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FLUX CREEP IN $Bi_2Sr_2Ca_1Cu_2O_{8+x}$ SINGLE CRYSTALS

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ABSTRACT

Dissipative effects have been investigated in $Bi_2Sr_2Ca_1Cu_2O_{8+x}$ single crystals by critical current and magnetic relaxation measurements. Activation energies for the flux motion have been determined from the temperature dependence of the critical current and from the time decay of the zero field cooled and the remanent magnetization. The effective activation energy has been found to increase with temperature, in agreement with the existence of a distribution of activation energies (E_0 20 meV at 4.2 K for H=10 kOe applied parallel to the c-axis).

1. INTRODUCTION

A great deal of effort has been recently devoted to the study of the large relaxation effects seen in the oxide superconductors (1-3). Relaxation processes, associated with the thermally activated flux motion, have been commonly observed in conventional superconductors. However, due to the high activation energy (1 eV) compared to the low thermal energy at 4.2 K, these processes are tolerably slow. Unfortunately, the picture is quite different for high-T_c superconductors. In fact, due to the short coherence length (e.g., 2A < ξ < 40A), which presumably affects the spatial range of pinning forces, and to the higher absolute operating temperatures, dissipative effects are certainly one of the most serious obstacles to applications requiring high magnetic fields.

In any superconductor in the mixed state, the flux lines are pinned by various types of inhomogeneities (impurities, grain boundaries, extended defects, etc.). Therefore, a number of different mechanisms are possible sources of the interaction between flux lines and defects and, in general, any theoretical description of flux pinning is simplified by assuming that the microscopic defect dimensions are small compared to the flux line lattice parameter. At present, the critical current density in bulk oxide superconductors at 77 K is far below the level of Nb-Ti at low temperatures, mainly because of the weak link nature of grain boundaries in high-T_c materials. However, high critical current densities have been observed in single crystalline thin films (4) and in bulk textured materials. Therefore, because of ambiguity in the morphology and the density of the dominant pinning centers, the nature of the pinning mechanism in high-T_c superconductors has not been clarified.

Much experimental evidence of large dissipative effects has been reported in high-T_c superconductors by different measurement techniques such as DC resistivity (5-8), DC susceptibility (3), time dependence of magnetization (9), and mechanical oscillator (10, 11). In this paper, we will focus our attention on the relaxation properties of a $Bi_2Sr_2Ca_1Cu_2O_{8+x}$ (nominal composition) single crystal. The study has been performed by measuring both the critical current density and the time decay of the magnetization as functions of temperature.

2. RESULTS AND DISCUSSION

2.1 Sample characterization

A single crystal (platelet of dimensions 2.2x1.7x0.3 mm³) grown by a flux technique (12) has been selected for the measurements. The analysis of the X-ray diffraction pattern indicated the presence of the 2212 phase only. This result has been further supported by the magnetic characterization carried out by AC susceptibility measurements (mutual inductance bridge, with H_{ac} = 1 Oe at ν = 200 Hz) and by DC magnetization measurements (commercial S.H.E. SQUID magnetometer), with the magnetic field applied both parallel and perpendicular to the c axis of the crystal. Both the AC (fig. 1) and the DC curves show only one transition at 85 K without any detectable drop at 110 K, thus confirming the absence of any contribution from the higher T_c phase. The lower critical fields at 4.2 K have been deduced by analysis of the low field region of the magnetization cycle; the H_{c1} values, estimated by the deviation from linearity of the M vs H plot, are H_{c1} (//c)=880 Oe and H_{c1} ($\perp$c)=140 Oe (corrected for the demagnetization factor). Values of H_{c1} reported in the literature commonly range from 10 Oe to 1000 Oe; however, the lowest values should actually reflect flux penetration through non-superconducting phases or intergrowths within the 2212 phase, and are not an intrinsic feature of the material itself.

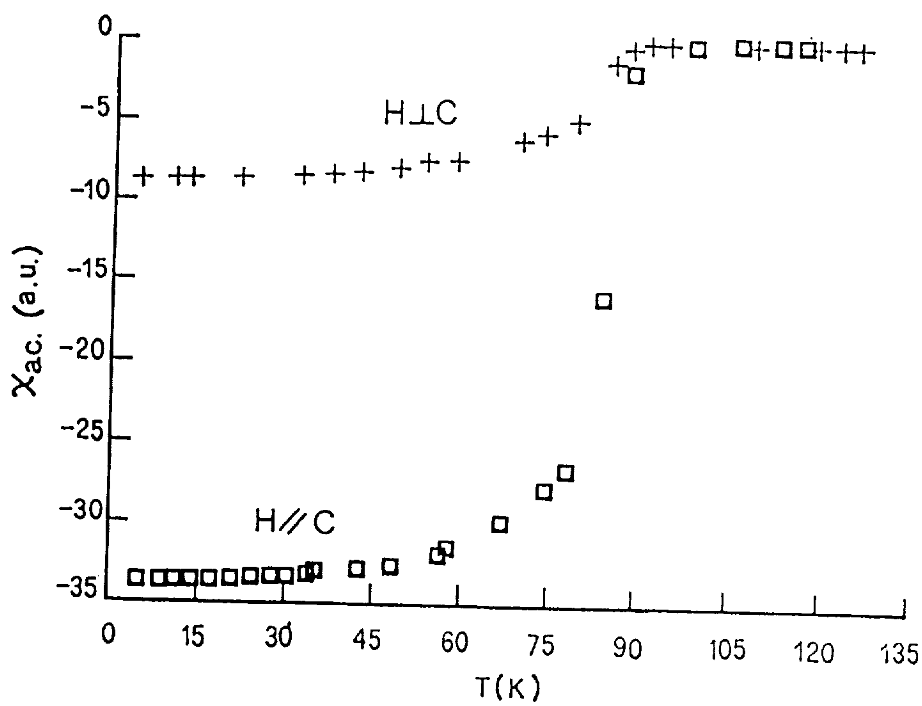

Figure 1. AC susceptibility curves.

2.2 Critical current measurements

Magnetization cycles up to 5 T have been performed at different temperatures (fig. 2). The cycle amplitude, connected to J_c in the Bean critical state model (13), decreases rapidly with increasing temperature. This results in an irreversible regime restricted only to low fields, thus indicating a strong field dependence of J_c even at temperatures well below T_c. This effect is also shown in fig. 3, where the magnetization at 2 kOe is reported as a function of temperature. The lower branch corresponds to the magnetization measured after increasing the field up to 2 kOe, while the upper one corresponds to the magnetization measured after a cycle 0->20 kOe->2 kOe. At 2 kOe there is no longer irreversibility above 20 K.

The Bean model approach, which assumes that the flux gradient is normal to the sample surface and has a magnitude of $4\Pi J_c$, allowed us to determine the critical current density J_c from the volume magnetization. For the H//c case, J_c is isotropic in the CuO_2 plane, allowing us to appproximate our sample as an isotropic cylinder of radius R=0.1 cm. For the H⊥c case, the sample cross section can be considered as a rectangle; this results in a current flowing both parallel as well as perpendicular to the planes and therefore not isotropic. Following Biggs et al. (14), the sample has been approximated as an infinite slab (thickness D=0.2 cm, in our case). J_c in zero field was measured by two different procedures. In the first case, the remanent magnetization was measured at 4.2 K after a cycle up to 5 T and then warming up to T_c. In the second case, after zero field cooling, a cycle has been performed at each temperature and the magnetization measured. The same behaviour was observed in both cases, thus reflecting that the temperature effect is much more important than the time effect. J_c decreases very rapidly with increasing temperature, revealing a high degree of thermal activation for flux motion across the energy barriers.

The temperature dependence of J_c is well decribed by the phenomenological law:

$$J_c(T) = J_c(0) \; [1- T/T_c]^8 \qquad (1)$$

as reported for YBaCuO (9). Actually, with increasing temperature, the applicability of the Bean model becomes questionable as the flux creep rate should be higher than the rate of field variation. Anyway, the phenomenological relation (1) gives an estimate of the rate of the temperature decrease of J_c with respect to conventional superconductors, where the exponent has been found to lie in the range of 1-2.5. The low temperature behaviour of T_c has been analyzed in the framework of the thermally activated flux creep model (15). Thermal activation increases the flux creep rate thereby reducing the observed critical current density, which is given by (15):

$$J_c(T) = J_{co} \, [1-(kT/U_o)1n(t/t_o)] \qquad (2)$$

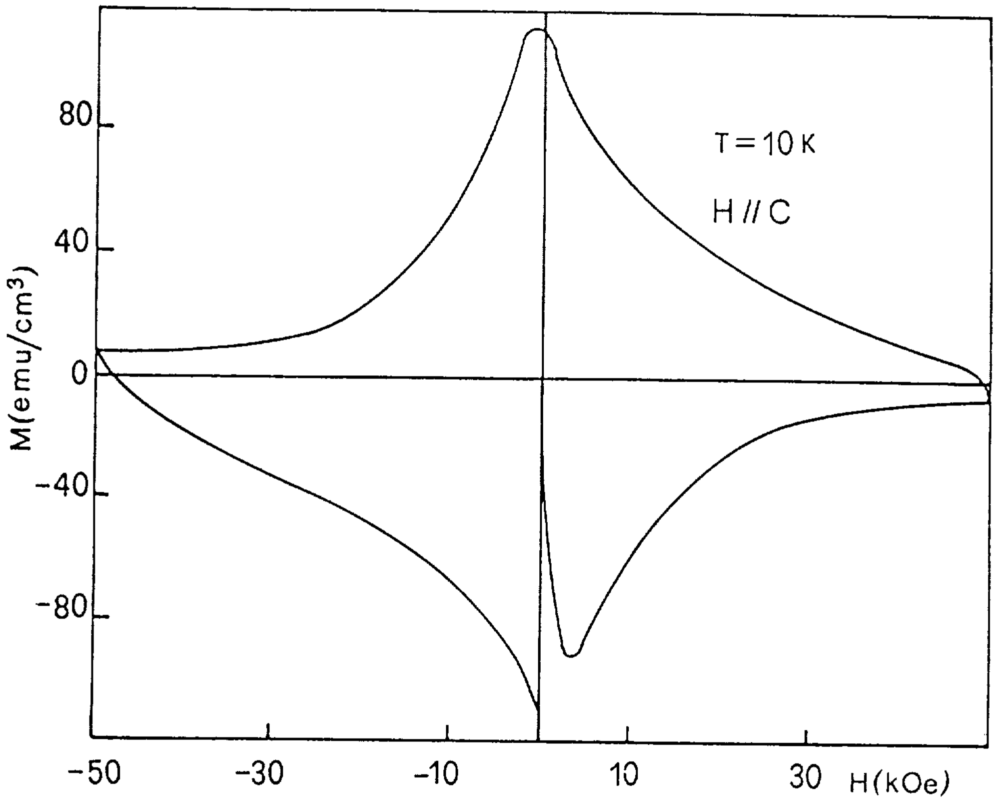

Figure 2. Magnetization cycle at 10 K.

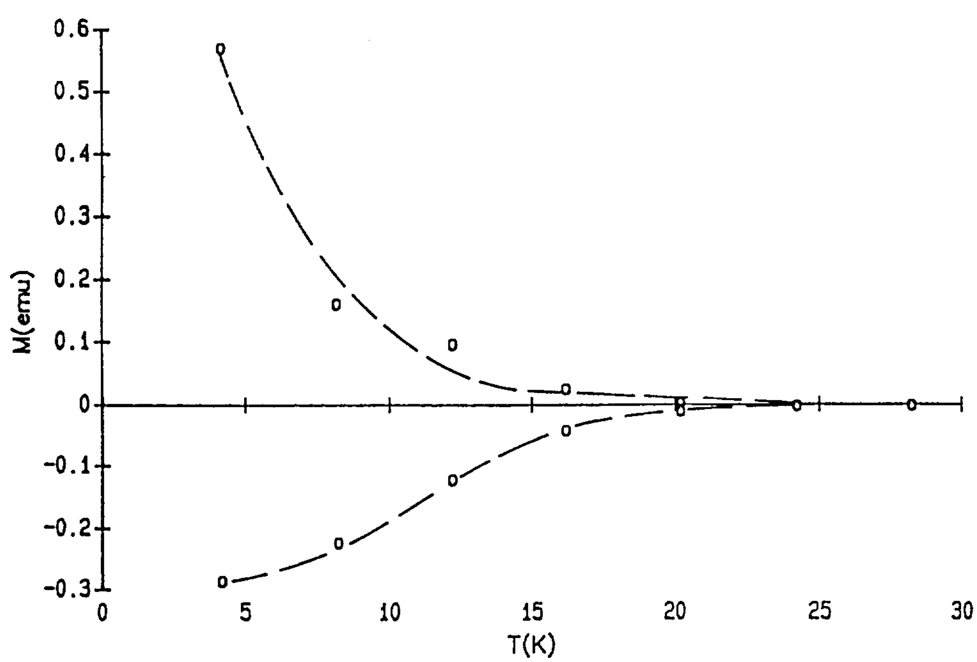

Figure 3. M(H=2 kOe) vs. T (see text).

where J_{c0} is the value of J_c in the absence of thermal activation of flux lines, U_0 is the depth of the pinning potential, t is a characteristic time for the experiment, and t_0 is a constant which depends on parameters such as the fluxon oscillation frequency, the average hopping distance of the fluxons, etc. (15). As a consequence of equation (2), the temperature dependence is much stronger than the time dependence and therefore, to a first approximation, J_c is time independent and linear in T at low temperatures. From the intercept of the straight line at T=O K, the following values of J have been deduced: $J_{c0}(//c) = 1.1 \cdot 10^5$ A/cm^2 and $J_{c0}(\perp c) = 1.5 \cdot 10^4$A/cm^2. From the observed slope, at $t \approx 10^4$ s and assuming $t_0 \approx 10^9$ s (14), the activation energy has been determined for both orientations: $U_0(//c)$ = 36meV and $U_0(\perp c)$ = 37 meV. The absence of anisotropy in U_0 would suggest that the flux motion perpendicular to the Cu-O planes is negligible; fluxons essentially move along the Cu-O planes even when the field is applied perpendicular to the c-axis (14).

However, it should be noted that equation (2) was deduced assuming a linear current dependence of U_0; this approximation is correct only for the case of a square-shaped flux line potential, which could not reflect the physics of the actual pinning mechanism.

2.3 Relaxation measurements

The relaxation properties of the Bi-Sr-Ca-Cu-O crystal have been investigated by measuring the time decay of the zero field cooled magnetization (M_{zfc}) and of the remanent magnetization (M_r). In the former procedure, the sample has been first cooled in zero field from above T_c and then, at different temperatures, a field H=10 kOe has been applied parallel to the c axis; in the latter one, the decay has been recorded in zero field, after a magnetization cycle up to 5 T. In fig. 4, the time decay of the magnetization, normalized to the first measured value, is reported. The observed relaxation rate is very fast (e.g., at T = 15 K after one hour, the relative decrease of the magnetization is 48%), which is consistent with the vanishing of J_c in low fields well below T_c.

The relaxation data have been analyzed in two ways, both within a thermally activated motion picture. In the first one, the classical flux creep model, which assumes the existence of energy barriers of the same height, has been applied. We substituted equation (2) into the Bean equations (which assume J_c independent of H) (13); for the H//c case, using the cylinder approximation and ignoring H_{c1}, the relaxation rate is given at the lowest order in kT/U_0 by (9):

$$\mathbf{d\,(4\Pi M)\,/\,d\ln t = -\,(H^2/H^*)\,[1-2/3(H/H^*)]kT/U_0} \qquad H<H^* \qquad (3a)$$

$$\mathbf{d\,(4\Pi M)\,/\,d\ln t = -\,(H^*/3)kT/U_0} \qquad H \geq H^* \qquad (3b)$$

where $H^* = 4\Pi J_{c0} R/10$ is the field at which flux first penetrates entirely through the sample. In our case, the applied field (10 kOe) is much larger (after the correction for the demagnetization factor) than H^*. From equation (3b), a value of U_0= 10 meV at 4.2 K has been deduced. Yeshurun et al. (16) have developed a more realistic model, which takes into account the field dependence of J_c and the onset of irreversibility at H_{c1}. In particular, they developed a formula for the magnetization of a slab in a field lying in the slab plane, with J_c taking the form $J_c = J_{c1}(H_{c1}/h)^n$ for $h>H_{c1}$, where J_{c1} is the maximum critical current at a given temperature, h is the local field

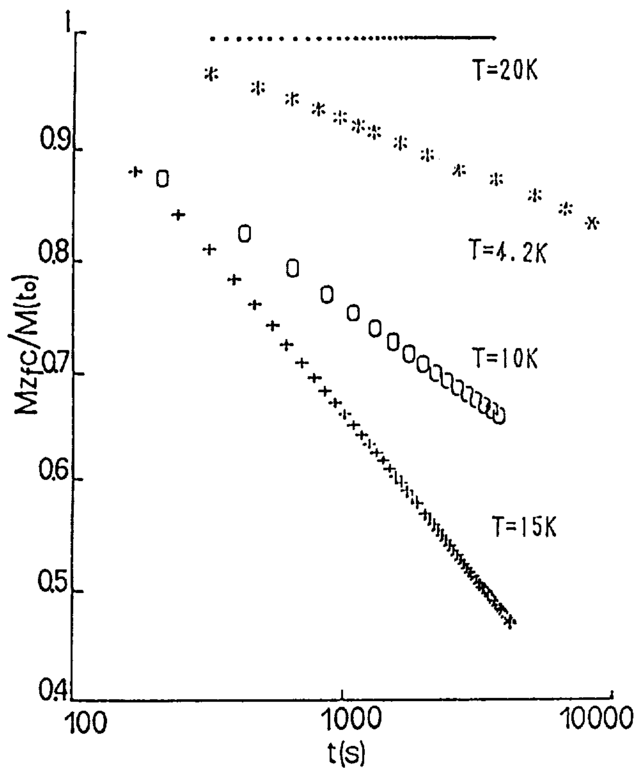

Figure 4. Time dependence of the ZFC magnetization for H=10 kOe //c.

at a distance,x, from the slab edge, and n, a phenomenological power. They found n=1 for YBCuO (with an U_0 value differing only by a factor of two from that deduced from the original Bean model) and n=0 (thus recovering the original Bean equations) for Bi-Sr-Ca-Cu-O single crystals (3). Moreover, the temperature dependence of the relaxation rate, going through a maximum, is only partially reproduced by the model.

On the other hand, assuming the existence of a distribution of activation energies as in the Hagen-Griessen model (17), the temperature dependence of the relaxation rate can be well described in the whole temperature range. According to this model, the relaxation rate (S) has the form:

$$\mathbf{S = |dM/(Mdlnt)|t_0 = - [E_0(T)/kT - ln(t_0/\tau)]^{-1}} \qquad (4)$$

where t_0 is the starting time for the decay recording, τ is a characteristic relaxation time which is presumably in the range of 10^{-12} s-10^{-6} s (this uncertainty does not affect the deduced $E_0(T)$ values by more than 10%), and $E_0(T)$ is an effective temperature-dependent activation energy; i.e., a weighted average of the local activation energies. The deduced values of $E_0(T)$ at T=4.2 K are the following: E_0(//c)= (18±2) meV and $E_0(\perp c)$= (37±2) meV from the relaxation of M_{zfc}; E_0(//c)=(20±2) meV and $E_0(\perp c)$=(56±2) meV from the relaxation of M_r. Our data are consistent with a distribution of activation energies peaked at E=40 meV, as found by Hagen and Griessen in their analysis of Yeshurun's relaxation data (3,17). Furthermore, our results confirm the absence of significant anisotropy in the observed E_0 which is found to increase with temperature ($E_0 \approx 3$ eV at 20 K), as implied in the Hagen-Griessen model. The activation energy of a single pinning center should decrease with temperature and therefore, the observed increase of $E_0(T)$ must be related to the existence of a distribution of activation energies.

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Some processes occur on a time scale shorter than the typical SQUID measuring time and, at higher temperatures, the measured relaxation is essentially that associated with the high-energy characteristic tail of the predicted distribution.

Another explanation of the observed increase in $E_0(T)$ and of the maximum commonly observed in S(T), has been attempted by Larkin and Geshkenbein (L.G. model) (18) generalizing the Anderson's flux creep model. This generalization is based on the assumption that there exist two kinds of pinning centers: many weak centers with rather low activation energy and few strong centers with high activation energy. At low temperatures, weak centers give the main contribution to the pinning and creep and S(T) monotonically increases with temperature. At high temperatures, the weak centers are excluded and the critical current is determined by strong centers for which creep is much slower. This results in a decrease of S(T) and in the observed increase of the effective activation energy $E_0(T)$, which is in turn, related to the existence of high barriers between equilibrium states of the vortex lattice. However, in the L.G. model, the kind of centers for which the pinning energy is high or low, is not clarified.

We would finally remark that the Anderson-Kim model and its extensions do not take into account possible collective effects of the vortex lines, i.e., the existence of interactions between bundles of flux lines. In fact, in the flux creep picture, flux lines are considered as "point particles." In a bulk superconductor, vortex lines are of course, one-dimensional objects but due to the presence of defects, they experience different pinning surroundings. Taking into account collective effects of the flux lines, novel flux states have been predicted (19,20), which are different from the conventional Abrikosov flux lattice. Recently, experimental evidence in favour of the existence of a "vortex glass" phase, implying both collective effects and the existence of a random potential, has been reported for epitaxial films of YBaCuO (21). Although these new concepts certainly require a more complex analysis of experimental data, their applicative implications are an intriguing object of debate.

3. CONCLUSIONS

Almost completely reversible magnetization cycles, except for low fields, above 30 K and a very strong relaxation of the magnetization have been observed in a $Bi_2Sr_2Ca_1Cu_2O_{8+x}$ single crystal. These results, compared with those reported for YBaCuO single crystals (9), indicate that in Bi-based compounds, the dissipative effects are much stronger and that they take place at much lower temperatures, well below T_c. While a significant difference between the values of the critical current at 4.2 K is not generally observed, the temperature dependence in the presence of magnetic fields is very different, thus revealing a much faster thermally activated flux motion in the Bi-based compounds. The difference in the pinning energies between BiSrCaCuO and YBaCuO compounds could be, in principle, associated with the different defect structures. In BiSrCaCuO, the pinning centers are supposed to be weak and randomly distributed point defects (e.g., cross substitutions, intergrowths, etc.). On the other hand, extended defects such as twin planes are present in $YBa_2Cu_3O_7$. Recent experiments on a series of YBaCuO single crystals with different twin boundary densities have shown that the magnetically deduced J_c at 4.2 K is not significantly affected by the presence of twin boundaries (22). However, a smaller irreversibility regime was found in the region near T_c for an untwinned crystal, thus implying lower pinning energies. At such high temperatures, the lattice defects with low pinning energy become less active and the twin boundaries can play an effective role.

The great difference in the electronic anisoptropy (a value of $3 \cdot 10^3$ for the superconducting effective mass anisotropy has been reported for BSCCO (23)) could be the main reason for the different pinning energies and therefore, for the different dissipative behaviour shown by BSCCO and YBCO. A large electronic anisotropy can indeed result in a reduction of the correlation length along the flux lines (L_c), implying a decrease in correlation between vortices in adjacent planes.While in YBCO the coherence length is comparable to the interplanar spacing, in BSCCO it is four times smaller, thus implying a more two-dimensional character.

A shorter correlation length along the vortices results in a smaller flux bundle volume and, consequently, in smaller activation energies: $U_o = J_c \chi B d^2_c L_c r_p$, where dc is the correlation length of the vortices in the planes and r_p is the spatial range of the pinning potential (24). Large dissipative effects are thus favored by small values of L_c, an intrinsic feature of anisotropic compounds and thin films, and by a short coherence length which holds for large K superconductors, including high-T_c materials.

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