Magnetic shielding in MgB2/Fe superconducting wires

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Magnetic Shielding in MgB_2/Fe Superconducting Wires

J. Horvat, S. Soltanian, X. L. Wang, and S. X. Dou

***Abstract*—Transport critical current (I_c) was measured for MgB_2/Fe round wires, with the magnetic field oriented perpendicular to the wire and parallel to it. Measurements were made on a wire with a pure MgB_2 core and another wire where the MgB_2 core was doped with nano-size SiC. This doping strongly improved the vortex pinning in MgB_2. The field dependence of I_c was strongly improved due to the presence of the iron sheath. At 30 K, I_c did not depend on the field for fields between 0.09 and 0.7 T. At lower temperatures, I_c increased with the field, after an initial decrease, resembling a "peak effect." This effect was extended to higher fields as the temperature was decreased: at 10 K the peak appeared at 3.5 T. This improvement was not due to mere magnetic shielding by iron, but more likely to an interaction between the iron sheath and the superconductor. Improvement of vortex pinning did not affect the range of fields within which this effect was observed. J_c of SiC doped MgB_2/Fe wires at elevated fields already satisfies the requirements for their use in production of superconducting magnets for particle accelerators.**

***Index Terms*—Critical current, magnetic shielding, MgB_2/Fe superconducting wires.**

I. INTRODUCTION

THE MgB_2 superconductor is a new candidate for making superconducting wires that can be used without the need for liquid helium. Its relatively high critical temperature of 39 K makes it possible to use it at 20 K, a temperature readily available with modern cryo-coolers. Quite early in the development of MgB_2 wires, it became clear that iron is one of the best materials for use as a sheath for the wires [1]–[4]. Transport critical current density (J_c) of 1.3×10^5 A/cm^2 was obtained at 20 K and 1.7 T for the samples measured here. In addition to providing a medium for obtaining MgB_2 in the chemical reaction at high temperature and ensuring the mechanical strength of the wires, iron is a ferromagnetic material that can be utilized to magnetically shield the superconductor from the external field. This could be very effectively employed for decoupling the superconducting filaments in a multifilamentary MgB_2/Fe wire, substantially lowering the AC loss in the wires.

Our first results on the influence of an iron sheath on the field dependence of transport J_c revealed a much better improvement of J_c than expected from mere magnetic shielding [5]. There was a range of fields where J_c did not change with field. This was attributed to the interaction between the superconductor and iron sheath, because it was measured at high fields, for which the magnetic shielding was no longer effective. This range of fields was found to widen with decreasing temperature, indicating that it may be possible to obtain a very weak field dependence of J_c at 20 K, at high fields. However, the lowest temperature at which the measurements could be performed was 32 K, which was limited by the maximum current available from the pulse current source. Here, we used an improved current source, enabling measurements at temperatures less than 20 K. Improving the vortex pinning by newly discovered nano-SiC doping [6], we also test how the vortex pinning affects the superconductor/sheath interaction.

II. EXPERIMENTAL PROCEDURE

Superconducting wires were prepared by filling an iron tube with a mixture of 99% pure powders of magnesium and boron. For one of the wires, 10 wt.% of amorphous nano-size SiC was added. The wires were drawn to a diameter of 1.4 mm, with the diameter of the inner core of 0.8 mm. Heating in flowing argon to 800 ° C for 15 minutes, MgB_2 was formed in a chemical reaction. As shown recently, addition of SiC strongly improves the vortex pinning of MgB_2, resulting in much improved field dependence of the critical current density (J_c) [6]. The details of the wire preparation can be found elsewhere [7]. The wires measured had the same outer diameter and diameter of superconducting core. The sheath was made from the same iron tube for all the wires, ensuring the magnetic properties of the sheath were the same for all the samples measured.

Because critical current for these wires was hundreds of amperes, the transport measurements had to be performed by a pulse-method to avoid heating. A pulse of current was obtained by discharging a capacitor through the sample, coil of thick copper wire and noninductive resistor connected in series. The current was measured via the voltage drop on the noninductive resistor of 0.01 Ohm. With a proper choice of the coil, the current reached its maximum value (700 A) within 1 ms. The voltage developed on the sample was measured simultaneously with the current, using a 2-channel digital oscilloscope. Because both channels of the oscilloscope had the same ground, the signal from the voltage taps was first fed to a transformer preamplifier (SR554). This decoupled the voltage taps from the resistor used for measuring the current, thereby avoiding creation of ground loops and parasitic voltages in the system, as well as of an additional current path in parallel with the sample. The transformer amplified the voltage 100 times, improving the sensitivity of the experiment. The reliability of this experimental set-up was checked by measuring the resistance of a copper wire with this method and a dc method, using the same current- and

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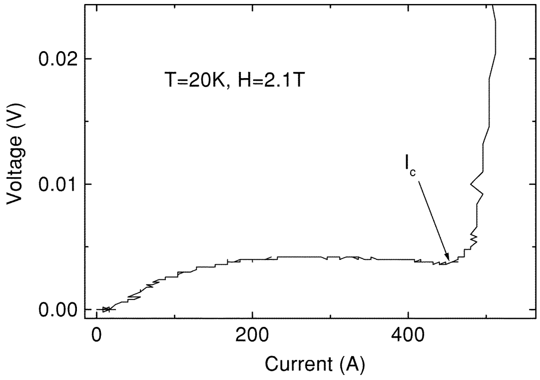

Fig. 1. A typical voltage-current characteristic for MgB_2/Fe wire obtained by the pulse-method.

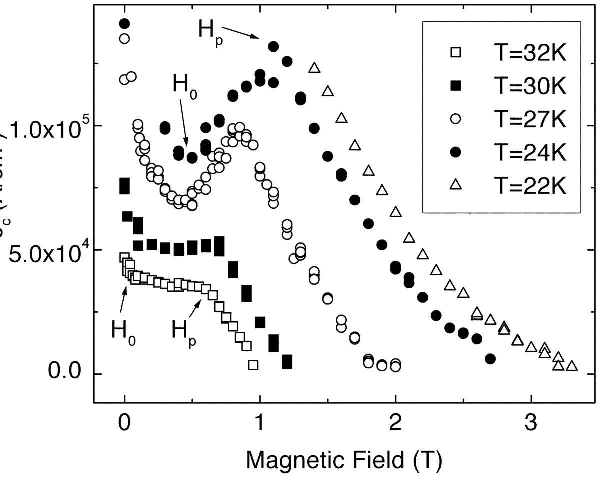

Fig. 2. Field dependence of J_c for an undoped MgB_2 wire with field perpendicular to the wire.

voltage-contacts. The measured resistance was the same within 1.7%.

A typical V–I characteristic is shown in Fig. 1. Self-field of the current pulse induced a voltage in the voltage taps, which gave a background voltage. This voltage increased gradually at the beginning of the pulse, but was almost constant for most of the pulse duration (Fig. 1). It was easy to distinguish the voltage created by the superconductor on this background, because the voltage developed very abruptly when the current reached the value of I_c.

The magnetic field was produced by a 12 T superconducting magnet. Sample mounting allowed for orienting the field either perpendicular to the wire, or parallel to it. In the latter case, the field was also parallel to the current passing through the sample. The sample was placed into a continuous flow helium cryostat, allowing the control of temperature to better than 0.1 K.

III. EXPERIMENTAL RESULTS

Fig. 2 shows the field dependence of J_c for a nondoped wire at $T = 32, 30, 27, 24$ and 22 K. For all the temperatures, there is an initial decrease of J_c with the field, up to a field H_0. After the decrease, J_c is almost independent of the field at $T = 30$ and 32 K, up to a value of field H_p. For $H > H_p$, J_c decreases with H exponentially. For lower temperatures, J_c starts increasing with the field for $H > H_0$, giving a field dependence of J_c resembling a "peak effect" (Fig. 2). J_c peaks at $H = H_p$ and it decreases exponentially with field for $H > H_p$ (Fig. 2). The occurrence of the plateau and peak in J_c vs. H improves the field dependence of J_c, as shown previously for $T > 30$ K [5]. This was shown to occur because of the interaction between the Fe sheath and superconductor. The field range with improved J_c widens with decreasing temperature. For lower temperatures, the critical current at low fields was higher than the maximum current available with our experimental set-up, and the peak could not be measured. Qualitatively the same results were also obtained for the SiC doped wire, which had improved field dependence of J_c for $H > H_p$.

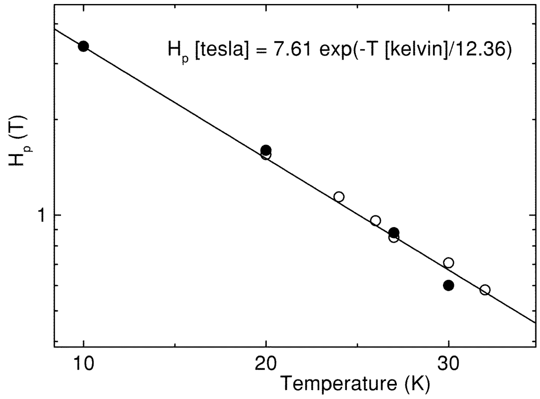

Fig. 3. Temperature dependence of H_p for undoped (open symbols) and SiC doped (solid symbols) MgB_2/Fe wires. Solid line is the fit with (1).

To study the temperature dependence of the field range with improved J_c, H_p is plotted as a function of temperature in Fig. 3. It should be noted that J_c is improved by Fe sheath even for fields higher that H_p for $T < 30$ K (Fig. 2), however there is no clear feature in J_c vs. H for $H > H_p$ to enable a clear distinction of the field range with improved J_c. As shown in Fig. 3, H_p decreases with temperature exponentially:

$$H_p\,[\text{tesla}] = 7.61\exp\left(-\frac{T\,[\text{kelvin}]}{12.36}\right). \tag{1}$$

The temperature dependence of H_p is shown in Fig. 3 by solid and open symbols for pure and SiC doped wires, respectively. Apparently, improvement of vortex pinning by doping does not affect the values of H_p.

Fig. 4 shows the field dependence of J_c for a pure MgB_2/Fe wire at 30 K with field parallel to the wire (open symbols), as compared to the field perpendicular to the wire (solid symbols). As opposed to the perpendicular field, J_c for the parallel field initially increases with the field, up to a field H_1. This is followed by an exponential decrease of J_c with field for $H > H_1$. At lower temperatures (below 27 K), J_c is almost constant for $H < H_1$. The value of H_1 decreases with temperature as: $H_1 = 3303$ Tesla $\exp(-T/3$ Kelvin) (Fig. 5), much faster than H_p.

IV. DISCUSSION

The plateau in the field dependence of J_c has been reported earlier for MgB_2/Fe wires, for $T > 30$ K [5]. The plateau

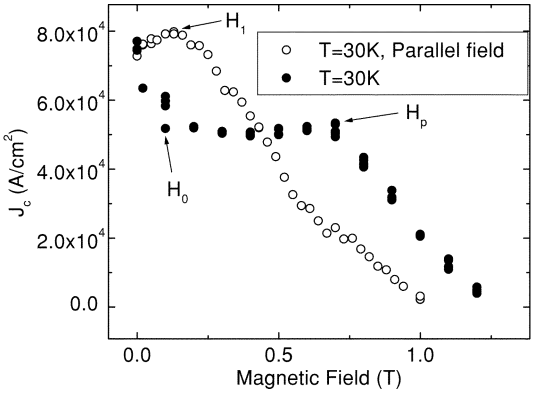

Fig. 4. Field dependence of J_c for an undoped MgB_2/Fe wire at 30 K, with field perpendicular (solid symbols) and parallel (open symbols) to the wire.

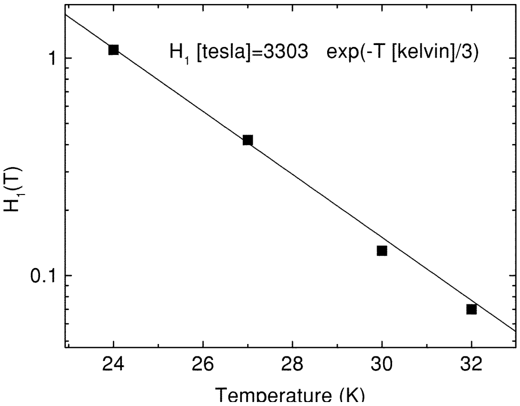

Fig. 5. Temperature dependence of H_1 for an undoped MgB_2/Fe wire with field parallel to the wire. Solid line is the fit with the exponential function.

was observed to widen with decreasing temperature. It was suggested that the plateau occurred as a consequence of the interaction between the superconductor and the iron sheath. In this work, we investigated the temperature dependence of the plateau for $T < 30$ K, thanks to an improved pulse current source enabling measurements of higher values of I_c.

The plateau was observed for $T > 30$ K in this work, as well. However, instead of the plateau, an increase of J_c with H was observed for $T < 30$ K, resulting in a peak in the field dependence of J_c (Fig. 2). The peak apparently develops from the plateau as the temperature decreases, because the temperature dependence of H_p follows the same exponential law for $T > 30$ K and $T < 30$ K. Measurements of magnetic shielding of hollow Fe cylinder showed that the shielding is effective up to about 0.2 T [5]. The effectiveness of the shielding should not vary strongly at temperatures between 20 and 32 K, because the Curie temperature of iron is much higher than this. Apparently, it is the change of superconducting properties of the MgB_2 core that is responsible for the exponential decrease of H_p with T. Because of this, strong improvement of vortex pinning with SiC doping was expected to affect the temperature dependence of H_p. To our surprise, this did not occur (Fig. 3).

The field dependence of J_c with the field parallel to the wire is also influenced by the iron sheath. It was shown earlier that there is a plateau in $J_c(H)$ for $H < 0.02$ T and $T = 32$ K [5]. This was interpreted as simple magnetic shielding of the iron sheath. Namely, measurements of the field inside the shield for the parallel field showed that the internal field was almost zero and constant for $H < 0.02$ T. All of the field in excess to 0.02 T penetrated the iron sheath for this field configuration. Here, we show that for $T < 32$ K, J_c slightly increases with the field (Fig. 4) and the field range in which this occurs ($H < H_1$) increases strongly with decreasing temperature (Fig. 5). The field dependence of H_1 is actually much stronger than that of H_p. In addition, it was shown earlier that the magnetic shielding for the parallel field is very weak [5]. Again, such strong temperature dependence of H_1 cannot be ascribed to simple magnetic shielding. Apparently, the interaction between the superconducting core and iron sheath is responsible for the anomalous improvement of the field dependence of J_c for both parallel and perpendicular field.

Improvement of critical current of a superconductor via interaction with its magnetic surrounding was studied theoretically by Genenko *et al.* [8]. In their model, critical currents were calculated for type II superconducting thin strips in partly filled vortex state in a magnetic surrounding. Only self-field of the transport current was considered, and the magnetic surrounding was supposed to be reversible, linear and homogeneous. They considered the influence of the magnetic surrounding on the current distribution in the central vortex-free part of the strip. The current distribution was found to be very sensitive to the shape of the magnetic surrounding and its distance to the strip. They predicted an increase of the maximum loss-free current by a factor of 100 when a superconducting strip is placed in an open magnetic cavity. However, for the smallest practically achievable distance between the superconductor and magnetic surrounding of 0.1 mm, the maximum loss-free current is predicted to be 7 times larger than the critical current without the magnetic surrounding. This increase of the apparent critical current occurs because of distribution of the current into the vortex-free region of the superconducting strip, whilst the vortices are confined to the edges of the strip. So far, no experiments have been reported to verify this model.

In the model of Genenko *et al.* [8], the vortices were confined to the edges of a thin superconducting strip by edge barriers. The model also considered the case of a partly flux filled thick superconducting strip with weak edge barriers and strong vortex pinning. Vortex pinning defined the critical current, according to the critical state model [9]. However, due to the pinning, the transport current is confined to the edges of the superconductor where there is a constant gradient in the density of magnetic vortices defined by the pinning, and J_c is constant. Therefore, vortex distribution for strong pinning with weak edge barriers is similar to the case of edge barriers with weak pinning. The magnetic surrounding causes a distribution of the transport current into the flux free region of the superconductor, similar to the case of weak pinning with edge barriers. This results in a loss-free current density exceeding the critical current defined by the critical state model [8]. Because of this, we expected to observe a change in the value of H_p with improvement of the pinning by SiC doping, because the flux profile in the superconductor changes with the change of the vortex pinning. However, no change in H_p was observed (Fig. 3).

The reason we did not observe the change in H_p with SiC doping may be that the model was devised only for the self-field, whereas in our experiment we used an additional external field. The geometry of our sample (round wire) was also not the same as the one in the model (strip). Because the model did not consider the case of external field, it is not clear if the change of the pinning should result in a change of H_p in the model (even though intuitively, one would expect this to occur).

There is also a possibility that H_p is a parameter that does not reflect the change of vortex pinning. Actual mechanisms for the occurrence of the peak effect are not known and the meaning of H_p is consequently not clear. Preliminary results of further research indicate that there are other characteristic fields associated with the occurrence of the peak effect, too[1]. Additionally, the magnetization state of the iron shield affects the peak effect, even though this does not seem to be the mechanism for its occurrence.[1]

V. CONCLUSION

It was found that, instead of the expected plateau in the field dependence of J_c, the value of J_c increases with field at low temperatures, resembling a peak effect. The field of the peak in $J_c(H)$ increases exponentially with decreasing temperature. Thanks to the peak, the value of J_c at 20 K and 1.7 T is almost the same as the zero-field J_c at that temperature, of the order of 10^5 A/cm^2. At still lower temperatures, the peak extends to higher fields, reaching 3.5 T at 10 K. Even though its exact origin is still not clear, this effect can be employed for improvement of the field dependence of J_c of $\mathrm{MgB_2}$ wires. It has already pushed the field performance of J_c (as measured by pulsed current method) of SiC doped $\mathrm{MgB_2}$/Fe wires at 20 K beyond the minimum requirements needed for production of the magnets employed in particle accelerators [10].

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[1] Measurements are still under way. The results are expected to be published in 2003.

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