Velocity measurements of the dendritic instability in $\text{YNi}_2\text{B}_2\text{C}$

B Biehler¹, B-U Runge¹, S C Wimbush^{2,3}, B Holzapfel²
and P Leiderer¹

¹ Department of Physics, University of Konstanz, Universitätsstraße 10, 78464 Konstanz, Germany

² IFW Dresden, PO Box 270016, 01171 Dresden, Germany

E-mail: Bjoern.Biehler@uni-konstanz.de

Received 19 July 2004, in final form 8 November 2004

Published 1 February 2005

Online at stacks.iop.org/SUST/18/385

Abstract

We measured the velocity of the flux front of an artificially nucleated dendritic instability in $\text{YNi}_2\text{B}_2\text{C}$. The required time resolution in the nanosecond regime was achieved by our magneto-optic pump-probe technique, utilizing a femtosecond laser system. The penetration velocity of the flux front is on the order of 360 km s^{-1} .

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The dendritic instability is a rapid redistribution of magnetic flux inside a type II superconductor (e.g. see [1]) and was found in 1967 by Wertheimer *et al* [2]; in $\text{YNi}_2\text{B}_2\text{C}$ it was first observed by Wimbush *et al* [3]. The instability can be triggered artificially by disturbing the screening current distribution inside the superconductor. This can be caused by sweeping the magnetic field [4], by applying a transport current [5] or by heating a small portion of the superconductor. The latter was used to determine the flux front velocity in YBCO, which was found to be on the order of 160 km s^{-1} [6]. Despite the efforts made to understand the details behind the instability mechanism they remain unknown. This is the reason why we want to put forward additional data on the *dynamic* behaviour of the dendritic instability in $\text{YNi}_2\text{B}_2\text{C}$.

2. Sample preparation

For this work, a thin film of $\text{YNi}_2\text{B}_2\text{C}$ was deposited in an ultrahigh vacuum (base pressure $<10^{-9}$ mbar) pulsed laser deposition system, as described in [7]. A polycrystalline $\text{YNi}_2\text{B}_2\text{C}$ target of stoichiometric composition, prepared by arc melting, was fired upon at 30 Hz with an energy density $\approx 5 \text{ J cm}^{-2}$, leading to a deposition rate of around 2 nm s^{-1} on the $\text{MgO}(001)$ substrate, polished on both

Figure 1. For time resolved pictures we use a pump-probe technique. The laser pulse is used to trigger the instability and some nanoseconds later for illumination. For non-time-resolved images a cold light source can be used for illumination. For clarity the lenses of the polarizing microscope (right part) are not shown.

sides, held around 2 cm above the target. The deposition temperature was 750°C , and the film thickness was around 350 nm. Structural analysis of the film was performed using x-ray θ - 2θ measurements followed by in-plane texture determination (pole figure measurement). θ - 2θ and pole figure x-ray characterization indicate *c*-axis oriented epitaxial film growth with the dominant orientation rotated by 45° in plane with respect to the substrate: $\text{YNi}_2\text{B}_2\text{C}(001)[110] \parallel \text{MgO}(001)[100]$. The superconducting transition temperature, T_c , was measured inductively using an alternating magnetic field shielding technique, yielding a T_c of 12 K with a transition width of 1.5 K.

³ Present address: National Institute for Materials Science, International Center for Young Scientists, 1-1 Namiki, Tsukuba, Ibaraki 305-0044, Japan.

Figure 2. Magneto-optical images of the flux distribution in $\text{YNi}_2\text{B}_2\text{C}$: (a) initial condition, (b) after 3.9 ns, and (c) ≈ 10 s (the final state). The external field was $B_{\text{ext}} = 1.32$ mT at 4.6 K. For clarity a plane was subtracted from the initial image (a) and the contrast enhanced. (b) and (c) were rescaled according to equation (1). The first arrow (1) in part (b) marks the minimum penetration length and the second arrow (2) marks the maximum compatible with the measurement. The white line on the right of each picture indicates the sample edge. Note that the front of the final state (c) is much clearer (indicated by arrow (3)). The length scale remains the same in each panel.

3. Experimental set-up

A sketch of the experimental set-up is shown in figure 1. We apply a pump-probe technique using a commercial femtosecond laser system. It produces pulses of $\tau_{\text{FWHM}} = 150$ fs at $\lambda = 800$ nm. We split the beam in two parts; one is used to perturb the current distribution by locally heating the superconductor. Under appropriate conditions [8] this will trigger the instability. The second part of the pulse is fed into a delay line which has been adjusted for time delays between 1 and 6.5 ns. After passing through a polarizer to ensure a well polarized beam, the light is used to take a magneto-optical image of the instantaneous flux distribution. This is done by an iron garnet film showing a large Faraday effect, i.e. the polarization of light is rotated proportionally to the local perpendicular magnetic field component. This gives a snapshot of the flux distribution just above the sample. We focused the pump beam at the sample edge, far away from the corners. As a camera we use a 12-bit slow scan CCD camera which was cooled to -40°C . Results of a similar experiment with YBCO thin films are published in [6].

4. Results and discussion

A typical experiment was conducted as follows. The sample was zero-field cooled to a temperature of $T = 4.6$ K and an external magnetic field $1.3 \text{ mT} \leq B_{\text{ext}} \leq 5.2 \text{ mT}$ was applied. Then the pump-probe run was conducted and after ≈ 10 s an additional picture of the final state was taken. We measured the energy E_{laser} of each laser pulse and scaled

the intensity of the images by this factor. In addition we applied a division/difference technique to improve the signal-to-noise ratio and reduce the effects of interference and uneven illumination. This was done by measuring the flux distribution: twice before (I_1 , I_2) and once during the pump-probe run (I_3). The final images as seen in figures 2(b) and (c) were constructed by the following calculation:

$$I_{\text{final}} = \frac{I_3/E_{\text{laser},3} - I_2/E_{\text{laser},2}}{I_1/E_{\text{laser},1}}, \quad (1)$$

where $E_{\text{laser},n}$ is the energy of the laser pulse with which the n th image was taken. The division of two pictures should be read as dividing the images pixel by pixel. Note that this will lead to an image emphasizing the changes of the flux distribution. Note that this procedure cannot be applied for the initial condition (figure 2(a)), since the subtraction would result in a uniformly black image.

Repeating this experiment for different external fields and various delay times gives snapshots of the momentary flux distribution. We measured the distance from the sample edge to the flux front; this is plotted in figure 3. The error bars indicate the maximum and minimum distance consistent with the magneto-optical images. The dotted line in figure 3 corresponds to a velocity of $\approx 360 \text{ km s}^{-1}$. This is much faster than the velocities measured in YBCO. There we were able to distinguish two well separated velocities: an early stage showing a dependence on the external field (i.e. a high field led to a high velocity of up to 160 km s^{-1}), and a decrease in velocity to 18 km s^{-1} at times larger than 10 ns, largely independent of the external field and temperature.

Figure 3. Flux penetration length as a function of (a) time and (b) externally applied field. The dotted line is a guide to the eye corresponding to a velocity of ≈ 360 km s $^{-1}$. Note the decrease in velocity for times ≥ 4 ns.

These well defined stages were not seen in $\text{YNi}_2\text{B}_2\text{C}$. A possible explanation may be that the low velocity of the flux front in YBCO was observed as the dendrite penetrated into the Meissner phase region of the sample. In the case of $\text{YNi}_2\text{B}_2\text{C}$ the Shubnikov phase extended over a region of ≈ 1.2 mm, which is approximately the total length of the dendrites investigated. Therefore we would expect the velocity to decrease as soon as the dendrite enters the Meissner region.

Acknowledgments

We are grateful for the sponsorship by the German Israeli Foundation. The work in Dresden was supported by the Deutsche Forschungsgemeinschaft as part of SFB 463 'Rare earth transition metal compounds: structure, magnetism and transport'.

References

- [1] Altshuler E and Johansen T H 2004 *Rev. Mod. Phys.* **76** 471–87
- [2] Wertheimer M R and Gilchrist J le G 1967 *J. Phys. Chem. Solids* **28** 2509
- [3] Wimbush S C, Holzapfel B and Jooss Ch 2004 *J. Appl. Phys.* **96** 3589–91
- [4] Johansen T H, Baziljevich M, Shantsev D V, Goa P E, Galperin Y M, Kang W N, Kim H J, Choi E M, Kim M-S and Lee S I 2002 *Europhys. Lett.* **59** 599–605
- [5] Bobyl A V, Shantsev D V, Johansen T H, Kang W N, Kim H J, Choi E M and Lee S I 2002 *Appl. Phys. Lett.* **80** 4588–90
- [6] Bolz U, Schmidt D, Biehler B, Runge B-U and Leiderer P 2003 *Europhys. Lett.* **64** 517–23
- [7] Wimbush S C, Häse K, Schultz L and Holzapfel B 2001 *J. Phys.: Condens. Matter* **13** L355–60
- [8] Biehler B, Runge B-U and Leiderer P 2004 *J. Low Temp. Phys.* **137** 117–23