# The Effect of Ultrafine MgO Doping on Flux Pinning Properties of Bi-2223/Ag Superconducting Tapes

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## Abstract

The ultrafine MgO particles were doped into Bi-2223 precursor powder. The effect of MgO doping on flux pinning properties of Bi-2223/Ag tapes fabricated by the powder-in-tube (PIT) technique was investigated. The transport critical current density ($J_c$) of 1 mass % MgO doped samples sintered at 835 and/or 839 °C is improved significantly in comparison with the undoped samples. The 1 mass % ultrafine MgO doped samples show superior $J_{ct} - B$ behaviour to the undoped ones. At 77 K, a $J_{ct}$ of 33.6 kA/cm$^2$ in self-field, and 11.2 kA/cm$^2$ at 0.1 T ($H \,||\, c$-axis) has been achieved in the 1 mass % MgO doped samples. However, excessive doping (≥ 3 mass %) and high sintering temperature are verified to damnify the transport properties because of severe agglomeration of MgO particles and the growth of residual secondary phase.

## INTRODUCTION

Since the discovery of Bi–Sr–Ca–Cu–O (BSCCO) high-$T_c$ superconductors [1, 2], intensive research efforts have been carried out to prepare superconducting wire with high performance. However, there are two major problems which hinder practical applications: weak links at grain boundaries [3], which lead to a low intergranular critical current density and flux creep (or giant flux creep) [4], resulting in poor magnetic field behaviour of the critical current density ($J_c$).

It is generally believed that flux creep effect is much more serious in the Bi-based materials than in YBCO since BSCCO is more anisotropic than YBCO [5, 6]. Many efforts have been made in order to enhance the flux pinning in the BSCCO system. For example, controlled melt process as a novel way was developed to introduce fine-dispersed $Bi_2Sr_2CaCu_2O_8$ (Bi-2212) and non-superconducting phases, which might act as possible flux pinning centres, in Bi-2223/Ag tapes [7, 8]. Recently, nanorods of magnesium oxide (MgO) were grown and incorporated into HTSCs to form nanorod-HTSC composites [9]. The $J_c$ of the nanorod-HTSC composites are enhanced dramatically at high temperatures and magnetic fields as compared with reference samples. In our previous works [10], ultrafine MgO doped Bi-2223/Ag tape made by tape casting method showed increased $J_c$ under magnetic field. The objective of this paper was to improve the current transport properties by introducing ultrafine MgO particles into powder-in-tube (PIT) processed Bi-2223/Ag tapes. The $J_c$ properties of MgO doped samples under magnetic field were investigated.

## EXPERIMENTAL

Precursor powder with the composition of $Bi_{1.8}Pb_{0.4}Sr_2Ca_{22}Cu_3O_x$ prepared by spray drying method was used as a starting material. Bi-2212 and other nonsuperconducting phases were the major phases. Bi-2223 had not been synthesized at this stage.

The particle size of MgO is about 10 nm. Various compositions of ultrafine MgO powder and the as-prepared precursor powder were mixed well. The details of powder mixing and PIT process can be seen elsewhere [11]. In order to extensively investigate the phase evolution of the samples, the thermomechanical treatment

TABLE 1
Transport critical current densities for undoped and MgO doped Bi-2223/Ag tapes in various sintering conditions

| Sample No. | MgO addition, mass % | Sintering temperature, °C | $J_{ct}$ (kA/cm$^2$) at 77 K, 0 T | |
|---|---|---|---|---|
| | | | Cycle 2 | Cycle 3 |
| 0M353 | None | 835 | 23.5 | 21.2 |
| 0M393 | | 839 | 12.5 | 22.2 |
| 0M443 | | 844 | 10.6 | 18.8 |
| 1M353 | 1 | 835 | 32.5 | 33.6 |
| 1M393 | | 839 | 32.8 | 33.4 |
| 1M443 | | 844 | 14.9 | 16.0 |
| 3M353 | 3 | 835 | 11.2 | 17.2 |
| 3M393 | | 839 | 11.9 | 15.3 |
| 3M443 | | 844 | 11.1 | 13.9 |
| 5M353 | 5 | 835 | 7.0 | 9.6 |
| 5M393 | | 839 | 5.2 | 4.7 |
| 5M443 | | 844 | 3.2 | 4.6 |

process is divided into four cycles according to pressing times. Cycle 0: S/70 h, cycle 1 : S/70 h + P + S/70 h, cycle 2: S/70 h + P + S/70 h + P + S/70 h, cycle 3: S/70 h + P + S/70 h + P + S/70 h + P + S/70 h. Here, S indicates sintering and P − uniaxial pressing. After each sintering period, the transport critical current ($I_c$) was measured by the standard four-probe method at 77 K with a criterion of 1 μV/cm. Magnetic field up to 0.1 T were applied perpendicular to the wider surface of tapes, and owing to the oriented microstructure of the oxide core this corresponded to having $H$ parallel to the c-axis ($H \,||\, c$). The magnetization critical current density ($J_{cm}$) was derived from magnetization hysteresis curves by assuming the Bean model of the critical state [12]. Magnetization measurements were performed at a temperature of 5 K in a SQUID magnetometer with applied fields perpendicular to the $c$-axis ($H \perp c$) and sweeping between ± 5 T.

## RESULTS AND DISCUSSION

Table 1 gives transport critical current density ($J_{ct}$) results for undoped and doped samples. The highest $J_{ct}$ value is obtained in 1M353 and/or 1M393, which is about 1.6 times higher than that in undoped samples (0M353 and 0M393).

Figure 1 shows the calculated magnetization critical current densities of 0M353 and 1M353 samples. In low-field regime (0.5 − 1.5 T), $J_{cm}$ value of the latter drops much more slowly than that of the former. However, it shows a slightly more rapid decrease compared with 0M353 sample at a magnetic field higher than 1.5 T. Table 2 contains the percentage drop of $J_{cm}$ values at various magnetic field ranges for 0M353 and 1M353 samples. The slow decrease in $J_{cm}$ of 1M353 in low-field regime suggests weak links has been diminished greatly even though MgO doping also slightly reduces the grain alignment. Nevertheless, the grain misalignment caused by MgO doping may lead to the degradation of intrinsic pinning which is generally believed to be responsible for the superior $J_{cm} - B$ behaviour of Bi-2223/Ag superconductor tapes at low temperatures, and thus

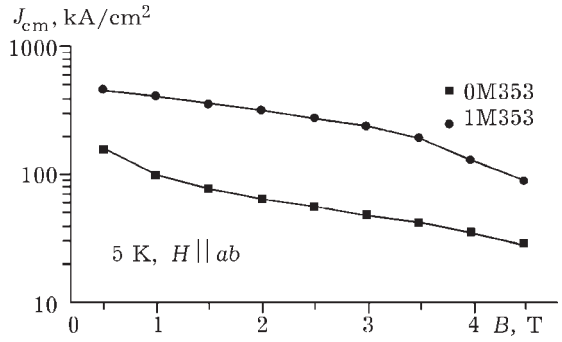


Fig. 1. Magnetic field dependence of magnetization critical current densities, $J_{cm}$, with the applied field perpendicular to the $c$-axis.

TABLE 2
Percentage drop of sample $J_{cM}$ values in various magnetic field ranges with the field perpendicular to the *c*-axis

| Sample No. | $\frac{J_{cm\ 1.0\ T}}{J_{cm\ 0.5\ T}}$ | $\frac{J_{cm\ 1.5\ T}}{J_{cm\ 0.5\ T}}$ | $\frac{J_{cm\ 4.0\ T}}{J_{cm\ 1.5\ T}}$ | $\frac{J_{cm\ 4.5\ T}}{J_{cm\ 1.5\ T}}$ |
|---|---|---|---|---|
| 0M353 | 60.9 | 47.7 | 44.0 | 35.2 |
| 1M353 | 88.3 | 76.8 | 34.8 | 23.7 |

induce more rapid decrease of $J_{cm}$ value in high-field regime.

Figure 2 shows the magnetic field dependence of transport critical current density for various samples at 77 K, with the applied field parallel to the *c* axis. In Fig. 2, *a* we find that the $J_{ct}$ of 1M353 always exhibit higher value than those of 0M353 and 3M353 both in low-field (0 – 0.03 T) and in high-field (0.03 – 0.1 T) regimes. This can be well explained as the improvement of weak links at Bi-2223 grain boundaries and significant enhancement of flux pinning strength resulting from the ultrafine MgO doping, which is consistent with the microstructure analysis [11]. For 0M353 and 3M353 samples, the $J_{ct}$ of the latter drops faster than that of the former in low-field regime, and then appear to merge with the former in high-field region. As mentioned before, excessive doping causes severe agglomeration of MgO particles and the growth of secondary phase. These nonsuperconducting phases are considered to be too large to act as flux pinning centres. On the contrary, they obviously lead to weak links at grain boundaries.

For comparison, $J_{ct}$ dependence on the magnetic field of undoped and 1 mass % MgO doped samples processed after 2 and 3 cycles is drawn in Fig. 2, *b*. The degradation of $J_{ct}$ of 0M352 and 1M352 samples with increasing field are roughly same. For the three-cycle-processed sample, the $J_{ct}$ of 1M353 shows much more slow decrease, while the $J_{ct} - B$ curves of 0M352 and 0M353 show a crossover at a certain field, *i. e.* the former decrease more slowly than the latter at fields above 0.03 T. It indicates that the effect of the third pressing-sintering cycle is different in 1 mass % MgO doped and undoped samples. 1 mass % MgO doped sample enhances considerably flux pinning strength after one more thermomechanical process. However, for the undoped sample, the final thermomechanical process seems detrimental to flux pinning properties owing to the further reduction of Bi-2212 and secondary phases which might be pinning centres in Bi-2223 matrix. Certainly, the thermomechanical process has also densified the oxide core, accelerated the reaction from Bi-2212 to Bi-2223, and in turn reduced weak links. Hence, 0M353 shows better $J_{ct} - B$ properties than 0M352 at fields below 0.03 T.

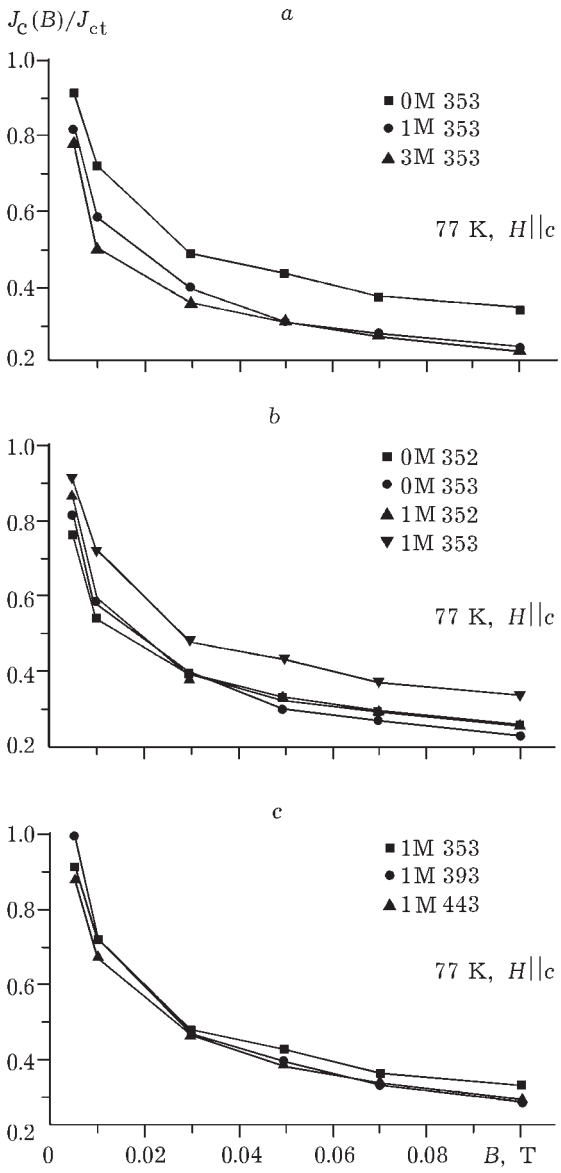


Fig. 2. Normalized $J_{ct} - B$ curves for Bi-2223/Ag sheathed tapes.

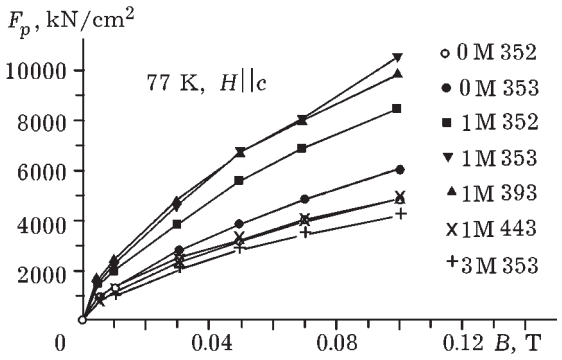


Fig. 3. The flux-pinning force density $F_p$ *vs* the applied magnetic flux density $B$.

Figure 2, *c* shows $J_{ct}$ dependence on the magnetic field of 1 mass % MgO doped samples sintered at various temperatures. In low-field regime, the decreasing rate of $J_{ct}$ value of 1M393 is the lowest among these three samples, indicating effective improvement of weak links. In high-field regime, 1M353 sample performs excellent current transport property. At 77 K and 0.1 T, 1M353 still holds 33.3 % of its initial $J_{ct}$ while 1M393 and 1M443 maintain only 29.1 and 29.7 % of its zero field $J_{ct}$, respectively. This suggests that 1M353 sample has the strongest flux pinning strength compared with the other two samples (1M393 and 1M443) in high magnetic fields.

Figure 3 shows the pinning force density defined as $F_p = J_c(B, T) \times B$ *versus* the applied magnetic flux density $B$ at 77 K for each sample. As expected from transport measurements, $F_p(B)$ peaks are highest in 1 mass % MgO doped samples sintered at 835 °C. Although the pinning force density does not say anything about the mechanism of flux lines, it does, however, give an indication of how relatively strongly the flux lines are being pinned as well as the shear strength of the flux-line lattice [13].

## CONCLUSION

The effect of ultrafine MgO doping on flux pinning properties of Bi-2223/Ag tapes fabricated by the PIT technique has been investigated. The transport critical current density of 1 mass % MgO doped samples sintered at 835 and/or 839 °C is improved significantly in comparison with the undoped samples. The 1 mass % ultrafine MgO doped samples show superior $J_{ct} - B$ behaviour to the undoped samples. However, excessive doping (> 3 mass %) and high sintering temperature are verified to damnify the transport properties because of severe agglomeration of MgO particles and the growth of residual secondary phase.

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