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Enhancement of a mechanical property of metal sheaths (Cu and Nb) of MgB_2 superconducting wires by E-beam irradiation

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Abstract

Effects of electron beam (EB) irradiation on the mechanical strength of Cu (conducting sheath) and Nb (diffusion barrier) of Cu/Nb/MgB_2 superconducting was investigated. Wire- and tape-type Cu/Nb/MgB_2 samples were irradiated at E-beam energy of 2.5 MeV and 5 mA and a maximum E-beam dose was $5x10^{17}$ e/m^2. The hardness value of Cu and Nb region was measured by the Vickers micro-hardness method. In the case of the wire sample, the hardness of Cu and Nb increased proportionally as the dose was increased up to $5x10^{17}$ e/m^2, whereas in the case of the tape sample, the hardness increased up to a dose of $0.5x10^{17}$ e/m^2, and decreased slightly $5x10^{17}$ e/m^2. The hardness increase of Cu and Nb is believed to be due to the decrease of the deformability of Cu and Nb due to the defects formed inside the materials by E-beam irradiation.

Keywords: MgB_2, Superconductor, E-beam irradiation, Cu and Nb, Vickers hardness, wire, tape

1. INTRODUCTION

A MgB_2 superconductor with a superconducting transition temperature (T_c) of 39 K [1] is a promising material to replace the conventional NbTi wire, which uses liquid helium as a refrigerant. If the operating temperature of the MgB_2 magnet is lowered to 20 K, MgB_2 wires can be cooled using only a refrigerator without using expensive liquid helium [2, 3].

Superconducting magnets used in MRI medical devices and other electrical devices like superconductor cables are mainly processed in the form of wires or tapes. When electrical current flows through the superconducting solenoid, a magnetic field is generated in the solenoid. When a magnetic field is generated, a Lorentz force is applied to the superconducting wire. To withstand the force generated when the superconducting devices is working, the superconducting wire should have adequate mechanical strength.

MgB_2 wires are fabricated by power-in-tube (PIT) method [4]. Mg and B powder, or MgB_2 powder, which are raw materials, are put in a metal tube and the tube is machined into a wire from by a mechanical process such as drawing and extrusion. In the PIT process, Cu or Cu-Ni alloy is usually used as a sheath and Nb is used as an inner sheath, which serves to prevent mutual diffusion of (Mg + B_2) and Cu. The sheath material is selected from materials that withstand the stresses encountered during mechanical wire processing.

To increase the critical current density (J_c) of MgB_2, the microstructure related to defects is controlled. When small defects are present in MgB_2, they serve to trap the magnetic field, thereby improving the J_c at magnetic fields [5, 6]. Defects can be created by chemical methods such as impurity doping [5, 6] or by physical methods such as particle irradiation [7-17]. For example, irradiation with neutrons on $YBa_2Cu_4O_8$ has been reported to form cascading defects composed of amorphous phases [12, 13]. When MgB_2 is irradiated with thermal neutrons, defects formed due to the $^{10}B(n,\alpha)^{7}Li$ reaction [14]. For heavy ion irradiation with YBCO [7, 8] and MgB_2 [15], columnar defect tracks were formed. In addition, proton irradiation on YBCO caused lattice distortion [16]. In our previous studies, J_c of YBCO thin films [10] and MgB_2 bulk [11] increased by electron (E)-beam irradiation. The increase of J_c was believed to be due to the formation of defects [10, 11]. The E-beam irradiation is thought to create the defects not only in the superconducting layer but also in the sheath materials. The defects can affect the mechanical properties of the metalic sheath materials. However, there are not many studies on the effect of E-beam irradiation on properties of the sheath material.

In this study, the Cu/Nb/MgB_2 superconductors were made into a wire and tape form by PIT process. The samples were irradiated by E-beam with various exposure time. The effect of E-beam irradiation on the mechanical properties of the sheath materials (Cu and Nb) of MgB_2 was estimated by a Vickers micro-hardness test.

2. EXPERIMENTS

2.1. Preparation of MgB_2 wire and tape.

Two different types (wire and tape) of MgB_2 superconductors were used in the experiment. The MgB_2

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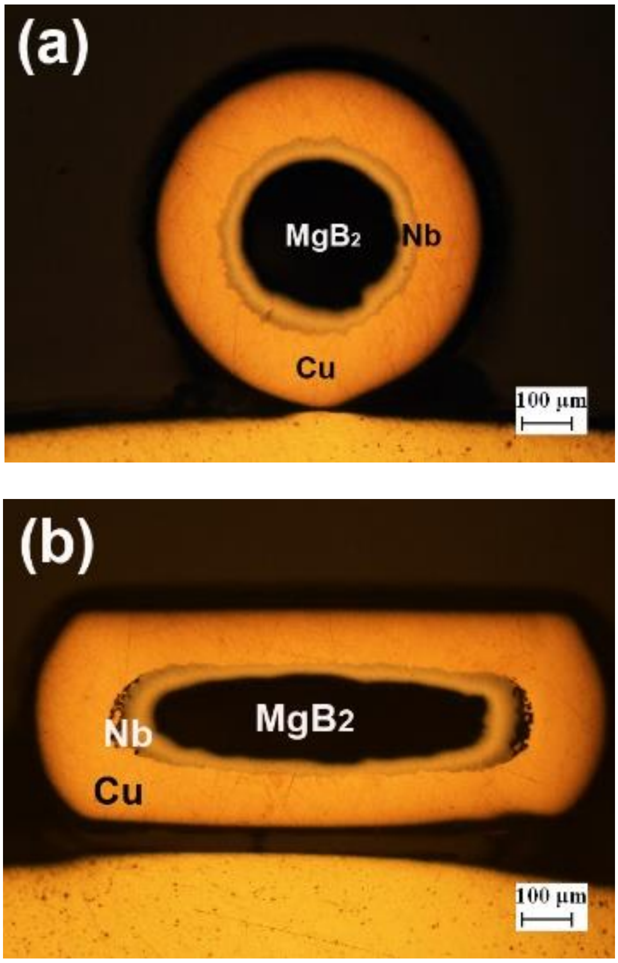

Fig. 1. Cross-sectional view of (a) wire and (b) tape form of MgB_2.

wire was manufactured by repeated drawing of Cu/Nb tubes containing Mg and B powder. Nb is as a diffusion barrier layer, and Cu is a conductive outer covering material. The MgB_2 wires with 0.9 mm dia. were heat-treated so that Mg and B powder reacted to form MgB_2, a superconducting phase. The detailed fabrication process of MgB_2 wires is described in other literatures [18, 19]. To understand the effect of the shape of MgB_2 wires, some of the round MgB_2 wires were uniaxially pressed into plat tapes with a thickness of 0.43 mm.

Figure 1 is a cross-sectional photograph of (a) wire and (b) tape form of MgB_2. As shown in the Fig. 1(a), a diameter of the MgB_2 core is about 320 μm, and thicknesses of the Nb and Cu tubes are 50 μm and 130 μm, respectively. On the other hand, the MgB_2 tape has a flat top and bottom and both sides of the tape have curvature (see Fig. 1(b)). The tape sample is wider and thinner than the wire sample.

2.2. E-beam irradiation experiment.

MgB_2 wires with a diameter of 0.9 mm and the tapes with a thickness of 0.43 mm were cut into a 50 mm length and were irradiated at E-beam energy of 2.5 MeV and 5 mA. The irradiation energy was controlled with exposure time. E-beam irradiation was reported to decrease T_c slightly and increased J_c of MgB_2 [11]. The detailed results

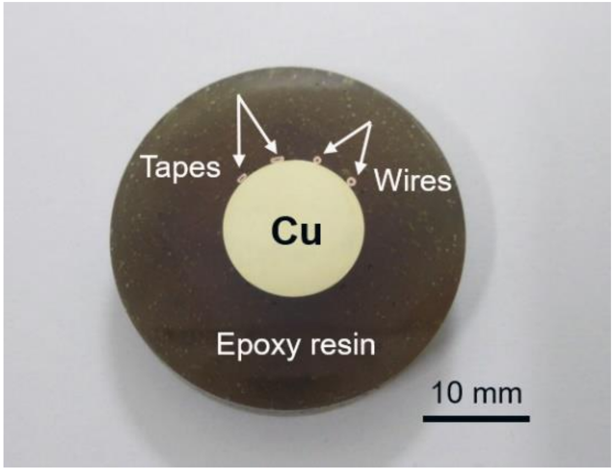

Fig. 2. Micro-polished copper rod where MgB_2 wire and tape samples were fixed using an adhesive.

of superconductor properties and microstructure by E-beam irradiation have been well documented in our previous work [10, 11], so we do not discuss it here. Since meaningful data on superconducting properties were obtained at E-beam doses of $0.05x10^{17}$-$5x10^{17}$ e/m^2, a hardness test was performed on the samples irradiated with the same doses.

2.3. Vickers micro-hardness test.

For Vickers hardness measurement, the MgB_2 wires and tapes were cut to a length of 0.5 to 0.7 mm, and then fixed vertically a the round edges of a 15 mm dia. copper tube using an adhesive. The copper rod was mounted by pouring a mixture of a liquid polyester resin for reinforced plastic and a curing agent. After the sample was completely hardened, coarse grinding was performed step by step using SiC papers of 60, 220, 400, and 800 grit, followed by polishing with 1 μm alumina powder.

Figure 2 shows a micro-polished sample. To reduce the error occurring during the measurement of Vickers hardness, the epoxy-mounted sample was carefully ground so that the top and bottom surfaces were parallel. If the two surfaces are not parallel, an exact diamond-shaped indentation cannot be obtained, so there may be an error in the measurement value. The hardness was measured for the cross-section of Cu and Nb surface of the wire and tape samples.

The widely used method to evaluate the mechanical properties of superconducting wires is the tesnile test [20]. With this method, the yield strength and elongation of superconducting wires can be evaluated. In this study, a microhardness test was performed, because the hardness test has the advantage of being able to measure the mechanical properties of the superconducting core, diffusion barrier layer (Nb), and conductive layer (Cu) separately.

The micro-hardness was calculated by the following Eq.(1) [21],

$$H_v = P/A = 1.854xP/d^2 \qquad (1)$$

where H_v is a hardness value, P is an applied load, A is an indentation area, and d is a diagonal length of the

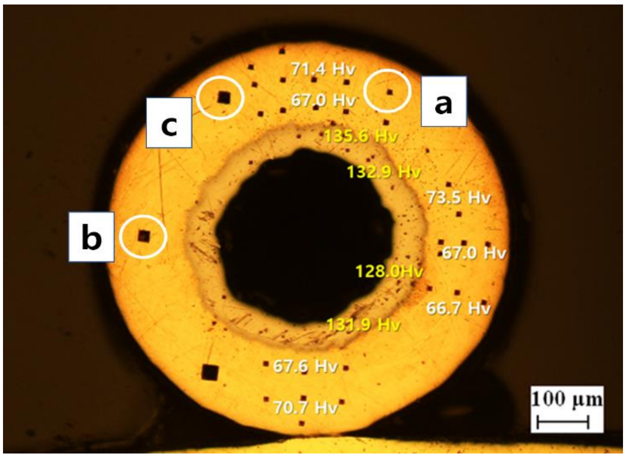

Fig. 3. Cross section of a Cu/Nb-sheathed MgB_2 superconducting wire after hardness test with various loads.

indentation mark. After the hardness test, the diamond-shaped indentation marks on the surface are photographed under a microscope and the diagonal of the marks is measured. According to this equation, the hardness of the subject material is the value of the applied load divided by the indentation cross-sectional area. By putting P and d value in Eq. (1) the hardness value of the surfaces is calculated.

The applied load and holding time were 0.01 kgf and 10 sec., respectively and test was carried out at room temperature. To reduce the error of the measurement, the same measurement was carried out not only at 0.01 kgf but also at 0.025 kgf and 0.05 kgf. As can be seen in Fig. 3, the size of the diamond shape indented on the surface depends on the applied load. As the load increases, the size of the indentation increases (see indentations marked by a, b and c). For the hardness test, two sets of wire and tape samples were irradiated at the given E-beam dose conditions and the average hardness value was obtained by repeating the measurement 30 times for the Cu and Nb surface.

3. RESULTS AND DISCUSSION

To obtain a reference point for hardness values, hardness measurements were first performed on non-irradiated samples. The average hardness of the Cu layer of the wire samples was 63.1 H_v, and the hardness of Nb was 110.4 H_v. The hardness of Nb was about 40 H_v higher than that of Cu. Also, the hardness of Cu and Nb of the tape sample were 61.7 H_v and 110.9 H_v, respectively, which are similar to those of the wire sample.

A Vickers hardness value is calculated from the indentation area. A high hardness means a small indentation area. In other words, a hard material is not easily deformed plastically. Plastic deformation is related to the crystal structure of each element. Cu has a face-centered cubic (FCC) structure [22], whereas Nb has a body-centered cubic (BCC) structure [23]. In FCC structure atoms are densely arranged than in BCC structure. As a result, plastic deformation in FCC is easier than in BCC structure. This is a reason why the hardness of Nb is higher than that of Cu.

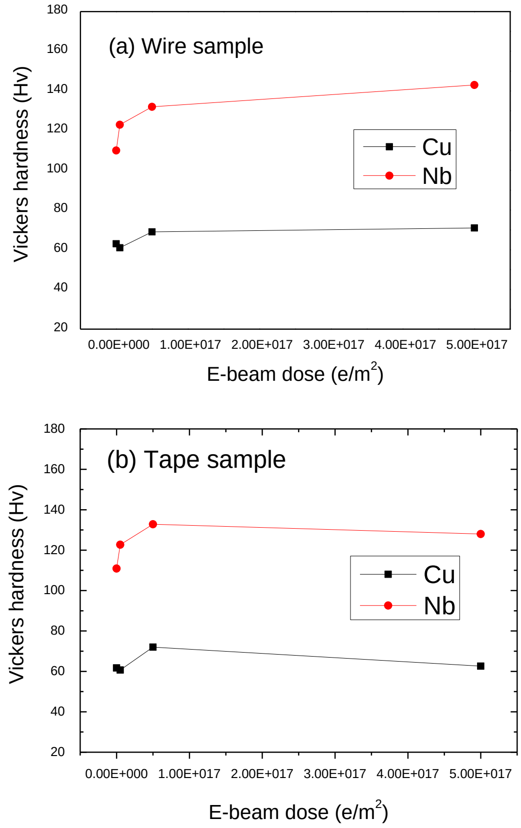

Fig. 4. Variation of hardness of Cu and Nb in (a) wire sample and (b) tape sample with E-beam irradiation dose.

Figure 4 shows the hardness of Cu and Nb in (a) wire samples and (b) tape samples as a function of E-beam irradiation dose. As shown in Fig. 3(a), at E-beam irradiation of 0.05×10^{17} e/m^2, the average hardness of Cu of the wire sample was 61.14 H_v, which is almost the same as that of non-irradiated sample. On the other hand, the hardness of Nb was 123.55 H_v, which increased by about 10 H_v. When the irradiation dose was increased to 0.5×10^{17} e/m^2, the hardness of Cu and Nb increased to 69.13 H_v and 132.1 H_v, respectively. When the dose was increased further to 5×10^{17} e/m^2, the hardness of Cu and Nb increased to 71.14 H_v and 143.88 H_v, respectively. Compared with non-irradiated samples, the E-beam irradiation resulted in 11% and 23% increase of hardness for Cu and Nb, respectively.

The change in hardness of Cu and Nb in the tape sample is similar to that of the wire sample. The hardness of Cu and Nb increased proportionally as the dose increased upto 0.05×10^{17} e/m^2. However, the hardness decreased slightly as the dose increased further to 5×10^{17} e/m^2. At this moment, it is difficult to explain the cause of the hardness decrease at the high dose. One possible reason is the difference in heat transfer capacity depending on the sample shape. The tape sample has a surface flatter and larger than the wire sample. The tape sample may absorb the electron beam faster, which can cause the sample temperature to rise faster. If the tape sample retains more heat than the wire sample, the defects can be annihilated by activated atomic diffusion [24].

The mechanical property of the sheath material of the superconducting wires is very important parameter for the

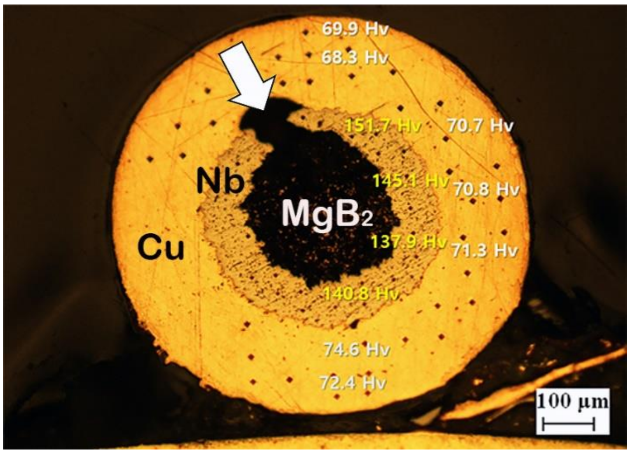

Fig. 5. Cross section of a locally fractured Cu/Nb/MgB_2 wire

superconducting devices. The sheath should have high electrical conductivity, adequate plastic workability and high strength when considering the mechanical forming and winding process of the superconducting wire, and operating of the devices in high magnetic fields.

Figure 5 shows the cross section showing the local fracture of Nb layer which surrounds the MgB_2 core. The MgB_2 core penetrated the Nb layer and migrated toward the outer Cu sheath. The fracture seems to occur during the drawing process for manufacturing the wire, and the cause is the low strength of Cu. As a part of the superconducting wire is torn, the current carrying capacity and mechanical strength of the superconducting wire are reduced. This result provides useful information on how to design superconducting wires from the point of view of material selection. Since pure Cu has good conductivity but low strength, Cu-Ni alloy [25], Ni [26], or Fe [19], which has a high strength, is usually used as a sheath.

The results of this study clearly showed that E-beam irradiation increased the hardness of Cu and Nb, which are the covering materials of MgB_2 wires. In addition to the generation of defects in the sheath material, E-beam irradiation also creates defects such as lattice distortions, vacancies, and amorphous phases in the superconducting phase, which increase of J_c of MgB_2 [11]. In conclusion, it can be said that E-beam irradiation increases not only the J_c of MgB_2 but also the mechanical properties of the sheath materials.

4. CONCLUSIONS

In this study, the effect of E-beam irradiation on the hardness of Cu and Nb, which are sheath materials of MgB_2 superconducting wire, was investigated. The wire and tape type samples were irradiated at E-beam energy of 2.5 MeV and 5 mA and maximum irradiation dose was $5x10^{17}$ e/m^2. In the case of the wire sample, the hardness of for both Cu and Nb increased proportionally as the irradiation dose was increased up to the maximum dose of this study, whereas in the case of the tape sample, the hardness increased as the dose increased, and the hardness decreased slightly at the maximum dose. The hardness increase of Cu and Nb is attributed to defects formed in the sheath materials by E-beam irradiation.

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