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Vortex channeling along twin planes in $YBa_2Cu_3O_{7-x}$

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We have studied the magnetic hysteresis of twinned and detwinned $YBa_2Cu_3O_{7-x}$ single crystals. Our results show that channeling of vortices occurs and that it decreases vortex pinning in the field region near the peak in the hysteresis width. We demonstrate that the effect of the twin planes cannot simply be described in terms of enhanced pinning within the twin planes. By varying the angle of the twin planes with the magnetic field we have found that vortices lock in to the twin planes and an upper bound on the lock-in angle of 3.5° at 60 K has been obtained.

Various defect structures may give rise to vortex pinning in cuprate superconductors. Microscopic point defects such as oxygen vacancies in the CuO_2 planes constitute weak randomly distributed pinning centers. On the other hand, coherent disorder can take the form of columnar defects, such as the disorder created by ion bombardment, or planar defects, such as the twin boundaries in $YBa_2Cu_3O_{7-x}$ (YBCO) or the intrinsic layered structure of these cuprate materials. The number of coherent defects will be much smaller than the number of random point defects. However, when a vortex is aligned with a coherent defect the resulting pinning may be strong. Recently much interest has focused on the motion of the system of vortices interacting with coherent disorder.

Ever since the discovery of superconductivity in the orthorhombic compound YBCO, theoretical[1-4] and experimental[5-19] investigations of the effect of twin planes in this compound on flux pinning have been of great interest. It is clear from experimental studies using different techniques (magneto-optical flux visualization,[5-7] Bitter decoration,[8,9] resistivity,[10-12] magnetization,[13-16] and torque[17-19]) that twin planes can act as effective pinning centers. It has also been found that the motion of vortices transverse to the twin boundaries is harder than longitudinal motion. Theoretical studies are still undecided whether the twin planes form regions with a decreased[20] or increased[21,22] value for the superconducting order parameter. Suggestions have been made that in the case of a decreased order parameter in the twin planes, channeling of vortices along twin planes could take place. However, Vlasko-Vlasov *et al.*[5] have argued, based on their magneto-optical studies, that twin planes are not channels for magnetic flux (they do not lead to increased vortex motion) although their presence gives rise to guided vortex motion. This interpretation of the magneto-optical results is still controversial. The conclusions from Ref. 5 are in agreement with resistivity measurements from which it has been deduced that the pinning is enhanced within the twin planes. We must stress, however, that the first technique probes only the regime of low applied magnetic fields, $H_a<0.1$ T, and hence these conclusions are not necessarily valid for higher magnetic fields, and the second one probes only the high temperature regime. As a consequence, many details of the interactions of the twin planes with the mixed state still need to be resolved. In this paper we will present clear experimental evidence from magnetic hysteresis measurements that magnetic flux does channel along twin planes for certain field regimes.

The crystals investigated were grown by a conventional self-flux method. The details of the growth, oxygenation, and detwinning process are described in Ref. 23. The four crystals have an oxygen content of 6.92 (i.e., $x=0.08$), $T_c=93.8$ K and $\Delta T_c<0.3$ K, and will be identified as crystal A, B, C, and D. They are all microtwinned except crystal D which has been detwinned; after detwinning, polarized light microscopy revealed a surface fraction of misaligned phase of less than 1%. The dimensions of the crystals are summarized in Table I. Crystals $A1$ and $C1$ were obtained, as described later, by breaking a piece of crystal A and C, respectively. Magnetization measurements were carried out on a 12 T vibrating sample magnetometer with a magnetic field applied parallel to c axis, unless otherwise indicated. The magnetic field was swept at a rate of 5 mT/s.

First we investigated the magnetic response of the four crystals. Examples of magnetic hysteresis curves up to 12 T and at $T=60$ K for crystals A, B, and C are given in Fig. 1(a). In this figure the magnetization is divided by the characteristic size, R, of the crystals [$R=3a_y(1-a_y/3a_x)/4$, where a_x and a_y are the length and width of the crystals[24]] which enables us to make a direct comparison between the different crystals. According to the Bean model, one expects all the $M(H_a)/R$ data to give identical curves, provided that all crystals have similar pinning properties. From Fig. 1(a) it

TABLE I. Dimensions of the YBCO crystals.

Crystal	a_x (mm)	a_y (mm)	mass (μg)
A	1.15	0.80	363
$A1$	0.71	0.47	120
B	0.88	0.80	64
C	0.90	0.70	483
$C1$	0.39	0.27	75
D	0.72	0.70	179

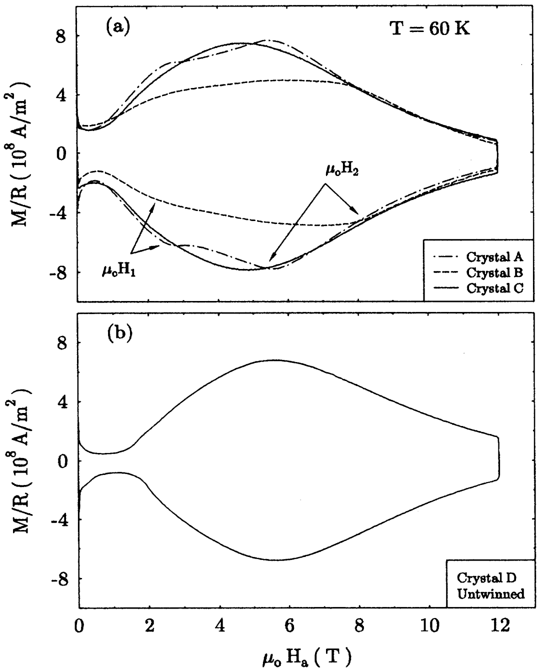

FIG. 1. Scaled magnetic hysteresis loops at 60 K for (a) the microtwinned crystals A, B, and C and (b) the detwinned crystal D.

is clear that there is a reasonable agreement between the different curves in particular at high fields. All curves exhibit a maximum (at a magnetic field value $H_{\max}$) in the hysteresis width, characteristic for YBCO. Near this maximum, in a field region which we will call the intermediate field region ($H_1<H_a<H_2$; see Fig. 1), the magnetization, M, does not scale accurately with R and the shape of the $M(H_a)$ curve varies between different crystals. The extent of the field range over which the peak flattens differs from sample to sample and even between different bits of a same crystal. However, in all cases, this field range narrows with increasing temperature and disappears above about 75 K. In what follows, we will attribute this behavior to the effect of twin planes. We will distinguish three magnetic field regions: the first one is the low field region below about H_1, the second one is between H_1 and H_2, and finally the high field region for $H_a>H_2$. For crystal C the magnetic hysteresis is not affected and hence no intermediate field region is present. In Fig. 1(b), we have represented the hysteresis loop of the detwinned crystal D. The position of the maximum in magnetization is close to that of the twinned crystals confirming the similarity in oxygen content. By comparing the hysteresis curves of Fig. 1(a) with one in Fig. 1(b), we have found that in the low field region, the presence of twin planes significantly increases the hysteresis width and therefore the effective pinning, in agreement with earlier reports,[13-16] whereas for high fields the twin planes have no effect on the hysteresis width. The behavior in the intermediate field region needs special attention since all crystals of Fig. 1(a) are microtwinned, but the effect of the twinning on the hysteresis varies between the different crystals.

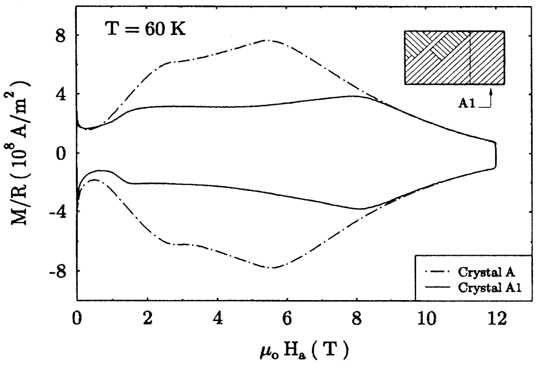

FIG. 2. Comparison of magnetic hysteresis at 60 K for crystal A and $A1$. Crystal $A1$, which has been broken of crystal A, contains only one direction of twin planes. Inset shows crystal A which consists of different domains, and the part which has become crystal $A1$.

As stated previously, the crystals investigated in Fig. 1(a) are all microtwinned with both types of twin planes, [110] and [1-10]. By means of a polarizing light microscope, we have established that the crystals contain domains which are microtwinned with a given type of twin planes. A well defined peak in the magnetization is only observed in detwinned crystals and in crystals having many domains (>10) which are well mixed, as in the case of crystal C. The magnetic hysteresis depression in the intermediate field region has only been observed in crystals having few domains (<4) such as crystals A and B. In this case, one can find many twin planes of one type crossing the whole crystal. we deduce form this that the depression of the magnetic hysteresis width is caused by the twin planes behaving as channels for the magnetic flux which reduces the overall pinning strength of the samples. In crystals with many domains, this process is less effective. At boundaries between different microtwinned domains we expect to find strong disorder[13] and hence these boundaries will form large defect structures inhibiting this type of vortex motion.

To further establish that flux channeling along twin planes causes the decrease of the hysteresis peak, we have broken crystal A containing several domains and isolated a part $A1$ containing only one domain, i.e., one type of twin planes (see inset, Fig. 2). Results of the magnetization measurements on crystal $A1$ are given in Fig. 2. The high field hysteresis for crystal $A1$ remains in good agreement with the data for crystal A. However, the hysteresis width in the intermediate field regime has decreased considerably. Hence for a crystal with a single domain of microtwinning the effective pinning is decreased. Similar results have been obtained with crystal C. It is clear that the absence of scaling in this field range is not a result of granularity since crystal $A1$ has a lower critical current density than crystal A. As far as we know, this is the first time that for a single crystal sample a part has a *lower* critical current density than the whole.

From the above studies we have deduced that the twin planes act to facilitate vortex motion in directions along the twin planes. This relies crucially on vortices being locked-in twin planes. A decisive test to establish that this is indeed the case is to study the overall pinning as a function of the angle

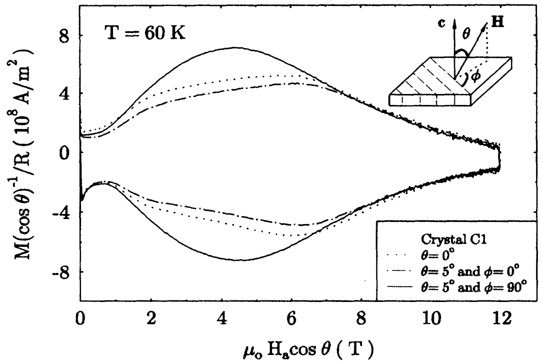

FIG. 3. Magnetic hysteresis at 60 K for crystal $C1$. Crystal $C1$ is part of C and contains only one direction of twin planes. The applied is tilted with respect to the c axis by an angle θ, as indicated. The angle ϕ is the angle between the projection of $\mathbf{H}_a$ in the crystal plane and the twin planes.

between the applied field and the twin planes. With this in mind, we have carried out hysteresis measurements on crystal $C1$, again with a single domain of microtwinning and hence a unique direction of twin planes, where the **c** axis has been tilted with respect to the applied field, by an angle $\theta = 5°$. We have investigated two orientations: the first one is with $\phi = 0°$ (see inset, Fig. 3) in which case the twin planes are parallel to $\mathbf{H}_a$ (the angle between $\mathbf{H}_a$ and the twin plane, $\alpha = 0°$) and the second orientation is with $\phi = 90°$, giving $\alpha = 5°$. Because of the anisotropy, the measured magnetization can for the purpose of our discussion be approximated by the projection of the component along the c axis of the magnetization, $M_\perp$. It is given by

$$M(H_a) = M_\perp(H_a \cos\theta)\cos\theta.$$

The data in Fig. 3 represent the magnetization $M_\perp$ as a function of the component of $\mathbf{H}_a$ along the c axis. Firstly, as stated previously, a reduction in the magnetization peak is observed at $\theta = 0°$ for crystal $C1$, although it originates from crystal C which showed initially a well defined peak (see Fig. 1). Similar results to the case $\theta = 0°$ are observed at $\theta = 5°$ and $\phi = 0°$; but when $\theta = 5°$ and $\phi = 90°$ we observe instead a well defined peak, as in crystal C. In the two first orientations $\alpha = 0°$, vortices are locked in to the twin planes and vortex channeling can take place. However, for the third orientation $\alpha = 5°$ there is no depression in the hysteresis width and vortices are not locked in to the twin planes. This is clear experimental evidence of vortex lock in by the twin planes. A further experiment at $\theta = 5°$ and $\phi = 45°$ also led to a well defined peak. In this case $\alpha = 3.5°$ and this constitutes the upper bound of the lock-in angle ($\alpha_c < 3.5°$). This upper bound is in agreement with values found previously.[11,17] For $\alpha > \alpha_c$ the peak in the magnetization recovers in the intermediate field regime to values similar to those found for crystals C and D. Hence when the vortices are not locked in to the twin planes the effect of the twin planes on the overall pinning is negligible for high fields ($H_a > H_{\max}$).

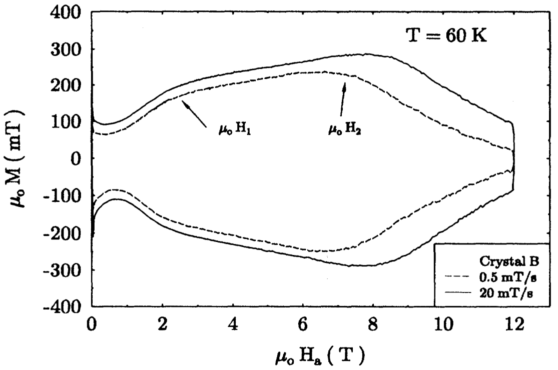

FIG. 4. Magnetic hysteresis at 60 K for crystal B for the indicated magnetic field sweep rates. The magnetic field H_2 clearly separates two relaxation regimes.

The above data demonstrates that the order parameter at the twin planes decreases. However, the "channel" formed by a twin plane does not have perfect translational symmetry along the twin plane and hence does not necessarily supply an easy path for vortex motion. Twin planes are areas with strong disorder and the order parameter will change strongly when moving along the twin planes (the "channel" has strong "depth" variations). The low field results by Vlasko-Vlasov *et al.*[5] can be explained in terms of vortices being pinned by the strong disorder within the twin planes causing guided motion through the interactions between vortices trapped by the twin planes and vortices in the untwinned regions. This explanation is in agreement with Ref. 5; however, Vlasko-Vlasov *et al.* conclude from this that twin planes act as *single* boundaries which can only impede vortex motion. Our results demonstrate that vortex channeling along the twin planes can reduce the overall pinning. The fact that this is only significant around the peak in the magnetic hysteresis suggests that channeling is only effective at fields for which the effective pinning in the untwinned regions between the twin planes becomes stronger. The pinning strength for a vortex in an untwinned region is expected to decrease more rapidly with temperature than the pinning strength for a vortex trapped in a twin plane because of the reduced dimensionality of the thermal fluctuations.[4] This agrees with our findings: vortex channeling and the field range from H_1 to H_2 decreases with increasing temperature. Above about 75 K the pinning in the untwinned regions is always lower than that in the twin planes and no flattening of the magnetic hysteresis shape has been observed. The vortices locked in the twin planes interact with neighboring vortices in the untwinned regions. This will alter the elastic constants, and therefore the pinning, of these vortices close to the twin planes. Hence the channeling of vortices can involve vortices within a certain interaction distance from the twin plane.

Figure 4 represents the effect of the magnetic sweep rate on the hysteresis loop for crystal B at $T = 60$ K. The magnetic field H_2 clearly separates two distinct relaxation regimes. We have found that, for detwinned crystals, this crossover in relaxation behavior takes place at $H_{\max}$. The presence of twin planes delays the appearance of the second relaxation regime until H_2 is reached. We suggest that this crossover in relaxation characteristics is determined by a transition from $3d$ to $2d$ vortex pinning. For $H_1<H_a<H_2$ vortex pinning is governed by vortices locked-in twin planes and their confinement prevents the crossover to $2d$ pinning.

In summary, we have found that twin planes can act as channels for vortex motion. However, due to the strong disorder in the twin plane, channeling of vortices along the twin planes only becomes favorable when the pinning in the untwinned regions becomes large. We also have found that vortex channeling only takes place for vortices locked in the twin plane. For applied magnetic fields making an angle larger than a critical angle ($\alpha_c<3.5°$) with the twin planes no decrease in overall pinning strength has been found.

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