Transport properties of IMD-processed 100 m class 6-filament MgB$_2$ wire and solenoid coil

Dongliang Wang, Yanwei Ma, Xianping Zhang, Da Xu, Chao Yao
Institute of Electrical Engineering, Chinese Academy of Sciences
Outline

1. Introduction of internal Mg diffusion (IMD) processed MgB$_2$ wires

2. C-doped IMD-processed wires with crystalline boron powders
   - Purity of crystalline boron powders
   - Wire diameter

3. 100 m multifilament IMD-processed MgB$_2$ wires
   - Filament configuration
   - Wire diameter
   - $n$ values
   - Uniformity of transport properties

4. IMD-processed MgB$_2$ solenoid coils
   - Specifications of solenoid coils
   - Superconducting properties

5. Summary
## Advantages of MgB₂

- Highest $T_c$ (~40K) among metallic superconductors
- No grain orientation required  
  (Easy to fabricate long tape or wire)
- Low materials cost
- Good mechanical properties
- Light weight material

### Superconducting Specifications of Practical superconductors

<table>
<thead>
<tr>
<th>Material</th>
<th>$T_c$ (K)</th>
<th>Anisotropy</th>
<th>$B_{c2}$ at 4.2 K (T)</th>
<th>$\xi (0)$ (nm)</th>
<th>$\lambda (0)$ (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NbTi</td>
<td>9</td>
<td>Negligible</td>
<td>11-12</td>
<td>4-5</td>
<td>240</td>
</tr>
<tr>
<td>Nb₃Sn</td>
<td>18</td>
<td>Negligible</td>
<td>25-29</td>
<td>3</td>
<td>65</td>
</tr>
<tr>
<td>MgB₂</td>
<td>39</td>
<td>1.5-5</td>
<td>&gt;30</td>
<td>10</td>
<td>50-100</td>
</tr>
<tr>
<td>Bi2223</td>
<td>110</td>
<td>50-200</td>
<td>&gt;100</td>
<td>1.5</td>
<td>150</td>
</tr>
<tr>
<td>YBCO</td>
<td>93</td>
<td>5-7</td>
<td>&gt;100</td>
<td>1.5</td>
<td>150</td>
</tr>
<tr>
<td>IBS-122</td>
<td>38</td>
<td>1-2</td>
<td>&gt;100 (0K)</td>
<td>3</td>
<td>200</td>
</tr>
</tbody>
</table>

### Application area

- 20-30 K
- 1-2 T

---

Invited presentation M2OrF-03 given at CEC-ICMC 2017, July 09-13, 2017, Madison, WI (USA).
Transport properties of PIT wires or tapes (1G)

Effective dopant: $C_{60}$

- Ball milling + C doping
- Cold pressing + $C_4H_6O_5$ doping


- Hot pressing + doping

W. Hassler, *SUST*, 21 (2008) 062001

- Grain connectivity problem?


- $6 \times 10^4$ A/cm² (4.2K & 10T)


Invited presentation M2OrF-03 given at CEC-ICMC 2017, July 09-13, 2017, Madison, WI (USA).
**Jc properties of IMD (or AIMI) wires (2G)**

- **Best Jc of monofilament wire**
  \[1.5 \times 10^5 \text{A/cm}^2 \ (4.2 \text{K} \& 10 \text{T})\]

- **Best Jc of multifilament wire**
  \[10^5 \text{A/cm}^2 \ (4.2 \text{K} \& 10 \text{T})\]

- **Good grain connectivity!**
IMD-processed wires with crystalline B

**Motivation**

The high $J_c$ has been developed using amorphous nano B powders by NIMS and OSU-HTR. Amorphous nano B: expensive and hard to get!

What about the cheap crystalline boron powders: 96% and 99.999% (5NB)?

<table>
<thead>
<tr>
<th>No.</th>
<th>Name</th>
<th>Boron</th>
<th>Process</th>
<th>Doped C (at.%)</th>
<th>Size (mm)</th>
<th>Reaction temperature (°C)</th>
<th>Reaction time (h)</th>
<th>$I_c$ at 4.2 K &amp; 10 T (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>P1</td>
<td>96B</td>
<td>PIT</td>
<td>8</td>
<td>0.55 * 3.8</td>
<td>800</td>
<td>1</td>
<td>4.4</td>
</tr>
<tr>
<td>2</td>
<td>I1</td>
<td>96B</td>
<td>IMD</td>
<td>8</td>
<td>1.75</td>
<td>650</td>
<td>5</td>
<td>31</td>
</tr>
<tr>
<td>3</td>
<td>I2</td>
<td>96B</td>
<td>IMD</td>
<td>8</td>
<td>1.75</td>
<td>700</td>
<td>1</td>
<td>28</td>
</tr>
<tr>
<td>4</td>
<td>I3</td>
<td>96B</td>
<td>IMD</td>
<td>8</td>
<td>1.75</td>
<td>800</td>
<td>1</td>
<td>11.2</td>
</tr>
<tr>
<td>5</td>
<td>P2</td>
<td>5NB</td>
<td>PIT</td>
<td>8</td>
<td>0.55 * 3.8</td>
<td>850</td>
<td>1</td>
<td>113</td>
</tr>
<tr>
<td>6</td>
<td>I4</td>
<td>5NB</td>
<td>IMD</td>
<td>8</td>
<td>1.75</td>
<td>650</td>
<td>5</td>
<td>108</td>
</tr>
<tr>
<td>7</td>
<td>I5</td>
<td>5NB</td>
<td>IMD</td>
<td>8</td>
<td>1.75</td>
<td>700</td>
<td>1</td>
<td>96</td>
</tr>
<tr>
<td>8</td>
<td>I6</td>
<td>5NB</td>
<td>IMD</td>
<td>8</td>
<td>1.75</td>
<td>800</td>
<td>1</td>
<td>—</td>
</tr>
<tr>
<td>9</td>
<td>I7</td>
<td>5NB</td>
<td>IMD</td>
<td>8</td>
<td>1.105</td>
<td>650</td>
<td>3</td>
<td>38.4</td>
</tr>
<tr>
<td>10</td>
<td>I8</td>
<td>5NB</td>
<td>IMD</td>
<td>8</td>
<td>1.105</td>
<td>650</td>
<td>5</td>
<td>52.2</td>
</tr>
<tr>
<td>11</td>
<td>I9</td>
<td>5NB</td>
<td>IMD</td>
<td>8</td>
<td>1.105</td>
<td>700</td>
<td>1</td>
<td>57.6</td>
</tr>
<tr>
<td>12</td>
<td>I10</td>
<td>5NB</td>
<td>IMD</td>
<td>8</td>
<td>0.63</td>
<td>650</td>
<td>3</td>
<td>16.2</td>
</tr>
<tr>
<td>13</td>
<td>I11</td>
<td>5NB</td>
<td>IMD</td>
<td>8</td>
<td>0.63</td>
<td>650</td>
<td>5</td>
<td>16.8</td>
</tr>
<tr>
<td>14</td>
<td>I12</td>
<td>5NB</td>
<td>IMD</td>
<td>8</td>
<td>0.63</td>
<td>700</td>
<td>1</td>
<td>13.8</td>
</tr>
</tbody>
</table>

IMD wire: denser MgB$_2$ layer

**PIT tape**

- holes, cracks
- HV: 252

**IMD wire**

- dense
- HV: 630
The transport $J_c$ values of the MgB$_2$ samples fabricated by the IMD method are less sensitive to the purity of the boron powder, compared with those fabricated by the PIT method.

$J_c$–$B$ properties of IMD wires are improved by using two kinds of boron powders, compared to PIT tapes.
Smaller diameter, higher $J_c$ values

- Small diameter
- Thin B layer
- Fully reacted MgB$_2$
Problem: B-rich particles

Plenty of B-rich particles in the MgB$_2$ layer is due to the large size B powders (several $\mu$m).

The $J_c$ of IMD wire will be further improved by using the nano-sized B powders.
Filament configuration

7-filament wire: longitudinal homogeneity is not good

6-filament wire: good uniformity for 100 m wire
Transport properties of 100 m 6-filamentary wire

- The \( J_c \) of 100 m 6-filamentary IMD wire with 1.02 mm diameter was \( 4.6 \times 10^4 \) A/cm\(^2\) at 4.2 K and 10 T.

- The \( J_c(J_e) \) values of 6-filament IMD wire with different diameter were almost same.
The thin B layer for multifilament wire is benefit for the full reaction between Mg and B, compared to the monofilament wire.
The $n$ values of IMD wires are around 30 at 4.2 K and 8 T. Larger $J_c$ led to a higher $n$ value.
The ratio of the standard deviation to the average value is 3.3%, suggesting that the $J_c$ values have a fairly uniform distribution throughout the long wire.

The lowest $J_c$ value is $1.09 \times 10^5$ A cm$^{-2}$ at 4.2 K and 8 T, which is close to the average value ($1.15 \times 10^5$ A cm$^{-2}$), indicating that there were no serious defects along the length of the wire.
Longitudinal homogeneity evaluation

**Challenge**
- The lowest $J_c$ value determined the $J_c$ value of the whole wire.
- To wind wire into a coil without significant loss of $J_c$.

---

**Indirect**

**Direct**

---

![Image of wire](image1.png)

---

Graph showing $J_c$ vs. Length (m):

- $J_c$ (10^6 A/cm²)
- Length (m)
- 6-filament IMD wire
- Diameter: 1.02 mm
- 650 °C / 5 h
- 4.2 K, 8 T

---

Short samples: $I_c$ and $n$ values

Fitting parameters of $I–V$ curves for short samples at 10 T

<table>
<thead>
<tr>
<th>Sample</th>
<th>$I_c$ (A)</th>
<th>$n$-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>head 1</td>
<td>37</td>
<td>21.5</td>
</tr>
<tr>
<td>head 2</td>
<td>37.2</td>
<td>22.6</td>
</tr>
<tr>
<td>tale 1</td>
<td>37.2</td>
<td>21</td>
</tr>
<tr>
<td>tale 2</td>
<td>37.4</td>
<td>23.1</td>
</tr>
<tr>
<td>Average</td>
<td>37.2</td>
<td>22.1</td>
</tr>
</tbody>
</table>

- Both $I_c$s and $n$-values of four short IMD wires are close to each other, indicating that the long six-filament IMD-processed MgB$_2$ wire is uniform from head to tail.
The $J_c$s of four short IMD wires are close to each other and our previous 100 m IMD wires at 4.2 K.
# MgB<sub>2</sub> solenoid coils

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Coil A</th>
<th>Coil B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wire structure</td>
<td>MgB&lt;sub&gt;2&lt;/sub&gt;/(Nb/Monel)</td>
<td>MgB&lt;sub&gt;2&lt;/sub&gt;/(Nb/Monel)</td>
</tr>
<tr>
<td>Number of filaments</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Wire diameter (mm)</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>Winding inner diameter (mm)</td>
<td>38</td>
<td>38</td>
</tr>
<tr>
<td>Winding outer diameter (mm)</td>
<td>57.6</td>
<td>57.8</td>
</tr>
<tr>
<td>Winding height (mm)</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Number of turns</td>
<td>178</td>
<td>174</td>
</tr>
<tr>
<td>Wire length (m)</td>
<td>26.7</td>
<td>26.1</td>
</tr>
</tbody>
</table>
The transport current of Coil A reached 599 A at 4.2 K.

Coil A generated a self-field of 1.67 T at the coil center.
Transport properties of Coil B

Three time excitation at 4.2 K and 10 T

Fitting parameters of $I–V$ curves for Coil B at 4.2 K and 10T

<table>
<thead>
<tr>
<th>No.</th>
<th>$I_c$ (A)</th>
<th>$n$-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>32.8</td>
<td>14.9</td>
</tr>
<tr>
<td>2nd</td>
<td>33</td>
<td>12.9</td>
</tr>
<tr>
<td>3rd</td>
<td>33.4</td>
<td>13.3</td>
</tr>
<tr>
<td>Average</td>
<td>33.1</td>
<td>13.7</td>
</tr>
</tbody>
</table>

- No training effect.
- $I_c$ (33.1 A) of Coil B is close to $I_c$ (37.2 A) of short samples.
Above 7 T, the $I$–$B$ curve of Coil B was straight and in good agreement with that of the short sample.

Both the magnetic fields generated by two coils ($H^\text{gen}$) coincide with the same formula: $H^\text{gen} = (28 \text{ Gs A}^{-1}) I_c$
Summary

1. The high $J_c$ of IMD wire is also achieved by using the crystalline boron powders. The best $J_c$ value of IMD wire is $6.2 \times 10^4$ A/cm$^2$ at 4.2 K&10 T. The $J_c$ can be further improved by decreasing the size of crystalline B powders.

2. We successfully fabricated a 100 m-level, Nb-reinforced, 6-filament MgB$_2$ wire by an IMD process. The highly uniform microstructure and transport performance are obtained for 100m long six-filament MgB$_2$ wire.

3. Two solenoid coils were made by a wind-and-react method using long wires. One coil exhibited $J_c$ of $4.5 \times 10^4$ A cm$^{-2}$ at 10 T and 4.2 K, which is similar to the short samples. Another coil generated a central field of 1.67 T and a maximum magnetic field of 1.8 T at zero external field.
Collaborators:

Satoshi Awaji, Kazuo Watanabe
Institute for Materials Research, Tohoku University, Japan

Pavol Kovac
Institute of Electrical Engineering, Slovak Academy of Sciences, Slovakia

Liwei Jing, Fengyuan Zhang, Dong Zhang, Wanshuo Sun, Junsheng Cheng, Guoming Zhang, Qiuliang Wang, Liye Xiao, and Liangzhen Lin
Institute of Electrical Engineering, Chinese Academy of Sciences, China

Fang Liu, Lei Lei and Huajun Liu
Institute of Plasma Physics, Chinese Academy of Sciences, China
Thank you for your attention!