Oscillatory dynamics of a superconductor vortex lattice in high amplitude ac magnetic fields

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We study by ac susceptibility measurements the evolution of the solid vortex lattice mobility under oscillating forces. It has already been shown that in YBCO single crystals, below the melting transition, a temporarily symmetric magnetic ac field (e.g., sinusoidal, square, triangular) can heal the vortex lattice (VL) and increase its mobility, but a temporarily asymmetric one (e.g., sawtooth) of the same amplitude can tear the lattice into a more pinned disordered state. In this work we present evidence that the mobility of the VL is reduced for large vortex displacements, in agreement with predictions of recent simulations. We show that with large symmetric oscillating fields both an initially ordered or an initially disordered VL configuration evolve towards a less mobile lattice, supporting the scenario of plastic flow.

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A rich variety of dc and ac dynamical behaviors arising from the competition between pinning, thermal and intervortex interactions has been observed in the vortex lattice (VL) of type II superconductors.[1] Forces between vortices favor the formation of an ordered hexagonal lattice, in opposition to the disorder that arises from interactions with pinning centers and thermal forces, leading to defective polycrystalline, or glassy structures.

In driven lattices, external driving forces participate in the formation of ordered and disordered structures. An example is the experimental[2] and theoretical[3] evidence of a two step depinning process of the VL as the driving force is increased. Initially, at low drives, the lattice undergoes plastic flow, vortices move past their neighbors tearing the VL and leading to the formation of a disordered lattice, with a high density of topological defects (e.g., dislocations). Increasing the drive above a threshold force, F_T, a dynamical crystallization occurs, as proposed by Koshelev and Vinokur.[3] At larger forces vortex-vortex interactions dominate over interactions with pinning centers which are accounted for by an effective temperature that decreases with the VL velocity.

Memory effects have been observed in low[4,5] and high T_c materials (HTSC),[6,10] where the resistivity or the apparent critical current density J_c, are found to be strongly dependent on the dynamical history of the VL. An increase in the mobility of the VL when set in motion by a temporarily symmetric (e.g., sinusoidal) ac field (or current)[4,5,7,10] is a characteristic which is common to all of these experiments. A proposed mechanism[8] for this effect in $YBa_2Cu_3O_7$ (YBCO) crystals is the annealing of bulk magnetic gradients in a platelet placed in a perpendicular dc magnetic field by a weak planar ac magnetic field. A second invoked mechanism is an equilibration process assisted by the ac magnetic field.[9,11]

Transport and ac susceptibility experiments[4,9,10,12] suggest that the response of a steady driven VL may differ qualitatively from the ac response observed in measurements involving comparable driving forces. In particular, markedly different effects for temporarily symmetric or temporarily asymmetric ac drives have been reported.[10] It was shown that the application of a temporarily asymmetric ac magnetic field (e.g., sawtooth) reduces the mobility of the VL, in contrast to the effect of a symmetric ac field (e.g., square, sinusoidal, triangular) of similar amplitude and frequency. These effects were observed to be weakly frequency dependent and to depend strongly on the number of shaking cycles. This is a main result that ruled out an equilibration process as a possible explanation to the change in vortex mobility.[10] At the same time, the dynamic crystallization scenario becomes inadequate to describe the observed changes in VL mobility of the solid vortex in twinned YBCO crystals.

Oscillatory dynamics has been described recently in molecular dynamics calculations,[7] where an oscillatory driving force below the crystallization threshold is able to order the VL after a number of cycles. The reordering of the VL is more efficient when vortex excursions are of the order of the lattice parameter a_0. This VL shaking promotes repeated interactions between neighbors that heal lattice defects (i.e., the number of vortices with five or seven first neighbors). At the same time, the average mobility of the VL increases logarithmically with the number of cycles. An important result is that for a tiny asymmetry in the amplitude of the force, the vortex lattice quickly disorders increasing the number of topological defects and the mobility is rapidly reduced after a few cycles, as observed in the experiments.[10] On the other hand, when the period of a symmetrical force was increased so that the excursion of vortices greatly exceeded the lattice constant, the VL did not reorder. It was argued that if the period of the oscillation was large enough, the system should behave as when driven by steady forces below the threshold force.

In this paper, we investigate the effect of shaking the vortex lattice with sinusoidal magnetic ac fields starting from a well defined and reproducible state. In these experiments the excursion amplitude of the vortices is controlled by the amplitude of the ac magnetic field which is varied between 1 and 150 Oe. We found that for amplitudes below a certain threshold, 20 Oe, the VL mobility increases as a function of the number of cycles of the shaking field. However, such an increase in the mobility is not observed above 20 Oe. Following previous experimental and theoretical results, we interpret this as an indication that plastic motion dominates the dynamical behavior of the VL. The reduced mobility would be a consequence of large vortex displacements which produce vortex lattice tearing and the generation of defects.

We measured the response of the vortex lattice to the shaking field by means of ac susceptibility measurements. Global ac susceptibility measurements ($\chi_{ac}=\chi'+j\chi''$) were made with the usual mutual inductance technique in two twinned $YBa_2Cu_3O_7$ single crystals,[13] with typical dimensions $0.6\times0.6\times0.02$ mm^3, and $T_c\sim92$ K at zero dc field and $\Delta T_c\sim0.3$ K (10%–90% criteria).We have obtained similar results for both crystals but we show the results obtained for one of them. The ac field, H_{ac}, was applied parallel to the **c** crystallographic axis and the dc field, H_{dc}, was applied at $\Theta=20^{\circ}$ away from the twin boundaries to avoid the effects of correlated defects.[6] In the temperature and field region of interest, high dissipation (χ'') [or low screening (χ')] implies high mobility, and low dissipation (or high screening) implies low mobility.[10]

The experiments to investigate the effect of the amplitude of the shaking field followed the protocol that is described immediately below. First, the VL lattice was prepared applying the ac configuration field (H_{cf}) for a number of cycles ($N\sim10^5, f=10$ kHz). A temporarily asymmetric (sawtooth) H_{cf} was used to prepare a low mobility configuration, LMC. A temporarily symmetric (sinusoidal) H_{cf} was used to prepare an initial vortex configuration with high mobility, HMC. It is worth noting that the lattice was always prepared in the LMC before applying the symmetric H_{cf} to attain the HMC. The configuration field and the measuring H_{ac} field were provided by the susceptometer primary coil. After setting the desired starting configuration, H_{cf} was turned off and a temporarily symmetric shaking ac field (H_{sh}) with an amplitude that could be varied between 1 Oe and 150 Oe ($f=1$ Hz) was applied. This field was supplied by the same electromagnet that provided the dc field. After shaking the vortex lattice for a number of cycles (N_{sh}), H_{sh} was turned off and the first harmonic of the magnetic ac susceptibility was measured with a sinusoidal ac field with an amplitude $H_{ac}=2$ Oe and $f=10.22$ kHz. The measured susceptibility is related to the mobility of the VL and quantifies the effect of the shaking field in it. With this protocol we can study the effect of N_{sh} cycles of the shaking field to an initial vortex configuration with either low (LMC) or high (HMC) mobility. This procedure is repeated for each measured value of N_{sh}.

Figure 1 shows ac susceptibility measurements χ'' vs T cooled in dc ($H_{dc}=2$ kOe, $\Theta=20^{\circ}$) and ac fields ($H_{ac}=2$ Oe, $f=10.22$ kHz). Differences between VLs with high and low mobility are measured for temperatures below the melting line (solid VL). We choose to make our measurements at $T\sim85$ K, where a larger difference between the measured signal of the high and low mobility states is observed. The lower point (point A) was obtained after field cooling to 85.5 K, turning off the measuring field and applying 10^5 cycles of a sawtooth ac magnetic field, $H_{cf}=7.5$ Oe and $f=10$ kHz. The 7.5 Oe ac field (that penetrates the sample completely[10]) was turned off and ac susceptibility was measured. The application of the temporarily asymmetric drive reduced vortex mobility, and we call this a low mobility configuration, LMC. The higher point (point B) was the dissipation level

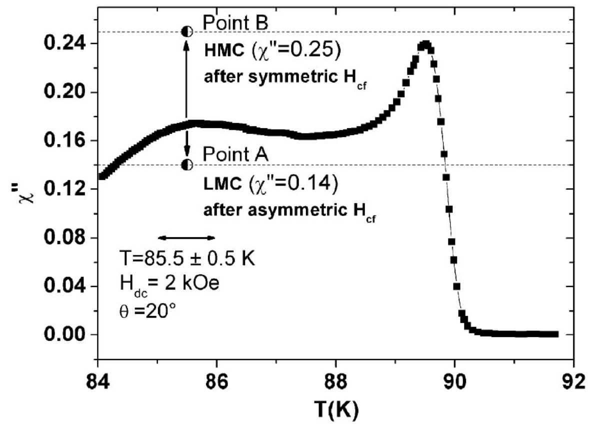

FIG. 1. The ac susceptibility measurements χ'' vs T. This measurement was made lowering temperature with H_{ac} and H_{dc} turned on.

obtained after setting a LMC (point A) and then applying 10^5 cycles of a sinusoidal ac field, $H_{cf}=7.5$ Oe and $f=10$ kHz. The 7.5 Oe ac field, was turned off and the ac susceptibility was measured. The mobility of the VL is clearly enhanced as a result of the application of the sinusoidal field. We call this vortex state a high mobility configuration, HMC.

Our next experiments were performed at a fixed temperature and dc magnetic field. As anticipated above, the temperature was chosen to correspond with the low temperature maximum in χ'' (see Fig. 1) in order to obtain a large observable difference between the measured susceptibility for low and high mobility VL configurations. For our samples, for a dc magnetic field of 2 kOe and with our selected measuring ac field, this temperature is around $T=85.0$ K.

In Fig. 2 we show χ'' versus the number of cycles (N_{sh}) of the shaking field. The shaking field was chosen to have different amplitudes (from 8 to a 120 Oe) and was applied to a LMC prepared with $H_{cf}=7.5$ Oe. Equivalent results are obtained for χ'. For shaking fields with the lowest amplitude (8 Oe), χ'' increases roughly as the logarithm of N_{sh}. The same dependence is observed for intermediate amplitudes (10–20 Oe) for which it is also observed that χ'' increases with the

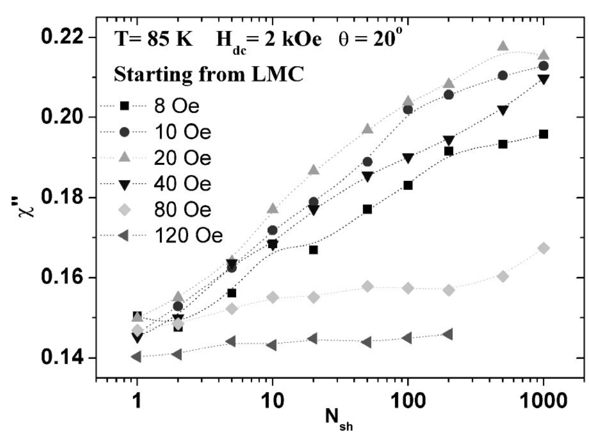

FIG. 2. χ'' versus the number of cycles of the shaking field (N_{sh}) for different amplitudes, starting from a low mobility configuration, LMC.

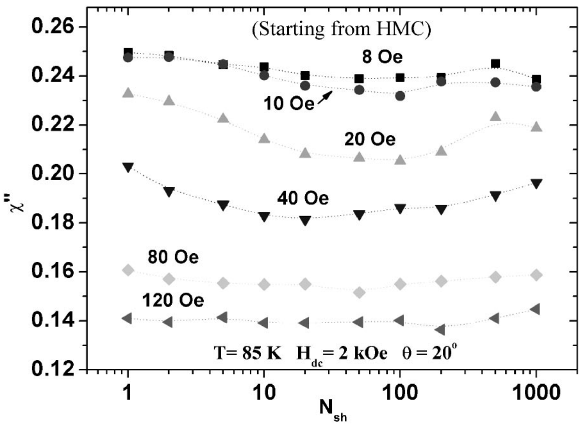

FIG. 3. χ'' versus the number of cycles of the shaking field (N_{sh}) for different amplitudes, starting from a high mobility configuration HMC.

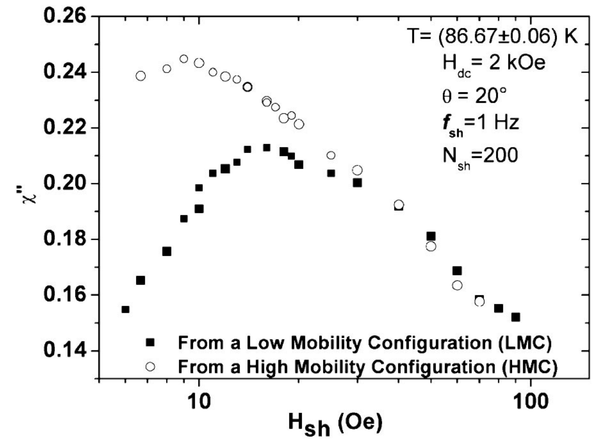

FIG. 4. χ'' versus the amplitude of the shaking field for $N_{sh}=200$, from low and high mobility configurations.

amplitude of the shaking field (for a given number of cycles, N_{sh}). It is interesting to note that this increasing trend in χ'' does not continue if the amplitude of the shaking field is further increased. Instead, we observed that χ'' reaches a maximum at around 20 Oe and starts decreasing for larger amplitudes. For H_{sh} above 80 Oe, the χ'' of the final state (after 1000 cycles) is in fact comparable to the χ'' of the initial LMC.

As a larger χ'' implies a larger VL mobility, these results indicate that there is an "optimum" amplitude of H_{sh}($\sim$20 Oe) for which a maximum mobility in the VL is obtained (for a given number of cycles). They also show that a high amplitude symmetric ac field is not effective in reordering and increasing the mobility of an initially disordered VL. By comparison with numerical simulations, it appears that large vortex displacements produce plastic tearing of the VL and the overall response becomes equivalent to the response of a lattice in a low mobility configuration.

We also studied the effect of the shaking field on an initially ordered VL (HMC). In Fig. 3 we show χ'' versus the number of cycles of the shaking field (N_{sh}) of different amplitudes starting from the HMC. At low amplitude magnetic fields ($<$10 Oe) χ'' (and the VL mobility) stays approximately constant, but at higher amplitudes (20–80 Oe) an overall reduction in χ'' is observed. Even one cycle is enough to significantly alter the VL configuration. As N_{sh} is increased, the value of χ'' seems to go through a shallow minimum but the χ'' never recovers to the initial value at $N_{sh}=0$. Shaking fields with an amplitude larger than 80 Oe strongly reduce χ'' to values, which are comparable to the one in a LMC. As discussed above, the results in Fig. 2 show that a large amplitude symmetric magnetic field is not effective in reordering and increasing the mobility of the VL. Figure 3 shows that such an oscillating magnetic field also distorts an initially ordered VL and reduces its mobility.

The effects of the amplitude of the shaking field H_{sh} are more clearly observed in Fig. 4, which shows χ'' as a function of the amplitude of the shaking field for a fixed number of cycles ($N_{sh}=200$). We show measurements that were performed, starting with high and low mobility configurations. Starting with a LMC, it can be seen that the ability of the shaking field to improve VL mobility increases up to a maximum ($H_{sh}\sim$10–20 Oe) and then decreases. For amplitudes $H_{sh}\sim$80 Oe the VL seems to have reached a configuration just slightly different from the starting LMC, i.e., a high amplitude sinusoidal field does not remove VL defects. For a HMC starting state, low amplitudes do not modify the dynamics of the VL. As H_{sh} is increased above 20 Oe, there is a clear reduction in mobility, and higher shaking amplitudes configure the VL close to the LMC state. In fact for $H_{sh}\geqslant$40 Oe the final mobility is independent of the starting configuration. It is interesting to note that this result is independent of the frequency of the shaking field in the range tested (0.1 Hz$<f_{sh}<$3 Hz). Given that the dissipation in the sample is directly related to the number of cycles per unit of time, this result implies that the observed effects are not related to local heating.

Following Ref. 7, when the average vortex excursion produced by the shaking field is comparable to the lattice constant, a_0, the VL mobility increases as the vortex lattice orders and moves in an increasingly coherent way (the calculated number of defects in the lattice and its mobility vary as the logarithm of the number of cycles of the oscillating force). On the contrary, calculations predict that when the excursion of vortices greatly exceeds the lattice constant, the VL mobility is reduced as the plastic motion tends to increase disorder. In order to relate our results with theoretical predictions, we estimated the average vortex displacement under the action of the oscillating ac field. The distance that a vortex at the sample boundary moves when a field perturbation H_{sh} is applied can be roughly estimated by

$$\langle u\rangle \approx \frac{1}{2}\frac{H_{sh}}{H_{dc}}r,$$

where r is the sample radius, assuming the magnetic induction $B\sim H_{dc}$. For our experimental conditions, $r\sim0.3$ mm and $H_{dc}=2000$ Oe, and considering a triangular lattice ($a_0\sim0.1$ μm), $<u>\sim a_0$ occurs at a shaking field amplitude $H_{sh}\sim2$ Oe. However, in our experiments the maximum dissipation (implying maximum mobility) occurs for $H_{sh}\sim10$ Oe (see Fig. 4), so that the above approximations slightly underestimate the shaking field limit. Note that the exact value at which the maximum in χ'' is observed could depend on the rigidity of the vortex lattice and the density of pinning centers. The more rigid the lattice the more difficult it is to create defects in it. This implies that the field amplitude estimated above for the position of the peak is a lower limit and could increase with vortex rigidity.

We find that our results are qualitatively in accordance with numerical simulations indicating that if vortices are forced to oscillate with amplitudes larger than the typical VL parameter, plastic motion introduces topological defects and reduces mobility. For smaller drives, vortices perform small excursions interacting repeatedly with neighbors and as the lattice becomes successively more ordered, its mobility increases.

To conclude, in this paper we have shown that temporarily symmetric vortex oscillations, forced by sinusoidal ac fields, increase the mobility of the VL in twinned YBCO crystals. However, when the amplitude is larger than a certain threshold, the temporarily symmetric oscillation reduces the mobility. This is an indication that large vortex displacements may produce vortex lattice tearing and the mobility is reduced. We have also shown that a healed lattice with initial high mobility can be torn by the driven symmetric oscillation, if vortex displacements are much larger than the VL parameter. The ordered VL reduces its mobility even with just one oscillation of the shaking field.

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