Fabrication and characterization of Bi2223/Ag tapes with interfilamentary oxide barriers for reducing AC losses

R Inada¹, Y Fukumoto¹, Y Mitsuno¹, T Yasunami¹, Y Nakamura¹, A Oota¹, C S Li² and P X Zhang²

¹ Toyohashi University of Technology, 1-1 Hibarigaoka, Tempaku-cho, Toyohashi, Aichi 4418580, Japan
² Northwest Institute for Nonferrous Metal Research, P O Box 51, Xi’an, Shaanxi 710016, People’s Republic of China

E-mail: inada@eee.tut.ac.jp

Abstract. We prepared and characterized Bi2223/Ag tapes with interfilamentary oxide barriers for AC loss reduction in external AC magnetic field. Ca₂CuO₃, Al₂O₃, and SrZrO₃ were selected as barrier materials. 20-30wt% Bi2212 were added to Ca₂CuO₃ and SrZrO₃ powders to improve their deformation properties for cold working. The multifilamentary tapes with interfilamentary oxide barriers were fabricated with a conventional powder-in-tube method. The influence of introducing different oxide barriers on the final tape properties such as the phase formation in filaments, critical current density $J_c$ and its uniformity along a tape length, was evaluated. Based on the results of the preliminary studies, we determined the oxide materials for fabrication of barrier tapes with twisted filaments. AC losses in barrier tapes with twisted filaments were measured at 77 K in transverse AC magnetic field. The AC loss characteristic of the tape with barrier was compared to the one of the tape without barrier.

1. Introduction
Ag-sheathed Bi2223 tapes more than 1 km are now fabricated successfully with high critical currents ($I_c$) of more than 150 A in 77 K and self-field [1]. Although this performance is enough for prototype configurations such as cables and transformers, the AC losses are still too high for practical applications. The large loss generation in the tapes is mainly attributed to the strong electromagnetic coupling between the filaments via the Ag matrix, which has a low resistivity at 77 K. To reduce the interfilamentary coupling in AC fields, it is necessary – in addition to twisting the filaments with a suitable pitch length – to increase the matrix resistivity by using Ag-alloy sheath as matrix [2, 3] or to introduce oxide layers between the filaments as highly resistive barriers [3–9].

The selection of oxide materials for barriers is most important for preparing barrier tapes with low AC losses – as several studies on the introduction of various oxide materials as interfilamentary resistive barriers in Bi2223 tapes have shown [3–9]. Oxide material usable as barrier should be highly-resistive and non-poisonous to the Bi2223 phase during sintering, as well as easily deformable during cold working such as drawing and flat rolling.

Here we report on Bi2223/Ag tapes prepared with various interfilamentary oxide barriers for filament decoupling in external AC fields. Ca₂CuO₃, Al₂O₃ and SrZrO₃ were selected as barrier materials. The influence of the barrier introduction on tape properties such as the phase formation
inside the filaments, the critical current density $J_c$ and its uniformity along the length of tape was investigated. In addition, we also prepared a barrier tape with twisted filaments and evaluated its AC loss characteristics at 77 K. The AC-loss characteristic of the tape with barrier was compared to the one of the tape without barrier.

2. Experimental

Bi2223/Ag tapes with interfilamentary oxide barriers were fabricated according to using a conventional powder-in-tube method. Before the preparation of barrier tapes with twisted filaments, non-twisted tapes with different oxide barriers were prepared, to investigate side effects of the barrier introduction on final tape properties. Ca$_2$CuO$_3$, Al$_2$O$_3$ and SrZrO$_3$ were selected as barrier materials. 20-30wt% Bi2212 were added to the Ca$_2$CuO$_3$ and SrZrO$_3$ powders to improve their deformation properties for cold working [8, 9]. The outside surface of the pure Ag-sheathed monocore wire was coated with a slurry of different oxide materials. After the heat treatment to decompose and evaporate the organic binder in the slurry, 19 pieces of coated monocore wire were stacked and packed into Ag-Mg alloy tubes. The composites were formed into tape shape by drawing and flat rolling. Finally, the tapes were sintered with an intermediate rolling to form the Bi2223 phase in filaments. For all tapes, the first and second heat treatments were carried out at 840°C for 80 h in air and 830°C for 80 h in 8%-O$_2$/92%-N$_2$ gas, respectively. XRD measurements were carried out to verify the phase formation in the filaments. The critical current density $J_c$ and its uniformity were measured of all tapes with four-probe DC method at 77 K and in self-field over several meters. Table 1 lists the specifications of all barrier tapes.

Based on the results of preliminary experiments, we determined the oxide materials for preparation of barrier tapes with twisted filaments. The AC losses at 77 K of twisted multifilamentary tapes with or without barriers were measured in parallel or perpendicular transverse magnetic field. For the loss measurements, the tapes with twist pitch lengths $(L_t)$ of 20 mm were used and lengths of all tapes were fixed to 80 mm. The AC losses were measured by using saddle shaped pick-up coil and lock-in amplifier [10]. The amplitude $(B_0)$ and frequency $(f)$ of the magnetic field were changed in the range of 1−50 mT and 10−400 Hz, respectively.

3. Results and discussion

3.1. Cross sections, phase formation and transport properties of tapes with different oxide barriers

Figure 1 shows the transverse and longitudinal cross-sectional views of the final tapes with different barriers. For all tapes, oxide barriers are introduced successfully with their thicknesses from 5 to 15 μm. In the tapes with Ca$_2$CuO$_3$/Bi2212 and Al$_2$O$_3$ barriers, distorted deformation of filaments was not observed. However, in the tape with SrZrO$_3$/Bi2212 barriers, outgrowths from each Bi2223 filament are clearly observable and the filament flatness is not so good. It is furthermore, evident that some filaments are directly connected with the barrier layers. These results are mainly caused by...
the poor deformation properties of SrZrO3 + Bi2212 barriers.

XRD measurements were carried out after removing the sheath part with an etching process. The volume fraction of Bi2223 phase after first or second heat treatments were calculated by using the intensity \( I \) of some selected peaks for Bi2223 and Bi2212 phases, which is expressed as follows:

\[
\%2223 = \frac{I_{2223}(0010) + I_{2223}(0014)}{I_{2212}(008) + I_{2212}(0012) + I_{2223}(0010) + I_{2223}(0014)}
\]  

The results are summarized in table 2. The Bi2223 phase formations in tapes with Ca2CuO3 or SrZrO3/Bi2212 were comparable to that in the tape without barriers prepared with the same fabrication process. The influence of these two oxide barriers on the phase formation inside the filaments is thus small. However, the tape with Al2O3 barriers has significantly lower volume fraction of Bi2223 phase than the tapes with other barriers, after the first as well as the second heat treatment.

Figure 2 shows the longitudinal critical current density distributions at 77 K in self-field for barrier tapes several meters long. The uniformity of \( J_c \) along a tape is almost the same for all tapes, but the absolute \( J_c \) values are quite different. The tape with Ca2CuO3/Bi2212 barrier has much higher \( J_c \) values than the other barrier tapes. Compared to the tape without barriers, the \( J_c \) of the tape with

| Table 1. Volume fractions of Bi2223 phase and \( J_c \) properties in tapes with and without barriers. |
|---------------------------------|----------------|----------------|----------------|
| Barrier material                | None           | Ca2CuO3 + 30wt% Bi2212 | Al2O3          | SrZrO3 + 20wt% Bi2212 |
| \%2223 after 1st heat treatment | 78%            | 75%             | 59%            | 76%               |
| \%2223 after 2nd heat treatment | 96%            | 94%             | 86%            | 97%               |
| Maximum \( J_c \) @ 77K, self-field | 17800 A/cm²       | 16000 A/cm²       | 11000 A/cm²       | 11200 A/cm²       |
| End-to-end \( J_c \) @ 77 K, self-field | 14700 A/cm²       | 13800 A/cm²       | 8700 A/cm²       | 9600 A/cm²       |
| Standard deviation of \( J_c \) along a tape length | 9.6% | 10.9% | 9.2% | 8.6% |

Figure 1. Transverse (left) and longitudinal (right) cross-sectional views of multifilamentary tapes with different oxide barriers: (a) Ca2CuO3 + 30wt% Bi2212, (b) Al2O3 and (c) SrZrO3 + 20wt% Bi2212.
the Ca$_2$CuO$_3$/Bi$_2$212 barrier is reduced by less than 10%, while a 30–40% degradation is caused in the other barrier tapes. This is attributed to good deformation properties as well as the better Bi$_2$223 phase formation in the Ca$_2$CuO$_3$/Bi$_2$212 barrier tape. According to these results, it can be considered that the use of Ca$_2$CuO$_3$ + 30 wt% Bi$_2$2212 as barriers is most favorable for preparation of barrier tapes with low AC losses.

3.2. AC loss properties in twisted multifilamentary tapes with Ca$_2$CuO$_3$ + Bi$_2$212 barriers

We used Ca$_2$CuO$_3$/Bi$_2$212 as barriers for the fabrication of twisted tape with 19-filaments and a twist pitch length $L_t$ of 20 mm. Figure 3 shows the dependence of AC losses $Q_m$ on field amplitude at 77 K and 45 Hz in parallel and perpendicular field. The measurements were carried out for the twisted and non-twisted tape without barriers. Note that the geometrical parameters of all tapes are almost identical. For direct comparison for losses in all tapes, the plotted loss values are normalized by $I_c$ of each tape [7–9]. Filament twisting has only some positive effect on decoupling the filaments in parallel field, but loss values at $B_0 > 10$ mT are considerably higher than the analytical values of the infinite slab model for completely decoupled filaments [7–9]. On the other hand, the loss reduction at $B_0 > 20$ mT in the twisted tape with Ca$_2$CuO$_3$/Bi$_2$212 barriers is more remarkable and the values are close to the curve for completely decoupled filaments. At $B_0 = 50$ mT and $f = 45$ Hz, the AC losses in the barrier tape are only about 25% of the values of the tape with completely coupled filaments. In perpendicular field, however, no remarkable effect of the barrier introduction on the AC losses was observed. All data are close to the analytical curve derived by Brandt and Indenbom for fully coupled filaments [2, 12].

Figure 4 shows the frequency dependence of the AC losses of twisted tapes with or without barriers at field amplitude $B_0 = 1$ mT in parallel and perpendicular field. The measured AC losses are dominated by the hysteresis loss ($Q_h$) in the filaments and the coupling current loss ($Q_c$). The
coupling current losses $Q_c$ per-cycle shows a maximum at characteristic frequency $f_c$ [2–6, 8, 9, 11]. To decouple the filaments and achieve a significant loss reduction, the $f_c$ value should at least be sufficiently above the operating frequency. In parallel field, the $Q_m$ curve for a tape without barriers has a maximum at around 40 Hz. By introducing Ca$_2$CuO$_3$/Bi$_2$212 barriers between the filaments, the $f_c$ value increases to 220 Hz which is much higher than power-grid frequencies. The decay time constant $\tau_c$ of the coupling currents ($= 1/(2\pi f_c)$) is proportional to $L_t^2/\rho_t$ [2–6, 11], where $\rho_t$ is the transverse resistivity of the metal matrix between the filaments. Since the geometries of all tapes are almost identical, the increase of $f_c$ in barrier tapes mainly comes from the increase of $\rho_t$. Consequently a significant loss reduction is achieved in twisted tapes with barriers in parallel fields.

Figure 3. Field amplitude dependence of normalized AC losses $Q_m / I_c$ at 77 K and 45 Hz for twisted tapes with or without Ca$_2$CuO$_3$/Bi$_2$212 barriers in (a) parallel and (b) perpendicular transverse magnetic field. The results for non-twisted tape without barriers are also shown for comparison.

Figure 4. Frequency dependence of AC losses $Q_m$ at 77 K and $B_0 = 1$ mT for twisted tapes with or without Ca$_2$CuO$_3$/Bi$_2$212 barriers. $Q_m$ values for each tape are normalized by the maximum value $Q_{m\text{max}}$ in our measurement range.
In perpendicular field, $f_c$ in barrier tapes is around 20 Hz, which is much lower than power-grid frequencies. Because of the large aspect ratio of the tape cross section, the hysteresis and coupling current losses in perpendicular field are much higher than in parallel field and the conditions for filament decoupling becomes more restrictive. The twist pitch length $L_t$ of 20 mm for our barrier tape is thus too long for filament decoupling in perpendicular field. Together with further improvements of the barrier layers, narrow tapes and tight filament twisting are probably necessary to the significantly reduce perpendicular field losses.

4. Conclusion

We prepared Bi2223/Ag tapes with various interfilamentary oxide barriers for the reduction of AC losses in external AC magnetic fields. Ca$_2$CuO$_3$, Al$_2$O$_3$ and SrZrO$_3$ were selected as barrier materials. 20-30wt% Bi2212 were added to the Ca$_2$CuO$_3$ and SrZrO$_3$ to improve the ductility for cold working. The Ca$_2$CuO$_3$/Bi2212 barriers show the least side effects on the final tape properties. We thus used Ca$_2$CuO$_3 + 30$wt% Bi2212 as barriers for the fabrication of twisted multifilamentary tapes and measured the AC losses in parallel and perpendicular transverse fields. The experimental results indicate that the combination of filament twisting and the introduction of Ca$_2$CuO$_3$/Bi2212 barriers are effective to suppress the interfilamentary coupling and also to reduce the AC losses in parallel field. However, the barrier introduction reduces AC losses only little in perpendicular field. The twist pitch length $L_t$ (= 20 mm) of our barrier tape is probably too long to decouple the filaments in perpendicular field. To reduce the perpendicular field losses remarkably, it should be necessary to fabricate narrow tapes with tight filament twisting and continuous barrier layers.

Acknowledgements

This work was partly supported by Grant-in-Aids for Scientific Research (No. 17206026) from the Japanese Society of the Promotion of Science (JSPS), by the Ministry of Education, Culture, Sports, Science and Technology of Japan (MEXT, No 17760233), by the Research Foundation of the Tokyo Electric Power Company (TEPCO), and by the grant for young researchers project of Research Center for Future Technology, Toyohashi University of Technology.

References

[1] Kikuchi M, Kato T, Ohkura K, Ayai N, Fujikami J, Fujino K, Kobayashi S, Ueno E, Yamazaki K, Yamade S, Hayashi K, Sato K, Nagai T and Matsui Y 2006 Physica C 445-448 717-21
[2] Martinez E, Yang Y, Beduz C and Huang Y B 2000 Physica C 331 216-26
[3] Eckelmann H, Quilitz, M, Oomen M, Leghissa M and Goldacker W 1998 Physica C 310 122-6
[4] Kwasnitzka K, Clerk St, Flükiger R and Huang Y B 1998 Physica C 299, 113-24
[5] Dhallé M, Polcari A, Marti F, Witz G, Huang Y B, Flükiger R, Clerc St and Kwasnitzka K 1998 Physica C 310 127-31
[6] Nast R, Eckelmann H, Zabara O, Schlachter S I and Goldacker W, 2002 Physica C 372-376 1777-80
[7] Ayai N, Hayashi K and Yasuda K, 2005 IEEE Trans. Appl. Supercond 15 2510-13
[8] Inada R, Iwata Y, Nakamura Y, Oota A and Zhang P X 2006 Adv. Sci. Technol. Vol. 47 137-42
[9] Inada R, Yasunami R, Iwata Y, Nakamura Y, Oota Y and Zhang P X 2007 IEEE Trans. Appl. Supercond. 17, 3087-90
[10] Inada R, Tateyama K, Nakamura Y, Oota A, Li C S and Zhang P X 2007 Supercond. Sci. Technol. 20 138-46
[11] Martinez M, Yang Y, Young E, Beduz C and Huang Y B 2002 Physica C 372-376 1766-70
[12] Brandt E H and Indenbom M 1993 Phys. Rev. B 48 12893-906