Study on Applicability of Rare Earth High-temperature Superconducting Wires to Superconducting Magnet for Maglev System

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Rare earth high-temperature superconducting wire (RE wire) has electrical and mechanical properties superior to those of conventional superconducting wire. It was clarified that a superconducting magnet with a simpler structure and higher reliability than the conventional type could be achieved for maglev system by applying this type of wire. A characteristic test was then carried out for RE wire, and an electric properties test was run on a trial coil of the wire in a small racetrack shape. The electrical properties of RE wire formations varying from a single wire shape to a wound coil shape were thus confirmed. The results obtained are expected to be useful to allowing the application of RE wire to superconducting magnet for maglev system.

Keywords: RE, HTS, wire, SCM, superconducting magnet, maglev

1. Introduction

Rare earth high-temperature superconducting wire (RE wire) has electrical and mechanical properties superior to those of conventional wire. It was clarified that a superconducting magnet with a simpler structure and higher reliability than the conventional type could be achieved for maglev system by applying this type of wire. A characteristic test was then carried out for RE wire, and an electric properties test was run on a trial coil of the wire in a small racetrack shape. The electrical properties of RE wire formations varying from a single wire shape to a wound coil shape were thus confirmed. The results obtained are expected to be useful to allowing the application of RE wire to superconducting magnet for maglev system.

Fig. 1 Image of critical temperature T_c for superconducting wire

2. High-temperature superconducting wire

Figure 1 shows a typical representation of the critical temperature (T_c) for superconducting wire. As temperature decreases, the resistance of general metal materials gradually approaches zero. However, the resistance of superconducting wire disappears at a certain temperature with transition from a normal conducting state to a superconducting state. This temperature is called the critical temperature (T_c), and acts as a representative index for superconducting materials. As there are similar indices (e.g., the critical magnetic field (B_c) and the critical current density (J_c) (Fig. 2)), the superconducting state is limited to the area satisfying these three critical conditions. For studies on application, it is therefore important to verify each of the critical conditions for superconducting wire.

Fig. 2 Critical condition for superconductivity state

High-temperature superconducting wire exhibits superconductivity at higher temperatures than conventional metal superconducting wire. In general, high-temperature superconducting wire has a T_c value higher than the temperature of liquid nitrogen. There are two kinds of high-temperature superconducting wire – Bi wire and RE wire – in practical use today. Both Bi wire, which includes bismuth, and RE wire, which includes rare earth elements such as yttrium, are copper oxide high-temperature su-

perconducting wires. Since the T_c value of Bi wire is 110 K and that of RE wire is 93 K, both types of wire can be superconducting state by cooling with liquid nitrogen.

Table 1 shows the main specifications of Bi wire and RE wire, and indicates that the mechanical characteristics of RE wire are at least as good as those of Bi wire. As a result of recent global research and development, the characteristics of RE wire (such as piece wire length, critical current and manufacturing cost) have improved remarkably, giving it the potential status of second-generation high-temperature superconducting wire and successor to Bi wire. Although Bi wire currently takes precedence for applications such as motors and cables, it is conceivable that the application of RE wire will become the mainstream in the near future.

Figure 3 shows the appearance of RE wire, and Fig. 4 shows its typical structure. It has a tape-like appearance, and features a laminated film structure on a non-magnetic substrate to provide mechanical strength.

Table 1 Specifications of HTS wire

	Bi wire ^(*)	RE wire ^(**)
Width	4.3 mm	4.4 mm
Thickness	0.23 mm	0.20 mm
Critical current (77 K)	< 180 A	< 90 A
Critical tensile stress	130 MPa	200 MPa
Critical bend diameter	70 mm	25 mm

* Sumitomo Electric Industries: DI-BSCCO Type H

** American Superconductor: Type 344C

Fig. 3 RE high-temperature superconducting wire

Fig. 4 Typical structure of RE wire

3. Advantages of applying RE wire to superconducting magnet for maglev system

Figure 5 outlines the advantages of applying RE wire to a conventional superconducting magnet using NbTi wire for a maglev system. Cryocooler-based conduction cooling is made practical by raising the operating temperature of the superconducting coils, thereby eliminating the need for liquid helium/liquid nitrogen coolants and the related tanks and piping. In addition, the conventional cryocooler can be replaced with a small lightweight type featuring low energy consumption. As a result of increased thermal capacity with high-temperature operation, the stability of superconducting coils against thermal disturbance is improved. In addition, if the operating temperature of a superconducting coil exceeds 50 K, no radiation shield is necessary, and downsizing of the outer vessel's cross section can be realized [1].

It was thus clarified that the application of RE wire allows superconducting magnet design with a simpler structure and improved stability.

Fig. 5 Merits of applying RE wire to superconducting magnet for maglev system
(Figure is schematic view of superconducting magnet with Nb-Ti coils)

4. Results of transport current properties testing on RE wire

To allow the application of RE wire to superconducting coils, it is essential to confirm its quantitative transport characteristics in relation to environmental variables such as temperature and magnetic fields. Due to a lack of published studies on these basic characteristics of RE wire then, we developed a system to evaluate its transport current characteristics under the conditions of current (I), magnetic field (B), magnetic field angle (θ), temperature (T) and bend diameter (ϕ). The system consists of an I-B- θ -T test device (Fig. 6) and an I- ϕ test device (Fig. 7). The I-B- θ -T test device works with a maximum current of 1000 A, a maximum magnetic field of 5.5 T and a minimum temperature of 10 K. Since the aspect ratio of the wire section is large and the crystal structure of the su-

perconducting layer is highly oriented, RE wire has high anisotropy in terms of transport current characteristics in magnetic fields. Accordingly, the device supports the evaluation of anisotropy for magnetic field angle θ formed by the wire surface and B (Fig. 8). The I- ϕ test device can also evaluate the bend diameter dependence of RE wire's transport current characteristics in liquid nitrogen at 77 K [2].

Using the I-B- θ -T test device, the characteristics of RE wire shown in Table 1 were evaluated. Figure 9 shows the magnetic field dependence of I_c at a magnetic field angle of 0 degrees. This outcome indicates that I_c simply decreases with higher temperatures and in higher mag-

Fig. 6 Schematic of I-B- θ -T test device

Fig. 7 I- ϕ test device

Fig. 8 Definition of θ

Fig. 9 Magnetic field dependence of critical current for RE wire

Fig. 10 Magnetic field angle dependence of critical current for RE wire

Fig. 11 Bend diameter dependence of critical current for RE wire

netic fields. Figure 10 shows the magnetic field angle dependence of I_c in a magnetic field of 1 T. The results indicate that I_c reaches its maximum value for a magnetic field angle of 0 degrees and its minimum value for a magnetic field angle of 90 degrees. This means that the magnetic field angle causes a difference of around 60% in I_c even under the same temperature and magnetic field conditions. As this anisotropy of transport current characteristics is problematic for the application of RE wire to superconducting equipment, RE wire manufacturers are currently pursuing research and development such as doping an artificial pinning center to address the issue [3].

Figure 11 shows the results of testing the bend diameter dependence of I_c for RE wire as outlined in Table 1 using the I- ϕ test device with a liquid nitrogen temperature of 77 K. The outcome indicates that there is no deterioration of I_c until a bend diameter of 20 mm, which is much smaller than the critical bend diameter of 70 mm for Bi wire as shown in Table 1. This characteristic against the bending transformation of RE wire is very advantageous in terms of coil design flexibility and ease of wire handling. It is also apparent that the deterioration of I_c with the outward high-temperature superconducting layer is remarkable compared to that of the inward layer.

5. Results of transport current properties testing on an RE coil

Using 100 m of RE wire with the characteristics outlined in Table 1, a small racetrack-shaped RE coil was produced with an inside diameter of 100 mm and a straight part measuring 150 mm. Figure 12 shows the coil, which was formed from a single pancake coil, and Table 2 outlines its specifications.

We carried out an I_c evaluation test on this RE coil using the I-B- θ -T test device under self-magnetic field conditions. Figure 13 shows the transport current dependence of the magnetic fields for the RE coil at 30 K. The results show the presence of magnetic fields of 0.85 T at the innermost layers at the center of the curved part and 0.3 T at the coil center. Figure 14 shows the temperature dependence of I_c for the RE coil, and confirms that the value decreases with higher temperatures as seen with the I_c behavior of RE wire itself. In the case of this coil, I_c at 77 K decreased to approximately a one-fifth of the value seen at 30 K.

Table 2 Specifications of racetrack shape RE coil

Wire length	100 m
Wire width	4.4 mm
Wire thickness	0.2 mm
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

Fig. 12 Racetrack shape RE coil

Fig. 13 Current dependence of magnetic field for RE coil (30 K)

Fig. 14 Temperature dependence of critical current for RE coil

6. Comparison of the transport current properties of RE wire and the RE coil

When the magnetic field angle θ is constant, the magnetic field B and the temperature T determine the I_c of the coil. If T is also given in addition to θ , the I_c value depends only on B . Here, B is the magnetic field that the coil itself generates with transport current. Because of the dimensions of the coil's cross section, the influence of B on the transport current characteristics of the wire that constitutes the coil reaches its maximum at the two points shown in Fig. 15. Briefly, the I_c of the coil can be calcu-

Fig. 15 Two positions where effect of magnetic field on transport current performance is remarkable

**Fig. 16 Temperature dependence of critical current for RE coil
(Comparison of test result and calculated result)**

lated by B at these two points.

Using the results of the test on the wire's transport current characteristics and the calculation method above, we calculated I_c at the points of maximum magnetic field B_{max} , where $\theta = 90$ degrees and $\theta = 0$ degrees. Figure 16 shows a comparison of the test results and the calculated results for the temperature dependence of I_c in the RE coil. Consistency was found between the test results and the calculated results for $\theta = 90$ degrees, as shown in Fig. 16. This outcome indicates that if the transport current

characteristics of the wire and the dimensions of the coil are known beforehand, it is possible to predict the transport current characteristics of the coil. This estimation method is also applicable to the study of coil design with a specific level of performance.

For studies on the applicability of RE wire to superconducting magnets for maglev system, both evaluation testing for the latest RE wire and analysis using the method to estimate coil transport current characteristics from those of the wire are important.

7. Summary

Several advantages, such as a simpler structure and a higher reliability, are gained from the application of RE wire to on-board superconducting magnets for maglev system. The points of this study can be summarized as follows:

- (1) Using a system to evaluate the transport current characteristics of RE wire, its critical current characteristics in relation to temperature, magnetic field, magnetic field angle and bend diameter were verified.
- (2) The temperature dependence of the critical current characteristics in a small racetrack-shaped RE coil made of RE wire was experimentally ascertained to complete the confirmation.
- (3) A method of estimating the transport current characteristics of the RE coil using the characteristics of the constituent wire and the coil dimensions was described.

The authors plan to continue evaluation testing for the latest RE wire and utilize the results to enable the application of RE wire in maglev system.

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