5T class superconducting bulk magnet using MgB$_2$ bulk doped with Ti

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Development of MgB$_2$ superconducting bulk magnets.

(Quasi-permanent magnet)

Tesla-class MgB$_2$ bulk magnets has been successfully obtained!
→ To get higher $B_T$, the pinning force must be enhanced.
Grain boundaries (GBs) are flux pinning centers, So their refining is expected to enhance the pinning force.

Hot pressed MgB$_2$ bulks using ball-milled powder were studied.

$B_T=5.4$ T@12 K was achieved.
Impurity doping is an usual method to introduce pinning centers. Ti and C are well known to be effective dopants.

Ti10% maximizes $J_c$.

TiB$_2$ layer at GB act as pinning center.

Ti-doping fines down MgB$_2$ grains.

→ densification
Literatures revealed that Ti-doping is quite effective for the enhancement of $J_c$ in magnetic fields and for the grain refining.

We examine an effect of Ti-doping on the trapped field and vortex pinning properties of MgB$_2$ bulks.
MgB$_2$ bulk preparation

**in-situ** HIP (Hot Isostatic Pressing) method

- Nominal composition: (Mg$_{1-x}$Ti$_x$)B$_2$ ($x=0.05, 0.1, 0.2$).
- Precursor pellet was sealed in SS container in vacuum.
- **in-situ** method: sintered at 900°C for 3h under 98 MPa.

### Bulks

<table>
<thead>
<tr>
<th>Bulks</th>
<th>Diameter (mm)</th>
<th>Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIP–Ti 5%</td>
<td>36</td>
<td>7</td>
</tr>
<tr>
<td>HIP–Ti 10%</td>
<td>36</td>
<td>7</td>
</tr>
<tr>
<td>HIP–Ti 20%</td>
<td>36</td>
<td>7</td>
</tr>
<tr>
<td>HIP–pristine</td>
<td>38</td>
<td>7</td>
</tr>
</tbody>
</table>

Schematic image of HIP machine
(from KOBELCO’s HP)
Measurements

- Trapped Field: Field cooled magnetization (FCM)
- Critical current density: Magnetic hysteresis loop by SQUID magnetometer and Bean’s model
- Phase evaluation: Powder X-ray diffraction
- Micro structure: EPMA, SEM
Ti-doping effect on $B_T$

- Ti-doping enhances $B_T$ by 1.3 times.  
  \[(2.7 \, T \rightarrow 3.6 \, T \text{ at } 13.4 \, K)\]
- $B_T$ is not sensitive to the Ti contents.
To eliminate the demagnetization effect, we measure the $B_T$ of the stacked bulk which consists of Ti 5% and 10% bulks. 

- **center**: $4.6 \, \text{T@14.1 \, K}$
- **surface**: $3.2 \, \text{T@16.3 \, K}$

1.3 times larger against for a single bulk.
Critical current density

- Ti-doping enhances $J_c$.
- $J_c$ hardly depends on the amount of Ti.

Result of $B_T$ properties
• Impurity phases of Ti and TiB$_2$ are observed in Ti-doped bulks.
• Their intensity increases with Ti-doping.
White regions (maybe Ti reduction) obviously increase with Ti-doping, which is consistent with XRD results.
- Size of Ti reduction is approximately 10 μm order.
- B exists around Ti→TiB₂(?) acts as a pinning center.
Summary

To obtain a higher trapped magnetic field of MgB$_2$ bulk, we examined an effect of the Ti-doping.

■ Ti-doping enhanced the critical current density ($J_c$) and the trapped field ($B_T$).
• $B_T$ of Ti-doped bulks are 1.3 times larger than that of the pristine bulk.
• The highest $B_T$ at the center of the stacked bulk was 4.6 T, which is 1.3 times larger than that of the single bulk.
• $B_{\text{irr}}$ at 20K of Ti-doped bulks exceeds 5 T.
• Macroscopic behaviors are not sensitive to the amount of Ti

Microscopic analysis
• Ti and/or Ti compounds increases with Ti-doping.
• B was concentrated around Ti $\rightarrow$ TiB$_2$ acts as a pinning center, which enhances $J_c$ and $B_T$.

Further studies are needed!
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Advantages of MgB$_2$ bulk for application

- Light weight
  - MAGLEV train (energy save), Wind power generator (supporting material save)
- Weak-link free (due to long coherence length)
  - polycrystalline bulk is applicable
  - homogeneous, easily enlargement
- Relatively high $T_c$ (~39 K) → cryo-cooler cooling
- High yield stress → reinforcement-free
  ★2~3 times larger than REBCO bulk

A. Murakami@Ichinoseki National College of Technology, (Private communication)
Reports on MgB$_2$ bulk magnet

- **1T**@27.5K (30mmφ) (Spark Plasma Sintered bulk)

- **2.3T**@6K (28mmφ) (High pressure (2GPa) sintered bulk)

 Recently, MgB$_2$ bulk magnets come into the spotlight again. Many presentation are found in this conference!