Recent progress on the development of MgB$_2$ wires in Hitachi

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Introduction

Potentials of MgB$_2$ wires

Promising for helium-free superconducting applications

- $T_c$ is relatively high (~40 K)
- Manufacturing cost is low
- Round shape is producible

MgB$_2$ applications

- 0.5 T OpenSky MRI was launched by Paramed
- R & D phase: 1.5–3.0 T MRI, SMES, motor, generator, cable, and so on

MgB$_2$ wires

- In situ and ex situ wires are commercially available from Hyper Tech and Columbus, respectively
- R & D phase: internal Mg diffusion (IMD), high pressure treatment (CHPD, HIP), and so on
# Introduction

## Hitachi’s R&D activity on MgB$_2$ wire

<table>
<thead>
<tr>
<th>Step 1</th>
<th>Step 2</th>
<th>Step 3</th>
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<tbody>
<tr>
<td>Enhance $J_c$</td>
<td>Multicore</td>
<td>Elongate (~km)</td>
</tr>
<tr>
<td>Tune up</td>
<td></td>
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</table>

### PIT
- Typical *In situ*

### Dense PIT
- Mechanical milling

### Thin film
- EB deposition

**Kusunoki T et al**
Contents

1. Tuning of in situ PIT process
2. Multicore in situ PIT wire
3. Next generation dense PIT wire
Contents

1. Tuning of *in situ* PIT process
2. Multi-core *in situ* PIT wire
3. Next generation dense PIT wire
As factors to determine \( J_c \) of MgB\(_2\), the following is especially important.

**Electrical connectivity**

\[
K = \frac{\Delta \rho_G}{\Delta \rho} \\
\Delta \rho = \rho(300 \text{ K}) - \rho(40 \text{ K}) \\
\Delta \rho_G = 6.32 \ \Omega \text{ cm}
\]

Effective cross-sectional area ratio for current

\( J_c \) should be proportional to \( K \)

**Intrinsic residual resistivity**

\[
\rho_0 = K \times \rho(40 \text{ K})
\]

Degree of dirtiness as a superconductor

The Increase in \( \rho_0 \) leads to the enhancement of the flux pinning strength by grain boundaries and \( B_{c2} \)
In *in situ* PIT wires, it is well known that these manufacturing conditions crucially affect $J_c$.

(a) **The area reduction ratio of cold work**

(b) **The choice of starting boron powder**

(c) **Heat treatment condition**
Yamamoto A *et al* *Appl. Phys. Lett.* **86** (2005) 212502

(d) **Carbon addition**
Dou S X *et al* *Appl. Phys. Lett.* **81** (2002) 3419
Kumakura H *et al* *Appl. Phys. Lett.* **84** (2004) 3669
1–3 Purpose & Method  Tuning of *in situ* PIT process

**Purpose**  To improve $J_c$ in *in situ* process

**Method**  We prepared monocore wires and investigated the relation between manufacturing conditions and $J_c$ determination factors ($K$ & $\rho_0$).

### Powder packing
- Iron pile
- Magnesium
- Boron
- Carbon additive

### Cold work
- Die
- 99.98% area reduction (0.5 mm in diameter)

### Heat treatment
- In argon
- 600–900°C
- 3–60 h

### Diagram
- Remove iron sheath
- MgB$_2$ core
- Measure the resistivity of only MgB$_2$ core (estimate $K$ & $\rho_0$)
1–4 Result (1) Tuning of \textit{in situ} PIT process

(a) Cold work

The cold work with the large area reduction is essential to enhance the packing factor and connectivity.

Yamamoto A \textit{et al}  

Kodama M \textit{et al}  

**In situ** wire  
(99.98\% area reduction)  
- black circle: heat-treated at 600–700°C  
- red circle: heat-treated at 800–900°C
1–5 Result (2) Tuning of *in situ* PIT process

(b) Boron size, (c) Heat treatment condition

Kodama M et al

The use of finer boron powder and lower-temperature heat-treatment make MgB$_2$ dirtier, resulting in the improvement of flux pinning strength and $B_{c2}$. 

**Boron size** (specific surface area)
- red: very fine (25.4 m$^2$ g$^{-1}$)
- blue: fine (12.8 m$^2$ g$^{-1}$)
- green: normal (8.4 m$^2$ g$^{-1}$)

**Heat treatment**
- solid: 600–700°C
- open: 800–900°C

**Flux pinning strength**

\[ J_c(20 \text{ K}, 0 \text{ T}) \propto \frac{1}{\rho_0} \]

**Transport, 0.9\rho(40 \text{ K})**

\[ B_{c2}(20 \text{ K}) \propto \frac{1}{\rho_0} \]
As proposed by Ye et al. (Kumakura group), we confirmed that coronene ($C_{24}H_{12}$) is a good carbon additive.
1-7 Result (4) Tuning of *in situ* PIT process

**J_c** property (optimum conditions)

Based on the clarified relation between manufacturing conditions and \( J_c \) determination factors, we obtained sufficiently high \( J_c \) for typical *in situ* process.

The very fine boron (PVZ NanoBoron, specific surface area: 25.4 m\(^2\) g\(^{-1}\)) was used.

Coronene (3%) was added.

Cold work with large area reduction (99.8%) was conducted.

The wire was heat-treated at low temperature (600\(^{\circ}\)C) for long duration (24 h).

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1. Tuning of *in situ* PIT process
2. Multicore *in situ* PIT wire
3. Next generation dense PIT wire
2–1 Purpose & Method  Multicore *in situ* PIT wire

**Purpose**  
To prove the homogeneity of *in situ* multicore wire

**Method**  
We fabricated a coil from 300-meter-long wire and compared its performance with that of the short sample.

### Wire preparation

- **Powder packing**
  - Iron pipe
  - Magnesium
  - Boron
  - Carbon additive

- **Cold work**
  - Die

### Coil fabrication and evaluation

- **Embedding**
  - Die

- **Cold work**

- **Braid insulation**
- **Wind & React process**
- **Resin impregnation**
- **Conduction cooling**
2-2 Result (1) Multicore *in situ* PIT wire

**Traverse section**

![Traverse section image]

**Longitudinal sections**

- White: Mg
- Gray: B

The size of MgB$_2$ cores is homogeneous and MgB$_2$ is well connected.

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Tanaka H *et al*

Kodama M *et al*
2-3 Result (2) Multicore in situ PIT wire

$J_c$ property of short sample

The $J_c$ of multicore wire is almost the same as that of monocore wire.
The result of coil evaluation

### The specification of wire
- Diameter: 1.5 mm
- Length: 300 m

### The specification of coil
- Inner diameter: 120 mm
- Outer diameter: 190 mm
- Height: 41 mm
- Inductance: 55 mH

The coil was successfully driven in $I = 286$ A and $B_{\text{max}} = 2.3$ T at 24 K. The coil $I_c$ is nearly equal to the value expected from the short sample.
Contents

1. Tuning of *in situ* PIT process
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3. Next generation dense PIT wire
3–1 Concept  Next generation dense PIT wire

**PIT (typical *in situ*)**

- **Metallic sheath**
- **Spaces between boron**
- **Void**
- **MgB**

**Dense PIT**  

- **Cold work**
- **Planetary mill**
- **No spaces between boron**
- **Volume reduction**

Partial generation of MgB**2** (Mechanical alloying)  

Metal-matrix-composite structure (Mechanical milling)  
3-2 Issue  Next generation dense PIT wire

Longitudinal sections
(fabricated from mechanically milled powder)

Heat treatment

Metal-matrix-composite particles are difficult to be deformed.

MgB$_2$ core is not connected well.
3-3 Purpose & Method

Next generation dense PIT wire

**Purpose**
To find the way to deform the metal-matrix-composite particles
To prove the concept of dense PIT wire (high packing factor & $J_c$)

**Method**
We investigated the influence of powder composition and cold work method.

<table>
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<tr>
<th>Specimen</th>
<th>Powder composition</th>
<th>Cold work method</th>
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<tbody>
<tr>
<td>Wire-1 (normal)</td>
<td>Undoped</td>
<td>Drawing</td>
</tr>
<tr>
<td>Wire-2</td>
<td>Undoped</td>
<td>Drawing + Cassette rolling</td>
</tr>
<tr>
<td>Wire-3</td>
<td>Coronene doped (2%)</td>
<td>Drawing + Cassette rolling</td>
</tr>
</tbody>
</table>

**Processes**
- Mechanical milling
- Powder packing
- Cold work
- Heat treatment

**In argon**
600°C 3 h

**Inorganic raw materials**
- Pot
- Ball
- Iron pipe
- Mixture
- Die
- Roll
- 0.5 mm in diameter
Coronene addition and cassette rolling are effective to obtain a well-connected core.

3–5 Result (2) Next generation dense PIT wire

Longitudinal sections

PIT wire (Typical \textit{in situ})

![PIT wire](image1)

Dense PIT wire (Mechanical milling)

![Dense PIT wire](image2)


We confirmed higher packing factor and higher connectivity for the dense PIT wire.
3–6 Result (3) Next generation dense PIT wire

**$J_c$ property**

- **Dense PIT wire**
- **PIT wire**


The dense PIT wire has higher applicable fields than the PIT wire.
Using accumulated knowledge and accurate evaluation, we optimized the manufacturing conditions (cold work, boron choice, carbon addition, and heat treatment) and improved $J_c$ of the $in situ$ PIT wire.

We prove the homogeneity of a 300-meter-long multicore $in situ$ PIT wire from the evaluation as a coil.

We demonstrated that the wire fabricated from mechanically milled powder had denser MgB$_2$ core and higher $J_c$ than typical $in situ$ PIT wires.
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