Memory effects in the dynamics of the vortex lattice in YBCO crystals: the role of correlated disorder

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Memory effects (ME) in the solid vortex lattice (VL) are observed in a wide range of superconducting materials. Experiments in twinned $YBa_2Cu_3O_7$ (YBCO) crystals in a DC magnetic field, tilted with respect to the twin planes, indicate that ME in these samples cannot be ascribed to an equilibration process. However, the extent of this behavior has not been explored so far. In this work, we study the role of correlated defects in ME by performing angular ac susceptibility measurements in YBCO crystals. We conclude that when uncorrelated disorder prevails, either in twinned or untwinned samples, ME have its origin in the oscillatory character of the vortex dynamics.

Keywords: Superconductivity; vortex dynamics; memory effects; ac susceptibility.

1. Introduction

The complex dynamical behavior of the vortex lattice (VL) in type II superconductors has been subject of continuous efforts in the last fifteen years. Particular attention has been directed toward understanding driven lattices in the vicinity of the peak effect (PE), which refers to an anomalous non-monotonous dependence of the critical current density $J_c$ with both temperature and magnetic field [1]. In this region, memory effects (ME) are observed in low [2] and in high Tc materials (HTSC) [3–5].

A general feature of the observed driven dynamics is the increased mobility of the VL after assisting it with a temporally symmetric (e.g. sinusoidal) ac field [2–5]. Among the various proposed mechanisms, the most invoked one is an equilibration process assisted by the ac magnetic field [6, 7].

However, experiments in twinned YBCO single crystals with DC field tilted out of the twin boundaries (TB) indicate that in these samples, this framework does not apply. It has been shown [5] that a VL, free from bulk field gradients, assisted by an asymmetric ac field (e.g. sawtooth - although a small temporarily asymmetry is enough) becomes less mobile. Moreover, mobility is also reduced if a temporarily symmetric ac field forces vortices into large excursions [8]. These striking features indicate that these effects have their origin in the oscillatory character of the vortex dynamics. Defects (e.g. dislocations), their creation or annihilation controlled by the different driven histories, might play a major role in the bulk VL response to an applied force [9]. A plausible picture is that the repeated interactions between vortex neighbors facilitates the healing of topological defects, while temporarily asymmetric ac fields or large vortex excursions promote their creation [10]. Moreover, in a recent work we have shown evidence that the PE in YBCO crystals originates from a drastic change in the dynamics of the VL [11]. How extensive is this behaviour is an open issue that has not been explored so far. Strong correlated disorder as that produced by columnar defects may suppress history effects [12]. In this framework, the role that extended TB play in the ME of YBCO crystals has been subject of controversies until now, and similar studies in other materials have to be addressed.

In this work we studied the role that correlated defects as TB and CuO planes play in the ME of YBCO single crystals. With this scope, angular ac susceptibility measurements in untwinned and twinned YBCO crystals have been performed. In each case, the picture presented in the paragraph above has been tested.

2. Experimental

Twinned YBCO crystals from two different sources have been used [13, 14]. The untwinned sample was detwinned with the same method used in Ref. 15. All the samples were $YBa_2Cu_3O_{7-δ}$ single crystals with $91K < T_c < 92 K$ in
accordance with slightly underdoped crystals [16]. Results shown in this work correspond to a twinned sample with a critical temperature (defined as the middle point of the linear ac susceptibility transition at 0 dc field) \( T_c = 91 \) K and an untwinned crystal with \( T_c \sim 91.6 \) K.

Global ac susceptibility measurements \( \chi' + i\chi'' \) were carried out with the usual mutual inductance technique. The measuring ac field is parallel to the crystal c axis. A cryostat with the static magnetic field \( H \) provided by a magnet was used, so that \( H \) could be rotated relative to the sample. All the measurements have been made at the same frequency \( f = 30\text{kHz} \). Curves were normalized to a total step \( \Delta\chi = 1 \) between the normal and superconducting response with \( H_{dc} = 0 \).

In ac susceptibility experiments, a larger VL mobility corresponds to a larger ac penetration depth (i.e. a larger \( \chi' \)). To test ME, various protocols or dynamical histories have been performed, where the sample is cooled in dc magnetic field avoiding bulk magnetic gradients, but each case differs in the applied assisting ac field.

An Asy protocol consists in shaking the VL with an asymmetric (sawtooth) ac field of large amplitude (\( \sim 4\text{Oe} \)) once the sample has been dc-field cooled, whereas a Sy protocol consists in applying a symmetrical (sinusoidal) large ac field (\( \sim 4\text{Oe} \)) after a complete Asy protocol. In both cases, the shaking field is turned off and the measurement begins. Moreover, ZFCW protocol corresponds to a dc field cool process without any assisting ac field, followed by a warming measurement. Finally, a FCC protocol is a cooling measurement during a dc field cool process assisted by the measuring ac field (\( \sim 1\text{Oe} \)).

3. Results and discussion

As has been reported in past work [4], in twinned YBCO crystals, ME are clearly observed when \( H \) is tilted away from the c axis (i.e. from the TB) in an intermediate angle \( \theta \). In fact, 4 angular regions with qualitatively different ac response are found. These regions agree with those reported in Ref. [15] identified by means of Bitter decoration.

The characteristic FCC \( \chi'(T) \) at various \( \theta \) corresponding to the 4 angular regions (R1, R2, R3 and R4) are shown in Fig. 1. A broad PE develops in R2 (light gray curves in the figure) (\( 10^\circ \leq \theta \leq 50^\circ \)), where the predominance of correlated pinning due to TB is expected to decrease. Approaching the TB planes (R1, dark gray curves) the shape of the curves is very different and the PE diminishes. At \( \theta \sim 60^\circ \) (R3, dashed curve), a softening of the VL occurs and PE disappears. Finally, in R4 (black curves), when \( \theta \) approaches 90°, the pinning is enhanced due to the CuO planes and mobility drastically diminishes.

In Fig. 2a, ZFCW and FCC curves for the same sample are shown. It can be seen that ME are well visible in R2, whereas approaching the TB planes (R1), they become inappreciable within our resolution. In R4, ME completely disappear due to the strong dominating correlated pinning of CuO planes.

In Fig. 2b, analogue experiments are shown in an untwinned crystal. In this particular sample, a PE develops at DC fields greater than 3000 Oe. In that case, the \( \chi'(T) \) curves in regions R1 and R2 are very similar, and ME are well visible at \( \theta \sim 0^\circ \).
Figure 3. Test probing that whenever ME are relevant, the symmetry of the shaking ac field affects the VL mobility in both twinned (a) and untwinned (c and d) samples. After a FCC (gray curves), Asy and Sy protocols (see text) are applied. Sample is warmed after the last Sy protocol (black curves). In R1 and R4 (b) there is no effect.

Notice that in both samples the VL is more mobile in the FCC curve, indicating that the measuring ac fields assist the VL to attain a more ordered configuration. Moreover, whenever ME are observed, the symmetry of the assisting ac field plays a mayor role. This fact is illustrated in Figure 3. In all the panels, the twinned and untwinned samples have been measured at various $\theta$ with the following sequence: The sample was field cooled (gray curve) until a fixed temperature $T$. Then the Asy (open triangles) and Sy (black squares) protocols were performed. Both protocols were repeated two or three times at this fixed $T$, and finally, after the last Sy protocol, the sample was warmed (black curve). Notice that in the angular regions where ME are not relevant (R4 and R1 in the twinned sample), the Sy and Asy protocols do not produce any change in the VL. On the contrary, in the regions affected by dynamical history, the asymmetric shaking leads to a VL in a less mobile configuration, whereas the symmetric shaking promotes a more mobile VL. These configurations are robust and repetitive.

4. Conclusions

By means of angular $\chi_{ac}$ measurements in YBCO crystals, we have observed that for angular regions where correlated disorder prevails (i.e., when the vortex direction is nearly aligned with the twin planes or CuO planes), the peak effect and memory effects diminish and/or disappear.

In the angular regions where uncorrelated disorder prevails, in accordance with previous work, memory effects present a particular phenomenology, where the most salient features are the following: any symmetric assistance of moderate amplitude able to move vortices out of pinning centers reorganizes the VL in a more ordered and more mobile configuration. On the contrary, an asymmetric shaking promotes a less mobile VL.

In this work, we have observed this behavior in crystals coming from different sources, with and without TB. Particularly, these features hold in untwinned crystals when the VL is aligned with the c axis. Therefore, we claim that these characteristics are not an artifact produced by twin boundaries, but are intrinsic of vortex matter in this HTSC.

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