Vortex Cutting in YBa$_2$Cu$_3$O$_{7-\delta}$

J. H. Durrell, E. Pardo$^1$, J. E. Evetts and M. G. Blamire

Department of Materials Science and Metallurgy, University of Cambridge, Pembroke Street, CAMBRIDGE. CB2 3QZ

E-mail: jhd25@cam.ac.uk

Abstract. Flux cutting, where two contiguous flux lines can interact and exchange line segments, has been studied in low $T_c$ superconductors since the 1970s. Recently there has been renewed interest in this phenomenon [Olsen-Reichardt C and Hastings M. B. PRL 92 (15): 157002 (2004)]. We present studies of flux channelling in both extrinsic and intrinsic geometries which demonstrate that flux cutting occurs in the cuprate superconductor YBa$_2$Cu$_3$O$_{7-\delta}$ . The angular dependence of the flux cutting effect can be straightforwardly modelled by considering a length independent cutting force, $f_{cut}$ per vortex segment. We describe the behaviour of the weakly pinned vortex segments prior to cutting and relate the experimentally derived cutting force to the properties of the vortex line.

1. Introduction

Previously [1, 2] we have studied two YBa$_2$Cu$_3$O$_{7-\delta}$ systems in which flux cutting [3, 4, 5] occurs. Although in one system the flux channel is extrinsic and in the other the flux channel is intrinsic, in both cases the onset of dissipation can be due to flux cutting, depending on field orientation. Having made this observation, it is possible to model the angular dependence of the critical current over the flux cutting region based on the force required to cut a single flux vortex segment. In this paper we explain how the experimentally derived flux cutting force derives from the behaviour of the weakly pinned vortex segment (or segments) in the weak pinning region. The consequences of the unambiguous demonstration of flux cutting in technical superconductors for development of coated conductors is discussed.

2. Experiment

Two sets of measurements were performed, on YBa$_2$Cu$_3$O$_{7-\delta}$ films grown on vicinal SrTiO$_3$ substrates and on artificial grain boundaries produced by growing films on a bi-crystal SrTiO$_3$ substrate. Current tracks were patterned lithographically onto the films using Ar-ion milling and the electrical properties measured with a four terminal resistance measurement. The films were characterised in a two-axis goniometer mounted in an 8 T magnet. This system is more fully described elsewhere [6]. It is however crucial to note that in both experiments the flux cutting phenomenon becomes apparent due to the reduced symmetry of the experimental system. In the first case this is achieved by using a vicinal substrate to ensure that the $a$-$b$ planes grow at an angle to the surface of the film and in the second case by arranging for the grain boundary to cross the current path at 45° rather than perpendicularly.

$^1$ Normally at: Department de Física, Grup d’Electromagnetisme, Universitat Autònoma de Barcelona, 08193 Bellaterra, Spain
Figure 1. Experimental geometry of the grain boundary (a) and vicinal film (b) experiments.

3. Discussion

It is straightforward to account for the reduction of the critical current when the applied field is aligned with the flux channel in both the systems discussed. When aligned the entire flux line may move under the Lorentz force in the weak pinning direction. This does not explain, however, the angular variation of the critical current either side of the “channelling minimum”. After only a small rotation the flux line will become strongly pinned over much of its length and would be expected to show behaviour similar to that of a vortex in the bulk. The reduced critical current arises since the small length of vortex which is in the weakly pinned channel can move by cutting and cross joining. The breakdown condition for flux motion becomes the force per vortex segment, not force per unit length, at which cutting and cross joining occurs.

3.1. Vicinal films

The vortex channelling effect in vicinal films of YBa$_2$Cu$_3$O$_{7-\delta}$ arises from the layered structure of the material. Since it is less anisotropic than other HTS materials over a wide range of applied field angles the vortices in YBa$_2$Cu$_3$O$_{7-\delta}$ can be described using the standard Ginzburg-Landau model extended to cover anisotropy [7]. However below 80 K flux lines applied near parallel to the a-b planes distort and kink into chain vortices [8]. These consist of alternating vortex “pancakes” located in the cuprate planes connected by vortex “strings” lying in the charge

Figure 2. Typical channelling minima observed at a 4° low angle grain boundary (a) and in a film grown on a 10° mis-cut substrate (b)
reservoir layers. The vortex strings are much less strongly pinned than the pancakes, thus when the flux line is entirely string-like the available flux pinning is greatly reduced. This effect is shown in Fig. 2b. It can be seen however that only a small tilt of the flux line will rapidly nucleate many pancakes which will serve to strongly pin the flux line. The flux cutting effect occurs, therefore, in the angular region where the Lorentz forces on the strings and pancakes are opposite. Here vortex strings will bow out between the pancakes and, given sufficient Lorentz force, will cut. The angular dependence of the critical current in the vortex cutting regime can be simply modelled assuming a certain pinning force per unit length on the vortex strings \( f_{p,\text{str}} \) and a flux cutting force per segment \( f_{\text{cut}} \) [1]. The vicinal angle is \( \theta_v \), and the interlayer spacing \( d_{il} \).

\[
j_c = \frac{1}{\phi_0} \left[ \frac{f_{\text{cut}} \tan \theta}{d_{il} \sin \theta_v} + \frac{f_{p,\text{str}}}{\sin \theta_v} \right]
\] (1)

3.2. Low angle grain boundaries
A low angle grain boundary can be treated as a flux channel of width \( d_{gb} \) [9]. In this case, therefore, flux cutting occurs because a flux line crossing the boundary has a short weakly pinned segment, this can bow under the influence of the Lorentz force and eventually cut and cross join with adjacent vortices. The cross over between vortex cutting and conventional vortex flow occurs when the Lorentz force required for vortex cutting exceeds the available pinning in the strongly pinned region, which is a combination of the flux cutting force per segment \( f_{\text{cut}} \) and the conventional pinning per unit length in the channel \( f_{\text{pin}} \). This is a function of the length of the weakly pinned segment which itself depends on the angular orientation of the flux line with respect to the boundary. This is why an angular dependent flux cutting/flux de-pinning cross over is observed.

This flux channelling behaviour can again be modelled as function of the grain boundary angle with respect to the current track \( \phi_{gb} \), \(-45^\circ\) in Fig. 2a, and the in-plane orientation of the applied field \( \phi \). It is important to note that even where the grain boundary is at an angle to the macroscopic current flow, for \( j \geq j_c \) the current must cross the grain boundary perpendicularly in the region where the grain boundary determines \( j_c \). Equation 2 is therefore extended from that given in [2] to cover the case of grain boundaries orientated at arbitrary angles to the current track. This is why in Fig 2a the flux channelling behaviour is symmetrical about \( \phi=-45^\circ \) and that in the grain dominated regime is symmetric about \( \phi = 0^\circ \).

\[
j_c = f_{\text{pin}} \frac{1}{\phi_0 \cos(\phi - \phi_{gb})} + f_{\text{cut}} \frac{1}{d_{gb} \phi_0} \tan |\phi - \phi_{gb}| \] (2)

4. Modelling
We have shown that the origin of the flux cutting behaviour in the flux channels discussed arises from essentially the same source. The ends of a weakly pinned vortex segment are fixed by being contiguous with flux lying in a strongly pinned region. If the Lorentz force required to cause flux cutting is less than that required to de-pin the entire line dissipation arises from flux cutting rather than flux flow. In this section we describe how the weakly pinned segments of vortex line behave in this geometry.

We can evaluate the cutting force from intrinsic vortex parameters by considering that the vortex self energy is proportional to its length with a line energy \( e_l \) [5] and that the single vortex approximation is valid. Then, the vortex can be considered as an elastic string with constant line tension \( e_l \). Considering a vortex segment strongly pinned between two points separated by a distance \( D \) and a current density \( j \) perpendicular to \( \mathbf{B} \), the vortex bows with the shape of a circular segment. In Fig. 3 \( D = d_{gb} \) at a grain boundary channel and \( D = d_{il} \) for the channel in a vicinal film. This is because the Lorentz force per unit length \( \mathbf{f}_d = \mathbf{j} \times \Phi_0 \) is uniform and
perpendicular to the vortex line, as well as the elastic force per unit length $f_e$. For our vortex geometry, $f_e = e_l/R$, where $R$ is the vortex curvature radius, and $f_d = j \Phi_0$.

It is straightforward to see that the maximum elastic force per unit length will be for $R = D/2$ (Fig. 3). Above this point the flux line segment is unstable since lengthening the vortex does not produce sufficient extra restoring force to prevent motion of the vortex segment. The segment will then move through the channel until it cuts and cross joins with another vortex. The current density for which the vortex cuts is therefore $j_{cut} = 2e_l/(D\Phi_0)$. The driving force that creates this current density is the cutting force, that is $F_{cut} = 2e_l$.

5. Conclusion
We have demonstrated that the flux cutting occurs both at intrinsic and extrinsic flux channels in YBCO. Furthermore we describe how the bowing of the vortex lines prior to flux cutting occurring can be described with a straightforward model. The existence of flux cutting over a wide range of fields and temperatures in strong pinning YBCO similar to technical conductors shows that it is not a mere curiosity but an effect which must be separately addressed in order to enhance critical current.

Acknowledgments
This work was supported by funding from the EPSRC and SCENET.
[1] Durrell, J. H., Burnell, G., Barber, Z. H., Blamire, M. G., and Evetts, J. E. Physical Review B 70(21), 214508 (2004).
[2] Durrell, J. H., Hogg, M. J., Kahlmann, F., Barber, Z. H., Blamire, M. G., and Evetts, J. E. Physical Review Letters 90(24), 247006 (2003).
[3] Blamire, M. G. and Evetts, J. E. Physical Review B 33, 5131 (1986).
[4] Brandt, E. H. Journal of Low Temperature Physics 37, 43 (1979).
[5] Wagenleithner, P. Journal of Low Temperature Physics 48(1-2), 25-37 (1982).
[6] Herzog, R. and Evetts, J. E. Review Of Scientific Instruments 65(11), 3574–3576 (1994).
[7] Blatter, G., Geshkenbein, V., and Larkin, A. Physical Review Letters 68(6), 875–878 (1992).
[8] Blatter, G., Feigelman, M. V., Geshkenbein, V. B., Larkin, A. I., and Vinokur, V. M. Reviews Of Modern Physics 66(4), 1125–1388 (1994).
[9] Gurevich, A., Rzchowski, M. S., Daniels, G., Patnaik, S., Hinaus, B. M., Carillo, F., Tafuri, F., and Larbalestier, D. C. Physical Review Letters 88(9), 097001 (2002).