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Total AC loss in Bi2223/Ag tape carrying AC transport current in external AC magnetic field of various directions

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Abstract

Total AC loss characteristics of a high temperature superconducting tape carrying AC transport current in external AC magnetic field with various applied directions to tape surface was experimentally investigated. We measured the AC transport current loss and the AC magnetization loss in the Bi2223/Ag-seath tape carrying the AC transport current in AC magnetic field by changing the angle to the tape surface and obtained the total AC loss as the sum of these losses. Based on the measured data, the dependence of the AC losses on the direction of the external AC magnetic field was discussed.

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Keywords: AC transport current loss; AC magnetization loss; Total AC loss

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1. Introduction

High temperature superconducting (HTS) tapes are expected to be applied for the electric power apparatuses such as power transmission cables, fault current limiters and transformers. Reduction of AC losses in HTS tapes is one of the important technical issues of the development for these HTS applications. In these electrical apparatuses, the HTS tapes are carrying the AC transport current and exposed to the external magnetic field of various directions to the tape. For the development of low AC loss HTS tapes, it is necessary to precisely evaluate the total AC loss characteristics of the HTS tapes in this electromagnetic condition. The pick-up coil method and the four terminal method are commonly used for the AC magnetization loss measurement and the AC transport current loss measurement, respectively. In our previous study, we have theoretically and experimentally investigated the applicability of the method that combines these two methods for the total AC loss measurement carrying the AC transport current in the AC magnetic field and its validity has been confirmed [1–3].

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In this study, we experimentally study the characteristics of the total AC losses in the HTS tape carrying the AC transport current in the external AC magnetic field with various directions. The AC transport current losses and the magnetization losses in a conventional Bi2223/Ag tape carrying the AC transport current in the external AC magnetic field of various directions to the tape surface were measured. In this paper, the details of the experimental setup are described and the measurement results are presented. The characteristics of the total AC losses in the HTS tape carrying the AC transport current in the external AC magnetic field are discussed in terms of their dependence on the applied direction of the external AC magnetic field.

2. Experimental

Table 1 lists the specifications of the sample tape used in the AC loss measurement. The arrangement of the test sample and the measurement circuit for the loss measurement are shown in Fig. 1. The test sample was placed in the gap of the copper dipole magnet. The sample tape can rotate in the magnet bore to change the applied angle θ of the external magnetic field as shown in Fig. 1.

The AC transport current loss was measured by the general four terminal method using lock-in amplifier. A proper arrangement of the potential lead loop is necessary to precisely measure the AC transport current loss in the external AC magnetic field [4]. In this potential lead loop arrangement, the two lead wires were spirally wound on a cylindrical thin tube surrounding the tape. With the spiral lead loop, the inductive voltage caused by the AC transport current and the external magnetic field can be much suppressed. By measuring the voltage across the potential contacts in-phase with the AC transport current V_s^{rms}, the AC transport current loss Q_s (J/m) was obtained by,

$$Q_s = \frac{V_s^{rms} \cdot I_t^{rms}}{f \cdot L_v}, \tag{1}$$

where I_t^{rms} is the root-mean-square of the AC transport current, L_v is the length between the potential contacts and f is the frequency.

Table 1
Specifications of sample tape

Superconductor/sheath	Bi2223/Ag
Width of tape	3.655 mm
Thickness of tape	0.263 mm
Width of filamentary region	3.462 mm
Thickness of filamentary region	0.194 mm

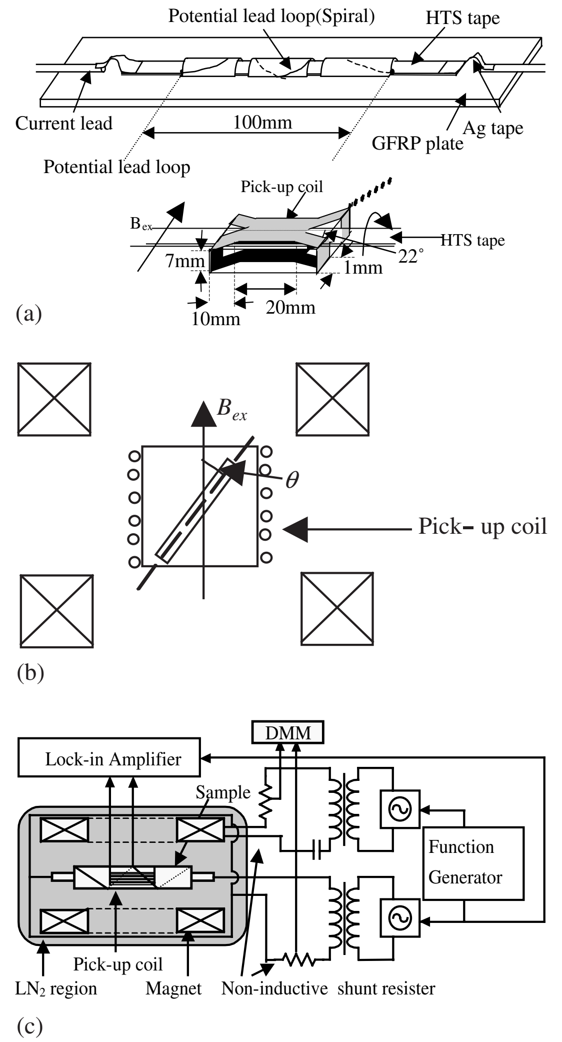

Fig. 1. Schematic illustration of measurement circuit and test sample: (a) sample, (b) arrangement of sample tape and pick-up coil, and (c) measurement circuit.

The AC magnetization loss was measured by the pick-up coil method. A saddle shape pick-up coil was wound on the sample tape in the measurement section as shown in Fig. 1. The dimension of the pick-up coil shown in Fig. 1 is designed based on the theory presented in [5]. The AC magnetization loss Q_{m} (J/m) was obtained by,

$$Q_{\mathrm{m}} = \frac{V_{\mathrm{pc}}^{\mathrm{rms}} \cdot B_{\mathrm{ex}}^{\mathrm{rms}} \cdot h}{f \cdot N_{\mathrm{pc}} \cdot \mu_0 \cdot L_{\mathrm{s}}}, \tag{2}$$

where $V_{\mathrm{pc}}^{\mathrm{rms}}$ is the pick-up coil voltage in-phase with the external AC magnetic field, $B_{\mathrm{ex}}^{\mathrm{rms}}$ is the root-mean-square of the external AC magnetic field B_{ex}, L_{s} is the length of the sample tape inside the pick-up coil. N_{pc} and h is the number of turns and the height of the pickup coil respectively. μ_0 is the permeability of vacuum.

3. Results and discussion

3.1. AC magnetization loss

The AC magnetization losses in the sample tape carrying the AC transport current for $\theta = 0°$, 15°, 45° and 90° are shown in Fig. 2. In Fig. 2(a), the theoretical hysteresis loss of the slab superconductor [6] of 0.194 mm thick by the critical state model for $\theta = 0°$ is also shown. The dased line in Fig. 2(d) represents the theoretical AC magnetization loss in a superconductor strip subjected to an external magnetic field applied perpendicular to tape surface which is expressed as [7],

$$Q_{\mathrm{m},\perp} = k\frac{4\pi a^2 B_{\mathrm{ex}}^2}{\mu_0} \cdot \frac{1}{b_{\mathrm{ex}}}\left[\frac{2}{b_{\mathrm{ex}}}\ln\cosh(b_{\mathrm{ex}}) - \tanh(b_{\mathrm{m}})\right], \tag{3}$$

where a is the width of the strip and $b_{\mathrm{ex}} = B_{\mathrm{ex}}/B_{\mathrm{c}}$; B_{c} is the characteristic field given by $B_{\mathrm{c}} = \mu_0 I_{\mathrm{c}}/2\pi a$; I_{c} is the critical current; k is the geometrical factor. The data reasonably agrees with the theoretical curves when the transport current is small and $B_{\mathrm{ex}} > 10\ \mathrm{mT_{peak}}$ as shown in Fig. 2(a) ($\theta = 0°$) and (d) ($\theta = 90°$). As shown in Fig. 2(a), the measured magnetization loss deviates from the theoretical hysteresis loss when $B_{\mathrm{ex}} < 10\ \mathrm{mT_{peak}}$. One of the possible reason of the discrepancy between the measured and calculated losses shown in Fig. 2(a) ($\theta = 0°$) has been discussed in [2]. In the low field region, the magnetization loss increases with increasing $I_{\mathrm{tp}}/I_{\mathrm{c}}$ (I_{tp} is the peak value of the AC transport current) and deviates from the theoretical value obtained by (3). The measured data shown in Fig. 2(a)–(d) also shows that the magnetization losses rapidly increase as the applied angle increase from 0° to 45° and they keep almost constant for $\theta = 45°$–90°. It should be also noted that the analytical expression of the magnetization losses for $\theta = 15°$ and 45° does not exist and the numerical analysis is necessary to obtain them.

3.2. AC transport current loss

Fig. 3 shows the measured AC transport current losses in the external AC magnetic field in

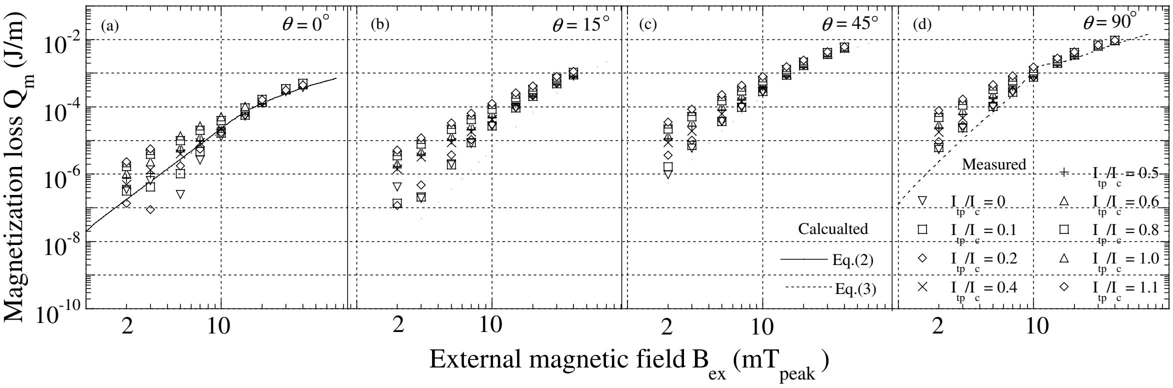

Fig. 2. Measured AC magnetization loss as a function of external magnetic field.

terms of loss normalized by I_c^2 at 60 Hz. The horizontal axis indicates the peak transport current normalized by I_c. In Fig. 3, the theoretical values of the self-field losses calculated by the Norris' formula [8] are also shown. It is shown in Fig. 3 that the slopes of the measured transport loss data in the logarithmic scale change from about 3 to 2 as B_{ex} increases. It is also shown in Fig. 3 that the normalized transport current losses sharply increase as the field applied angle is increasing from 0° to 45° and they saturate for $\theta = 45°–90°$ as similar to the magnetization loss characteristics presented above.

3.3. Total AC loss carrying AC transport current in AC magnetic field

The total AC loss Q_{total} in the sample tape carrying the AC transport current in the AC magnetic field are plotted in Fig. 4(a) as a function of the applied angle of the external magnetic field. The measured Q_{total} was obtained by the summation of the measured Q_s and Q_m. The curves shown in Fig. 4(b) are obtained by the following way based on the discussion presented in [9,10]. According to the fact that the total AC loss in a slab superconductor depends on B_{ex}^{α} (practically $\alpha \cong 1–3$), by assuming that the contributions of the parallel magnetic field ($B_{ex}\cos\theta$) and the perpendicular field ($B_{ex}\sin\theta$) are independent, the dependence of the total AC loss on the applied angle is approximately expressed as,

$$Q_{total} = Q_{total}(B_{ex}, \theta = 0°) \cdot \cos^{\alpha}\theta + Q_{total}(B_{ex}, \theta = 90°) \cdot \sin^{\alpha}\theta. \qquad (4)$$

By properly selecting the value of α depending on B_{ex} as indicated in Fig. 4(b), the curves calculated by (4) are well fitted to the measured data. It is found that α decreases as increasing B_{ex} and the obtained value of α to fit the measured data shown in Fig. 4(a) is well expressed by the following expression:

$$\alpha = A_1 \exp(-A_2 \cdot B_{ex}), \qquad (5)$$

where $A_1 = 3.10$ and $A_2 = 11.07$ for the measured data shown in Fig. 4(b). By assuming the relation between α as (5), with the limited number of measured data changing B_{ex} and θ, the total AC losses can be reasonably predicted in the wide range of B_{ex} and θ. At present, the theoretical basis of this fitting method is still not sufficient. However, this is practically useful.

4. Concluding remarks

We experimentally studied the characteristics of the total AC loss in the Bi2223/Ag-sheath tape carrying the AC transport current subjected to the external AC magnetic field with various

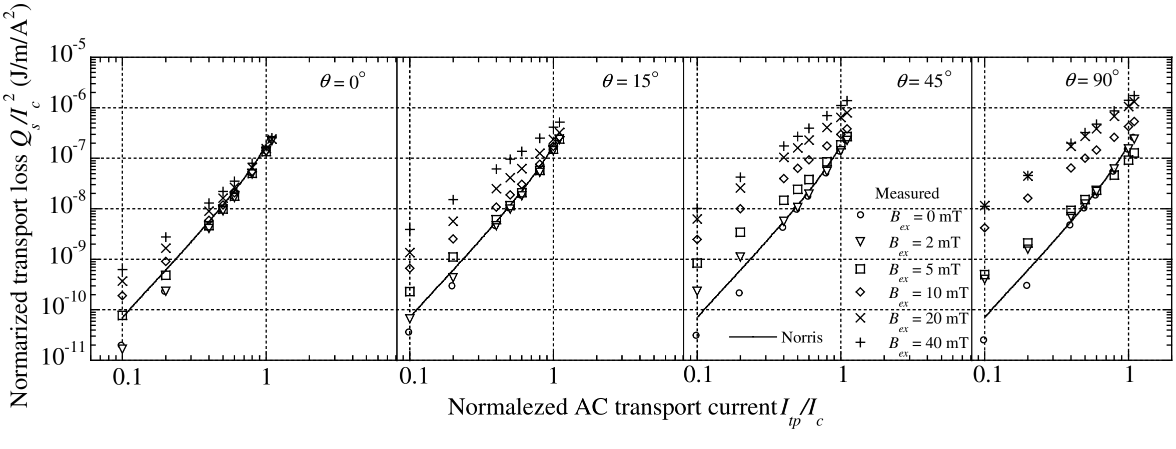

Fig. 3. Measured normalized AC transport current loss as a function of normalized transport current.

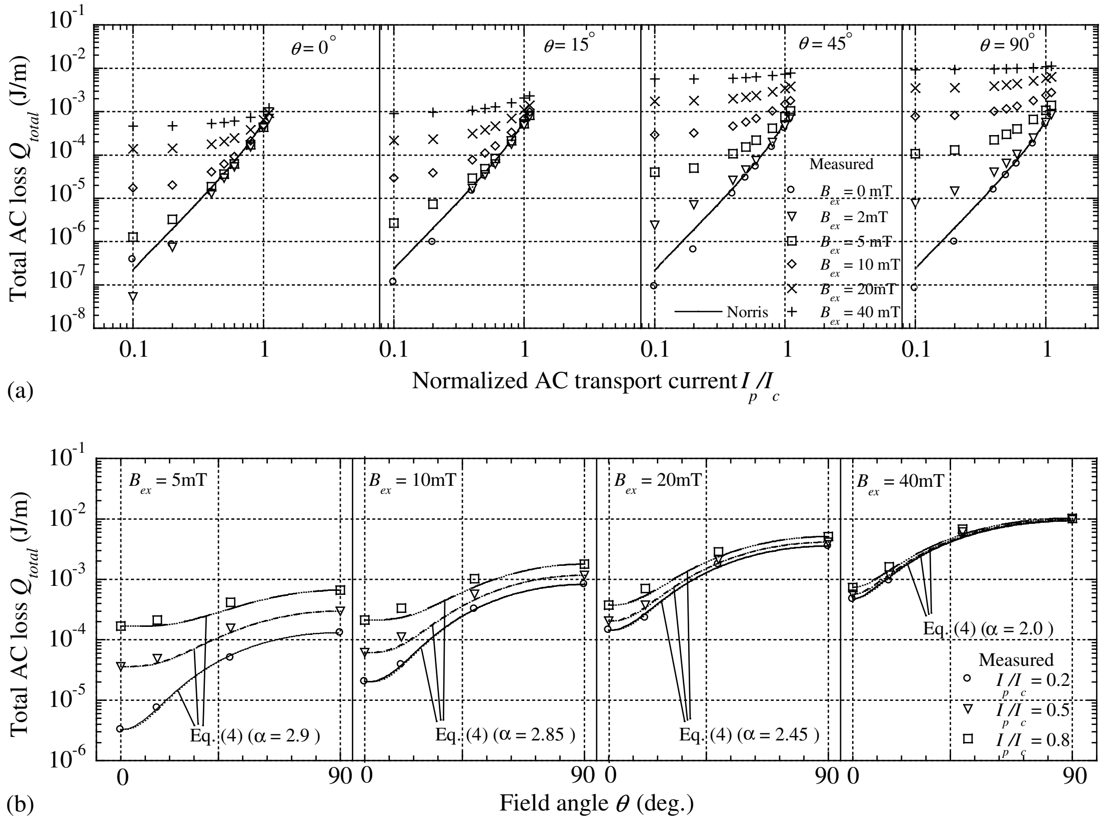

Fig. 4. Measured total AC loss: (a) total AC loss vs. I_{tp}/I_c and (b) total AC loss vs. θ.

applied directions. The magnetization and transport current loss measurements were conducted for the various applied angles of the external magnetic field to the tape surface. The measured dependence of the total AC loss on the applied angle were explained by the expression given in [9,10].

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References

[1] H. Tonsho, S. Fukui, T. Sato, M. Yamaguchi, S. Torii, T. Takao, K. Ueda, IEEE Trans. Magn. 3 (2) (2003) 2368.
[2] H. Tonsho, S. Fkui, H. Nakayama, M. Yamaguchi, S. Torii, K. Ueda, T. Takao, Physica C 392–396 (2003) 224.
[3] S. Fukui, M. Ikeda, T. Sano, H. Sango, M. Yamaguchi, T. Takao, IEEE Trans. Appl. Supercond. 11 (1) (2001) 2212.
[4] S. Fukui, Y. Kitoh, T. Numata, O. Tsukamoto, Adv. Cryog. Eng. 44 (1998) 723.
[5] M. Iwakuma, M. Nanri, M. Fukui, Y. Fukuda, K. Kajikawa, K. Funaki, Supercond. Sci. Techol. 16 (5) (2003) 545.
[6] M.N. Wilson, Superconducting Magnets, Oxford University Press, New York, 1983.
[7] E.H. Brandt, M. Indenbom, Phys. Rev. B 48 (1993) 12893.
[8] W.T. Norris, J. Phys. D 3 (1970) 489.
[9] M.P. Oomen et al., Appl. Phys. Lett. 70 (1997) 3038.
[10] J.J. Rabbers et al., Inst. Phys. Conf. Ser. 167 (2000) 859.