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Study of Vortex Motion in a Sintered High T_c Superconductor by a Vibrating Reed Technique

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Abstract : Using a vibrating reed technique in a subresonant excitation mode, dissipation mechanisms have been studied in sintered $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ superconductors with different grain sizes. Experimental results are interpreted within the critical state model. Results deduced from vibrating reed technique are compared with ac susceptibility measurements. It is shown that both techniques give consistent results.

The flux lines dynamic in high- T_c superconductors can be studied using mechanical oscillator experiments [1] or ac susceptibility technique [2,3]. In this paper, vibrating reed measurements on bulk $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ polycrystals of different grain sizes are reported, and measurements on one polycrystalline sample using both techniques are compared. Using a critical-state model, important characteristics such as the critical current density and the activation energy associated with flux creep are determined for the intragranular contribution.

1. EXPERIMENTAL

Sintered $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ samples have been synthesized from oxides (Y_2O_3 and CuO) and carbonates (BaCO_3) by a solid state sintering technique [4]. The three studied samples, have been sintered at 950°C in air, for three different times, to achieve different grain sizes: $3\text{--}4\text{ }\mu\text{m}$ (sample 1), $12\text{ }\mu\text{m}$ (sample 2) and $20\text{ }\mu\text{m}$ (sample 3). Samples, used for the vibrating reed technique are disks of 10mm of radius and 1mm thick. The one, used in ac susceptibility, is a thin parallelepiped with dimensions $(2 \times 1.85 \times 0.47)\text{ mm}^3$.

The mechanical measurements were performed using a vibrating reed technique, set into forced oscillations in the subresonance frequency range [5]. The vibrating reed is simply used as an holder for superconducting sample. The imposed vibration frequency can be freely chosen in the range 10^{-2} - 10 Hz. The vibrating amplitude was excited and detected capacitively, so that the real deflexion of the reed is not exactly known. Typical damping values corresponding to phase lags between 10^{-5} - 10^{-4} radian can be readily obtained. The specimen, exposed to a constant magnetic field H_{dc} , larger than the critical magnetic field H_{c1} , parallel to the sample surface, experiences an ac transverse ripple field $h_{ac} = \alpha H_{dc}$, when it tilts of α (the angular displacement). The flux line lattice is then deformed in a tilt mode. The complex oscillator response $G = \sigma / \alpha$, where σ is the applied stress, can be related to the magnetic susceptibility for small angular tilts. The phase lag $\arg G$, that represents the losses of the reed, is equivalent to the imaginary part of the susceptibility (χ'') [1]. The reed deflexion has been found to vary from 30 to $90\text{ }\mu\text{m}$, corresponding to h_{ac} varying from 4 to 12 Oe when a dc field of 3800 Oe is applied. Same measurements have been systematically done in two modes of cooling: without any field application (ZFC mode) or under the application of a field at $T > T_c$ (FC mode).

Complex ac susceptibility measurements have been achieved on sample 2, using an ac SQUID magnetometer in a magnetic dc field of 3500 Oe at different ac field amplitudes $0.01\text{ Oe} \leq h_{ac} \leq 3\text{ Oe}$ ($f=1$

Hz) and at frequencies $1 \text{ Hz} \leq f \leq 1000 \text{ Hz}$ ($h_{ac}=1 \text{ Oe}$). In this experimental set up, the ac field is parallel to the dc field and to the surface. The ripple shield current induced by h_{ac} , creates a lorentzian force perpendicular to the vortices which, alternatively tends to compress and to expand the flux line lattice. The deformation mode of the lattice is then a compressive mode, compared with the tilt mode in case of the vibrating reed experiment. The out of phase (χ'') susceptibility signal corresponds to the resistive losses in the material.

2. RESULTS

The $\arg G$ data for the three different samples are plotted in fig. 1(a). In the FC mode, both inter- and intragranular contribution in all samples are observed. The corresponding peaks appear at temperatures T_p^j and T_p^g with $T_p^j < T_p^g$ (notations are given in fig. 1(a)). The positions of the both inter- and intragranular peaks depend on the grain size. With increasing grain size, the peaks shift to higher temperature. Furthermore, the intergranular peak seems to shift faster than the other. With increasing grain size, the intensity ratio of the inter- over the intragranular peak decreases. This latter behaviour could be explained by a decrease of the intergranular volume [2].

Figure 1: The temperature dependence of dissipation in $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ polycrystals for 0.1 Hz , $h_{ac}=8 \text{ Oe}$ and $H_{dc}=0.38 \text{ T}$: (a) FC mode, for different grain sizes ((O) sample 1 (3-4 μm), ($\square$) sample 2 (12 μm), (Δ) sample 3 (20 μm)) and (b) ZFC and FC modes, for sample 3 (($\blacksquare$) ZFC and ($\square$) FC).

A strong supplementary damping at low temperature is observed when the measurement is done in the ZFC mode (fig. 1(b)). Explanation of such phenomenon is beyond the scope of this paper. The phenomenon becomes stronger when the grain size increases. It depends strongly on the temperature and on the frequency. It is only seen at frequencies below 1 Hz and increases when the frequency decreases. The same difference between ZFC and FC, is also found in ac susceptibility measurements (at 1 Oe and 1 Hz). The comparison between the both experiments is not discussed because their initial flux magnetic profile is probably not the same. Indeed, due to relaxation effects, this profile - and then the dynamical response - depends strongly on the time spend to establish the dc magnetic field [6].

In fig 2, a strong difference between ac susceptibility and vibrating reed measurements at low temperature is evidenced (the only different parameter being the sample geometry). The intergranular peak is shifted to lower temperature in ac susceptibility measurements and a similar peak position, as in vibrating reed measurements, is found for a smaller h_{ac} .

YBaCuO granular materials are described by Clem [8] and Müller [9] in terms of anisotropic grains of stoichiometric material, separated by layers of nonstoichiometric interface material which act as Josephson junctions. The dependence on h_{ac} of their ac behaviour is explained using a critical state model [8,9]. When the applied magnetic field is weak ($h_{ac} > h_c^j$), the magnetic flux penetrates the intergranular weak-links network. For higher fields ($h_{ac} > h_c^g$), magnetic flux penetrates the grains. The losses become

maximum when the Josephson vortices reach the center of the slab (intergranular peak) or when Abrikosov vortices reach the center of the grains (intragranular peak). Within the critical state model, the shift to lower temperature of T_p^j and T_p^g with increasing h_{ac} or with decreasing sample dimensions [7] could be explain. This latter phenomenon could explain the difference of response using both techniques.

Figure 2: Dynamical response for sample 2, in FC mode obtained with vibrating reed (a) and ac susceptibility measurements (b) (the numbers, near the peaks, are the applied ac field values).

For increasing h_{ac} , the force exerted on the vortices is stronger, while the pinning strength is the same. Thus, the magnetic field reaches the sample center at lower temperature. Furthermore, because the intergranular pinning force is rather weak, the intergranular peak shifts considerably with increasing h_{ac} , compared to intragranular peak. Indeed, in ac susceptibility measurements, for two particular values of h_{ac} , we can estimate the intergranular peak shift with h_{ac} : $\delta_{ac}^j \approx 150$ K/Oe, while the intragranular peak shift is $\delta_{ac}^g \approx 0.6$ K/Oe.

The inter- and intragranular critical current densities are given by [10]:

$$J_c^j(T_p^j) \equiv 2f \frac{h_{ac}(T_p^j)}{d} \quad \text{and} \quad J_c^g(T_p^g) \equiv 2f \frac{h_{ac}(T_p^g)}{R_g}$$

with d a typical dimension of the specimen (minimum dimension perpendicular to ac perturbation: 0.47mm in ac susceptibility measurement and 10mm in vibrating reed measurements), R_g the mean grain size and f a geometrical factor, due to demagnetization effects ($\approx \pi w/4d$ for a slab (width w , thickness d) when h_{ac} is perpendicular to the surface, and, ≈ 1 when h_{ac} is parallel to the surface [1]). f is about 1 for susceptibility measurements and 7 for vibrating reed measurements. The temperature dependence of the intragranular critical current density, obtained by both techniques is shown in fig. 3. The results seem consistent.

Figure 3: The dependence on temperature of the intragranular critical current density for sample 2, calculated within a critical state model, from vibrating reed (■) and ac susceptibility measurements (x).

The increase of T_p with frequency could be explained by thermally activated motion of flux lines over pinning barriers [11]. In this case, the frequency dependence of T_p obeys an Arrhenius law [12]:

$$f_p = f_0 \exp\left(-\frac{U}{kT_p}\right),$$

where f_0 depends on v_0 an attempt frequency and U is an effective thermal activation energy, depending on applied magnetic field and temperature. The temperature dependence of the activation energy may be linearized near T_c [13] by $U(H,T)=U_0(H)(1-T/T_c)$. The plot of $\ln f$ vs $1/T_p$, for a dc field of 3800 Oe and an ac field of 8 Oe, allow us to calculate the activation energy U_0 for the intragranular peak. The shift is nevertheless very small, leading to high values of activation energy. A higher activation energy is found for the sample with large grain size: 5.2 eV (sample 3) compared to 3.9 eV (sample 2). For sample 2, the ac susceptibility measurements give a similar result (3.6 eV). Such values of the activation energy and even higher one, have already been observed [14], despite the fact their physical signification is not clear.

3. CONCLUSION

It has been shown that, with the vibrating reed technique, at low temperatures and at low frequencies ($f < 1$ Hz), the ac losses in ZFC and FC modes are strongly different. In the FC mode, two peaks characteristic of a polycrystal are obtained: an inter- and an intragranular peak. Despite a different deformation mode of the flux lines lattice, similar characteristics such as J_c and U_0 are obtained using vibrating reed and ac susceptibility techniques, when geometrical differences between the samples are taken into account.

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