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Ac susceptibility of a coated conductor with high-temperature superconducting film and covered copper stabilizer

D.-X. Chen *

Departament de Física, Universitat Autònoma de Barcelona, 08193 Bellaterra, Barcelona, Spain

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ABSTRACT

The ac susceptibility, $\chi = \chi' - j\chi''$, of a nearly square sample, cut from a coated conductor tape consisting of a high-temperature superconducting film and a covered copper stabilizer, is measured as a function of temperature, *T*, at several values of frequency, *f*. It is found that the $\chi(f)$ at $T > T_c$ can be well simulated by a modeling eddy-current susceptibility of the stabilizer, and there is an extra low-*T* stage, where χ is not constant as expected and may be separated into two parts. The *T*-independent part is contributed by Meissner currents in the film with over-low $|\chi'|$, indicating that the film edge was damaged by cutting during tape and sample preparation. The *T*-dependent part is contributed by both eddy-currents and supercurrents, having a special *f* dependence with unknown mechanism. Both currents are interacted to each other in a complex way in the *T* range below and near T_c, resulting in interesting features in $\chi(T, f)$.

1. Introduction

As the second generation (2G) high-temperature superconducting (HTS) wire, coated conductors not only consist of a HTS film coated on a metallic substrate but also have a normal conducting stabilizer covering the film or both the film and substrate. In this case, the study of the electromagnetic properties of the HTS film will be interfered by the eddy-current effect in the stabilizer, and a study on its low-field ac susceptibility as a function of temperature and frequency will be interesting.

We will perform such a study in the present work. The measurements will be carried out using a well calibrated high-quality ac susceptometer, so that the experimental results may be analyzed quantitatively in comparison with existing models. Trying to explain the observed phenomena, we find some results to be normal and well understood, but some others to be anomalous and difficult to be explained. The latter will extend our knowledge of the combined contribution of supercurrents and eddy-currents to ac susceptibility.

The samples and measurements are described in Section 2. The measured results are analyzed and discussed in Section 3. Some concluding remarks are presented in Section 4.

* Tel.: +34 665095211.
E-mail address: duxingchen039@gmail.com

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2. Experimental

The studied coated conductor was a SuperPower 2G HTS tape of thickness about 0.1 mm and width $w = 4$ mm, which was cut from a wider tape according to the factory description [1,2]. For the studied tape, a (RE) BCO HTS film of thickness $t = 1$ μm was epitaxially deposited on a non-magnetic 50 μm thick Hastelloy substrate with a total thickness 0.2 μm of buffer layers in between and was covered by a silver overlayer of thickness 2 μm. Both the substrate and overlayer were finally covered by copper stabilizer of thickness 20 μm. A rectangular sample for measurements was cut from this tape with length $l = 5.1$ mm.

The perpendicular ac susceptibility, $\chi = \chi' - j\chi''$, of the sample after zero-field cooling was measured at field amplitude $H_m = 80$ A/m, several values of frequency *f*, and step increased temperature *T* with an ac susceptometer of Quantum Design PPMS, which had been calibrated by using a copper cylinder [3,4]. A χ magnitude correction was made by multiplying a constant factor, so that the measured $\chi(T, H_m)$ became very accurate at $f = 1111$ Hz, and the errors for the magnitude and phase of χ were within ±0.7% and ±0.3°, respectively, in a *f* range between 111 and 1111 Hz. The magnitude error can reach 1% and the phase error can reach $-0.6°$ at $T < 20$ K for *f* beyond this range.

The measured χ' and χ'' as functions of *T* are shown in Fig. 1 for *f* = 333, 1111, 3333, and 10,000 Hz. In the calculation of χ, magnetization was calculated by the sample magnetic moment divided by the volume *wlt* of the HTS film.

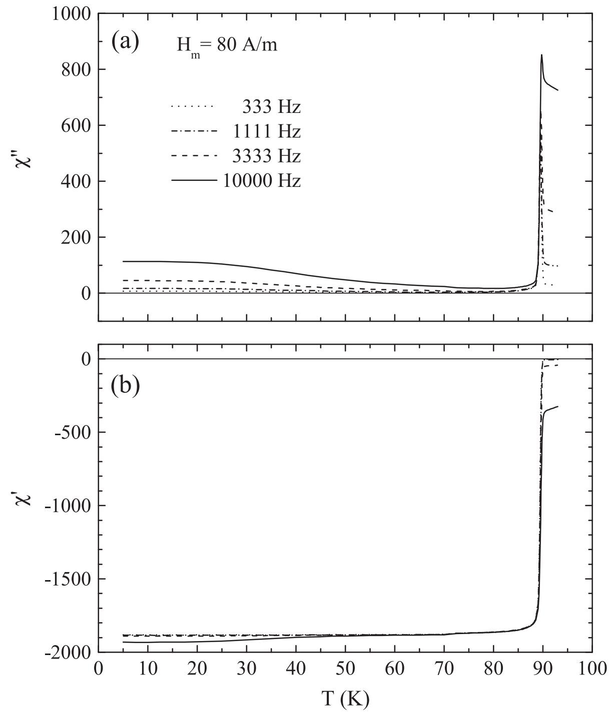

Fig. 1. The ac susceptibility $\chi = \chi' - j\chi''$ of the studied sample as a function of temperature T, measured at field amplitude $H_m = 80$ A/m and frequency $f = 333,\ 1111,\ 3333$, and 10,000 Hz.

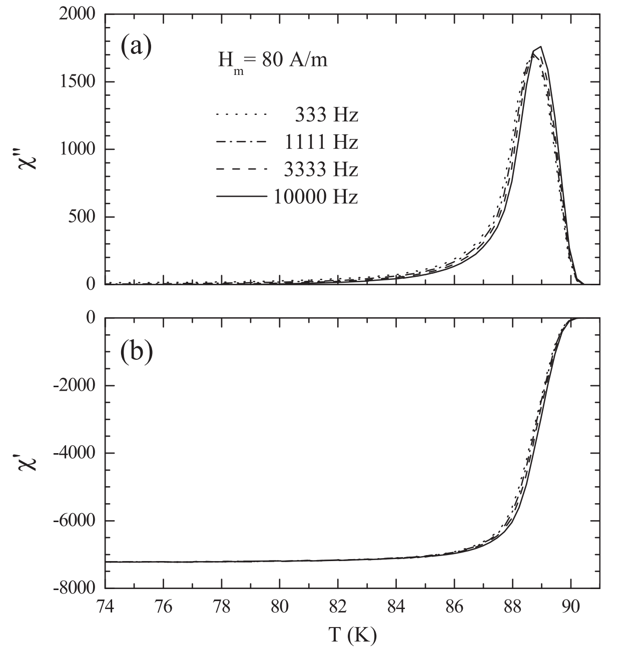

Fig. 2. The ac susceptibility $\chi = \chi' - j\chi''$ of the standard sample as a function of temperature T, measured at field amplitude $H_m = 80$ A/m and frequency $f = 333,\ 1111,\ 3333$, and 10,000 Hz.

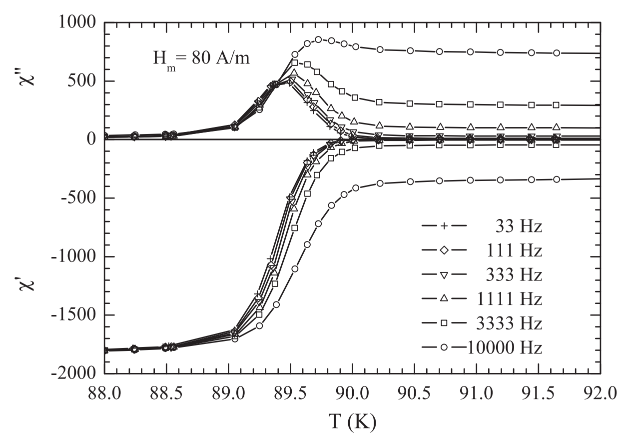

Fig. 3. The high-T portion of Fig. 1 in refined T scales with $f = 33$ and 111 Hz added.

In order to describe the feature of the measured results, we use the results of a high-quality standard sample as a reference. This standard sample was an epitaxial YBCO film grown by chemical solution deposition on a $5 \times 5\ \text{mm}^2$ $LaAlO_3$ crystal [5]. The film was patterned into a square shape by optical lithography, in order to have a well defined geometry and to avoid any defects on the edges. Final film dimensions were $w = 4.00 \pm 0.01$ mm in sizes and $t = 0.250 \pm 0.025$ μm in thickness (the latter error signifies the surface roughness), which were measured by using an optical microscope and a profilometer, respectively. The ac susceptibility of the standard sample has been systematically studied in [6]. Relevant to the studied sample, the measured χ' and χ'' of the standard sample at $T \geqslant 74$ K are shown in Fig. 2.

We observe in Fig. 2 that for a high-quality YBCO film with increasing T, χ' maintains a negative constant in a large T range and increases to zero when T approaches T_c, whereas χ'' increases from zero to a maximum χ''_m at $T(\chi''_m)$, where χ' increases rapidly, and then decreases to zero at $T = T_c$. Both $T(\chi''_m)$ and χ''_m increase slightly with increasing f.

Different from Fig. 2, there is an extra low-T stage for the studied sample shown in Fig. 1; with increasing T from 5 K, χ' increases from a negative value to another negative value and the positive χ'' decreases from a steady value to a minimum before further increases. This stage is more pronounced at higher f. Another obvious difference occurring at $T > T_c$, where both χ' and χ'' of the studied sample are nonzero and highly f dependent. These interesting features are worth to be understood.

3. Analysis and discussion

3.1. Eddy-current susceptibility at $T > T_c$

With two more values of f than in Fig. 1, $\chi(T, f)$ of the studied sample is plotted in Fig. 3 in finer T scales around T_c, in order to have a detailed observation. Since there are covered normal conductors of copper and silver in the studied sample but not in the standard sample, the high-T nonzero χ' and χ'' in Fig. 3 should arise from the eddy-currents flowing in the normal conductors. The eddy-current effect is enhanced by increasing f and conductivity σ, which increases with decreasing T, so that the magnitudes of both χ' and χ'' increase with increasing f and decreasing T. The change of χ' and χ'' with T may be approximated as linear in the narrow T range around T_c, and $T_c = 90.5$ K is thus determined from the deviation from linearity. We analyze the data at $T = 92\ \text{K} > T_c$, where χ is totally contributed by eddy-currents, as follows.

We first convert χ in Fig. 3 to those corresponding to the normal conducting part, χ_{EC}, by multiplying a factor of the volume ratio of the HTS to the normal conducting parts, 1/42. For a rectangular normal conducting plate of width w, length l, and thickness equal to the total thickness 42 μm of normal conductors, the high-frequency limit of the perpendicular susceptibility $\chi_{0,EC}$ is calculated to be -50.93 using a general procedure proposed in [7]. Regarding the rectangular sample to be square of surface area equal to lw, a simple version of such calculations with slightly different value