Reproducible Nucleation Sites for Flux Dendrites in MgB_2

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Magneto-optical imaging was used to study dendritic flux penetration in films of MgB_2. By repeating experiments under the same external conditions, reproducible features were seen in the pattern formation; dendrites tend to nucleate from fixed locations along the edge. However, their detailed structure deeper inside the film is never reproduced. The reproducibility in nucleation sites is explained as a result of edge roughness causing field hot spots.

1. Introduction

Many recent studies using magneto-optical imaging have revealed that thin film superconductors often show abrupt flux penetration in the form dendritic structures when the superconductor is subjected to an increasing magnetic field perpendicular to the film [1-3]. The flux dendrites are formed in distinct events, so that once a structure is created it remains as is, and the next event occurs at a different place in the sample. It is believed that this behavior is due to a thermal runaway [4], where two effects play the main role: (i) motion of magnetic flux (i.e., superconducting vortices) releases energy and hence increases the local temperature, and (ii) the temperature rise reduces the flux pinning and hence facilitates further flux motion. In general, one finds that the flux structures formed during this thermomagnetic instability appears to show little or no reproducibility if the experiments are repeated under the same external conditions. In this work, we investigate to which degree this is actually the case, and we seek to find any systematic correlation between the patterns formed during repeated experiments with the same sample.

2. Experimental

In-situ MgB_2 films were made by pulsed laser deposition on Al_2O_3 substrates. A first layer was deposited using a stoichiometric MgB_2 target under low pressure of argon gas while maintaining the substrate at 250°C. This was followed by the deposition of an 800 nm thick magnesium cap layer. The sample was then annealed in the deposition chamber at 685°C in argon for 1 minute under 1 atm. pressure. More details of the sample preparation can be found in Ref. [5].

Shown in Fig. 1 is a magneto-optical image of flux penetration in a film of thickness d = 300 nm initially zero-field cooled to 4 K. The image was taken while an applied field perpendicular to the film was slowly increased and reached B_a = 3.4 mT. Already below a field of 1 mT one observes that flux suddenly starts to invade the film in the form of dendritic structures. This behavior, which deviates dramatically from the common critical-state be-

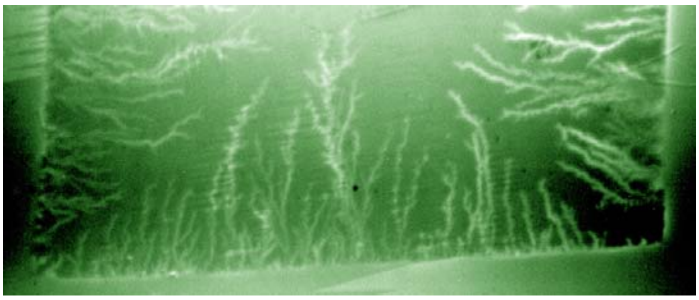

Fig. 1. Magneto-optical image of dendritic flux penetration in an MgB_2 film at 4 K. The brightness in the image represents the local flux density. The lateral size of the sample is $2w$ = 4 mm.

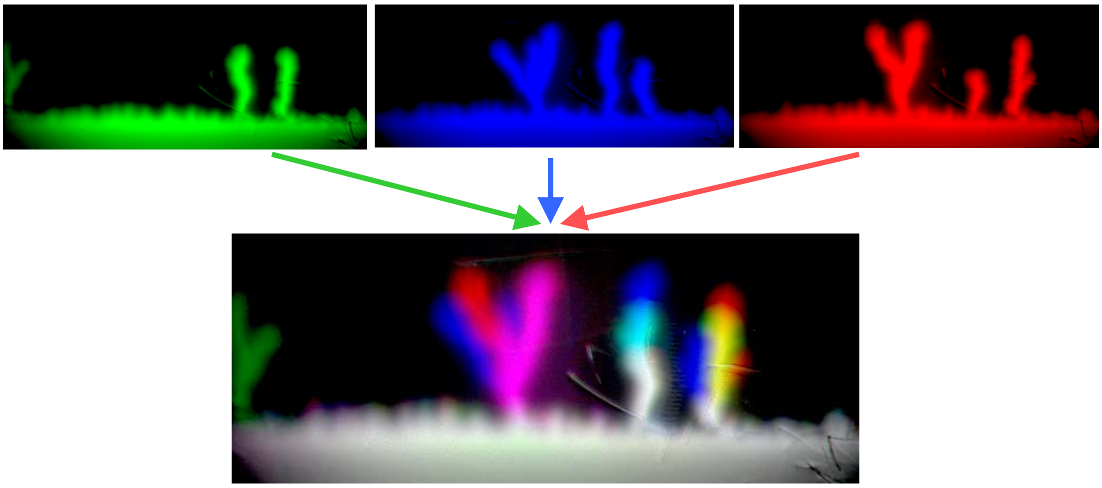

Fig. 2. (top) Magneto-optical images of flux penetration in 3 experiments under identical external conditions. (bottom) A sum image of the 3 images above. Overlap of colored regions in all 3 images appears as white, whereas no or only partial overlap appears as another color.

havior, was reported earlier for MgB_2 films [2] and also for films of other superconducting materials [1,3].

As in earlier reports we find also here that to a large extent the dendritic patterns are not reproduced when the experiment is repeated under exactly the same external conditions. This shows that the behavior is not due to an underlying structure of defects creating easy channels of flux penetration in the film, but rather due to an inherent unstable behavior.

However, despite the clear irreproducibility in the branching flux patterns, we find that the places along the edge where they nucleate and start to grow have a strong tendency to repeat. To show this we performed 3 identical experiments, where the applied field was slowly ramped up while the temperature was kept at 4 K. Between each experiment, the sample was heated above T_c. The result is shown in Fig. 2, where magneto-optical images from the 3 experiments are shown in different colors. The images are taken from the same location along the edge. It is evident that the nucleation points tend to repeat. This is most efficiently illustrated by adding the 3 images, see the lower frame. The colors were chosen so that when all 3 images are added, a white-gray color appears where they all overlap. We see that at two places, a dendrite nucleates in all 3 experiments. Moreover, in the red and blue image there is a branching structure growing from the same edge site. However, this flux structure is missing in the green image, which instead has a dendrite growing at its far left side of the image. Note that in the cases where the dendrites develop from the same nucleation site, they always develop differently as they extend further into the film.

3. Discussion

According to the theoretical results obtained in [4], the fingering instability will occur, provided the electrical field in the film exceeds

$$E_c = (\mu_0 j_c d)^2 \frac{|j_c'(T)|\kappa}{0.4C^2} \quad ,$$

but only first when the applied magnetic is ramped above the value,

$$B_{\text{fing}} = \frac{\mu_0 j_c d}{\sqrt{\pi}} \left[\frac{\kappa}{w^2 |j_c'(T)| E} \right]^{\frac{1}{4}} .$$

Using the following set of parameter values, $j_c = 10^{10}$ A/m^2, $C = 10^3$ J/Km^3, $\kappa = 10^{-2}$ W/Km, $T^* = [\mathrm{d}\ln(j_c)/\mathrm{d}T]^{-1} =$ 10 K, all typical for MgB_2 films under the present conditions, we obtain $E_c \sim 10^{-4}$ V/m and $B_{fing}(E_c) \sim 1$ mT. Thus, there is a very good agreement between the thermal runaway model and experimental data.

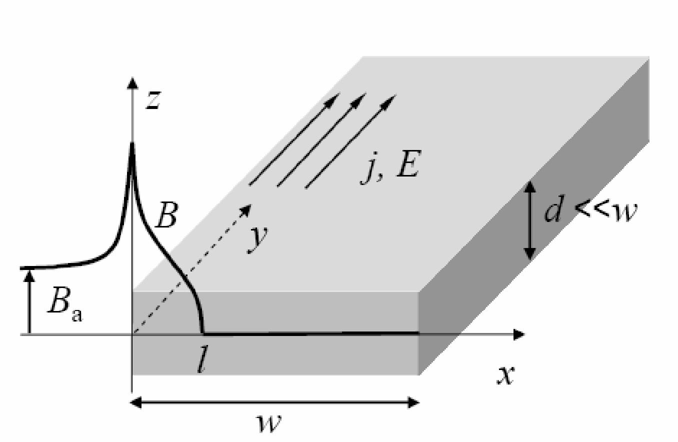

Fig. 3. Schematic of fields and currents in a long thin superconducting strip during ramping up of a perpendicular applied magnetic field. Only the left half of the strip is shown.

Within this physical picture, how can one understand that the flux dendrites have preferred nucleation sites along the rim? A closer look on the edge of the present films immediately shows there is a significant degree of roughness, and one finds that dendrites tend to grow from places where there is a concave dent in the edge. Conversely, we never observe dendrites growing from the convex corners of a film, see Fig.1.

We interpret this in the follow way. Using magneto-optical imaging one always finds that a concave dent in the rim of a film causes the external field to focus into extraordinary high values. Such a field "hot spot" arises due to the sharp bending of the shielding current around such an edge defect. It is here the strong curvature of the current flow leads to the field amplification. At convex corners, however, the current curvature is opposite, and hence reduces the external field locally. In films showing dendritic flux penetration, it is a matter of where along the rim the external field is exceeding the threshold field value. This will then in most cases occur on cites with geometrically induced field hot spots. Since these cites obviously are fixed, it leads to a high degree of reproducibility as to exactly where along the edge dendritic structures start to grow.

However, the sequence in which these cites launch a flux dendrite is much less reproduced, thus showing that fluctuations are also playing a major role in triggering the instability. It is expected that this description applies not only to the case of MgB_2, but for all thin films that display this instability.

Acknowledgments

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