bi-2223 grains observed in Fig. 3 forms along the circumference of metal Ag wire improving connectivity among grains. It was found that the results of J_c properties shown in Figs. 3 and 4 were conformed to the results of crystalline characteristic by SEM observations.

3.2 Mechanical Property

As Bi-2223 superconductor oxide bulk is applied to large-sized current lead, it is necessary to check mechanical property of the Bi-2223/Ag wires composite bulk. We measured mechanical property using a three point bending test on the Bi-2223/Ag wires composite bulks at room temperature. Figure 5 shows the relationship between displacement and bending stress in the Bi-2223 bulks composed with Ag wires of 0.2 mm diameter. And the relationship between deflection and bending stress in the Bi-2223 bulks composed with Ag wires of 0.2 mm diameter is shown in Fig. 6.

The maximum bending stress is about 60 MPa in Bi-2223 bulk without Ag wire, and 70 MPa in the composite with forty-two Ag wires of 0.2 mm diameter. This tendency is confirmed the other bending test. At least, degradation of the bending strength by the composite of Ag wires has not been observed. The Ag wire may become good adhesion with Bi-2223 matrix. The Bi-2223 bulk fractured separately after the maximum bending stress, and then the bending stress dropped to zero. On the other hand, the composite of Ag wires did not fracture separately and then the bending stress is kept some fixed value. The fixed value was increased with increasing the number of composed Ag wires. That is, the composed Ag wires play a major role in sustaining the ruptured sample as "bridge". We found that the toughness as oxide bulk material was improved by composite of Ag wires. In addition, we tried to observe microstructure of fracture surface using SEM. We observed that the crack did not penetrate by the barrier of Ag wires from SEM observation. This is regarded as generating the rupture by the crack only in the oxide. The composed Ag wires are effective to prevent the propagation of the crack. This means that composite of Ag wires is able to fabricate the high crack propagation resistance oxide bulk. Moreover, we confirmed to be able to transport some current through the composite sample after the bending test. Ag wires can also act as the electrical bypass circuit in accidents such as the mechanical and/or electrical fracture.

The bending stress for the deflection of composite

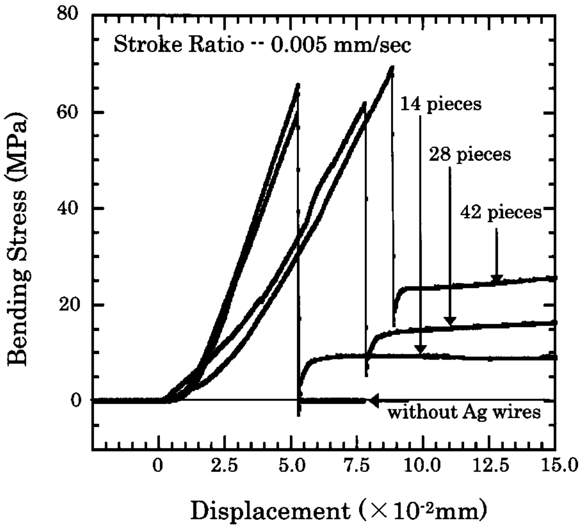

Fig. 5 The relationship between displacement and bending stress in the Bi-2223 bulks composed with Ag wires of 0.2 mm diameter.

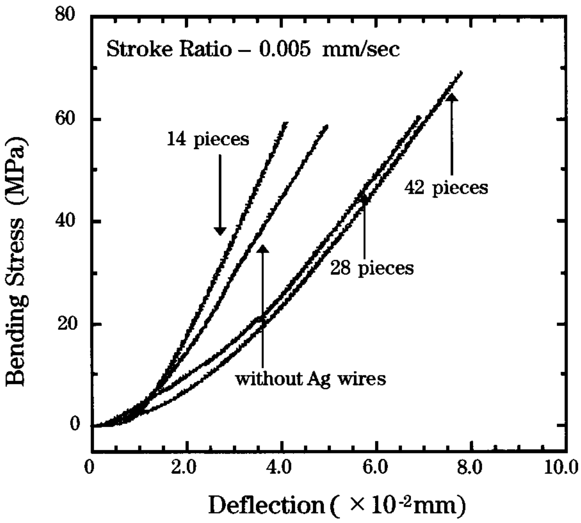

Fig. 6 The relationship between deflection and bending stress in the Bi-2223 bulks composed with Ag wires of 0.2 mm diameter.

samples shown in Fig. 6 were appeared remarkably non-linear and discontinuity behavior in 40 MPa of bending stress. This guessed that deformation process of the Bi-2223/Ag composite bulk was stepping repetition of the elastic-plastic deformation, and rupture of Bi-2223 matrix was generated in 40 MPa of bending stress. The apparent rigidity calculated from bending stress and deflection with near the fracture of the Bi-2223/Ag composite bulk is divided two groups such as about 30

GPa and 20 GPa. The density of composed Ag wires per one layer may affect on the apparent rigidity. It is clear that the apparent rigidity of the sample composed forty-two Ag wires is similar value to that of the sample composed twenty-eight Ag wires which density of composed Ag wires per one Ag layer is same.

4. Summary

We found that J_c values of the Bi-2223/Ag composite bulks were improved by composite of Ag wires. The highly c-axis oriented, homogeneous and densely structured Bi-2223 plate-like grains were formed near the region along the circumference of the Ag wire. We confirmed that the composed Ag wires were effective to improve toughness and prevent the propagation of the crack. The composed Ag wires improved effectively not only the J_c values but also the mechanical property. The composite of Ag wires is one of the advantageous methods in the development of Bi-2223 sintered bulk current lead for large-scaled application such as a fusion reactor.

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