Preliminary study of HTS magnet using 2G wires for maglev train

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Abstract. There are several advantages by applying a high temperature superconducting wire to an on-board superconducting magnet for the maglev train. At first, an increase of thermal capacity of superconducting coils contributes a stability of the superconducting state of the coils. In addition, a reliability of superconducting magnet improves by simplification of the magnet structure. And the weight of the superconducting magnet and the energy consumption of the on-board cryocooler will decrease. Therefore, we examined the possibility on application of the 2G wire with a high critical current density in a high magnetic field. We performed numerical analysis regarding the weight of a superconducting magnet and the energy consumption of an on-board cryocooler in consideration of the characteristics of the 2G wire. Furthermore, we have carried out the \( I_c \) measurement for the commercial 2G wires under various experimental conditions such as temperature, magnetic field strength and angle. We also performed the trial manufacture and evaluation of \( I_c \) characteristics for the small race track-shaped superconducting coil.

1. Introduction

Since superconducting magnets are used in the maglev high-speed mass transportation, it is desirable that they are highly reliable, lightweight, and low cost.

The development of 2G wires has progressed remarkably in recent years. Last year, Selvamanickam and Xie reported a critical current (\( I_c \)) in excess of 800 A/cm with a wire \( \geq 1 \text{ m} \) in length, and future progress is expected [1]. For application in superconducting systems, 2G wires have two main advantages over Bi wires (1G wires): First, the critical current density at high temperature and high magnetic field is large; second, the mechanical strength of the wire itself is excellent even it is bent into a curve with a radius of 10 mm, there is little degradation of \( I_c \).

We believe that it is feasible to create a lightweight and reliable superconducting magnet for the maglev transportation, applying wires with such characteristics. If the wire performance improves and we can raise the operating temperature of a superconducting coil to approximately 50 K, some of the concepts as evident in Figure 1 will come into reality.

With an increasing thermal capacity, the stability of the coils will improve dramatically. For example, in the case of copper, the specific heat at 50 K is approximately 1,000 times of that at 4 K. 2G coils can be cooled using a single stage cryocooler, whereas a Gifford-McMahon/Joule-Thomson (GM/JT) cryocooler is required to cool Nb-Ti coils. If the temperature of the coil is 50 K, radiation
shield plates and thermal anchors are not required. Consequently, the heat insulation structure can be simplified drastically, and the cross section of the superconducting magnet can be reduced. Moreover, we expect to reduce both the superconducting magnet’s mass and manufacturing costs.

Since the electric gap between a superconducting coil and a ground coil also decreases when the superconducting magnet’s cross section is reduced, the magnetomotive force of the superconducting coil can be reduced.

First, as a fundamental study, we estimated the mass of the main parts of a superconducting magnet using the $I_c$ characteristics of 2G wires, as measured by Holesinger and Civale, and investigated the relationship with the coil operating temperature [2]. The main parts are the superconducting coils and on-board cryocoolers. The mass of both greatly depends on the coil operating temperature.

2. Feasibility study

2.1 Estimation of the mass of superconducting coils

The $I_c$ of 2G wire improves because of the introduction of an artificial pinning center. The improvement of $I_c$ at 77 K in a self-magnetic field is reported in many papers. However, to estimate the mass of the superconducting coil, we have to know the magnetic field dependencies of $J_c$ at various temperatures. There are few reports with such comprehensive data. Holesinger and Civale investigated the magnetic field dependencies of $J_c$ at various temperatures by measuring magnetization of a small sample of 2G wire [2]. We decided to use this data for our calculation. Although the angular dependencies of the magnetic field are important for 2G wires, it was not taken into consideration in this calculation; instead, the $J_c$ characteristics when applying a magnetic field parallel to the c axis were used. It is assumed that the coil cross section is a rectangle and the central line has a racetrack shape. The long axis length of the racetrack is 1.07 m and the short axis length is 0.5 m. The magnetomotive force is 700 kA and the wire load factor is 80%. The wire width is 4.4 mm and its thickness is 0.1 mm. The thickness of the superconducting layer is assumed to be 1 μm. Therefore, the engineering current density ($J_e$) of the wire decreases to 1/100 of $J_c$. Here, one coil is a formed by lamination of six element pancake coils, and the coil width is 26.4 mm. The coil thickness in the radial direction depends on the $J_e$ characteristics of 2G wires.
On the other hand, the cooling temperature and the peak field to which a coil is exposed ($B_{\text{peak}}$) determine the operating current (density) of the coil. When current density is increased while maintaining a constant magnetomotive force, since current increases, $B_{\text{peak}}$ also increases, as shown in Figure 2. The design points of a coil are the crossings of this $J_e$–$B$ curve and the $J_e$–$B_{\text{peak}}$ curve at each temperature. In this way, the operating current density at each temperature was determined. The cross section of a coil, which determines the coil mass, is obtained from the operating current density.

One superconducting magnet consists of four coils; thus, Figure 3 shows the mass of four coils. When the wire load factor is taken into consideration, operating current density becomes 80% of $J_c$. According to Fig. 3, the mass of a coil increases rapidly with a rise in the operating temperature. Since this result changes with the characteristics of 2G wires, we need to investigate the characteristics of critical currents in commercial wires.

### 2.2 Estimation of the mass and power consumption of cryocoolers

In general, if the cooling capacity is constant, the mass of the cryocooler decreases with the cooling temperature, because mass is proportional to power consumption. Nisenoff investigated a number of commercial cryocoolers and created a very useful plot of the mass and power consumption of cryocoolers operating at various temperatures and cooling capacities, as shown in Figure 4 [3]. From the data for temperatures between 20 and 77 K, we produced the following approximate expressions.

$$Q_{\text{in}} = 111943 \times Q_{\text{out}}^{0.8437} \times T_{\text{op}}^{-0.0247} \times Q_{\text{out}}^{-1.7332}$$

$$M = Q_{\text{in}} / 20$$

Here, $Q_{\text{in}}$ is the input or power consumption (W) of a cryocooler, $Q_{\text{out}}$ is the cooling capacity (W), and $M$ is the mass (kg). Because this data is obtained from commercial cryocoolers, it is possible to develop a cryocooler with lighter mass and less power consumption than the results obtained from these expressions.

We considered three main factors of heat leaks to the superconducting magnet: radiation, conduction from current leads, and conduction from supports. The mass and power consumption of the required cryocooler at various operating temperatures were calculated using these equations by assuming a certain amount of heat leakage. We examined two cases.

The first case is where a magnet has radiation shield plates and thermal anchors cooled to 77 K; the second case is where the radiation shield plates and thermal anchors are omitted for simplification of the magnet structure. In the first case, we assume that high-temperature superconducting (HTS)
current leads are used [4]. Because these current leads are made from a high-temperature bulk superconductor, they can drastically reduce heat leakage. In this case, mass and power consumption were calculated supposing two cryocoolers: a 77 K cryocooler that cooled radiation shield plates and a cryocooler that cooled the coils directly.

The second case assumes that only one cryocooler is cooling the coils. Because there is no thermal anchor, the HTS current leads cannot be used. Figure 5 shows the calculation results. Since power consumption is proportional to mass, mass is shown on the left axis and power consumption is shown on the right axis. At temperatures higher than 50 K, there is no remarkable difference due to the presence of shield plates and thermal anchors.

However, at lower temperatures, the effect of shield plates and thermal anchors is remarkable. Figure 6 shows the total mass of coils and cryocoolers. In the case where shield plates and thermal anchors were omitted, the mass of coils and cryocoolers has a minimum at approximately 50 K; for the case with shield plates and thermal anchors, they reach the minimum at approximately 30 K. This latter minimum is lower by approximately 200 kg than the former.

3. Evaluation of 2G wires

Although it was not taken into consideration in the previous section, when shield plates and thermal anchors are removed, there may be weight savings and cost reduction. The characteristics of the wire used for these calculations greatly influenced the results. 2G wires are being developed in many countries, and improvements in performance are expected in the near future. Most reports from a wire manufacturer are improvement in the characteristic at 77 K and in self magnetic field. However, to
examine its application to a superconducting magnet, it is essential to detect accurately its characteristics at lower temperatures or in a higher magnetic field region.

3.1 I-B-θ-T test device

This device features a temperature condition that can be arbitrarily set and a high magnetic field with variable direction. Its purpose is to test the transport characteristics of 2G wires with various parameters consisting of magnetic field strength, magnetic field direction and temperature.

Figure 6 shows a schematic diagram of the device, and Table 1 describes its principal specifications. The end of the vacuum vessel containing the wire sample is inserted into the bore space (400 mm in diameter) of the superconducting coil as the magnetic field source. The wire sample is placed on a sample holder whose axis is perpendicular to the magnetic field direction. In addition, the sample holder can be turned about its axis to confirm the anisotropy of the transport characteristics. After that, θ defines an angle made from the c-axis of the sample wire and the magnetic field direction. The magnetic field of the superconducting coil is a maximum of 5.5 T in consideration of application to superconducting magnets for the Maglev system. The temperature condition can be set to a minimum of 10 K through conduction cooling by a GM cryocooler and heater control. It takes approximately 12 hours to cool an HTS wire sample from room temperature to 10 K using this device.

3.2 Test results

Figure 7 shows the temperature and magnetic field dependence of $I_c$ in the sample 2G wire as shown in Table 2.

**Table 1.** Specifications of I-B-θ-T test device.

| Current ($I$) | $0 \sim 1000$ A |
|--------------|------------------|
| Magnetic field ($B$) | $0 \sim 5.5$ T (Superconducting magnet) |
| Field angle ($\theta$) | $0$, $30$, $45$, $60$ and $90$ deg. |
| Temperature ($T$) | $10$ K $\sim$ (Cryocooler conduction) |

**Table 2.** Specifications of sample 2G wire.

| Width | 4.4 mm |
|------|--------|
| Thickness | 0.2 mm |
| Min. $I_c$ | 70 A (77 K, s.f.) |
| Process | YBCO(TFA-MOD) / Ni-W(RABiTS) |

**Figure 6.** Schematic of I-B-θ-T test device.

**Figure 7.** Temperature and magnetic field dependence of $I_c$ for the sample 2G wire at each $\theta$. 

θ = 0 deg.  \hspace{1cm} θ = 60 deg.  \hspace{1cm} θ = 90 deg.
These results indicate that the $I_c$ value increases with low temperatures and low magnetic fields at a magnetic field angle of 90 degrees. In addition, Figure 7 shows that the transport characteristics at a magnetic field angle of 60 degrees and those at 0 degrees are approximately equal. Accordingly, in application to machinery with a coil-like magnetic field, it is necessary to design with attention to the anisotropy of the wire’s transport characteristics.

4. Trial production and evaluation of small race track-shaped superconducting coil using 2G wires

By using 100 m 2G wire of Table 2, we produced a small race track-shaped coil of 100 mm inside diameter and 150 mm straight part. Figure 8 shows the small race track-shaped coil and Table 3 describes its specifications. This coil is formed from one single pancake coil of 1/4 size for race track dimensions of actual superconducting magnets.

We carried out an $I_c$ evaluation test for this coil with I-B-$\theta$-T test device under a self magnetic field condition. Figure 9 shows the test results and the calculated values of $I_c$. The calculated values of the $I_c$ were obtained from two conditions, one is the $I_c$ characteristics of sample 2G wire like Figure 7 and another one is the magnetic field distribution which occurs at the time of electrification to this coil. Figure 9 shows that there is consistency of the test results and the calculated values at $\theta = 0$ deg. Here, $\theta = 0$ deg means the point that became greatest the self magnetic field which through wire surface perpendicularly.

For the application of 2G wire, the technique to estimate the transport current characteristic of the coil from such of the wire is important.

Table 3. Specifications of trial superconducting coil.

| Wire spec. | See Table 2 |
|------------|-------------|
| Wire length | 100 m       |
| Inside diameter | 100 mm      |
| Outside diameter | 175 mm      |
| Straight part length | 150 mm      |
| Number of turns | 138 turns   |
| Number of pancakes | 1 single pancake |
| Inductance | 6.8 mH      |

Figure 8. Trial superconducting coil of small race track-shape.

Figure 9. Temperature dependence of $I_c$ for trial superconducting coil
5. Summary
There are several advantages by applying a high temperature superconducting wire to an on-board superconducting magnet for the maglev train. Using 2G wires especially is effective in stability of superconducting state, in simplification of magnet structure and in reliability of superconducting magnet.

With the data of references for the 2G wires, the effectiveness to apply 2G wires became clear by estimating the weight and the energy consumption of the on-board superconducting magnet and the cryocooler for the maglev train. The authors therefore carried out firstly the evaluation test for transport current characteristics of actual 2G wires to 20 K in minimum, 5 T in maximum at various magnetic field directions. In addition, the trial production and the evaluation test for small race track-shaped superconducting coil using 2G wires were carried out. In these ways, the basic Ic characteristics of both a wire shape and a coil shape for 2G wires were shown and compared. For the application of 2G wire, the technique to estimate the transport current characteristics of the coil from such of the wire is important.

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