Superconducting Properties of a Prototype Pancake Coil using a MgB$_2$ Rutherford-type Stranded Conductor

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Abstract. Our group has developed a coil using MgB$_2$ wires for SMES. In this paper, a prototype coil using a MgB$_2$ Rutherford-type stranded conductor was fabricated based on react-and-wind (R&W) method. In the R&W method, a Rutherford-type conductor in which nine MgB$_2$ wires were wound at pitch of 450 mm around a copper former were manufactured using reacted wires (performed by Columbus Superconductors SpA), and then coiling was performed. The coil was cooled by conduction cooling and the $I$-$V$ properties were evaluated under magnetic field. As a result, in the R&W method, critical current of a coil was degraded, since making a coil by hand would cause the strain beyond the scope of the assumption which was the marginally allowable bending strain. This result suggests the coil for SMES proposed in ASPCS is difficult to react before twisting, and Rutherford-type conductors should be fabricated before reacting, which means that coil processing should be performed based on the React after making stranded conductors and Wind method, or the wind-and-react method.

1. Introduction

Many developments have been made since the discovery of magnesium diboride (MgB$_2$). The manufacturing costs of MgB$_2$ are lower than that of other high temperature superconducting wires since MgB$_2$ consists of only light elements, so that raw materials and production processes are low cost. Furthermore, MgB$_2$ has a relatively high superconducting transition temperature of $\sim 39$ K [1], and can
be operated in the liquid hydrogen (LH$_2$) temperature region, whereas many conventional superconducting materials are operated in the liquid helium, which is very expensive and severely depleted, temperature range. Thus, applications using MgB$_2$ wires are one of the most promising materials for superconducting applications operated in LH$_2$. In this background, our group and other groups have proposed a combined hybrid storage system, which is composed of a Superconducting Magnetic Energy Storage (SMES) and fuel cell-H$_2$-electrolyzer devices and is installed adjacent to a LH$_2$ for vehicles [2]–[10]. Therefore, our group has proposed MgB$_2$ coils for SMES in the Advanced Superconducting Power Conditioning System (ASPCS) [5], [8]. In ASPCS, several kJ class coils are required for SMES and MgB$_2$ wires are required to carry 600 A under 1.5 T at 20 K [9], [10]. In recent years, many groups have developed prototype applications using MgB$_2$ strands, and in coil applications, coils using MgB$_2$ single wires has been mainly conducted [11],[12], while our group has developed coils using MgB$_2$ stranded conductors. In this paper, in order to prove the possibility of the MgB$_2$ coil made of a high current Rutherford-type stranded conductor by the react and wind (R&W) method, strain analyses on stranded conductor [13] and coiling were conducted since reacted MgB$_2$ wire is very sensitive to bending strain. A small prototype coil was designed with the marginally allowable bending strain of 0.24, which is the manufacturer’s nominal value. Furthermore, the critical current ($I_c$) of a MgB$_2$ wire and small prototype coil was evaluated as a function of external magnetic field ($B$) and temperature ($T$).

2. EXPERIMENTAL
In order to design a MgB$_2$ Rutherford-type stranded conductor and coil by the R&W method for SMES in ASPCS, the characteristics of the reacted MgB$_2$ straight wire (performed by Columbus Superconductors SpA) as a function of the external magnetic field and temperature under conduction cooling were evaluated. Developed $I_c$-$B$-$T$ characteristic evaluation system for a straight MgB$_2$ wire was composed of a cooling system with a vacuum vessel and 10 K refrigerator, a current introduction part with a 3600 A current supply and HTS leads, and 10 T superconducting magnet. The MgB$_2$ 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 (Figure 1). Based on these results and catalog allowable strain limit, a small prototype coil was designed and the characteristics in the magnetic field were evaluated.

![Figure 1](image)

**Figure 1.** Developed $I_c$-$B$-$T$ characteristic evaluation system for MgB$_2$ wire

3. RESULTS & DISCUSSION
The current-voltage characteristics at 20 K under 1.5 T of a single MgB$_2$ wire is shown in Figure 2. Thermal runaway phenomena was not observed and $I_c$ was over 200 A at 20K under 1.5 T. Here, $I_c$ was
defined as the current in the critical electric field of 1 μV/cm. Thus, we succeeded in developing \( I_c-B-T \) characteristic evaluation system in conduction cooling condition and this developed system enabled us to measure a series of \( I_c \) as a function of \( B \) and \( T \). \( I-V \) measurements were carried out at temperatures intervals from 20 K to 30 K and in various external magnetic fields (1-2.5 T). Figure 3 shows \( I_c-B-T \) properties of a single MgB\(_2\) wire. \( I_c \) decreased systematically with the increase of temperature and magnetic field, and \( I_c \) under 1.5 T at 20 K exceeded 200 A. Thus, we succeeded in getting fundamental data of \( I_c \) at various temperatures and in various external magnetic fields, which is necessary for designing the stranded conductor.

In ASPCS, several kJ class coils are required for SMES and MgB\(_2\) wires are required to carry 600 A under 1.5 T at 20 K [9], [10]. Commercially available single MgB\(_2\) wire is unable to meet these requirements, so we attempted to make a stranded conductor that can carry 600 A under 1.5 T at 20 K using a number of MgB\(_2\) wires. In view of the risk of coil degradation and burnout, a Rutherford-type stranded conductor consisted of nine MgB\(_2\) wires wound around a racetrack copper former. Figure 4 shows the external appearance of a small prototype coil using the conductor and a schematic diagram of the cross-section of the conductor. Table 1 shows the specifications of the MgB\(_2\) coil. The cross-sectional dimensions of the conductor are 5.26×3.26 mm\(^2\) with the twist pitch of 450 mm, and the dimensions of the coil were 250 mm inner diameter and 303 mm outer diameter. In order to keep the designed bending strain below the allowable bending strain, therefore, a conductor pitch of 450 mm that can maintain the shape was designed. Thus the designed maximum bending strain was 0.19 % which met the supplier’s requirement of less than 0.24%.

![Figure 2. The current-voltage characteristics of a single MgB\(_2\) wire at 20 K under 1.5 T in conduction cooling condition.](image1)

![Figure 3. The \( I_c-B-T \) properties of a single MgB\(_2\) wire at various temperatures (20-30 K) and in various external magnetic fields (1-2.5 T).](image2)

![Figure 4. External appearance of a small prototype coil using a Rutherford type stranded conductor and schematic diagram of the cross-section of the conductor.](image3)
Table 1. Specifics of MgB$_2$ coil

| Production method | R&W |
|-------------------|-----|
| Inner diameter (mm) | 250 |
| Outer diameter (mm) | 303 |
| Num. of turns ( - ) | 5 |
| Nominal current (A) | 600 |
| Height (mm) | 4.21 |
| Twist pitch of conductor (mm) | 450 |

To check the degradation by cabling and coiling, the superconducting properties of the prototype coil were measured. The coil was cooled below 20 K by refrigerators and $I$-$V$ measurements were carried out at various temperatures (20–30 K) and in various external magnetic fields (1–2.5 T). Figure 5 shows the current-voltage characteristics at 20 K under 1.5 T of a small prototype MgB$_2$ coil. Thermal runaway phenomena was not observed, while $I_c$ was over 300 A at 20 K under 1.5 T half as much as the target value of 600 A. Figure 6 shows $I_c$-$B$-$T$ properties of a small prototype MgB$_2$ coil. $I_c$ decreased systematically with the increase of temperature and magnetic field.

![Figure 5](image1)

**Figure 5.** The current-voltage characteristics at 20 K under 1.5 T of a small prototype MgB$_2$ coil under conduction cooling.

![Figure 6](image2)

**Figure 6.** The $I_c$-$B$-$T$ properties of a small prototype MgB$_2$ coil at various temperatures (20-30 K) and in various external magnetic fields (1-2.5 T).

Compared with the result of $I_c$ of the single MgB$_2$ wire as shown in figure 3, $I_c$ of the MgB$_2$ coil is considerably lowered. One of the reasons is that the coil was designed with the limit of allowable bending strain of 0.24 and manufactured by hand, so that strain beyond the scope of the assumption was added during production processes such as twisting wires for a Rutherford-type stranded conductor. According to various researches of other groups [14], it is well-known that strain over allowable bending strain results in significant degradation of $I_c$ for a commercially available MgB$_2$ wire. Therefore, this result suggest some of the 9 MgB$_2$ wires deteriorated, decreasing in the overall critical current value.

As a result, it is difficult to employ reacted wires for the coil for SMES proposed by ASPCS, which is required current-carrying capacity beyond that of the single MgB$_2$ wire. Therefore, to achieve the high current-carrying capacity by a stranded conductor, it is necessary to fabricate stranded conductors before...
React in which MgB$_2$ phase is produced, which means that coil processing should be performed based on the React after making stranded conductors and Wind method, or the W&R method.

4. Conclusion
In ASPCS, several kJ class SMES were examined. In this paper, we fabricated and evaluated a R&W MgB$_2$ coil using a Rutherford-type stranded conductor. In order to confirm its fundamental performance, the critical current characteristics of the MgB$_2$ wire and fabricated coil at various temperatures and in various external magnetic fields were evaluated under conduction cooling. In case of MgB$_2$ wire, thermal runaway phenomena was not observed and $I_c$ was over 200 A at 20K under 1.5 T. On the other hand in case of MgB$_2$ R&W coil, thermal runaway phenomena was not observed, while $I_c$ was over 300 A at 20 K under 1.5 T half as much as the target value of 600 A. These results raise grave concerns about degradation of designed coils with the marginally allowable bending strain based on the R&W method. In R&W method coil, since the maximum bending strain is applied during conductor processing, the method of reacting after conductor processing is more suitable. The W&R method in the previous report has been found to show no significant degradation [15]. These results suggest that coil processing should be performed by the reacting R&W method after making the conductor, or the W&R method.

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