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The relevance of the self-field for the 'peak effect' in the transport Jc(H) of iron-sheathed MgB2 wires

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The relevance of the self-field for the 'peak effect' in the transport $J_c(H)$ of iron-sheathed MgB$_2$ wires

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Abstract
A ferromagnetic sheath around a superconducting wire results in an unusual
transport $J_c(H)$. For the field perpendicular to the current, there is a plateau
in $J_c(H)$ at high temperatures and intermediate fields. This plateau develops
into a peak at lower temperatures—resembling a 'peak effect'. A model
based on cancellation of the self-field of the current and the external field
within the iron sheath was proposed for the explanation of the plateau in
$J_c(H)$. We test this model in three key experiments. Firstly, we show that
the form of $J_c(H)$ for round MgB$_2$/Fe wires is strongly temperature
dependent. This is in contradiction with the model, because the properties of
the iron sheath do not change in the measured temperature range. However,
the temperature dependence of J_c might still account for the change of
$J_c(H)$. Secondly, the model requires a substantial component of the
self-field to be parallel to the external field. Our measurements of $J_c(H)$ for
a field parallel to the current show a peak in $J_c(H)$ at high temperatures and
a pronounced plateau at low temperatures. The model cannot explain this
because the self-field and external field are perpendicular in this experiment.
Thirdly, the iron sheath was made thinner on one side of the wire, which
should produce an asymmetry in $J_c(H)$ in the model for two different
orientations of the external field. Such asymmetry was not observed. These
experiments show that the effect of the self-field is of much lower
importance than an as yet unknown effect that results in the observed plateau
and peak in $J_c(H)$. Such an effect is likely to be based on a specific
interaction between the superconductor and ferromagnet, perhaps similar to
the overcritical state effect.

1. Introduction

The concept of using a ferromagnetic sheath to improve
the field dependence of the critical current density, $J_c(H)$,
and reduce the ac loss has been suggested for high
temperature superconductors (HTS) [1]. However, chemical
incompatibility of ferromagnetic materials with HTS was a
major problem, impeding the practical implementation of this
concept. After the discovery of superconductivity in MgB$_2$, it
became clear that the best J_c for MgB$_2$ wires can be obtained
with Fe as the sheath material [2–7]. Because of this, the
concept of magnetic shielding as a way of reducing ac loss
and improving $J_c(H)$ was reconsidered for MgB$_2$. Due to
magnetic shielding, the field inside the sheath would be almost
zero, up to a certain value of the external field [8]. This would
result in an almost constant value of J_c up to that particular
field, followed by a decrease of J_c with H for higher fields in the
same manner as if there was no iron sheath. The improvement
of the ac loss is expected to occur for multifilamentary MgB$_2$
wires, where the iron sheath between the filaments prevents
magnetic coupling of the filaments [1, 9, 10]. As opposed to
the case for thin high temperature superconducting films coated

with a ferromagnetic material [1], the ac loss of the iron sheath is negligible in comparison to the ac loss of the MgB_2 core [11]. This is because the volumes of the iron and superconducting core are comparable to each other, and because of the large J_c of MgB_2 and very small coercive field of iron, compared to MgB_2.

The revival of interest in the effects of an iron sheath on $J_c(H)$ started with the transport measurements of $J_c(H)$ for round iron-sheathed MgB_2 wires at temperatures around 30 K [8]. Because of the large values of the critical currents, the measurements had to be performed by a pulsed current method. The measurements showed that J_c initially decreased strongly with H up to about 0.2 T, and that this was followed by an almost constant J_c up to about 0.6 T, and by a more gradual decrease for larger fields [8]. Subsequent measurements showed that the constant J_c at intermediate fields is replaced by an increase of J_c with H at lower temperatures, resembling a peak effect in $J_c(H)$ [12]. Measurements showed that the iron sheath was shielding the MgB_2 core from the external field almost completely up to about 0.2 T [8]. The shielding was gradually diminished for higher fields and finally all of the additional field above 0.4 T was passed through the shield without attenuation. The magnetic properties of the iron sheath remained almost the same in the measurement temperature range. Therefore, the measured temperature dependence of $J_c(H)$ was very different to that expected from the effect of a simple magnetic shielding.

The explanation of the observed $J_c(H)$ was initially suggested in terms of the overcritical state model of Genenko et al [13–15]. However, the overcritical state model was developed for superconductors in the form of thin strips and it is debatable whether it can be applied for explanation of the peak in $J_c(H)$ observed for the round superconducting wires. Even though measurements of the magnetic J_c for round iron-sheathed MgB_2 wires show that J_c for the iron-sheathed MgB_2 is larger than J_c for the bare MgB_2 core [16], the relevance of the overcritical state as the mechanism for obtaining a peak and plateau in the transport $J_c(H)$ [8, 12] is questionable. That is, there was no transport current in the magnetic measurements of the hysteresis loops, from which the magnetic J_c was obtained [16]. Therefore, the experimental conditions in these experiments were different to those in the model of the overcritical state [13–15] and in our measurements of the transport $J_c(H)$ [8, 12]. Further, the removal of the iron sheath may have slightly damaged the MgB_2 core, resulting in a lower J_c for the sample without the sheath.

There was a possibility that the unusual $J_c(H)$ for the iron-sheathed MgB_2 wires was an artefact arising from using the pulsed current method. However, Kovač et al [17] measured the transport $J_c(H)$ of multifilamentary Bi2223 tapes before and after putting an iron sheath around the tapes, using the dc method. They reported a $J_c(H)$ similar to the ones obtained by us using the pulsed method for MgB_2. This showed that the pulsed current measurements were not giving an artificial field dependence of J_c. Moreover, these results showed that the observed $J_c(H)$ for the iron sheathed superconducting cores is not limited to MgB_2 superconductor and that it can also be obtained for multifilamentary superconductors.

The chemical composition of all the samples was MgB_2 with less than 10% of MgO. There were no other superconducting transitions detected either in the measurements of the resistive transition or in those of the superconducting screening. Therefore, the peak effect could not have occurred as a consequence of secondary superconducting phases. Measurements of Kovač et al [17] further support this, because the peak effect was not observed without the iron sheath.

Kovač et al also proposed a simple model for explanation of the observed $J_c(H)$ [17, 18]. They performed a numerical analysis of a superconducting iron sheathed wire placed in a perpendicular magnetic field, with the current passing along the wire. The self-field produced by the current points in the opposite direction to the external field on one side of the wire, and in the same direction as the external field on the opposite side of the wire [17]. Consequently, the value of the net field inside the iron sheath is lower than that of the external field on the former side of the wire and higher than that of the external field on the latter side. Their numerical analysis shows that the resulting average field inside the iron sheath is suppressed more strongly than in the case of simple magnetic shielding without the self-field. This leads to a $J_c(H)$ similar to the one obtained for iron-sheathed wires at high temperatures [17], i.e. a fast decrease of J_c in small fields is followed by a plateau in intermediate fields and a faster decrease in high fields. Therefore, their model seems to be able to explain many of their experimental observations.

However, not all experimental observations can be explained using this model. In particular, their numerical analysis could not produce a peak in $J_c(H)$, observed in our measurements for iron sheathed MgB_2 at low temperatures [12] and in some of their dc measurements on the iron-sheathed Bi2223 tapes [17]. This peak is a dominant feature of $J_c(H)$ for high quality MgB_2 wires over most of the temperature range below T_c [12]. Further, because the magnetic properties of iron remain unchanged in the measurement temperature range, the cancellation of the self-field and external field in the iron sheath should also remain unchanged in this temperature range. Therefore, it would be difficult to explain the observed strong temperature dependence of the plateau and peak in $J_c(H)$ [12] using this model.

In this paper we present the results of three different experiments, designed to test whether the model based on the cancellation of the self-field and external field in the iron sheath [17] can be used to describe the observed $J_c(H)$ over a broad temperature range. The reliability of the pulsed current method is further tested by comparing the results of the pulsed current measurements at low fields to the dc measurements on the same samples at higher fields, measured for the iron and for the copper sheathed round wires.

2. Experimental procedure

A number of different MgB_2/Fe wires were measured. While exact preparation conditions for each of the wires varied, they were all prepared by the powder in tube method. Pure iron tubes were filled with a homogeneous mixture of magnesium and boron powders. The wires were drawn to a desired diameter, usually about a millimetre. They were heated in high purity argon to temperatures ranging from 800 to 900 °C, for times between 1 and 15 min. The resulting MgB_2 core was of high purity, giving values of J_c at 20 K of the order of 10^5–10^6 A cm^{-2}. Some of the wires were doped with nano-SiC

and some with carbon nanotubes. The doping improved the value of J_c and its field dependence, but there was no obvious influence of the doping on the general shape of the $J_c(H)$. The detailed description of the preparation of these wires can be found in the literature [2, 3, 19, 20].

Some of the wires had iron sheath on the outside and the copper sheath in between the MgB_2 and the iron sheath. They were prepared in the same way as the iron-sheathed MgB_2, with variation of the heating procedure to avoid chemical reaction with copper [21, 22].

The phase purity was checked with x-ray diffraction analysis. The cores of all the samples contained more than 90% of MgB_2. The critical temperature T_c was obtained from the ac susceptibility measurements, using the amplitude and frequency of the excitation field of 1 Oe and 117 Hz, respectively. The value of T_c for all samples, obtained as the onset temperature for superconducting screening, was 38–39 K.

The transport critical current (I_c) was obtained from the voltage–current (V–I) characteristics, using the four-probe method. Because the values of I_c for our samples were well in excess of 100 A, V–I characteristics were measured with the pulsed current method. The duration of the ascending part of the current pulse was 1 ms, which was short enough for avoiding any effects of the heating. A detailed description of the experimental set-up can be found elsewhere [12]. This method results in a parasitic voltage, induced in the voltage taps by the self-field of the changing current. However, this voltage did not affect our values of I_c because the voltage increased very abruptly at $I = I_c$ [12]. Only in large fields was the voltage increasing more gradually with current as the current reached I_c. The measurements were terminated at the fields for which the V–I characteristics were no longer abrupt at $I = I_c$, to make sure that only reliable results are analysed.

The dc current was used for measurements of I_c at high fields. However, the value of I_c was decreasing with the time for which the current was passing through the sample, for currents larger than about 1 A. Therefore heating of the current contacts was affecting the value of I_c and it was measured only for the fields where its value was lower than 1 A. In this method, I_c was obtained using the standard 1 μV cm^{-1} criterion. The values of J_c were obtained by dividing I_c by the cross-sectional area of the superconducting core.

3. Results and discussion

We begin with the comparison of the dc and pulsed current measurements, to further validate our results on the pulsed $J_c(H)$. This is followed by three different sets of experiments, designed to test whether the model based on the sum of the self-field and external field in the volume of the iron sheath [17, 18] is appropriate for the explanation of our results: the temperature dependence of $J_c(H)$, $J_c(H)$ for the field parallel to the wire length, and the effect of the asymmetry of the iron sheath.

3.1. Pulsed and dc $J_c(H)$

Figure 1 shows the field dependence of J_c for a copper-sheathed MgB_2 wire, measured with the pulsed current (solid
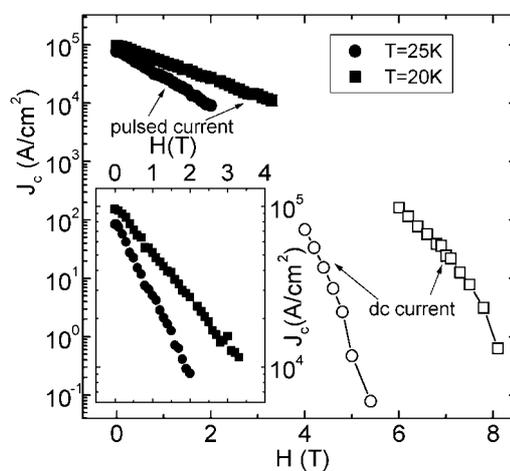

Figure 1. The field dependence of the critical current for a typical copper-sheathed MgB_2 wire at 20 and 25 K. Solid and open symbols show the data obtained by the pulsed current and dc current methods, respectively. Inset: an enlarged section showing only the pulsed current data.

symbols) and dc current (open symbols). There is a gap in the data obtained, because the value of I_c could not be measured reliably for higher fields. On the other hand, in the dc current measurements, the temperature of the sample started increasing significantly for currents higher than about 1 A.

Despite the gap in figure 1, there is very good agreement between the dc and pulsed current measurements. Such good agreement was obtained thanks to very weak thermal excitations of the vortices in MgB_2, resulting in a sharp increase of voltage for $I = I_c$ at low fields. Therefore, the pulsed current measurements performed at low fields gave reliable values of I_c despite the background signal being of the order of 1 mV. On the other hand, the measurements with the dc current did not have a background signal and their accuracy was in the region of 1 μV. Because of such high resolution, a reliable value of I_c was obtained in the dc measurements even though the voltage did not increase abruptly with the current at $I = I_c$.

The inset to figure 1 shows an enlarged view of $J_c(H)$ for the pulsed measurements on the copper-sheathed wire. It is obvious that the copper-sheathed wires do not exhibit a peak or a plateau of the type reported for the iron-sheathed wires [8, 12, 17, 18]. Instead, $J_c(H)$ resembles a stretched exponential function, the same as that obtained in the magnetic measurements on the MgB_2 pellets, or MgB_2 wires with the iron sheath stripped away [23].

As opposed to this, pulsed measurements of the iron-sheathed wires exhibit a peak in $J_c(H)$ (figure 2), as reported earlier. It is clear from figure 2 that the measurements with the dc currents (open symbols) are in agreement with the measurements performed with the pulsed currents (solid symbols), as for the copper-sheathed samples.

Therefore, the peak in the $J_c(H)$ obtained with the pulsed current method is not an artefact of the experimental method used. That is, the same method does not give a peak for the copper-sheathed wire and there is also a good agreement between the pulsed and dc current measurements. This is further supported by the measurements on iron-sheathed
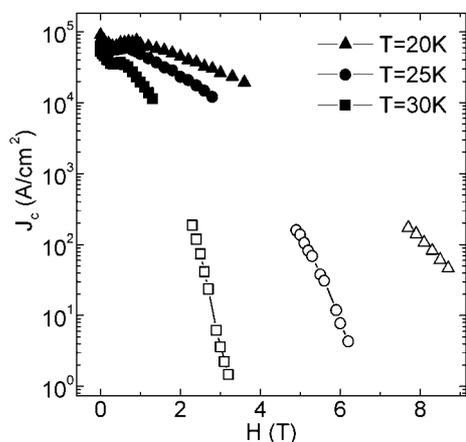
Figure 2. The field dependence of the critical current for a typical iron-sheathed MgB$_2$ wire at 20, 25 and 30 K. Solid and open symbols show the data obtained by the pulsed current and dc current methods, respectively.
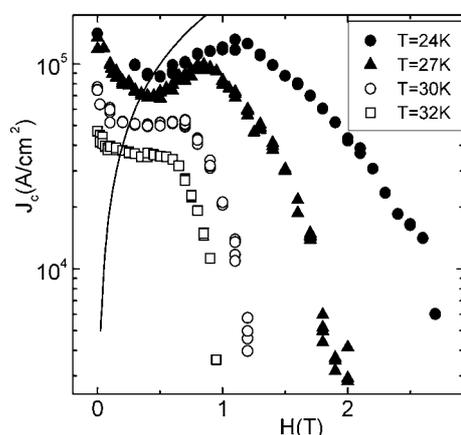

Figure 3. The field dependence of I_c for an iron-sheathed wire in temperature range 24–32 K. The solid curve shows the value of the self-field produced at the interface between the MgB$_2$ core and the iron sheath.

Bi2223/Ag tapes, where a similar peak in $J_c(H)$ was obtained with the dc current method [17].

3.2. Temperature dependence of $J_c(H)$

Figure 3 shows a typical field dependence of J_c for round iron-sheathed MgB$_2$ wires at different temperatures. There is a strong temperature dependence of the shape of the $J_c(H)$ curves. At temperatures higher than 30 K, J_c initially decreases with the field. This is followed by an almost constant value of J_c at intermediate fields, followed by a gradual decrease of J_c with H for high fields. However, a peak in $J_c(H)$ appears at intermediate fields for temperatures lower than about 30 K. This peak becomes more prominent as the temperature decreases. The value of the field at which the peaks attain a maximum (H_p) also strongly increases with lowering temperature (figure 3). The solid curve in figure 3 shows the value of the self-field at the interface of the iron sheath and the MgB$_2$ core. At low temperatures, the value of H_p is less than double the value of the self-field produced by the critical current at the peak maximum. At high temperatures,
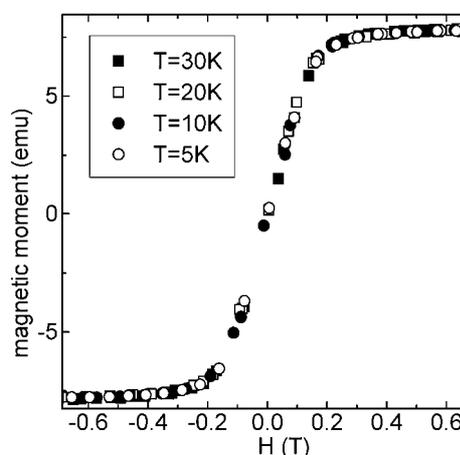

Figure 4. The magnetization curve for the iron in the temperature range between 5 and 30 K.
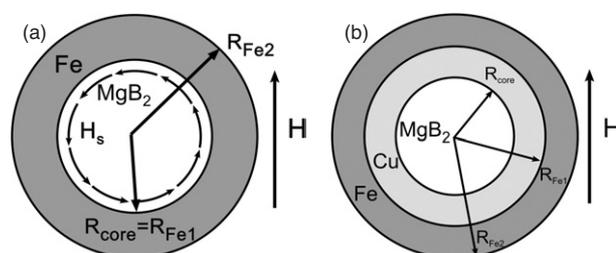

Figure 5. (a) Schematic diagram of a cross-section through an iron-sheathed wire. The inner and outer radii of the iron sheath are R_{Fe1}, R_{Fe2}, respectively. The circular self-field H_s of the current is represented by short arrows. The external field H is either added to or subtracted from H_s, depending on which side of the wire is considered. (b) Schematic diagram of a cross-section through an iron- and copper-sheathed wire.

the value of the field at the transition between the plateau in $J_c(H)$ and the gradual decrease of J_c with H at higher fields is more than double the value of the self-field corresponding to the I_c of the plateau.

Figure 4 shows the magnetization curves for an iron sheath without an MgB$_2$ core in the temperature range 5–30 K. There is no discernible difference between these curves. This result is not surprising, because the Curie temperature of iron is 1043 K, way above the temperatures at which $J_c(H)$ was measured.

In the model of Kovač *et al* [17, 18], the width of the plateau in $J_c(H)$ should depend on the magnetic susceptibility χ of the iron sheath. According to figure 4, χ for iron does not change with temperature in the measurement temperature range and χ cannot be a parameter responsible for the observed change of $J_c(H)$ with temperature (figure 3).

However, the value of the critical current I_c is strongly temperature dependent. It should be examined whether the change of I_c affects the value of the self-field in the iron sheath and whether this change of the self-field is a parameter that could in principle introduce the temperature dependence of $J_c(H)$ in the model of Kovač *et al* [17, 18].

The current I that flows through the superconducting core of MgB$_2$/Fe wire produces a radial self-field H_s. Its amplitude at the interface between the MgB$_2$ and iron is $H_s(R_{core}) = I/(2\pi R_{core})$ (figure 5(a)), where R_{core} is the radius of the MgB$_2$ core. With the external field H applied perpendicular to the

wire, the self-field and external field cancel each other out on one side of the wire for $H = H_s(R_{core})$ (figure 5(a)). On the diametrically opposite side of the wire, the fields are added. However numerical simulations show that the net field inside the iron sheath is still smaller than the external field minus the magnetic shielding of the iron sheath. This decrease of the field inside the sheath is the mechanism that leads to a plateau in $J_c(H)$ in the model of Kovač *et al* [17, 18]. If the current I exceeds the value of I_c, the MgB_2 core becomes abruptly resistive and almost all the current is pushed into the iron sheath. With this distribution of the current, the self-field increases linearly from zero at the inner edge of the iron sheath ($R_{Fe1} = R_{core}$) to $H_s(R_{Fe2}) = I/(2\pi R_{Fe2})$ at the outer edge of the sheath (R_{Fe2}). Therefore, the mechanism of cancellation of H by H_s at the surface of the superconducting core is not effective any longer when I exceeds I_c, because $H_s(R_{Fe1}) = 0$. According to this model, a larger value of I_c would result in larger $H_s(R_{core})$ and in a larger value of H being needed to obtain the cancellation of the two fields at $R = R_{core}$. Because I_c increases as the temperature decreases, the plateau in $J_c(H)$ would shift to higher values of H, up to a certain maximum field defined by the iron sheath. Therefore, the temperature dependence of the plateau in $J_c(H)$ could at least in principle occur in this model because of the essentially different profiles of the self-field for $I > I_c$ and $I < I_c$.

To check this further, we modified our experiment so that the change of the distribution of the self-field at $I = I_c$ is minimized. This was achieved by inserting a copper sheath between the MgB_2 core and Fe sheath (figure 5(b)). Because the resistivity of the copper sheath was nine times lower than that of the iron sheath at 20 K, most of the current for $I > I_c$ flowed through the copper sheath. Therefore, the profile of the self-field through the iron sheath remains qualitatively the same for $I < I_c$ and $I > I_c$. Because $H_s(R_{Fe1})$ always takes a non-zero value for $I > 0$, the self-field and external field can cancel each other out, irrespective of the value of I_c, as long as I is large enough.

In the framework of the model of Kovač *et al*, $V–I$ characteristics should show some typical features for Cu/Fe-sheathed samples. If I_c for the MgB_2 is smaller than the current needed to produce the self-field that can cancel out the external field on one side of the sample, the $V–I$ characteristic in a magnetic field should exhibit more than one step. At $I = I_c$, V should abruptly increase due to the resistance of copper and to some extent that of the iron sheath. However, as I is increased beyond I_c, the self-field produced by the copper sheath should continue decreasing the internal field further, according to the model. Because the value of I_c was in the first place suppressed by the field, this lowering of the average internal field by the self-field should make I_c recover some of its suppressed value. For a particular combination of temperature and field, the value of I_c should again become higher than I. At this stage, the current should again flow entirely through the superconducting core and a drop of voltage should be observed. However, no $V–I$ characteristics resembling this scenario were observed in our experiments.

3.3. Field parallel to wire

The cancellation of the external and self-fields cannot occur if the external field is parallel to the current flowing through
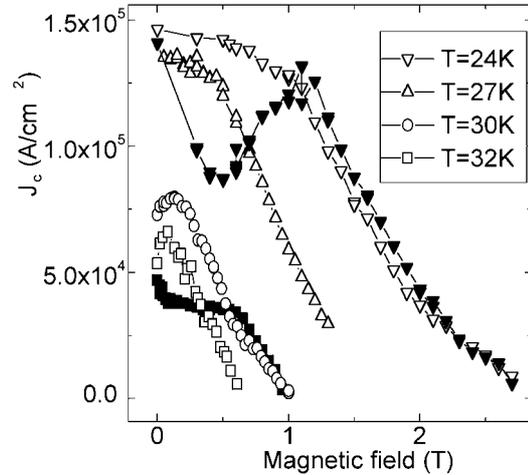

Figure 6. Field dependence of the critical current density for an iron-sheathed wire in the temperature range between 24 and 32 K. Open symbols are for the field parallel to the current and the wire long axis. Solid symbols are for the field perpendicular to the current.

the wire, because the self-field is then perpendicular to the external field. Therefore, if the observed peak and plateau in $J_c(H)$ are affected by the cancellation of the self-field and external field [17, 18], these features should not be observed for the current parallel to the external field.

Figure 6 shows $J_c(H)$ for the external field applied parallel to the current flowing through the MgB_2/Fe wire, and therefore along the wire length (open symbols). The field was aligned with accuracy better than $1°$, thanks to a sharp peak in the angular dependence of J_c when the field is aligned close to the sample length [8]. The solid symbols show $J_c(H)$ at 24 and 32 K for the field perpendicular to the wire, for comparison. $J_c(H)$ for the parallel field exhibits a peak at high temperatures and a plateau at low temperatures, in contrast to $J_c(H)$ for the perpendicular field. There is also a strong temperature dependence of the range of fields at which the peak or plateau appears. The peak and plateau for the parallel field are by no means less pronounced than for the perpendicular field.

These results cannot be explained using the model based on the cancellation of H_s and H [17, 18], even taking into account inhomogeneous structure of the MgB_2 core. That is, the current does not flow along the MgB_2 core in a straight line [8]. It meanders between agglomerates of MgB_2 grains in an irregular manner, accounting for the field dependence of J_c even though the overall current is parallel to the field; i.e. the average Lorentz force is zero [8, 23]. The meandering of the current also produces localized self-fields with their vectorial projections parallel to the external field. However the values of these localized self-fields are very small. They are contributed only by small fraction of the currents that are nearest to the interface between MgB_2 and the iron sheath, since the random contributions of the currents flowing deeper in the core average themselves out. Figure 6 shows that the effect of the iron sheath on $J_c(H)$ is of approximately the same magnitude for parallel and perpendicular H. This cannot be accounted for by the local random self-fields, which are much smaller than the overall self-field of the current.
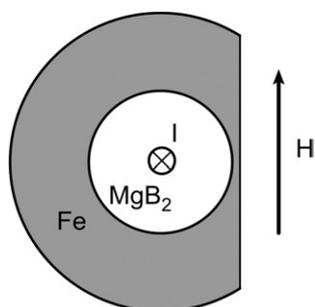
Figure 7. Schematic diagram of a cross-section through an iron-sheathed wire for which much of the iron sheath was removed from one side of the wire, making a plane parallel to the external field.

3.4. Asymmetry of iron sheath

The model of Kovač *et al* is based on the cancellation of the self-field and external field in the iron sheath on one side of the wire [17, 18], which results in a lower average field inside the iron sheath than expected from a simple magnetic shielding of the iron sheath. This mechanism is effective as long at the relevant portions of the iron sheath are not fully magnetized. Therefore, a thicker sheath is expected to result in the plateau in $J_c(H)$ extending to higher fields.

This model was developed for a cylindrical core and sheath, whose axes overlap. However, if the iron sheath is asymmetrical with respect to the axis of the wire, the relative directions of the current and external field should affect the $J_c(H)$ in this model. We introduced asymmetry to the iron sheath by carefully polishing one side of the sheath, as shown in figure 7. The field was applied parallel to the flat surface obtained by the polishing and perpendicular to the current (figure 7). If the field pointing up and current flowing into the plane of the paper in figure 7 are both designated as positive $(+H, +I)$, H_s and H will be oriented in the opposite directions in the thin portion of the iron sheath that was polished. The same will occur if both field and current are negative. However, if only one of them is negative, H_s and H will be oriented in opposite directions on the diametrically opposite side of the sheath (figure 7). The thin portion of the sheath can be fully magnetized in a lower external field because the magnetic flux in it is higher than in the thicker portion on the opposite side. Therefore, there should be a significant difference in $J_c(H)$ for H and I having the same and opposite signs. This difference should be reflected only in those features of $J_c(H)$ that are governed by the mechanism of the cancellation of H_s and H in the iron sheath [17, 18].

Figure 8 shows $J_c(H)$ for an MgB$_2$/Fe wire, with one side of the sheath made thinner than the original (figure 7). The thickness of the iron sheath in the original wire was 0.3 mm. After removing part of the sheath, as in figure 7, the thinnest part of the iron sheath was 0.1 mm thick. There is a clear overlap of $J_c(H)$ for $(+H, +I)$ and $(-H, -I)$ combinations. Equally good overlap is obtained for $(+H, -I)$ and $(-H, +I)$ combinations. However, there is only a slight difference between these two groups of $J_c(H)$. This difference is obtained for the intermediate fields, where the peak in $J_c(H)$ occurs. Nevertheless, the main features of the $J_c(H)$ remain unchanged, regardless of the relative signs of H and I. There
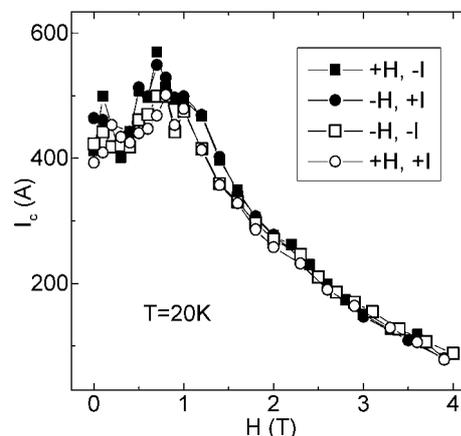

Figure 8. Field dependence of the critical current for the iron-sheathed wire with the iron sheath partly removed, as in figure 7. All combinations of the relative directions of the external field and current are shown.

is always a pronounced peak in $J_c(H)$ at the same value of H, regardless of the combination of the signs of H and I. This implies that the occurrence of the peak in $J_c(H)$ is not governed by the cancellation of H and H_s in the iron core. This mechanism seems to have only a secondary role, altering the value of J_c much less than its variation within the peak in $J_c(H)$. These measurements show that the effect of the plateau obtained in the numerical simulation of Kovač *et al* [17, 18] is added to the much stronger effect of the peak and plateau in $J_c(H)$ that occur for fields both perpendicular and parallel to the wire length. The exact origin of the latter effect still remains unknown.

4. Conclusions

The model based on the cancellation of the self-field and external field in the iron sheath [17, 18] seemed to be an intuitively good explanation for the occurrence of the plateau in $J_c(H)$ for iron-sheathed superconductors. Even though the experimentally observed peak was not predicted in this model, it can easily be assumed that the peak may also be obtained if the model is refined. However, the model is in disagreement with the experiments presented in this paper, which were designed to test its key points. In particular, it would be difficult to reconcile the model with the observed plateau and peak in $J_c(H)$ for the field parallel to the wire length (figure 6) and the insignificant effect of the asymmetry of the iron sheath on the peak in $J_c(H)$ (figure 8).

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