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Interfilamentary coupling properties of Bi2223/Ag tapes with oxide barriers subjected to AC perpendicular magnetic field

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ABSTRACT

In this paper, we fabricated Bi2223 tapes with interfilamentary oxide barriers and evaluated interfilamentary coupling properties under an AC perpendicular magnetic field at 77 K. To avoid the side effect on Bi2223 phase formation during sintering process, $SrZrO_3$ was selected for barrier materials. Moreover, 20 wt.% Bi2212 was mixed with $SrZrO_3$ to improve its ductility for cold working. Monocore Ag-sheathed rods were coated by the oxide barriers with slurry before stacking with a honeycomb structure. By twisting the filament with twist pitch length below 10 mm and introducing interfilamentary barriers, the coupling frequency (f_c) under an AC perpendicular field, which is inversely proportional to the decay time constant (τ_c) of coupling current, exceeded 100 Hz. At perpendicular field amplitude above full-penetration field, the magnetization losses of the twisted barrier tape were reduced by 30–40% around power-grid frequency, compared with analytical values for fully-coupled filaments. However, the loss values were still considerably higher than the prediction of the hysteresis loss (Q_h) for the completely decoupled filaments. From the frequency dependence of losses, it was suggested that the loss reduction of twisted barrier tape around power-grid frequency were limited by not only the contribution of coupling current loss (Q_c) but also the insufficient Q_h reduction due to the presence of physical connection among the filaments positioned near the center of a tape section.

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1. Introduction

Ag-sheathed $(Bi,Pb)_2Sr_2Ca_2Cu_3O_x$ (Bi2223) tapes fabricated by powder-in-tube (PIT) process are most applicable high-T_c superconducting (HTS) wires for 77 K usage at present stage. Although the performance of the tapes such as critical current (I_c) above 150 A over the length of km-class are enough for the prototype configuration such as power cables and transformers [1], their AC losses are still too large for the practical applications. The large loss generation under an AC external magnetic field is mainly attributed to strong electromagnetic coupling among the filaments [2–4]. The interfilamentary coupling is caused by the low resistivity of Ag-matrix and physical connection between the filaments by interfilamentary bridging. Moreover, because of the large aspect ratio of the tape cross section, both hysteresis loss (Q_h) in superconductor and coupling current loss (Q_c) in a perpendicular magnetic field becomes much higher than in a parallel field. Moreover, also due to the geometrical anisotropy of tape and its demagnetization effect under a perpendicular field, the decay time constant of coupling current (τ_c) among the filaments becomes much larger so that the conditions for decoupling filaments becomes more restrictive than in a parallel field case [1–4]. To achieve the remarkable loss reduction in a perpendicular field, therefore, not only twisting the superconducting filaments tightly but also increasing the matrix resistivity is necessary [4].

The introduction of highly-resistive layers as barriers around each Bi2223 filament is considered to be an effective method to increase the matrix resistivity. Most popular method for introducing barriers is the coating of oxide powder on the surface of monocore wire [5–16]. The oxide material usable as barriers should be highly-resistive, non-poisonous to Bi2223 phase formation during heat treatment, and also should be deformable during cold working such as drawing and flat rolling. $BaZrO_3$ is known to be effective to increase the matrix resistivity and also to decouple the filaments, but they cause significant degradation of critical current density (J_c) due to their poor ductility [5,7,9]. The tapes with $SrCO_3$ barriers show reasonably good transport properties [10,11], but it has been pointed out that $SrCO_3$ barriers is not sufficient to increase transverse resistivity and to suppress the filament coupling [10]. In our preliminary studies [12–15], it was confirmed that Ca_2CuO_3 + 30 wt.%-$Bi_2Sr_2CaCu_2O_y$ (Bi2212) barriers have little side

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effect on Bi2223 phase formation and J_c. However, the continuity of Ca_2CuO_3 + Bi2212 barriers was significantly degraded after the heat treatment to form Bi2223 phase inside the filaments [15], resulting the insufficient enhancement of transverse resistivity. The $SrZrO_3$ barriers also have small influence on Bi2223 phase formation, but J_c degradation by $SrZrO_3$ barrier introduction was slightly larger than Ca_2CuO_3 + Bi2212 barrier [14–16]. The poor ductility of $SrZrO_3$ causes the deterioration of filament smoothness, misalignment of Bi2223 grains and also generates many cracks inside filaments, which degrades the current transport capability. However, in fully reacted tapes, the continuity of the $SrZrO_3$ barriers is far superior to the Ca_2CuO_3 + Bi2212 barriers [15]. This suggests that the use of $SrZrO_3$ as interfilamentary resistive barriers is favorable for decoupling the filaments in an AC external magnetic field.

In this paper, we prepared non-twisted and twisted Bi2223 tapes with $SrZrO_3$ + 20 wt.%-Bi2212 as interfilamentary barriers and evaluated their AC magnetization loss characteristics in an AC perpendicular magnetic field at 77 K. Based on the magnetization loss properties, interfilamentary coupling properties of barrier tapes in an AC perpendicular field were examined.

2. Experimental

Bi2223 tapes with interfilamentary oxide barriers were prepared by using a conventional powder-in-tube (PIT) method. $SrZrO_3$ powders with the mean grain size below 1 μm were selected as barrier materials. Based on the previous study for Ca_2CuO_3 barrier tapes [9–11], additional Bi2212 powder corresponding to 20 wt.% was mixed with $SrZrO_3$ to improve its ductility for cold working. The precursor powders were packed into pure Ag tube with an outer diameter of 9.4 mm and a wall thickness of 0.7 mm. Then, the composite was deformed into a hexagonal cross-sectional shape by drawing. The outside surface of the monocore wire was coated by $SrZrO_3$ + Bi2212 pastes with the slurry in a thickness of ~0.1 mm. After the heat treatment to decompose and evaporate the organic binder, 19-pieces of coated monocore wire were stacked with a honeycomb structure and packed into Ag–Mn alloy tube with an outer diameter of 15.4 mm and a wall thickness of 0.7 mm. The composite was drawn to the diameter of 1.45 mm (shown in Fig. 1) and then twisted. Finally, the twisted round wire was formed into tape shapes by flat rolling and sintered at 830–840 °C with an intermediate rolling. To investigate the influence of twisting on the filament shape, DC transport properties and also on the AC magnetization loss properties, non-twisted barrier tape was also fabricated by using same fabrication process. The geometrical parameters for all tapes are summarized in Table 1. Twisted barrier tape with twist pitch length L_t = 9 mm was named "B-TW" while non-twisted one did "B-NT", respectively. The geometrical parameters of both tapes were almost identical.

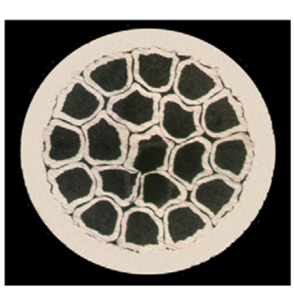

Fig. 1. A transverse cross-sectional view of a round wire with $SrZrO_3$ + Bi2212 barrier.

Table 1
Specifications of $SrZrO_3$ + Bi2212 barrier tapes with or without filament twisting.

Sample name	B-NT	B-TW
Number of filaments	19	19
Tape width	3.12 mm	3.15 mm
Tape thickness	0.27 mm	0.26 mm
Width of filamentary region (w_c)	2.89 mm	2.88 mm
Thickness of filamentary region (t_c)	0.20 mm	0.18 mm
Filament width (averaged) (w_f)	0.48 mm	0.49 mm
Filament thickness (averaged) (t_f)	0.020 mm	0.020 mm
Twist pitch length (L_t)	Not twisted	9 mm
I_c at 77 K, 0 T	23.8 A	13.2 A
J_c at 77 K, 0 T	13,500 A/cm^2	7500 A/cm^2
Fraction of SC filaments	22.0%	23.0%

The critical current density (J_c) at 77 K in self-field was evaluated using a conventional DC four-probe method with an electric field criterion of 1 μV/cm. The AC magnetization losses at 77 K under an AC perpendicular magnetic field were measured by using saddle-shaped pick-up coil and conventional lock-in technique [17]. For the loss measurements, the lengths of the samples were fixed to 80 mm. The deterioration in the I_c value for both tapes during the loss measurements was found to be negligibly small (less than a few percent).

3. Results and discussion

The transverse cross sections of non-twisted or twisted tapes with $SrZrO_3$ + Bi2212 barriers are shown in Fig. 2. Comparing the non-twisted barrier tape B-NT, it is clearly confirmed that some filaments near the center part of twisted tape B-TW were deformed irregularly. Moreover, several interfilamentary connections were also observed at an inner part of a tape section, while the filaments positioned in the outermost layers of a tape section were partitioned by barriers. As shown in Table 1, the J_c values in $SrZrO_3$ + Bi2212 barrier tapes were deteriorated by 40% with decreasing L_t below 10 mm. This might be attributed to the increase of cracks and misaligned Bi2223 grains in irregularly deformed filaments. Particularly in twisted tapes with $SrZrO_3$ + Bi2212 barriers, therefore, more precise control of deforming parameters during both twisting and flat rolling processes should be necessary to avoid the irregularly deformed filaments and also to improve the J_c properties. The optimization of the deforming parameters (during drawing, twisting and flat rolling) in barrier tape fabrication is currently being studied.

For the composite multifilamentary superconducting wire with normal metal matrix, it is widely known that the coupling current loss Q_c per-cycle in the matrix part show the maximum at a coupling frequency f_c, which is related to the decay time constant of a coupling current, τ_c with following equation [4–7,10]:

$$\tau_c = 1/2\pi f_c \quad (1)$$

In addition, the time constant τ_c in a twisted tape with a twist pitch length L_t has the following relation [4]:

$$\tau_c \propto nL_t^2/\rho_{t\perp} \quad (2)$$

Here, ρ_t is a transverse resistivity and n does the shape factor depending on both the field direction and the conductor geometry. For a typical Bi2223 tape, n in a perpendicular field nearly corresponds to the aspect ratio of filamentary region (=w_c/t_c) [2,4].

Although Q_c per-cycle decreases with an increasing frequency when an operating frequency f_{op} is higher than f_c, the superconducting filaments start to couple among them and their hysteresis loss Q_h at B_0 above the full-penetration field B_p becomes larger than the value for decoupled state [18,19]. To achieve a significant loss

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