Architecture and Transport Properties of Multifilamentary MgB$_2$ Strands for MRI and Low AC Loss Applications

F. Wan, M. D. Sumption, M. A. Rindfleisch, M. J. Tomsic, and E. W. Collings

Abstract—Standard in-situ type MgB$_2$ strands manufactured by Hyper Tech Inc have 19 – 36 subelements, a monel outer sheath, and a Cu interfilamentary matrix. Typical transport $I_c$s of the strands are 2×10$^5$ A/cm$^2$ with $n$-values of 20 – 30 at 4.2 K and 5 T. This work introduces two new MgB$_2$ conductor designs. First, a new class of MgB$_2$ strand is designed for magnetic resonance imaging applications. This type has a higher Cu content designed to enhance protection of a magnet wound with it, and a larger diameter to increase the critical current. Second, a new class of low AC loss MgB$_2$ strand with high filament count and a high resistance matrix is discussed. Transport properties at 4.2 K and fields up to 10 T are reported. Optical techniques are used to study the macro- and micro-structures of these MgB$_2$ strands.

Index Terms—MgB$_2$ strand, magnetic resonance imaging, low AC loss conductor, critical current density, strand design.

I. INTRODUCTION

MAGNESIUM DIBORIDE is a promising superconductor for practical applications because of its transition temperature, $T_c$ of 40 K [1] and low cost. One application is the magnet of a magnetic resonance imaging system (MRI). Compared to NbTi which has been widely utilized in MRI magnets, MgB$_2$ can greatly improve the stability of the MRI magnet due to the moderately high $T_c$ [1]-[5]. In previous years, Hypertech Research Inc (HTR) and the Ohio State University have significantly improved the $I_c$ and $n$-value of the MgB$_2$ wires. Typical $I_c$ values of in-situ MgB$_2$ wires fabricated by HTR are 1×10$^5$ A/cm$^2$ at 4.2 K, 5 T and even 1×10$^5$ A/cm$^2$ at 4.2 K, 7 T [6]. Because the superconducting wire for an MRI magnet requires a much higher level of electrical stabilization and protection to operate in a helium free environment, we increased the volume fraction of Cu from 15% to 31% and decreased the subelement number from 36 to 18.

For practical superconducting applications, there is also interest in AC-loss reduction by the introduction of a resistive matrix and by twisting the multifilamentary strand [7]. However, the twisting process has the potential to introduce defects and suppress the $I_c$ [8]-[13] and the $n$-value. But Yuan et al., reported that HTR has developed high filament MgB$_2$ strands which can tolerate substantial pre-reaction twisting; for example, powder-in-tube MgB$_2$ strands with 54 filaments and 10-100 mm twist pitch did not exhibit any $I_c$ suppression at 4.2 K [13]. In this paper, we further decreased the twist pitch of MgB$_2$ strands to 5 mm and simultaneously increased the filament count to 114 in order to study the influence of the twisting process on the transport properties of multifilamentary MgB$_2$ strands.

On the path towards a high quality MgB$_2$, B powder is considered as a significant factor. One type of B powder used by HTR is fabricated by Specialty Materials Inc (SMI). The formation of SMI B powder is based on the reaction between BCl$_3$ and H$_2$ gases [14]. In addition, gaseous CH$_4$ is mixed with BCl$_3$ and H$_2$ for carbon doping [14]. Recently, HTR began to use the B powder from the Pavazyum (PVZ) Chemical Company. The PVZ B powder is formed by decomposing B$_2$H$_6$ gas [14]. This paper also describes the relative transport properties of powder-in-tube MgB$_2$ strands with SMI B and PVZ B.

II. EXPERIMENTAL

A. Samples

The multifilamentary MgB$_2$ strands used in this research (Table I and Table II) were manufactured and provided by HTR. All of the MgB$_2$ wires were heat-treated in a tube furnace and furnace-cooled. The soak temperature and heat treatment time were 675 °C and 60 min for standard and MRI wires; the MgB$_2$ low AC loss wires were heat treated at 650 °C/60 min.

B. Measurement of MgB$_2$ Wires

The transport $I_c$ and $n$-value were measured in pool boiling liquid helium in transverse magnetic fields up to 10 T. The voltage criterion of $I_c$ and $n$-value measurements was 1.0 μV/cm. The “standard” and MRI type wires were measured on ITER barrels [15]. For such a measurement, a 1 m-long MgB$_2$ wire was helically wrapped along a 9-turn groove in a Ti-Al-V alloy cylinder 30 mm in diameter and the ends of the wire were soldered to the Cu caps of the alloy cylinder [6], [15], [16]. The separation of the voltage taps of each “standard” or MRI type wire was 500 mm. The 50 cm-long low AC loss wires (LAL 1-3) were measured in a short-sample holder. For low AC loss wire, the gauge length of voltage taps was 4 or 5 mm.

III. RESULTS AND DISCUSSION

A. Transport $I_c$ and n-Value of Standard MgB$_2$ Strands

The strand ST 1, ST 2, STT 1 and STT 2 were filled with the SMI B with 2.0% C doping and the SPVZ series wire...
(SPVZ 1) was filled with 2.5% C doped PVZ B powder. The $J_c$ and $n$-values of the standard MgB$_2$ wires are shown in Fig. 1 and Fig. 2, respectively. It can be seen that the transport $J_c$ and $n$-value at 5 T and 4.2 K of strand ST 1 are $1.77 \times 10^5$ A/cm$^2$ and 27, respectively, which are the best $J_c$ and $n$-value of the ST-series wires. Fig. 3(a) shows the transverse cross sectional area of the sample ST 1.

### TABLE I: THE STRUCTURE AND CHEMICAL COMPOSITION OF THE STANDARD AND MRI WIRE

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Trace No.</th>
<th>Filament No.</th>
<th>B Source</th>
<th>T.P. (mm)</th>
<th>Cu %</th>
<th>Mg:B %</th>
<th>MgB$_2$ %</th>
<th>Dia. (mm)</th>
<th>H.T. (°C/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ST 1</td>
<td>3613</td>
<td>36</td>
<td>SMI</td>
<td>-</td>
<td>15</td>
<td>1:2</td>
<td>2.0</td>
<td>11.0</td>
<td>0.84</td>
</tr>
<tr>
<td>ST 2</td>
<td>3560</td>
<td>36</td>
<td>SMI</td>
<td>-</td>
<td>15</td>
<td>1:2</td>
<td>2.0</td>
<td>15.6</td>
<td>0.84</td>
</tr>
<tr>
<td>SPVZ 1</td>
<td>3497</td>
<td>36</td>
<td>PVZ</td>
<td>-</td>
<td>15</td>
<td>1:15:2</td>
<td>2.5</td>
<td>16.3</td>
<td>0.84</td>
</tr>
<tr>
<td>STT 1</td>
<td>3560</td>
<td>36</td>
<td>SMI</td>
<td>300</td>
<td>15</td>
<td>1:2</td>
<td>2.0</td>
<td>14.8</td>
<td>1.06</td>
</tr>
<tr>
<td>STT 2</td>
<td>3560</td>
<td>36</td>
<td>SMI</td>
<td>200</td>
<td>15</td>
<td>1:2</td>
<td>2.0</td>
<td>14.8</td>
<td>1.06</td>
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<td>MRI 1</td>
<td>3648</td>
<td>19</td>
<td>SMI</td>
<td>-</td>
<td>31</td>
<td>1:2</td>
<td>2.0</td>
<td>8.7</td>
<td>0.84</td>
</tr>
<tr>
<td>MRI 2</td>
<td>3665</td>
<td>18</td>
<td>SMI</td>
<td>-</td>
<td>31</td>
<td>1:2</td>
<td>2.0</td>
<td>7.6</td>
<td>0.95</td>
</tr>
<tr>
<td>MRI 3</td>
<td>3614</td>
<td>18</td>
<td>SMI</td>
<td>-</td>
<td>31</td>
<td>1:2</td>
<td>2.0</td>
<td>7.5</td>
<td>0.84</td>
</tr>
<tr>
<td>MPVZ 1</td>
<td>3676</td>
<td>18</td>
<td>PVZ</td>
<td>-</td>
<td>31</td>
<td>1:15:2</td>
<td>2.5</td>
<td>10.0</td>
<td>0.95</td>
</tr>
<tr>
<td>MPVZ 2</td>
<td>3619</td>
<td>18</td>
<td>PVZ</td>
<td>-</td>
<td>31</td>
<td>1:15:2</td>
<td>2.5</td>
<td>11.1</td>
<td>0.95</td>
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</table>

### TABLE II: THE STRUCTURE AND CHEMICAL COMPOSITION OF THE LOW AC LOSS WIRE

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Trace No.</th>
<th>Filament No.</th>
<th>B Source</th>
<th>T.P. (mm)</th>
<th>Mg:B %</th>
<th>MgB$_2$ %</th>
<th>d$_{eff}$ (µm)</th>
<th>Dia. (mm)</th>
<th>H.T. (°C/min)</th>
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<tr>
<td>LAL 1</td>
<td>3606</td>
<td>114</td>
<td>SMI</td>
<td>5, 30</td>
<td>1:2</td>
<td>11.2</td>
<td>20</td>
<td>0.60</td>
<td>650/60</td>
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<tr>
<td>LAL 2</td>
<td>3606</td>
<td>114</td>
<td>SMI</td>
<td>5, 50</td>
<td>1:2</td>
<td>13.9</td>
<td>30</td>
<td>0.80</td>
<td>650/60</td>
</tr>
<tr>
<td>LAL 3</td>
<td>3667</td>
<td>114</td>
<td>SMI</td>
<td>5, 30</td>
<td>1:2</td>
<td>12.3</td>
<td>33</td>
<td>1.00</td>
<td>650/60</td>
</tr>
</tbody>
</table>

Sample number for internal purposes, $^b$ SMI: 2% C-doped SMI B, PVZ: 2.5% C-doped PVZ B. $^c$ Twist pitch of MgB$_2$ wire, $^d$ Percentage of Cu in the MgB$_2$ strand, $^e$ Carbon doping level, $^f$ Powder percentage of the MgB$_2$ in the whole strand, $^g$ Effective filament diameter, Note: All MgB$_2$ standard and MRI wires used Nb barrier, monel outer sheath, Cu central filament, and Cu interfilament, while MgB$_2$ low AC loss wire used Nb barrier, Cu10Ni subelement sheath, Cu30Ni outer sheath, Cu10Ni central filament, and Cu interfilament.

![Fig. 1: Field dependence of the transport $J_c$ of the standard MgB$_2$ wires.](image1)

![Fig. 2: Field dependence of the $n$-values of the standard MgB$_2$ wires.](image2)
Compared to the ST series wires, the SPVZ series strand has slightly lower transport \( J_c \)s at all measured magnetic fields. For multifilamentary standard MgB\(_2\) wires, the sample SPVZ 1(Fig. 3(b)) had the best \( n \)-value of all standard strands at 4.2 K in all fields of 4 T to 10 T, although further measurements and statistical analysis would be needed to see if any general conclusion can be made on this point. The ratio of Mg to B for SPVZ series wire is larger than 1:2, which possibly makes the transport properties of the SPVZ series wire different from the ST series wires. The ratio of Mg to B for SPVZ series wire was chosen to be 1.15:2 in order to optimize the transport \( J_c \) of the MgB\(_2\) wires filled with PVZ B according to previous (unreported) studies.

The STT series wires represent the standard MgB\(_2\) wires processed with twisting. Sample STT 1 with 300 mm twist pitch and STT 2 with 200 mm twist pitch are the twisted versions of sample ST 2. The strand STT 2 attained the best \( J_c \) at 6 T and 4.2 K (1.26×10\(^5\) A/cm\(^2\)) of all the standard MgB\(_2\) wires.

MRI MgB\(_2\) wire based on PVZ B powder, exhibited slightly lower transport \( J_c \) than the MRI series wires based on the SMI B in the fields of 7 T to 10 T. But the sample MPVZ 1 (Fig. 6(b)) attained the higher \( n \)-values than the MRI series strands did in fields of 5 T to 9 T and the sample MPVZ 2 attained the best \( n \)-value at 5 T (74) of all the MRI-type MgB\(_2\) wires.

A series of strands for MRI was studied; the \( J_c \)s and \( n \)-values are shown in Fig. 4 and Fig. 5, respectively. The strand MRI 1 attained the best \( J_c \) (2.2 \times 10^5 A/cm\(^2\)) at 5 T and 4.2 K, of all the MgB\(_2\) wires wound with MRI-type strand. Fig. 6(a) shows the transverse cross sectional area of the sample MRI 2. MPVZ series wires (MPVZ 1 and MPVZ 2), which are the MRI MgB\(_2\) wire based on PVZ B powder, exhibited slightly lower transport \( J_c \) than the MRI series wires based on the SMI B in the fields of 7 T to 10 T. But the sample MPVZ 1 (Fig. 6(b)) attained the higher \( n \)-values than the MRI series strands did in fields of 5 T to 9 T and the sample MPVZ 2 attained the best \( n \)-value at 5 T (74) of all the MRI-type MgB\(_2\) wires.
infinity (untwisted). The LAL series strands exhibited no twisting-induced suppression in transport \(J_c\)s at all measured fields. Some strands with a 5 mm twist pitch attained the same or even slightly higher transport \(J_c\)s than the untwisted strands. At 4.2 K and 7 T, all the wires have \(n\)-values larger than 20 except sample LAL 1 with 5 mm twist pitch. However, considerable scatter in the \(n\)-values of the wires is seen. In any case, the transport \(J_c\) of the strands was not degraded by twisting down to 5 mm.

![Fig. 6. Optical image of (a) MRI 2 and (b) MPVZ 1.](image)

![Fig. 7. Optical image of the transverse cross sectional area of the sample LAL 1 with 5 mm twist pitch.](image)

![Fig. 8. Field dependence of transport \(J_c\) for low AC loss wires.](image)

![Fig. 9. Field dependence of \(n\)-value for low AC loss wires.](image)

**IV. CONCLUSION**

A series of in-situ powder-in-tube multifilamentary MgB\(_2\) strands manufactured for general applications and MRI have been studied. The best transport \(J_c\) at 4.2 K and 5 T was \(2.2 \times 10^5\) A/cm\(^2\), obtained by MRI 1 and the best \(n\)-value was 74 at 4.2 K and 5 T obtained by MPVZ 2. MRI MgB\(_2\) strands have attained transport \(J_c\)s and \(n\)-values similar to those of the standard MgB\(_2\) wire and higher Cu content enable the MRI MgB\(_2\) strands to have improved quench protection (or lead to magnets with better quench protection). It seems that the PVZ B is as good as the SMI B for multifilamentary MgB\(_2\) strands. A new class of low loss MgB\(_2\) strands has been demonstrated which has a high filament count, and is capable of very low twist pitch value, with no \(J_c\) degradation.
REFERENCES


