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A Review on AC Loss Characteristics of High T_c Superconductors

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***Abstract*-- This paper reviews AC loss characteristics of high T_c superconductors. The mechanisms of AC loss generation are explained briefly, and AC losses are classified by the magnetic field components which generate them. A couple of analytical formulae of AC losses, which are useful for simple and rough AC loss estimations, are presented. AC loss characteristics of single BSCCO multifilamentary conductors and single YBCO coated conductors are reviewed based on previous experimental and numerical studies. AC loss characteristics of those two types of practical high T_c superconductors are compared with each other.**

1. INTRODUCTION

AC loss reduction is one of the critical issues for realization of electrical power devices using high T_c superconductors, because AC losses deteriorate the novel advantage of superconductors, which can carry electrical current without any power dissipations.

In this review paper, first, the authors explain briefly the mechanisms of AC loss generations. Then, AC losses are classified by the magnetic field components which generate AC losses. This classification is very important, because we must use different approaches for reductions of AC losses generated by different kinds of magnetic field components. A couple of analytical formulae of AC losses, which are useful for simple and rough AC loss estimations, are presented. Based on previous experimental and numerical studies, AC loss characteristics of BSCCO multifilamentary conductors, which are currently available in an industrial production scale, as well as those of YBCO coated conductors, which are expected to the second generation high T_c superconductors, are reviewed, and they are compared with each other.

2. MECHANISMS OF AC LOSS GENERATIONS

AC losses in superconductors can be classified into hysteresis loss, coupling loss, and eddy current loss based on the electromagnetic mechanism of their generation.

(1) Hysteresis loss

We consider a type II superconductor, which carries a transport current, or in which a shielding current against the external magnetic field is induced. In this type II superconductor, a magnetic flux penetrates as flux lines: at a steady or at a quasi-steady state, Lorentz force acting to a flux line is balanced with a pinning force. When the current (magnetic flux) distribution changes, the Lorentz force moves flux lines against the pinning force. The hysteresis (or hysteretic) loss is the energy dissipated in this process.

(2) Coupling loss

As shown later, the hysteresis loss due to the transverse magnetic field can be reduced by subdividing a superconductor into fine filaments and connecting them in parallel with some transverse resistance. This type of conductors is called multifilamentary conductor. When a multifilametary conductor is exposed to an AC transverse magnetic field, shielding current can flow in a loop comprising superconductor filaments and transverse normal resistances between filaments. This shielding current is called coupling current. The coupling loss is the Joule heat generation at the transverse normal resistance.

(3) Eddy current loss

If the path of the shielding current is confined into normal metal only, the Joule heat generation by this shield current is called the eddy current loss.

In commercially-available BSCCO multifilamentary conductors, filaments are connected by superconducting interconnections, and they practically behave as monofilament conductors electromagnetically. Usual YBCO coated conductors comprising monolithic YBCO layer and normal metals. In both the usual BSCCO multifilamentary conductors and the usual monolithic YBCO coated conductors, practically no coupling losses are generated, and the eddy current loss is negligible.

3. CLASSFICATIONS OF AC LOSSES BY MAGNETIC FIELD COMPONENTS GENERATING THEM

AC losses are generated by AC magnetic fields. Therefore, they can be classified by magnetic field components generating them.

Magnetic fields to which a superconductor is exposed can be classified primarily to the self magnetic field generated by its own transport current and the external magnetic fields. The self magnetic field surrounds the superconductor mostly-azimuthally. The external magnetic fields can be classified by their direction as shown in Fig. 1:

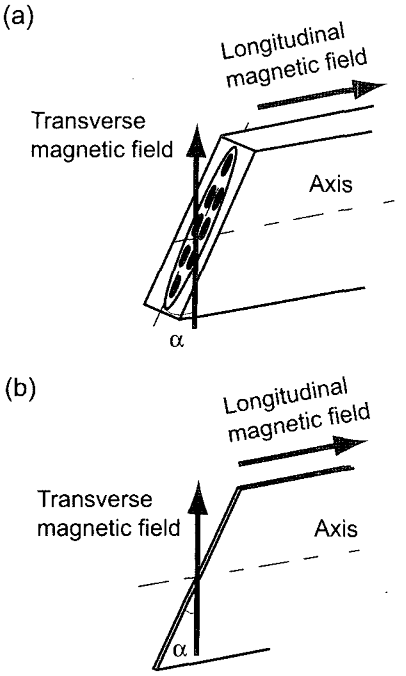

Fig. 1. Classification of external magnetic field: (a) in BSCCO multifilamentary tape, (b) in YBCO coated conductor.

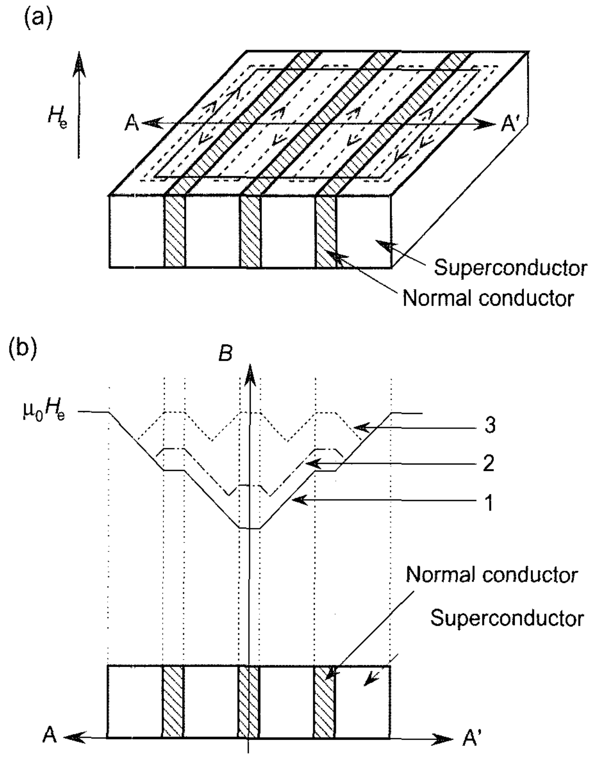

Fig. 2. Model of composite high T_c superconductors: (a) sandwich structure of superconductor and normal conductor, (b) magnetic flux distribution.

transverse and longitudinal magnetic field. In case of tape conductors as BSCCO multifilamentary conductors or YBCO coated conductors, the typical transverse magnetic fields are parallel and perpendicular transverse magnetic fields that are parallel and perpendicular to the conductor wide-face, respectively. Generally, tape conductors are exposed to a transverse magnetic field with arbitrary field angle α which is the angle between the transverse magnetic field and the wide face of the conductor as shown in Fig. 1.

Based on the magnetic field components classified above, AC losses can be classified as follows.

(1) Magnetization loss

The loss in superconductors due to an external AC magnetic field is referred to as magnetization loss. The nature of the magnetization loss is the hysteresis loss, the coupling loss, and the eddy current loss.

Here, we show the details of magnetization loss of a composite conductor such as BSCCO multifilamentary conductor in an AC transverse magnetic field. We consider a sandwich structure to investigate its electromagnetic behavior. The sandwich structure consists of superconductors (corresponding to superconducting filaments) and normal conductors (corresponding to the matrix), as shown in Fig. 2 [1]. When an AC transverse magnetic field is applied to the sandwich structure, a shielding current is induced to shield the interior from the magnetic field. The shielding current first flows across the normal conductor along a big loop, denoted by the solid line as illustrated in Fig. 2(a). This current is the coupling current. The coupling current decays because of the resistance of the normal conductor, and the decay of the current accompanies sequential changes in the magnetic field distribution in the sandwich structure (1, 2, and 3) as shown in Fig. 2(b). The time constant of the decay is referred to as the coupling time constant τ_c which is determined by the magnitude of the transverse resistance and the inductance of the coupling current path. If τ_c is smaller than the characteristic time of the change in the external magnetic field, the magnetic field distribution denoted with 3 appears (decoupled state): the magnetic flux penetrates from the edges of each filament rather than from the edges of the entire conductor to reduce the hysteresis loss at the decoupled state.

(2) Transport loss

The loss in superconductors, carrying an AC transport current, due to self magnetic field is referred to as transport loss. In fact, the transport loss can be considered as a hysteresis loss due to the self magnetic field.

(3) Total loss

In practical electrical devices, a superconductor must carry an AC transport current in an AC external magnetic field. The loss in the superconductor due to both external and self magnetic fields is referred to as total loss.

4. ANALYTICAL FORMULAE OF AC LOSSES

Analytical formulae are convenient for simple and rough estimations of AC losses, because they are easy to use. Here, we present a useful set of analytical formulae for hysteresis losses.

(1) Magnetization loss in superconductor slab exposed to AC magnetic field parallel to its faces

We consider an infinite large superconductor slab, as shown in Fig. 3, with a thickness of t, in an AC external magnetic field parallel to both sides of the slab with amplitude of H_e. According to the Bean model and the Maxwell equations, the hysteresis loss in the slab with constant critical current density J_c can be given as follows [1],

$$Q_{\mathrm{h,slab}} = \frac{4\mu_0}{3}\frac{H_e^3}{J_c t}, \qquad H_e < \frac{J_c t}{2}, \tag{1}$$

$$Q_{\mathrm{h,slab}} = t\mu_0 J_c\left(H_e - \frac{J_c t}{3}\right), \qquad H_e > \frac{J_c t}{2}, \tag{2}$$

where $Q_{\mathrm{h,\,slab}}$ is the hysteretic magnetization loss per unit volume of the slab per cycle. A large magnetic field region where $H_e > J_c t/2$ is practically important, and we find from (2) that the hysteresis loss per unit volume has reduced in proportion to the thickness of the slab. This is the reason for AC loss reduction by multifilamentary architecture.

These formulae are often used for tape conductors exposed to parallel transverse magnetic field.

(2) Magnetization loss in superconductor strip exposed to AC magnetic field perpendicular to its face

We consider an infinite thin superconductor strip, as shown in Fig. 4 with a width of w in an AC magnetic field perpendicular to the strip with amplitude of H_e. The hysteresis loss in the strip with critical current I_c is given by Brandt and Indembem based on the Bean model [2],

$$Q_{\mathrm{h,strip}} = \mu_0 w I_c H_e \cdot g\left(\frac{H_e}{H_c}\right) \tag{3}$$

where $Q_{\mathrm{h,\,strip}}$ is the hysteretic magnetization loss per unit length of the strip per cycle, w is the conductor width, H_c is $I_c/w\pi$, and $g(x)$ is the function given by (4).

$$g(x) = (2/x)\ln\cosh x - \tanh x\,. \tag{4}$$

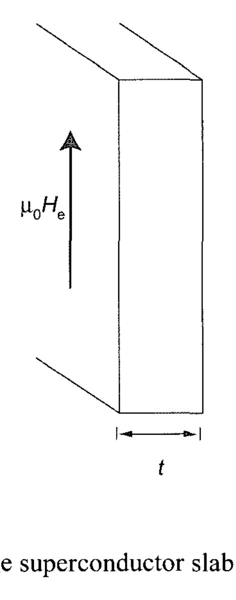

Fig. 3. Infinite large superconductor slab.

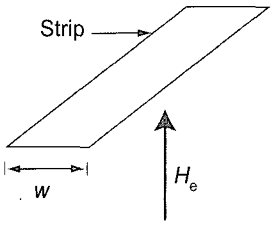

Fig. 4. Infinite thin superconductor strip.

(3) is often used for coated conductors exposed to an AC transverse magnetic field. In this case, the perpendicular magnetic field component $H_m \sin\alpha$ (H_m: field amplitude) is used as H_e in (3).

(3) Transport loss in superconductor with elliptical cross-section carrying AC transport current

The transport loss in superconductor with elliptical cross-section carrying AC transport current is given by Norris based on Bean's critical state model [3],

$$Q_{\mathrm{t,\,N\text{-}e}} = \frac{I_c^2\mu_0}{\pi}\cdot\left\{\left(1-\frac{I_t}{I_c}\right)\ln\left(1-\frac{I_t}{I_c}\right)+\left(2-\frac{I_t}{I_c}\right)\left(\frac{1}{2}\cdot\frac{I_t}{I_c}\right)\right\}, \tag{5}$$

where $Q_{\mathrm{t,\,N\text{-}e}}$ is the hysteretic transport loss per unit length of the conductor per cycle, I_c is the critical current, and I_t is the amplitude of the transport current, respectively.

This formula is often used for the transport loss in a BSCCO multifilamentary conductor.

(4) Transport loss in superconductor strip carrying AC transport current

The transport loss in superconductor strip carrying AC transport current is also given by Norris based on Bean's critical state model [3],

$$Q_{\mathrm{t,\,N\text{-}s}} = \frac{I_c^2\mu_0}{\pi}\cdot\left\{\left(1-\frac{I_t}{I_c}\right)\ln\left(1-\frac{I_t}{I_c}\right)+\left(1+\frac{I_t}{I_c}\right)\ln\left(1+\frac{I_t}{I_c}\right)-\left(\frac{I_t}{I_c}\right)^2\right\}, \tag{6}$$

where $Q_{\mathrm{t,\,N\text{-}s}}$ is the hysteretic transport loss per unit length of the conductor per cycle, I_c is the critical current, and I_t is the amplitude of the transport current, respectively.

This formula is often used for the transport loss in an YBCO coated conductor.

(5) Total loss in superconductor slab carrying AC transport current and exposed to AC magnetic field parallel to its faces

The total loss in an infinitely large slab of superconductor with constant critical current density J_c in a parallel transverse magnetic field with amplitude B_m fed with a transport current with amplitude I_t is given by Carr [4-5],

$$Q_{\mathrm{total,\,Carr}} = \frac{2B_p^{\,2}}{3\mu_0}(i^3 + 3\chi^2 i) \qquad \text{for } \chi < i, \tag{7}$$

$$Q_{\mathrm{total,\,Carr}} = \frac{2B_p^{\,2}}{3\mu_0}(\chi^3 + 3\chi i^2) \qquad \text{for } i < \chi < 1, \tag{8}$$

$$Q_{\mathrm{total,\,Carr}} = \frac{2B_p^{\,2}}{3\mu_0}\left(\chi(3+i^2) - 2(1-i^3) + 6i^2\frac{(1-i)^2}{(\chi-i)} - 4i^2\frac{(1-i)^3}{(\chi-i)^2}\right) \qquad \text{for } \chi > 1, \tag{9}$$

where $Q_{\mathrm{total,\,Carr}}$ is the hysteretic total loss per unit volume of the slab per cycle, $B_p = \mu_0 J_c t/2$ is the penetration field of a slab with thickness of t, $\chi = B_m/B_p$, and $i = I_t/I_c$, respectively.

5. AC LOSS CHARACTERISTICS OF BSCCO MULTIFILAMENTARY CONDUCTORS [6-10]

5.1. Magnetization loss without transport current

There were lots of reports on the magnetization loss in not-twisted BSCCO multifilamentary conductors without transport current. The magnetization loss in the parallel AC magnetic field almost equals the analytical value given by (1) and (2) as shown in Fig. 5. The magnetization loss is much larger in the perpendicular AC magnetic field than in the parallel AC magnetic field. That in the perpendicular magnetic field almost agrees with the analytical value given by ten Haken and Rabbers as shown in Fig. 6 [6]. The limited effect of twisting to reduce the magnetization loss was also reported.

5.2. Transport loss without external magnetic field

There were also many reports on the transport loss in BSCCO multifilamentary conductors without any external magnetic field. The transport loss almost agrees with the analytical value given by (5) as shown in Fig. 7.

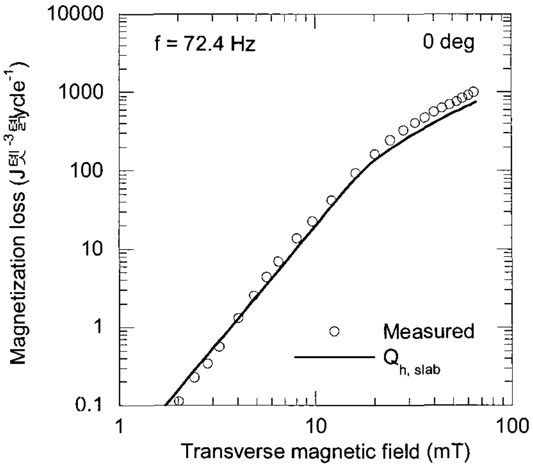

Fig. 5. Magnetization loss of BSCCO multifilamentary conductor in parallel magnetic field.

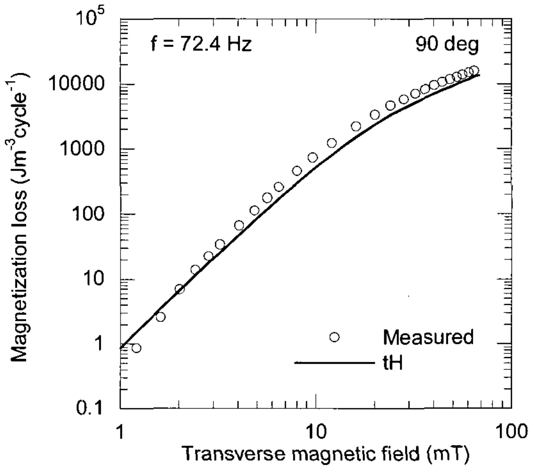

Fig. 6. Magnetization loss of BSCCO multifilamentary conductor in perpendicular magnetic field.

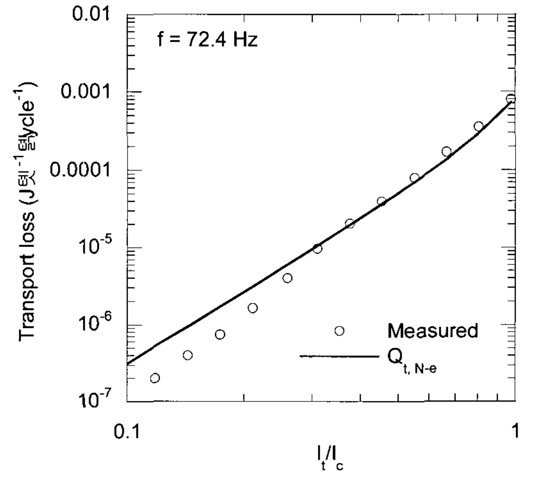

Fig. 7. Transport loss of BSCCO multifilamentary conductor without any external magnetic field.

5.3. Total loss

In Fig. 8, the measured total losses in a BSCCO multifilamentary conductor carrying AC transport current in the AC parallel magnetic field are plotted against the amplitude of the AC parallel magnetic field. In this figure, the numerically calculated total loss and the analytical value given by (7), (8), and (9) are also plotted. The measured total loss almost agrees with the numerically-calculated total loss. The measured value deviates from the analytical value at the small external magnetic field region, because the analytical model neglects the large loss generation due to the self magnetic field at the edge of the conductor.

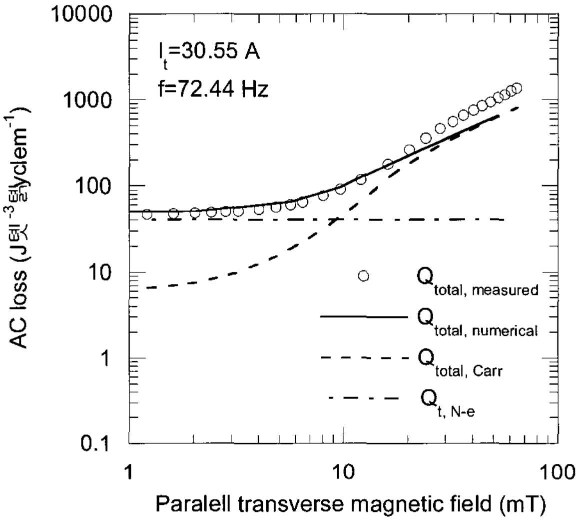

Fig. 8. Total loss of BSCCO multifilamentary conductor carrying transport current in parallel magnetic field.

6. AC LOSS CHARACTERISTICS OF YBCO COATED CONDUCTORS [11-22]

6.1. Magnetization loss without transport current

Very thin cross-section of coated conductors leads to very anisotropic AC loss characteristics against AC transverse magnetic field. In Fig. 9(a), magnetization losses of an YBCO coated conductor exposed to transverse magnetic fields with various field angles α are plotted against the amplitude of the transverse magnetic field $\mu_0 H_m$. Magnetization loss increases with increasing α. In Fig. 9(b), same measured magnetization losses are plotted against the perpendicular magnetic field component $\mu_0 H_m \sin \alpha$: the magnetization loss plots for various α collapse to one line and almost agree with the analytical value given by (3). The experimental results show that magnetization losses of YBCO coated conductors in AC transverse magnetic fields are mostly determined by the perpendicular magnetic field component, and that the

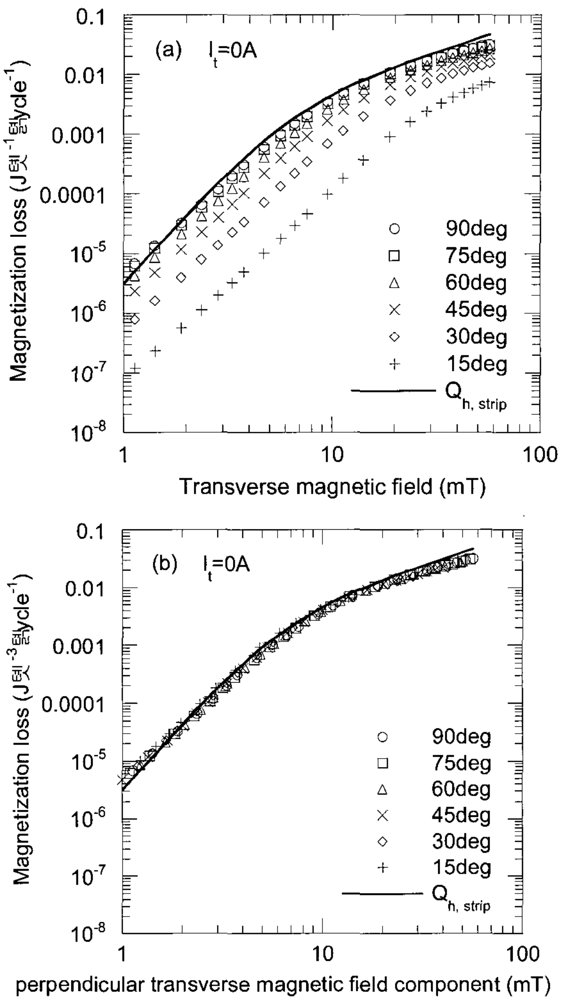

Fig. 9. Magnetization loss of YBCO coated conductor in transverse magnetic field with various field angles. Influence of the parallel magnetic field component is negligible.

6.2. Transport loss without external magnetic field

There were also many reports on the transport loss in YBCO coated conductors without any external magnetic field. When the measured transport losses are plotted against the transport current, the plots often fall between the analytical values by (5) and those by (6) as shown in Fig. 10. It was pointed out that the non-uniform critical current distribution in an YBCO coated conductor cause the deviation of the measured transport losses from the analytical values by (6).

6.3. Total loss

In Fig. 11(a), total losses of an YBCO coated conductor carrying AC transport current in AC transverse magnetic fields with various field angles α are plotted against the amplitude of the transverse magnetic field $\mu_0 H_m$. Total loss

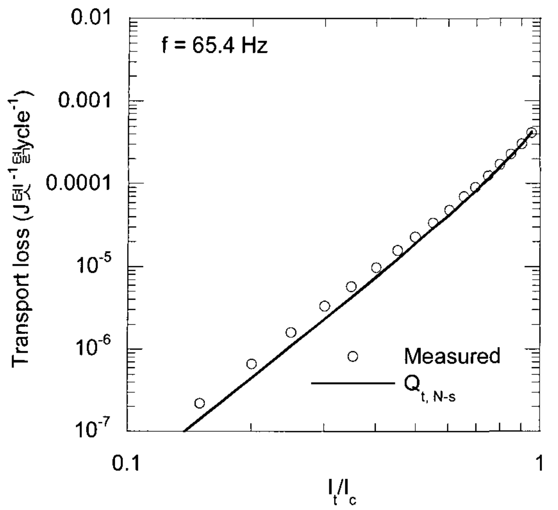

Fig. 10. Transport loss of YBCO coated conductor without any external magnetic field.

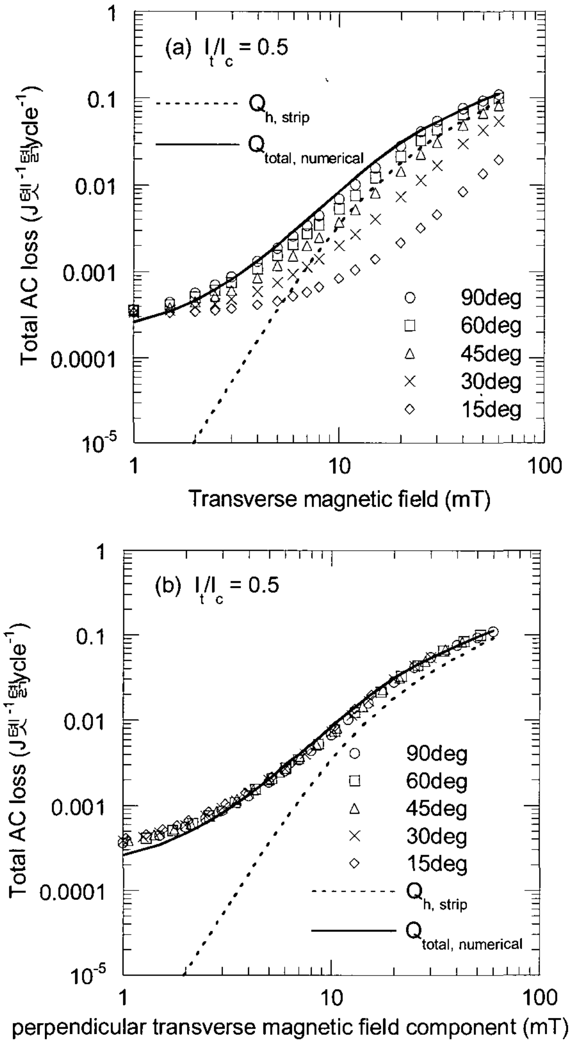

Fig. 11. Total AC loss of YBCO coated conductor carrying AC transport current in AC transverse magnetic field with various field angles.

increases with increasing α. In Fig. 11(b), same measured total losses are plotted against the perpendicular magnetic field component $\mu_0H_m\sin\alpha$: the total loss plots for various α collapse to one line and almost agree with the numerically-calculated values. The total losses of YBCO coated conductors are mostly determined by the perpendicular magnetic field component and the transport current (self magnetic field).

7. COMPARISON BETWEEN AC LOSS OF BSCCO MULTIFILAMENTARY CONDUCTOR AND THAT OF YBCO COATED CONDUCTOR [16, 23]

Amemiya *et al.* reported that the total AC losses of YBCO coated conductors that carry the AC transport current in an AC transverse magnetic field with various orientations are proportional to the width of YBCO coated conductors [16]. We can then scale the total AC losses of a 10-mm-wide YBCO coated conductor to those of a YBCO coated conductor whose width is the same as of a untwisted 3.9-mm-wide BSCCO multifilamentary conductor. In Fig. 12, the scaled total AC losses of the 3.9-mm-wide YBCO coated conductor are compared with those of the untwisted BSCCO multifilamentary conductor, when they carry an AC transport current in an AC transverse magnetic field. In the figure, the values along the vertical axis represent the ratios of the total AC loss, Q_{total}, of the 3.9-mm-wide YBCO coated conductor to that of the untwisted 3.9-mm-wide BSCCO multifilamentary conductor. A ratio of 1 indicates that the total AC losses of the 10-mm-wide YBCO coated conductor and the 3.9-mm-wide BSCCO multifilamentary conductor are the same. In this case, $\alpha = 5$ and 90 degrees, and $I_t/I_c = 0.5$ in both samples. Fig. 12 shows that the total AC loss of the 3.9-mm-wide YBCO coated conductor where $\alpha = 5$ degrees is smaller than that of the BSCCO multifilamentary conductor almost along the

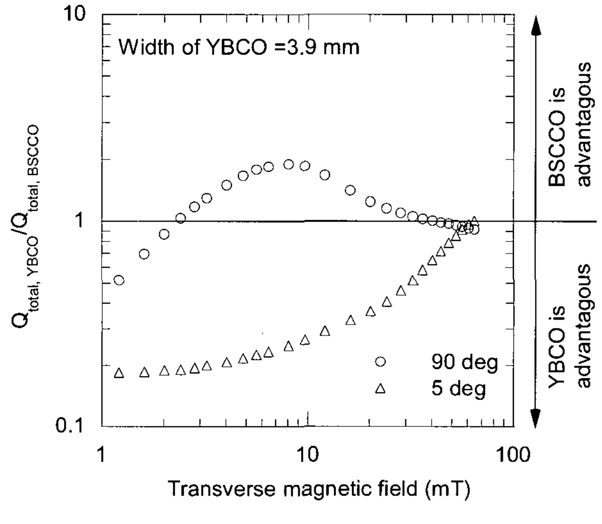

Fig. 12. Ratio of the total AC losses Q_{total} of 3.9-mm-wide YBCO coated conductor to that of the 3.9-mm-wide BSCCO multifilamentary conductor.

entire range of the transverse magnetic field. The data obtained for $\alpha = 5$ degrees are useful for cable application. When $\alpha = 90$ degrees, the total AC loss of the BSCCO multifilamentary conductor is smaller than that of the YBCO coated conductor in the middle magnetic field region, whereas the total AC losses of the YBCO coated conductor and BSCCO multifilamentary conductor tend to become equal in the high magnetic field region. The results indicate that the 3.9-mm-wide YBCO coated conductors compete with BSCCO multifilamentary conductor s in a large magnetic field region. The result obtained when $\alpha = 90$ degrees in a large magnetic field region are useful for coil applications such as superconducting transformers, motors, and fault current limiters.

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