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Peak effect and scaling of irreversible properties in untwinned Y-Ba-Cu-O crystals

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We measured the peak effect in the magnetic hysteresis loop of an untwinned $YBa_2Cu_3O_{7-\delta}$ crystal in the vicinity of the critical temperature and studied its temperature, time, and angular dependence. The location of the peak is determined by the component of the field along the c direction. The pinning force density $F_p(B)$ is scaled into a single curve for all measured isotherms (75–87 K) and time scales (4–1500 sec), and its functional form reflects the observed peak effect. The scaling field is related to the irreversibility field of oxygen-deficient regimes. The results indicate that pinning in this system is due to inhomogeneity of the oxygen deficiency and that the peak is related to the formation of a percolationlike network of reversible regimes.

The critical current of a superconductor, at a given temperature, usually decreases with the applied magnetic field. Hence, the width ΔM of the magnetic hysteresis loop, which is proportional to the critical current,[1] decreases as the field is increased. However, there are several reports[2–7] on an anomalous increase of ΔM at intermediate fields. Such observations have been reported since 1961 and denoted as a "peak effect."[2] More recently, similar anomalies were observed in high-temperature superconductors, and they were referred to as "anomalous peaks"[3] or "fishtails."[4]

Different pinning mechanisms induce different anomalous peaks which are classified by their temperature dependence, their location relative to H_{c2} and by their width. In $YBa_2Cu_3O_{7-\delta}$ (YBCO), peaks are most clearly observed in the vicinity of the critical temperature T_c and as we show below, their location is clearly temperature dependent. Two mechanisms have been proposed for the peak effect in YBCO: (a) Suppression of superconductivity in oxygen deficient regions as field is increased transforms these regions into efficient pinning centers.[3] (b) A crossover from single to collective flux-creep[8] induces slower magnetic relaxation at intermediate fields and, as a result,[4,6] a peak is formed. The present study in an untwinned YBCO crystal supports the first approach. It also shows that the location of the peak is related to the formation of a percolationlike network of reversible regimes of oxygen deficient phases.

Our measurements were done on an untwinned YBCO crystal of $2\times2\times0.25$ mm^3 and $T_c \sim 92$ K. Sample preparation is described in Ref. 9. All our measurements were done on an "Oxford Instruments" Vibrating Sample Magnetometer (VSM), which allows the rotation of the sample relative to the field. Due to the location of the sense coils, we measure the component of the magnetization in the field direction.

Figure 1(a) shows the magnetization curves taken with

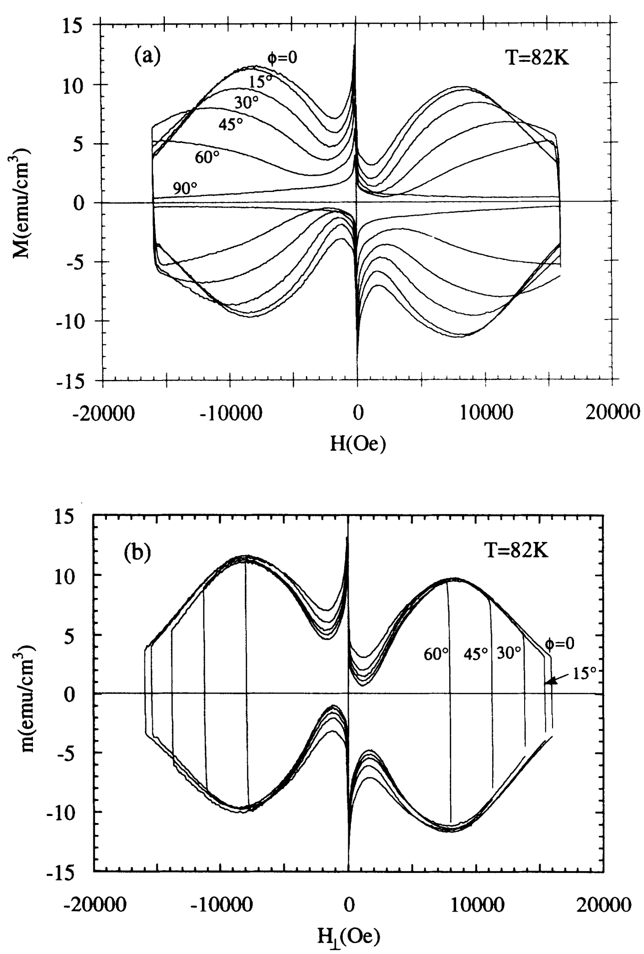

FIG. 1. (a) Magnetization curves with the applied field at different angles relative to the c direction at $T = 82$ K. (b) The same as in (a), but $m = M/\cos\phi$ where M is the measured magnetization and $H_\perp = H\cos\phi$.

the field H at various angles ϕ relative to the c direction. The magnetization curves were measured in steps of 100 Oe, with a waiting time of 4 seconds at each field. The peaks are apparent at all angles except for H in the ab plane where a peak is absent. The location of the peak is angle dependent. However, when the curves are plotted as a function of the component of the field along the c direction, $H_\perp$, and we take into account that the actual magnetization is $m = M/\cos\phi$,[10] the regions near the peak for various angles become overlapping, see Fig. 1(b). This indicates that the peak effect is related to critical currents in the CuO_2 planes. Note that the effect of self-fields is already negligible above 100 Oe due to the low value of ΔM in this temperature range.

Valuable information on pinning mechanisms has been obtained from the functional form of the pinning force density $F_p'(B) = J_c B$. Figure 2(a) exhibits F_p' as a function of H (we take $H \approx B$) for our YBCO sample. With the decrease of temperature, F_p' increases and H_{max} is shifted to higher fields. Figure 2(b) shows the normalized pinning force $F_p \equiv F_p'/F_{p,max}'$ as a function of $b^* = H/H_{max}$ (for YBCO, due to the difficulty in determining H_{c2}, it is more convenient to use H_{max} and not H_{c2} as the scaling field, where H_{max} is the field for which F_p' reaches its maximum[11]). The figure demonstrates that all isotherms scale to a single curve up to H_{max}. The inset of Fig. 2(b) exhibits the value of F_{max} as a function of H_{max}. The solid line in the inset is a fit to $F_{max} \approx 28.3 H_{max}^{3/2}$. We thus conclude that $F_p \approx 28.3 H_{max}^{3/2} f(b^*)$. The scaling of F_p vindicates the notion that a single pinning mechanism is involved and the functional form of $f(b^*)$ is determined by the microscopic pinning mechanism.[2,12] Among the known functional forms, the only one which fits our data (for that part of the curve which does scale) is $f(b^*) = 3b^{*2}(1 - 0.67b^*)$. This functional form demonstrates the fact that for some intermediate field interval, the critical current increases with the field. Note that other functional forms of F_p were previously reported.[11,13] These reports, however, focused on twinned samples in which pinning is also affected by twin boundaries.

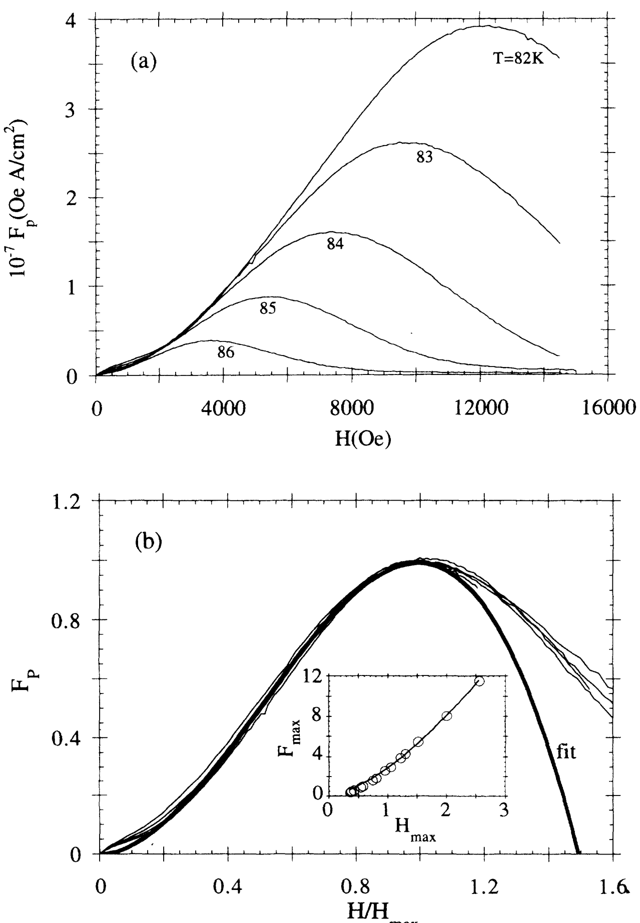

FIG. 2. (a) The density of the pinning force as a function of the applied field for temperatures between 82 and 86 K. (b) The rescaled density of the pinning force as a function of the reduced field, $b^* = H/H_{max}$. The thick line is a fit of $f(b^*) = 3b^{*2}(1 - 0.67b^*)$. Inset: F_{max} as a function of H_{max}. The solid line is a fit of $F_{max} \approx 28.3 H_{max}^{3/2}$.

The peak effect is associated with dynamical features. We have thus measured relaxation of the magnetization at various fields in the following way. The field was increased (decreased) to $+(-)1.5$ T and was then decreased (increased) to set field at a rate of 500 Oe/sec; this change of field is large enough to create a critical state at the set field. We started measuring the magnetization during the field ramping so we have data of the magnetization starting from a few seconds after the set field was reached. The solid lines in Fig. 3 connect 72 different points that correspond to equal relaxation times. It is clear that the peak shifts towards lower fields with time. The inset shows F_p for the differently relaxed magnetization curves and it is apparent that they scale up to H_{max}. The solid line is a fit with the same functional form as in Fig. 2(b). Thus, although the relaxation does shift the location of the peak to significantly lower fields, F_p remains practically the same. As emphasized above, the functional form of F_p reflects the fact that at intermediate field

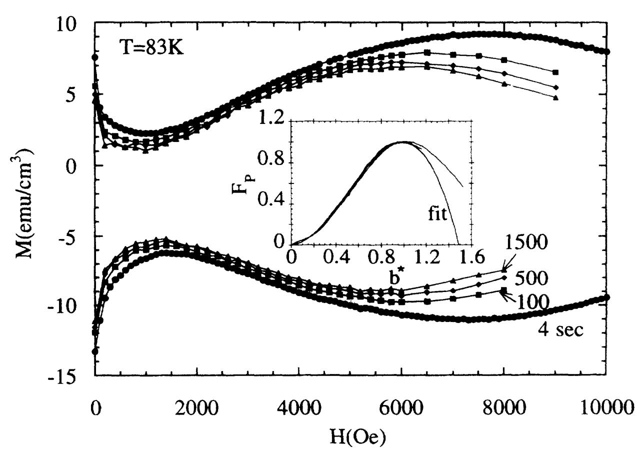

FIG. 3. Magnetization curves as a function of the field along the c axis after different elapsed times at $T = 83$ K. Inset: the rescaled density of the pinning force as a function of the reduced field for the same time as in the figure. The thick line is a fit of $f(b^*) = 3b^{*2}(1 - 0.67b^*)$.

range J_c increases with the increase of the field. If we assume that this is the shape of F_p in the limit of $t=0$ as well, it would imply that the peak effect is not formed due to relaxation processes. This conclusion, based on extrapolation to $t=0$, should be taken with caution because of the fact that all the present measurements are done at relatively high temperatures where the relaxation processes are accelerated and thus 4 sec may represent quite a long effective time. Thus, further study is needed in order to establish that the peak effect is present at $t=0$ as well. It is worth noting that it was recently demonstrated[7] that in Bi-Sr-Ca-Cu-O the peak is *absent* at short times and is built up gradually with time. However, the peak in Bi-Sr-Ca-Cu-O has completely different characteristics from the peak in YBCO regarding the temperature and field ranges and the general shape of the peak.

Daeumling, Seuntjens, and Larbalestier[3] suggested that a variation of oxygen deficiency in the sample is the source of new pinning centers responsible for the peak effect; above H_{peak} the crystal becomes "granular" and the magnetization decreases again. The granularity means that the flux penetrates into different parts ("grains") of the sample independently and it leads to a reduction in the measured magnetization. The fact that the single crystal behaves as if it is granular above H_{peak} was attributed to the formation of a percolatinglike[14] network of normal zones by oxygen deficient regions. This implies that H_{peak} should be related to the upper critical field of these oxygen deficient regions. In order to examine this interpretation of H_{peak}, we studied the temperature dependence of H_{peak}. Figure 4 shows the critical currents (deduced from the width of the magnetization curves) for fields along *c* and for temperatures between 79 and 86 K. The inset shows the temperature dependence of H_{peak}. It is quite clear that dH_{peak}/dT (*total* change of about 1 T between 80 and 86 K, see Fig. 4) is much lower than the reported values for $S \equiv dH_{c2}/dT = 0.7-10$ T/K[15,16] Thus, the suggestion that H_{peak} is related to the formation of a percolating network of *normal* zones is not justified. We emphasize here, for reasons to be apparent in the next paragraph, that the slope S depends only weakly on the value of δ in $YBa_2Cu_3O_{7-\delta}$ for samples with low oxygen deficiency ($\delta < 0.07$).[16] For these range of values of δ, T_c may be changed by several degrees and S is changed by 30–40 % at most.[16,17]

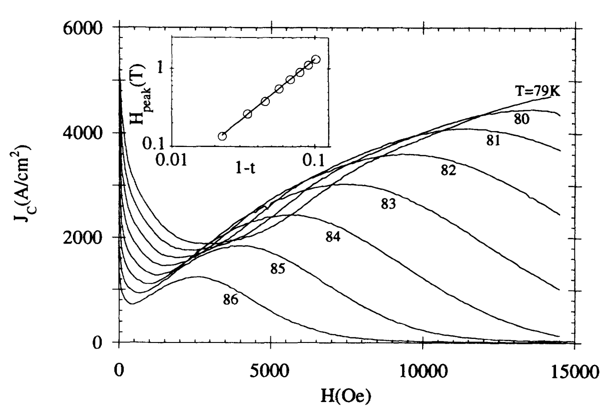

FIG. 4. The critical current density as a function of magnetic field for temperatures between 79 and 86 K. The field was applied along the *c* direction. Inset: the reduced temperature dependence of H_{peak}, the solid line is a fit of $H_{peak} = 4.2\times 10^5(1-t)^{(3/2)}; t = T/89$.

Assuming a power-law behavior for H_{peak} we find an excellent fit, shown in the inset of Fig. 4, $H_{peak} = 4.2\times 10^5(1-t)^{(3/2)}$ where $t = T/89$. A fit with the same exponent and a similar prefactor was obtained in Ref. 18 for the irreversibility field in YBCO crystals. This remarkable similarity between the fits suggest that the peak may be related to the fact that certain zones of the sample with a T_c of 89 K reached the irreversibility field. At this field value (together with zones of lower irreversibility field) a percolating network of *reversible* zones is formed. Inasmuch as granularity in magnetization measurements is concerned, it makes no difference whether the percolating network consists of normal zones (as suggested by Daeumling) or of reversible zones (as suggested here). In both cases the flux penetrates into different parts of the sample independently. Our interpretation also yields a simple explanation for the shift toward lower fields of the peak in the relaxed magnetization curves. At fields slightly lower than H_{peak}, there are still some regions that prevent percolation of reversible regimes. However, these regions are of relatively weak pinning. Therefore, after waiting long enough these regions will become effectively reversible, which means that the field at which granularity is formed decreases. This may also account for the angular dependence of the peak effect since the irreversible properties are very anisotropic and in the *ab* direction there is an intrinsic granularity due to the space between the CuO_2 planes.

It is tempting to relate the functional form of $f(b^*)$ to a microscopic mechanism as was done for conventional superconductors. It may be interesting to notice that the function $f(b^*)$ (though with H_{c2} as the scaling field) has been analytically derived and used in the past for samples with $\Delta\kappa$ pinning,[12] and that inhomogeneity in oxygen deficiency may yield such a variation of κ within the sample. However, there are several difficulties in such an interpretation. The scaling holds only up to H_{peak}; deviations from scaling are observed at higher fields. Similar deviations were observed[11] in other cases as well and were attributed to the effect of flux creep. Our data, which show scaling over different time scales, imply that the origin of the deviation is more subtle and is related to the appearance of granularity above H_{peak}, where a different scaling field may be required. Another related problem is the scaling field. The functional form to which we compare $f(b^*)$ was derived for low-temperature superconductors, for which the scaling field is the upper critical field. On the other hand, for high-temperature superconductors the irreversibility field or H_{peak} are usually used as scaling fields. Nevertheless, in spite of the reservations mentioned, it seems that this similarity is not completely coincidental. However, more study is needed in order to establish rigorously its relevance.

In conclusion, our scenario for the peak effect is as follows. The distribution of the oxygen deficiency induces

$\Delta\kappa$ pinning which is known to yield an increase in the critical current with field. As the field exceeds a threshold where a percolating part of the sample becomes reversible, the sample becomes granular and the measured magnetization decreases. As temperature or waiting time is increased the threshold field decreases due to the temperature and time dependence of the irreversibility field of the oxygen deficient regions. In both cases the evolution of the reversible network is the same up to the peak which yields the success of scaling. The angular dependence reflects the fact that the irreversibility field along the planes is much higher than the one along the *c* direction.[19] Thus, the setting of granularity (which determines the location of the peak) is mainly related to the latter.

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