Novel Critical Current Estimation Method for Internal-Mg-diffusion-processed MgB$_2$ Wires Based on Magnetic Microscopy

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Background: Recent $J_c$ of MgB$_2$ Wires

Recent performance improvement of MgB$_2$ wires by...

- internal Mg diffusion (IMD) process
- boron powder preprocessing (carbon coating, coronen...)

$J_c > 10^5$ A/cm$^2$ @ 4 K, 10 T
Background: Recent $J_e$ of MgB$_2$ Wires

Recent performance improvement of MgB$_2$ wires by...

- internal Mg diffusion (IMD) process
- boron powder preprocessing (carbon coating, coronene...)

$J_c > 10^5$ A/cm$^2$  @ 4 K, 10 T

$J_e > 10^4$ A/cm$^2$

**Graphs:**
1. $J_e$ vs. $B$ at 4.2 K, showing performance improvements with different processes.
2. Engineering $J_e$ vs. Magnetic Field $B$, illustrating the magnetic field dependence of $J_e$.
Background: Estimation of $I_c$ of MgB$_2$ Wires

Performance around 5 T or less should be evaluated for MgB$_2$ wires for promising applications such as MRI, cable, but…

Important region for practical applications

Four-probe method: difficult in measurement for very high $I_c$ condition

General magnetization method: difficult in $I_c$ estimation due to magnetic sheath: Iron, Monel

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Monel sheath

OSU & Hyper Tech

Objective

Development of $I_c$ Estimation Method for Recent High-performance MgB$_2$ Wires with Magnetic Sheath Materials

Method:
- Magnetic Microscopy & FEM analysis

Sample:
- AIMI mono-core wire with Monel sheath fabricated by Hyper Tech

Important region for practical applications
Scanning Hall-probe Microscope (SHPM)

External magnetic field: up to 5 T
Stage temperature: down to 5 K
Scanning area: 10 x 10 mm²
Scanning resolution: 0.5 x 0.5 x 0.25 μm³
Active area of Hall sensor: 50 x 50 μm²

Sample:
MgB₂ wire with
- mono core
- 0.55 mm in diameter
- Monel sheath

5 T magnet for the application of external magnetic field to the sample
Low-Temperature Scanning Hall-Probe Microscope (LT-SHPM)
Magnetic field distribution at low $B_{ex} @ 10$ K

1 mm

Hall-probe Scanning

Monel
Nb
MgB$_2$

0.2 mm

100 mT as a low magnetic field
Magnetic field distribution at low $B_{ex} @ 10$ K

1 mm

Hall-probe Scanning

Monel
Nb
MgB$_2$

Wire absorbs magnetic fluxes

Magnetic flux density $B_z$ (T)
Position in width direction $y$ (mm)

0.10
0.11
0.0 0.5 1.0 1.5
Magnetic flux density $B_z$ (T)
Position in width direction $y$ (mm)

100 mT

0.10
0.11
0.0 0.5 1.0 1.5
Magnetic flux density $B_z$ (T)
Position in width direction $y$ (mm)
Magnetic field distribution at high $B_{ex} @ 10$ K

Hall-probe Scanning

- Monel
- Nb
- MgB$_2$

400 mT as a high magnetic field
Magnetic field distribution at high $B_{\text{ex}}$ @ 10 K

Hall-probe Scanning

Monel
Nb
MgB$_2$

Wire shields magnetic fluxes

Magnetic flux density $B_z$ (T)
Position in width direction $y$ (mm)

0.39
0.40
0.41
0.0 0.5 1.0 1.5

400 mT

0.39
0.40
0.41
0.0 0.5 0.5 1.0 1.5
What Governs the Electromagnetic Behavior

Magnetic sheath:
- relative permeability ($\mu_r$)
- saturation flux density ($B_s$)

Superconducting filament:
- critical current ($I_c$)

The Monel sheath absorbs fluxes due to its high permeability.

The MgB$_2$ filament shields fluxes after the saturation of the Monel.
Estimation of Permeability @ 40 K > $T_c$

Magnetic sheath:
- relative permeability ($\mu_r$)
- saturation flux density ($B_s$)

Superconducting filament:
- critical current ($I_c$)

Hall-probe Scanning

Magnetic flux density $B_z$ (T)
Position in width direction $y$ (mm)

- Monel
- Nb
- MgB$_2$

$dB / dH = \mu_0$
$dB / dH = \mu_r \mu_0$

$0.09$
$0.10$
$0.11$
$0.12$

$0.0 0.5 1.0 1.5$

$0.09$ $0.10$ $0.11$ $0.12$

$0.0$ $0.5$ $1.0$ $1.5$

SHPM

100 mT
Estimation of Permeability @ 40 K > $T_c$

Magnetic sheath:
- relative permeability ($\mu_r$)
- saturation flux density ($B_s$)

Superconducting filament:
- critical current ($I_c$)

Hall-probe Scanning

Comparison with FEM → find $\mu_r$ before saturation

$dB / dH = \mu_0$

$dB / dH = \mu_r \mu_0$

Monel
Nb
MgB$_2$

0.2 mm

100 mT

B

$B_s$

Magnetic flux density $B_z$ (T)

Position in width direction $y$ (mm)

SHPM
FEM

$\mu_r = 10$

0.090.100.110.12

0.0 0.5 1.0 1.5
Estimation of Field Saturation @ 40 K > \( T_c \)

Magnetic sheath:
- relative permeability (\( \mu_r \))
- saturation flux density (\( B_s \))

Superconducting filament:
- critical current (\( I_c \))

\[
\frac{dB}{dH} = \mu_0
\]
\[
\frac{dB}{dH} = \mu_r \mu_0
\]

\( B \)

Monel
Nb
\( \text{MgB}_2 \)

0.2 mm

600 mT

Hall-probe Scanning

\[ B \]

\[ dB / dH = \mu_0 \]

\[ dB / dH = \mu_r \mu_0 \]

\[ H \]

Magnetic flux density \( B_z (T) \)

Position in width direction \( y \) (mm)

\( \mu_r = 10 \)

SHPM

\[ 0.59 \quad 0.60 \quad 0.61 \quad 0.62 \]

\[ 0.0 \quad 0.5 \quad 1.0 \quad 1.5 \]

K. Higashikawa et al., ICEC 25 - ICMC 2014
Estimation of Field Saturation @ 40 K > $T_c$

Magnetic sheath:
- relative permeability ($\mu_r$)
- saturation flux density ($B_s$)

Superconducting filament:
- critical current ($I_c$)

Hall-probe Scanning

Comparison with FEM → find $B_s$ after saturation

Monel
Nb
MgB$_2$

$\frac{dB}{dH} = \mu_0$

$\frac{dB}{dH} = \mu_r \mu_0$

$B = B_s$

$dB/dH = \mu_0$

$dB/dH = \mu_r \mu_0$

$B_s = 320 \text{ mT}$

$\mu_r = 10$

$B = 600 \text{ mT}$

$\mu_r = 10$

$B_s = 320 \text{ mT}$

Comparison with FEM → find $B_s$ after saturation

Hall-probe Scanning
Estimation of $I_c$ @ 5 K, Remanent

Magnetic sheath:
- relative permeability ($\mu_r$)
- saturation flux density ($B_s$)

Superconducting filament:
- critical current ($I_c$)

Hall-probe Scanning

Magnetic flux density

$B$

$dB / dH = \mu_0$

$dB / dH = \mu_r \mu_0$

$B_s$

$H$

Relative permeability ($\mu_r$) = 10

Saturation flux density ($B_s$) = 320 mT

0.2 mm

SHPM

Monel
Nb
MgB$_2$

remanent

$B_0 (T)$

Magnetic flux density

$B_z (T)$

Position in width direction $y$ (mm)

K. Higashikawa et al., ICEC 25 - ICMC 2014
Estimation of $I_c @ 5$ K, Remanent

Magnetic sheath:
- relative permeability ($\mu_r$)
- saturation flux density ($B_s$)

Superconducting filament:
- critical current ($I_c$)

Comparison with FEM → $I_c$ was finally estimated!!

Hall-probe Scanning

Monel
Nb
MgB$_2$

$0.2$ mm

remanent

$B$

$B_s$

$dB / dH = \mu_0$

$dB / dH = \mu_r \mu_0$

$H$

$\mu_r = 10$

$B_s = 320$ mT

$I_c = 500$ A
Two-dimensional Mapping @ 5 K

Measured magnetic field on the plane

\[ B_z \text{ (mT)} \]

-6.0 \quad 46.5

1 mm
Longitudinal $I_c$ variation can be estimated by this method.
Success in $I_c$ Characterization in High $I_c$ Condition

- difficult for four-probe method due to heat generation, system limitation
- difficult for general magnetic method due to magnetic sheath material

$J_e$ (A/cm$^2$) vs. $B$ (T)

$I_c = 600$ A
$I_c = 500$ A

Important properties for possible applications (MRI, SMES, cable,…)

Summary

We have developed a noncontact $I_c$ characterization method for recent high-performance MgB$_2$ wires with magnetic sheath

1. $I_c$ value was successfully estimated for high $I_c$ condition (below 5 T) where four-probe method could not be applied

2. Noncontact $I_c$ characterization was achieved whereas general magnetic method was not successful because of magnetic sheath material

3. Longitudinal variation of $I_c$ was estimated

Attractive characterization method for taking data for application design and for the optimization of wire fabrication processes

Thank you very much for your kind attention!