Dependence of transport current losses in coated conductors on magnetic property of substrate

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Abstract. Influence of ferromagnetism of the substrates on transport current losses in HoBaCuO-123 tape-shaped coated conductors with ferromagnetic Ni-alloy substrates was investigated by measuring the losses as a function of an external DC magnetic field. The losses were measured by electric and calorimetric methods simultaneously to prove the validity of the measured data. The experimental results showed significant influence of ferromagnetism of the substrates, when the substrates were not magnetically saturated by an external DC magnetic field. On the other hand, when the substrates were saturated, the loss characteristics were less influenced.

1. Introduction

We measured AC transport current losses in HoBaCuO-123 coated conductors with two different kinds of ferromagnetic textured Ni alloy substrates, as a function of an external DC magnetic field using electric and calorimetric measurement methods. The ferromagnetic substrates are used for cost reduction because the ferromagnetic Ni alloy is well-textured by simple processes. However, the ferromagnetic properties of the substrates may affect the AC loss characteristics. Previously, we measured the losses in the conductors subjected to DC external magnetic fields \( B_{dc} \parallel \) and \( B_{dc} \perp \) to the tape face by an electric method and the following results were obtained [1]. When \( B_{dc} \) was lower than the value to magnetically saturate the substrates \( B_{dc,s} \), ferromagnetic property of the substrate strongly affected the AC transport current losses (\( B_{dc,s} \) is dependent on whether \( B_{dc} \) is parallel or perpendicular). On the other hand, when \( B_{dc} \) exceeds \( B_{dc,s} \) and the substrates were saturated, influence of the substrates on the losses was much reduced. However, there are possibilities that the measurement method itself was affected by the ferromagnetism and that the obtained results were not valid. Therefore, the losses were measured by using electric and calorimetric methods simultaneously to check the validity of the experimental results.

2. Experiment

In the experiment, two kinds of HoBCO coated conductors[2] with strongly and weekly ferromagnetic substrates, samples A and B, were used. The specifications of the conductors are listed in Tab.1.
According to our preliminary measurements of magnetic flux density $B$ vs. magnetic field $H$ characteristics, the substrates used in the samples A and B started to magnetically saturate around $H\sim 100\text{A/m}$ ($B\sim 1.3\text{T}$) and $2500\text{A/m}$ ($B\sim 0.08\text{T}$), respectively. Fig.1 illustrates the sample arrangement for simultaneous measurements of transport current losses by the electric method (a four terminal method using spiral voltage leads and lock-in amplifier [3]) and the calorimetric method developed by S. Ashworth et al.[4]. The whole sample arrangement was immersed in a liquid nitrogen bath which was placed in a bore of a conduction cooling DC superconducting magnet. A transverse DC magnetic field parallel to the wide face of conductor $B_{\text{DC//}}$ was applied by the DC superconducting magnet. The transport current losses were measured changing the magnetic properties of the substrates by changing $B_{\text{DC//}}$.

3. Experimental results and discussions

Dependences of the critical currents $I_c$ of the samples A and B on $B_{\text{DC//}}$ are shown in Fig.2, where $I_c$ is normalized by the critical current at the zero external magnetic field. The transport current losses of the samples A and B measured by electric and calorimetric methods are plotted against the amplitudes of the transport currents $I_{\text{tm}} = 20 \sim 100\%$ of $I_c$ at 60Hz in Fig.3 (a) and (b) for $B_{\text{DC//}} = 0 \sim 0.5\text{T}$, respectively. In Fig.3 (a) and (b), the transport current losses per unit length of the conductor per cycle $Q_t [\text{J/m/cycle}]$ and $I_{\text{tm}}$ are normalized by the conductor critical currents $I_c$ at the applied $B_{\text{DC//}}$ as $q_t = Q_t / I_c^2$ and $i = I_{\text{tm}} / I_c$ and theoretical curves of the Norris strip and elliptical models [5] are also plotted. $Q_t$ could not be measured by the calorimetric method for $B_{\text{DC//}} \geq 0.3\text{T}$ because $I_c$ became low and $Q_t$ became below the lower limit of the sensitivity of the calorimetric method. Therefore, the data for $B_{\text{DC//}} \geq 0.3\text{T}$ were measured only by the electric method. As seen in Fig.3 for $B_{\text{DC//}} \leq 0.2\text{T}$, both of the data measured by the electric and calorimetric methods agreed well with each other. Those results are a proof that the both of the electric and calorimetric methods used in the experiment were valid and

![Figure 1](image1)

**Figure 1.** Sample arrangement to measure the AC losses by electric and calorimetric method.

![Figure 2](image2)

**Figure 2.** Dependences of critical currents $I_c$ of the samples A and B on $B_{\text{DC//}}$.

| Table 1. Specifications of HoBCO conductors used in the experiment |
|---------------------------------------------------------------|
| **Sample A** | **Sample B** |
| **Superconductor layer** | | |
| Thickness/width | $0.37\mu\text{m}/0.8\text{mm}$ | $0.37\mu\text{m}/0.8\text{mm}$ |
| $I_c$ at 77K, 0T | 29.3A | 58.6A |
| $n$ value at 0T | 20.4 | 25.1 |
| **Substrate** | | |
| Magnetic property | ferromagnetic | weakly ferromagnetic |
| Thickness/width | $100\mu\text{m}/10\text{mm}$ | $100\mu\text{m}/10\text{mm}$ |
| Material | Ni-Fe alloy | Ni alloy |
| Saturation magnetic flux density $B$ | $B\sim 1.3\text{T}$ at $H\sim 1\times 10^3\text{A/m}$ | $B\sim 0.08\text{T}$ at $H\sim 2.5\times 10^3\text{A/m}$ |
that the data in Fig.3 were valid. As seen in Fig.3 $q_t$ is strongly dependent on $B_{DC//}$. Obviously from Fig.3 (a) and (b) $q_t$ decreases in the whole range of $i = 0.2 \sim 1$ as $B_{DC//}$ increases from 0T and falls to the same curve for $B_{DC//} > 0.1T$. $q_t$ is getting close to the Norris curve of the elliptical model as $i$ is close to 1 where $B_{DC//}$ exceeds 0.1T. However, $q_t$ vs. $i$ curves are, as a whole, apart from the Norris curves of both the elliptical and strip models including the case that $B_{DC//}$ exceeds 0.1T. Those results can be explained as follows. When $B_{DC//}$ is smaller than 0.1T, the substrates are not magnetically saturated and values of $\mu_{sd}$ in the saturated region become small to be loss 1. Therefore, $B_m$ and the losses in the substrates become small, so that the losses in the superconductor layer dominate the total losses. Influence of ferromagnetic properties on the losses is diminished. Thus, curves of the losses in the superconductor layers $q_t$ vs. $i$ fall to the same curve regard less of $I_c$ when the substrates are non-magnetic [6]. It is supposed that $q_t$ vs. $i$ curves should be close to the Norris analytical models in the case that the ferromagnetism of the substrates disappears. However, there are still discrepancies between measured data and the Norris analytical curves even in the case that substrates are magnetically saturated, as seen in Fig.4 where $q_t$ vs. $i$ curves are shown only for $B_{DC//} = 0.1 \sim 0.3T$. An example of $q_t$ vs. $i$ of an YBCO conductor with non magnetic Hastelloy substrate ($I_c = 51.7A$, 1cm wide) measured at $B_{DC//} = 0T$ [7] are also shown in Fig.4 for the comparison. The discrepancies are much larger for the HoBCO than those for the YBCO. Those discrepancies can be explained to be due to non-uniform critical current density distribution in the cross section superconductor layer [6]. When the HoBCO conductors used in the experiment were made, both of the tape edge areas 1mm from the edges of the substrates were covered by fixtures to fix the substrates in the process to develop superconductor layers. Therefore, the critical current densities in the tape edge areas were much lower than those in the tape center areas. $q_t$ vs. $i$ curves were calculated for the sample A and B by use of the method described in the reference [7] assuming the critical current density per unit width $\sigma_c$ [A/m] distributed as shown in Fig.4 and compared with the measured data. As seen in Fig.4 the calculated curve well fits to the measured data. Discrepancies of the YBCO data were also explained by non uniform $\sigma_c$ distribution [6]. Therefore, the discrepancies between the measured data and the Norris curves can be explained by the non uniform $\sigma_c$ in the cross section of the HoBCO layer. These results suggest that the difference of loss characteristics of HoBCO conductors with magnetically saturated substrates and
YBCO conductors can be explained by the difference of $\sigma_c$ distributions and not by difference of superconductive materials.

4. Concluding remarks

The following conclusions were obtained in this study:

· The simultaneous measurements by electric and calorimetric methods proved the validity of the measured AC transport current losses in HoBCO conductors with ferromagnetic substrates. The loss characteristics were different from those of YBCO conductors with non-magnetic Hastelloy substrates [6].

· In both cases of the HoBCO samples A and B, hysteresis losses in the substrates were larger than the losses in the superconductor layers and increased the total transport current losses, when the substrates were not saturated by the external DC magnetic field. On the other hand, when the substrates were saturated, the ferromagnetic properties of the substrates were diminished and the losses in the superconducting layer dominated the total losses.

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