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Pinning potentials of the vortex lattice in YBCO crystals in the peak effect region

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Abstract

Memory effects in the dynamic response of the vortex lattice (VL) in type II superconductors and its relationship with the controversial peak effect, have attracted great interest for a long time. In the last years, these features have been observed in YBCO single crystals, with the DC magnetic field tilted away from the twin planes and were related with robust dynamical states characterized by different degrees of mobility. Recently, we reported that the previous dynamical history of the VL can modify not only its dynamic response, but can even modify its static properties as well. In the present work, we try to understand the nature of the peak effect in YBCO crystals by sensing the effective AC penetration depth in the linear Campbell regime. We report history dependent effective pinning potential well curvatures and study the stability of the different static configurations. Interestingly, we observe that the more pinned VL configuration is not the more stable. Results agree with a dynamic scenario undergoing the Peak Effect.

1. Introduction

In the vicinity of the phenomenon known as the peak effect (PE), a rich and complex vortex lattice (VL) dynamic is generally observed. The PE refers to a non-monotonic dependence of the critical current density J_c with both temperature and magnetic field. In that region of field and temperature both the mobility of the VL and the *measured* J_c are found to be dependent on the dynamical history of the sample in low-T_c-[1] and high-T_c [2,5] materials (HTCs). In particular, in recent experiments in YBCO crystals, it was shown that the mobility of the VL increases after assisting the system with a symmetric AC field (or current) [2]. On the other hand, when vortices are assisted by an asymmetric AC field, the VL becomes less mobile [2]. This striking feature indicates that these effects cannot be ascribed to an equilibration process, but have their origin in the oscillatory character of the vortex dynamics.

We note that most of the experiments describe non-equilibrium properties: vortices move,

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changing the VL configuration. In addition, the *measured* J_c in HTCs is drastically affected by creep phenomena. In this framework, it is clear that one of the keys to definitely understanding these complex phenomena is to investigate the VL behaviour in the vicinity of the various static configurations acquired immediately after assisting it with a specific dynamical history. In a recent work [3], the solid VL in YBCO single crystals was prepared with different dynamical histories and explored using a very small AC field to measure AC susceptibility. In that way vortices oscillate inside their effective pinning potential wells without modifying the configuration of the system. Results show that oscillatory dynamical history not only determines the degree of mobility, but also directly modifies the effective pinning potential wells.

In the present work, a puzzling question about the nature of the PE in YBCO crystals emerges. We try to answer it by studying different history-dependent static configurations in the PE region. Warming–cooling protocols allowed us to analyze their stability. We found very different characteristic decay times that probably involve distinct creep mechanisms. A possible scenario is proposed.

2. Experimental

The samples were twinned $YBa_2Cu_3O_7$ single crystals with $T_c \sim 92\,K$ and $\Delta T_c \sim 0.3\,K$. AC susceptibility measurements were carried out with the usual mutual inductance technique. The AC field is parallel to the c axis and the static magnetic field H_{dc} was tilted in $\theta = 20^\circ$ away from the twin planes to avoid the Bose glass phase.

3. Results and discussion

Pinning potentials corresponding to different VL configurations were explored measuring the linear real penetration depth λ_R in the Campbell regime. In this non-dissipative linear regime, $\lambda_R = (\lambda_L^2 + \lambda_c^2)^{1/2}$, where λ_L and $\lambda_c = (\phi_0 B/4\pi\alpha_L)^{1/2}$ are the London and Campbell penetration depths, respectively, and α_L is the curvature of the effective pinning potential well [4]. The inductive component of the AC susceptibility χ' is determined by the experimental geometry and the dimensionless parameter λ_R/D, where D is a characteristic sample dimension. We approximated our experimental geometry by a thin disk of radius R and thickness δ in a transverse AC magnetic field [4] and defined the characteristic length of the sample as $D = (\delta R/2)^{1/2}$.

In Fig. 1 full curves of $\chi''(T)$ for different amplitudes of the applied AC field are shown. The curves corresponding to the lower amplitudes are in the linear regime. In the inset curves of the linear components $\chi''(T)$ and $\chi''(T)$ for $H_{dc} = 0$ and $H_{dc} = 2.2\,kOe$ are shown. The upper temperature limiting the Campbell regime for $H_{dc} = 2.2\,kOe$ is indicated with a vertical line. Below this temperature, dissipation is very small ($\chi'' \approx 0$) and χ' is frequency independent. The Campbell penetration depth was extracted from this region. A typical set of Campbell data is added and encircled in the same inset.

It can be seen from Fig. 1 that while PE is clearly displayed in the non-linear curves corresponding to the higher amplitudes it is absent in the T dependence of the linear curves. This fact has been reported in other works [5], but no explana-

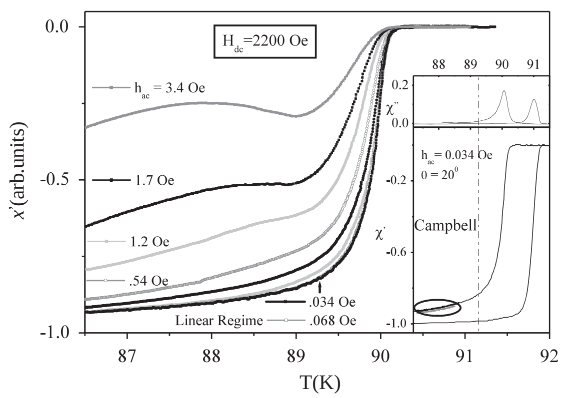

Fig. 1. $\chi'(T)$ curves measured with different amplitudes of the AC fields ranging from 0.034 Oe (linear regime) to 3.4 Oe. The non-linear curves measured at high AC field display the peak effect. Inset: linear AC susceptibility components $\chi'(T)$ and $\chi''(T)$ for $H_{dc} = 0$ (dashed) and $H_{dc} = 2.2\,kOe$ (full line). Vertical line identifies the Campbell regime limit. Data used to build curves shown in Fig. 2 are added (encircled area).

tions were provided. We understand that this is a key factor for the understanding of the nature of peak effect in YBCO crystals.

In fact, assisted by large enough AC fields, vortices perform inter-valley motion and the non-linear penetration depth is directly related to the measured J_c, while for the lower amplitudes, inter-valley motion dominates and the shape of the effective pinning potential well is sensed.

Above the onset of the PE a more disordered (and more pinned) VL is expected. However, our results indicate that, if there were an increase in the number of dislocations above the onset of the PE, it would not affect the pinning static properties, but only the dynamics dominated by creep.

A first obvious objection to the above arguments is that measurable changes in the observed J_c could be related to very small changes in the Labusch constant, undetectable with our experimental technique. We rule out this possibility. In previous works, we have shown that we are able to measure changes in the Labusch constant promoted by the dynamical history, that can only have their origin in a different VL configuration (i.e. a change in the number or distribution of dislocations). In the following the stability of these different dynamic-modelled static configurations in the region of the PE is investigated, in order to clarify these issues.

We will refer to two different configurations of the VL that were obtained following two protocols or dynamical histories before the measurement began. In both cases, the sample is cooled in DC magnetic field to a target temperature. The first case is a less mobile VL configuration (that we call Asy) that is obtained assisting the VL with 910^5 cycles of an asymmetric (sawtooth) AC field. A more mobile configuration (Sy) is obtained assisting the VL with 910^5 cycles of a symmetrical (sinusoidal) AC field immediately after the Asy protocol. Both (sawtooth and sinusoidal) assisting AC fields have an amplitude of 3.5 Oe and a frequency $f = 30$ kHz. The measuring field in the linear regime has the same frequency and an amplitude two orders of magnitude lower (40 mOe).

In Fig. 2 the evolution of λ_R/D during a very slow warming – cooling $(W-C)$ excursion of

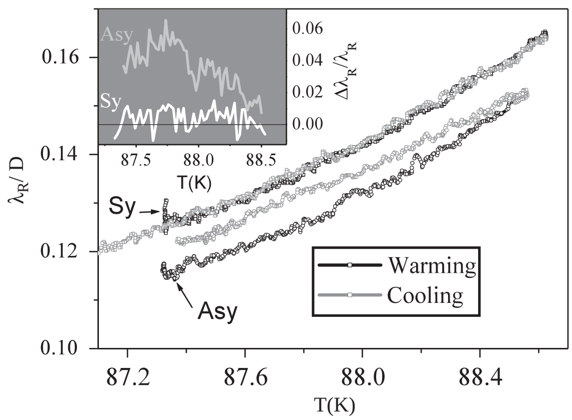

Fig. 2. Evolution of λ_R/D during a warming (black symbols) followed by a cooling (gray symbols) process, after preparing the VL in the Sy and Asy configurations (see text). The more pinned Asy configuration relaxes slowly during the warming process. Inset: comparison of the relative change in λ_R for both starting configurations (Sy in white, Asy in light gray).

approximately 1.3 K after preparing the VL in the Sy and Asy configurations at $T \approx 87.3$ K are compared. As was shown in previous works [3], a clear difference in the linear penetration depth of both configurations can be observed: the VL is more pinned in the Asy than in the Sy configuration. It can be seen that the Sy configuration has an initial fast accommodation and after that it remains reversible for the whole measured temperature range. On the contrary, the more pinned Asy configuration relaxes slowly during the warming process. The difference in behavior is more clearly displayed in the inset, where the relative change $(\lambda_R(W) - (\lambda_R(C))/(\lambda_R(W))$ as a function of temperature for both processes is compared. Although very clean curves are difficult to measure because the signal involved is small, the relaxation of the Asy configuration is evident and reproducible in other samples.

We then performed a series of tests to investigate the nature of such a relaxation, whose details are published elsewhere [3]. An important result is that we observe the same final state after repeating the $W-C$ process without application of the small measuring AC field. This suggests that the relaxation is due to a thermally activated process and it is supported by the fact that in an inverse cooling–warming process beginning at the same temperature, no relaxation is observed. As another test, we repeated the same procedure in a lower temperature range. We observed that in these cases the response is reversible. We also prepared the system in other initial configuration not shown in this work. All the evolutions seem to get closer to a unique AC penetration depth with a degree of pinning similar to the one observed in the initial Sy configuration.

Let us now underline a possible scenario to explain the above results: Numerical simulations [6] recently confirm that the more mobile Sy configuration is more ordered, while the less mobile Asy configuration is characterized by a greater number of topological defects or dislocations.

On the other hand, recent theoretical works [7] have predicted that plastic creep, in a dislocated vortex solid, would have higher exponents for the power-law divergence of the creep barrier than elastic vortex creep.

In this framework, the fast initial decay in the Sy configuration could be associated to a small elastic creep, where vortices only slightly adapt better to the pinning potential without modifying the structure of the VL. On the contrary, the slow thermal decay in the torn Asy configuration can be due to plastic creep, where the number of dislocations is being reduced and the system evolves towards a less strained (and less pinned) configuration.

The relaxation processes shown in Fig. 2 close the picture for a possible explanation to our original question. Note that warming curves reached temperatures above the onset of the PE. It seems that the protocol creating the Asy configuration, promotes more dislocations than the existing number in the stable configuration even at these high temperatures. A possible scenario is that such a great number of dislocations modifies the correlation volume of the VL and directly affects the static properties. However, the intrinsic increase of dislocations at the peak effect is not enough to modify the pinning and only affects creep mechanisms.

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