Vibrating reed studies on high- T_c superconductors

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Abstract. We present vibrating reed (VR) measurements on single crystal and ceramic “1-2-3” and melt-processed polycrystalline Bi-based compounds in a wide range of temperature (4.2–100 K) and magnetic field ($B = 0$ –4 T). The “depinning line” (DL) determined by the VR technique is equivalent to the “irreversibility line” determined by magnetization and susceptibility measurements. A comparison of the results on single crystal and polycrystalline 1-2-3 compounds indicates that the VR technique is sensitive to the intragranular properties of the polycrystalline reed. It is found that the DL for 1-2-3 compounds is much steeper than that for Bi-based compounds, reflecting an intrinsically different pinning in both the materials, in agreement with the measured elastic coupling (Labusch constant $\alpha(B, T)$).

Keywords. Flux pinning; flux motion; vibrating reed.

1. Introduction

The dynamics of the flux line lattice (FLL) motion in high- T_c superconductors is governed by the coupling between the FLL and the atomic lattice. Due to a relatively low pinning potential, thermally-activated motion at high temperatures gives rise to unexpected phenomena. Numerous different experiments like dc-magnetization, ac-susceptibility, resistivity, I – V characteristics, mechanical oscillators, have been performed to study the response of these materials under magnetic field. To interpret these experiments, concepts like a superconducting glass state (Müller *et al* 1987), giant flux creep (Yeshurun and Malozemoff 1988), thermally-assisted flux flow (TAFF) (Kes *et al* 1989), a vortex glass state (Fischer 1989), FLL melting (Nelson 1988; Brandt 1989a), and thermally-activated depinning (Gupta *et al* 1989a), have been invoked.

In the present work, we have addressed the question of the FLL dynamics by performing vibrating reed (VR) measurements in a magnetic field on a single crystal, as well as on ceramic and melt-processed Y- and Bi-based superconductors.

2. Experimental procedure and samples

The VR technique has been successfully used to study the FLL coupling to atomic lattice in high- T_c superconductors (Gupta *et al* 1989a, b, c). We measured both the resonance frequency and damping of the VR as a function of temperature (10–100 K) at fixed fields as well as varying fields (0–4.2 T) under isothermal conditions. In this work we report results on a variety of high- T_c superconductors: Y(6% Gd)Ba₂Cu₃O_{6.83}

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single crystal ($T_c = 67$ K, $B \perp c$ -axis), low-density ($\rho = 5.4$ g/cm³) ceramic YBa₂Cu₃O_{7-x} ($T_c = 87$ K), high density melt-processed single phase Bi₂Sr₂CaCu₂O_{8-x} ($T_c = 83$ K, $\rho = 5.96$ g/cm³) and ceramic Bi_{1.5}Pb_{0.5}Sr₂CaCu₂O_{8-x} ($T_c = 70$ K, $\rho = 4.9$ g/cm³) samples.

3. Results

The measured dissipation of a superconducting vibrating reed in the presence of a field $B > B_{c1}$, is due to the movement of the FLL relative to the pinning centres of the sample (Brandt *et al* 1986; Esquinazi *et al* 1986). Our measurements indicate that the absolute value of the damping Γ is similar and there is no need to invoke extra contributions to the damping due to the difference of connectivity in the materials studied. As reported earlier (Gupta *et al* 1989a, b) a peak in Γ in high- T_c materials occurs at a field $B(T) < B_{c2}(T)$, at a characteristic temperature T_D . This damping peak is similar to the peak of χ'' in ac-susceptibility measurements and has the same origin (Gupta *et al* 1989c; Kes *et al* 1989).

There is a basic difference in the damping mechanism below and above the peak. In figure 1, the damping of the Gd-1-2-3 crystal is plotted as a function of driving voltage at different temperatures in a field $B = 0.5$ T. By varying the driving voltage one can vary the amplitude of the VR, which is equivalent to changing the ac-field in ac-susceptibility experiments or the Lorentz force in resistivity measurements. At 30 K (i.e. far below the peak), Γ increases monotonically with driving voltage. However, at 64 K, (slightly above the peak) Γ initially increases and then decreases with amplitude. At 65 K, Γ decreases slightly at low driving voltages and finally becomes independent of amplitude. This difference in the response of the VR above and below the peak in Γ is a highly significant result. It is known from VR theory (Brandt *et al* 1986) that Γ is mainly caused by hysteretic FL jumps. Clearly, this process is responsible for the increase of Γ with amplitude below T_D . At temperatures $T \geq T_D$, the FLL is depinned and dissipation is caused by viscous damping. Thus the peak in Γ marks a transition from hysteretic- to viscous-dominated regime. Such a transition was also observed in polycrystalline materials by Gupta *et al* (1989b). This crossover is entirely equivalent to

Figure 1. Damping Γ versus driving voltage for the Gd-1-2-3 single crystal.

the transition from an “irreversible” to a “reversible” region marked by the χ peak in ac-susceptibility or the “irreversibility line” in dc-magnetization measurements (Kes *et al* 1989; Gupta *et al* 1989c).

Each peak in Γ is accompanied by a change in the resonance frequency ν of the reed (Gupta *et al* 1989a, b) which is a consequence of the finite pinning of the FLL in the reed (Brandt *et al* 1986; Esquinazi *et al* 1986). Our results indicate that there is no broadening of the transition for the polycrystalline material compared to the single crystal. This fact reinforces the interpretation that in the VR one observes mainly the intragranular FLL behaviour.

From the variation of ν with field and temperature, the Labusch constant $\alpha(B, T)$ (Labusch 1968) can be calculated, as shown by Brandt *et al* (1986) and Esquinazi *et al* (1986). The Labusch constant characterizes the elastic coupling between the FLL and the pinning centres. It is defined as $\alpha = \nabla^2 U$, where U is the average pinning potential which the FLL feels. For appropriate pinning models we can approximate,

$$\alpha(B, T) = U(B, T)/V_C s_p r_p(1),$$

where V_C is the coherence volume of a flux “bundle”, r_p is the range of the pinning potential and $s_p \simeq a_o/2\pi$ (a_o is the FL spacing).

Figure 2 shows the variation of α as a function of temperature for the Gd-1-2-3 crystal at $B = 0.56$ T. The field dependence at 55 K and 20 K is given in the inset, where the values for melt-processed Bi(2-2-1-2) at 15 K are included as well. It is tempting to relate the temperature dependence of the pinning potential $U(t)$ with the temperature dependence of the Labusch constant $\alpha(t)$ for a fixed vortex density, i.e. neglecting the possible T -dependence of V_C and r_p . A conventional choice is $U(t) = H_C^2(t) \xi^n(t)$. The continuous curve in figure 2 is given by $((1 - t^2)^{0.8}(1 + t^2)^{1.2}/1.04)$, which means $n = 2.4$. At higher temperatures $T \geq 0.8 T_c$, thermal activation becomes important and thermally-activated depinning takes place. As a consequence, the rapid decrease of the calculated α is only apparent and does not reflect the intrinsic, activation-free, FLL to atomic lattice coupling. Thus, the intrinsic elastic properties of the FLL-atomic lattice coupling cannot be derived in the temperature range near T_D .

The Labusch constant α increases as B^m ($m \simeq 1.8$) for both the Gd-1-2-3 single crystal and melt-processed Bi(2-2-1-2) sample (see figure 2). The value of α for the Bi-compound is almost three orders of magnitude lower than for the Gd-1-2-3 compound, suggesting that the pinning potential is intrinsically lower in the Bi-based superconductor.

In figure 3 we compare the DLs of the three samples obtained by the VR method. Two criteria have been used to define T_D : at the peak of Γ or at $\Delta\nu = 0$, determined by a linear extrapolation of $\Delta\nu(T)$ at the transition. The DLs defined by the peak in Γ and $\Delta\nu = 0$ are displaced with respect to each other for all the three samples. As shown by Gupta *et al* (1989c) the peak in Γ occurs when the diffusion coefficient of the vortices is of the order of $\pi\nu l^2$, where l is a characteristic dimension (≈ 0.4 of the reed length) parallel to the magnetic field direction in the sample (see also Brandt 1989b). The main variation of $D(B, T)$ comes from the variation of $U(B, T)$ (Kes *et al* 1989). Thus, parallel DLs indicate similar B and T dependence of the pinning potential. This is the case for the Gd-1-2-3 crystal and $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ ceramic (figure 3). The relative shift in the reduced temperature scale of the DL of the 1-2-3 ceramic does not mean lower pinning potential but is due to different critical temperatures (i.e. the absolute temperature enters in the diffusion constant). On the other hand, the difference in the slopes of the

Figure 2. Reduced Labusch constant vs reduced temperature. The solid line is the function $(1 - t^2)^{0.8} (1 + t^2)^{1/2} / 1.04$. Inset: Log-log plot of Labusch constant as a function of applied field. The increase of $\alpha(20\text{ K})$ at low fields for the Gd-1-2-3 crystal is spurious and is due to the non-negligible diamagnetic contribution of the VR which is not considered in the calculations.

Figure 3. Depinning lines of: (*) Gd-1-2-3 single crystal, (■) melt-processed Bi(2-2-1-2), (○) 1-2-3 ceramic, (Δ) data from Palstra *et al* (1988, 1989) (◇) data from Gammel *et al* (1988).

DLs between Gd-1-2-3 crystal and Bi-based superconductors, which appears to be independent of the preparation conditions (see Gupta *et al* 1989b) indicates different temperature and field dependence of $U(B, T)$. In particular $U(B, T)$ for Bi-based compounds should decrease much faster with increasing field than as in the 1-2-3 compounds. Since the B -dependence of α is the same for both Bi- and Y-based compounds (inset, figure 2), we conclude from (1) that the B -dependence of $V_C(B, T)r_P(B, T)$ should be different.

4. Discussion

It was shown that the broadening of the resistivity transition with magnetic field in high- T_C materials can be interpreted in terms of thermally-activated flux motion. Within the model of flux diffusion the measured resistivity ρ is proportional to the diffusion coefficient $D(B, T)$ (Kes *et al* 1989; Brandt 1989b; Esquinazi 1990). Choosing a resistivity criterion to define a DL is equivalent to choosing a constant diffusion coefficient criterion like in susceptibility or VR measurements. As shown in figure 3 using the results of Palstra *et al* (1988, 1989) (6) with $\rho = 10^{-3} \mu\Omega\text{cm}$, we obtain a DL parallel to the Γ peak criterion in VR measurements. A lower ρ criterion will yield a DL closer to the DL determined by the Γ peaks.

The idea of FLL melting in high- T_C materials was used by Gammel *et al* (1988) to explain the results of mechanical oscillator measurements in a magnetic field. Figure 3 shows the DL obtained by Gammel *et al* (1988) for the 1-2-3 single crystal for $B \perp c$ -axis. Their data match with the resistivity and our VR data. As pointed out above, the relative position of the DLs on the reduced temperature scale does not depend only on the pinning potential but also on the kind of experiment, definition of T_D , and on the definition of the critical temperature.

The interpretation of the observed depinning in terms of FLL melting (the FLL flowing almost freely between widely spaced pins) is not realistic in three-dimensional FLL, because each of the FLs interacts with many pins along its length. A low pinning density as assumed by Markiewicz (1989) is neither a necessary condition to explain the broadening of the resistivity in terms of flux creep nor does it have a clear experimental support. Recent calculations of the diffusion coefficient in terms of densely distributed pinning sites (Inui *et al* 1989) reproduce the resistivity $\rho(T, B)$ measured by Palstra *et al* (1988, 1989). Moreover, the shear modulus c_{66} is expected to decrease gradually with increasing temperature; thermal FLL disorder would be superimposed onto pinning-caused disorder (Brandt 1989a). Therefore, no sharp transition should occur in three dimensions, in contrast to the experimental observation. It is important to note that, were the observed anomalies a manifestation of "melting", then the irreversible to reversible crossover should be driving force independent, i.e. it should depend only on the applied magnetic field. The experimental results (figure 1 of Gupta *et al* 1989b) clearly contradict this interpretation.

5. Conclusions

We have shown that the high- T_C compounds behave very similar in VR measurements irrespective of their microstructure. The VR technique can be used successfully to

obtain the DLs of polycrystalline materials with reasonable mass densities. The DL obtained for the 1-2-3 ceramic sample is similar to that obtained for the Gd-1-2-3 single crystal, indicating that the pinning of the FLs would be intrinsic rather than due to defects, e.g. oxygen vacancies or twinning planes. The smaller values of the Labusch constant and the behaviour of the depinning temperature obtained for the Bi-based melt sample indicates an intrinsically different pinning potential $U(B, T)$ as for the 1-2-3 compounds in agreement with resistivity data (Palstra *et al* 1988, 1989). The mechanical oscillator response can be understood in terms of thermally-activated depinning. Due to the thermally-activated depinning, from the frequency response of the VR, no information can be obtained of the intrinsic elastic coupling $\alpha(T, B)$ at temperatures $T \geq T_p$. The possibility of "melting" of the FLL or of any anomaly in the elastic constants of the FLL at $T \geq T_p$ remains highly speculative.

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