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J. Horvat
University of Wollongong, jhorvat@uow.edu.au

X. L. Wang
University of Wollongong, xiaolin@uow.edu.au

Saeid Soltanian
University of Wollongong, saeid@uow.edu.au

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

Improvement of critical current in MgB$_2$/Fe superconducting wires by a ferromagnetic sheath

J. Horvat, X. L. Wang, S. Soltanian, S. X. Dou
Institute for Superconducting and Electronic Materials, University of Wollongong, NSW 2522, Australia

Transport critical current (I_c) was measured for Fe-sheathed MgB$_2$ round wires. A critical current density of 5.3 x 10^4 A/cm^2 was obtained at 32K. Strong magnetic shielding by the iron sheath was observed, resulting in a decrease in I_c by only 15% in a field of 0.6T at 32K. In addition to shielding, interaction between the iron sheath and the superconductor resulted in a constant I_c between 0.2 and 0.6T. This was well beyond the maximum field for effective shielding of 0.2T. This effect can be used to substantially improve the field performance of MgB$_2$/Fe wires at fields at least 3 times higher than the range allowed by mere magnetic shielding by the iron sheath. The dependence of I_c on the angle between field and current showed that the transport current does not flow straight across the wire, but meanders between the grains.

Soon after discovery of superconductivity in MgB$_2$[1], superconducting wires were produced with large macroscopic critical current densities (J_{c0})[2, 3, 4]. Fe sheathed MgB$_2$ wires are currently the most promising conductors, giving a J_{c0} of about 10 kA/cm^2 above 30K in a 1T field[5]. Majoros et al. predicted theoretically that magnetic shielding could decrease transport ac loss[6]. A model by Genenko et al.[7] predicted either a suppression or enhancement of the loss-free transport current of a superconducting strip in magnetic surroundings. Earlier measurements[5, 8] indicated the existence of magnetic shielding in MgB$_2$/Fe tapes. In this paper, we present the first detailed measurements of the field dependence of transport J_c, influenced by magnetic shielding and interaction between the Fe sheath and the superconductor in round MgB$_2$/Fe wires. It was found that interaction between the sheath and superconductor leads to a plateau in $J_c(H)$, which can be utilised to improve J_c in fields three times higher than the maximum field for which the magnetic shielding of the sheath is still effective.

Three superconducting Fe-sheathed round wires were prepared by filling the Fe tubes with a mixture of Mg and B powder, drawing them into thin wires, and heating in argon for 10 minutes at 820, 890 and 850° C for samples S1, S2 and S3, respectively. The details of the wire production are described elsewhere[9]. The dimensions of the samples and J_{c0} at 32K are given in Table 1. The critical temperature of all the samples was 38.5K, as obtained from the measurements of magnetic ac susceptibility. The density of the samples was within experimental uncertainty (5%) the same for all the samples, about 65%. However, we expect S3 to have the highest density because

it was drawn to the smallest diameter and had the highest value of J_{c0} (Table 1). SEM images showed all three samples had the same average grain size, about 100nm.

Voltage-current characteristics were measured using a 6 milliseconds long pulse of current. The current was swept at a constant rate, with the maximum current 250A. The signal from the voltage taps was filtered by a low-pass filter and pre-amplified by a SR560 preamplifier. The current through the wire was measured via the voltage drop on a non-inductive resistor, connected in series to the wire and current source. Both voltage and current signals were fed into a digital oscilloscope. The measured data were transferred into a computer for analysis. Using a high enough cut-off frequency of the low-pass filter prevented distortions of the voltage signal and the phase shift between the current and voltage signals.

The measured MgB_2/Fe wire was placed in a continuous flow cryostat, with temperature control better than 0.1K. The cryostat was placed in an electromagnet on a rotating base, enabling the angle between the field and long axis of the wire to be changed. Measurements were limited to the temperature range between 32 and 35K, due to the limitations of the current source. V(I) measurements showed a very sharp increase in the voltage at the critical current (I_c).

Figure 1 shows the angular dependence of I_c for S1, at 33.7K and 0.4T. The field was perpendicular to the long (cylindrical) axis of the wire for $\theta = 90°$. I_c was at a maximum for $\theta = 90°$ and it decreased by 75% of its maximum value within 30°. However, only a negligible change in I_c was obtained for the remaining 60° (Fig.1). These measurements helped to accurately align the field into a perpendicular orientation. The inset to Fig. 1 shows the temperature dependence of I_c for S1 in zero field. I_{c0} decreased linearly with temperature between 32 and 36 K, at a rate of 46.4 A/K. For higher temperatures, I_{c0} decreased more gradually, approaching zero at about 38.5K.

Figure 2 shows the field dependence of I_c for sample S3 at 32K. The solid and open symbols are for $\theta = 90°$ and $\theta = 0°$, respectively. In the latter case, the field is parallel to the long wire axis, and therefore to the current. The solid line shows the value of the self-field produced by the critical current at the surface of the superconducting core. For $\theta = 0°$, I_c does not change with the field up to about 0.03T (open symbols in Fig.2). For higher fields, an exponential decrease in I_c is obtained: $I_c = I_{c0} \exp(-H/H_0)$. For all the samples measured, $H_0 \approx 0.35T$ at 32K.

For $\theta = 90°$, the field dependence of I_c is the same as for $\theta = 0°$ with H>0.6T. However, for $0.2T < H < 0.6T$, there is a plateau in $I_c(H)$, where I_c decreases with the field by less than 5% of I_{c0} (Figure 2). For H< 0.2T, I_c decreases with the field by about 20% of I_{c0}. The inset to Fig.2 shows that the experimental points for the two field orientations overlap by adding 0.38T to the parallel field.

The same results were obtained for the other samples measured, except for the difference in I_{c0} and the field by which $I_c(H)$ for $\theta = 0°$ had to be shifted to obtain overlapping with $I_c(H)$ for $\theta = 90°$ (Inset to Fig. 2). The values of this field for S1 and S2 were 0.39T and 0.33T, respectively.

The results shown in Fig.2 are affected by the magnetic shielding due to the Fe sheath, as well as by the interaction between the sheath and superconductor. To identify the effects of shielding only, the field inside and outside the sheath was measured, with the MgB_2 removed. This was performed by inserting tiny pick-up coils into the sheath and using external ac magnetic field with frequencies between 20 and 60 Hz, and a field amplitude up to 0.6T. The length of the coils corresponded to the distance between the voltage contacts when measuring $I_c(H)$. Comparing the

results for different frequencies, we obtained that the dynamic effects (eddy currents) were negligible below 30Hz.

Figure 3 shows the field inside the sheath against the external field for $\theta = 90°$ (open symbols). The solid symbols were measurements with the sheath removed from the pick-up coil ($H_{in}=H_{out}$) and the solid line shows theoretical shielding[10] for an infinite cylinder of the same dimensions and magnetic susceptibility as our Fe sheath.

For H<0.2T, the shielding from external field was almost total, with $H_{in}= 0.04 H_{out}$ at 0.2T (Fig.3). For higher fields, the shielding rapidly weakened and for H>0.4T the entire external field additional to 0.4T was passed through the Fe sheath, i.e. H_{in} against H_{out} was parallel to the data with no shield for H>0.4 T. These measurements are in good quantitative agreement with calorimetric measurements of ac loss in a similar MgB$_2$/Fe wire[8]. However, the measured shielding is better than that given by the analytical expression for an infinite cylindrical shield of the same thickness and magnetic permeability[10] (solid line in Fig.3). Still, extrapolation of the experimental results to high fields is in agreement with the theoretical prediction. The discrepancy at low fields is probably due to the finite length of the measured sheath.

The inset to Fig.3 shows the measured shielding for $\theta = 0°$. The dashed line represents $H_{in}=H_{out}$. The shielding was almost total for H< 0.02T. For H>0.025T, the entire field higher than 0.025T was passed through the shield. The hysteresis was due to magnetic hysteresis of the iron.

$I_c(H)$ for $\theta = 0°$ can be explained by the shielding effect. The initial plateau is a consequence of complete shielding from the external field. Above 0.025T, $I_c(H)$ is the same as with no shield, except for about 0.025T which is screened out by the shield. The same is obtained for $\theta = 90°$ and H>0.6T, except that the value of the screened-out field is about 0.3T (Fig.3). However, $I_c(H)$ for H<0.6T cannot be explained by simple screening. Instead of the expected constant I_c with the external field fully screened out for H<0.2T, I_c actually decreases with the field (Fig. 2). For 0.2T<H<0.6T, I_c decreases very little with field (Fig.2), despite the full penetration of field through the Fe sheath (Fig.3).

Overlapping of $I_c(H)$ for $\theta = 0°$ and $\theta = 90°$ above 0.6T (Inset to Fig.2) shows that the current does not flow through the wires in a straight line. If that were the case, $I_c(H)$ corrected for the shielding of the iron sheath would differ for the two orientations of the field. This is because $I_c(H)$ is defined by the Lorentz-like force on magnetic vortices[11]. This force is proportional to H * sinθ. Therefore, for $\theta = 0°$, Lorentz force would always be zero and I_c would not depend on the field. This is in contrast to the experimental results in the Inset to Fig.2. These results suggest that the current meanders between the superconducting grains, resulting in a variation of local θ. Averaging over the whole sample volume gives the same $I_c(H)$ for $\theta = 90°$ and 0° after shifting of $I_c(H)$ by 0.38T along H-axis (the shift is needed to account for the shielding by the iron sheath). The decrease in I_c for H<0.2T cannot be ascribed to weak links, because such a decrease was not also observed for the case $\theta = 0°$ (Fig.2).

In conclusion, we demonstrate by direct transport measurements of I_c that an iron sheath can be used as a very effective magnetic shield with MgB$_2$ superconducting wires. The initial decrease in I_c with field and a plateau in intermediate fields is a newly observed effect, originating in an interaction between the Fe sheath and superconductor. Better understanding of this effect can lead to extending the plateau to higher fields and improving the field performance of MgB$_2$/Fe wires further. It was also shown that the current path in the wires meanders between the grains, since I_c

depends on H in the Lorentz-force-free orientation of magnetic field ($\theta = 0°$), as shown in the Inset to Fig.2.

Sample	d_o (mm)	d_i (mm)	l(mm)	J_{c0}(A/cm^2)
S1	1.50	0.85	14	38,700
S2	1.52	0.95	14	21,000
S3	1.30	0.65	13	53,300

Table 1: Dimensions of the samples measured: d_o, d_i, and l are outer diameter, inner diameter and length, respectively. J_{c0} is the critical current density in zero external field, at temperature 32K.
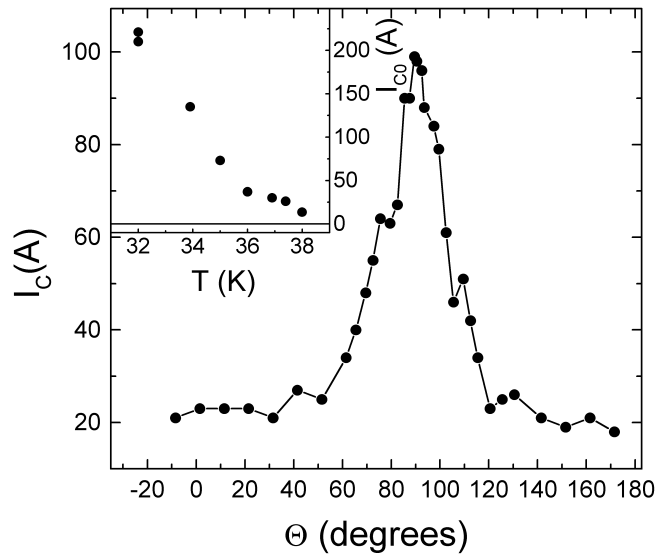
Figure 1: Angular dependence of critical current for sample S1 at 33.7K and 0.4T. Inset: Temperature dependence of critical current in zero field for S1.
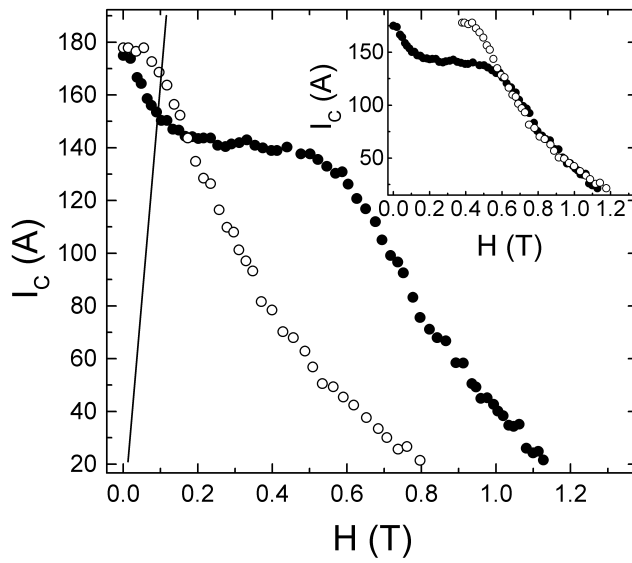

Figure 2: Field dependence of critical current for sample S3 at 32K. The solid and open symbols are for perpendicular and parallel field (i.e. $\theta = 90°$ and $0°$), respectively. The solid line is the self-field produced on the surface of the superconductor by the critical current. Inset: The same, with 380mT added to the parallel field.
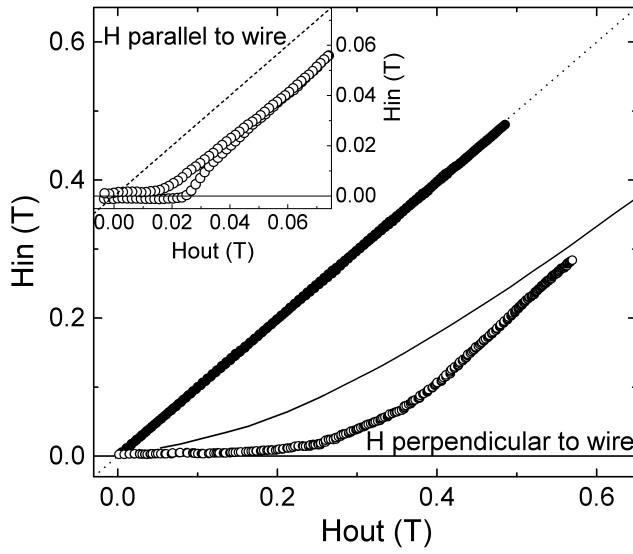
Figure 3: The magnetic field inside the iron sheath, H_{in}, against the external field, H_{out}, for perpendicular field, $\theta = 90°$ (open symbols). When the iron sheath is removed, $H_{in}=H_{out}$ (solid symbols). The solid line shows theoretical H_{in} against H_{out}. Inset: H_{in} against H_{out} for a parallel field, $\theta = 0°$ (solid symbols). The dashed line shows $H_{in}=H_{out}$.

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