Development of a Real-scale REBCO Coil for the Demonstration of a Magnetomotive Force of 700 kA

Katsutoshi MIZUNO  Motohiko SUGINO  Minoru TANAKA  Masafumi OGATA
Cryogenic Systems Laboratory, Maglev Systems Technology Division

REBCO (Rare-Earth Barium Copper Oxide) is a high temperature superconducting material and allows on-board superconducting magnets on maglev trains to operate at higher temperatures. Because of the high operating temperature, the magnet can be cooled without liquid helium, reducing the magnet's energy consumption by nearly half. The basic technologies for making the magnet using REBCO coated conductors are still under development. A real-scale REBCO coil for application to maglev trains was therefore built. When excited at 35 K the real-scale coil demonstrated it had a magnetomotive force of 700 kA, which is the same as existing on-board magnets. This paper describes the manufacturing process of the coil and gives details of the excitation test.

Keywords: REBCO, coated conductor, Maglev, on-board magnet, coil fabrication

1. Introduction

REBCO coated conductors are attracting attention because of their excellent current capacity. Application of these conductors to maglev, fly wheel, etc., has already been investigated. Most existing superconducting magnets employ Nb-Ti superconductors, which have a critical temperature of 9 K. Nb-Ti magnets therefore need to be cooled with liquid helium or 4 K cryocoolers. REBCO coated conductors have a high transition temperature, and their current density in high magnetic field environments is superior to other superconductors. For example, the current density of a REBCO coated conductor at 40 K is almost the same as that of a Nb-Ti conductor at 4 K [1].

A high operating temperature offers several advantages, namely: the magnets can be cooled by cryocooler without cryogens, such as liquid helium or nitrogen. The cooling system of the magnet can be simplified, and the cooling operation simply requires the cryocooler to be switched on. This significantly cuts the operating cost of the magnet. In addition, the cryocooler consumes less energy, because energy consumption depends on cooling temperature. For maglev, low energy consumption has another advantage: If the cryocooler consumes less energy, then the on-board power supply can be downsized enabling the maglev vehicle to meet the requirement to be light.

Although REBCO coated conductors can help to reduce the weight of the maglev vehicle and lower operating costs, there are still some technical problems. REBCO magnet development for practical applications to maglev, MRI, NMR, or accelerator, etc., is still relatively new, and establishing a coil production process and stable operating methods are important.

A coil manufacturing process which does not reduce current capacity while ensuring excellent cooling properties has now been developed [2]. A real-scale REBCO coil was therefore produced which can generate the magnetomotive force of 700 kA. This paper describes the coil production process and excitation tests results.

2. Production of a real-scale REBCO coil

The target of this coil production is to ensure that the REBCO coil matches actual magnetic fields. In other words, the REBCO coil must generate the same figure as the LTS (Low Temperature Superconducting) coil and generate a magnetomotive force of 700 kA. However, the cooling system or coil structure does not need to follow LTS magnet design, rather, the design should make the magnet lighter weight and with better thermal stability.

2.1 Specifications of the REBCO coil

The specifications of the coil for the production process were decided considering the operating temperature, heat load and productivity [3] (see Table 1). The heat load from the current leads is proportional to the operating current. Therefore, the operating current was set at 250 A, which is half that of the LTS coil [4]. The number of turns was doubled to equalize the magnetomotive force. Due to the tape-shaped coated conductor, fabrication of the pancake coils is easier than that of solenoids. For this reason, the real-scale coil consists of stacked pancake coils.

The upper limit temperature of excitation, estimated on the basis of Ic-B-θ-T characteristics, was approximately 39 K. Since coated conductor has improved over the past few years, it is expected that in the near future, this upper limit temperature will reach 50 K [5].

The coil is operated in the driven mode, because superconducting connections are still being developed and not applicable to coil fabrication yet. Furthermore, the length of the commercial conductor is only several hundred meters. That means that there are a number of soldered connections in the coil. If the coil is operated in persistent current mode, the current quickly decays. Establishment of the superconducting connection technique [6] and commercially available long-length coated conductors [7] are desired to allow persistent current mode operation.
Table 1 Specifications of the real-scale REBCO coil [3]

| specification           | value                                                                 |
|-------------------------|----------------------------------------------------------------------|
| Type of conductor       | SuperPower Inc.                                                      |
|                         | SCS6050-AP                                                           |
| Conductor shape         | 6mm in width, 0.1 mm in thickness                                    |
| Turn insulation         | Polyimide tape                                                       |
| Operating current       | 250 A in driven mode                                                 |
| Number of pancake coils | 8                                                                    |
| Number of turns         | 2800 turns (350 turns per pancake coil)                              |
| Total length of the coated conductor | 7600 m (950 m per pancake coil)                                      |
| Conductor weight without former | 43 kg                                                                  |
| Inductance              | 12 H                                                                 |
| Operating current       | 30 to 40 K (40 to 50 K in the future)                                |

Table 2 Critical currents of pancake coils at 77 K

| ID (Stacking order) | #1 | #2 | #3 | #4 | #5 | #6 | #7 | #8 |
|---------------------|----|----|----|----|----|----|----|----|
| Ic (A)              | 68 | 74 | 66 | 57 | 54 | 63 | 71 | 73 |

2.2 Pancake coil production

As shown in Table 1, the real-scale coil consists of 8 pancake coils. The former material used was GFRP, and the length of the coated conductor was 950 m per pancake coil. The length of the single coated conductors prepared for the fabrication of the coils was 100 m or 200 m. Therefore, there were 5 to 9 soldering connection in each pancake coil. A low temperature solder was used, and each soldering length was 100 mm.

Due to the conduction cooling, the pancake coils must be thermally stable. Copper plates were affixed with thermoplastic resin to the surfaces of the wound coated conductor (see Fig. 1). Copper plates enhance thermal conduction and remove heat from the conductor. A commercial thermoplastic resin, Nucrel® was used in this case because its adhesive strength has already been confirmed [2]. Nucrel® does not cause the degradation of the coated conductor, and its fabrication process is easier than epoxy impregnation.

For the confirmation of the soundness, each pancake coil was cooled with liquid nitrogen and the critical current (Ic) was measured. The results are shown in Table 2. The Ic indicates some variations, from 54 A to 74 A. This was caused by the variability of the coated conductors. Some pancake coils were made of better coated conductors by design. In a large coil, like this real-scale coil, the load factors (ratio of the operating current to critical current) of the pancake coils are very different due to the magnetic field distribution. Basically, the outer pancake coils (top and bottom) show higher load factor (the details are mentioned in the 4th chapter). Therefore, the distribution of pancake coil Ic were as expected. This result also indicates that the coated conductor did not degrade during the winding or adhesion process.

3. Design and fabrication of coil case

3.1 Design of coil case

The real-scale REBCO coil had to be designed to receive a huge electromagnetic force, called hoop stress. Since the pancake coils are not strong enough to withstand such a force, they must be housed in a strong coil case. In the LTS magnet, this coil case is called an inner vessel, because it also works as liquid helium bath. Since the inner vessel requires a gas tight structure, it is made of stainless steel [8] and assembled by welding. Other materials could be used for the REBCO coil housing because liquid helium is unnecessary. The aim was to find a light weight and low cost material suitable for the maglev. Considering the specific strength, price and workability, Duralumin (JIS: A7075P-T651) was chosen as the coil case material.

Hoop stress (electromagnetic force due to excitation) is
the biggest stress to which the coil has to be exposed. The coil case was designed in parallel with the execution of its structural analysis. There are 8 load support members in the same way as in the case of a LTS coil. Four of them are located on the outer side of the race track. Therefore, the coil case is rectangular-shaped and the curved sections are sufficiently strong. By contrast, the hoop stress exerted on the straight sections is huge and the coil case will be bent outwards in the worst case (Fig. 2). The average magnetic field is approximately 0.55 T perpendicular to the racetrack surface. The electromagnetic force reaches 220 kN. In this coil case design, the safety factor was set at 3.

The strength of an aluminum alloy depends on thickness as well as its composition. The thickness of the coil case is approximately 100 mm. The yield strength of the A7075P-T651 with 100 mm thickness is more than 360 MPa [9]. In addition, yield strength depends on temperature. Yield strength at 77 K is 20 % higher than that at room temperature [10]. Therefore, the yield strength of the coil case is more than 430 MPa. Since the safety factor was set at 3, the maximum von Mises stress must be less than 140 MPa.

A commercial 3D CAD was used for the design and the analytical modeling, and NASTRAN NX was used for the structural analysis. The final design of the coil case and the stress distribution are shown in Fig. 3. The two support beams inside the racetrack and the outer side of the straight sections receive high stress. However, the maximum von Mises stress in these areas is 134 MPa, which satisfies the design requirement of 140 MPa. The total mass of the coil including the pancake coils and the heat transfer members is approximately 140 kg, while the mass of the coil case is 43 kg.

3.2 Strength test with a model coil

In the structural analysis, the stress was evaluated in detail including bolt axial tension. However, the actual REBCO coil has a complicated structure, raising the possibility of a concentration of stress between the pancake coils. Therefore, a model coil was built to imitate the straight section and load tests were performed to confirm its strength.

The model coil consisted of a coil case, aluminum (JIS: A1050) plates as heat transfer members and GFRP plates which imitated the pancake coils. There was a bore at the center of the model coil. Three-point bending test was carried out; both the sides of the coil case were supported, and the GFRP plates were loaded directly through the center bore (see Fig. 4).

Four strain gauges were attached to the coil case, and deformation was measured with a laser displacement meter. When the load reached 140 kN, the strain at the bottom of the coil case was 1700 μST, which was converted to a stress of 130 MPa. The coil case was not deformed plastically and the bolts were neither deformed nor damaged. These results indicate that the coil can withstand a stress equivalent to hoop stress.

4. Excitation tests

The factors which cause degradation to the REBCO coated conductors have not been completely identified yet. Therefore, the prediction of characteristics of the REBCO coil based on the coated conductor properties is inadequate, and actual coil fabrication and verification tests are important in this research. We carried out excitation tests at the temperature over 30 K.
4.1 Prediction of the upper limit temperature of excitation

The upper limit temperature of excitation was estimated in advance of the actual excitation tests. First, detailed critical currents were measured using a coated conductor manufactured in 2014. That coated conductor was a part remaining from pancake coil production. The characteristics of a coated conductor depend not only on the manufacturer but also on the production batch. Therefore, $I_c$ measurements are necessary for each coil production to obtain a precise prediction of the upper limit temperature of excitation. Next, magnetic field distribution in the coil cross-section was analyzed in parallel with the coil design. The magnetic flux was concentrated in the middle of the curved section of the racetrack coil. The load factor (ratio of the operating current to the critical current) in the curved section is the highest in the coil and determines the operating temperature. According to the magnetic field analysis and the measured $I_c$, the load factor reaches 90% at 36 K. Figure 5 shows the detailed load factor distribution in the cross section in the middle of the curved section. Half the pancake coils (#5 to #8) are omitted due to symmetry.

Incidentally, the $I_c$ data for the prediction was measured using the coated conductor manufactured in 2014. The pancake coils were produced at two different times: two of the coils were made in 2014 and the other 6 coils in 2015. The upper limit temperature should be upwardly revised because the current density of the coated conductor was improved in 2015. Based on the latest measurement, the upper limit was estimated to be 39 K.

4.2 Experimental apparatus

The pancake coils were installed in the coil case and set in a cryostat as shown in Fig. 6. The cryostat has a single-stage cryocooler and no radiation shield. The radiation shield is a thermal insulation structure and is essential for a LTS magnet. However, with respect to a REBCO coil with an operating temperature above 30 K, the magnet can be downsized because the radiation shield is unnecessary. Because of the strict weight limitation on maglev vehicles, downsizing is a huge advantage.

In a conduction-cooled magnet, multipoint temperature measurements are important. If heat transfer members are insufficient, the coil temperature will not be uniform and the magnet electrodes will heat up depending on the connection resistance between the current leads. Consequently, temperature sensors were attached over the whole coil, especially around the electrodes. The current leads and the cryocooler temperatures were also measured. Strain gauges were put on the coil case to measure the stress due to excitation (see Fig. 7). A hole sensor was also installed at the center of the coil to confirm the magnetic field which should reach 1.1 T at the magnetomotive force of 700 kA.

4.3 Excitation tests results

The REBCO coil was cooled to 35 K and excited until the magnetomotive force reached 700 kA. Current was increased stepwise; at every 10 A increase (at every 5 A increase above 200 A), the current was held until the superconducting state of the coil was confirmed. When the current reached 250 A, which means a magnetomotive force of 700 kA, the current was held until the coil voltage and temperature stabilized. Excitation current and coil voltage variation are shown in Fig. 8.

During the current sweep, the coil voltage was over-ranged due to the coil inductance (approximately 12 H).
When the current was stable, the coil voltage was only several millivolts. For example, 40 minutes after reaching 250 A, the coil voltage was less than 4 mV. This coil voltage is due to the soldering resistance of the coated conductor and connection resistance of the current leads. The coil voltage decay pattern at a stable current indicated that the coil maintained a superconducting state and still had current margin. This voltage decay is caused by a shielding current. Near the critical current, the shielding current decreases and the voltage decays rapidly.

The magnetic flux density at the center of the coil was 1.1 T at 250 A. The magnetomotive force of 700 kA was confirmed based on the magnetic field too. The temperature distribution around the coil is shown in Fig. 9. The temperature difference was less than 1 K in the coil. This result indicates that heat load due to the excitation was negligible. However, the thermal resistance between the coil and the cold head was not small enough, making the temperature difference about 3 K. The plan to reduce this temperature difference, is to use high thermal conducting material such as high purity aluminum and also to reduce the number of bolt connection areas.

Table 3 shows the results of the strain measurements. The strain of the support beam shows good agreement with the result of the structural analysis. This result indicates that the expected electromagnetic force was being exerted on the support beam. On the other hand, the strain was less than half that found through analysis at the opening sections of the electrodes and the straight section. In the analysis, the strength of the pancake coils was excluded and it was assumed that hoop stress would act uniformly on the straight sections. However, due to the strength of the pancake coils, the actual stress was not uniform and was higher on the parts which had little deformation. The actual stress was smaller than the result of the analysis, which means that the safety factor was larger than 3.

5. Summary

The REBCO coated conductor is superior to other HTS superconductors in terms of current density in high temperature and high magnetic field environments. Using these coils and coated conductors would lower the operating cost and weight of on-board maglev magnets. However, few reports exist on producing large REBCO magnets, so production and verification tests are required on methods for producing full-size REBCO coils. In this research, a real-scale REBCO coil which can generate the actual magnetomotive force was produced and excited. The following conclusions were obtained:

1. The upper limit temperature of the excitation was estimated at 40 K based on the performance of the coated conductor.
2. The magnetomotive force of 700 kA was achieved at 35 K. The normal voltage due to the connection resistances was less than 5 mV. The coil temperature was also stable during the excitation.
3. A coil case for the REBCO coil was designed and produced based on a structural analysis. The coil case was made of duralumin (JIS: A7075P-T651), and its design strength and safety factor were confirmed in model experiment and actual excitation tests.

Vibration tests are now planned to reproduce assumed running conditions to evaluate the durability of the REBCO coil and heat load due to vibrations.

| Table 3 Strain on the coil case at the 700 kA excitation |
|---------------------------------|----------------|----------------|----------------|
| Near the open area              | Straight section (hoop stress) | Support beam | Straight section (case warpage) |
| Predicted strain (μST)          | 1600            | 1300           | 1000           | 600 |
| Measured strain (μST)           | 765             | 612            | 817            | 466 |
Acknowledgment

This work was financially supported by the Japanese Ministry of Land, Infrastructure, Transport and Tourism.

References

[1] Nagashima, K., Ogata, M., Mizuno, K., Arai, Y., Hasegawa, H. and Sasakawa, T., “Study on Component of Superconducting Magnet for Maglev Using High-temperature Superconducting Wire Based on Rare Earth Barium Copper Oxide,” *RTRI Report*, Vol.25, No.3, pp.17-22, 2011 (in Japanese).

[2] Mizuno, K., Ogata, M. and Hasegawa, H., “Manufacturing of a REBCO racetrack coil using thermoplastic resin aiming at Maglev application,” *Physica C*, Vol.518, pp.101-105, 2015.

[3] Mizuno, K., Sugino, M. and Ogata, M., “Experimental Production and Evaluation of Racetrack Coils for On-board REBCO Magnet,” *RTRI Report*, Vol.29, No.11, pp.11-16, 2015 (in Japanese).

[4] Tsuchishima, H. and Terai, M., “The Superconducting Magnet System for MAGLEV Vehicles in 550km/h Operation on the Yamanashi Test Line,” *TEION KOGAKU* (J. Cryo. Super. Soc. Jpn.), Vol.33, No.10, pp.516-523, 1994 (in Japanese).

[5] Nakasaki, R., Y. Zhang, P. Brownsey, A. Sundaram, D. Hazelton, Sakamoto, H. and Fukushima, T., “Continuous Improvements in Performance and Quality of 2G HTS Wires Produced by IBAD-MOCVD for Coil Applications,” Presented at *MT-24 Conference*, Seoul, Korea, 2015.

[6] Y. Zhang, T.F. Lehner, Fukushima T., Sakamoto H. and D.W. Hazelton, “Progress in Production and Performance of Second Generation (2G) HTS Wire for Practical Applications,” Presented at IEEE 2013 International Conference on Applied Superconductivity and Electromagnetic Devices (ASEMD), October 25-27, 2013, Beijing, China.

[7] Jin, X., Yanagisawa, Y., Maeda, H. and Takano, Y., “Development of a superconducting joint between a GdBa₂Cu₃O₇-δ-coated conductor and Yba₂Cu₃O₇-δ bulk: towards a superconducting joint between RE (Rare Earth) Ba₂Cu₃O₇-δ-coated conductors,” *Supercond Sci Technol*, Vol.28(7), 075010 2015.

[8] Jizo, Y., Akagi, H., Terai, M. and Shinobu, M., “Heat Load Characteristics and New Type Design by Using 1 Coil Model Superconducting Magnet,” *TEION KOGAKU* (J. Cryo. Super. Soc. Jpn.), Vol.29, No.10, pp.516-523, 1994 (in Japanese).

[9] JIS H 4000:2014, Aluminium and aluminium alloy sheets, strips and plates.

[10] Japan Aluminium Association, “Alminium handbook,” Japan Aluminium Association, pp. 42-44, 1990 (in Japanese).

Authors

Katsutoshi MIZUNO
Assistant Senior Researcher, Cryogenic Systems Laboratory, Maglev Systems Technology Division
Research Areas: Superconducting Technology

Motohiko SUGINO
Assistant Senior Researcher, Cryogenic Systems Laboratory, Maglev Systems Technology Division
Research Areas: Vibration Engineering, Superconducting Technology

Minoru TANAKA, Dr.Eng.
Senior Researcher, Cryogenic Systems Laboratory, Maglev Systems Technology Division
Research Areas: Electrical Engineering, Superconducting Technology

Masafumi OGATA, Dr.Eng.
Senior Chief Researcher, Laboratory Head, Cryogenic Systems Laboratory, Maglev Systems Technology Division
Research Areas: Superconducting Technology