High Trapped Fields in C-doped MgB$_2$ Bulk Superconductors Fabricated by Infiltration and Growth

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Magnesium Diboride

- Superconductivity discovered in 2001
- Conventional superconductor (Phonon mediated superconductivity)
- $T_c = 39$ K (Highest amongst intermetallics)
- Larger coherence length
- Strongly linked current flow in polycrystals makes fabrication easier
- Relatively inexpensive
- Light weight

Boron atomic %

**Applied Phy. Let. 78, 2678 (2001)**
Sintering

**Sintering (Ex-situ)**
- Low sinterability
- High Temperature
- High pressure
- Poor intergrain coupling
- Poor connectivity

**Sintering (In-situ)**
- High Mg vapor pressure
- Large porosities (upto 50%)
- Brittle
- High pressure
- Dense structure possible by diffusion route, But small cross section

Scope to improve connectivity and coupling.

Infiltration and Growth

• Simple method to obtain near-net shaped bulk

• Ba-Cu-O liquid phase infiltration into $Y_2BaCuO_5$ preform and then growth of $YBa_2Cu_3O_7$ phase

• Ambient pressure, No requirement of high pressure apparatus.

• Scaling up is much easier.

• Complex shapes (other than cylindrical shape) are possible

• Final product has significantly reduced porosity

$Y-211+ Ba-Cu-O \rightarrow Y123$
Infiltration and Growth Process

$\text{Mg} + 2\text{B} \rightarrow \text{MgB}_2$

SF$_6$ helps form a continuous MgF$_2$ layer

(density $\approx$ 2.45 g/cc)

A. G. Bhagurkar et al SuST 28 015012, 2015
**Challenge**

In-field performance of bulk MgB$_2$ must be enhanced if LTS are to be replaced.

**High Anisotropy**

Rapid drop in $J_c$ with external field!

**Solution?**

- **Grain refinement $\rightarrow$ Pinning**  
  (Increased Grain Boundary Density)
- **Irradiation $\rightarrow$ Pinning**  
  (Vacancy, dislocations, stacking faults)

**C-Doping $\rightarrow$ Impurity Scattering $\rightarrow$ $H_{c2}$**

$\rightarrow$ Reduced Anisotropy

$\rightarrow$ Lattice strains $\rightarrow$ Pinning
SiC and $B_4C$

Subject to IG process

$(100-x)\%B + x\% B_4C/\text{SiC}$

$x$ in weight proportion

$x_i$: Actual doping in $\text{Mg}(B_{1-x_i}C_{x_i})_2$

M-T

SiC: Broad

$B_4C$: Sharp

$\sigma$ band filling by electron doping.

$B_4C$: Homogeneous distribution of C at the atomic scale
Phase Analysis

Maximum $x_i=0.15$

MgB$_2$C$_2$: C Precipitation
Strain: $a$-$b$ plane only

$x_i=9\%$

Strain Analysis: Williamson-Hall Method

Un-doped ~ Strain-free

\[ (\beta_{\text{observed}} - \beta_{\text{instrumental}}) \cos \theta = \frac{K \lambda}{L} + 4\varepsilon_N \sin \theta \]

Williamson and Hall *Acta metallurg.* 1 22(1953)
\( J_c \) and Pinning Force

Trade off between enhancement in \( J_c \) and reduction in \( T_c \).

\( h: 0.2 \rightarrow 0.15 \)

Volume Pinning?

Gradient of \( F_k \) correlates with strain
Eliminating Mg channels

Presence of residual Mg, especially in the form of continuous channels, may have an adverse effect on bulk properties such as the trapped field, despite superior local $J_c$.

**Modified Precursor IG Method**

\[ \rightarrow \text{Incorporated (10\% mole) MgB}_2 \]

- Lowered self field $J_c$
- In field pinning retained
Trapped Field measurements

- Trapped field of 4.15 T, highest amongst samples under ambient pressure.
- Increase achieved by simple B\textsubscript{4}C addition, without using expensive techniques.
- Flux distribution needs further attention.

<table>
<thead>
<tr>
<th>C doping</th>
<th>Enhanced trapped field</th>
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<tr>
<td>Less than 1% difference</td>
<td>in trapped field recorded on top and bottom.</td>
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Field Decay

- **Logarithmic** decay with time
- Faster decay with C-doping
- \( U = U_0 \left(1 - \frac{T}{T_c}\right)^{\alpha_c} \)  \( U \): Height of potential well

Flux lines can overcome pinning barrier and migrate relatively easily

\[ v = v_0 e^{\frac{-U_0}{k_B T}} \]

\( v \): Jump Frequency

flux jump frequency increases with temperature
Summary

- **B₄C** helped achieve a more **homogeneous** C distribution. Due to higher reactivity of B₄C with Mg and an atomically uniform distribution of C in the bulk microstructure.
- **Enhancement in** \( J_c \), particularly at lower temperature and higher fields. Generation of lattice disorder in the MgB₂ phase accompanied by the effects of C-doping. Analysis of the pinning force also suggested the possibility of a contribution to enhanced \( J_c \) from volume pinning.
- A significant increase in trapped field was observed in C-doped MgB₂ bulk superconductors. The trapped field obtained (4.15 T) is the **highest reported to date** for MgB₂ bulk superconductors synthesized under ambient pressure conditions.
- **Finer particle size of** B₄C is likely to yield more efficient and uniform C-doping, without the formation of MgB₂C₂ and leaving residual B₄C. This, together with nano-sized boron powder, would potentially yield an optimum combination of enhanced grain boundary pinning and increased \( H_{c2} \).