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Influence of the iron sheath on the local supercurrent distribution in MgB$_2$ wires

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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
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 $B_a$ 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 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 $2.47 \times 10^9$ A/m$^2$ at $T = 15$ K. In comparison, the maximum current density $J$ calculated from the MO images is of the order of $5 \times 10^6$ 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 ($B_{c1} \approx$ 60 mT) and the measured saturation field ($B_s \approx$ 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 shear 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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