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Magnetic microscopy for characterization of local critical current in iron-sheathed MgB₂ wires

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Abstract

We have developed a characterization method of local critical current in iron-sheathed MgB_2 wires. Local homogeneity was visualized by the scanning Hall-probe microscopy (SHPM). The value of local critical current was quantified with the aid of the finite element method (FEM) considering the ferromagnetic properties of the iron sheath. The results suggested that MgB_2 wires fabricated by internal Mg diffusion processes still have large longitudinal inhomogeneity and much higher potential than that estimated by the four-probe transport method. This will be very important information for making a correct strategy for further development of MgB_2 wires.

Keywords

MgB_2 ; critical current; local homogeneity; scanning Hall-probe microscopy

1. Introduction

MgB₂ has the highest critical temperature among metallic superconductors: ~39 K [1]. This enables us to use liquid hydrogen as a cryogen which cannot be used for other metallic superconductors such as Nb-Ti and Nb₃Sn. Furthermore, MgB₂ wire also has an advantage in persistent current operation based on its high n -value [2] and the availability of superconducting splices [3] compared with high-temperature cuprate superconducting wires. However, it is a well-known fact for MgB₂ wires that further improvement in critical current densities and their magnetic properties has been needed for practical magnet applications.

To improve the wire performance, it is necessary to find a performance limiting factor and then to feed back the information to wire fabricating processes. In general, the performance is evaluated by the four-probe transport method as critical currents and critical current densities; these items are estimated as averaged values between the voltage taps. On the other hand, the performance limiting factor is often investigated by SEM and/or TEM observations with a very local field of view though these allow us to obtain detailed microstructural information in nano-scale. Due to such large difference in the length scale, it has been difficult to find a direct relationship between the wire performance and its microstructure.

From this viewpoint, we have been trying to characterize local critical currents and/or local critical current densities in superconductors based on scanning Hall-probe microscopy [4]. This method has been recognized as a powerful technique for the characterization of local properties in superconductors [5], and its validity has been reported by comparing with other measurement

techniques [6]. Furthermore, some characterization results have already been reported for an MgB_2 wire fabricated by powder-in-tube (PIT) processes [7, 8]. The principle is simple; the intensity of superconducting current densities in a sample can be estimated from the measured magnetic field distribution. However, such an inverse problem of the Biot-Savart law cannot be solved analytically when the sample includes a ferromagnetic material. This means that we cannot quantitatively apply this powerful characterization method to MgB_2 wires with iron sheaths even though they are often used for such wires.

In this study, we have developed a characterization method of local critical currents in iron-sheathed MgB_2 wires based on the combination of the scanning Hall-probe microscopy (SHPM) and a numerical analysis of finite element method (FEM).

2. Measurement by Scanning Hall-probe Microscopy (SHPM)

The sample was prepared from an iron-sheathed MgB_2 wire fabricated by the internal Mg diffusion (IMD) process [9]. Fig. 1 (a) and (b) show the schematic diagram and the optical micrograph of the sample, respectively. The sample was made by polishing a resin-impregnated wire with the Buehler polisher. This is an indispensable procedure to pick up magnetic signals from the MgB_2 filament by the SHPM; otherwise magnetic fluxes cannot leak out of the iron sheath due to its high magnetic permeability.

The sample was mounted on a cooling stage of the SHPM system, and cooled down to 10 K. Then, the external magnetic field of 5 T was applied perpendicular to the polished surface, i.e., in z

direction. This magnetic field is sufficiently higher than the saturation magnetic field of the iron sheath, e.g., 2 T; magnetic flux can fully penetrate the MgB₂ filament. Then the external magnetic field was removed in order to make a remanent state.

Fig. 1 (c) shows the remanent magnetic field distribution in the sample measured by scanning a Hall-sensor at the lift-off distance of 200 μm from the sample surface. It was confirmed that the magnetic fluxes were successfully trapped in the MgB₂ filament. According to the critical state model, higher remanent magnetic fields correspond to larger critical currents. This means that the sample has inhomogeneous distribution of local critical currents along its longitudinal direction. In this way, the SHPM can detect the positions of performance limiting factors which should be clarified by SEM and/or TEM observations. The direct relationship between the local superconducting performance and the microstructure will be discussed elsewhere as a next study.

3. Estimation of Local Critical Current with the Aid of Numerical Analysis by Finite Element Method (FEM)

If the sample does not include any ferromagnetic materials, the value of the critical current can be analytically estimated from that of the measured magnetic field by considering the Biot-Savart law. However, the sample has the iron-sheath in this study. Therefore, numerical analysis is needed to investigate the relationship between the value of the critical current and that of the remanent magnetic field.

Fig. 2 shows the numerical analysis model for the FEM. Assuming the ideal remanent state, the

current was applied to $+x$ direction for $y < 0$ and to $-x$ direction for $y > 0$ at uniform critical current densities. The relative permeability of 2000 and the saturation magnetic field of 2 T were considered for the iron sheath. These values were estimated by the experiment. Then the corresponding magnetic field distributions along the arrows, i.e., for different two lift-off distances of 30 μm and 200 μm , were calculated.

Fig. 3 (a) shows the results for the critical current density of 3 MA/cm^2 ; the perpendicular component of magnetic field is plotted as a function of the width position by the solid curves. On the other hand, the open symbols were obtained by the SHPM measurement along the arrow in Fig. 1 (c) for the same lift-off distances. It can be seen that the results agree very well with each other independent of the lift-off distance. This means that the SHPM results shown in Fig. 1 (c) can be regarded as the ideal remanent state as expected and that the local critical current density at this longitudinal position can be estimated to be 3 MA/cm^2 . Considering the cross-sectional area of the MgB_2 filament, this value corresponds to the local critical current of 600 A. In this way, the local critical current in the sample can be estimated by the combination of the SHPM and the FEM.

For more simple analysis, the relationship between just the peak value of the magnetic field, B_{max} , and the critical current density, J_c , were estimated by the numerical analysis. Fig. 3 (b) shows the results; the solid symbols indicate the calculation point, and the solid line indicates the linear fitting for them:

$$J_c = \frac{B_{\text{max}}}{25 \text{ mT}} \times 1.0 \times 10^6 \text{ A}/\text{cm}^2 \quad (1)$$

By using this equation, the local critical current density, J_c , as a function of longitudinal position for

the sample was finally estimated as shown in Fig. 1 (d). It was found that this sample had still inhomogeneous properties. On the other hand, the maximum value of $J_c = 4.5 \text{ MA/cm}^2$ and $I_c = 900 \text{ A}$ will be the potential for this wire at 10 K and self-field. This quantification will be very important information to make a strategic plan, e.g., improving the longitudinal homogeneity or changing the materials, to achieve some target value of J_c and/or I_c in MgB₂ wire developments.

4. Conclusion

We developed a characterization method of local critical currents in iron-sheathed MgB₂ wires. The results indicate that MgB₂ wires fabricated by IMD processes still have large longitudinal inhomogeneity although the situation for MgB₂ wires fabricated by PIT processes would be different. In other words, MgB₂ wires fabricated by IMD processes have much higher potential in local I_c than the global value estimated by the four-probe transport method. We believe that the performance limiting factors will be clarified by the combination with the SEM observation in near future.

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Figure Captions

Fig. 1. Experimental results obtained by scanning Hall-probe microscopy: (a) schematic diagram, (b) optical micrograph, (c) remanent magnetic field distribution at 10 K and the lift-off distance of 200 μm , and (d) local critical current density as a function of longitudinal position of the sample. One-dimensional distribution along the arrow in (c) was measured not only at the lift-off distance of 200 μm but also at 30 μm as shown in Fig. 3; the corresponding longitudinal position is indicated as the closed circle in (d). The values of local critical current densities in (d) were estimated from the relationship shown in Fig. 4.

Fig. 2. Analysis model of the sample for finite element method.

Fig. 3. (a) Comparison of magnetic field distribution along the width direction at the longitudinal position shown in Fig. 1 (c) between the experimental results by the SHPM and the numerical results by the FEM at critical current density of 3.0 MA/cm²; The results were obtained for two different lift-off distances from the top surface of the sample as shown in Fig. 2: 30 μm and 200 μm .

(b) Relationship between the peak of the remanent magnetic field and the critical current density at a longitudinal position estimated for the lift-off distance of 200 μm by the FEM.

Fig. 1

Fig. 2

(a)

(b)

Fig. 3