AC Loss Property of Stacked REBCO Superconducting Multifilamentary Tapes under Perpendicular Magnetic Field

H Sasa¹, T Ito¹, M Iwakuma¹, S Miura¹, T Izumi², T Machi² and A Ibi²

¹Research Institute of Superconductors Science and Systems, Kyushu University, Fukuoka 819-0395, Japan
²Research Institute of Advanced Industrial Science and Technology, Ibaraki 305-8564, Japan

E-mail: sasa@sc.kyushu-u.ac.jp

Abstract. For AC applications of high-temperature superconductors, such as REBa₂Cu₃O₇₋ₓ (REBCO, RE = rare earth) superconducting tapes, an AC loss is a great part of total heat load of cooling systems. In the case of conduction cooling, it may cause a serious temperature rise of the superconducting systems. Therefore, it is very important to reduce the AC loss in superconducting windings and grasp its properties under various conditions. For AC loss reduction, REBCO tapes should be scribed into a multifilamentary structure by the laser-scribing technique. In this study, AC loss properties in the non-scribed and scribed tapes were investigated, especially for $B_m < B_p$, where $B_p$ is the breaking point of the AC loss curve and corresponds to the penetration field where the magnetic flux penetrates to the center of the tape or filaments. Further, the dependences of $B_p$ on the number of stacking tapes and filaments were investigated from the viewpoint of demagnetization effect. It was cleared that the AC loss for $B_m < B_p$ decrease and $B_p$ increase with increasing number of stacked tapes.

1. Introduction

Many projects for AC applications of REBa₂Cu₃O₇₋ₓ (REBCO, RE = rare earth) superconducting tapes are in progress globally. Various experimental and theoretical studies on AC loss of REBCO tapes have been conducted [1]-[4]. REBCO superconducting tapes can be used even at high temperature and high magnetic field because of its excellent critical current properties and high critical temperature. For AC use, the reduction of AC loss is the most important problem. The AC loss of REBCO superconducting tape is proportional to the width of the tape as predicted by conventional theory. Our research group has developed the laser-scribing technique to make a REBCO tape into a multifilamentary structure with little degradation of the critical current [5]. Denoting the applied magnetic field amplitude as $B_m$ and the penetration field where the magnetic flux penetrates to the center of the tape or filaments as $B_p$, the AC loss of a REBCO tape with $N$ filaments decrease to $1/N$ of those of the non-scribed one for $B_m > B_p$. $B_p$ corresponds to the breaking point of AC loss vs $B_m$ curve. On the other hand, the details of the AC loss properties for $B_m < B_p$ have not been investigated yet. In our previous papers, it was revealed that the AC losses for $B_m > B_p$ coincide regardless of the number of stacked tapes when the number of filaments is one or four [6]. On the other hand, the AC losses for $B_m < B_p$ decrease as the number of stacked tapes increases [6]. In this paper, focusing on the difference in AC loss of scribed and non-scribed tapes especially for $B_m < B_p$, we investigated the AC loss properties of 8-filament tapes besides non-scribed and 4-filament tapes. Moreover, the AC loss properties of the REBCO tapes stacked into 1, 3 and 6...
layers were measured to investigate the dependences of $B_p$ on the number of stacked tapes and the number of filament of a tape from the viewpoint of the demagnetizing effect.

2. Experimental setup

2.1. Parameters REBCO superconducting tapes

The parameters of sample REBCO superconducting tapes are listed in table 1. The REBCO tapes were fabricated by IBAD and the PLD technique. By doping BaHfO$_3$ to the EuBa$_2$Cu$_3$O$_y$ superconducting matrix as pinning centers, the critical current properties have been improved [7]. For AC reduction, the superconducting layers were divided into four or eight filaments by laser-scribing technique. The details of laser-scribing technique were reported in [5]. The tapes were stacked into 1, 3 and 6 layers perpendicularly. Every tape was covered with kapton tape to insulate with each other. In the case of stacked tapes, the distance between the neighboring superconducting layers was 208.4 μm. The $I_C$ of the 4- and 8-filament tapes calculated from measured $M$-$B$ curves were 305.7 A and 201.6 A respectively. There was no degradation by scribing.

| Table 1. Parameters of the EuBCO tapes. |
|----------------------------------------|
| non-scribed and 4-filament tapes | 8-filament tapes |
| Dimensions of the tape | 5 mm in width, 112 μm in thickness | 5 mm in width, 106 μm in thickness |
| Substrate | Hastelloy (100 μm) | Hastelloy (100 μm) |
| Buffer layer | CeO$_2$ + LaMnO$_3$ + MgO + Y$_2$O$_3$ + Gd$_2$Zr$_2$O$_7$ (1 μm) | CeO$_2$ + LaMnO$_3$ + MgO + Y$_2$O$_3$ + Gd$_2$Zr$_2$O$_7$ (0.7 μm) |
| Superconducting layer | EuBa$_2$Cu$_3$O$_y$ + BaHfO$_3$ [3.5 mol%] (3.6 μm) | EuBa$_2$Cu$_3$O$_y$ + BaHfO$_3$ [3.5 mol%] (0.7 μm) |
| $I_C$ of the tape at 77 K, self-field | 300 A | 200 A |

2.2. Experimental Equipment

In this study, a saddle-shaped pick-up coil was used to measure the magnetization and AC loss of the superconducting tapes [6]. The external magnetic field was applied in perpendicular to the tape face by using a NbTi superconducting magnet. The range of the amplitude and the frequency were from 0.004 to 4.3 T and from 0.01 to 0.2 Hz, respectively. Temperature ranged from 25 to 77 K. The AC loss, $W$, per cycle and unit volume was evaluated by integrating the magnetization, $M$, by the applied magnetic field, $B$, for a single period. It corresponds to the inner area of the $M$-$B$ curves.

$$W = \int_0^B BdM = -\oint MdB$$

We confirmed in the previous study that AC loss of REBCO tapes has no frequency dependence [8]. So the combination of frequency and amplitude was not cared.

3. Results and discussion

3.1. Behaviour of AC loss for $B_m < B_p$

The AC loss of REBCO tapes increases monotonically with increasing temperature [4]. Figure 1 shows the observed field amplitude, $B_m$ dependences of AC losses of the non-scribed and scribed tapes which were stacked into 1, 3 and 6. The arrows in figure 1 indicate each $B_p$. 
Figure 1. Observed $B_m$ dependences of the AC losses of (a) non-scribed (b) 4-filament (c) 8-filament tapes at 50 K. $N$ indicates the number of the stacked tapes.

$B_p$ was determined from the intersection point of two asymptote lines for simplicity as shown in figure 1(a). As for the non-scribed tapes, the AC losses decrease with increasing number of the stacked tapes for $B_m < B_p$. This property can be explained from the viewpoint of demagnetizing effect as follows. Generally, the effectively applied magnetic field to superconducting tape, $B_{\text{eff}}$, is different from the external applied magnetic field, $B_{\text{ext}}$, because of the diamagnetic field, $B_d$, which is caused by the shielding current in the tape. The relation between them are expressed as

$$B_{\text{eff}} = B_{\text{ext}} + B_d$$

In the Meissner state, using the demagnetizing coefficient, $\nu$, the diamagnetic field is expressed as

$$B_d = \nu B_{\text{eff}}$$

Substituting equation (3) to equation (2), we can obtain

$$B_{\text{eff}} = B_{\text{ext}}/(1 - \nu)$$
On the other hand, using the magnetization, \( M \), the inner magnetic field of the superconductor, \( B_m \), is expressed as

\[
B_m = B_{\text{eff}} + M
\]  

(5)

Considering the case of \( B_m = 0 \), i.e. \( B_m < B_p \), following equation is obtained from above equations.

\[
- M = B_{\text{eff}} = B_{\text{ext}}/(1 - \nu)
\]

(6)

\( \nu \) is determined by the shape of the superconducting material and the direction of the applied field. In the case that the field is applied in parallel to a superconducting infinite slab, \( \nu = 0 \). On the other hand, in the case that the field is applied in perpendicular to the slab, \( \nu \) is close to one. When \( \nu \) is close to one, \( B_{\text{eff}} \) is much larger than \( B_{\text{ext}} \). So, the AC loss is larger than in the case smaller \( \nu \).

When the superconducting tapes were stacked into multilayer, \( \nu \) becomes smaller and \( B_{\text{eff}} \) becomes smaller. So, the AC loss decreases with increasing number of the stacked tapes. On the other hand, for \( B_m > B_p \), the AC losses roughly agree with each other regardless of the stacking number of tapes. \( \nu \) for \( B_m > B_p \) is almost zero regardless of the shape of the tapes because the field penetrates throughout the tape. Therefore, the AC losses also have no dependence on the number of stacked tapes.

Next, the AC losses shown in figure 1 are replotted in figure 2 for comparison between the filament number dependences. In figure 2, for simplicity, the smaller graphs in each graph shows the enlarged view for large field amplitude and the arrows indicate each \( B_p \).

**Figure 2.** \( B_m \) dependences of the AC losses of the case of (a) \( N = 1 \) (b) \( N = 3 \) (c) \( N = 6 \) at 50 K.
For \( B_m > B_p \), the AC losses decrease with increasing number of filaments. That can be expected from the conventional theory [5]. On the other hand, for \( B_m < B_p \), the AC losses increase with increasing number of filament. For \( B_m < B_p \), in the case of scribed tapes, the applied field penetrates the tape more easily than the case of non-scribed tapes. Therefore, the AC losses of the scribed tapes are larger than those of the non-scribed tapes. That can be also predicted from the conventional theory.

Figure 3 shows the field amplitude dependences of the ratios of AC losses in the non-scribed, 4-filament and 8-filament tapes to those in the one-layer tape at 50 K for \( B_m < B_p \).

![Figure 3. Comparison between field amplitude dependences of ratio of AC losses in non-scribed, 4-filament and 8-filament tapes to those in the one-layer tape at 50 K for \( B_m < B_p \).](image)

In the case of the non-scribed tapes, the ratios roughly correspond to approximately \( 1/N \). Increasing \( N \), the whole shape of the tapes becomes longer perpendicularly, and then the demagnetizing coefficient decreases. Then, from equation (6), the magnetization decreases and AC loss decreases. From equation (1), it means that the AC loss of the \( N \)-layer stacked tapes decreases to \( 1/N \) compared with that of one-layer tape. In the case of the multifilamentary tapes, the ratios are higher than \( 1/N \) and increase as increasing the filaments and \( B_m \). For \( B_m < B_p \), in the case of multifilamentary tapes, the applied field penetrates each filament more easily than the case of non-scribed tapes because the shielding current is directly proportional to the width of the filament [4]. Thus, the AC losses increase with increasing filaments.

3.2. Behaviour of \( B_p \)

Figure 4 shows that the temperature dependences of \( B_p \) for each number of the filaments and the stacked tapes.
Figure 4. Temperature dependences of $B_p$ for non-scribed, 4-filament, 8-filament tapes, $N = 1, 3$ and 6.

$B_p$ decreases with increasing $T$ in every case. Increasing $T$, the critical current decreases and the magnetic field can penetrate the tapes more easily. Consequently, $B_p$ decreases. $B_p$ increases as increasing the stacking number. Increasing $N$, the whole shape of the tapes becomes longer perpendicularly, and then the demagnetizing coefficient decreases. Then, from equation (6), the magnetic field applied effectively to the tapes is small. Therefore, the applied field requires larger amplitude to penetrate to the center of the tapes, i.e. $B_p$ increases as increasing the stacking number. The number of filaments dependences of $B_p$ can be explained from the viewpoint of the shielding current. $B_p$ decreases as increasing the number of filaments. It can be explained by the shielding current dependence of the AC loss mentioned above. For multifilamentary tapes, especially for 8-filament tapes, $B_p$ barely depends on $N$. In the case of multifilamentary tapes, the width of the filaments is much smaller than that of the non-scribed tapes. Therefore, the magnetic flux can penetrate more easily than the case of the non-scribed tapes. It means that the demagnetizing coefficient of the multifilamentary tape is much smaller than that of the non-scribed tapes. Consequently, $B_p$ barely depends on $N$.

4. Conclusion
The AC loss properties of EuBCO superconducting tapes were investigated under various conditions with temperature, the number of stacked tapes and the number of filaments as a parameter. The AC losses for $B_m < B_p$ decreased with increasing number of the stacked tapes. The ratios of AC losses in the stacked tapes to those in one-layer tape depended on the number of filaments. That can be explained by the difference in demagnetizing coefficient. $B_p$ was influenced by temperature, the number of stacked tapes and the number of the filaments. These are also caused by the difference in demagnetizing coefficients of the tapes for each condition. The laser-scribing technique is useful to decrease $B_p$ and reduce the AC loss of EuBCO superconducting tapes for $B_m > B_p$.

Acknowledgement
This research was partially supported by the Japan Science and Technology Agency (JST): Advanced Low Carbon Technology Research and Development Program (ALCA) and the Japan Society for the Promotion of Science (JSPS): Grant-in-Aid-for Scientific Research (JP26249042 and JP17H06931).

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