Plasticity and Memory Effects in the Vortex Solid Phase of Twinned $YBa_2Cu_3O_7$ Single Crystals

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We report on marked memory effects in the vortex system of twinned $YBa_2Cu_3O_7$ single crystals observed in ac susceptibility measurements. We show that the vortex system can be trapped in different metastable states with variable degree of order arising in response to different system histories. The pressure exerted by the oscillating ac field assists the vortex system in ordering, locally reducing the critical current density in the penetrated outer zone of the sample. The robustness of the ordered and disordered states together with the spatial profile of the critical current density lead to the observed memory effects.

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Continuous efforts have been made to understand the remarkably rich variety of liquid and solid phases in high temperature superconductors [1]. A subject that has recently attracted much interest is the connection between these thermodynamic phases and the driven motion of vortices, in particular concerning the presence of topological defects (like dislocations) and the evolution of the spatial order of the vortex structure (VS) at different driving forces [2–10]. In systems containing random pinning, theoretical [2] and experimental [3,5–7] results have shown that, at the depinning transition, the VS undergoes plastic flow in which neighboring parts of the flux lattice move at different velocities thereby disordering the VS.

Changes in the volume in which vortices remain correlated may modify the critical current density J_c and lead to a thermomagnetic history dependence in the transport and magnetic properties of the superconductor in a way reminiscent of other disordered systems such as spin glasses [11]. History effects recently observed in conventional low-T_c superconductors [6,9,10,12] were attributed to plastic deformations of the VS; however, little is known about the exact mechanism involved in these phenomena. In $YBa_2Cu_3O_7$ (YBCO), the importance of plasticity has been revealed through magnetic [8,13–15] and transport [16] measurements below the melting transition, though detailed history effects studies have not been performed up to now.

In this Letter we report on thermomagnetic history effects in the solid vortex phase of pure twinned YBCO single crystals by measuring the ac susceptibility with the ac field parallel to the c axis of the sample. ac susceptibility is a sensitive tool to detect changes in J_c and, therefore, in the translational correlation length of the VS. Our results show that the VS may be trapped in different metastable states depending on its thermomagnetic history. For example, if the sample is cooled from above T_c with no applied ac field, the VS is trapped in a more disordered state than when the ac field is turned on during the cooling process. In addition, we find evidence that the cyclic pressure exerted by the ac field induces a dynamical reordering of the VS in the penetrated outer zone of the sample that persists when the ac field is turned off and, as a result, different parts of the sample may be in different pinning regimes. The resulting spatial variation of J_c leads to a strong history dependence of the ac response and accounts for the observed memory effects. The character of the reordering induced by the ac field seems to be related to the flow of dislocations in a similar way as in ordinary solids under cyclic stress [17].

Magnetic field orientation relative to the twin boundaries (TB) is another ingredient that determines the overall ac response. The effective strength of pinning at the TB's can be tuned by rotating the applied dc field out of the twin planes. At small angles, where pinning by TB's is expected to be more effective, history effects are weak. At larger angles, however, the influence of TB's diminishes and then pronounced history effects are observed.

Global ac susceptibility measurements with the mutual inductance technique were carried out in two twinned single crystals of YBCO. We present the data obtained with one of them (dimensions $0.56 \times 0.6 \times 0.02$ mm^3). The crystal has a T_c of 92 K at zero dc field ($h_{ac} = 1$ Oe) and a transition width of 0.3 K (10%–90% criterion). Polarized light microscopy revealed that the crystal has three definite groups of twins oriented 45° from the crystal edge as shown in the inset of Fig. 1. Susceptibility data were recorded under different angles θ between the applied field and the c axis. The axis of rotation is shown in the inset of Fig. 1, and it was chosen so that the field can be rotated out of all twin boundary planes simultaneously.

We begin by describing briefly the angular dependence of the ac susceptibility, and then we focus our discussion on the memory effects. Figure 1 shows the real component of the ac susceptibility, χ', for four values of θ. The data were obtained while decreasing the temperature in the usual field cooled procedure at a rate of 0.2 K/min, with $H_{dc} = 3$ kOe, and a superimposed ac field of amplitude $h_{ac} = 2$ Oe and frequency $f = 10.22$ kHz.

The diamagnetic screening, χ', presents a dramatic evolution as θ is increased from $\theta = 0°$ ($H_{dc} \parallel c$). The

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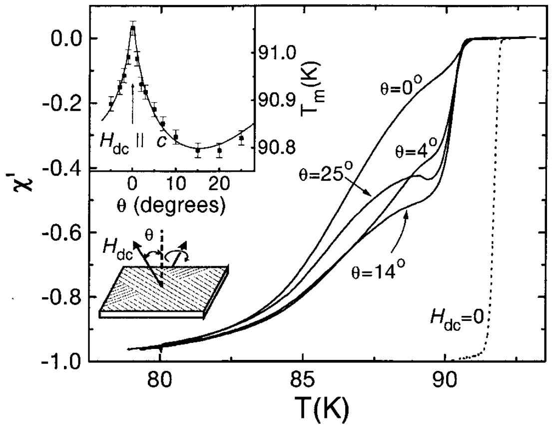

FIG. 1. Temperature dependence of the screening χ' for the twinned YBCO single crystal for different orientations of the dc field relative to the c axis of the sample. $H_{\mathrm{dc}} = 3$ kOe, $h_{\mathrm{ac}} = 2$ Oe, and $f = 10.22$ kHz. The upper inset shows the angular dependence of T_{m}. The line is a guide to the eye. The lower inset shows the orientation of the magnetic field and twin boundaries.

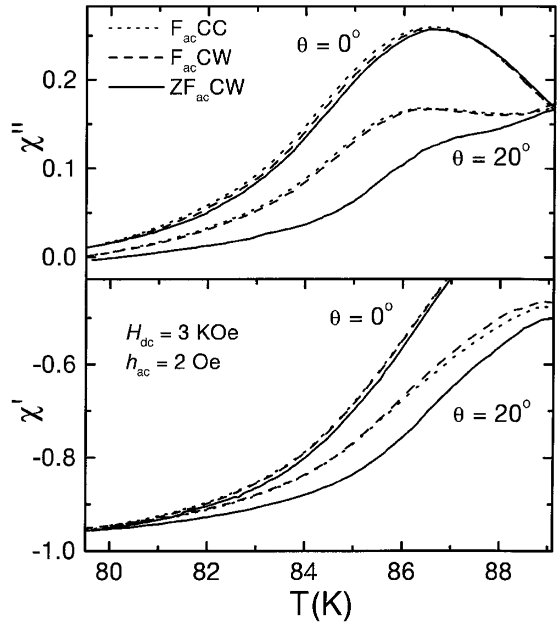

FIG. 2. $\chi'(T)$ and $\chi''(T)$ for different magnetic histories. Dotted curves were obtained on cooling, $F_{\mathrm{ac}}CC$. Dashed curves were obtained on warming after measuring the dotted curves, $F_{\mathrm{ac}}CW$. Solid curves were obtained on warming after cooling with no ac field applied, $ZF_{\mathrm{ac}}CW$. $H_{\mathrm{dc}} = 3$ kOe, $h_{\mathrm{ac}} = 2$ Oe, and $f = 10.22$ kHz.

pronounced changes are a consequence of the effective pinning strength of the TB's. Figure 1 shows that, when the dc field is tilted from the TB's direction, a sharp onset in the susceptibility develops. A sharp onset in the susceptibility was observed in untwinned YBCO single crystals [18,19] and was demonstrated to coincide closely [19] with a sharp resistivity drop that is generally accepted as a fingerprint of a melting transition between a vortex liquid phase and a vortex solid phase with long-range order [20,21]. We identify the steplike onset of χ' as the melting temperature, T_{m}. The absence at small angles of the sharp onset in χ' suggests that the first order melting transition is suppressed by the TB's. The nature of the transition for $H_{\mathrm{dc}} \parallel c$ is generally accepted to be a second order phase transition to a Bose-glass state [22]. A peak at $\theta = 0°$ in the angular dependence of T_{m}, as seen in the inset of Fig. 1, has been related to this transition [21,22].

The angular dependence of the ac susceptibility in twinned samples is still a matter of debate. The observed minimum in the shielding at low temperatures and $\theta = 0°$ has been recently explained by vortex channeling along TB's [23]. According to Refs. [23,24], as the field is rotated out of the TB's, the channeling is partially suppressed. This would explain the initial increase in χ' at small angles. However, above a threshold angle, $\theta_{\mathrm{k}} \sim 14°$, a new reduction in χ' is observed (Fig. 1, $\theta = 25°$). One reason may be that, for these angles, the influence of TB's vanishes and a more ordered VS can form [13], leading to a reduction in J_c.

We turn now to the memory effects. The main results of our investigation are summarized in Figs. 2 and 3. The measurements in Fig. 2 were performed by varying T at fixed H_{dc}, h_{ac}, and θ. Dotted curves were obtained on cooling (C) as the ones in Fig. 1, while solid and dashed curves were obtained on warming (W). The difference between solid and dashed curves is the way the sample was cooled prior to the measurements. Dashed curves were performed after cooling from $T > T_c$ with applied ac field ($F_{\mathrm{ac}}CW$), e.g., after measuring the dotted curves. Solid curves were also obtained after cooling from $T > T_c$ but with $h_{\mathrm{ac}} = 0$ ($ZF_{\mathrm{ac}}CW$). It is apparent that when cooling the sample with no applied ac field the vortex system solidifies in a more strongly disordered and pinned state (with a higher effective critical current density J_c^{dis}), as can be inferred from the enhanced shielding and the reduced dissipation.

The angular dependence of the thermomagnetic history exhibits interesting features. At small θ, the three curves are very similar, though a closer look shows that the maximum shielding (and minimum dissipation) corresponds to the $ZF_{\mathrm{ac}}CW$ case. As θ is increased, but kept below θ_{k}, the thermomagnetic history becomes more and more relevant. For angles near θ_{k}, the importance of the history rapidly increases and the $ZF_{\mathrm{ac}}CW$ case strongly separates from the other two curves (see Fig. 2). The relative variation between the measured χ' for different sample histories is seen to be as high as 20%. The magnitude of the history dependence at angles beyond θ_{k} suggests that the first order melting transition and the translational order of the VS are key factors to explain this behavior.

The results presented above can be understood in terms of a dynamical reordering of the VS caused by the shaking movement induced by the applied ac field during the cooling process in the $F_{\mathrm{ac}}CC$ and the $F_{\mathrm{ac}}CW$ cases. Because of this dynamical ordering the correlation length of the VS grows and J_c diminishes ($J_c = J_c^{\mathrm{ord}} < J_c^{\mathrm{dis}}$). Note that when $H_{\mathrm{dc}} \parallel c$ a long-range ordered structure is unlikely

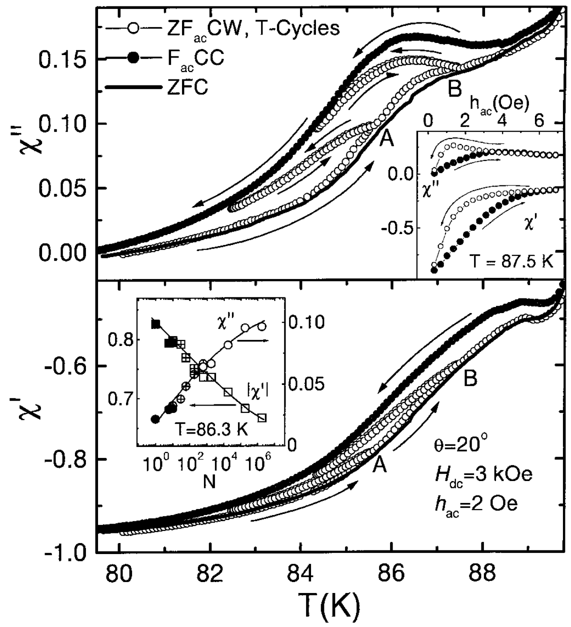

FIG. 3. Memory effects. Main panel: $\chi'(T)$ and $\chi''(T)$ measured during temperature cycles. Measurements start at $T \sim 80$ K after $ZF_{\rm ac}C$ (open circles). Also shown are the $F_{\rm ac}CC$ (solid circles) and ZFC (solid line) curves. Arrows indicate the direction of the temperature sweep. $\theta = 20°$, $h_{\rm ac} = 2$ Oe. Top inset: Cycles in ac field amplitude. $T = 87.5$ K. Arrows indicate the direction of the ac field sweep. Bottom inset: $|\chi'|$ (squares) and χ'' (circles) vs N. $h_{\rm ac} = 1$ Oe, $f = 10.22$ kHz. Solid symbols were measured after ordering with $h_{\rm ac} = 2$ Oe and $f = 0.1$ Hz, + in center symbols with $f = 1$ Hz, and open symbols (from left to right) with 10 Hz, 30 Hz, 300 Hz, 3 kHz, and 30 kHz. Lines are guides to the eye.

to form as TB's prevent vortices from occupying positions favored by their mutual interaction. This seems to be the case even when the ac field is applied manifesting in the faint history effects shown in Fig. 2. However, when the field is tilted from the twins their influence weakens and history effects become more evident suggesting the dynamical ordering of the VS by the ac field.

This reordering or *annealing* of the VS occurs in the penetrated outer zone of the sample which depends on the ac field amplitude and the temperature (as J_c is temperature dependent). If the VS is initially disordered (e.g., $ZF_{\rm ac}C$), an increase in T or $h_{\rm ac}$ will order the VS as the ac field front progresses towards the center of the sample. The VS at the inner region will remain disordered if the condition $J < J_c^{\rm dis}$ is satisfied at *all* times and an elastic Campbell-like regime applies with most of the vortices pinned [25]. From this follows that the *spatial profile* of J_c is determined by the *history* of the sample. If the sample is cooled from $T > T_c$, it will be measured the smallest shielding for the applied ac field ($F_{\rm ac}CC$ and $F_{\rm ac}CW$ cases), as observed in Fig. 2.

If the above reasoning is correct, memory effects in both T and $h_{\rm ac}$ should be observed because the inner disordered state is able to sustain a higher current without vortex movement, thereby enhancing the shielding $|\chi'|$ and reducing the dissipation χ'' in the sample. Moreover, the existence of the disordered region should become more evident in χ when the ac flux front is near its boundary. These memory effects are clearly depicted in Fig. 3. Starting at $T \sim 80$ K with a disordered state ($ZF_{\rm ac}C$) we measured the susceptibility while increasing temperature ($ZF_{\rm ac}CW$). As T increases, J_c decreases and the ac field front penetrates further into the sample ordering the VS. If warming is stopped and the temperature is lowered (point A) the measured susceptibility shows a hysteretic behavior as the outer part of the sample is now ordered. Furthermore, when the sample is driven to low enough temperatures the measured susceptibility tends to that obtained in the $F_{\rm ac}CC$ procedure because the ac field is unable to sense the inner disordered region that was never reached by the ac field front. If now the temperature is increased once again, the susceptibility closely follows the last cooling curve because the order-disorder profile was not changed during the cooling process. As expected, beyond point A the ac response matches the $ZF_{\rm ac}CW$ case. The procedure was repeated at point B where an equivalent description can be made. It is worth noting that the long term memory (our experiments take more than 1 h) indicates that both the disordered and the ordered metastable states are very robust.

Analogous cycles in $h_{\rm ac}$ that corroborate the above explanation can be performed starting with $h_{\rm ac} = 0$ after $ZF_{\rm ac}C$ (top inset of Fig. 3). Note that for ac field amplitudes higher than 5.5 Oe no hysteretic behavior is observed in either χ' or χ''. In this case, the ac field has penetrated in the whole sample suppressing the disordered region. As the VS has been fully annealed, the system loses memory of the highest ac field that was applied.

We also studied what happens when the sample is zero field cooled (ZFC) (both ac and dc). The dc field rate was 50 Oe/s. In these measurements, the ac field is turned on after the dc field has reached its final value. The warm-up curves obtained after preparing the system at $T \sim 80$ K are also contained in Fig. 3 (solid line). The results are close to the disordered $ZF_{\rm ac}CW$ ones. We interpret this in terms of disorder yielded by plastic motion of vortices. It is well established from Bitter decoration [7], small-angle neutron scattering [3], noise [4], and transport experiments [6,9] that when a current near J_c drives the flux lattice a disordered plastic motion occurs. On the other hand, there is experimental [8] and theoretical [26] evidence suggesting the existence of a dislocation mediated plastic creep of the vortex structure that would be analogous to the diffusive motion of dislocations in solids [17]. In our experiment, when the magnetic field is applied, vortices can start penetrating only when the induced current J is of the same order of J_c. In this situation, a small dispersion in the pinning strength will destroy the long-range order generating a high density of defects. As this plastic motion proceeds, the screening current decreases and the lattice will be unable to reorder as detected when we apply the ac field [27].

While from the above discussion it is clear that the ZFC case will correspond to a disordered state, one can then ask on the character of the VS annealing when an ac field is applied. The mechanism involved in this phenomenon may be analogous to the flow and rearrangement of dislocations that leads to the softening of hard atomic solids under cyclic stress [9,17]. The bottom inset of Fig. 3 shows evidence of this cycle-dependent softening in the VS. Starting from a $ZF_{\mathrm{ac}}C$ disordered state, the sample is cycled with a large ac field to anneal the VS. After N cycles the ac field is turned off and the state of the VS is sensed by measuring the ac susceptibility with a smaller probe ac field at 10 kHz. This procedure is repeated for each point in the figure. As discussed above, the degree of exclusion of the probe and therefore the susceptibility are a function of the critical current of the sample at the moment the probe is applied $[J_c(N)]$. The cycle-dependent behavior of the susceptibility nicely demonstrates that J_c is also cycle dependent.

In conclusion, we have presented susceptibility measurements on twinned YBCO single crystals. We find that the vortex system can be trapped in different metastable states as a consequence of different thermomagnetic histories. When measuring susceptibility, the oscillating applied field assists the vortex structure in ordering, locally reducing the critical current density. As a result, different parts of the sample can be in different pinning regimes. The robustness of these states and the associated spatial variation of the critical current density manifest in strong memory effects in both temperature and ac field. The angular dependence of these effects is consistent with an increase of the correlation length of the VS when the dc field is rotated out of the twin planes.

We expect that similar effects will be present in transport measurements because, in most cases, the applied (ac) current will not flow homogeneously inside the sample and will force a field redistribution in a similar manner as when applying an external ac field.

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