Dependences of AC Loss in Stacked REBa$_2$Cu$_3$O$_y$
Superconducting Tapes on the Interval among Tapes under
Perpendicular Magnetic Field

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Abstract. In this study, we focused on the dependence of the AC loss in REBa$_2$Cu$_3$O$_y$ (REBCO, RE = rare earth, Y, Eu, Gd) superconducting tapes stacked perpendicular to the tape face on the interval between the superconducting layers. The AC loss of the 2-layer stacked tapes with various interval in perpendicular field was investigated by pickup-coil method. The AC loss for external applied magnetic field, $B_m$, below the penetration field, $B_p$, increases with increasing the interval. In the case that the ratio of the distance between the neighboring superconducting layer, $D$, to the width of the tape, $w$, ($D/w$) is smaller than 0.1, the AC loss of 2-layer tapes decreased to 1/2 of that of 1-layer tape. On the other hand, in the case of $D/w$ being larger than 0.1, the AC loss of 2-layer tapes was larger than 1/2 and it approached the AC loss of 1-layer tape with increasing $D/w$. From the result obtained in this study, it is predicted that, for $B_m$ below $B_p$, the AC loss of stacked REBCO tapes with large $D/w$, such as multifilamentary tapes, is larger than the AC loss of stacked non-scribed REBCO tapes. However, for $B_m$ above $B_p$: a large AC loss region, it is known that the AC loss of the multifilamentary tapes decreases compared with that of non-scribed tapes. Next step, AC loss of the multifilamentary tapes for $B_m$ below $B_p$ will be investigated experimentally and theoretically.

1. Introduction
REBa$_2$Cu$_3$O$_y$ (REBCO, RE = rare earth, Y, Eu, Gd) is expected as a new generation material of superconducting tapes because it can be used even at high temperatures and high magnetic fields due to its excellent critical current densities and high critical temperatures. For AC applications of REBCO superconducting tapes, the AC loss generated in the tapes is one of the serious issues because it may cause a severe temperature rise of superconducting windings and result in thermal runaway. Therefore, the AC loss reduction and understanding its property in detail are absolutely essential to the AC applications. The AC loss of REBCO tapes depends on various operating conditions such as the magnetic field amplitude, $B_m$, the operating temperature, $T$ [1], the number of the stacked tapes, $n$ [2][3], the number of the filaments of the tape [4], the angle between the field and the tape face [5] and so on. The goal of our study is to establish a method which can easily estimate the amount of the AC loss for such various conditions from less experimental results.
In practical coil-based applications, the REBCO tapes are usually wound into a multilayer coil. In the case of the stacked superconducting strips, whole of them can be considered as one-body when the ratio of the distance between the neighboring strips, \(D\), to their width, \(w\), \((D/w)\) is smaller than 0.1 [6]. Recently, we found that the AC loss of the REBCO tapes stacked into \(n\)-layer with \(D/w < 0.1\) decreases to \(1/n\) of that of 1-layer tape [2][3]. However, the REBCO tapes are preferred to be divided into a multi-filamentary structure by laser scribing technique in order to reduce the AC loss for \(B_m\) above \(B_p\) [7]. Here, \(B_p\) is the penetration field when the magnetic flux reaches the center of the filament. The \(D/w\) of each filament of the scribed tape should exceed 0.1. Therefore, the dependence of the AC loss on \(D/w\) which is larger than 0.1 should be investigated. The objective of this paper is to clarify the \(D/w\) dependence of the AC loss of stacked REBCO tapes with changing \(D\) in \(B_m\) below \(B_p\). This study will be a help to establish AC loss estimation method for the condition of large \(D/w (> 0.1)\) such as the stacked multifilamentary REBCO tapes. The AC losses of the 2-layer stacked non-scribed tapes with various \(D/w\) under perpendicular magnetic field were measured by pickup-coil method.

2. Experimental setup

2.1. Parameters of REBCO superconducting tapes
Parameters of REBCO superconducting tapes are listed in table 1. The sample tapes were provided by the National Institute of Advanced Industrial Science and Technology. The REBCO superconducting tapes were fabricated by the combination of an ion beam assisted deposition technique and a pulsed laser deposition method. To improve the flux pinning property of the tape, \(\text{BaHfO}_3\) was doped to the \(\text{EuBa}_2\text{Cu}_3\text{O}_y\) superconducting matrix as an artificial pinning center [8]. The REBCO tapes were stacked into two layers with the various interval perpendicularly to the tape face as shown in figure 1. The intervals were determined in order for their ratio to be approximately 1:2:4:8. The tapes were covered with kapton tape to insulate each other. The two tapes used in this study were cut off from one long tape. In this study, \(D\) indicates the distance between the neighboring superconducting layers as shown in figure 1.

Table 1. Parameters of the EuBCO tapes.

| Parameters of the tape | Value |
|-----------------------|-------|
| Dimensions of the tape | 5 mm in width, 106 \(\mu\)m in thickness |
| Stabilizing layer | Ag (5 \(\mu\)m) |
| Superconducting layer | \(\text{EuBa}_2\text{Cu}_3\text{O}_y + \text{BaHfO}_3 [3.5 mol\%] (0.7 \(\mu\)m)\) |
| Buffer layer | \(\text{CeO}_2 + \text{LaMnO}_3 + \text{MgO} + \text{Y}_2\text{O}_3 + \text{Gd}_2\text{Zr}_2\text{O}_7 (0.7 \(\mu\)m)\) |
| Substrate | Hastelloy (100 \(\mu\)m) |
| \(I_C\) of the tape at 77 K, self-field | 200 A |
| Number of stacked tapes | 1, 2 |
| Interval between the neighboring a superconducting layer (corresponding \(D/w\)) | 0.29, 0.65, 1.15, 2.37 mm (0.058, 0.130, 0.230, 0.474) |
2.2. Experimental equipment
In this study, the magnetization of the REBCO superconducting tapes was measured by using a saddle-shaped pick-up coil [9]. From the measured magnetization and following equation, the AC loss of the tapes was calculated.

\[ W = \int B dM = - \oint M dB \] (1)

This equation says that the AC loss per unit volume per cycle, \( W \), can be evaluated by integrating the magnetization, \( M \), by the applied field, \( B \), and it corresponds to the inner area of the measured \( M-B \) curve. The external magnetic field was applied perpendicularly to the tape face by a NbTi superconducting magnet cooled by liquid helium. The experimental conditions in this study are listed in table 2. It was confirmed that the AC loss of REBCO tapes has no frequency dependence [10].

| Table 2. Experimental conditions. |
|----------------------------------|
| Temperature                      | 25-77 [K]                     |
| Field amplitude                  | 0.004-4.3 [T]                 |
| Field frequency                  | 0.01-0.2 [Hz]                 |
| Field angle                      | Perpendicular to the tape face|
| Method                           | Saddle-shaped pick-up coil method |

3. Results and discussion
Figure 2 shows the observed \( B_m \) dependences of the AC loss of a REBCO tape and the 2-layer REBCO tapes with various \( D/w \) for \( B_m \) below \( B_c \) at 50 K. The inset shows the observed AC loss curves in a broad range. The case of 1-layer tape can be considered as the case of 2-layer tapes separated infinitely. The influence due to the magnetic field occurred by another tape is infinitely small in the case of the infinitely separated two tapes. Therefore, the 1-layer case is considered as the case of the 2-layer tapes with \( D/w \) being infinity in this study.
Figure 2. Observed $B_m$ dependences of the AC loss of 1-layer tape and of 2-layer tapes with $D/w = 0.474, 0.230, 0.130$ and $0.058$ at 50 K.

The $B_p$ corresponds to the breaking point of the AC loss curve and can be determined from the intersection point of two approximate lines for above and below $B_p$ as shown in the inset figure 2. The $B_p$ values are 0.1-0.17 T at 50 K. The AC loss for $B_m$ above $B_p$ has no interval dependence. In $B_m$ above $B_p$, $B_m$ is much larger than the diamagnetic field and the difference of the magnetization due to the difference of the interval is very small. Therefore, the AC loss has no interval dependence. On the other hand, the AC loss for $B_m$ below $B_p$ increases as increasing $D/w$. In the case of the narrow interval, the demagnetization field is mutually intensified by the magnetic field created by the shielding current in another tape, and the penetration depth is smaller than the wider interval case. Therefore, the AC loss increases with increasing $D/w$. Similar property could be also observed at other temperatures. Such observed property that the AC loss for $B_m$ below $B_p$ increases with increasing the interval agrees with the result obtained from the numerical calculation [11].

The AC losses for $B_m$ below 1/2 of $B_p$ at 50 K normalized by the following equation are shown in figure 3. In equation (2), the units of the AC loss and the field amplitude $B_m$ are [J/m$^3$cycle] and [T], respectively.

$$6.81 \times 10^{10} B_m^{3.03}$$

(2)

The power of equation (2) was determined from the average value of the power of the approximation curve of the AC loss curves below $B_p$ for each $D/w$. The coefficient of equation (2) was determined in order for the average value of the normalized AC loss of 1-layer tape to be one.
The horizontal lines in figure 3 and the values written above or below the lines correspond to the average values of the normalized AC losses for each $D/w$. In figure 3, the AC losses for $B_m$ below $10^{-2}$ T are omitted because they include large errors compared with those for $B_m$ above $10^{-2}$ T due to the small magnetization.

The average values of normalized AC losses obtained in the same way are plotted in figure 4. Note that the horizontal axis of figure 4 is $w/D$. For comparison, the theoretical prediction which is for the case that the number of the stacked tapes is infinity and expressed as following equation [6][12] is also shown as dashed line in figure 4.

$$W = \frac{1}{wt} \frac{\mu_0 I_C^2}{\pi} \left( \frac{H_0}{I_C / 2\pi w} \right)^4 \left( \frac{\tanh(\pi w/2D)}{\pi w/2D} \right)^2$$

Here, $t$, $I_C$ and $H_0$ are the thickness of the superconducting layer of the tapes, the critical current of the tapes and the field amplitude, respectively.
Figure 4. The interval dependence of the average values of the normalized AC losses of 2-layer tapes for $B_m < B_p$ at each temperature.

The observed interval dependence of the AC loss for $B_m$ below $B_p$ has no temperature dependence. As mentioned earlier, it has been already cleared that the AC loss of the $n$-layer tapes with $D/w < 0.1$ (i.e. $w/D > 10$) decreases to $1/n$ of that of 1-layer tape. Therefore, for $w/D > 10$, the theoretical prediction curve shown in figure 4 is almost zero. In the case of experimental results of 2-layer tapes, the normalized AC loss converges almost $1/2$ for $w/D > 10$. The reason why the AC loss of 2-layer tapes with $D/w < 0.1$ decreases to $1/2$ of that of a single tape is explained in Ref. [3] in detail. Brief explanation is as follows. In the case of stack with $D/w < 0.1$, the stacked two tapes can be regarded as twice the thickness of a single tape [6]. The magnetization of the 2-layer stacked tapes is $1/2$ of that of a single tape from the viewpoint of the demagnetization coefficient. Therefore, the AC loss decreases to $1/2$. The reason for the normalized AC loss slightly below $1/2$ might be non-uniform superconducting-property distribution due to its local inhomogeneity. The experimental result and the theoretical prediction for infinity stack have the similar property, which the normalized AC loss for $w/D > 10$ approaches each convergence value and that for $w/D < 10$ increases sharply with decreasing $w/D$. It is predicted that the experimental result approaches the theoretical curve as increasing the number of the stacked tapes.

4. Conclusion

In this study, the dependence of the AC loss of 2-layer stacked EuBCO superconducting tapes on the interval between the neighboring superconducting layer was investigated experimentally. The AC loss for $B_m$ above $B_p$ had no interval dependence, whereas the AC loss for $B_m$ below $B_p$ increased with increasing the interval. Such observed property agreed with the numerical analysis. Furthermore, in comparison with the theoretical prediction for infinite stack, the observed results showed similar interval dependence of the AC loss. This study will be helpful to understand the AC loss property of the stacked multifilamentary REBCO tapes. Next step, the influence of the magnetic field by the filaments located side by side should be considered.
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References
[1] Iwakuma M, Nigo M, Inoue D, Miyamoto N, Funaki K, Iijima Y, Saitoh T, Yamada Y, Izumi T and Shiohara Y 2006 Supercond. Sci. Technol. 19 350-8
[2] Sasa H, Ito T, Iwakuma M, Miura S, Izumi T, Machi T and Ibi A 2018 J. Phys.: Conf. Ser. 1054 012037
[3] Sasa H, Kawasaki G, Miura S, Iwakuma M, Izumi T, Machi T and Ibi A J. Appl. Phys. (Submitted)
[4] Ito T, Iwakuma M, Miura S, Izumi T, Adachi K, Machi T and Ibi A 2018 IEEE Trans. Appl. Supercond. 28 8200505
[5] Iwakuma M, Nigo M, Inoue D, Kiss T, Funaki K, Iijima Y, Saitoh T, Yamada Y and Shiohara Y 2005 IEEE Trans. Appl. Supercond. 15 1562-5
[6] Mawatari Y 1996 Phys. Rev. B 54 13215-21
[7] Katayama K, Machi T, Nakamura T, Takagi Y, Nakaoka K, Yoshizumi M, Izumi T and Shiohara Y 2014 Physics Procedia 58 142-5
[8] Tobita H, Notoh K, Higashikawa K, Inoue M, Kiss T, Kato T, Hirayama T, Yoshizumi M, Izumi T and Shiohara Y 2012 Supercond. Sci. Technol. 25 062002
[9] Iwakuma M, Nanri M, Fukui M, Fukuda Y, Kajikawa K and Funaki K 2003 Supercond. Sci. Technol. 16 545-56
[10] Iwakuma M, Hayashi H, Okamoto H, Tomioka A, Konno M, Saito T, Iijima Y, Suzuki Y, Yoshida S, Yamada Y, Izumi T and Shiohara Y 2009 Physica C 469 1726-32
[11] Pardo E, Sanchez A and Navau C 2003 Phys. Rev. B 67 104517
[12] Mawatari Y 1997 IEEE Trans. Appl. Supercond. 7 1216-9