Overcritical State in Fe-sheathed MgB_2 Superconducting Wires

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Magnetization measurements carried out on MgB_2 superconducting round wires have shown that the critical current density J_c in wires sheathed by iron can be significantly higher than in the same unsheathed wires over a wide range of magnetic fields applied transversely to the cylindrical wire axis. Magnetic interactions between the magnetic sheath and the superconducting core are responsible for the enhancement. A phenomenological model is proposed to account for the observed overcritical behaviour.

1. Introduction

An enormous effort has been made in order to investigate and enhance the current-carrying ability of long superconductors for practical use in large scale applications, such as power lines, magnets, motors, generators, etc. A dissipation-free current flow in a type-II superconductor can exist in the magnetic flux-free Meissner state, as well as in the Shubnikov (mixed) state, as long as the magnetic vortices traversing through the superconductor in this state are pinned. The operational range of the Meissner state is usually too narrow and transport super-currents, flowing only in a thin surface layer with the thickness equal to the magnetic field penetration depth, are too small to satisfy practical needs. Therefore, in order to enhance the performance of the wires one has to find ways for further improvement of the current-carrying ability in the *mixed state*. So far, most efforts have been made to enhance pinning of magnetic vortices on structural inhomogeneities in superconductors, since the movement of the unpinned vortices generates an electric field along the superconductors, eventually leading to a total collapse of the superconductivity.

Recently, a novel (additional) method for further improving the dissipation-free current-carrying ability of superconductors was suggested in a series of theoretical works by Genenko *et al.* [1,2]. It was proposed that superconductors which are placed in a soft magnetic environment possessing high magnetic permeability can exhibit overcritical transport currents I^{oc} higher than the critical currents I_c. It was actually shown that in some cases the maximum current in the superconductor can be higher by a factor of seven than the critical current itself [2]. However, the superconducting strips considered in Refs. [1,2] require peculiar geometrical shapes for their magnetic environment. This obstacle makes it difficult to exhibit the effect in practice. Only recently, magneto-optical investigations on $YBa_2Cu_3O_7$ films placed in a soft magnetic environment experimentally showed that flux penetration next to the magnets was strongly modified, which led to *overcritical* current densities J_c^{oc} in the Meissner state calculated by an inversion of the Biot-Savart law [3].

New promising horizons for practical employment of the magnetic environment method have been opened up in MgB_2 superconducting wires, which normally achieve their best performance when sheathed by ferromagnetic iron (Fe) or nickel, creating an "unavoidable" soft magnetic environment [4-6]. In this work, we clearly show that this environment creates an overcritical state with J_c^{oc} significantly larger than J_c in the same wires with their Fe-sheaths removed over a wide range of magnetic field applied transversely to the cylindrical axis of the round MgB_2 superconducting wire.

2. Experimental details

Magnetization measurements on MgB_2 superconducting wires sheathed by iron were performed with a help of a Quantum Design MPMS SQUID magnetometer within an applied magnetic field range of $|B_a| \leq 5$ T at different temperatures and both parallel and perpendicular field orientations with respect to the round wire axis. The results of the measurements on sheathed wires were compared to those carried out under absolutely the same conditions on the bare wires. The bare wire is obtained by careful and thorough mechanical removal of the iron sheath from the wire so that the superconducting volume of the MgB_2 core remains the same.

The Fe-sheathed MgB_2 superconducting wires were made by employing the powder-in-tube technique [5]. Initial Fe-tubes packed with Mg+2B powder were drawn into final wires of about 2 mm diameter followed by in-situ Mg+2B powder reaction heat-treatment for MgB_2 superconducting core formation. A final transverse cross-section of a similar wire can be found in Fig. 1(a) of [6]. The wires obtained had the critical temperature T_c = 38.6 K measured at B_a = 2.5 mT.

3. Results and Discussion

As was shown in [6] the ferromagnetic signal of iron dominates in the magnetic response of the Fe-sheathed wires not only above, but also below T_c. To elucidate the superconducting contribution of the core below T_c, we employed the procedure used in [6] and subtracted the Fe-sheath contribution measured above T_c.

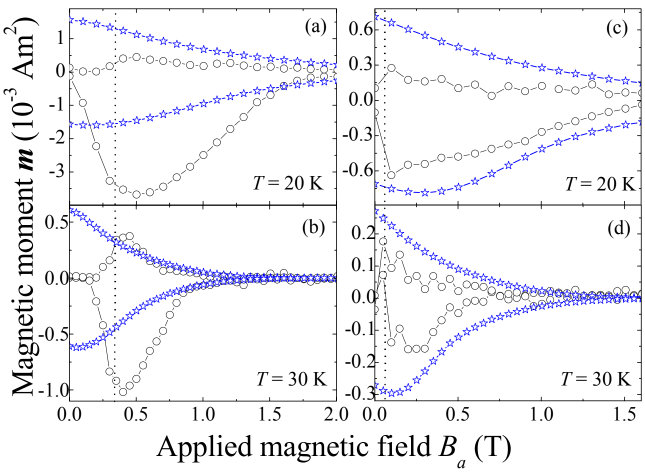

Fig. 1. Magnetization curves of the Fe-sheathed and bare wires for the transverse (a,b) and longitudinal (c,d) field orientations at different temperatures. The curve legend is given in the text.

The so-obtained magneti-zation curves are exhibited in Fig. 1 for the magnetic field applied perpendicular (Fig. 1 (a,b)) and parallel (Fig. 1 (c,d)) to the cylindrical axis of the round wire at T = 20 and 30 K. Every graph for each temperature contains curves measured under the following conditions. Field-cooled magneti-zation loops, starting at B_a = 5 T swept to –5 T and then back to 5 T, for the Fe-sheathed wire are plotted by open circles. Due to the inverse symmetry of the curves with respect to the m-axis, only the first and fourth quadrants for the positive applied field are shown. In order to visualize directly the influence of the Fe-sheath on the electromagnetic properties of the superconductor, we carried out the same measurements for the bare wire obtained after removal of the sheath from the same sample. Note that the direct comparison is valid since the superconducting volume of the sample remained unchanged. These results are plotted by open star symbols.

Strikingly, one finds numerous discrepancies between the magnetization behaviour of the Fe-sheathed and bare wires. Obviously, these discrepancies are consequences of the magnetic interactions between the ferromagnetic sheath and the superconducting core. Some of the observed effects have been described in [6]. Here, we just mention that the strongly suppressed magnetisation signal within the magnetic field range $|B_a| \leq B_s$ is due to the magnetic screening of the superconducting core by the highly permeable magnetic sheath [6], which is of the same origin as that described in [7]. B_s (dotted lines in Fig. 1) is the magnetization saturation field of the Fe-sheath. In this paper, we concentrate on the overcritical current state phenomenon observed for the transverse field orientation only (Fig. 1 (a,b)). By the term “overcritical state”, which is the most scientifically interesting and practically important among all the observed phenomena, we imply that the width of the hysteresis loops ΔM (which is known to be directly proportional to J_c) of the sheathed wire is larger than the width of the magnetization loops in the bare wire within a certain range of the applied field.

The main question to be answered in this work is why the sheathed wire can have $J_c^{oc} > J_c$ of the same *stripped* wire. As mentioned above the problem was addressed in [2] for a hard (possessing strong pinning) strip superconductor. The main idea is that for some magnetic configurations, with the most pronounced effect observed for an open convex magnetic cavity, the current profile over the strip can be redistributed so that the current is pushed from the magnetic flux-filled strip edges to the central flux-free part of the strip, resulting in $I^{oc} > I_c$ [2]. However, it was further shown in [2] that the cylindrical magnetic cavity, which can be assumed in our case of the round wire, is a much less favourable configuration for a current enhancing redistribution. Moreover, it can lead to a significant *undesirable* current enhancement at the strip edges if the magnet is brought into direct contact with the strip surface. This resembles the case of the strip placed between magnets parallel to the strip surface [1] and hence eliminates any probability for the occurrence of the overcritical state. This configuration can also be imagined in our case at points A and B in Fig. 2. Thus, one could be quite pessimistic about the realization of an overcritical state in the case of the round wire. Fortunately, experiments carried out on such wires clearly indicated that this state does exist [6] in wires that are ready for practical use. As yet, only one experimental indication of the overcritical state has been recently provided for a strip within the Meissner state [3].

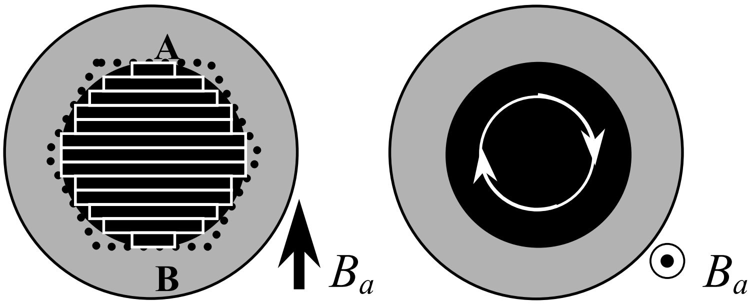

Fig. 2. Electro-magnetic schematics of the sheathed wire cross section in the case of the transverse (left) and longitudinal (right) field orientations. The superconducting core can be approximated as a stack of strips with their own Meissner shielding current confined within ach strip. The dotted line shows a hexagonal approximation of the iron sheath. The white circular arrows denote shielding currents.

To explain the overcritical state for a round wire placed in a cylindrical magnetic environ-ment (Fe-sheath) we constructed a phenomenological model which can be described with a help of the schematic in Fig. 2. In the case of the field applied perpendicular to the wire axis we assume that each Meissner shielding current stream-line flows within a quasi two-dimensional plane. Then, the wire can be considered as a stack of strips [8] tightly packed in the cylindrical cavity. Strips at the top (A) and bottom (B) of the cavity experience the undesirable parallel magnet configuration with only one side exposed to the magnet (Fe-sheath). At the same time these strips shield the centrally situated strips from the parallel magnet influence. The central strips would then experience a similar interaction to that described for the case of the perpendicular magnet configuration, developing a beneficial current enhancing redistribution [1,2]. Moreover, the most central strips can be considered to be placed in a configuration similar to a convex cavity (dotted line in Fig. 2), which was found to be the only one developing large *overcritical* currents in *hard superconductor* strips [2]. The interplay between all the above-mentioned factors is likely to be responsible for the measured overcritical signal in Fig. 1 (a,b).

In the case of the field applied parallel to the wire axis (Fig. 2), no overcritical state is measured in agreement with [2]. In fact, the bare wire J_c is higher than that of the sheathed wire (Fig. 1 (c,d)), which is most probably associated with the negative influence of the magnetic material on the superconductivity. The strongly asymmetrical magnetic history dependent effect observed in Fig. 1 for the magnetization loops of the sheathed wire arises due to the irreversibility induced by pinning. This factor is also well in-line with the predictions for strips in the magnetic environments [2].
In conclusion, we showed that an overcritical current state exists in round superconducting MgB_2 wires sheathed by iron with $J_c^{oc} > J_c$ by a factor of up to 1.6. A phenomenological model has been constructed in order to explain the observed behaviour.

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