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The Bean Model and ac Losses in $Bi_2Ca_2Cu_3O_{10}$/Ag Tapes

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ABSTRACT

The Bean model is almost solely used to interpret ac losses in the powder-in-tube processed composite conductor, $Bi_2Sr_2Ca_2Cu_3O_{10}$/Ag. In order to examine the limits of the applicability of the model, a detailed comparison was made between the values of critical current density J_C for Bi(2223)/Ag tapes which were determined by standard four-probe-dc measurement, and which were deduced from the field dependence of the ac losses utilizing the model. A significant inconsistency between these values of J_c were found, particularly at high fields. Possible sources of the discrepancies are discussed.

KEY WORDS: power frequency ac losses, the Bean model, $Bi_2Sr_2Ca_2Cu_3O_{10}$/Ag tapes

INTRODUCTION

In the last few years, very significant progress has been made in the fabrication of $Bi_2Sr_2Ca_2Cu_3O_{10}$/ Ag, [Bi(2223)/Ag] tapes [1] to the extent that a number of relatively large model devices for electric power applications and for magnets are being made [2-4]. For the successful system integration of these devices in the electric power grids, it is increasingly apparent that one of the most important factors is the reduction of ac losses induced in the Bi(2223)/Ag composite conductors. For this reason, extensive studies of ac losses in these conductors have been carried out over the past few years [5]. In most of the cases, the Bean critical-state model [6], which assumes magnetic-field-independent critical-current density J_c, is employed in interpreting the measured losses. Although it is well known that the values of J_c for these tapes are a strong function of applied magnetic field, the Bean model can apparently describe the magnetic field dependence of the ac losses in these tapes quite well in many cases [7].

Here, we will make a quantitative comparison of the values of J_c determined from dc transport measurements and from ac losses by the application of the Bean model. For this comparison, ac losses are measured for the Bi(2223) tapes by the magnetically induced current method. One of the often-used measurement techniques for ac losses are by the transport of ac currents through the specimen. The dependence of the losses, which was determined by this method, on the amplitude of ac currents is shown to be very consistent with the expression by Norris [8] which is based on the Bean model. However, we will not consider the results from this type of the measurements since the field range in this measurement is rather limited, and the magnetic field distribution in the tape due to the current does not simulate most of the conditions in the devices contemplated for utility applications.

METHOD OF MEASUREMENT

In the magnetically induced current method for ac losses, a specimen is placed in an external sinusoidal magnetic field H(t) with a period τ and the average power loss P in W per unit length in the direction of H(t) is determined by the following expression:

$$P= (1/N\tau) \int_0^{\tau} H(t)\, e_i(t)\, dt \qquad (1)$$

where e_l(t) is the loss voltage from a N-turn pick-up coil on the specimen and H(t) is calculated by integrating the voltage e_m(t) from a single-turn pick-up coil which is placed above the specimen area. Both e_l(t) and e_m(t) values are stored in a digital storage oscilloscope and the calculation is performed with a desk-top computer [7]. Using this method, the losses for the fields applied parallel and perpendicular to the tape face can easily be measured. In the case of the perpendicular field, it was necessary to stack a number of tapes (up to 20 where the height of the stack is approximately equal to or greater than the width of the tape) to simulate an infinite-slab condition and to minimize a demagnetization effect on the losses [9,10]. The effect of dc transport current on the magnetically induced ac losses can also be measured in this arrangement by placing a saddle-shaped pick-coil on the tape while a dc transport current is applied to the specimen [11]. These measurements were performed at 77 K in applied fields of up to ~ 10 rms A/m (≈ 0.18 T peak field) for most of the cases.

For making the comparison between the dc critical-current density, dc J_C, and the ac critical-current density, ac J_C, deduced from the ac loss measurements, dc J_C was determined by a standard four-probe method with the voltage tap distance of 10 mm at 77 K. (We will differentiate the values of J_C's determined from the ac and dc measurements, respectively.) These values were determined for the field applied parallel and perpendicular to the tape face. Also, the critical electric field of 1.0 μV/mm was used to define the value of critical current I_C.

METHOD OF ac J_C DEDUCTION and dc $J_C(H)$

The values of J_C can be deduced by fitting the ac loss data with the expression for the hysteresis loss based of the Bean critical-state model [6]. Here, for convenience of calculating a total loss of a given device, we use the expressions for the losses where the loss P in mks is given for the unit length of the tape along the rolling direction [12]:

$$P = (2/3)\,\mu_0\,(H_0^3/H_0^*)Sf, \qquad \text{for } H > H_0^* \tag{2}$$

$$= 2\mu_0 H_0 H_0^*[1-(2/3)H_0^*/H_0]Sf \qquad \text{for } H < H_0^*\;, \tag{3}$$

where S and f are the cross sectional area and the frequency of the applied magnetic field, respectively. H_0 is the amplitude (peak height) of the ac magnetic field (while H, i.e., without the subscript 0, is the rms value in A/m unless otherwise stated), and H_0^* is the full penetration field given by

$$H_0^* = dJ_C\;, \tag{4}$$

where d is the half width of the tape edge or face which is perpendicular to the applied field. μ_O is the magnetic permeability of the free space.

It was found that one can deduce the value of J_C by fitting Eqs. (2) and (3) simultaneously to the experimentally determined loss [7], as shown in Figs. 1 and 2. Here H_0^* and d are the fitting parameters, and since these are related by Eq.(4), they are not independent parameters. It was found that the deduced value of ac J_C, is quite sensitive to these fitting parameters, and the uncertainty in the values of ac J_C determined by this method is less than ~ 10%. Here, we neglect the measured loss due to the eddy current in the Ag sheath for the parallel field case as it was previously shown to be very small at 77 K [7]. However, the eddy-current loss in the perpendicular case can be substantial and thus, the losses in Fig. 2 were measured at 20 Hz and the losses were multiplied by 3 to make the hytersesis losses equivalent to those at 60 Hz.

DISCLAIMER

From Fig. 1, the best fit to the data is obtained for H* = 3500 rms A/m and d = 0.06 mm. This translates to an ac J_c of approximately 8.2 x 10^7 A/m^2 for the central area containing the filaments. Note that we assume that the filaments are completely coupled and act as a single superconducting core with an average J_C [12]. Similarly, for the case of the perpendicular field, H* = 1600 rms A/m and d = 1.8 mm are obtained. From these, ac J_c is determined to be 1.4 x 10^7 rms A/m^2. However, this value is the value of J_C for the entire wire cross section. By converting it for the core region of the tape, ac J_C is approximateed to be 2.3 x 10^7 rms A/m^2. Thus, ac J_c for the parallel field is ~ 3.5 times greater than that for the perpendicular case. Also, dc critical currents I_C are determined for the applied field directions parallel and perpendicular at 77 K and up to 0.2 T. The results are shown in Fig. 3.

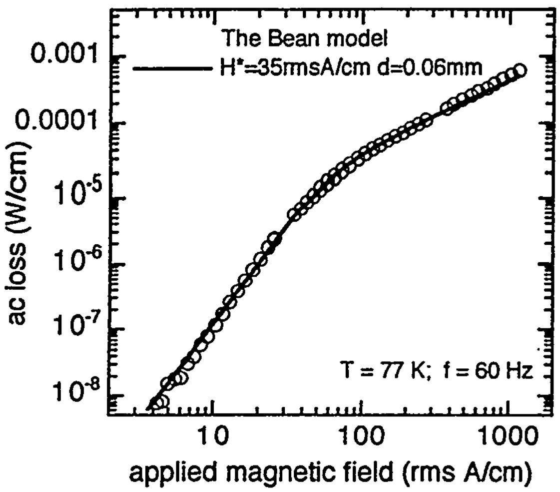

Fig. 1. ac losses for a Bi(2223) multifilamentary tape with H parallel to the tape face at 60 Hz and 77 K.

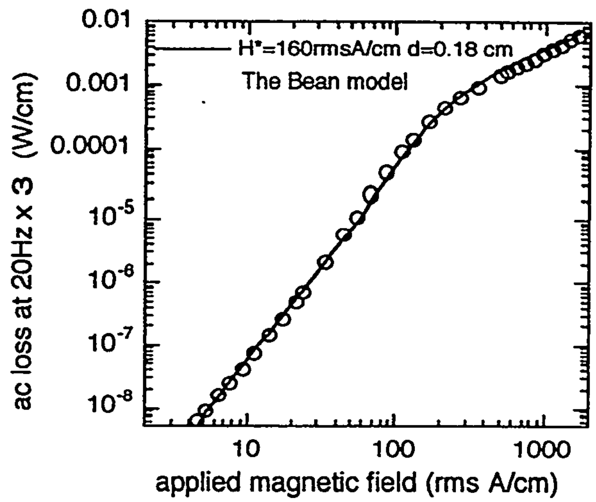

Fig. 2. ac losses for a 20-stack Bi(2223) multifilamentary tape with H perpendicular to the tape face.

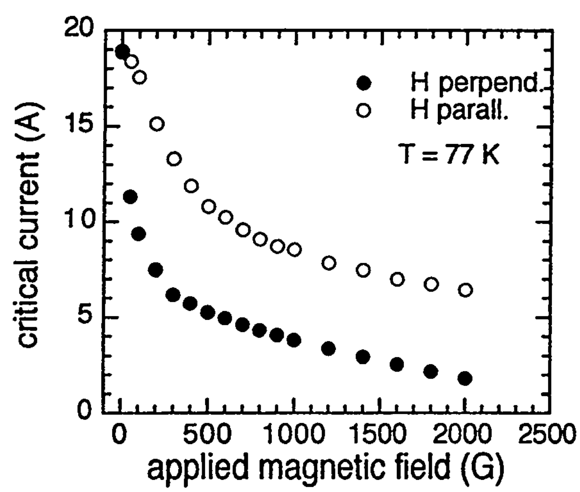

Fig. 3. dc critical currents I_C for the parallel and the perpendicular directions measured at 77 K. A 10 mV/m electric field criterion was used for I_C determination.

Table 1. dc Critical Current Densities for the Area Containing the Filaments.

H(T)	$dcJ_c(H)$	(10^7A/m^2)
	H(‖)	(H⊥)
0	3.6	3.6
0.018	3.0	1.5
0.180	1.3	0.4

DISCUSSION

As can be observed quite clearly in Figs. 1 and 2, and also pointed out previously [7], the Bean model describes the ac field dependence of the losses very well with a set of parameters for the field range of the present measurements, i.e., up to ~ 0.18 T in the peak field. Furthermore, the values of the core thickness d, which were used as one of the fitting parameters, are quite reasonable for the both cases, i.e., they are within (10-15)% of the actual core sizes, the thickness and the width. However, the critical-current densities (ac J_C), which were deduced from fitting the model to the loss data, are significantly different for the values of dc J_C which were determined by the dc measurements as shown in Table 1 and Fig. 3. In the previous measurements of the losses with the field parallel to the face of the tapes, the ratios of (ac J_C/dc J_C) were found to be between 1.5 - 2 depending on the nature of the tapes and on the measurement conditions such as temperature and superimposed dc fields. Previously, we have justified these differences to the existence of superconducting areas which are not connected through the length of the tape. These areas do not contribute to dc J_c, but can contribute to the hysteresis loss [7]. However, the value of dc J_C decreases to 1.3 x 10^7 from 3.6 x 10^7 A/m^2 as H is increased to 0.18 T from 0. The measured losses do not reflect this drop in J_C, i.e., the losses at high fields should be well below the calculated value by Eqs. (2) and (3).

In the case of the applied field perpendicular to the tape face, the ac J_C is substantially smaller than the dc $J_C(0)$, but approximately equal to the value for H = 0.018 T. Again, the field dependence of the loss does not reflect the very large drop in dc J_C from 3.6 x 10^7 at the self-field and 0.4 x 10^7 A/m^2 at H = 0.18 T. These discrepancies are very difficult to reconcile without further investigation of the exact mechanism(s) for which the losses are determined in these highly anisotropic and geometrically complicated superconductors such as Bi(2223)/Ag tapes. A systematic investigation to determine the source(s) of these discrepancies is currently being conducted.

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