Origin of dendritic flux patterns in MgB$_2$ films

M. Baziljevich [a], A.V. Bobyl [a], D.V. Shantsev [a], E. Altshuler [b], T.H. Johansen [a,*],
S.I. Lee [c]

[a] *Department of Physics, University of Oslo, P.O. Box 1048, Blindern, N-0316 Oslo, Norway*
[b] *Superconductivity Laboratory, IMRE-Physics Faculty, University of Havana, Cuba*
[c] *Department of Physics, National Creative Research Initiative Center for Superconductivity,
Pohang University of Science and Technology, Pohang 790-784, South Korea*

Abstract

The dendritic patterns of magnetic flux motion formed during field penetration into an MgB$_2$ film were observed using magneto-optic imaging. To investigate the origin of the dendrites, experiments were performed where the sample was partially covered with an thermally conducting foil serving as an efficient heat sink. We observed that the dendrites are formed only in areas lacking the thermal conductor. When dendrites develop in the uncovered part they never invade into the covered region. The results strongly suggest that the dendritic instability is thermal in origin. © 2001 Published by Elsevier Science B.V.

Keywords: Dendritic flux penetration; Thermo-magnetic origin; MgB$_2$ film; MO imaging

Only a few months after the discovery of superconductivity in MgB$_2$ [1], one succeeded to produce films with a critical current density J_c as high as 10^7 A/cm^2 [2], which demonstrates the high potential for practical application of this material. However, in measurements of the integral magnetization versus field one often observes abrupt jumps or noise in the magnetization data, suggesting the presence of an instability which substantially suppresses the J_c. Such jumps are found in thin films [3], wires [4] and polycrystalline material [5]. Spatially resolved studies using magneto-optical (MO) imaging have shown that in films these jumps are associated with an abrupt invasion of dendritic flux

structures [6,7]. Similar dendritic structures have been observed earlier in films of Nb [8–10] and YBa$_2$Cu$_3$O$_7$ [11,12]. So far, there is no general agreement about the mechanism underlying this dramatic instability. Conventionally, abrupt magnetization jumps are explained by a thermo-magnetic instability due to the heat produced by vortex motion. Rise in the local temperature then facilitates further motion, resulting in a macroscopic vortex avalanche. During this process the superconductor is usually heated to above T_c, and the flux density ends up distributed uniformly throughout the sample. The thermo-magnetic scenario is thought to apply also to the dendritic instability. This is supported by computer simulations where the characteristic temperature dependent morphology of the dendritic flux patterns have been well reproduced [6,13]. On the other hand, alternative

---

* Corresponding author.
E-mail address: t.h.johansen@fys.uio.no (T.H. Johansen).
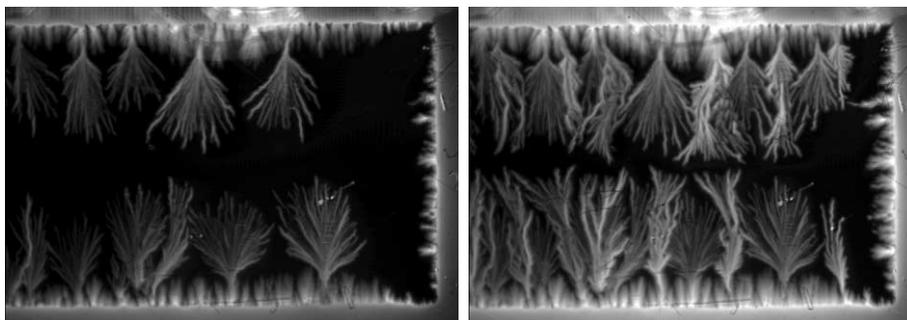
Fig. 1. MO images of flux penetration (image brightness represents flux density) into a zero-field-cooled MgB$_2$ film at 3.6 K. The images were taken at perpendicular applied fields of 8 (left) and 14 mT (right). See also [14].

mechanisms have also been suggested [9,11], and conclusive experiments are still lacking. The present paper reports direct experimental evidence that the dendritic instability in MgB$_2$ films is suppressed by placing the superconducting film in close contact with a metal foil, presumably changing the thermal conditions of the vortex dynamics.

Films of MgB$_2$ were deposited on $(1\bar{1}02)$ Al$_2$O$_3$ substrates using pulsed laser deposition. Typical films have a sharp superconducting transition at $T_c = 39$ K, and a high degree of c-axis alignment perpendicular to the plane [2]. A 300 nm thick film shaped as a rectangle of size 10×3 mm^2 was prepared for the present series of MO imaging investigations.

Shown in Fig. 1 are two MO images of the flux penetration in magnetic fields of 8 and 14 mT applied perpendicular to the film. These measurements were carried out at 3.6 K, and the characteristic dendritic patterns are clearly visible. The sweeping rate of the applied field was slow, of the order of 1 mT/s. Nevertheless, the growth of the dendritic structures proceeds extremely fast, where each tree-like structure is formed during less than 1 ms (the time resolution of our CCD camera system). However, once formed, each dendrite appears frozen and does not gain more flux as the applied field increases and other dendrites appear. This is contrary to the typical penetration observed in absence of dendrites, where the penetration is gradual with increasing field. The dendrites formed at the larger applied fields are seen to be brighter, i.e., they contain more flux than the ones formed at a lower field.

Fig. 2. Schematic of sample configuration where two pieces of Al-foil is placed between the MgB$_2$ film and the garnet indicator. The space above the central part of the MgB$_2$ film is empty. The MO indicator is in this way placed with a constant distance from the superconductor, ensuring good conditions for the imaging.

To decide whether the thermal contact between the superconducting film and its environment plays a role for the dendrite formation, a set of new MO imaging experiments were performed with the sample mounted as shown schematically in Fig. 2. An Al-foil of thickness 10 μm was inserted between the MgB$_2$ film and the garnet indicator. Two pieces of the foil were used, leaving a central part of the MgB$_2$ film uncovered. The sandwich structure was pressed together to make a good thermal contact between the Al-foil and MgB$_2$ film.

Fig. 3 shows the results of the new experiments, which were carried out at 3.5 K. In (a)–(d) one sees how the flux penetration pattern develops as the applied magnetic field is increased from 0 to 12 mT. The field-of-view relative to the sandwich structure is indicated in Figs. 2 and 3(a) and (b) the position of the Al-foil edge is indicated by dashed lines. It is evident that in the part of the MgB$_2$ film covered by Al-foil the dendritic behavior is largely
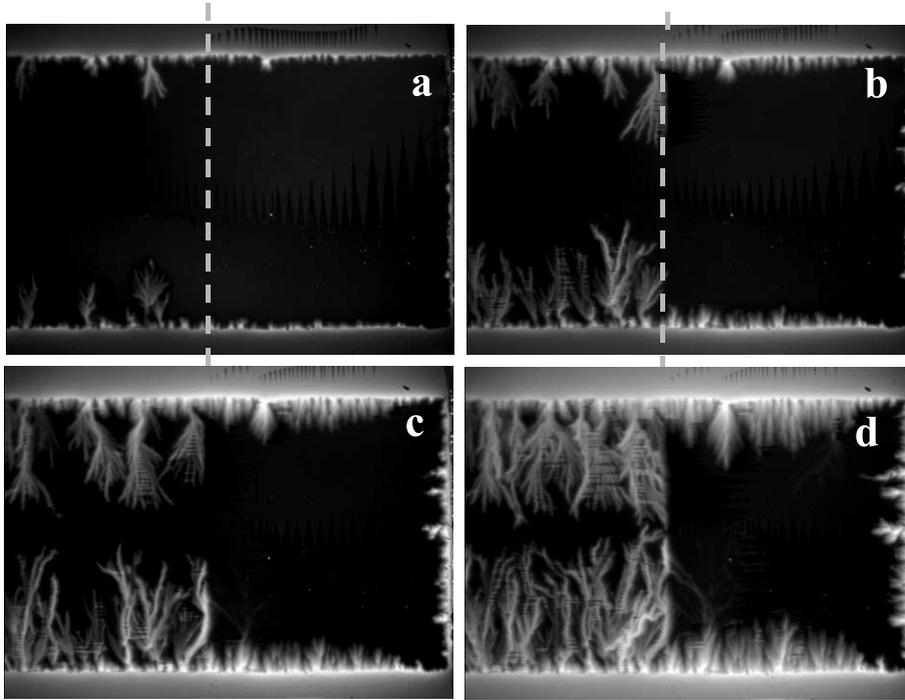
Fig. 3. (a)–(d) MO images at 3.5 K of the partly covered MgB$_2$ film in applied fields of 3.4, 5.0, 8.5 and 12 mT, respectively. The dashed line shows the boundary between covered and uncovered sample. Dendrite formation is suppressed where the Al-foil is in contact with the superconductor, showing the importance of thermal stabilization.

suppressed. Firstly, no dendrite is seen to be nucleating there (small fan-like shapes seen at high fields are typical for films with a rough edge and are obviously of different origin as they grow gradually with the field increase). Only at the higher fields one can see weak traces of a few dendrites superimposed on a conventional critical-state type of flux penetration. Secondly, even the dendrites that are nucleated in the uncovered part of the film do not propagate into the adjacent covered part, as seen clearly in (b, c). The suppression of the dendritic instability by providing a good thermal contact strongly suggests that the dendrite growth is associated with local heating.

An additional test experiment was performed to ensure that a possible non-uniform heating of MO garnet indicator due to thermal contact with the Al foil does not affect our results. A thin thermal insulator was placed between the garnet and the foil, and the MO images turned out to be essentially the same as shown in Fig. 3.

In conclusion we have demonstrated, using an efficient thermal conductor as a heat sink, that the dendritic formation is suppressed in areas covered by the heat sink. In the area that is not covered by the thermal conductor, flux behavior remains completely dominated by dendritic flux motion. Thereby we have confirmed our previous simulation work based on the assumption that the phenomenon is of thermo-magnetic origin.

Acknowledgements

References

[1] J. Nagamatsu et al., Nature 410 (2001) 63.
[2] W.N. Kang et al., Science 292 (2001) 1521.

[3] Z.W. Zhao et al., cond-mat/0104249, Phys. Rev. Lett., submitted for publication.

[4] S.X. Dou, X.L. Wang, J. Horvat, D. Milliken, E.W. Collings, M.D. Sumption, cond-mat/0102320.

[5] S. Jin, H. Mavoori, C. Bower, R.B. van Dover, Nature 411 (2001) 563–565.

[6] T.H. Johansen et al., Phys. Rev. Lett., cond-mat/0104113, submitted for publication.

[7] T.H. Johansen et al., Supercond. Sci. Technol. 14 (2001) 726–728.

[8] M.R. Wertheimer, J.G. de Gilchrist, J. Phys. Chem. Solids 28 (1967) 2509.

[9] C.A. Duran et al., Phys. Rev. B 52 (1995) 75.

[10] V. Vlasko-Vlasov et al., Physica C 341-348 (2001) 1281.

[11] P. Leiderer et al., Phys. Rev. Lett. 71 (1993) 2646.

[12] U. Bolz et al., Physica B 284-288 (2000) 757.

[13] I. Aranson et al., Phys. Rev. Lett. 87 (2001) 067003.

[14] For high-quality images and a movie see http://www.fys.uio.no/faststoff/ltl/results/biology.