Transport Critical Current Density of Ag-Sheathed Bi-Sr-Ca-Cu-O Multifilament Superconductor Tapes with Magnetic Nanopowders $\gamma$-Fe$_2$O$_3$

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Abstract: The transport critical current density of multifilament Ag/Bi-Sr-Ca-Cu-O tapes with the addition of magnetic nanopowder ($\gamma$-Fe$_2$O$_3$) has been measured. The tapes were prepared using the powder in tube method with 30 filaments. Three types of Bi-Sr-Ca-Cu-O starting materials namely from solid state reaction without $\gamma$-Fe$_2$O$_3$, solid state reaction with $\gamma$-Fe$_2$O$_3$ addition and ultrafine powders prepared by coprecipitation method with $\gamma$-Fe$_2$O$_3$ have been used. The starting composition of the $\gamma$-Fe$_2$O$_3$ added samples is Bi$_{1.6}$Pb$_{0.4}$Sr$_2$Ca$_2$Cu$_3$O$_{10-\delta}$($\gamma$-Fe$_2$O$_3$)$_{0.01}$. The first intermediate rolling enhances $J_c$ but subsequent rolling shows no improvement in $J_c$. Tapes prepared from coprecipitation powders with $\gamma$-Fe$_2$O$_3$ added showed the highest $J_c$ of 7890 A/cm$^2$ at 77 K and in self-field after the first intermediate rolling. These results suggest that intermediate rolling and magnetic nanopowders can be used to improve the critical current density of multifilament Ag/Bi-Sr-Ca-Cu-O superconductor tapes.

1. Introduction

Bi-Sr-Ca-Cu-O compound is one of the widely studied superconductors for application purposes. However the transport critical current density ($J_c$) of existing Ag/Bi-Sr-Ca-Cu-O tapes is still not high enough for large scale applications. The main factors that limit the $J_c$ are current limiting barriers and microcracks. These defects are normally produced when the tape undergoes intermediate deformation [1]. Since $J_c$ is lower in tapes made by rolling than by pressing, intermediate rolling were introduced to improve the transport current density [2].

Nanoparticles have been employed recently to increase the transport critical current density of these materials. Nano MgO increases the critical current in YBCO superconductor [3] but no significant enhancement in $J_c$ was observed in YBCO with nanometric SnO$_2$ [4].

Flux line network and magnetic texture can interact effectively if their characteristic scales have the same order of magnitude. The characteristic scales for flux line network is the coherence length $\xi$ which is less than 10 nm in the high $T_c$ superconductor materials. Another characteristic length is the penetration depth $\lambda$ which is in the range of 60 to 1000 nm. The ratio of the energy per unit length of infinitely long flux line with interaction energy per unit length of magnetic rod and flux line is given as

$$\delta_{MS} = \frac{\varepsilon_M}{\varepsilon_{fl}} = \left(\frac{R^2}{V_M}\right)^2 S r_e g_M,$$

where $\varepsilon_{fl}$ is the interaction energy per unit length of magnetic rod and flux line, $\varepsilon_M$ is the energy per unit length of infinitely long flux line, $R$ is the radius of the rod, $g_M$ is a numerical factor, $V_M$ volume of unit cell of the magnetic material, $r_e$ is radius of classical electron and $S$ is the spin per unit cell [5]. For $\delta_{MS} > 1$, magnetic rod generates flux line which is tightly bound with the rod resulting in a frozen flux superconductor. In a magnetic system with characteristic length $L$, where $\xi < L < \lambda$, strong interaction between flux line network and magnetic subsystem can be expected.
It is interesting to investigate the possibility of a frozen flux superconductor in such a superconductor-magnet hybrid system. Based on the above considerations, magnetic nanopowders γ-Fe₂O₃ have been introduced into multifilament Ag/Bi-Sr-Ca-Cu-O tapes system to act as flux pinning centers. The Bi-Sr-Ca-Cu-O powders have been prepared from conventional solid state reaction method as well as co-precipitation method. The effect of intermediate rolling and sintering temperature on these tapes are also reported in this paper.

2. Experimental details
Two types of Bi-Sr-Ca-Cu-O powders with nominal composition (Bi₁.₆Pb₀.₄)Sr₂Ca₂Cu₃O₁₀ were prepared by solid state reaction and coprecipitation method. For solid state technique, powders of Bi₂O₃, PbO, SrO, CaO and CuO of at least 99.9 % purity were used. The powders from the coprecipitation route were synthesized using method described elsewhere [6]. The precursor powders were ground and added with 0.01 weight % of γ-Fe₂O₃ before being packed into Ag tubes. The inner and outer diameter of the tube is 4.43 and 6.03 mm, respectively. The weight % were based on our previous studies on bulk samples where 0.01 weight % of γ-Fe₂O₃ optimized the superconducting property of the system [7]. To study the effect of magnetic nanoparticles addition on \( J_c \), tapes from solid state powder without γ-Fe₂O₃ were used as a reference.

The Ag/Bi-Sr-Ca-Cu-O multifilament tapes with 30 filaments were prepared by the standard powder in tube technique. All deformations processed were carried out using a rolling cylinder 20 mm in diameter and rolling speed of about 0.6 mm/min. The tape were cut into 2 cm long section and divided into several groups. Each group was sintered at 845 °C for 50 hours in air. With additional intermediate rolling, the tapes were heated further for 50 hours at 845 °C.

The phases in the tapes were identified using the powder X-ray diffraction (XRD) method using a Bruker D8 Advance diffractometer with a CuKα source. The \( J_c \) were measured at liquid nitrogen temperature using the dc four-probe technique with the 1 \( \mu \)V/cm criterion. The microstructure was observed with a LEO 1450VP scanning electron microscope and a Philips energy dispersive X-ray analyzer PV99 was used to determine the distribution of γ-Fe₂O₃ in the tapes.

3. Results and discussions
Figure 1(a) shows the micrograph of randomly oriented rod-like shape γ-Fe₂O₃, approximately 200 nm long and 50 nm radius. Figure 1(b) shows the distribution of γ-Fe₂O₃ in a typical tape. Table 1 lists the \( J_c \) for multifilament tapes of Ag/(Bi₁.₆Pb₀.₄)Sr₂Ca₂Cu₃O₁₀ by solid state reaction without γ-Fe₂O₃ (MFSS-P), with γ-Fe₂O₃ (MFSS) and coprecipitation method with γ-Fe₂O₃ (MFCP). For all multifilament tapes without intermediate rolling, \( J_c \) for MFSS-P is 6200 A/cm², for MFSS is 7010 A/cm² and for MFCP is 7200 A/cm². The addition of nanomagnetic particles γ-Fe₂O₃ increased the \( J_c \) value. The \( J_c \) value without intermediate rolling for MFCP is higher than MFSS due to the ultrafine powder made by coprecipitation method. The fine and homogeneously distributed particles in precursor have been generally responsible for higher \( J_c \) value.

Figure 2 shows the \( J_c \) at 77 K and in self-field versus number of intermediate rolling of the three type of tapes studied in this work. The value of \( J_c \) for MFSS-P increases to 6740 A/cm² after one intermediate rolling and increase further to 6890 A/cm² after the second intermediate rolling. However, this value is lower compared to 7300 A/cm² for first and second intermediate rolling, respectively the for MFSS tapes. For MFCP tapes, \( J_c \) increases to 7890 A/cm² after the first rolling but decreases to 7670 A/cm² after the second intermediate rolling. This result agrees with findings from previous reports that intermediate rolling steps improve the alignment of the superconductor grains. However, increasing the sintering time to 150 hours after two intermediate rolling reduces the amount of strong links and decomposed the Bi-2223 phase which contributed to lower \( J_c \) [8].

In multifilament tapes, the deformation of layers is nonuniform for composite layers consisting of different materials. The transformation of oxide core powder to solid occurs during intermediate processing. The resistance of deformation of the oxide core increases much faster than
the Ag sheath. This will further enhance the difference of deformation resistance between Ag sheath and oxide core and produce ‘sausaging’ effect. However, there is no direct correlation between sausaging effect and $J_c$ and from this study. These results show that the quality of the precursor powder has a much stronger influence on $J_c$ [9].

![Micrograph of nanorod-like structure of $\gamma$-Fe$_2$O$_3$ and micrograph of Bi-Sr-Ca-Cu-O tapes with $\gamma$-Fe$_2$O$_3$ in white (false color).]

**Figure 1.** (a) Micrograph of nanorod-like structure of $\gamma$-Fe$_2$O$_3$ and (b) micrograph of Bi-Sr-Ca-Cu-O tapes with $\gamma$-Fe$_2$O$_3$ in white (false color).

![Graphs showing $J_c$ at 77 K versus number of intermediate rolling of the three multifilament tapes heated at 845 °C and the effect of sintering temperature on $J_c$.]

**Figure 2.** (a) $J_c$ at 77 K versus number of intermediate rolling of the three multifilament tapes heated at 845 °C and (b) the effect of sintering temperature on $J_c$. 
Table 1. $J_c$ at 77 K and in self-field of the multifilament tapes with number of intermediate rolling. (MFSS-P are tapes from solid state reaction with no $\gamma$-Fe$_2$O$_3$, MFSS are tapes from solid state reaction with $\gamma$-Fe$_2$O$_3$ and MFCP are tapes from coprecipitation powders with $\gamma$-Fe$_2$O$_3$).

| Intermediate rolling | MFSS-P $J_c$ (A/cm$^2$) | MFSS $J_c$ (A/cm$^2$) | MFCP $J_c$ (A/cm$^2$) |
|----------------------|--------------------------|------------------------|------------------------|
| 0                    | 6210 ± 310               | 7010 ± 110             | 7220 ± 300             |
| 1                    | 6740 ± 370               | 7300 ± 180             | 7890 ± 300             |
| 2                    | 6890 ± 170               | 7300 ± 200             | 7670 ± 200             |

4. Conclusion
The addition of $\gamma$-Fe$_2$O$_3$ into the Bi-Sr-Ca-Cu-O powder from solid state reaction and coprecipitation method enhanced $J_c$ in multifilament tapes. This work demonstrates that magnetic nanoparticles can enhance the transport capacity of high temperature superconductor tapes. $\gamma$-Fe$_2$O$_3$ can further enhance the $J_c$ of the Bi-based tapes if prepared under the optimum condition. Magnetic impurities generally suppress superconductivity, however, our result shows that magnetic nanoparticles can be employed to enhance the flux pinning capability of Ag/Bi-Sr-Ca-Cu-O superconductor tapes and improve the transport critical current density in line with previous calculation on frozen flux superconductor with magnetic nanoparticles as pinning centers.

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