Fundamental Study of MgB_{2} Superconducting Coil for Storage Devices

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The authors carried out a basic study on a power storage coil made of MgB_{2} superconducting wires which was expected to require less cooling and lower manufacturing costs. First, for manufacturing the storage coil, the basic characteristics of MgB_{2} superconducting wire were evaluated. The characteristics at 20 K under 1.5 T were a critical current of 170 A for the in-situ MgB_{2} wire and 200 A for the ex-situ MgB_{2} wire. Based on these results, MgB_{2} conductors and prototype storage coils were produced and their performance was evaluated. The prototype was successfully energized to 600 A under 1.5 T at less than 25 K, which are the basic requirements for several 10 kJ class coils, and there was no significant deterioration through conductor and coil processing.

**Keywords:** superconducting wire, superconducting coil, power storage device, characteristic evaluation, manufacturing technology

1. Introduction

Superconductivity is a phenomenon whereby certain materials have exactly zero electrical resistance when they are cooled below a certain temperature, and these materials are called superconductors. Figure 1 shows superconducting material divided into "superconducting bulk" and "superconducting wire," depending on the form it takes, and active research and development is underway on these materials, to find new ways to use them.

The superconducting bulk used as a block is expected to significantly improve the performance of various devices by applying it to magnetic field sources of analyzers, magnetic transport of medicines, current leads, magnetic bearings, etc. The magnetic strength of a typical permanent magnet is less than 1 Tesla (T), while that of superconducting bulk reaches over 17 T [1, 2]. On the other hand, the superconducting wire used in a state where it is thinly stretched can be energized with zero electrical resistance, and no heat is generated by the energization, so a large current can be energized. In an attempt to make the most of such properties, research and development is being conducted in power application fields, for products such as superconducting magnets, superconducting coils, and superconducting cables [3].

RTRI is currently engaged in research and development on a wide range of areas, from producing superconducting materials to their various applications. Research centers not only on using standard superconducting materials in equipment, but also increasing superconducting performance, by improving manufacturing processes and
the shape of the material to achieve optimal performance suited to the device or equipment in question.

Currently NbTi and Nb3Sn are used for superconducting magnetic energy storage devices (SMES) which are power storage devices. Although NbTi and Nb3Sn are highly stable and reliable, running costs are high when using them, because liquid helium which is employed as the refrigerant is expensive. Fundamental studies were conducted on MgB2 superconducting coils for storage, and power storage devices for power systems and railways were developed.

2. Magnesium diboride (MgB2) superconductor

The MgB2 superconductor is a relatively new discovery made in 2001[4]. It has the highest critical temperature of 39 K in metal-based superconductors, and operates at higher temperatures which reduces cooling costs. Furthermore, MgB2 is light weight and inexpensive, as it is composed of only light elements such as boron (Ba) and magnesium (Mg). As such, research into practical applications of this material is actively underway.

Conventional superconducting bulks are made using rare earth (RE)-based superconducting bulks consisting mainly of RE oxides, barium (Ba) and copper (Cu). However, since crystal growth from a seed crystal is required in the manufacturing process, it is difficult to manufacture large samples and poor yields are a problem. MgB2 superconducting bulk can be used at lower temperatures than RE-based superconducting bulk, and can be manufactured by sintering the materials under uniform pressure, making it possible to manufacture large bulks of φ100 mm. Furthermore, MgB2 superconducting bulk can easily be manufactured into any shape, making it suitable for precision instruments such as NMR and MRI.

In the case of superconducting wires, metal-based superconductors such as NbTi and Nb3Sn are generally employed to make superconducting coils and magnets, which require liquid helium to cool them. Recent research, however, has brought progress for high-temperature superconducting materials such as RE-based superconducting materials and superconducting bulks. These materials are available at liquid nitrogen temperatures and are very promising in their applications. The key drawback, however, with these materials is that REs are expensive, and manufacturing is complex, generating higher costs. To minimize material cost therefore, work was launched to develop and commercialize MgB2 wire. Development of MgB2 wire has just started, and in the next 10 years, the goal is to raise the existing critical current characteristics of the material at 20 K of 3 T, to five times this level, and cut costs to 1/20 [5]. RTRI has therefore been working on the production of a storage coil using the MgB2 wire, which is expected to reduce manufacturing and cooling costs [6].

3. Development of a prototype storage coil

With a view to developing a 33 kJ class storage coil, a small prototype storage coil was produced for a basic study to evaluate the superconducting characteristics that would be required for manufacture. Table 1 shows the specifications required for a 33 kJ class coil, which indicates that achieving the target energy storage should be possible through energization at 600 A. 600 A was therefore supplied to the prototype coil, and its performance was evaluated at 1.5 T. The current capacity of a single strand of MgB2 wire, however, is small. Therefore, multiple strands of wire need to twisted together to achieve the current capacity required for the storage coil. Following this, the MgB2 wire characteristics were evaluated in a magnetic field. Prototypes of multiple strand MgB2 conductors were prepared, that could be energized to over 600 A at 20 K under 1.5 T, and then storage coils using these different wire configurations were also produced.

| Stored energy [kJ] | 33 |
|-------------------|----|
| Inductance [H]    | 0.18 |
| Operational current [A] | 600 |
| Maximum B field [T] | 1.5 |
| Inner diameter [mm] | 450 |
| Outer diameter [mm] | 660 |
| Height [mm]       | 77.4 |
| Items [-]         | 8 DP |
| Num. of turns [-] | 500 |

3.1 Specifications of MgB2 wires

MgB2 wires need to heat-treated before it can be used as a superconductor. Heat treatment however weakens the material to bending strain and causes deterioration. Nevertheless, in order to produce a large coil, heat treatment must be applied before coiling because it is impossible to heat-treat the wire after coiling unless there is an available furnace large enough to house the coil. This paper compares the characteristics of both heat-treated MgB2 wire (performed by Columbus Superconductors SPA) and non-heat-treated MgB2 wire (30-NM made by HyperTech Research Inc.).

The heat-treated MgB2 wire made by Columbus Superconductors SPA was heat-treated before shipment, and
electric field criterion

**3.2 Specifications of MgB₂ wires**

In order to evaluate the characteristics of the MgB₂ straight wire, the critical current value as a function of the external magnetic field and temperature were evaluated. The characteristic evaluation system for MgB₂ wire is a device combining a vacuum vessel, a refrigerator and a current lead. The MgB₂ wire was cooled in a refrigerator, an external magnetic field was applied using a 10 T superconducting magnet, and electricity was supplied using a DC power supply (Fig. 4).

As a result, it was found that the wire manufactured by Columbus had a critical current value of over 200 A under 1.5 T at 20 K (Fig. 5). The magnetic field dependence of the critical current at 2 K intervals from 20 K to 30 K is shown in Fig. 6. This method made it possible to acquire the data, such as temperature range, and magnetic field

**Fig. 3** Cross section of MgB₂ wire made by HyperTech Research Inc

consisted of a copper core, an iron layer and 12 MgB₂ filaments covered with nickel arrayed from the centre, as seen in Fig. 2 showing a cross section of the wire. The non-heat-treated MgB₂ wire made by HyperTech Research Inc. was not heat-treated before shipment, so heat treatment was performed at 650°C for 1 hour in an argon atmosphere. Figure 3 showing its cross section therefore illustrates copper core 30 MgB₂ filaments covered with niobium and monels arrayed from the centre.

**Fig. 4** The characteristic evaluation system for MgB₂ wire

**Fig. 5** I-V property of MgB₂ wire made by Columbus Superconductors SPA

**Fig. 6** Magnetic field dependence of critical current of MgB₂ wire made by Columbus Superconductors SPA

**Fig. 7** I-V property of MgB₂ wire made by HyperTech Research Inc
range, required for twisting the wire.

It was found that as for the wire manufactured by HyperTech Research Inc., a critical current value of about 170 A was obtained at 20 K under 1.5 T (Fig. 7). The magnetic field dependence of the critical current at 2 K intervals was retrieved, is shown in Fig. 8. It became clear that the temperature and the magnetic field dependence of the critical current was similar in both wires.

As mentioned above, the basic data which can be reflected in the design of a conductor or a coil were able to be acquired for the MgB₂ wire made by HyperTech Research Inc., and the MgB₂ wire made by Columbus Superconductors SPA. Based on these characteristics, the authors designed and manufactured a storage coil.

### 3.3 Specifications of the prototype storage coil

There are two well-known methods for manufacturing coils, one is the Wind & React method (W&R method) in which heat treatment is performed after coil winding, and the React & Wind method (R&W method) in which coil winding is performed after heat treatment. In manufacturing the storage coil, it is important to verify under various conditions such as the type of MgB₂ wire, the shape of the stranded conductor, and the winding method. At first, in this paper, prototype coil was manufactured using the W&R method using a Rutherford-type MgB₂ conductor (Fig. 9). The specifications are shown in Table 2. Non-heat treated MgB₂ wire was used to allow more bending strain than the heat-treated MgB₂ wire. The Rutherford-type MgB₂ conductor consisted of 4 Cu-Ni wires with the same diameter as a MgB₂ wire and 8 non-heat-treated MgB₂ wires made by HyperTech Research Inc. would around a Cu racetrack former. When designing the Rutherford-type MgB₂ conductor and coil, the complex strain exerted on the wire strands was analyzed using differential geometry. Figure 10 shows the strain on the wire at each coordinate with the coil centre as the origin.

Figure 10 shows an example of composite strain distribution in a design for coiling the conductor with a twist pitch of 51 mm and radius of 100 mm. The maximum strain by design must fall within the tolerance of 1.54%. The structure of the manufactured storage coil was wound with 10 turns with an inner diameter of 200 mm. After coiling, heat treatment was performed in a vacuum at 650 °C for 1 hour, followed by resin impregnation to further im-

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### Table 2 Specifications of prototype storage coil

| Type                          | Single Pancake |
|-------------------------------|----------------|
| Production methods            | W&R            |
| Inner diameter [mm]           | 200            |
| Outer diameter [mm]           | < 320          |
| Num. of turns [-]             | 10             |
| Nominal current [A]           | 600            |
| Stored energy [J]             | 7.3            |
| Maximum B field [T]           | 0.17           |

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Fig. 8 Magnetic field dependence of critical current of MgB₂ wire made by HyperTech Research Inc

![Fig. 8 Magnetic field dependence of critical current of MgB₂ wire made by HyperTech Research Inc](image)

Fig. 9 Cross section of MgB₂ conductor

![Fig. 9 Cross section of MgB₂ conductor](image)

Fig. 10 Analytical model for stranded bending strain of coil

![Fig. 10 Analytical model for stranded bending strain of coil](image)

Fig. 11 Prototype storage coil

![Fig. 11 Prototype storage coil](image)
prove its mechanical properties. The resulting storage coil is shown in Fig. 11.

3.4 Characteristic evaluation of the storage coil

The storage coil characteristics are evaluated using the same method as for the wire: a vacuum vessel, a refrigerator, and a current lead (Fig. 12). The storage coil was cooled in a refrigerator, an external magnetic field was applied using a 5 T superconducting magnet, and electricity was supplied using a DC power supply. The magnetic field dependence of the current-voltage characteristics at 20 K of the storage coil is shown in Fig. 13.

![Fig. 12 The characteristic evaluation system for MgB₂ coil](image)

At 20 K, voltage did not rise even when a current of 600 A was applied under less than 2.0 T. The temperature dependence of the current-voltage characteristics under less than 1.5 T of the storage coil is shown in Fig. 14. At 1.5 T, the voltage did not rise even when a current of 600 A was applied under a magnetic field at less than 24 K. The temperature-magnetic field dependence of the critical current is shown in Fig. 15.

At the maximum B field 1.5 T of a 33 kJ class coil, it was possible to obtain an operating current of 600 A can at 25 K or below, and even when the conductor of the present configuration was wound into a coil, there was no deterioration in performance such as a significant decrease in critical current density. This confirmed that performance could be guaranteed.

4. Conclusions

A storage coil using MgB₂ superconducting wire was developed with a view to reducing manufacturing and cooling costs. As a result, the following findings were obtained:

![Fig. 13 Magnetic field dependence of I-V property of MgB₂ coil at 20 K](image)

![Fig. 14 Temperature dependence of I-V property of MgB₂ coil under 1.5 T](image)

![Fig. 15 Magnetic field and temperature dependence of critical current of MgB₂ coil](image)
(1) The superconducting properties of two types of MgB$_2$ wire were evaluated in the temperature range of 20 K to 30 K under a magnetic field of 3.5 T or less, which are the basic requirements for stranding and coiling: non-heat treated superconducting wires made by HyperTech Research Inc.; and heat-treated superconducting wire produced by Columbus Superconductors SPA.

(2) The superconducting properties of the conductor after coiling were evaluated. As a result, it was confirmed that there is no significant drop in the critical current due to coiling the conductor within the appropriate strain range, and that performance can be guaranteed even if stranded wire is wound onto a coil.

(3) It was confirmed that within the 33 kJ class coil operating range of 1.5 T and when energized with a constant 600 A at less than 25 K, it was possible not to generate voltage. Also, by obtaining the temperature and magnetic field dependence of the critical current characteristics required for coiling across a wide range of conditions, it was possible to secure the necessary coil characteristics even when the configuration of the 33 kJ class coil was changed.

Based on the data obtained from this study, and by continuing to investigations into the design and manufacture of large coils such as the 33 kJ class coil, future work will aim to develop coils for large-capacity storage devices that can be used for railways and, more generally storage of electric power.

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