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Hysteresis losses in BSCCO(2223)/Ag multifilamentary tapes

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Abstract

In order to investigate hysteresis losses on Ag-sheathed BSCCO(2223) multifilamentary tapes, we perform hysteresis loop measurements, with the external magnetic field H_e perpendicular to the tape surface, for different sweep rates of the magnetic field and at different temperatures T. The experimental results show a sweep rate dependence, equivalent to a frequency dependence of the hysteretic losses. In order to consider the role of the thermally activated flux creep in the losses we numerically solve the diffusion equation for the magnetic field B inside a superconducting slab. For magnetic field lower than 2.5 T and in the temperature and frequency range investigated, the numerical and experimental results show that the losses have a logarithmic dependence on the sweep rate. For higher field and increasing temperature, the logarithmic behaviour is no longer observed at higher frequencies.

Keywords: Hysteretic losses; Flux creep; BSCCO/Ag tape

1. Introduction

In the last years, much effort was employed to understand the losses mechanisms in type II superconductors and especially in the high T_c superconductors [1].

In a composite superconductor, three factors share in losses. Hysteretic losses due to the bulk pinning properties of the superconductors, eddy current losses generated by viscous or flux flow motion in the superconductor and coupling losses due to the induced currents in the normal matrix which usually embedded the superconducting wires or stripes in the superconducting cables and tapes.

The hysteresis losses in type II superconductor are given by

$$Q = \oint M \, \mathrm{d}B, \qquad (1)$$

where M is the superconductor magnetisation. Q is stated to be independent of the frequency ν [2–4], while, on the contrary, the other two basic mechanisms depend on ν. However in the hysteresis loop measurements performed on HTS samples, the value of M depends on the ramp rate of H_e and therefore on first sight the loop area Q depends on the frequency.

The focus of this paper is the study of the frequency dependence of the hysteretic losses in multifilamentary BSCCO/Ag tapes. In order to recognize the mechanism of the observed behaviour we have performed numerical computations of the diffusion equation for magnetic induction $B(x, t)$ in a superconducting slab.

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For low external field amplitudes up to 2.5 T, in the range of the frequencies and temperatures investigated, the experimental and numerical results show a logarithmic dependence on sweep rate of Q. This behaviour can be ascribed to flux creep dynamics in BSCCO materials.

2. Experimental

Our sample is a multifilamentary (37 filaments) BSCCO(2223)/Ag tape prepared by standard PIT technique. The dimensions of the sample are $0.35 \times 0.02 \times 0.46$ cm^3, and the superconducting fraction is 30% of the whole volume.

In order to measure the magnetisation of our sample we use a vibrating sample magnetometer VSM equipped with a 16 T superconducting magnet. The samples vibrate in a region where the field has a homogeneity of 10^{-6}.

Measurements of $M(H)$ are performed in the temperature range from 4.2 to 35 K. Magnetic field amplitudes H_m up to 6 T are applied perpendicular to the sample surface ($H \| c$-axis) with sweep rate ranging from 4.16 to 66.7 G/s. Before each measurement, the sample is zero-field cooled (ZFC).

3. Numerical method

In this section we shortly describe a numerical method used to analyse how the flux creep affects the frequency dependence of hysteresis loop. We numerically resolve the non linear diffusion equation for the magnetic induction $B(x,t)$ inside the superconducting slab with $2d$ thickness in an external field H_e parallel to the sample surface [5].

The spatial–temporal evolution of the magnetic induction B in this case is given by:

$$\frac{\partial B}{\partial t} = \frac{\partial}{\partial x}\left[\frac{\rho(B,j)}{\mu_0}\frac{\partial B}{\partial x}\right], \tag{2}$$

where $\rho(B,j)$ is the resistivity, which depends on the local magnetic induction $B(x,t)$ and on local current density $j = \mu_0^{-1}(\partial B/\partial x)$. We assume that the resistivity ρ is given by the parallel of the flux creep (ρ_{cr}) and the flux flow (ρ_{ff}) resistivities [6]:

$$\frac{1}{\rho(B,J)} = \frac{1}{\rho_{cr}} + \frac{1}{\rho_{ff}}. \tag{3}$$

The flux creep resistivity depends on B and j according to the equation:

$$\rho_{cr}(B,J) = 2\rho_{ff}(B)\frac{j_c(B,T)}{j}\exp\left(-\frac{U_p(B,T)}{k_B T}\right) \times \sinh\left(\frac{jU_p(B,T)}{j_c(B,T)k_B T}\right), \tag{4}$$

where $j_c(B,T)$ and $U_p(B,T)$ are respectively the critical current density and the pinning potential depending on B and T and k_B is the Boltzmann constant.

The flux flow resistivity follows the Bardeen Stephen model

$$\rho_{ff}(B) = \rho_n(T)B/B_{c2}(T), \tag{5}$$

where ρ_n is the normal state resistivity of the superconductor which depends linearly on T according to $\rho_n = \rho_0[1 + \alpha(T - 273.15)]$, where ρ_0 is the normal resistivity at 0 °C and α is the thermal coefficient. $B_{c2}(T)$ is the upper critical field which depends on temperature as follows:

$$B_{c2}(T) = B_{c2}(0)(1-\tau^2)/(1+\tau^2), \tag{6}$$

where $\tau = T/T_c$ and T_c is the critical temperature of the superconductor.

Eq. (2) is numerically solved by means of NAG Library routines [7], with $B(x, t=0) = 0$ as initial conditions and $B(\pm d, t) = H_e(t)$ as boundary conditions. The magnetisation M can be calculated from the difference between the volume average of the profile $B(x,t)$ and the instantaneous value of the applied magnetic field $H_e(t)$.

The field dependence of the critical current density j_c has been derived by our measurements on the BSCCO tape of the magnetisation loops, using the simple Bean's rule [8]:

$$j_c = (M_{up} - M_{dw})/d, \tag{7}$$

where M_{up} and M_{dw} are the magnetisation measured in the hysteresis loop $M(H)$ for increasing and decreasing field, respectively.

The experimental result is well described by the usual Kim law:

$$j_c(B) \propto 1/(1 + B/B_0), \tag{8}$$

where $B_0 = 0.3$ T.

In the numerical computations we use the parameters which pertain to BSCCO material. Namely we choose the critical temperature $T_c = 110$ K, the upper critical field at zero temperature is $B_{c2}(0) = 140$ T and the thermal activation energy normalized at $T = 4.2$ K, $U_p/k_BT = 70$ K. The external field ramps with sweep rate varying from 8.33 to 66.67 G/s which are the same value used in experimental measurements.

4. Results and discussion

In Fig. 1 the $M(H)$ curves measured experimentally at $T = 35$ K are reported. The maximum amplitude of the external magnetic field is 6 T, ramped with sweep rate ranging from 8.33 to 66.67 G/s. A similar sweep rate dependence is observed at the lower temperatures.

For value of H_e higher than 2 T, the magnetization, in descending field ramp, is negative. For these temperatures and field values, in the sample the equilibrium magnetization M_{eq} is not negligible respect to the irreversible portion of M (M_{irr}). In our case for $H_e > 2$ T, M_{eq} is higher than M_{irr}.

The results of the numerical computations of the diffusion equation are shown in Fig. 2. We can see the $M(H)$ curves calculated for $T = 35$ K with H_m up to 6 T. The sweep rate dependence of the area enclosed in the $M(H)$ loops is weaker than the one found in the experimental curves. A possible reason could be in the values assumed for BSCCO parameters in numerical calculations. However the aim of our computations is to verify if the sweep rate dependence of hysteretic losses can be understood in the flux creep framework [3].

We have measured the Q value for different temperatures and for several field amplitudes. In Fig. 3 we can observe in semi-log scale, the plot of the losses as function of the sweep rate. The loss values at different sweep rate are normalized with the Q value measured at 8.33 G/s. This is an arbitrary choice. The normalized losses are measured for $H_m = 2.5$ T and for $T = 4.2$, 10, 15, 30, and 35 K.

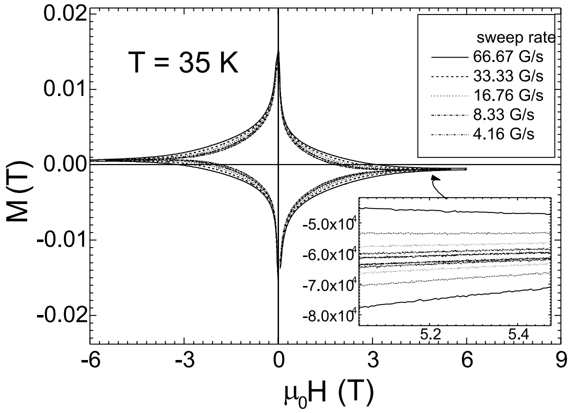

Fig. 1. Hysteresis loops at $T = 35$ K with different sweep rate. In the inset there is a magnification of one region.

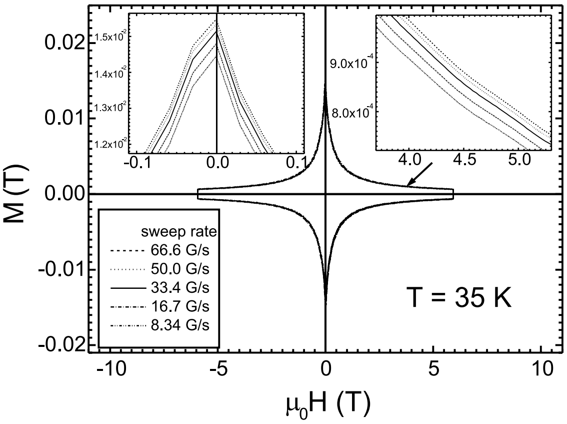

Fig. 2. Numerically computed hysteresis loop for a BSCCO slab. The two inset are magnification of the same figure.

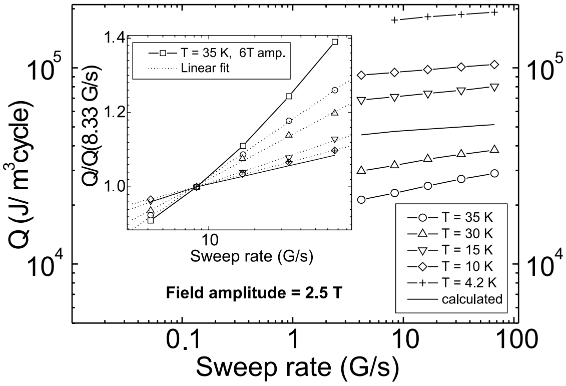

Fig. 3. Losses versus sweep rate measured experimentally and computed for a slab. In the inset the curves are normalized at the value corresponding to the sweep rate 8.33 G/s.

The linear fits show that the losses are proportional to the logarithm of the field sweep rate. We have compared the experimental behaviour of Q with the one numerically calculated by using the diffusion equation, which is also reported in Fig. 3. We can observe the same proportionality found in the experimental curves. Therefore, we can deduce that the flux creep phenomena are the basic mechanism of the dependence observed in the hysteretic losses.

Moreover this behaviour can be observed for temperature, field and frequency values where the flux creep is dominant. In Fig. 3 the Q curve measured for $H_m = 6$ T is shown and we no longer observe a logarithmic dependence. As we can observe in Fig. 1, for $H = 6$ T the superconducting state is near the reversible line and the flux dynamic is very complex.

In summary we have observed a frequency dependence of hysteresis losses in BSCCO tape. For lower temperatures, magnetic field amplitudes and sweep rates, we find a logarithmic dependence on sweep rate of the losses. The numerical computations of diffusion equation for B show that flux creep is the basic mechanism. For higher field amplitudes and increasing the frequency values, the losses do not follow the logarithmic law.

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