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Marie Roussel
University of Wollongong, mr58@uow.edu.au

Alexey V. Pan
University of Wollongong, pan@uow.edu.au

Sihai Zhou
University of Wollongong, sihai@uow.edu.au

S X. Dou
University of Wollongong, shi@uow.edu.au

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Influence of the iron sheath on the local supercurrent distribution in MgB_2 wires

M Roussel, A V Pan, S Zhou and S X Dou

Institute for Superconducting and Electronic Materials, University of Wollongong, NSW, 2522, Australia

E-mail: `roussel@uow.com.au`

Abstract. The magnetic behavior of iron sheathed magnesium diboride (MgB_2) wires was investigated. Global magnetization measurements have shown unusual critical current density variations compare to a superconductor with no magnetic environment. Local quantitative studies, through MO images, are linked to these global magnetization measurements in order to better understand the observed results. It is shown that the current distribution is affected by the soft magnetic sheath interacting with the superconducting core.

1. Introduction:

Increasing the critical current density in type II superconductors is usually done by enhancing their pinning strength. However, increasing the pinning usually results in a deterioration of the microstructure which in turn can impede other superconducting properties such as the critical temperature T_c. Recent theoretical works from Genenko *et al* [1, 2] have shown the possibility of increasing the current capabilities of type II superconducting samples by placing them in a soft magnetic environment. This was confirmed by experimental observations on YBCO thin films [3] and MgB_2 wires [4, 5, 6]. Indeed, soft magnets placed at the edge of a sample enable the redistribution of the magnetic flux over the superconducting area, thus decreasing the intensity of the magnetic flux peaks usually present at the edge of the superconductor which favor the magnetic flux penetration.

In this work, we present the first quantification of the magnetic flux in the superconducting core of iron sheathed MgB_2 wires. The results of this quantification enable a first evaluation of the local current density J in the superconducting core following the equation from Welp *et al* [7]: $\partial B/\partial x = -(\mu_0 J/2)(1 - w/\pi t)$ with w and t the width and thickness of the sample respectively.

2. Experimental:

The MgB_2 wires investigated were produced by the powder-in-tube technique. Detailed the fabrication process can be found elsewhere [8].

The global magnetic measurements were done using a Quantum Design MPMS SQUID magnetometer with the magnetic field applied perpendicularly to the core. The data obtained were used to calculate the critical current density (J_c) as a function of the applied field (B_a).

To observe the local behavior of the magnetic flux with the MO technique, a sample was polished to the white line depicted on Figure 1a). The sample was then connected through

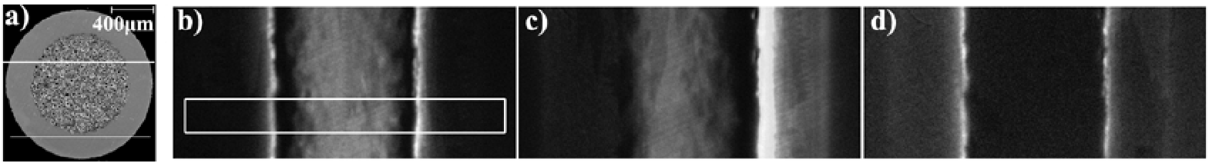

Figure 1. a) SEM image of the MgB2 wire used for MO imaging, the white lines demarcate the border of the sample once polished for observation. b), c) and d) are typical MO images taken after field cooling the sample in 33 mT and switching off the external field at 5 K. b) with no applied current, in c) $I_t = 10$ A, whereas in d) $I_t = 15$ A. The white rectangle in b) corresponds to the area used to calculate the quantified flux profile of Figure 2.

copper wires to a current source and placed on the sample holder in the cryostat. An epitaxial ferrite-garnet magneto-optical indicator film was then placed on top of the sample. With a polarizing microscope, the surface of the MO active layer was observed. The variation in brightness of the obtained pictures correspond to the distribution of the component of the flux density perpendicular to the MO indicator film: the brighter the image, the stronger the flux density. More details about this technique are available in the extensive review from Jooss *et al* [9].

3. Results and discussion:

The results obtained from global magnetic measurements, J_c as a function of B_a, are not presented in this article. However, they are similar to the ones shown in recent work from Pan *et al* [4, 5, 10]. In our case, the iron magnetic saturation field B_s was evaluated to be 0.51 mT and the maximum critical current density at 15 K is $J_c = 2.47 \times 10^9$ A/m^2 at an applied field $B_a \approx B_s$. The maximum J_c for lower temperatures could not be determine due to flux jumps usually occurring in MgB$_2$ superconductors.

To better understand the local magnetic behavior MO imaging has been used. Typical MO images are presented in Figure 1b), c) and d). For these pictures, the sample was field cooled then the applied field was turned off. Figure 1b) has been taken just after B_a was switched off, with no applied current ($I_t = 0$) whereas c) and d) were taken with $I_t = 10$ A and 15 A respectively.

Figure 2 show two sets of magnetic flux and current density profiles for different I_t at $T = 5$ K. To obtain these profiles, the sample was field cooled (FC) in an external field $B_a = 33$ mT. Figures a) corresponds to the behavior of the wire when only I_t is applied while for b), $B_a = 33$ mT was applied in addition to I_t.

The same sets of profiles were calculated in the case of zero field cooled (ZFC) state. However, these ZFC profiles do not show any unusual behavior, with only negligible supercurrents flowing in the MgB$_2$ core. Therefore this study will focus on the profiles obtained after the sample was FC.

In Figure 2b) stronger magnetic flux is visible in the iron sheath due to the additional applied field $B_a = 33$ mT. This leads to much steeper flux gradients, thus higher J values in the core near the superconductor/sheath boundary. Another obvious observation is the asymmetry in B and J profiles at the edge of the core in Figure 2b) due to the superposition of the I_t self field and B_a. This asymmetry increases with increasing I_t and a dip is forming around $x = 1.2$ mm in the B profiles as the applied current rises. This dip might be a sign of a supercurrent redistribution, which becomes much more apparent at higher fields, eventually resulting in overcritical currents at $\sim B_s$ [5]. A change in the B profile for $I_t = 15$ A in Figure 2b) is also manifest, the regular slope across the superconducting core corresponding to a relatively small flow of current over

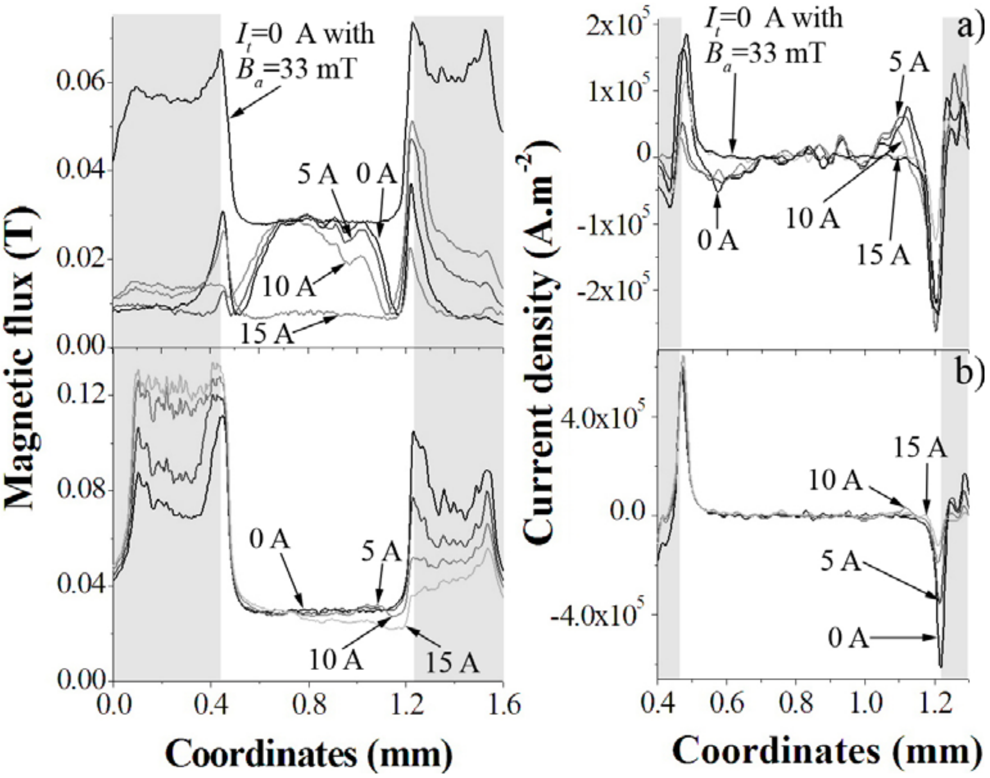

Figure 2. Magnetic flux and current density profile of the Fe-sheathed round wire with different applied current at 5 K after the wire was field cooled. In a) only transport current is applied on the wire while in b) transport current and an external magnetic field $B_a = 33$ mT are applied. The greyed areas correspond to the iron sheath. Note the different scale for B and J in each figure.

the entire MgB_2 core as seen in [6].

In Figure 2a), the highest curve of B profiles was acquired just before turning off the external field. It should be noted that the maximum flux density frozen in the core is lower than 33 mT, due to the incomplete shielding effect of the Fe sheath. The subsequent curves have been obtained in $B_a = 0$ T and a broad peak is formed in the superconducting core corresponding to the frozen flux. Some of the MO images used to calculate this profiles are shown in Figure 1 with increasing I_t from b) to d).

In Figure 1 and Figure 2a), a shift of the flux density peak to the left hand side is observed as I_t is increased. This occurs due to the superposition of the I_t self-field and B_a as in the case shown in Figure 2b. The J profiles clearly indicates that supercurrents flow inside the core and not only in a thin layer on its edges. In addition, the peaks at the core edges of the J profiles are lower, but wider if compared to Figure 2b) or the profiles calculated in the ZFC state. This indicates that a larger area is utilized for the current flow.

The maximum current possible in the wires is the depairing current density $J_0 = \phi_0/(3\sqrt{3}\pi\mu_0\lambda^2\xi)$, which in our case is $J_0 = 8.6 \times 10^{11}$ A/m^2. J_c controlled by the pinning has been found with the help of global magnetization measurements to be equal to 2.47×10^9 A/m^2 at $T = 15$ K. In comparison, the maximum current density J calculated from the MO images is of the order of 5×10^6 A/m^2 at $T = 5$ K (Figure 2b)). It follows that $J < J_c < J_0$, i.e. no overcritical currents are observed in the sample over the investigated ranges of temperature, applied field and applied current. However, it should be mentioned that the applied field of 33 mT is below MgB_2 first critical field ($B_{c1} \simeq 60$ mT) and the measured saturation field ($B_s \simeq 500$ mT). This could impede the visualization of overcritical parameters.

Overcritical currents have been observed in MgB_2 wires [5] when iron sheathed MgB_2 wires where compared to bare MgB_2 wires. They are presumably due to redistribution of the supercurrent, resulting in a more effective use of the wire interior. This trend can be observed in Figure 2a) as described above.

We argue that the overcritical currents might not be observed in our work due to the following reasons. (i) The are no "overcritical" currents as such (i.e. $J > J_c$), so that the overcritical state observed in the global experiments in MgB_2 wires would be governed by the current redistribution or more effective use of the superconductor interior in a particular field range. In this case, one should not expect to find $J > J_c$ in the superconductor (this is in contrast to thin superconductors considered in [1, 3]). (ii) The field limitation in the MO imaging setup do not allow us to reach the condition $B_a \geq B_s$ at which the overcritical state was observed in the global experiments [4, 5, 10]. (iii) The pinning and magnetic sheath properties in the investigated wires may have properties, which are not favourable for overcritical state observation. Indeed, the effect of different sheath properties and pinning properties on the overcritical state is unclear at present. Although, indications that these parameters strongly affect the overcritical state have been demonstrated in [4, 10]. Transport current experiments targeting low field region in samples with various sheath and pinning parameters are necessary to understand the origin of the overcritical state in Fe-sheathed MgB_2 wires.

4. Conclusion

We investigated the interaction of the magnetic sheath and superconductor in MgB_2 Fe-sheathed wire with global magnetization measurements and local MO imaging for perpendicular applied field. Such interactions are mainly visible in the case of FC state and with $B_a = 0$. In this case, a redistribution of supercurrents is observed and supercurrents flow in the center of the core as well as in wider areas at the edges. The magnetic flux and J profiles were quantified, but no overcritical currents ($J > J_c$) have been observed. More transport experiments in low field region are needed to clarify the origin of the overcritical state in MgB_2 wires sheathed in iron.

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