Development of the ultrafine MgB_2 superconducting wires and flexible cables

Akihiro Kikuchi, Yasuo Iijima, Hiroaki Kumakura, Masaru Yamamoto, Masatoshi Kawano, and Masato Otsubo

***Abstract*— We successfully fabricated the ultrafine MgB_2 mono-core superconducting wires through the general *in-situ* powder-in-tube process by using a starting mixture of commercial Mg and B powders without C doping. In addition, some bundled cables were fabricated by using ultrafine MgB_2 wires. Those cables showed surprisingly flexible mechanical performance even after the heat treatment. The critical current (I_c) decreased monotonically with decreasing the wire diameter, meanwhile, the critical current density was almost the same value with decreasing the wire diameter down to 0.05 mm. The I_c of the twisted cables was increased almost by the number of bundled wires. This is a very promising result from a practical application point of view. In addition, we recognized the Monel outer sheath was very effective in improving the cold-die-drawability to forward the ultrafine diameter. It was fabricated 4 km of long piece length without the wire breakage for the Monel sheathed mono-core wire 0.05 mm in diameter. Furthermore, we challenged the limits of diameter reduction in the present drawing technique, and eventually, the Monel sheathed MgB_2 mono-core superconducting wire with 0.015 mm in diameter and 135 m in length was obtained. This is currently the thinnest MgB_2 superconducting wire in the world.**

***Index Terms*—MgB_2, wire, in-situ process, powder in tube process, die-drawing, fine diameter, twisted cable, flexibility**

I. Introduction

FACING global environmental problems, such as climate change, global warming, etc., we have to enable a sustainable world as soon as possible. Hydrogen is world-widely garnering attention as a crucial energy resource in achieving carbon neutrality [1]. If liquid hydrogen becomes familiar to our society, superconducting applications operating at 20 K may be able to contribute to saving energy. MgB_2 superconducting wire is promising for practical conductor at 20 K because it has a high T_c of 39 K [2], small superconducting anisotropy [3], no weak-link problem [4], lightweight, simple chemical composition, possibly to make round wires [5], [6], expect low production cost [7], etc. The critical current in MgB_2 superconducting materials depends on the connectivity between grains and the density of pinning centers [8], [9]. Although MgB_2 multifilamentary wires are already being developed and commercially available from several companies at present [10], [11]. However, in order to meet wide practical applications including AC use with liquid hydrogen, there remain some issues, such as mechanical brittleness, stability, AC loss, etc.

Recently, we are promoting R&D of ultrafine A15 type superconducting wires having a very small diameter much less than human hair. In principle, the bending strain decreases with decreasing the wire diameter, therefore, we may expect that the brittle compound superconducting wire becomes flexible through the wire diameter reduction. This is a big advantage of applying the React and Wind method for magnet fabrication, and it would minimize the fabrication cost and improve the magnetic field quality. So far, we successfully fabricated the jelly-rolled Nb_3Al monofilament wires having 0.05 mm in outer diameter and over 400 m in length [12], [13] as well as the bronze processed Nb_3Sn 19 filaments wires having 0.05 mm in outer diameter and over 7 km in length [14].

In this paper, we studied the limit of the diameter reduction of general in-situ powder-in-tube (PIT) processed MgB_2 mono-core wires through the cold die-drawing technique. The drawing of PIT wires up to very small diameters is not a trivial process and the critical current density of thin wires is usually reduced for diameters [15]. We also made the bundled cables using the obtained ultrafine MgB_2 wires. Their superconducting properties, such as the critical temperature and the critical current were investigated.

II. Experimental Procedures

A. In-Situ PIT(Powder-In-Tube) Process

We made the precursor wires through the *In-Situ* PIT(Powder-In-Tube) process using commercial Mg powders (99.8% purity, under 45 μm of particle size) and commercial amorphous B powders (99.0% purity, under 350 nm of particle size). The outermost tubes 14.3 mm in outer diameter and 10 mm in inner diameter used the OFC (oxygen-free Cu) and Monel (Ni-based Cu alloy). The pure Nb tube was inserted in the OFC or Monel for a diffusion barrier. Mg and B powders were manually mixed with an atomic ratio of 1:2 in the groove

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box in the Ar atmosphere, and the mixtures were filled in the Nb tube with applying a vibration. It was no carbon doping in this study. Both ends of the Nb tube were tightly stuffed with Cu caps and it has been avoided a remarkable oxidation of powder mixtures after taking it out into the open air.

B. Wire Drawing

Eventually, the PIT precursor billet had an outer diameter of 14.3 mm and a length of about 200 mm. Before the wire drawing, the billet diameter was reduced by using the swaging machine from 14.3 mm to about 5.0 mm. Then, the wire drawing from 5.0 mm to 0.6 mm in diameters were performed by using general hard steel metal dies and a lubricant of a rapeseed oil. It is used 4 meters draw-bench for drawing from 5.0 mm to 2.0 mm in diameter, and is used a horizontal single-head drawing machine for drawing from 2.0 mm to 0.6 mm in diameter. An area reduction ratio between dies was consistently about 11 % and the drawing speed was approximately 5.0 m/min. No wire-breakages were happened down to 0.6 mm. And the wire drawing from 0.6 mm to 0.05 mm in diameters was performed by using the wet typed continuously multiple cold drawing machine with diamond dies. The entrance angle for every die was 60 degrees. The approach angle was selected at an appropriate angle between 6 and 15 degrees. The die-bearing length was 30% of the inner hole diameter. A general area reduction ratio between dies was 10-20 % and the drawing speed was 50-100 m/min. A part of the 0.05 mm wire has been tried additionally to draw down to a much smaller outer diameter. In addition, some ultrafine wires were used for fabricating 7 or 49 bundled primally twisted cables in one step.

C. Superconducting Properties and Microstructures

The resistivity critical temperature was measured by DC four probe method with appropriate constant current. The distance between the voltage taps and the current taps are 10 mm and 40 mm, respectively. Measurement wire samples were set at an appropriate stable temperature position from the surface of liquid helium and a temperature was controlled by small coil heater with a ramping rate of 4.0 K/h. The critical current in liquid helium (4.2 K) was also measured by DC four probe method under the applied magnetic field using 18T superconducting magnet at National Institute for Materials Science. The external magnetic fields were applied perpendicular to the wire/cable samples.

Microstructures of the cross-section of the wire and cable samples were studied by using an optical microscope (Nikon, ECLIPSE-LV150) and a scanning electron microscope (Hitachi, TM3030Plus).

III. Experimental Results

A. The OFC sheathed Wires and Cables

Fig. 1 shows the enlarged SEM images of the transverse cross-section of the powder-filled core on the OFC sheathed MgB_2 wires with different outer diameters, (a) 0.6 mm, (b) 0.4 mm, (c) 0.2 mm, and (d) 0.12 mm, respectively. There is a large difference of two orders of magnitude in the particle size between Mg and amorphous B raw powders. It was clearly observed that a crack in the coarse Mg particle as shown in Fig. 1 (a), and was also observed Mg particle size became small with a decrease in the wire diameter. Thus, it was recognized that coarse Mg powders surrounded by B fine powders would be gradually grounded through a drawing process. The wire breakage happened not frequently for the outer diameter from 0.6 mm to 0.12 mm, but that happened below 0.12 mm in outer diameter. The maximum piece lengths of 1,115 m, 1,001 m, and 478 m were obtained for the MgB_2 wires with 0.12 mm, 0.07 mm, and 0.05 mm in outer diameter. The wire drawing speed from 0.6 mm to 0.05 mm was a constant which was 100 m/min. Fig. 2 (a) is the optical microscope image of the transverse cross-section of the 7 strands bundled cable fabricated by using MgB_2 wire 0.05 mm in diameter (to be shown as 7/0.05). The twist pitch length is 5.0 mm and the cable diameter is 0.15 mm. Fig. 2 (b) is that of

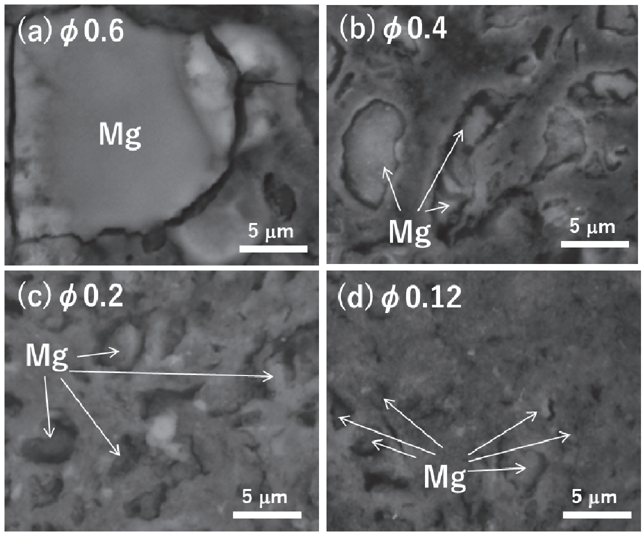

Fig. 1. The enlarged SEM images of the transverse cross-section of the powder-filled core on the OFC sheathed MgB_2 wires with different outer diameters, (a) 0.6 mm, (b) 0.4 mm, (c) 0.2 mm, and (d) 0.12 mm, respectively.

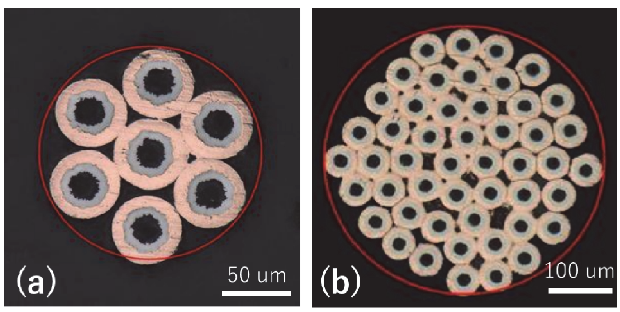

Fig. 2. Optical microscope images of the transverse cross-section of (a) the 0.05 mm and 7 strands MgB_2 bundled cable (7/0.05) and (b) the 0.05 mm and 49 strands MgB_2 bundled cable (49/0.05). The cable diameters are 0.15 mm and 0.41 mm, and twist pitch lengths are 5.0 mm and 8.0 mm, respectively. The twist direction of both cables is the same as S (clockwise) direction.

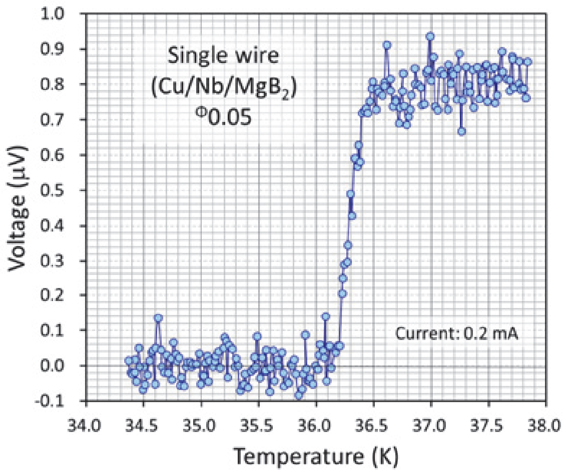

Fig. 3. The voltage and temperature curve of MgB_2 mono-core wire 0.05 mm in diameter after the reaction at 650 ºC for 30 min. The voltage tap distance is 10 mm and measurement current is 0.3 mA.

the 47 strands bundled cable (to be shown as 49/0.05). The twist pitch length is 8.0 mm and the cable diameter is 0.41 mm. The twist direction of both cables is the same as S (clockwise) direction. These cables show surprisingly flexible mechanical performance after heat treatment, although the central core of all wires of the cable is MgB_2 which is a brittle compound.

Fig. 3 is the voltage versus temperature curve of MgB_2 mono-core wire 0.05 mm in diameter with the heat treatment at 650 ºC for 30 min. The critical temperature, T_c (on set) is about 36.5 K and T_c (off set) is about 36.2 K. The superconducting transition width is about 0.3 K, which would be a sharp transition. In General, heat treatment of the in-situ MgB_2 wire is performed at a rather lower temperature, such as around 650 ºC, in order to reduce remarkable grain growth. Therefore, those T_c values are somewhat lower than that of the MgB_2 bulk sample (~39 K), because MgB_2 crystal structure in the wire sample may slightly be disordering and off stoichiometry composition. In addition, T_c value is more depressed by C doping because C contributes the lattice parameter changes [16]. Fig. 4 shows the transport critical current (I_c) at 4.2 K under the applied magnetic field (B) of MgB_2 mono-core wire with different diameters, 0.5 mm, 0.2 mm, 0.12 mm, 0.07 mm, and 0.05 mm. The I_c criterion was used as 1 μV/cm. Fig. 5 shows the critical current density (J_c) which was calculated from the I_c as shown in Fig. 4 divided by the cross-sectional area of superconducting MgB_2 core. The I_c was decreased monotonically with decreasing the wire diameter, but the J_c has kept the mostly same values for all wires. This result may suggest that remarkable sausaging did not happen even though the wire drawing was performed to 0.05 mm in diameter, which is much less than that of human hair. Fig. 6 shows the comparison in the transport I_c -B curves of 0.05 mm single wire, 7/0.05 cable, and 47/0.05 cable. The transport I_c was increased almost by the number of bundled wires. This is very promising results for the practical application point of view because the current capacity could be increased easily by increasing the number of bundles.

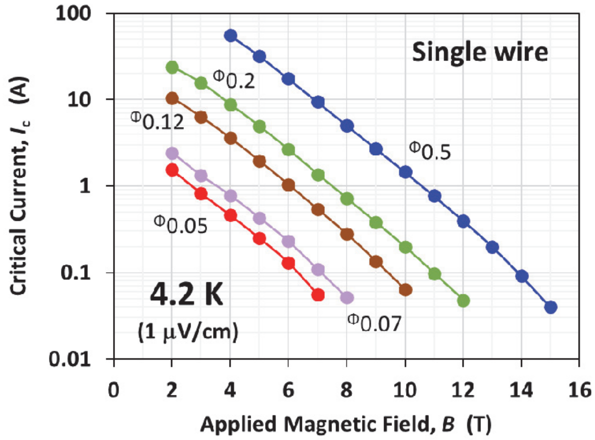

Fig. 4. The critical current (I_c) at 4.2 K under the applied magnetic field (B) of MgB_2 mono-core wire with different diameters, 0.5 mm, 0.2 mm, 0.12 mm, 0.07 mm, and 0.05 mm. The I_c criterion was used as 1 μV/cm.

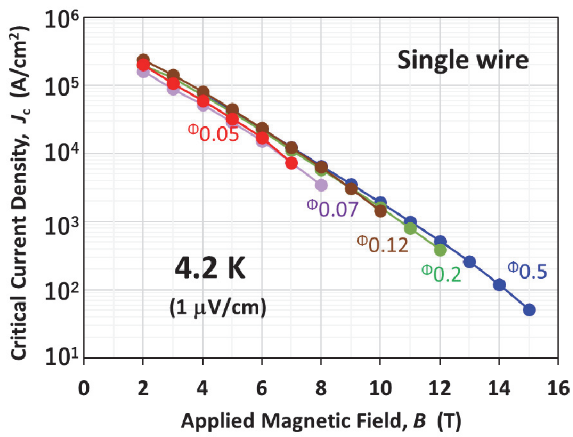

Fig. 5. The critical current density (J_c) at 4.2 K under the applied magnetic field (B) of MgB_2 mono-core wire with different diameters, 0.5 mm, 0.2 mm, 0.12 mm, 0.07 mm, and 0.05 mm. The J_c was calculated from the I_c as shown in Fig. 4 divided by the cross-sectional area of MgB_2 core.

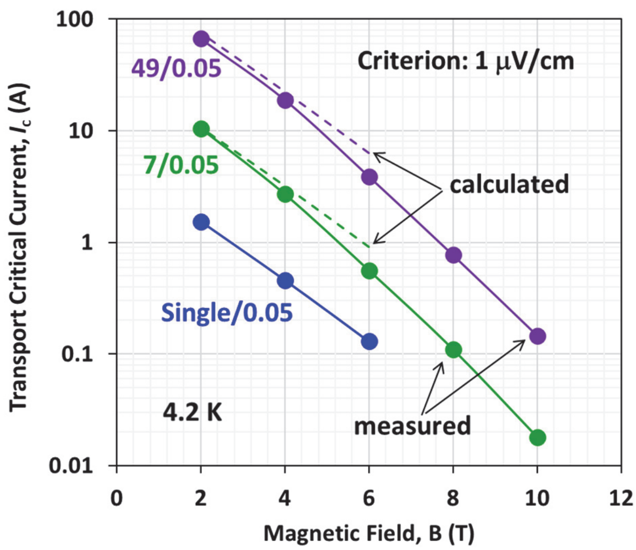

Fig. 6. The critical current (I_c) at 4.2 K under the applied magnetic field (B) of 0.05 mm single wire, 0.05 mm and 7 strands bundled cable (7/0.05) and 0.05 mm and 49 strands cable (49/0.05).

B. The Monel sheathed Wire

Monel, which is Ni-based Cu alloy, is known to show mechanical performance both high strength and excellent plastic workability, and is already used as the sheath material for some of commercial MgB_2 wires [10], [11]. For improving the wire drawability, the outermost sheath material switched from OFC to Monel in this study. The wire breakage was apparently decreased and it was successfully obtained 4 km of long piece length for Monel sheathed MgB_2 mono-core wire 0.05 mm in diameter. The OFC sheathed wire 0.05 mm in diameter showed 720 MPa of tensile strength and 1.3 % of elongation at room temperature. On the other hand, The Monel sheathed wire showed 1,450 MPa of tensile strength and 2.4 % elongation at room temperature at the same diameter. Both values of the Monel sheathed wire are approximately two times larger than those of the OFC wire. In addition, it was also obtained 3 km long piece length for the Monel sheathed wire 0.033 mm in diameter. Furthermore, we tried to draw down a much thinner diameter and finally could fabricate the Monel sheathed MgB_2 mono-core superconducting wire 0.015 mm in diameter and 135 m in length. This is the thinnest MgB_2 superconducting wire in the world at the moment. The SEM image of the transverse cross-section of 0.015 mm MgB_2 ultrafine wire is shown in Fig. 7. The MgB_2 superconducting core diameter is about 0.0055 mm. After the heat treatment at 650 °C for 30 min, T_c is obtained about 35.5 K, which was slightly lower than that of the wire 0.05 mm in diameter.

IV. Conclusion

We successfully fabricated the ultrafine MgB_2 superconducting wires with small diameters which is less than a human hair. Those bundled cables show surprisingly flexible mechanical performance even after the heat treatment. In addition, very low AC loss could be strongly expected because of maintaining a low hysteresis loss due to a small SC filament size and a low coupling loss by increasing the contact resistance between the bundled wire surfaces. Therefore, we would conclude that these ultrafine MgB_2 wires and flexible cables in this study are promising for the React & Wind coils probably for AC application in liquid hydrogen.

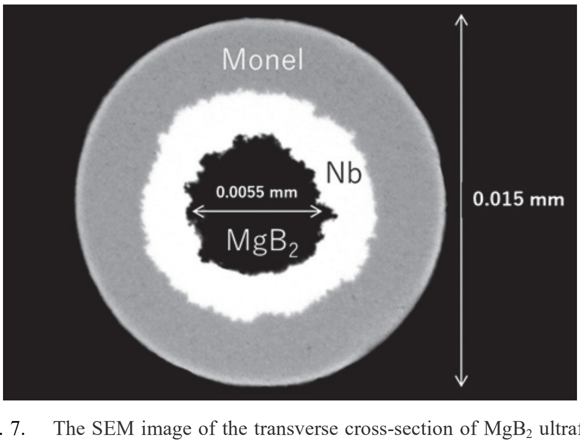

Fig. 7. The SEM image of the transverse cross-section of MgB_2 ultrafine wire 0.015 mm in diameter and 135 m in length.

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