ac losses in circular disks of thin $YBa_2Cu_3O_7$ films in perpendicular magnetic fields

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The ac losses at 20 and 30 Hz were measured for two disk-shaped $YBa_2Cu_3O_7$ films in perpendicular peak applied magnetic fields up to ~0.2 T in liquid nitrogen. One of the films had a significantly higher critical-current density than the other as determined from the loss measurements. Also, it exhibited a more-uniform flux penetration around the circumference of the disk than the other as observed by magneto-optical images of these films in perpendicular dc fields. The results from this film were compared with theoretical predictions of ac losses for disks of thin superconducting films in perpendicular magnetic fields using the Bean model [J. R. Clem and A. Sanchez, Phys. Rev. B **55**, 9355 (1994)], and the Kim critical-current model [D. V. Shantsev *et al.*, Phys. Rev. B **61**, 9699 (2000)]. The asymptotic Bean model predictions for low and high fields were in reasonably good agreement with the data. The numerical calculation of the losses following Shantsev *et al.* was found to give extremely good agreement with the loss data throughout the entire field range of the measurement when the Kim model for the critical-current density was used. [DOI: 10.1063/1.1579130]

I. INTRODUCTION

Over the last few years, significant improvements in the fabrication of so-called $YBa_2Cu_3O_7$ (YBCO) coated conductors have been made. Now a few meters of the conductor, YBCO on metallic substrates, which carry over 10 A/mm width in self-fields at ~77 K, are being made.[1] Along with this development, the use of these conductors for electrical utility devices is being planned. One of the main concerns in the applications of these conductors to utility devices is the level of ac losses from the conductors in operating conditions. Particularly, applications of perpendicular magnetic fields on the conductors, which are highly anisotropic in geometry, are known to generate large losses. However, studies of ac losses in these films in perpendicular fields are very limited.[2] On the other hand, a number of excellent theoretical studies[3–7] on the subject have been available over the years. The earlier studies[3–5] employed the Bean model for the critical current density J_c to investigate the magnetic flux penetration in the films, and to analyze the ac losses in the films. More recently, theories on ac losses in these films which incorporated the field-dependent critical-current densities $J_c(B)$ became available.[6,7] The latter found that the incorporation of a field-dependent $J_c(B)$ improved the agreement between the calculated and measured susceptibility over the use of a field-independent J_c. These measurements of the real and imaginary parts of the ac magnetic susceptibility, χ' and χ'' respectively, were mostly performed at very low applied field amplitudes, $\sim 1-10\times 10^{-7}$ T, at relatively high frequencies, $\sim 10^3$ Hz,[8] and at high temperatures, 85–90 K. These conditions are far from the possible operating conditions for utility devices using these conductors, e.g., 50–60 Hz, 0.01–0.2 T, and ~77 K. In spite of strong interests in the use of these conductors to electric applications, no detailed comparison of these above-mentioned theories and the experimentally determined losses has been performed yet where data were taken at magnetic fields and frequencies of interests to electric power applications.

In this article, we report on measurements of ac losses in circular disks of thin YBCO films on single-crystalline substrates, $SrTiO_3$, as a function of ac magnetic fields up to peak magnetic fields of ~0.2 T at frequencies 20 and 30 Hz, and at temperature ~77 K. The results were compared with two theories, Clem and Sanchez[4] and Shantsev *et al.*,[7] which employed the Bean model and field-dependent critical-current models, respectively, in calculating the losses. We have also utilized a magneto-optical imaging technique to observe the manner of magnetic field penetration into the disks to assist the evaluation of the uniformity of the films with respect to the field penetration.

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II. EXPERIMENTAL PROCEDURE

Two 1-μm-thick YBCO films were prepared on the (001) plane of single-crystalline $SrTiO_3$ substrates, whose dimensions were 10×10 mm^2 in area and 0.5 mm in thickness, by the so-called BaF_2 process[9] at the Brookhaven National Laboratory. In this process, the stoichiometric YBCO precursor films were codeposited by electron beam evaporation of Y and Cu, and by thermal evaporation of BaF_2. The compound synthesis was performed in a 50-mm-diam quartz tube in a tube furnace at 735 °C with a flowing process gas, which consisted of a mixture of O_2 and H_2O in nitrogen. Standard θ–2θ x-ray diffraction measurements indicated that these were c-axis-textured YBCO films. Then, the circular disks, which were 5.5 mm in diameter, were made lithographically from these films. Although critical temperatures T_c of these films were not measured, T_c of similarly processed YBCO films were ~90 K.

The ac losses in perpendicular magnetic fields were made at Kyushu University by using a rig, which was a standard susceptometer arrangement.[10] Here, a precalibrated pick-up coil for magnetization was used for the loss measurements. The coil was 20 mm in diameter and 50 mm in length having 221 turns of Cu wire. The specimen was placed at the center of the pick-up coil, which in turn was placed in an ac magnet wound with Cu wire. The losses, $Q(B_a)$, in (J/m^3/cycle) were determined electronically by performing the integration of the expression, $\mu_0\int M(t)\times(dH/dt)dt$, over a cycle where B_a is the amplitude of the applied magnetic field, while the magnetization curves were determined by calculating $M(t)$ separately by integration of dM/dt. The loss measurements were mostly performed at 30 Hz, but in a few instances, 20 Hz was used to provide slightly higher applied field values up to ~0.2 T in peak magnetic fields. These frequencies were chosen since the maximum fields obtainable at higher frequencies, e.g., at 50–60 Hz, were limited due to the capacity of the power supply. Although these frequencies were lower than power frequencies, the results are applicable to the losses at power frequencies since the losses are hysteretic.

In order to determine the overall uniformity of the films, we utilized a magneto-optical imaging technique,[11] which uses Faraday effects in a garnet film. When this film is placed directly on the specimen in perpendicular dc magnetic fields, the penetration of the field into the films can be optically observed. In this manner, the locations of easy-field penetration due to defects in the films can be identified.

III. RESULTS AND ANALYSIS

ac losses $Q(B_a)$ for the two YBCO films are presented in Fig. 1 as a function of applied ac fields. As shown in Fig. 1, the critical current for the film No. 1 appears to be substantially (by 2–3 times) higher than that for the films No. 2 even though both of them were synthesized in the same manner. This difference may be traced to the fact that the latter film was exposed to moisture twice before it was coated with a protective layer of a thin oil film and measured for ac losses. On the other hand, the former was coated before it was tested. In order to observe physically the differences in the manner in which the magnetic flux penetrated into the disks, these films were observed by a magneto-optical imaging technique, and the results are shown in Fig. 2. Although the observations were made at temperatures ranging ~5–80 K and dc magnetic fields up to ~0.1 T, the images, which were taken at 60 K and at 30 and 50 mT are shown here. Note that only a portion of the films' edge was observable at a time owing to the limited size of the imaging garnet film relative to the size of the YBCO films. [The edges of film No. 1 are toward the slightly upper-right-hand side of the images, (A) and (B), and of film No. 2 are at the bottom of the images, (C) and (D).] However, it is clearly seen that the flux penetration into film No. 1 was much less than that for No. 2, and was macroscopically uniform around the film's circumference except for one location where a significant flux penetration was observed. This is barely observable in image (B) on the left-hand side. The penetration of the flux was not only easier in film No. 2, but also it was irregular around its circumference. In addition, there were some linear

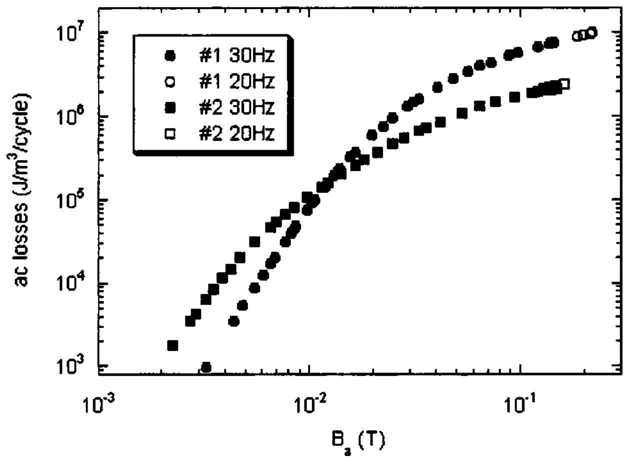

FIG. 1. ac losses of two YBCO films in perpendicular ac magnetic fields, B_a, at 77 K.

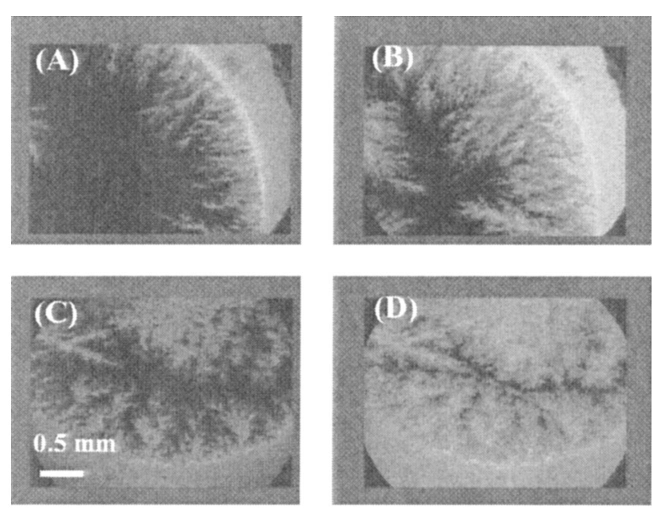

FIG. 2. Magneto-optical images of the YBCO films in perpendicular applied dc fields taken at 60 K. (A) and (B) film No. 1 at 0.03 and 0.05 T, respectively and (C) and (D) film No. 2 at 0.03 and 0.05 T, respectively. Light regions are the areas with magnetic field penetration.

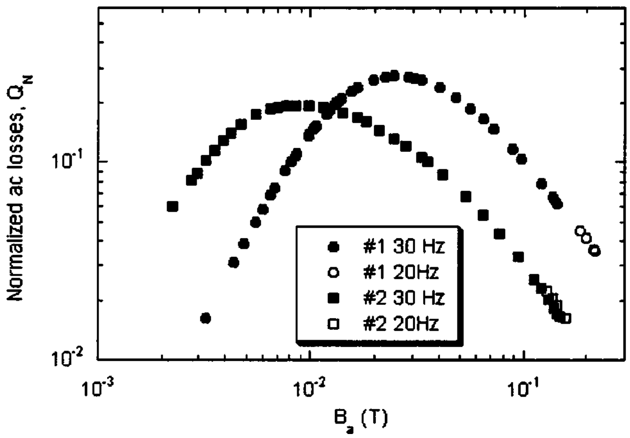

FIG. 3. ac losses for film Nos. 1 and 2 films in Fig. 1 are replotted as normalized ac losses, $Q_N(B_a)$, as a function of applied field amplitudes, B_a.

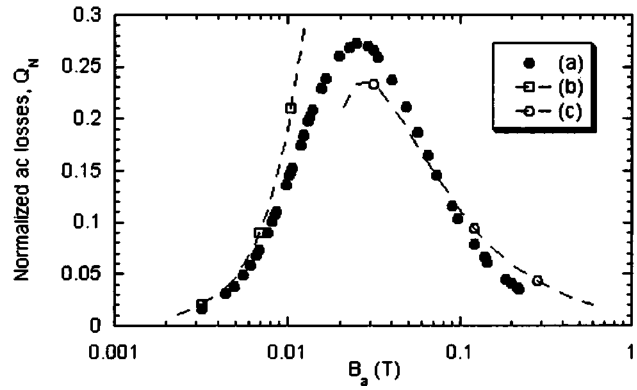

FIG. 4. Calculated normalized losses using the Bean (see Ref. 4) critical-current models are compared with the experimentally measured losses in film No. 1: (a) experimental losses, (b) low-field and (c) high-field asymptotic expressions, Eqs. (2) and (3), respectively.

defects in this film for easy field penetration, which might have been caused by a scratch during handling or a defect in the substrate. Thus, a detailed comparison of the theoretical predictions will be performed only with the data from film No. 1.

Since the analysis of ac losses by Clem and Sanchez[4] with an assumption of the Bean model for critical-current densities, J_{cB}, provided simple analytical predictions for the losses, we will first compare the data with their results, and then present the result of the numerical calculation of the losses following the work by Shantsev *et al.*[7] using the Kim model for the critical-current densities. In comparing the measured and calculated losses, it is more convenient to replot the data as the normalized losses $Q_N(B_a)$ versus applied fields B_a, as shown in Fig. 3. Here, $Q_N(B_a)$ is defined as

$$Q_N(B_a)=[Q(B_a)]/(\pi B_a^2/\mu_0)/(3\pi d/8R), \tag{1}$$

where d and R are the thickness and the radius of the film, respectively. This expression is equivalent to χ''/χ_0, which is often used to express the losses in susceptibility measurements with $\chi_0=8R/3\pi d$. Also, the normalized losses can be thought of as the fraction of the magnetic energy of the peak applied field that is lost as heat in the specimen.

According to Clem and Sanchez,[4] the maximum value of the normalized losses, Q_{Nm}, was predicted to be 0.24. We find from Fig. 3 that Q_{Nm} for film No. 1 is 0.27 in good agreement with the prediction. They also provided asymptotic expressions for the losses at low and high fields as

$$Q_N(B_a)\cong(B_a/B_c)^2/\pi \quad \text{for } B_a/B_c\ll 1, \tag{2}$$

$$\cong(B_c/B_a)-1.06(B_c/B_a)^2 \quad \text{for } B_a/B_c\gg 1, \tag{3}$$

where B_c is the characteristic magnetic field given by $B_c=\mu_0 J_{cB}d/2$ and J_{cB} is the critical current density in the Bean model. B_c is also related to the experimentally determined field by $B_c=B_{am}/1.94$ where B_{am} is the amplitude of the field at which Q_N is at its maximum. In this case, $B_{am}=25\,\text{mT}$ from Fig. 3. Then, $B_c=12.9\,\text{mT}$. Also, we calculate the Bean critical-current density of the film from the value of B_c to be $J_{cB}\sim 2\times 10^{10}\,\text{A/m}^2$, which indicates that this film is a very good film. Using the above value of B_c and Eqs. (2) and (3), we calculated the losses for low and high fields, and the results are compared with the measured losses in Fig. 4. As shown in Fig. 4, the agreement between the measured and the calculated losses is quite good, particularly, at very low fields. Although the calculated losses are quantitatively in good agreement with the measured ones in the region $B_a\sim 0.9\,\text{T}$ or $B_a/B_c\sim 5$, the slopes of the losses between the measured values and those calculated with Eq. (3) are quite different. This deviation is due to the fact that J_c is dependent on the applied fields as shown below.

Shantsev *et al.*[7] investigated, in detail, the effects of the field-dependent critical-current densities on ac losses in thin superconducting discs in perpendicular magnetic fields. They examined two types of the field-dependent critical-current densities, $J_c(B_a)$, the Kim model, $[J_c(B_a)=J_{cK}(0)/(1+B_a/B_{0K})]$ and an exponential model, $[J_c(B_a)=J_{cE}(0)\exp(-B_a/B_{0E})]$, where $J_{cK}(0)$ and $J_{cE}(0)$ are the critical-current densities at $B_a=0$, and B_{0K} and B_{0E} are the characteristic fields for each model. In general, they found that the inclusion of field-dependent critical currents resulted in moving the maximum of the normalized losses Q_{Nm} to larger values, while the field B_{am} at which this occurred was lowered from that for the Bean model. Hence, the observed peak value, which was somewhat larger than the prediction by the use of the Bean model, may also be an indication of the need to use a field-dependent critical-current density for the analysis of the loss data.

Since it is useful to determine which of the field-dependent $J_c(B)$ models is appropriate for this analysis prior to performing the calculation, we deduced the critical-current density from the experimental magnetization curve by the use of the standard relationship, $J_c(B_a)=(3d/2R)\times\Delta M(B_a)/\mu_0$ where $\Delta M(B_a)$ is the width of the hysteresis curve at B_a. We found that the Kim-model expression,

$$J_c(B_a)=J_{cK}(0)/(1+B_a/B_{0K}), \tag{4}$$

with $J_{cK}(0)=2.67\times 10^{10}\,\text{A/m}^2$ and $B_{0K}=80\,\text{mT}$, which was determined by a least-squares fit, reproduced the experimental data very well, as shown in Fig. 5, while the exponential model did not fit as well as the Kim model.

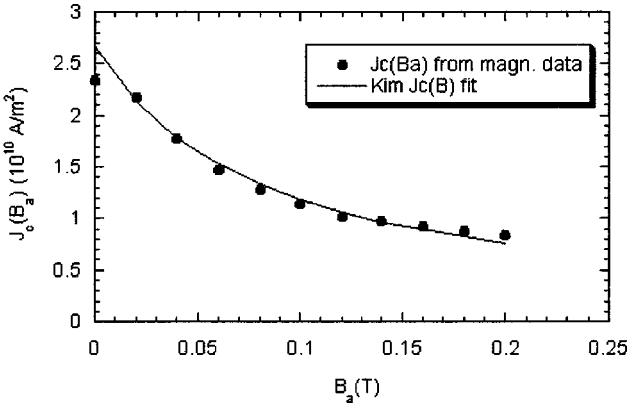

FIG. 5. Kim $J_c(B_a)$ model, Eq. (4), fitted to the experimental critical current densities derived from the magnetization curve.

Knowing that the Kim expression for the field-dependent critical-current density is the proper one in this case, we performed a numerical calculation for the losses, and the result is shown in Fig. 6 [see line (b)]. As shown in Fig. 6, the agreement between the measured and calculated losses is excellent throughout the entire field range, except perhaps at the extreme high-field range where a small discrepancy is seen. The experimental peak value of the normalized losses ($Q_{Nm}=0.27$ at $B_{am}=25\,\mathrm{mT}$) was used in this calculation. This uniquely determines that $B_{0K}/B_c=3.5$ and $B_{am}=1.6B_c$. These relationships give $B_{0K}(=56\,\mathrm{mT})$ and B_c $(=16\,\mathrm{mT})$.

Since the numerical calculation of the losses with field-dependent J_c is a difficult one, it is valuable to have asymptotic expressions for low- and high-field losses. The low-field expression, which was given by Shantsev *et al.*,[7] is the same as Eq. (2) in the Bean model except that B_c is replaced by $B_{c\,\mathrm{eff}}$, which is defined as

$$B_{c\,\mathrm{eff}}=B_c(1-\alpha B_c/B_{0K}), \tag{5}$$

where α is 0.36 for the Kim model. The asymptotic expression for the high-field losses can be easily derived as

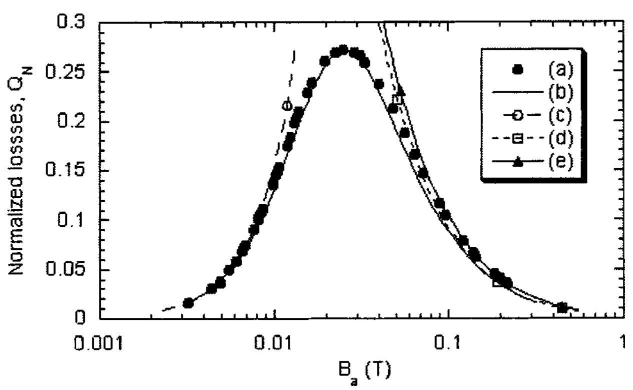

FIG. 6. Calculated normalized losses using the Kim model for $J_c(B)$ are compared with the experimentally obtained losses in film No. 1: (a) experimental losses, (b) numerically calculated losses, and (c) the low-field asymptotic losses, Eqs. (2) and (5), (d) the high-field asymptotic losses, Eq. (6), and (e) high-field asymptotic losses, Eq. (6), but using the value of B_{0K} from the Kim model fit for the magnetization $J_c(B_a)$ data, Eq. (4).

$$Q_N(B_a)=\chi''/\chi_0=(B_cB_{0K}/B_a^2)\ln(1+B_a/B_{0K}). \tag{6}$$

Then, from the above values of B_c and B_{0K}, we obtain the asymptotic losses at both low- and high-field regions, and these are shown in Fig. 6 [see lines (c) and (d), respectively]. As expected, the agreement between the calculated and measured losses is very good in these field regions. Also, it is interesting to note that the value of $B_c(=16.7\,\mathrm{mT})$ determined from $J_{cK}(0)$ in the Kim model, Eq. (4), agreed very well with the B_c that was deduced from the above fit to the loss data. [Note that the use of the magnetization width directly in deducing $J_c(B_a)$ underestimates their values at very low fields, $B_a<B_c$.[7] Thus, the use of the extrapolated $J_{cK}(0)$ in the Kim model fit for the calculation of B_c is more appropriate than the experimental value of $J_c(0)$ determined from the magnetization width at $B_a=0$]. However, the values of B_{0K} determined by these two approaches, were quite different. That is, $B_{0K}=56$ and 80 mT from the numerical and the magnetization results, respectively. Furthermore, it was found that the high-field losses agreed very well if the value of B_{0K} from the magnetization was used in the asymptotic expression for the high-field losses, Eq. (6), as also shown in Fig. 6 [see the line (e)]. The slight discrepancy between the losses determined from the numerical calculation and the magnetization data is possibly traced to the fact that the macroscopic flux penetration was not completely uniform around the circumference of the disk as mentioned above. Nevertheless, the agreement between the calculated and measured losses is extremely good. Also, surprisingly, it suggests that uniform flux penetration on the scale of a few mm is important and sufficient in determining the ac losses in thin superconductors in perpendicular fields. Furthermore, the nonuniform flux penetration on the scale of 10 s of μm or smaller as seen in Fig. 2 appears not to influence the overall losses.

Finally, as discussed above, these agreements between the theoretical and the experimental results were found only in the specimen in which the magnetic field penetration around the circumference of the disk was macroscopically uniform. Also, the peak value of the normalized losses in a uniform film cannot be smaller than the 0.24 given by Clem and Sanchez,[4] since the incorporation of field-dependent critical-current densities in the loss calculations increases this value.[7] Thus, if the measured losses exhibit a maximum of the normalized losses smaller than 0.24 as observed for film No. 2, this indicates that the film is defective, and the field penetration is not uniform. Thus, one can use this value as a gauge for the uniformity of the film that is being investigated.

IV. SUMMARY

It was shown that the ac losses of a superconducting thin circular film in perpendicular fields follow the numerical critical-state model solution by Shantsev *et al.*, which include a magnetic-field-dependent critical-current density.[7] A very close fit to a Kim model behavior was obtained over the entire field range, i.e., below and above the "full" penetration field. Simultaneously, the magnetization data converted to $J_c(B)$ was well fitted by essentially the same model parameters. Our article also reports the asymptotic expression for the losses in the high-field region of the Kim model. It was also shown that the loss expression at low fields, given by Clem and Sanchez using the Bean model,[4] is substantially applicable for $B_a/B_c < \sim 0.5$.

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