Journal of Superconductivity, Vol. 9, No. 1, 1996

Estimation of Intragrain Magnetic Flux Motion Viscosity in High-Temperature Superconductors

A. A. Kordyuk[1] and V. V. Nemoshkalenko[1]

Received 5 January 1995

A simple method for evaluation of the lower limit of intragrain magnetic flux motion viscosity is presented. We have also shown that in our experiment the energy loss in an alternating magnetic field in a granular $YBa_2Cu_3O_{7-x}$ superconductor prepared by the standard sintering method is determined by thermally assisted magnetic flux flow into superconducting grains and does not depend on the intergrain space.

KEY WORDS: Granular superconductors; flux motion; energy losses; levitation.

1. INTRODUCTION

The study of the macroscopic magnetic properties of high-temperature superconductors (HTSC) has attracted the interest of researchers [1]. This is understandable since such fundamental parameters as the coherence length, the magnetic field penetration depth, and information on pinning and magnetic flux motion, namely critical currents and viscosity, may be obtained. Determination of the values of these parameters is necessary both for construction of theoretical models and for the successful practical application of HTSC.

In the study of the magnetic flux dynamics in HTSC, vibromechanical methods of research are especially convenient. These methods combine the advantages of noncontact methods with the simplicity of interpretation of experimental results. It is possible here to divide the method into two classes: (i) methods using a HTSC vibrating in a magnetic field (with high-Q mechanical oscillator [2], vibration reed experiments [3], and oscillator studies of ceramic superconductors [4]); (ii) methods using a stationary HTSC sample and a vibrating permanent magnet [5,6].

In our previous papers [7–11] a simple (from the point of view of experimental realization) system, where the permanent magnet (PM) was freely suspended above the HTSC sample, was investigated. The many parameters of such a system that can be found experimentally permits one to obtain extensive information on the properties of the HTSC samples studied. In [7,8] we described the observable properties of such a system, and in [10,11] their dependence on the HTSC structure [9] and the magnetic properties of the grains were determined.

In this paper, with the help of such a PM–HTSC system we have shown that in our experiment the energy losses in an alternating magnetic field in the granular $YBa_2Cu_3O_{7-x}$ superconductor prepared by the standard sintering method are determined by intragrain magnetic flux motion. We have also evaluated the lower limit of intragrain flux motion viscosity. Its large value may be considered as the independent confirmation of the existence of thermally assisted flux flow (TAFF) [12,13] in the HTSC grains.

2. EXPERIMENTAL

In this work we focused on the granular $YBa_2Cu_3O_{7-x}$ superconductor prepared by the standard sintering method [14]. Typical dimensions of the component grains were 10–12 μm. Two types of samples were used in our experiments, ceramic samples and composite samples. All samples were 0.8 cm thick pellets of 4 cm diameter. The first ones

[1]Institute of Metal Physics, National Academy of Science of Ukraine, Vernadsky pr. 36, 252680 Kiev 142, Ukraine.

0896-1107/96/0200-0077$09.50/0

were cut from sintered superconductor. The composite samples were formed from dispersed grains of superconductors in an insulating paraffin. The dispersed grains were obtained by grinding a piece of Y-superconductor. The volume fraction of the ceramic grains was 62%. The absence of electrical contacts between grains was verified by resistance measurements. For comparison we have also investigated ceramic and composite samples made of $(Pb_{0.16}Bi_{0.84})_2Sr_2Ca_2Cu_3O_y$ superconductor [15].

We investigated our samples using the method of permanent magnet (PM) forced oscillations. This method was described in detail in [7]. The PM of $SmCo_5$ had the shape of a spheroid with mass $m \approx 0.021$ g and magnetic moment $\mu \approx 1.2\ \mathrm{G \cdot cm^3}$. It levitated above the HTSC sample at a height of $x_0 \sim 0.10$–0.25 cm with μ oriented parallel to the HTSC surface. PM forced oscillations with frequency ω were excited by an alternating magnetic field generated by an AC coil. The amplitude of the PM oscillations was determined by a microscope with 4μm precision. As the sample sizes were much greater than x_0 which was greater than the PM size, we could consider the PM as a point magnetic dipole above an infinite HTSC surface [8].

3. RESULTS AND DISCUSSION

There are five modes of PM oscillations in such a PM–HTSC system: three translation and two rotation (or torsion) oscillations. The parameteters of these modes, such as the resonance frequency ω and the damping δ for PM amplitude $A \to 0$, have been presented in [9] and [10] for Y and Bi samples, respectively. In [10] we have also presented the characteristic amplitude dependences of these parameters for all modes for Y and Bi samples. The interesting feature of the $\delta(A)$ dependence is the distinct plateau for $A < A_c$ (which corresponds to the maximum amplitude of the magnetic field on the HTSC surface <15G, while the value of the direct magnetic field component is ~ 100 G) for the Y sample (see also [7]), which speaks of the viscous nature of the energy losses

$$W = 2\pi m \delta \omega A^2 \tag{1}$$

which may be written as $W \propto \omega^2 A^2$, where $\omega(A) \approx \mathrm{const}$.

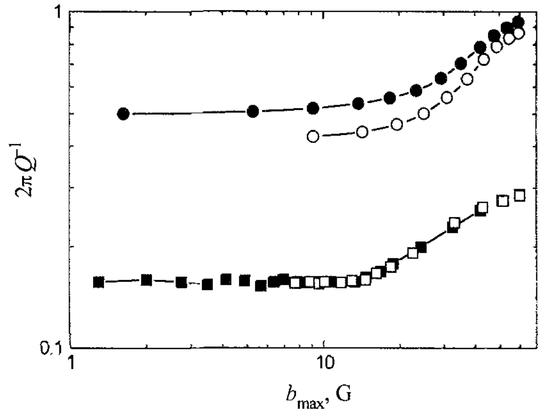

Fig. 1. The reverse Q-factor vs the maximum amplitude of magnetic field on the HTSC surface for the ceramic (closed symbols) and composite (open symbols) samples made of $YBa_2Cu_3O_{7-x}$ (squares) and $(Pb_{0.16}Bi_{0.84})_2Sr_2Ca_2Cu_3O_y$ (circles) superconductors.

The important task here is to determine where the main losses happen: in the grains or in the intergrain space. With this purpose, in Fig. 1 the reverse Q-factor ($Q^{-1} = 2\delta/\omega$) dependences on the maximum amplitude of the magnetic field on the sample surface are presented. It is convenient for the following reason. The total energy losses may be presented as the sum of intra- and intergrain losses: $W = W_g + W_e$. The augend (intragrain losses) is proportional to the fraction of superconducting grains α and, by virtue of their viscous nature [7], is determined by the same dependence on the distance x_0 ($W_g \propto \alpha x_0^{-5}$ [11]) as the storage energy (see [8]) that is determined only by the interaction among grains and the PM field [15]. Then the reverse Q-factor may be considered as two summands determined by intra- and intergrain processes: $Q^{-1} = Q_g^{-1} + Q_e^{-1}$, where $Q_g^{-1} = W_g / 2\pi W_0$ and does not depend on α and x_0 in the area where $Q(A) =$ const.

Thus, the alignment of the dependences for Y samples shows the dominant contribution of intragrain flux motion in the energy losses. Here it is necessary to note that in the usual case the energy depends on the frequency and, hence, on the distance. However, as was shown before [10], this dependence for translation oscillations is weak and our conclusion about the primary contribution of the grains to the losses is true. For Bi samples such dependences do not coincide (Fig. 1). This may be explained by some energy losses related with intergrain flux flow [15]. At the same time, it is possible to conclude that even for Bi ceramics the energy loss is basically defined by intragrain flux motion.

From the above, it is possible to evaluate the range of viscosities of the intragrain flux motion. The linear viscosity η_l is the proportionality factor between the viscous frictional force per vortex length and the vortex velocity: $\mathbf{f}_v = \eta_l \mathbf{v}$. We may also write the volume viscosity $\eta_V = \eta_l B/\phi_0$ [7], where B is the magnetic field in the superconducting grains and ϕ_0 is the magnetic flux quantum. The energy loss during the period may be obtained by integration of the work done by frictional force over the period and its summation with respect to all vortices [7]: $W = \pi \eta_l \omega \langle a^2 \rangle V_0 B/\phi_0$. Here $\langle a^2 \rangle$ is the mean square oscillation amplitude of vortices and V_0 is the volume of the superconductor in which the main energy dissipation occurs. Comparing this equation with (1) we obtain

$$\eta_l = \frac{2m\phi_0\delta}{V_0 B\alpha^2} \qquad (2)$$

where $\alpha^2 = \langle a^2 \rangle / A^2$. For estimating the viscosity due to the steeply decreasing dipolar magnetic field of the PM, $H \propto 1/x^3$, we may write $V_0 \approx x_0^3$ [7]. We will consider the vertical translation mode of the PM oscillations. Then, assuming $B \approx H \approx \mu / x_0^3$ and taking into account the experimental value of $\delta = 3.8\ s^{-1}$ [10], we may write $\eta_l \approx 2\mu\phi_0\delta/\mu\alpha^2 \approx (1.3 \times 10^{-8}/\alpha^2)$ g/cm · s. For quantitative estimation of η_l we should know the mechanism of vortex penetration into the grain, but we may estimate the lower limit of η_l if we replace $\langle a^2 \rangle$ by a_0^2, its maximum value: $a(\omega, r) \leq a(0, r) \leq a(0, R) = a_0$, where r is the vortex position in the grain, R is the grain radius, and a_0 is the amplitude of quasistatic oscillations of vortices with $r \approx R$. Then $2a_0/R = |dB/B| = 3A/x_0$ and $\alpha < 3R/2x_0 \approx 7 \times 10^{-3}$. For the viscosity we obtained $\eta_l > 3 \times 10^{-4}$ g/cm · s (or $\eta_V > 10^{-5}$ g/cm^3 · s), which exceeds the flux flow viscosity $\eta_{FF} \sim 10^{-7}$ g/cm · s [7] by more than three orders of magnitude. Such a great viscosity may be explained by other mechanism of viscous flux motion, namely TAFF [12,13].

4. CONCLUSIONS

In this work we have obtained an independent confirmation of the existence of TAFF processes in HTSC grains and evaluated the lower limit of intragrain flux motion viscosity. It is also shown that the dynamic properties of a PM–HTSC system, resonance frequency and damping, are determined by the interaction of the PM field with grains and do not depend on the intergrain space. Such a simple system allows one to investigate the intragrain dynamics of magnetic flux in granular HTSC.

In summary, we note that studies of the dynamic properties of all five modes of PM oscillations are promising since they give information on the mechanisms of magnetic flux dynamics and penetration and their dependences on frequency, amplitude, and orientation of the alternating magnetic field can be obtained.

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