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New Method for the Fabrication of Al-Stabilized Fe/MgB_2 Wires

A. V. Shcherbakov, A. V. Pan, S. X. Dou, and E. W. Collings

***Abstract*—To employ Al stabilizer on Fe sheathed MgB_2 wire the hot aluminizing technique was used. The present technique allows us to form MgB_2 superconductor by an *in-situ* reaction technique and apply Al stabilizer simultaneously, because the processing temperature of MgB_2 is similar to the melting temperature of Al. Two types of Fe sheathed MgB_2 wires—"reacted" and "green" (unreacted)—were immersed in an Al bath to produce a layer of Al stabilizer on the surface of the superconductor. The magnetic and transport $J_c(B_a)$ curves for both "reacted" and "green" Al/Fe-sheathed wires have been measured at 10 and 20 K and showed the same trend. The concept of Al stabilized Fe/MgB_2 coil fabrication is discussed.**

***Index Terms*—Aluminum stabilized superconductor, fabrication method, hot aluminizing, *in-situ* Fe/MgB_2.**

I. Introduction

SINCE the discovery of superconductivity in MgB_2 [1], this material has been produced in different forms—bulk, tapes and wires. For practical application of superconductors, wires and tapes with high critical current are necessary. Considerable work has been done to investigate and optimize the properties of MgB_2 wires and tapes with different sheath materials such as Ag, Cu, Monel, Ni, Nb, Stainless Steel and Fe (see for example [2]–[10] and references therein). Chemical compatibility with MgB_2, high hardness, low specific weight, and the low price of Fe make it the most suitable sheath material for fabrication of long length MgB_2 wires and tapes. For instance, a critical current density as high as $5 \times 10^5\ \mathrm{A/cm^2}$ at 20 K and 0 T has been achieved in Fe sheathed MgB_2 wire [11]. However, Fe creates a low thermal conductivity barrier for heat sinking to the cryogen bath or cryocooler. This can result in thermomagnetic instability [12] and trigger the transition from the superconducting to the normal state in superconducting coils at high currents due to avalanche-like heat release.

It is well known that one of the most important goals for practical large current applications of the wires/coils is good thermal stabilization. To minimize thermomagnetic instability in superconducting MgB_2 wires sheathed in iron, a normal metal with high electrical and thermal conductivity, such as Cu or Al, can be used for stabilization. It has been long recognized that high purity aluminum offers several potential advantages in the stabilization of superconductors. Specifically, aluminum is commercially available with a residual resistance ratio (RRR) in excess of 2500, compared to a maximum of approximately 200 for copper. The magnetoresistance of aluminum also saturates rather quickly, so that the specific resistivity of RRR 2500 aluminum is approximately 1/20 that of RRR 200 copper at 12 T. Aluminum also offers well recognized weight and radiation transparency advantages [13], [14]. Attempts to employ Al stabilizer with LTS superconductors such as NbTi and Nb_3Sn were successful, and these results can be found in the literature (see for example [15]–[18] and references therein). In case of MgB_2, however, direct employment of Al for fabrication of Al-sheathed MgB_2 wire by the *in-situ* process will result in serious damage or even loss of superconductivity in case of a reaction between the Al and the unreacted Mg $+2$B powder during the sintering process [20], [21]. On the other hand, the $J_c(B_a)$ performance of Al/MgB_2 *ex-situ* wires will not be high enough, due to the low mechanical strength of the Al (see for example [22] and references therein). Different approaches to the production of Al-stabilized/sheathed MgB_2 wires/tapes with reasonably high $J_c(B_a)$ performance can be found elsewhere [22], [23].

To overcome the problems in the fabrication of Al-stabilized MgB_2 wires that were mentioned above, we have employed the hot aluminizing technique [24]. The present technique allows us to apply Al stabilizer to a completely fabricated and optimized Fe/MgB_2 composite. In this case, Fe plays the role of a barrier preventing diffusion of Al into MgB_2. In addition, the high toughness of Fe enables us to produce a reasonably high-density MgB_2 superconducting core. Furthermore, the hot aluminizing technique can be modified to the simultaneous process of fabrication of Al stabilized wires/coils and *in-situ* MgB_2 formation because the processing temperature of *in-situ* MgB_2 formation (650 $^\circ$C) is similar to melting temperature of Al (660 $^\circ$C) [25]. This process is very attractive for the construction of MgB_2 superconducting magnets. In this paper, we report the first results on simultaneous fabrication of *in-situ* Fe/MgB_2 wire and coating this Fe/MgB_2 wire with an Al-layer for stabilization purposes.

II. Experimental Procedure

Fe-sheathed MgB_2 wire has been fabricated using the *in-situ* process and the standard PIT method. An Fe tube with an outer diameter (OD) of 10 mm and a wall thickness of 1 mm was filled with a mixture of pure Mg (99%) and amorphous B (99%) with

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the stoichiometry of MgB_2. The composite was drawn to an OD of 1.4 mm. Several short samples were sintered in a tube furnace at 750 °C for 30 min in flowing high purity argon to prevent oxidation. The resultant Fe/MgB_2 with no Al is referred to below as the reference sample. After completing the heat treatment process, the surface of the reacted Fe/MgB_2 wires was plated with Al using the hot aluminizing technique. Short samples of reacted Fe/MgB_2 wire were immersed for 3 min in a molten Al bath kept at a temperature of 750 °C under flowing high purity argon. After coating, the sample had an OD of 1.32 ±0.05 mm. These samples are denoted as the "reacted" Al/Fe/MgB_2 in the text. To investigate the possibility of a simultaneous process for Al plating and *in-situ* MgB_2 formation, short samples of unreacted Fe/MgB_2 wire were immersed for 5 to 30 min in a molten Al bath kept at a temperature of 670 or 770 °C under flowing high purity argon. These samples are denoted as the "green" Al/Fe/MgB_2 in the text.

The phase investigation was performed with the help of an x-ray diffractometer with CuKα radiation. The magnetization loops for the Fe and Al/Fe sheathed MgB_2 wires were measured at 10 and 20 K using a Physical Property Measurement System (PPMS, Quantum Design) with a magnetic field applied perpendicular to the wire long axis. As there is a large sample size effect on the magnetic J_c for MgB_2 fabricated by the reaction *in-situ* process [26], all of the samples for measurement were shaped to the same length of 3.4 mm for comparison. The magnetic J_c was derived from the width of the magnetization loop using Bean's model. The transport J_c was measured with the four-probe method using a pulsed current source. This technique is described in details in [27]. The voltage contacts were attached directly onto the Al surface with Sn-9%Zn solder.

III. Results and Discussion

Fig. 1 shows XRD patterns for the core of the "green" Al/Fe/MgB_2 samples after immersing unreacted Fe/MgB_2 wire in an Al bath kept at a temperature of 670 °C for 5, 15 and 30 min and at a temperature of 770 °C for 5 and 10 min. As can be seen, at lower temperature (670 °C) the reaction between Mg and B could be achieved after 30 min. Only a small peak of unreacted magnesium could be found. For the higher temperature Al bath (770 °C), the *in-situ* reaction of MgB_2 formation was fully completed in 10 min. A small peak of MgO could be found in all the samples studied. It is to be noted that there is no evidence of any reaction between Al and MgB_2 after the aluminizing routine, indicating the good properties of Fe as a barrier.

SEM investigation of the Al/Fe/MgB_2 wire cross section showed a continuous coating of the Fe sheathed MgB_2 wire with ∼ 10 μm thin Al layer (Fig. 2 and Fig. 3). A diffusion layer of Al_3Fe alloy had a thickness of about 9 μm at the Al/Fe interface. This diffusion alloy layer indicates good connectivity between the two materials (Fe and Al). It is worth noting that as a result of the hot aluminizing procedure the thickness of the Fe barrier was slightly reduced compared to the Fe/MgB_2 sample due to the reaction between Fe and Al. Increasing the Al bath temperature or time of exposure in hot Al resulted in a further reduction of the Fe barrier thickness (Fig. 3). This is beneficial in case of wire stabilization. As was discussed above, Fe has

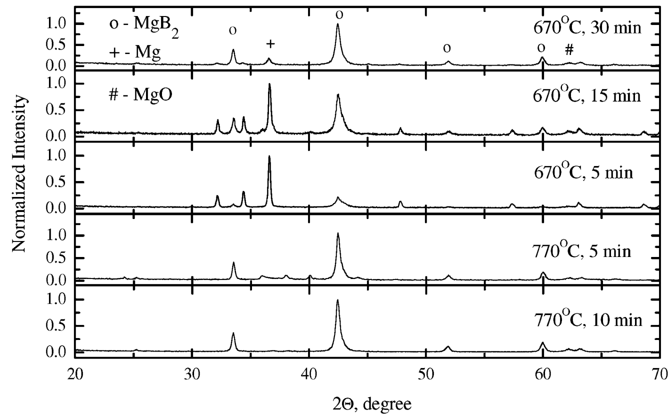

Fig. 1. X-ray diffraction patterns for the "green" MgB_2/Fe wire samples immersed in an Al bath at 670 °C for 5, 15 and 30 min and at 770 °C for 5 and 10 min.

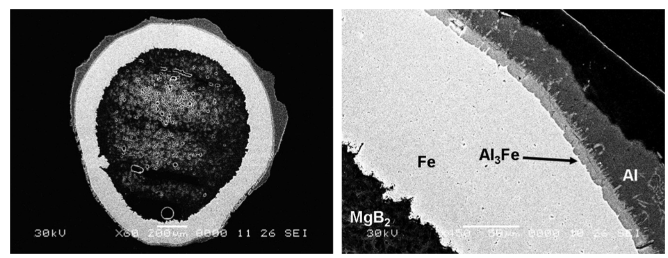

Fig. 2. SEM images of the "reacted" Al/Fe/MgB_2.

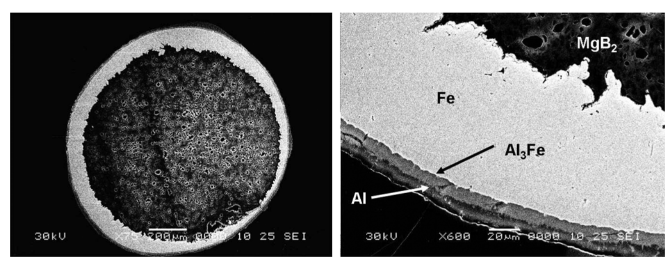

Fig. 3. SEM images of the "green" Fe/MgB_2 wire sample immersed for 10 min in an Al bath kept at 770 °C.

undesirably low thermal conductivity. On the other hand, the Fe barrier should prevent the diffusion of Al into the MgB_2 core that may cause severe damage to the superconductor. The formation of the diffusion Al_3Fe alloy may set limits to the desirable Fe barrier thickness and sintering parameters for the hot aluminizing process.

Fig. 4 shows the magnetic J_c values for the reference Fe/MgB_2, as well as for the "reacted" and "green" Al/Fe/MgB_2 wires with the magnetic field applied perpendicular to the wire long axis. For MgB_2 with the sole Fe-sheath and "reacted" Al/Fe/MgB_2 wire samples magnetic J_c values are similar over the entire range of temperatures and fields measured, although the former is slightly higher than the latter. It is worth noting that the Fe-sheathed MgB_2 wire exhibited more strongly pronounced flux-jump behavior in the low field region (0–2 T) compared to the Al-stabilized MgB_2 wire at 10 K. On the other hand, similar magnetic $J_c(B_a)$ performance indicates that the hot aluminizing process did not affect the properties of the MgB_2 superconducting core. This is a significant advantage of

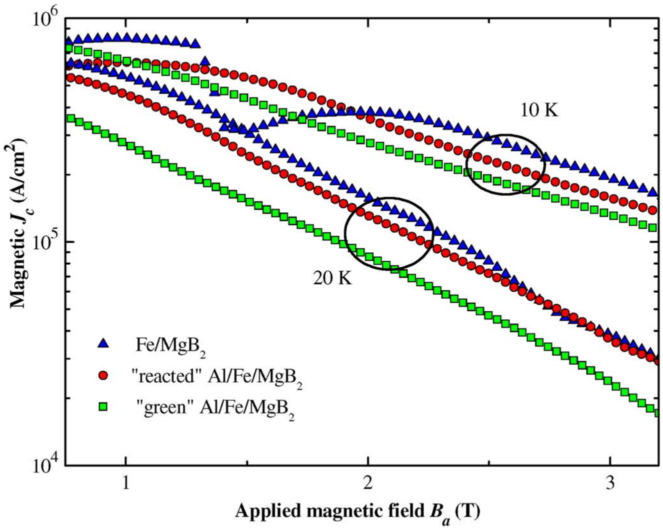

Fig. 4. Magnetic $J_c(B_a)$ curves at 10 K and 20 K for the reference Fe/MgB$_2$, and for the "reacted" and "green" Al/Fe/MgB$_2$ wires. The "green" Al/Fe/MgB$_2$ wire was reacted in an molten Al bath kept at 670 °C for 30 min.

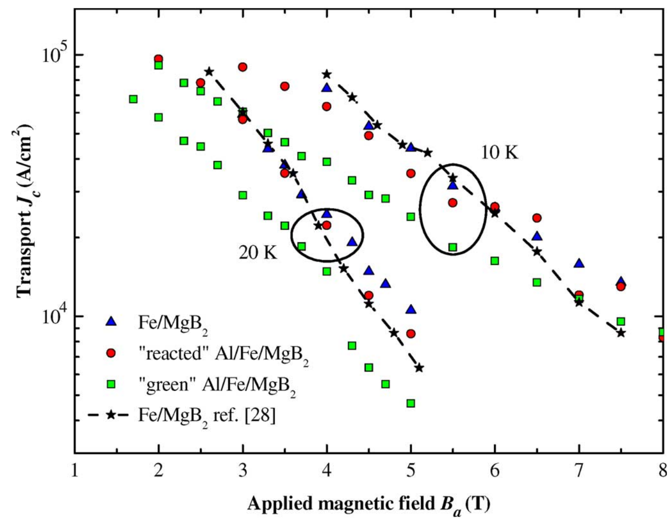

Fig. 5. Transport $J_c(B_a)$ of sole Fe/MgB$_2$, and the "reacted" and "green" Al/Fe-MgB$_2$ wires. The "green" Al/Fe/MgB$_2$ wire was reacted in an molten Al bath kept at 670 °C for 30 min.

the aluminizing process, which turns out to be a non-destructive approach to thermomagnetic stabilization.

As can be seen from Fig. 4, Al-coating of the Fe-sheathed MgB$_2$ wires results in better thermomagnetic stabilization at 10 K. Further improvement of stabilization at temperatures below 10 K can be achieved by increasing the Al to superconductor ratio, decreasing the thickness of the Fe barrier, and reduction of the Fe/MgB$_2$ wire diameter.

It is to be noted that "green" Al/Fe/MgB$_2$ wire showed a similar trend in the magnetic $J_c(B_a)$ curve to the reference Fe/MgB$_2$ and the "reacted" Al/Fe/MgB$_2$ wire, although the $J_c(B_a)$ values are slightly lower (Fig. 4). At this stage, J_c values of 3.6×10^4 and 2.3×10^4 $\mathrm{A/cm^2}$ have been reached at 20 K and 3 T for the "reacted" and "green" Al/Fe/MgB$_2$ wires, respectively. These results are in agreement with those for Fe/MgB$_2$ wires reported by other groups [6], [10].

The transport $J_c(B_a)$ values of the reference Fe/MgB$_2$, and the "reacted" and "green" Al/Fe/MgB$_2$ wires are presented in Fig. 5. The $J_c(B_a)$ curves nearly coincide for Fe-sheathed $\mathrm{MgB_2}$ and "reacted" Al/Fe-sheathed MgB$_2$ wires at $\mathrm{B}_a > 4$ T at 10 K, as well as at $\mathrm{B}_a > 3.3$ T at 20 K. The transport J_c values of "reacted" Al/Fe/MgB$_2$ wire are in agreement with previous results on Fe/MgB$_2$ [5], [7], [28] results, included for comparison in Fig. 5. As can be seen, at 20 K and 3 T the J_c values reached 3.7×10^4, 3.6×10^4 and 2.2×10^4 $\mathrm{A/cm^2}$ for sole Fe/MgB$_2$, and the "reacted" and "green" Al/Fe/MgB$_2$ wires, respectively.

It is expected that the application of the hot aluminizing technique can be further improved by optimization of the melt-processing temperature and dipping time, Fe sheath thickness, and other parameters. Moreover, the aluminizing technique, which is demonstrated in this work for Fe/MgB$_2$ wires, can be further extended to fabrication of Al-stabilized Fe/MgB$_2$ coils. We expect that a coil with a wound Fe-sheathed MgB$_2$ "green" wire, can be heated up to the MgB$_2$ reaction temperature. While the reaction is complete or in process, the spool can be immersed in a molten Al bath and cooled down. It is obvious that this dual process of *in-situ* MgB$_2$ formation and coating of Fe/MgB$_2$ wire/coil by Al will simplify the coil fabrication and markedly improve the cost feasibility of the MgB$_2$ conductor applications. In addition, Al/Fe/MgB$_2$ conductors mainly made up of low-density components will be advantageous for airborne, aerospace, and other applications where weight is an important issue.

IV. Conclusion

In summary, we have demonstrated a new approach for simultaneous (i) fabrication of *in-situ* Fe/MgB$_2$ wires and (ii) coating with the Al stabilizer. The transport critical current density of thus-fabricated Al/Fe/MgB$_2$ wire achieved the level of 2.2×10^4 $\mathrm{A/cm^2}$ at 20 K and 3.5 T, which is only slightly lower than $J_c = 3.7 \times 10^4$ $\mathrm{A/cm^2}$ of the reference Fe/MgB$_2$ sample. The magnetic measurements show that the Al layer stabilizes the Fe/MgB$_2$ wires in the lower field region at measured temperature range. This method can be easily extended to the production of coils, resulting in reduction of fabrication time and cost of MgB$_2$ conductor products due to eliminating one processing stage. The light weight of most elements in the Al/Fe/MgB$_2$ system pave the way for possible use of this superconductor in various applications where weight is a crucial parameter.

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