Evaluation AC Losses in Large-Scale Conductors Consisting of Stacked REBCO Tapes[*]

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In this work, stacked model conductors consisting of dozens of YBCO tapes were fabricated and experimentally investigated to determine whether the hysteresis and coupling losses affect each other. When an oblique magnetic field is applied to the tape, hysteresis and coupling losses are expected to be generated simultaneously. A uniform AC transverse magnetic field was applied to the sample in liquid nitrogen, and the AC losses were measured via the pickup coil method. The measurements were carried with the magnetic field applied at various angles with respect to the tape wide surface. The measured AC losses were separated into hysteresis and coupling losses. The measured hysteresis losses well agreed with the theoretical values for a square cross-section superconductor. This indicates that hysteresis losses can be considered in terms of the magnetic field component perpendicular to the flat face of the YBCO tape. The coupling time constant was found to be independent of the applied magnetic field angle. This shows that coupling losses can be considered in terms of the magnetic field component parallel to the tape's wide surface, and the permeability in the conductor can be assumed to be the vacuum permeability.

Keywords: hysteresis loss, coupling loss, REBCO, conductor

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1. Introduction

Superconducting conductors composed of multiple REBCO tapes stacked and twisted are being investigated as a candidate of the conductors used in superconducting magnets for fusion experimental devices [1–4]. These conductors are exposed to a changing magnetic field with the tapes being electrically connected and twisted; thus, during the magnet excitation and discharging processes, inter-tape coupling losses are generated in these conductors in addition to hysteresis losses. Hysteresis losses in REBCO tapes have been investigated from both theoretical and experimental perspective and are considered to be relatively easy to be predicted [5–8]. However, checking whether the obtained results are in good agreement with the predicted ones is necessary even under conditions of coupling current flow in the conductors. In addition, coupling losses depend on the twist conditions and structure of the conductors, so their properties are not sufficiently clear. Studies that have investigated the conditions in which inter-tape coupling losses and hysteresis losses occur simultaneously are limited. Some experimental studies have investigated the effect of inter-strand resistances on inter-tape coupling losses; however, these studies have not focused on the effect of the interaction between hysteresis and coupling losses [9, 10].

Therefore, the purpose of this study is to evaluate AC losses in a REBCO conductor consisting of stacked REBCO tapes and to deepen the understanding of AC losses in an actual conductor. Whether hysteresis and coupling losses affect each other is particularly important. To this aim, AC losses were measured under a transverse magnetic field diagonally applied to the wide surface of the tape line that constitutes the model conductor.

2. Experiment

The permeability and conductivity of the conductor strongly influence coupling losses. The magnetization of the superconducting layers may affect the magnetic field distribution in the samples. As a result, the interlinkage magnetic flux between tapes in the samples may be affected by the magnetization of the superconducting layer. Similar effects have been reported on the low temperature superconducting multifilamentary wires by Irie *et al.* [11]. According to their work, the effective permeability of the wire is affected by the magnetic fields applied to the wires. This means that hysteresis losses may affect coupling losses.

The present study discusses experimental results un-

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der the conditions whereby hysteresis losses and inter-tape coupling losses are simultaneously produced in conductors consisting of stacked YBCO tapes. For this purpose, the measurements were conducted on a 100-mm straight sample, and the corresponding results have been described in detail. Although this conductor was not twisted, a closed-loop in a 100-mm length consists of several tapes in the conductor. Thus, coupling losses corresponding to a closed-loop in the 100-mm long sample were generated via the magnetic field applied parallel to the tape face.

In the experiments, coupling losses and hysteresis losses were measured in samples under a transverse magnetic field applied at different angles with respect to the flat face of the tapes. Confirming whether the magnitude of the magnetic field affects the coupling loss property is important.

In this section, the details of the samples, measuring method, and results of the measurements are described.

2.1 Parameters of the sample

The parameters of the tapes used for the conductor and the sample are listed in Tables 1 and 2, respectively. And an overview of the sample is provided in Fig. 1. The investigated conductor is composed of 50 YBCO tapes with a width of 6 mm, wrapped in a 4-mm wide copper tape that holds them in place; furthermore, the whole conductor is soldered. The shape of the conductor is straight and non-twisted, and its length is 96 mm. The YBCO tape in the conductor was fabricated by SuperOx; its critical current in liquid nitrogen, under the self-field, is 200 A. The perimeter of the tape was surrounded with a copper layer. The substrate of the tape consists of Hastelloy C276.

Table 1 Parameters of the YBCO tape.

Width	6 mm
Substrate material	Hastelloy C276
Thickness of substrate	63±3 µm
Thickness of silver layer	2 µm
Surround copper layer	20 µm per side
Minimum Ic at 77 K, s.f [a]	200 A

[a] s.f : self-field

Table 2 Parameters of the sample.

Superconducting material	YBCO
Width	6mm
Thickness	7mm
Length	96mm
Number of tapes	50
I_C of a tape	200A
Refrigerant	Liquid nitrogen

Fig. 1 Overview of the short sample of the conductor consisting of stacked YBCO tapes without twist. YBCO tapes were fabricated by SuperOx. The number of tapes in the conductor was 50. The conductor was spirally wrapped in a copper sheet.

2.2 Measuring method

AC losses in the sample were measured via the pickup coil method. The arrangement of the measuring system is shown in Fig. 2. The sample, pickup coils, and magnet used to apply the external magnetic field are illustrated in the figure. The pickup coil covered the whole sample, so that the coupling current could flow over the entire length of the sample. The external magnetic field was measured via another pickup coil placed at a symmetrical position with respect to the sample. The measurements were performed in liquid nitrogen, i.e., at a temperature of 77 K.

The angle of the transverse magnetic field was controlled by tilting the sample around its axis. The angles formed by the applied magnetic field and the flat face of the tape were set to 0 - 90°. The applied magnetic field amplitude and frequency were set to 3.2 - 79.7 mT and 0.2 - 360 Hz, respectively. The pickup coils were calibrated via eddy current losses in the copper conductor with a rectangular cross section.

2.3 Measurement results

The measurement results for the magnetic field dependence of the AC losses are shown in Fig. 3. In this case, the frequency was set to 3 Hz. On the *y*-axis, AC losses are shown per cycle of the applied magnetic field and per unit volume of the sample. The solid lines in the figure represent the theoretical hysteresis losses obtained under the assumption of specific approximations regarding the cross-sectional shape of the superconductor exposed to the changing transverse magnetic field. The red curve corresponds to hysteresis losses in a single strip, calculated based on Brandt's formula [12]. The other three curves represent losses corresponding to a sample cross section of a circle, square, and slab [13, 14]. The theoretical hysteresis losses in the strip, circle, and slab are referred to as $W_{\mathrm{h,strip}}$, $W_{\mathrm{h,circle}}$, and $W_{\mathrm{h,slab}}$, respectively. In the following equation, d and w are used to denote the thickness and

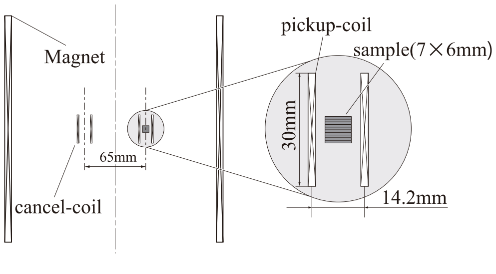

Fig. 2 Measuring system.

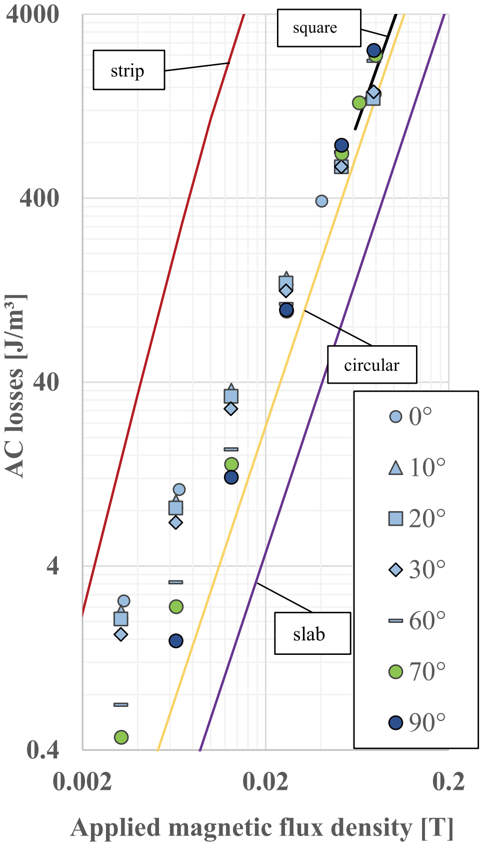

Fig. 3 Measured AC losses in the short straight sample of the YBCO stacked conductor. The four lines represent the calculated hysteresis losses for different cross-sectional shapes, namely, strip, square, circular, and slab. The slope of the measured AC losses as a function of the applied magnetic field decreases upon decreasing the field angle.

width of the tape, respectively, μ_0 is the permeability in vacuum, I_c is the critical current of the tape, and H_e is the amplitude of the applied magnetic field. $W_{\mathrm{h,strip}}$ can then be expressed according to [12]:

$$W_{\mathrm{h,strip}} = \frac{1}{d}\mu_0 I_c H_e \cdot g(h),$$
$$h = \frac{H_e}{H_C},\ H_C = \frac{I_c}{w\pi}, \tag{1}$$
$$g(x) = \left(\frac{2}{x}\right)\ln\cosh x - \tanh x.$$

$W_{\mathrm{h,circle}}$ is given by [13]:

$$W_{\mathrm{h,circle}} = \frac{4}{3}(2h_e{}^3 - h_e{}^4)\mu_0 H_p{}^2,\quad \text{for } h_e \ll 1,$$
$$h_e = \frac{H_e}{H_p},\quad H_p = \frac{2}{\pi}J_c r, \tag{2}$$

where r is the radius of the superconducting round wire, and J_c is the critical current density.

Finally, $W_{\mathrm{h,slab}}$ can be expressed as [13]:

$$W_{\mathrm{h,slab}} = \frac{4\mu_0}{3}\frac{H_e{}^3}{J_c t},\quad \text{for } H_e/J_c t \ll 1, \tag{3}$$

where t is the thickness of the superconducting slab. In these approximations, the critical current density was determined assuming that the sample had a uniform cross section, and the loss value was calculated using such critical current density. In addition, the dependence of the critical current density on the magnetic field was not considered. The theoretical values for the square cross-section case were estimated from Ref. [14], where numerical analysis results on hysteresis losses were discussed for this specific geometry. In the paper used for the estimation, the external magnetic field amplitude was calculated only up to a certain range; hence, the present estimate is valid only for a limited field range. Thus, the lower limit of the calculated range of the magnetic field corresponds to the magnitude of 0.06 T in our experiments.

The measured loss values are between the theoretical loss values of the slab and strip cross sections and are close to the estimated values for the square cross-section case. These results are reasonable because the actual sample cross section ($6 \times 7\ \mathrm{mm}^2$) is close to being a square.

For an applied magnetic field angle of 90°, the measured value is found to be proportional to the third power of the applied magnetic field amplitude. No coupling currents are induced between the tapes because the inter-tape linked magnetic flux is almost zero. Therefore, the measured values are because of hysteresis losses only.

For an applied magnetic field angle of 0°, the measured value is found to be proportional to the second power of the applied magnetic field amplitude. Therefore, coupling losses are considered to be the dominant source of the measured losses. In this case, the perpendicular magnetic field applied along the face of the YBCO tapes is almost zero; therefore, the hysteresis losses should be negligible.

Furthermore, with the magnetic field being applied at 10°, 20°, and 30°, the dependence of the measured value is found to be roughly proportional to the square of the applied magnetic field, indicating that coupling losses are dominant. In the case of 60° and 70° magnetic field angles, the dependence differs between the lower and higher magnetic field ranges. This is because of the fact that coupling losses are dominant in the low magnetic field range, whereas hysteresis losses are dominant in the high magnetic field range.

3. Discussion

As explained in the previous section, both hysteresis losses and coupling losses were generated in this sample during the measurements. In this section, the influences of these losses on each other are discussed. For the discussion, the hysteresis losses without frequency dependence and the coupling losses with frequency dependence are separated from each other. The properties of each loss contribution are discussed.

The procedure to separate the losses into two distinct categories is as follows. Firstly, the frequency dependence

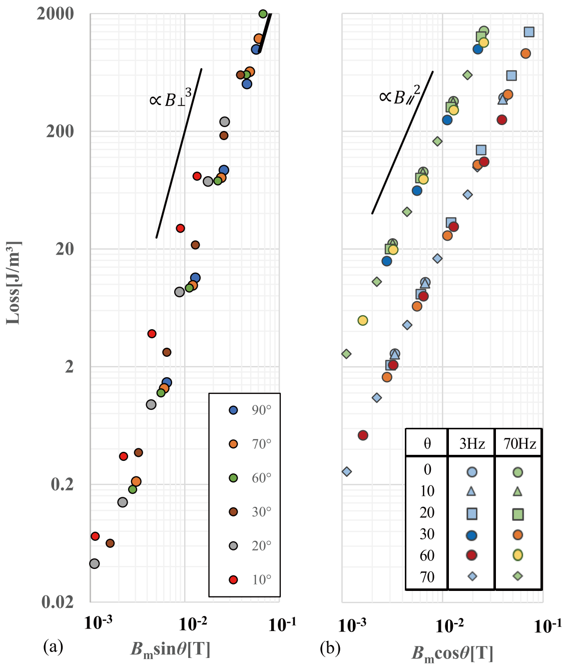

Fig. 4 (a) Hysteresis losses and (b) coupling losses derived from the measured losses. The dashed lines are calculated for losses proportional to the third and second power of the applied magnetic field, respectively. The solid line is estimated from Ref. [14], where hysteresis losses were calculated in a superconductor with a square cross section.

of the losses was measured in the low frequency region. Next, the fitting function of the measured losses was obtained, assuming that the frequency dependence of the losses is linear. Moreover, the hysteresis losses were obtained as the intercept of the fitting function, because hysteresis losses are not proportional to the frequency. Finally, coupling losses were obtained by subtracting the hysteresis losses from the measured values at all frequencies.

The results of the separation of the measured losses using the abovementioned procedure are shown in Fig. 4. The hysteresis losses are illustrated in Fig. 4 (a). On the x-axis is the sine component of the applied magnetic field, $B_{\mathrm{m}\perp}$, which is perpendicularly applied to the tape face. The dashed line in Fig. 4 (a) is proportional to the third power of $B_{\mathrm{m}\perp}$. It can be seen that the hysteresis losses exhibit almost the same slope as this line. In addition, the losses agree well with the solid line obtained assuming hysteresis losses in a superconductor with a square cross section. This line is the same as the one displayed in Fig. 3. In the calculation, the superconductor was assumed to be uniform. This indicates that the hysteresis losses in the stacked conductors composed of REBCO tapes can be estimated by assuming that the cross section of the conductor is uniform, regardless of the discrete configurations.

Figure 4 (b) illustrates the coupling loss properties at 3 and 70 Hz. On the x-axis is the cosine component of the applied magnetic field, $B_{\mathrm{m}//}$, which is applied parallel to the tape face. The dashed line in Fig. 4 (b) is proportional to the square of $B_{\mathrm{m}//}$. It can be seen that the coupling losses have almost the same slope as this line.

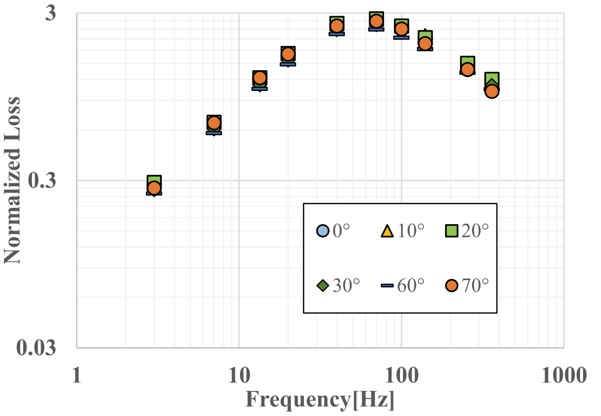

Fig. 5 Frequency dependence of the coupling losses. The y-axis represents the coupling losses per one cycle normalized by $\mu_0(H_\mathrm{m}\cos\theta)^2$. All data obtained at different angles of the applied magnetic fields overlap on the same curve.

The hysteresis losses are roughly proportional to the third power of the magnetic field and are approximately determined by the magnetic field applied in the direction of perpendicular to the flat face of the YBCO tapes. However, an increase in hysteresis losses with a decrease in the magnetic field angle can be clearly observed. The cause of this trend is unlikely to be because of an undesired angle drift, as the sample angle could be determined with an accuracy of less than 1°. In Ref. [8], similar properties were reported for REBCO tapes, which are commercially available tapes. Therefore, the increase in the loss at small angles in the present measurements is considered to be an intrinsic property of the tapes. In addition, the effect of the small-angle losses on the total losses is not very important under the present circumstances because of the following reasons. In general, most stacked tape conductors are twisted around their axis. Thus, the direction of the applied magnetic field with respect to the tapes rotates around the tape axis when moving along the axis of the conductors. Hence, the local hysteresis losses vary along the conductor under these conditions. The local losses are determined by the field perpendicularly applied to the tape face. Therefore, the total losses in conductors with one twist pitch are dominated by large-angle losses.

From the coupling loss properties, it is clear that the coupling losses are proportional to the square of the cosine component of the magnetic field, and these losses overlap in the graph at every angle and frequency. The trend does not vary with frequency. Therefore, it can be inferred that the coupling losses are determined by the cosine component of the applied magnetic field.

The frequency dependence of the coupling losses is illustrated in Fig. 5. The y-axis shows the coupling losses normalized by $\mu_0(H_\mathrm{m}\cos\theta)^2$. Here μ_0 and H_m are the vacuum permeability and magnetic field amplitude, respectively. The frequency is plotted on the *x*-axis. The frequency dependence of the coupling losses exhibit the whole Debye curve [15, 16]. The peak frequencies, at which the normalized losses are maximum, are almost identical for the different angles of the applied magnetic field. Because the peak frequencies are in the range of 60 - 70 Hz, the coupling loss time constant of the sample can be calculated to be about 2.5 msec. When the angle of the magnetic fields is 0°, the magnetization of the superconducting layer is negligible because the superconducting layer is very thin. Therefore, the permeability in the conductor might be assumed to be the same as μ_0 in this case. For different angle values, the coupling losses are determined by the cosine component of the magnetic field, and the obtained coupling time-constants are identical. Therefore, the coupling losses can be calculated using μ_0 as the magnetic permeability of the conductor and taking into account the linked magnetic flux among the tapes. In other words, no influence of the magnetization of the superconducting layer on the coupling losses was observed.

From these results, it can be concluded that the magnetic field perpendicular to the tape face determines the hysteresis losses. Similarly, the magnetic field parallel to the tape face determines the inter-tape coupling losses. No influences of the magnetization of the superconducting layer on the coupling losses could be observed. Thus, the component of the conductor's inner permeability that is parallel to the tape face can be assumed to be the vacuum permeability for the applied transverse magnetic field's direction.

4. Conclusions

In this paper, the AC loss properties of a model conductor were measured and discussed in order to obtain the required information to estimate AC losses in actual conductors composed of stacked REBCO tapes.

It was found that hysteresis losses can be determined via the component of the magnetic field perpendicular to the flat face of the YBCO tapes, and the whole conductor can be approximated as a uniform superconductor for calculating the hysteresis losses. On the other hand, the coupling losses can be determined via the component of the magnetic field parallel to the flat face of the tapes. In this case, the permeability of the sample can be assumed to be equal to the vacuum permeability μ_0. Therefore, the two loss components were found to have no effect on each other. Thus, hysteresis and coupling losses in actual conductors can be independently evaluated.

Acknowledgments

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