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An alternative method for determination of the lock-in angle in twinned superconductors

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An alternative method for determining the lock-in angle \( \varphi_L \) for pinning of the vortices on extended defects has been developed. This method does not require any preassumed criterion for defining \( \varphi_L \). Highly twinned Sm\(_{1+\delta}\)Ba\(_{2-x}\)Cu\(_{3}O_{6+y} \) single crystal was used for demonstrating the method. Appropriate scaling of the hysteresis loops measured for different angles between the field and twin planes in highly twinned SmBaCuO single crystal led to a clear discrimination between two vortex dynamics regimes. From this scaling, the lock-in angle was determined to be \( 6^\circ \pm 0.1^\circ \) for the single crystal investigated. This method significantly reduces the uncertainty in determining the lock-in angle when compared to all the other currently employed methods. © 2006 American Institute of Physics. [DOI: 10.1063/1.2171772]

I. INTRODUCTION

The investigation of flux pinning by twin planes has attracted considerable attention, since the naturally formed twin planes occur regularly in Y123 crystals.\(^1\)–\(^3\) One of the characteristic properties of vortex pinning by twin planes is a cusplike dependence of the irreversibility field \( H_{\text{irr}} \) on the angle \( \varphi \) between the twin plane and the magnetic field. The cusp appears around \( \varphi = 0^\circ \), within the angular range \( \varphi_L \).\(^4\)–\(^6\) The angle \( \varphi_L \) is called the lock-in angle. The measurement of the angular dependence of \( H_{\text{irr}} \) has been the principal method used to study the locking of magnetic vortices by twin planes and the determination of \( \varphi_L \). However, the pinning by twin planes is effective only at high temperatures close to \( T_c \).\(^7\)–\(^9\)

Unfortunately, the determination of \( H_{\text{irr}} \) at these temperatures is subject to a high degree of uncertainty. Because of this, it is highly desirable to develop an alternative method for obtaining \( \varphi_L \), which relies on the universal physical principles instead of arbitrary definitions. Such a method is presented in this work. It is based on the scaling of magnetic hysteresis loops, measured with different angles \( \varphi \) between magnetic field and the crystalline \( c \) axis. The scaled hysteresis loops fall into two distinct families, one for \( \varphi < \varphi_L \) and the other for \( \varphi > \varphi_L \), with a transition at sharply defined angle \( \varphi_L \).

II. EXPERIMENT AND MICROSTRUCTURE

The preparation procedure for the present type of crystal with the chemical formula Sm\(_{1+\delta}\)Ba\(_{2-x}\)Cu\(_{3}O_{6+y} \) \((x = 0.04)\) can be found elsewhere.\(^10\) The crystal studied in the present work has a rectangular geometry and a size of \(0.514 \times 1.773 \times 2.101 \) mm\(^3\). It is a highly twinned sample with the value of the twin spacing ranging from a few micrometers down to a few tens of nanometers, as obtained by both optical light microscopy techniques [Fig. 1(a)] and bright field transmission electron microscopy (TEM) [Fig. 1(b)]. The twinned interfaces can clearly be seen [arrowed in Fig. 1(b)] in the TEM image. Figure 2 is a selected area electron-diffraction pattern from this phase. Analysis of this pattern is consistent with it being the [001] zone axis of an orthorhombic crystal structure. The (110), (220), etc., reflections are marked. It can be seen that there is splitting of the reflections along this [image reference].

![Image](http://example.com/image1)

Fig. 1. (a) Optical micrograph of the Sm123 single crystal, which is highly microtwinned. The scale bar indicates 7.5 \( \mu \)m. (b) The presence of twins in the Sm123 sample was also confirmed by bright field transmission electron microscopy (marked by arrows).
row due to twinning. This implies that the twin planes are not only all parallel to the crystal c axis but also that they have (hk0) orientation.

X-ray-diffraction analysis of the sample gave a single-phase spectrum. The strong and narrow peaks correspond to Miller indices (00l), with \( l = 1, 3, 5, 6, \) and 7, which is an indication of a high degree of preferred orientation of the crystallographic planes perpendicular to the c axis. From the energy dispersive x-ray spectroscopy (EDS) map, the oxygen distribution was found to be uniform. Analysis of the diffraction data of a sample grain was again consistent with the presence of an orthorhombic phase.

III. MAGNETIC MEASUREMENTS

The magnetic measurements were performed with an MPMS-5T superconducting quantum interference device (SQUID) magnetometer. The critical temperature of the crystal was obtained from measurements of the magnetic moment with an applied field of 20 Oe. Its value was obtained to be \( T_c = 95 \) K, with transition width \( \Delta T = 2 \) K. Since extended defects are directional pinning centers, the dominant defect structure can be determined by changing the angle between the applied field and the extended defects.\(^{11}\) Figure 3 shows the magnetic hysteresis (\( m-H \)) loops recorded at 89.5 K, with the applied field (\( H \)) inclined at various angles \( \phi \) relative to the crystal c axis. This was the lowest temperature for which closure of the loop for \( \phi = 90^\circ \) at the highest accessible field, 5 T, was possible. It can be seen that the \( m-H \) loops display the secondary peak effect over the entire angular range of \( 0^\circ < \phi < 90^\circ \). The maximum of the secondary peak is at the field \( H_{\text{peak}} \), and \( H_{\text{peak}} \) increases with \( \phi \). The inset of the figure shows the temperature dependence of the upper critical field and the irreversibility line for the two principal directions of the field. After the sample was zero field cooled the upper critical field was determined by scanning the temperature from far below \( T_c \) to above \( T_c \) at different fields, and the criterion of \( \Delta m = 10^{-5} \) emu was selected to mark the onset of deviation from the horizontal axis. The irreversibility line was determined from the merging point of the field-cooled (FC) and zero-field-cooled (ZFC) curves with the same criterion as the upper critical field. The ratio of the two upper critical fields was obtained to be about 10, which is of the same order as the anisotropy parameter for yttrium barium copper oxide (YBCO).\(^{12,13}\)

In order to compare the commonly used method of determining lock-in angle via appearance of the cusplike feature in the irreversibility field and the method presented in this paper, the irreversibility field was determined from the merging point of the upper and lower branches of the hysteresis loop at each angle, using the same numeric criteria as for FC-ZFC curves. Figure 4 is the result of this measurement, which was carried out at 89.5 K. For angles \( \phi \) close to \( 0^\circ \) and in the range dominated by the twin planes, the hysteresis loop measurements were performed with smaller angle increments to extract any cusplike dependence of \( H_{\text{irr}} \) on \( \phi \). Despite the presence of a high density of twin planes (Fig. 1) no cusplike feature could be observed due to small signal-to-noise ratio close to the irreversibility field, as can be seen in the inset. In what follows, it is shown that the lock-in angle can be extracted from the same data with-
out conducting any extra measurements, using a different approach in the data analysis. In order that the intrinsic anisotropic properties of the superconductor, which are related to its layered structure, are not confused with the effects of twin boundaries, the anisotropic effects must be taken into account in this analysis. According to Blatter et al., an anisotropic superconductor can be mapped onto an isotropic superconductor using a scaling method. In this approach, the measured hysteresis loop must be scaled using $H_e(\varphi)$ and $m/\varepsilon(\varphi)$, where $\varepsilon(\varphi) = \cos^2 \varphi + \Gamma^2 \sin^2 \varphi$. $\Gamma$ is the anisotropy parameter. Taking $\Gamma^{-1} = 10$, the hysteresis loops are scaled using the approach of Blatter et al., as shown in Fig. 5. The results of the scaling for angles from $0^\circ$ to $90^\circ$ showed that all loops except for the ones close to $\varphi = 0^\circ$ and $\varphi = 90^\circ$ are well scaled. (The loops for angles close to $90^\circ$ have not been shown, for clarity.)

It has already been mentioned that for twinned samples there is a characteristic angle between the field and the crystal $c$ axis called the lock-in angle $\varphi_L$. The vortex structure for angles above $\varphi_L$ assumes a zigzag-shaped pattern (kinked vortices). Oussena et al. showed that for $\varphi < \varphi_L$, vortices are trapped on the twin planes and the vortex system forms a Bose glass phase. With increasing $\varphi$, the vortices are liberated from the twin planes and point disorder would be the dominant type of pinning, implying that a transition to the vortex glass regime occurs. The overlap of the scaled hysteresis loops (Fig. 5) for $0^\circ < \varphi < 90^\circ$ (but not close to the extreme angles) shows that the isotropic point disorder has the dominant role in governing the vortex dynamics in this angular range. On the other hand, the twins and Cu–O planes determine the vortex dynamics for the extreme cases of $\varphi = 0^\circ$ and $\varphi = 90^\circ$, respectively.

In order to investigate the lock-in transition for twin boundaries in the sample, hysteresis loops for angles $\varphi$ between $0^\circ$ and $16^\circ$ were measured with a $0.5^\circ$ increment [Fig. 6(a)]. From Fig. 6(b), which is an enlargement of the marked area, two opposite trends on the two sides of the converging point around $0.18$ T are observed: with the angle $\varphi$ decreasing from $16^\circ$, the peak effect is gradually suppressed and the minimum in the magnetic moment at low fields disappears. This trend has also been reported by other groups (e.g., see Fig. 6 in Ref. 17) and seems to be a general behavior for twinned superconductors at high temperatures. Despite the observations of this trend, no attention has been paid to the possible scaling of loops. In some reports, the anisotropy factor of the superconductor has been disregarded and the scaling factor $\varepsilon(\varphi) = \cos \varphi$ has been employed, which is only suitable for highly anisotropic superconductors such as Bi2212. Our data analysis showed that $\varepsilon(\varphi) = (\cos^2 \varphi + \Gamma^2 \sin^2 \varphi)^{1/2}$ can be used for less anisotropic superconductors, such as 123 systems.

Figure 7 (which is one of the major results of this work) shows the results of the scaling of the data of Blatter et al. for $0^\circ < \varphi < 16^\circ$, presented in Fig. 6(a). This scaling reveals two groups of hysteresis loops, those for $\varphi$ between $0^\circ$ and $6^\circ$ and those for $\varphi$ above $6^\circ$. Whereas the minimum at low fields and the maximum (i.e., the second peak in magnetic hysteresis loop) are clearly seen for the latter group, the former group does not exhibit a pronounced second peak. Because the scaling divides the hysteresis loops into two distinct groups and the scaled loops are angle independent within each of the groups, two separate pinning mechanisms are responsible for the observed behavior.
matches the mean vortex distance (matching effect).\textsuperscript{20} The vortex lattice parameter can be calculated via 
\( a = (\phi_0/B)^{1/2} \), where \( \phi_0 \) is the magnetic-flux quantum with a value of 
\( 2.07 \times 10^{-7} \) Oe cm\(^{-2} \). For fields between 700 and 1800 Oe, 
the vortex lattice parameter is obtained to be \( \leq 17 \) \( \mu \)m, 
which corresponds to the average measured twin plane spacing. 
This is supported by the work of Pradhan et al.,\textsuperscript{20,21} where 
the low-field peak in the double peak structure of a 
defect-free twinned \( \text{Nd}_{1+\text{x}}\text{Ba}_{2-x}\text{Cu}_{3}\text{O}_{7-\delta} \) single crystal is 
ascribed to the matching effect by twin planes. The suppression 
of the second peak in the hysteresis loop for \( \varphi < 6^\circ \) is 
believed to be a result of channeling or shearing of vortices 
along the twin walls.\textsuperscript{18,22}

In this way, the scaling of the hysteresis loops measured 
at different values of \( \varphi \), as a function of the lock-in angle 
of \( 6^\circ \). For \( \varphi > 6^\circ \), the pinning is dominated by the isotropic 
point disorder, which forms a vortex glass structure. The main 
advantage of this method over the conventional method 
of measuring the cusp in \( H_{\text{ir}} \) vs \( \varphi \) is that it does not rely on 
an arbitrary definition of \( H_{\text{ir}} \), and it can give a more accurate 
value of \( \varphi_L \), due to the sharp transition between the 
two groups of the scaled hysteresis loops.

The above method for obtaining \( \varphi_L \) was performed with 
a scaling based on the anisotropy factor (\( \Gamma \)), which was 
determined by the ratio of the two upper critical fields. These 
fields are themselves defined by an arbitrary criterion. 
However, the splitting of the scaled hysteresis loops into two 
groups occurred at the same value of \( \varphi_L \), regardless of the 
criterion employed for \( H_{\text{ir}} \). It should be noted that the twin 
boundaries are effective pinning centers only at high temperatures, 
\( 7^\circ-9^\circ \), where it is difficult to measure \( H_{\text{ir}} \) reliably. 
The presented method for obtaining \( \varphi_L \) does not suffer from 
the lack of sensitivity at these temperatures and its accuracy 
is only limited by the accuracy of measuring \( \varphi \).

We expect that the method developed in this work 
should work well for other twinned RE123 systems, too. 
Namely, the pinning mechanism on twin planes is the same 
for all these systems.\textsuperscript{5,16-18,23} The only difference between 
them will be the temperature range in which the pinning 
on twin boundaries dominates over other types of pinning. They 
will all have a well-defined lock-in angle below which 
the vortices are pinned strongly by twin boundaries, for which 
our method will give two distinct families of the scaled 
hysteresis loops at a well-defined angle. This is confirmed by 
the investigation of Oussena et al. for Y123 system, which 
shows that the shape of hysteresis loops significantly 
depends on the number of twin domains in the sample.\textsuperscript{18} It 
seems to be possible to scale magnetic hysteresis loop width 
\( \Delta M \) at a particular field with the angle \( \varphi \) for Y123, at 
temperatures above 60 K.\textsuperscript{13} There is a clear dip in the value of 
\( \Delta M \) at the lock-in angle. This is again consistent with what is 
presented in this report. The dip in \( \Delta M \) can also be used for 
obtaining the lock-in angle.\textsuperscript{13,15} However, this method can 
only be used for fields and RE123 systems where channeling 
of magnetic vortices along the twin planes occurs, causing a 
decrease of the effective vortex pinning by the twin planes. 
The method presented in this manuscript is a more general 
one, requiring only the locking of the vortices on the twin 
planes.

\textbf{IV. CONCLUSION}

In conclusion, an alternative method for determining the 
lock-in angle for vortices pinned by twin planes was found, 
employing anisotropic scaling of magnetic hysteresis loops 
for fields at different angles from the crystal c axis. This 
method was employed at \( 89.5 \) K for a highly twinned Sm- 
BaCO single crystal. The uncertainty in the determination of 
the lock-in angle by this method is considerably lower than 
with the conventional method using the cusplike dependence of 
the irreversibility field on the angle between the applied 
field and the c axis.

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