Numerical Analysis of Hysteresis Loss in Stacked REBCO Tapes for Large Current-Carrying Conductors*)

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To evaluate the hysteresis loss in stacked HTS tapes for large current-carrying conductors, a single REBCO tape and 50 stacked REBCO tapes were modeled with the finite element method, including T-A formulation. Using the model, hysteresis losses in the single and stacked tapes were calculated under a condition that the direction of an external varying magnetic field was perpendicular to the tape plane. The calculation results were in good agreement with the measurement results. Consequently, the developed models are valid for a hysteresis loss calculation. In addition, we investigated magnetic field penetration into the stacked tapes using the model. The investigation shows that the external varying magnetic field used in the measurements cannot penetrate the center of the stacked tapes.

Keywords: HTS conductor, REBCO tape, hysteresis loss, modeling, FEM, T-A formulation

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1. Introduction

Various large current-carrying conductors composed of stacked high temperature superconducting (HTS) tapes have recently been proposed for the purpose of realizing a higher magnetic field of fusion magnets [1, 2]. During excitation and discharging processes of the magnets wound with the conductors, there was a concern that large AC losses occur in the magnet due to the usage of stacked HTS tapes in the conductor. To investigate AC losses in the stacked HTS tapes, we have measured them by using a sample composed of 50 REBCO tapes with a width of 6 mm, which was cooled with liquid nitrogen [3]. The REBCO tapes are a currently promising type of HTS tapes [4]. The measurement results show hysteresis and coupling losses in the stacked REBCO tapes under an external maximum magnetic field of approximately 0.1 T. Regarding the measurements, the conditions of external magnetic fields for the sample were limited, due to the performance of the experimental apparatus.

In this study, we investigated the hysteresis loss in the sample under various conditions of external magnetic fields by using an FEM model, simplifying the cross-section of a single and 50 stacked REBCO tapes. The model was developed based on T-A formulation [5]. Additionally, magnetic field penetration into the stacked tapes were investigated using the model when the tapes are subjected to an external varying magnetic field.

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2. Modeling

2.1 Details of the samples

Two samples were used to measure AC loss in REBCO tapes by the pickup coil method [3, 6]. One was the single REBCO tape sample. The other was simply 50 stacked REBCO tapes bundled with the Kapton tapes. The specifications of the REBCO tape and the stacked tape sample are listed in Table 1 and Table 2, respectively.

2.2 FEM models

A hysteresis loss in each sample was calculated using the finite element method (FEM) model based on T-A formulation [5]. The FEM model for the single tape sample

Table 1 Specification of REBCO tape.

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

*s.f: self-field.

Table 2 Specification of the stacked REBCO tape sample.

Number of the tapes	50
Width	6 mm
Thickness	7 mm
Length	96 mm

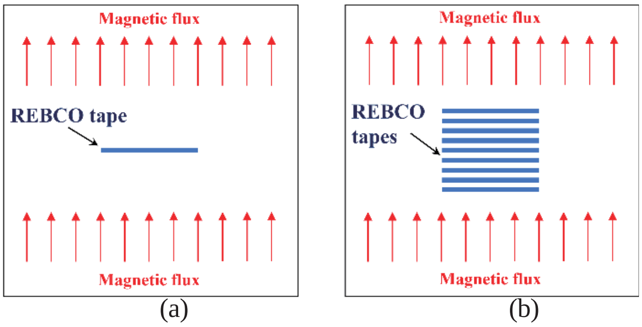

Fig. 1 Schematic view of the models of a single tape (a) and stacked tapes (b).

is composed of an air region and one REBCO tape. And the model for the stacked tape sample is composed of an air region and 50 REBCO tapes, evenly spaced vertically. The schematic view of the models is shown in Fig. 1. In both models, the thickness of the REBCO tape is ignored.

The T-A formulation used in the model is composed of the following equations.

$$\boldsymbol{J} = \nabla \times \boldsymbol{T}, \tag{1}$$

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t}, \tag{2}$$

$$\boldsymbol{B} = \nabla \times \boldsymbol{A}, \tag{3}$$

$$\nabla \times \boldsymbol{H} = \boldsymbol{J}, \tag{4}$$

$$\boldsymbol{E} = E_0 \left(\frac{|\boldsymbol{J}|}{J_c} \right)^{n-1} \frac{\boldsymbol{J}}{J_c}, \tag{5}$$

where $\boldsymbol{J}$ is the current density, $\boldsymbol{T}$ is the current vector potential, $\boldsymbol{E}$ is the electric field, $\boldsymbol{B}$ is the magnetic flux density, $\boldsymbol{A}$ is the magnetic vector potential, $\boldsymbol{H}$ is the magnetic field, J_c is the critical current density, E_0 is the critical electric field, and n is the n-value. In the model, E_0 and n are 1 μV/m and 20, respectively. Eqs. 1 and 2 are governing equations for REBCO tapes, and Eqs. 3 and 4 are the equations for an Air region. With regard to critical current density J_c(B), a modified Kim [7, 8] model was used as follows:

$$J_c(B) = \frac{J_{c0}}{\left(1 + \frac{\sqrt{k^2|B_{\|}|^2 + |B_{\perp}|^2}}{B_0}\right)^{\alpha}}, \tag{6}$$

where $\alpha = 0.7$, $k = 0.3$, $B_0 = 0.04265$ T, $J_{c0} = 3.33 \times 10^9$ A/m^2, $B_{\|}$ and $B_{\perp}$ are parallel and perpendicular components of the magnetic field for REBCO tapes.

Figures 2 and 3 show mesh configurations of the single and stacked tape models, respectively. When making mesh, we made its size around the tape smaller, to investigate electromagnetic phenomena on the inside and surroundings of the REBCO tape. On the other hand, to shorten computation time, the mesh size in the space away from the tape was increased. The calculations were conducted using an FEM software which is COMSOL Multiphysics 6.0 with AC/DC module [9].

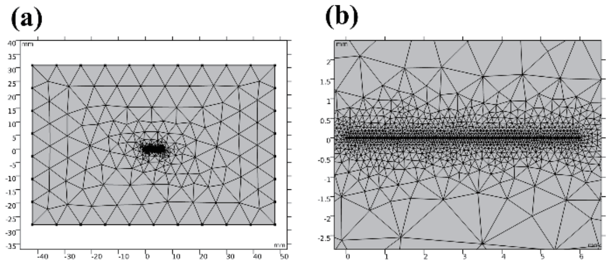

Fig. 2 Mesh configuration of the single tape model. (a) Mesh for the whole model. (b) Mesh for the single tape and its surroundings.

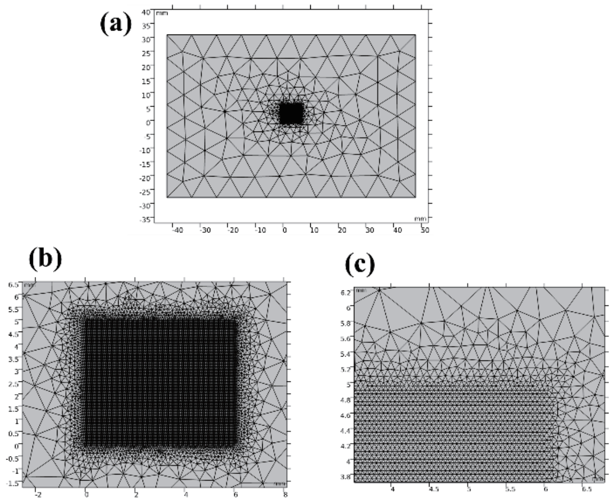

Fig. 3 Mesh configuration of the stacked tape model. (a) Mesh for the whole model. (b) Mesh for the stacked tapes and their surroundings. (c) Mesh at the corner of the stacked tapes.

3. Validation of the Model

Using the models, the hysteresis losses in the two samples were calculated under a condition that the direction of an external varying magnetic field was perpendicular to the tape plane of the samples and the frequency of the field was 3 Hz with a sinusoidal wave. Figure 4 shows the results of the measurement and the calculation regarding the hysteresis loss in the single tape sample. As for the single tape sample, the calculation result almost corresponds with the measurement result.

With respect to the hysteresis loss in the stacked tape sample, the results of the measurement and the calculation are shown in Fig. 5. The calculation is in good agreement with the measurement results. As a result, the models are valid for calculating the hysteresis loss in the two samples.

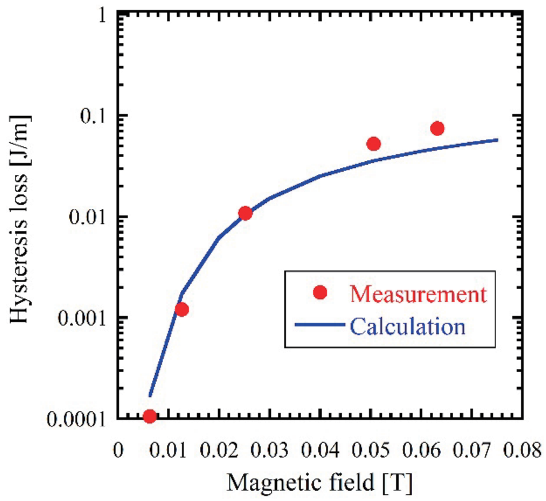

Fig. 4 Comparison between the measurement and the calculation of the hysteresis loss in the single tape sample.

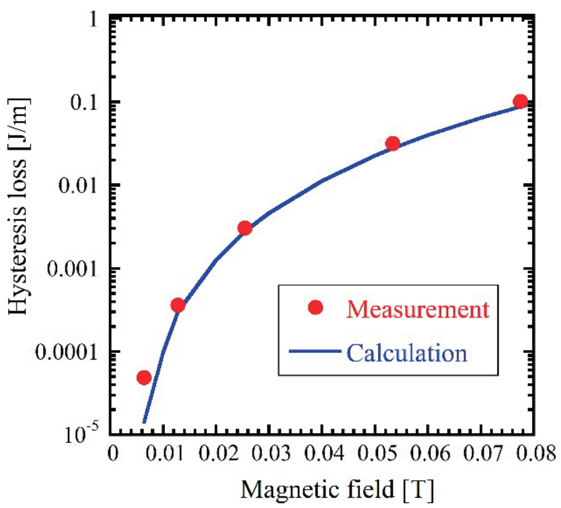

Fig. 5 Comparison between the measurement and the calculation of the hysteresis loss regarding the stacked tape sample.

4. Calculation Results and Discussion

4.1 Hysteresis loss in the stacked tape sample subject to higher magnetic fields than the measurement conditions

In the measurement of the hysteresis loss for the samples, the maximum external magnetic field was approximately 0.08 T, due to the limitation of the experimental apparatus. Therefore, the hysteresis loss in the sample was calculated using a model under the condition that the external magnetic field was much larger than the maximum magnetic field used in the measurement. And the direction, the waveform and the frequency of the external field was the same as the measurement condition. Figure 6 shows the calculation result of the hysteresis loss in the stacked tape sample, subject to the external field. As the external field becomes larger than the maximum magnetic field

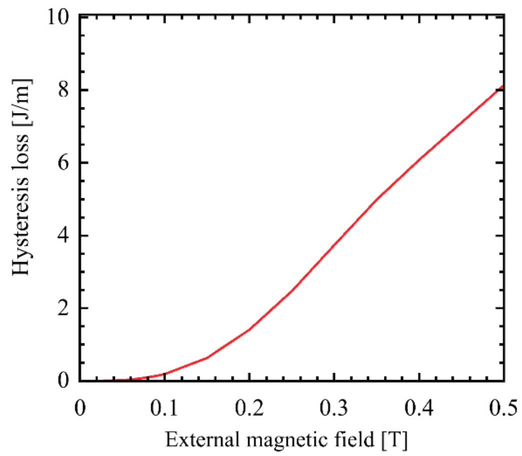

Fig. 6 Calculation result of the hysteresis loss in the stacked REBCO tape sample.

used in the measurement, which is approximately 0.08 T, the hysteresis loss rapidly increases. Besides, the hysteresis loss increases linearly with an external magnetic field from around 0.2 T.

4.2 Magnetic field penetration into the stacked tape sample

As described in Section 4.1, the magnitude of the external magnetic field has an impact on the hysteresis loss in the stacked tape sample. In this section, the magnetic field penetrating into the sample was simulated in order to investigate the effect of external magnetic fields on the inside of the sample. The simulation was conducted based on the calculation condition used in the previous section.

Figure 7 shows magnetic field penetration inside the stacked tape sample subject to each magnitude of the external field, when the phase of a sinusoidal wave is $\pi/2$ rad.

When an external magnetic field is 0.08 T, which is the maximum field in the measurement, it can hardly penetrate inside the stacked tape sample. A magnetic field larger than the applied external field occurs at the side of the sample. In a case where the external field is 0.25 T, the magnetic field penetrates the sample, compared to an applied external field of 0.08 T. However, the magnetic field cannot reach the center of the sample. Under an applied external field of 0.5 T, the magnetic field completely penetrates the sample. Therefore, the calculation results shown in Figs. 6 and 7 indicate that the hysteresis loss in the stacked tape sample increases as the magnetic field penetrates the sample.

4.3 Magnetic field penetration of multiple stacked REBCO tapes for a large current-carrying conductor

As a large current-carrying conductor for fusion magnets, a conductor's cross-sectional shape, in which multiple stacked REBCO tapes were arranged, had been pro-

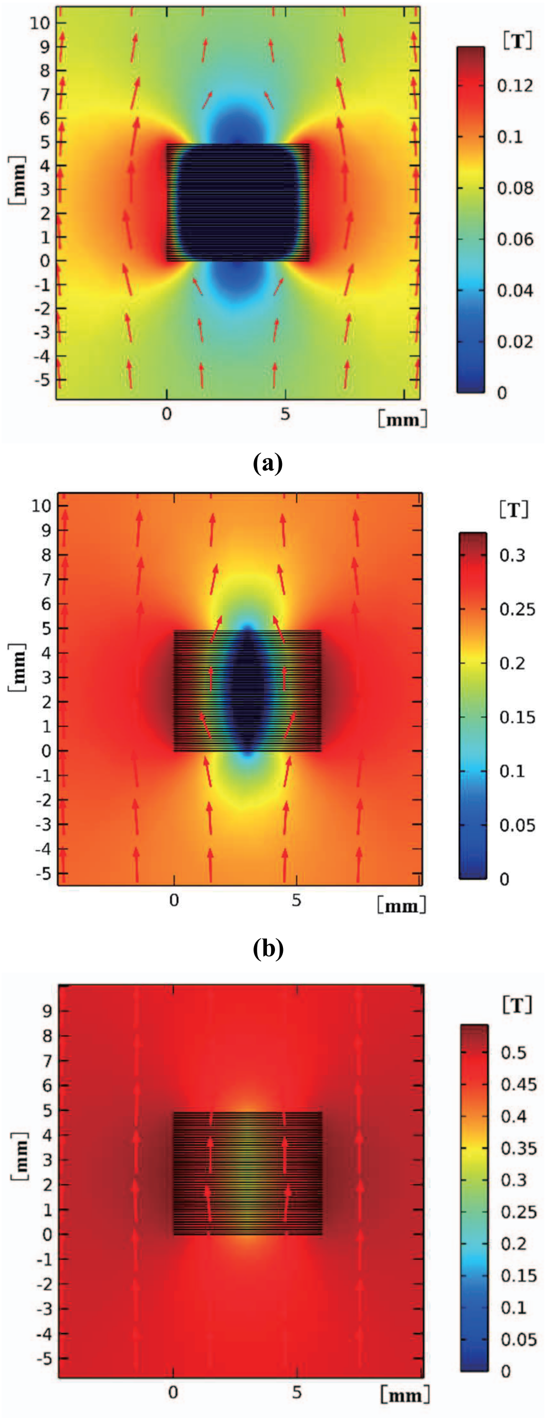

Fig. 7 Magnetic field distributions inside the stacked tape sample under each magnitude of an external field, (a) 0.08 T, (b) 0.25 T, and (c) 0.5 T. In the figures, red arrows show magnetic fluxes.

posed, such as the STARS conductor [2]. When using the conductor, there was concern about electromagnetic coupling between each bundle composed of stacked REBCO tapes. Therefore, we investigated the effect of the stacked tape arrangement on magnetic field penetration into the conductor, by utilizing the simulation described in Sec-

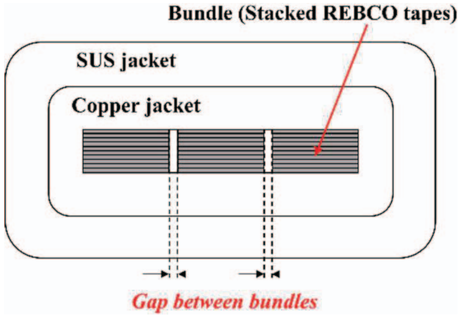

Fig. 8 Schematic view of the cross-section of the STARS conductor which is composed of multiple stacked REBCO tapes.

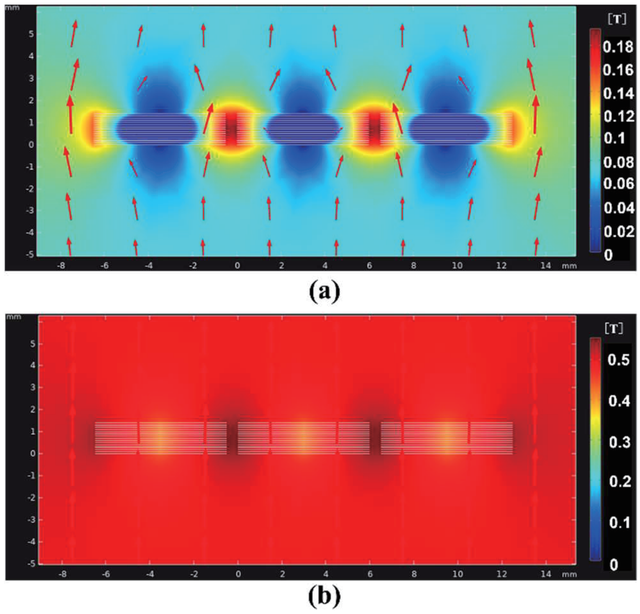

Fig. 9 Magnetic field distributions inside the bundles under each magnitude of an external field, (a) 0.08 T and (b) 0.5 T. In the figures, red arrows show magnetic fluxes.

tion 4.2. Figure 8 illustrates the conductor cross-section composed of multiple stacked REBCO tapes, which was modeled in the simulation. Regarding the model, there were three bundles, each of which consisted of 15 REBCO stacked tapes and the details of the tape are listed Table 1. And the gap between the bundles was 0.5 mm. In the simulation, the direction of an external varying magnetic field was perpendicular to the tape plane of the bundles, and the frequency of the field was 3 Hz with a sinusoidal wave.

Figure 9 shows magnetic field penetration inside the bundles, subject to each magnitude of the external field when the phase of a sinusoidal wave is $\pi/2$ rad. In a case where the applied external magnetic field is 0.08 T, a larger magnetic field is generated between bundles. Regarding the three bundles, the one located in the middle has more field penetration than the others. When an applied field is 0.5 T, on the other hand, there is no difference in the field penetration among the three bundles. The results indicate that electromagnetic coupling effects occur in each bundle at a lower magnetic field.

5. Conclusion

A single REBCO tape and 50 stacked REBCO tapes for a large current-carrying conductor were modeled through the FEM with T-A formulation. Using the models, hysteresis losses in REBCO tapes were calculated. As a result, the calculations were in good agreement with the measurements. The results indicate that the models are valid for hysteresis loss calculation in a single and stacked tapes. In addition, under each magnitude of external magnetic field, their penetration into the stacked tapes was investigated using the model. The magnetic field can hardly penetrate inside the stacked tapes when the external field is 0.08 T, which is the maximum in the measurement. On the other hand, the magnetic field completely penetrates the tapes under an external field of 0.5 T. As a result, the hysteresis losses in the stacked tapes increase as the magnetic field penetrates the tapes.

Moreover, we investigated the effect of a stacked tape arrangement on magnetic field penetration into an HTS conductor. Consequently, electromagnetic coupling effects occur between bundles consisting of stacked REBCO tapes at a lower magnetic field.

Acknowledgments

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