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SUPPRESSION OF AC (HYSTERETIC) LOSS BY MAGNETIC SHIELDING OF MgB_2/Fe SUPERCONDUCTORS: THE PSEUDO-MEISSNER EFFECT

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ABSTRACT

The *M-H* loops of MgB_2 materials in bulk sintered form, as well as for PIT wire and tape MgB_2/Fe monofilamentary composites, have been measured at various temperatures. The influence of Fe on the *M-H* loops of the tape and wire are discussed. The normal Fe response is subtracted with the use of *M-H* loops taken above T_c and the remaining magnetization suppression of the MgB_2 is described in terms of field shunting in the Fe "shield". The level of Fe shielding, both of regions outside of the sample from the MgB_2, as well as the MgB_2 from the outside is discussed, the latter is quantified in terms of a ΔB. Using finite element analysis, ΔB is calculated locally for the tape in both FO and EO field orientations (with the field perpendicular to and along the wide side of the tape, respectively) as well as for the wire sample. It is seen that this ΔB effect can be phenomenologically modelled as a pseudo-Meissner effect. Direct measurements of hysteretic loss vs applied field sweep amplitude, H_m, give a pseudo-Meissner field, H_{PS1}, of 2 kOe for the round wire sample in reasonable agreement with calculation. The hysteretic loss above H_{PS1} (and below the penetration field) was found to fit well to an expression proportional to $(H-H_{PS1})^3$. By comparing calculations with and without H_{PS1} it was seen that the Fe sheath significantly reduced the hysteretic loss in externally applied fields for these MgB_2/Fe composites.

INTRODUCTION

In response to a time-varying external magnetic field a bulk superconductor experiences hysteretic loss, which can be reduced if it is surrounded by a magnetic shell or shield. The optimal field-sweep amplitude for AC-shielding will depend on the magnetic properties of the shield (shape and material). If the field is relatively low, the shielding is almost total, and the loss minimal. If the field is higher, the sample is still partially shielded

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from external field, and the loss is suppressed. The values of loss suppression can be quite significant at low and moderate fields, and may be very relevant for the likely applications of MgB_2 (e.g., transmissions lines). By appropriate design of the magnetic circuits, the alternating flux can be mostly confined to Fe paths rather than the superconducting windings themselves. Provided the amplitude of the applied AC field is sufficiently low advantage can be taken of MgB_2's *in-situ* magnetic shield to reduce or eliminate the superconductor's hysteretic loss.

Of course it is possible to quantify this effect by FEM methods or approximate it by analytical expressions. Alternatively, this paper demonstrates that some of the most important aspects of this effect (***on externally applied fields***) can be phenomenologically (and approximately) treated in terms of a simple model where the Fe shell acts as a kind of pseudo-Meissner shielding. The general applicability of this as a heuristic idea can be seen immediately when looking at the loss data generated from these MgB_2/Fe composite samples. First, if the field sweep amplitude, H_m, is less than some critical value, the loss is very near zero. Once this value is exceeded, the loss is similar to what could be expected from a superconductor with a significant Meissner shield – i.e. some portion of the field is shielded from the MgB_2 even at higher fields, leading to reduced loss. Below we more fully develop this model and use it to describe and quantify the shielding, showing both the utility of this simple method, and the effectiveness of the shielding in these composites.

BACKGROUND

Genenko [1] et al. have mathematically modeled the current-carrying states of a superconducting (SC) strip, either entirely flux free (Meissner state) or *partly* penetrated by magnetic flux, in an applied magnetic field and surrounded by a bulk high-permeability medium. In both cases the current distributions in the flux-free regions were very sensitive to the presence of the magnetic medium, depending on the shape of which the total loss-free transport current could be strongly suppressed or enhanced. Glowacki et al. (University of Cambridge IRC Group) have postulated and modelled the reduction of transport AC loss in multifilamentary (MF) SC tapes in which the filaments were coated by magnetic material [2-6]. The transport self-field AC loss of a monocore imbedded in a high-permeability medium depends strongly on its cross-sectional shape. If the cross section is circular, the transport AC loss is unaffected by the presence of the magnetic surrounding, while if elliptical an increase in loss up to one order of magnitude can be expected, depending on aspect ratio. In the case of MF strands large decreases in self-field AC loss can be expected as individual high-permeability coatings magnetically decouple the filaments. According to the Cambridge Group the magnetic self-field shielding principle is quite general and applicable to both high-T_C and low-T_C MF superconductors [4]. So far these ideas for the reduction of transport self-field loss do not seem to have been implemented in any practical way with respect to either high-T_C or low-T_C strand or, the subsequently discovered new intermediate-T_C superconductor MgB_2. But, equally important to practical applications of superconductors are hysteretic, eddy-current, and interstrand coupling loss, in the presence of an AC external field. The present study focuses primarily on hysteretic loss, but many of the same principles can be expected to apply to these other areas as well.

Since Fe or low-alloy steels seem necessary primary cladding materials for the powder-in-tube processing of MgB_2 strand, both from the standpoints of mechanical-and chemical-compatibility, the resulting wires automatically become ideal candidates upon which to explore and exploit the principles of magnetic shielding. In a collaboration between The Ohio State University (OSU) and the University of Wollongong (UoW), Australia, transition temperature, T_c, critical current density, J_c, and magnetic hysteresis (*M-H*-loop) measurements have been used to study the magnetic shielding effects in aspected Fe-clad tape [7]. This study represents a further focus on the magnetic hysteresis properties.

EXPERIMENTAL

Sample Preparation

Standard powder-in-tube methods were used for fabricating the Fe clad MgB_2 tape. The pure Fe tube had an outside diameter (OD) of 10 mm, a wall thickness of 1 mm, and was 10 cm long. One end of the tube was sealed, and the tube was filled in with magnesium (99% purity) and amorphous boron (99%) with the stoichiometry of MgB_2. The remaining end was crimped by hand. The composite was drawn to a 2-3 mm diameter rod 2 meters long, with the drawing followed by subsequent cold rolling to ribbon over many steps. Several short samples 2 cm in length were cut from the ribbon. These pieces were then sintered in a tube furnace over a temperature range from 600-1000°C for 1-48 h. A high purity argon gas flow was maintained throughout the sintering process. The mass loss after sintering is very small, less than 1%. The sample measured here (denoted tape) had dimensions 1.5 x 0.21 x .0063 cm. We also measured a round wire, (denoted wire), the sample was 1.5 cm long and had a 0.77 mm radius. For comparison a sintered MgB_2 (denoted bulk) sample with no sheath was prepared with dimensions 0.35 x 0.65 x 0.174 cm.

Measurements

Using the vibrating sample magnetometer magnetization, *M*, measurements were made at a sample temperature of 15 K (sufficiently high to avert flux jumping) with gradually increasing field-sweep amplitudes, H_m -- from 0 to 17 kOe. This series of measurements was repeated at 40 K, just above the T_c of MgB_2, in a measurement of *M-H* for the Fe sheath itself. Subtraction of $M\text{-}H_{Fe}$ from $M\text{-}H_{wire}$ led to the as-externally-measured loss per cycle, Q_h, of the superconducting core as a function of H_m.

RESULTS AND DISCUSSION

M-H measurements were made on the bulk sample with the field applied along the 0.174 cm side. The results are shown in FIG 1 at 15, 25, and 30 K; the results are "typical" for a bulk, sintered superconductor of good quality. On the other hand the wire gave quite different results, as shown in FIG 2. Some consideration makes it clear that the strange shape of the loop is due to the Fe contribution. In order to subtract this contribution, we measured the M-H at 40 – just above the T_c of the MgB_2. The result of this electronic subtraction are shown in FIGs 2 and 3. However, the loop so revealed still has a strange suppression of the magnetization at low fields (a low field "bite"). This is due to the fact that while at high fields the Fe shields the SC from the outside field, at high fields the outside is shielded from the SC. That is, the field lines are "shorted" through the Fe and do not result in emanating field lines (see FIG 4). FIG 4 represents the results of a calculation of flux density for a Bean-state superconductor in the trapping mode, with no applied field, surrounded by Fe, illustrating this effect. We note that we must be cautious before attempting to deduce the superconductor's local response from the VSM results. The magnetic response measured by the instrument's pick-up coils is viewed again through the magnetic shield

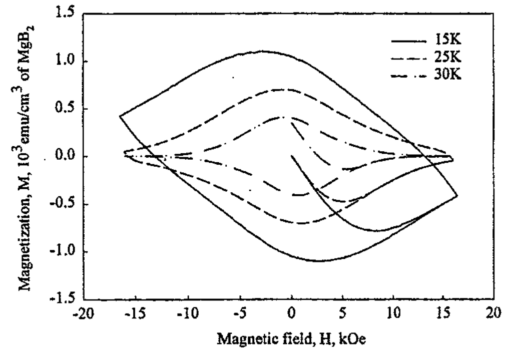

FIGURE 1. *M-H* for bulk MgB_2 sample at various temperatures.

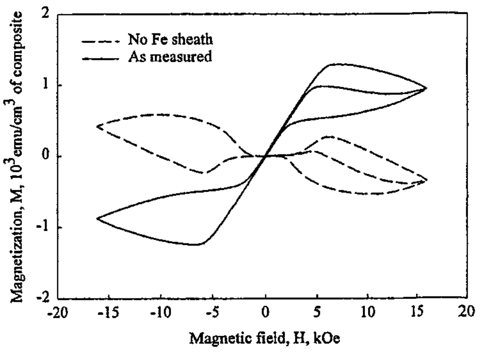

FIGURE 2. *M-H* for round wire sample at T = 15 K.

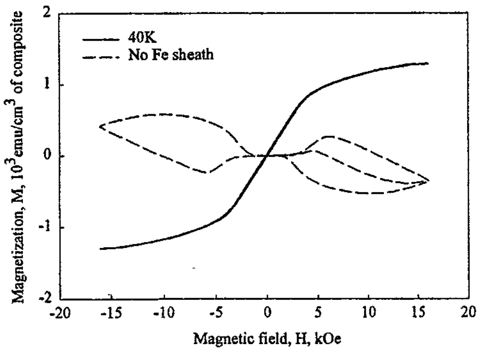

FIGURE 3. *M-H* loops for Fe (wire sample at 40 K), and 15 K result with Fe subtracted.

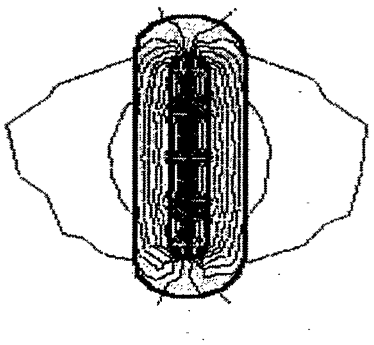

FIGURE 4. Field diagram for Bean state SC with Fe shield at zero applied field.

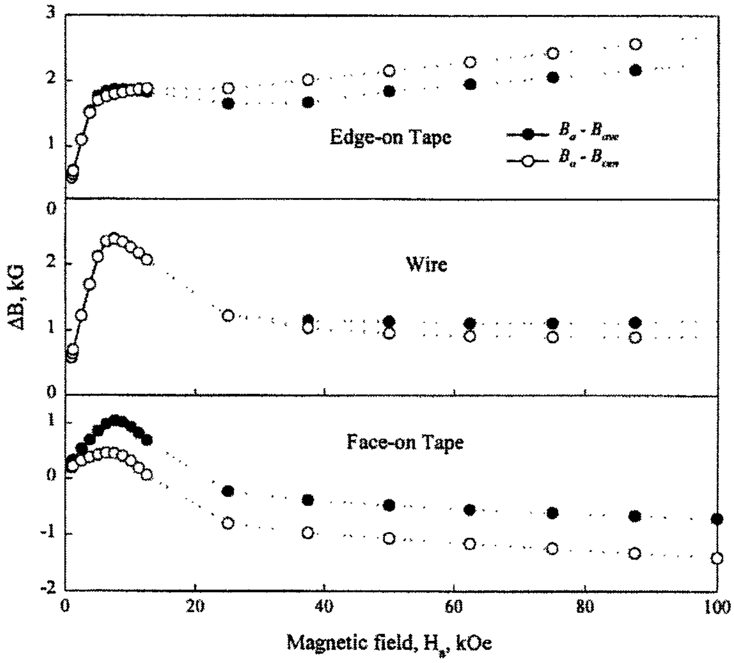

FIGURE 5. FEM results for EO, FO, and round wire geometry showing ΔB, the difference between the inside and outside field as a function of applied field.

Now let us go back to the initial question and look at how the Fe affects the externally applied field. FIG. 5 is an FEM calculation of the shielding due to the Fe. It calculates the average field and the field at the center for a rectangular sample in EO and FO orientations as well as that for a round sample. The actual sample dimensions are the dimensions of our tape sample, and the Fe M-H loop is the measured loop of our tape sample EO. Here we have set the μ of the MgB_2 region to 1 in order to obtain the field *that will be applied* to the MgB_2. In the case of the EO tape, the shielding rises quickly and saturates to a relatively constant value – very much like the influence of a Meissner shield. For the FO sample and the wire, the results are similar, except that there is a maximum in the shielding near the saturation, and a significant drop in the shielding field before the plateau is reached. FIG 6 shows FEM

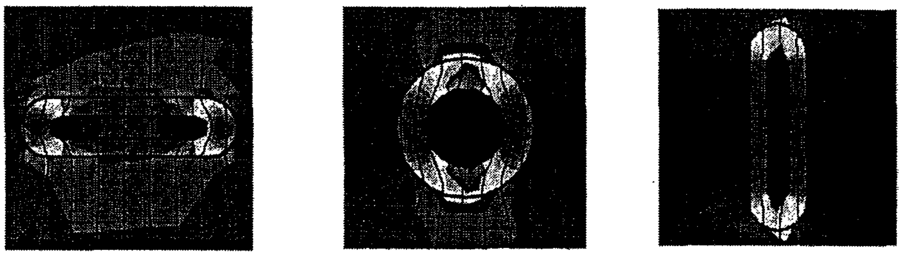

FIGURE 6. FEM field distributions for EO, FO, and round wires with H = 10 kOe. Lines and shading represent B-intensity.

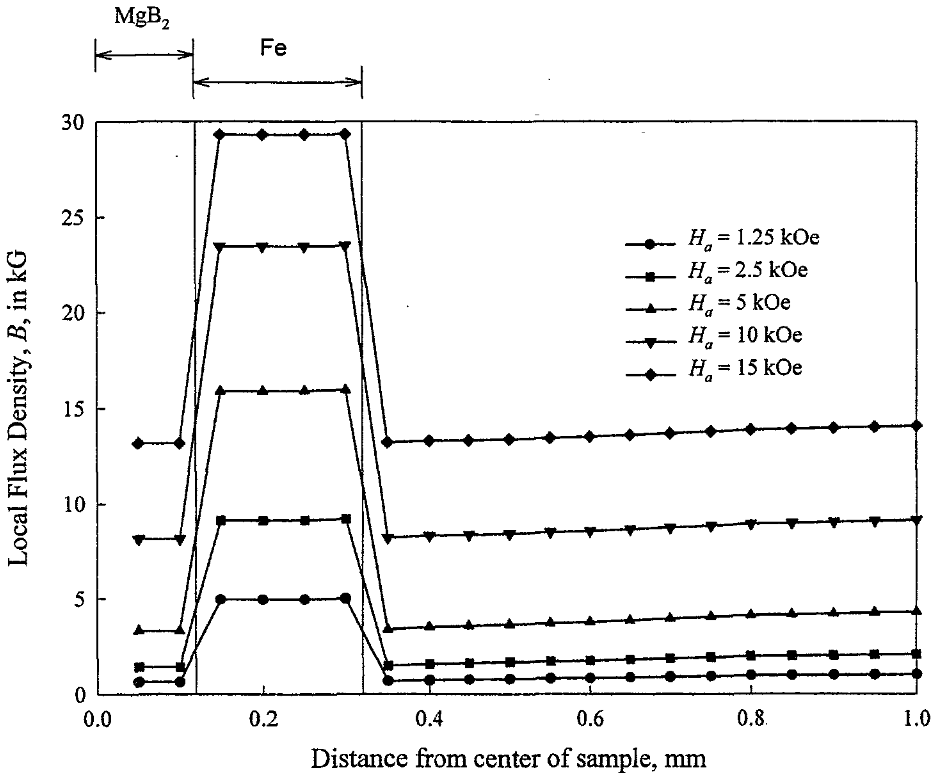

FIGURE 7. B-field distribution within the Fe and the MgB_2 regions at various applied fields for the tape sample in the EO orientation.

diagrams for these three situations at an applied field of 10 kOe. FIG 7 shows the calculated field distributions within the MgB_2 and the Fe. The small level of B-variation across the sample in FIG 7 and the moderate difference between the average and center ΔB values in FIG 5 argue for a spatial variation of B within the MgB_2 volume which can be treated as zero to a first order approximation. From these results we can argue that the Fe acts as an effective Meissner shield, although FIG 7 makes it again clear that the Fe does this by pulling field in rather than repelling it. Nevertheless, this will act to effectively shield the superconductor.

Measurement of Pseudo-Meissner H_{PSI}

FIG 8 shows the loss results for the round wire sample measured at T=15 K as a function of applied field. It is reasonable to assign a "pseudo H_{C1}" value of 2 kOe to this shield. We note that this is much larger than the actual H_{C1} for MgB_2, and is therefor certainly due to the Fe. As can be seen from FIG 8, the loss below H_{PSI} is essentially zero, as would be expected.

Reduced Loss Above H_{PSI}

If we can in fact treat the shielding effect in this way, then the loss at higher fields (above H_{PSI}) should be suppressed. We will look at the region below full field penetration, were the loss should fit

$$Q_h = \frac{10}{3\pi J_c R_0}(H_m - H_{PS1})^3 . \tag{1}$$

The units here are cgs-practical, with loss in erg/cm^3 per cycle, H in Oe, and J_C in A/cm^2. This

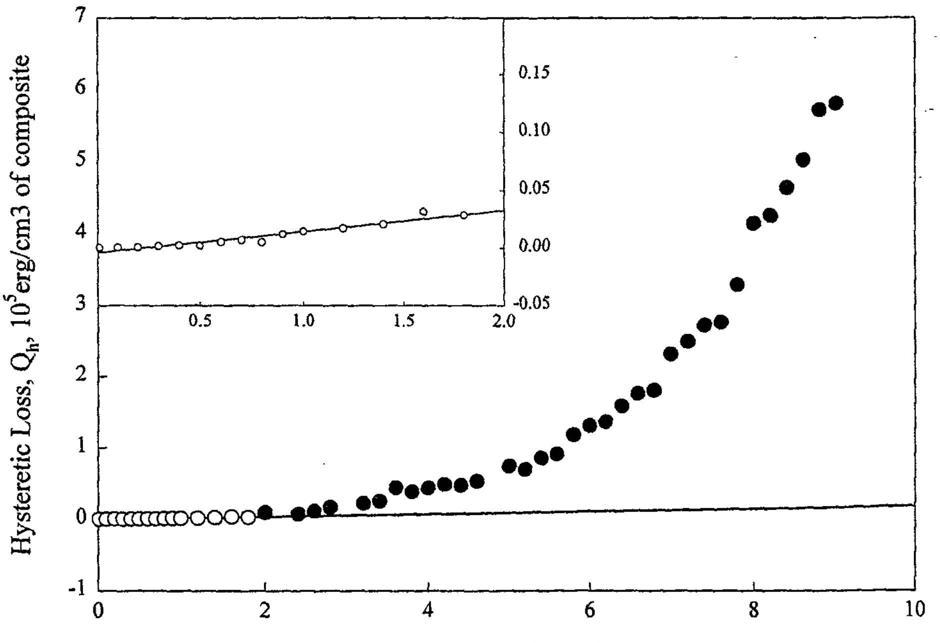

FIGURE 8. Q vs H_m for wire sample showing loss suppressed below a pseudo-Meissner H_{PSI} field.

SUMMARY AND CONCLUSIONS

The *M-H* loops of MgB_2 materials in bulk sintered form, as well as for PIT wire and tape MgB_2/Fe monofilamentary composites, were measured at various temperatures. The influence of Fe on the *M-H* loops of the tape and wire were discussed. The normal Fe response was subtracted with the use of *M-H* loops taken above T_c and the remaining magnetization suppression of the MgB_2 was described in terms of field shunting in the Fe "shield". The level of Fe shielding, both of regions outside of the sample from the MgB_2, as well as the MgB_2 from the outside was discussed, the latter was quantified in terms of a ΔB. Using finite element analysis, ΔB was calculated locally for the tape in both FO and EO field orientations (with the field perpendicular to and along the wide side of the tape, respectively) as well as for the wire sample. It was seen that this ΔB effect could be phenomenologically modelled as a pseudo-Meissner effect. Direct measurements of hysteretic loss vs applied field sweep amplitude, H_m, gave a pseudo-Meissner field, H_{PS1}, of 2 kOe for the round wire sample in reasonable agreement with calculation. The hysteretic loss above H_{PS1} (and below the penetration field) was found to fit well to an expression proportional to $(H-H_{PS1})^3$. By comparing calculations with and without H_{PS1} it was seen that the Fe sheath significantly reduced the hysteretic loss in externally applied fields for these MgB_2/Fe composites.

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