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Influence of twins on the peak effect and vortex pinning in $YBa_2Cu_3O_y$ single crystals

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Investigating twinned and detwinned $YBa_2Cu_3O_{7-\delta}$ single crystals, we have observed differences in the shape of the peak effect, in the field dependence of the relaxation rate, and in the values of the irreversibility field and shielding current. It is shown that twins produce an additional peak or a plateaulike behavior in the magnetization hysteresis at an intermediate temperature range. A significant smaller value of the irreversibility field was found in the detwinned samples. The influence of twins on the shielding current j_s changes with the variation of the bulk pinning force. Twin boundaries increase j_s in the region of small currents. However, for stronger bulk pinning they reduce the current and presumably become channels for easier flux penetration. The influence of twin boundaries on pinning is significant only within the trapping angle of about 15°.

The peak effect in conventional superconductors was for a long time a topic of controversial and intensive discussions.[1,2] Experimentally, this feature corresponds to the anomalous increase of the critical current with the magnetic field, resulting in a peak significantly above the self-field region. Its origin is not yet completely understood in spite of several different explanations.[1] New impetus for further study was the discovery of a peak behavior in high-temperature supercondcutors, which was called the "fishtail" or "butterfly" feature.[3,4]

Recently it was found that in $YBa_2Cu_3O_y$ single crystals this single peak behavior may be accompanied by the appearance of a second maximum.[5,6] This second peak differs from the standard fishtail by its weak dependence on temperature and oxygen content. Very often the interference between the two peaks results in a plateaulike behavior as observed previously in Refs. 7 and 8. The origin of the second peak was related to the matching effect of vortices with the twin boundary structure.[6] Similarly, the importance of twin boundaries for the appearance of the plateaulike anomaly was pointed out recently.[9] The authors stressed the importance of vortices lock into the two planes providing a channeling effect. However, the relation of twins to all these anomalies still requires a direct confirmation, which will be given in this paper.

Another important aspect of the presented study is the analysis of the influence of twins on the pinning of vortices. This problem is still not resolved and suffers from contradictory statements (e.g., Refs. 9 and 10). The fragmentary data available so far do not provide a full picture for the whole range of temperature and magnetic field. The use of uniaxial stress induced detwinning provides the possibility to compare the properties of the same crystal in a twinned and detwinned state. This is very important for such a study because of the relatively small effect of twins.

The $YBa_2Cu_3O_y$ single crystals studied were grown in Y_2O_3-stabilized ZrO_2 crucibles as discussed elsewhere.[11] Two samples with different oxygen treatment were investigated. One of the crystals, sample 1, was annealed at 1 bar oxygen and 480 °C for two weeks. This provided an oxygen content of $y=6.94$. The superconducting transition temperature of this sample was 91.4 K and the transition width 0.8 K. This crystal was cut into two pieces with rectangular shape parallel to the a and b directions. They had dimensions $1.5\times1.0\times0.08\ \mathrm{mm}^3$ and $2.0\times1.5\times0.08\ \mathrm{mm}^3$ (a, b, c directions), for samples $1A$ and $1B$, respectively. Another crystal sample 2 ($1.72\times0.98\times0.14\ \mathrm{mm}^3$ along a, b and c, respectively) was annealed at 1 bar oxygen and 440 °C during two weeks and then furnace cooled. This crystal had higher oxygen content $y=6.97$, which corresponded to lower $T_c=90.5$ K.[11] The transition width was 0.36 K.

In the initial state, all these samples were densely twinned, containing twin complexes of both (110) and (1-10) direction with a characteristic size of several tenth of millimeter. The twin boundary pattern was identical on both surfaces of the crystal. Detwinning was achieved by applying a uniaxial pressure of about $10^8\ \mathrm{N/m}^2$ at temperature of 400 °C for about 10 min. Some twin boundaries remained, however. Samples 2, $1A$, and $1B$ were about 90, 60, and 75 % monodomain, respectively. To check the reproducibility of the observed behavior, the last two crystals were twinned back by heating to 400 °C for about 10 min. After this procedure $1A$ was detwinned again resulting in about 50% of the crystal in a monodomain state.

The magnetization measurements were performed with a vibration sample magnetometer (VSM), in magnetic field $H\leqslant120$ kOe parallel to the c axis. The field was cycled with constant sweep rates. The relaxation rate was determined by applying regression analysis to 8–12 such loops, with sweep rates of the magnetic field ranging typically from 30 to 120 Oe/s. Measurements of the angular dependence have been performed in a split-coil VSM with magnetic fields $\leqslant70$ kOe. The angular resolution was ~0.1°. The superconducting transition temperature was determined as the middle point of zero field cooled transition measured by a superconducting quantum interference device magnetometer in $H=1$ Oe.

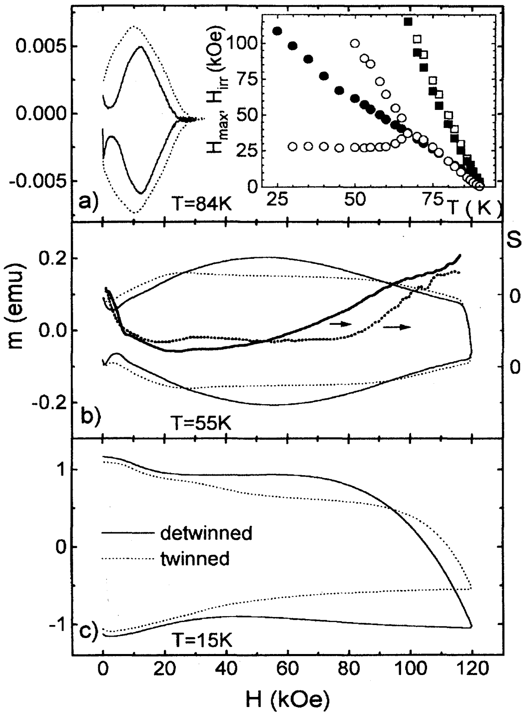

FIG. 1. Magnetization hysteresis of a $YBa_2Cu_3O_{6.97}$ single crystal (sample 2) in the initial twinned (dotted line) and detwinned (full line) states, for different temperatures. The inset in (a) shows temperature dependences of the peak position, H_{max} (circles), and the irreversibility line, H_{irr} (squares) in the initial (open symbols) and detwinned states (closed symbols). For the twinned state, the low field H_{max} was determined by the position of the maximum of the irreversible magnetization M_{irr} and the end of the plateau $M_{irr}(H)$ was taken as the high field H_{max} in this sample, which showed plateau instead of the second peak. (b) presents also the field dependence of the normalized relaxation rate, S in the initial (dotted line) and detwinned (full line) states.

As was previously reported[6–8] most of the twinned samples with high oxygen content show three different types of magnetization hysteresis curves, occurring at different temperatures. As can be seen from Fig. 1, detwinning produces qualitatively different effects in each of these regions.

The conventional fishtail behavior, observed at high temperatures $T > 60–70$ K does not change qualitatively, besides appearance of a minimum at low fields. However, detwinning decreases the values of the irreversibility field H_{irr}, shielding currents j_s and, to a lesser extent, influences the position of the $j_s(H)$ maximum, H_{max} [Fig. 1(a)]. This behavior was observed for all studied samples and was reproducible after the samples were subsequently twinned and detwinned again. However, H_{irr} and j_s were slightly different from the original twinned state. This can be explained by the differences observed in the initial and recovered twin structure.

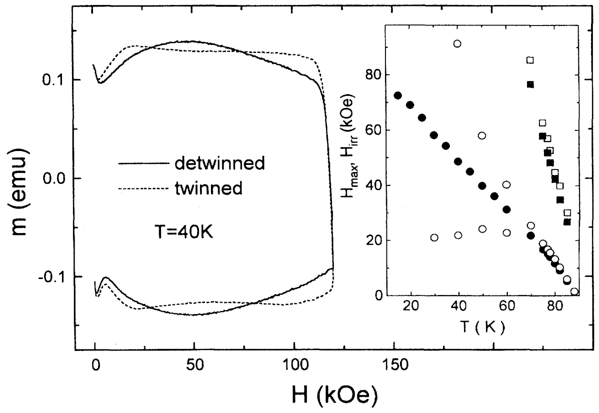

FIG. 2. Magnetization hystersis of $YBa_2Cu_3O_{6.94}$ single crystal (sample 1*A*) in the initial twinned (dotted line) and detwinned (full line) states, for $T = 40$ K. This sample showed two peaks in the twinned state. The inset shows temperature dependences of the peak position, H_{max} (circles), and the irreversibility line, H_{irr} (squares) in the initial (open symbols) and detwinned states (closed symbols).

The drastic changes of the magnetization hysteresis loop occur in the intermediate temperature region 20 K$<$T$<$60 K [Figs. 1(b) and 2]. The double peak of plateau structure originally observed in this interval totally disappears after detwinning. Instead, the conventional fishtail behavior appears. The maximum is observed roughly in the middle of the two initial peak positions or the plateau [Figs. 1(b), 2, and inset of Fig. 1(a)]. The current in the remanent state practically does not change with detwinning but significantly increases in the region of the fishtail peak. Sample 2 showed higher currents near the peak in the detwinned state up to 80 K and samples 1*A*, *B* did this up to 60 K. However, far from the fishtail peak the current in the twinned sample is higher [Fig. 1(b) and 2]. In correspondence with the transformations of the magnetization behavior, significant changes in the normalized relaxation rate S are observed. As can be seen from the data of the detwinned sample presented in Fig. 1(b), the minimum of S occurs approximately at $H_{max}/2$, which is the usual behavior for the fishtail peak.[12] Whereas in the twinned state the low field minimum of the relaxation rate S is close to the position of the corresponding maximum H_{max} pointing to a "mirrorlike" behavior.[6,8]

In the low temperature region, $T < 20$ K, only a monotonic decrease of the current with field H was observed in the twinned samples. However, detwinning spreads the fishtail feature to this T interval, too [Fig. 1(c)]. In the detwinned state, the values of the current increased for the whole field range.

For further elucidation of the importance of vortex trapping by the twin planes,[13] we have studied the angular dependence of the magnetization hysteresis. The magnetic field was tilted away from the *c* axes in a plane (parallel to one sample side) which forms an angle of ~45° with twin boundaries. As can be seen from Fig. 3(a), a sharp maximum in the dependence of the hysteresis width Δm on the tilting angle Φ is observed for the field direction along the *c* axis. It exists for the whole field range, being less pronounced near H_{max} and $H = 0$. The $\Delta m(\Phi)$ peak is accompanied by a similar angular behavior of the irreversibility line [Fig. 3(a)]. In the intermediate temperature region, for the magnetic field between the two peaks or in the region of plateau, a well pronounced dip in the hysteresis width $\Delta m(\Phi)$ is found for the direction of the magnetic field along the *c* axes [Fig. 3(b)], whereas in fields below and above this region a peak in $\Delta m(\Phi)$ is observed [Fig. 3(b)]. The double peak or pla-

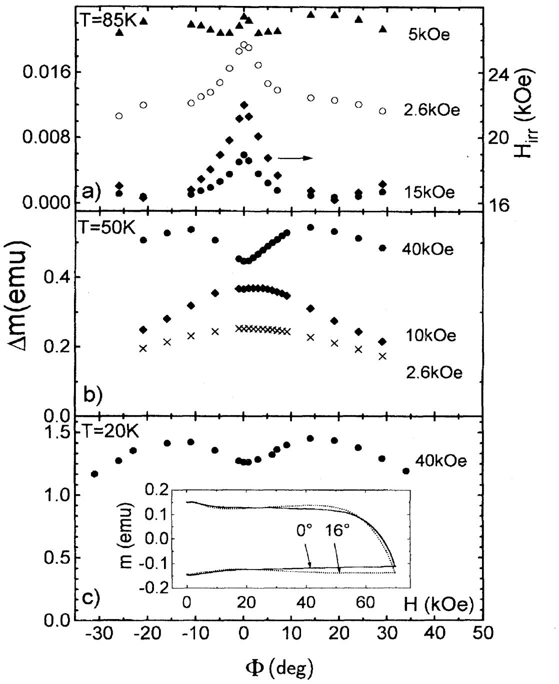

FIG. 3. Angular dependences of the hysteresis width, for different magnetic fields at temperature, T:(a) 85 K, (b) 50 K, and (c) 20 K, for a $YBa_2Cu_3O_{6.94}$ single crystal (sample 1B). (a) presents also the angular dependence of the irreversibility field. The inset in (c) shows magnetization hysteresis for the tilting angles $\Phi=0°$ and 16°.

teau structure is replaced by the fishtail behavior as the magnetic field is tilted away from the c axis. In the low temperature region, the angular dependence of the hysteresis width $\Delta m(\Phi)$ shows a well pronounced dip, at all magnetic fields above the self-field value [Fig. 3(c)]. For tilt angles above 15°, as can be seen from the inset to Fig. 3(c), the fishtail behavior replaces the monotonic decrease of the current at low temperatures. Summarizing, the behavior of $\Delta m(\Phi)$ observed with the tilting of the magnetic field away from the c direction and, consequently, from the twin planes is found to be in qualitative agreement with the effect of detwinning.

In our discussion, we first formulate general conclusions from the experimental results presented above. The data obtained, prove that the intermediate temperature anomaly is produced by twins. They also show that the mirrorlike behavior of the relaxation rate at intermediate temperature range originates from twins. On the other hand, the absence of qualitative changes in the high temperature fishtail behavior despite drastic changes in the twin structure rules out their importance for the fishtail peak. This is in agreement with previous studies of untwinned samples.[4,14] Moreover the recovery of the fishtail behavior in the detwinned samples, in the low temperature interval, suggests that in twinned samples this region is determined by a twin boundary pinning. At low T, twin boundaries suppress the fishtail mechanism and produce a monotonic decrease of the current with H in the twinned state. The influence of twins on the current was found to change with temperature. For the twinned state, pinning is significantly increased in the high T region, pointing to twin boundaries as being strong pins. However, for the low T interval, only a decrease of the current was found. In this case twin boundaries provide easier flux penetration thus behaving as weak links. With the increase of the tilting angle Φ, vortices should leave twin planes and align with the direction of the magnetic field. In this case the influence of twins should be drastically decreased and the observed changes in $\Delta m(H)$ are qualitatively similar to that produced by detwinning. However, this correspondence is not direct because of the change of intrinsic parameters with Φ, which should decrease $\Delta m(\Phi)$ even for isotropic pinning centers. From the analysis of the angular dependences the value of the trapping angle[13] can be estimated as $\sim 15°$.

Further, we want to consider possible mechanisms of the observed behavior. Theoretical aspects of the attractive twin boundary pinning were considered in Refs. 13 and 15–19. According to Refs. 16 and 17, the behavior of a twinned sample is determined by the competition between point and correlated disorder. Pointlike disorder, originating from oxygen vacancies or atomic impurities, disrupts the Abrikosov vortex lattice and induces a vortex-glass phase. This state is characterized by random and enhanced wandering of vortex lines. The correlated disorder originating from twin boundaries is expected to suppress the vortex-glass phase and induce a transition to the Bose-glass state, which is characterized by the suppressed wandering and localization of vortex lines into the twin planes. For the comparable strength of both disorders a mixture of both phases is, probably, realized. However, close to the melting transition the influence of pointlike disorder is expected to be suppressed.[16] This is supported by the observed angular dependence of the irreversibility line, which shows a cusp near the c axis similar to the behavior of the Bose-glass melting line in the transverse magnetic field.[16]

We believe that the fishtail effect present in the detwinned samples almost at the whole temperature range originates from the pinning by pointlike disorder. The possible mechanisms were analyzed previously in Ref. 6. The low field peak observed in the twinned samples at intermediate temperature region we relate to the matching effect, presumably, between intervortex and twin boundaries distances. In this case one should expect a peak of the current due to the adjustment of vortex and pinning structures.[1] The matching origin of the low field peak is supported by the previous observation[6] that its position is nearly independent of temperature and oxygen content. According to high-resolution electron microscopy and x-ray diffractometer studies of the $YBa_2Cu_3O_y$ single and polycrystals the quasiperiodic twin microstructure is characterized by the distances $d=20$–50 nm (e.g., Ref. 20) which corresponds to a matching magnetic field of $H_m \sim \Phi_0/d^2 \sim 10$–50 kOe in agreement with the experiment. The disappearance of this peak at high temperatures may result from the temperature induced suppression of the twin boundary pinning.[16] This increases the relative importance of vortex-vortex interaction, which is less temperature dependent, and suppresses the adjustment of vortices to the disordered pinning structure. At low temperatures, the self-field exceeds the 2–3 T value and the low field peak smears out. The high field peak can be related to the increase of the twin boundary pinning by the shear interaction with the vortices pinned in the bulk.[19]

Next we analyze the influence of twinning on the vortex pinning. From the geometrical point of view, the twin boundaries could produce pinning only in the transverse direction and no pinning is expected parallel to ideal walls. In reality, the longitudinal pinning should differ from zero due to (i) oxygen vacancies, (ii) pointlike impurities, (iii) strain fields, and (iv) interfaces of rectangular twin complexes. However, the pinning induced by these mechanisms is not expected to be as strong as in the transverse direction. Consequently, twin boundaries should represent highly anisotropic pinning centers with significantly higher transverse f_{tw}^t than longitudinal f_{tw}^l pinning force. For the most field range (the crossover field may be estimated similarly to B_{rb} in Ref. 16), vortices are pinned both in twin boundaries and in the bulk. In the case of single vortex pinning the dissipation is determined by the system with smaller pinning forces f_{tw}^l or f_b. One should expect a change of their relation with the temperature. Taking into account that the vortex core is elongated along a twin plane (Ref. 19), f_b should exceed f_{tw}^l at low temperature. However, at higher temperatures the dimensional reduction of thermal fluctuations can lead to an enhanced pinning force along the twin planes.[13] A collective pinning theory gives[13] an exponential decrease of the critical current for the three-dimensional (3D) single vortex pinning by pointlike defects and a weaker algebraic dependence for the 2D pinning of vortices by twin boundaries. In this case, the high temperature region (with $f_b<f_{tw}^l$) is dominated by the dissipation produced by the vortices moving in the bulk with pointlike disorder and a fishtail behavior is observed. The higher value of the current in the twinned sample in comparison with the detwinned one, probably originates from the interaction of moving vortex bundle with twin boundaries or vortices pinned in twin boundaries.

With decreasing temperature, we expect the bulk pinning to increase faster than the longitudinal pinning force. At low temperatures ($f_{tw}^l<f_b$), the Lorentz force first sets into motion the vortices in twin boundaries whereas vortices in the bulk remain still pinned. The guided slipping of vortices or vortex bundles in twin boundaries can be considered as a channelling process.[9,21]

In the intermediate temperature region, the relation between bulk and twin boundary pinning changes with the magnetic field due to the presence of the fishtail effect, for f_b, and, presumably, monotonic decrease of f_{tw}^l. Near the fishtail peak ($f_{tw}^l<f_b$), twins decrease the current. However, in small and high magnetic fields ($f_{tw}^l>f_b$), they increase it.

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