Method for Controlling Frictional Heat inside Superconducting Coils

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In the JR maglev system, trains are operated by the electrodynamic force between ground coils and on-board superconducting magnets (SCMs). When a train is running, SCMs are vibrated by the electromagnetic disturbance that occurs when the train passes over the ground coils. Such a phenomenon generates frictional heat in the SC-coil. It has been surmised that this frictional heat is caused by the relative microscopic slips between the structural components of the SC-coil. The dual aims of this study were firstly to elucidate the mechanism of frictional heat inside an SC-coil, and secondly to reduce frictional heat. A fretting test was performed at liquid-helium-cooled boundaries between the structural components of an SC-coil. The test results demonstrated that frictional heat had occurred at the boundary between an epoxy-impregnated superconducting coil and the coil fasteners. Furthermore, a method to reduce the frictional heat inside an SC-coil was considered by using a correlation between the hardness of the frictional surface and the amount of frictional heat. Then, an effect to reduce the frictional heat was demonstrated by means of a liquid-helium-cooled fretting test.*

Keywords: maglev, superconducting coil, vibration, fretting, liquid helium, heat generation

1. Introduction

In the JR maglev system, trains are operated by the electrodynamic force between ground coils and onboard superconducting magnets (SCMs). When a train is running, SCMs are vibrated by the electromagnetic disturbance that occurs when the train passes over the ground coils.

This phenomenon generates a heat load in the SCM cryogenic equipment¹⁾. The SCMs vibrate at between 0 and 309 Hz corresponding to the vehicle speeds from 0 to 500 km/h. In that frequency range, the evaporation of liquid helium grows significantly at the resonance frequency of the SC-coil. It has been surmised that the friction-generated heat inside an SC-coil is caused by the relative microscopic slips between structural components of the SC-coil and by hysteresis energy from the elastic deformation of the SC-coil^{2) 3)}. However, previous research has suggested that the hysteresis heat was approximately 1/10 or less of frictional heat³⁾.

A vibration test using an actual SC-coil was performed at RTRI to investigate a correlation between SC-coil vibration and frictional heat^{1) 2) 3)}. It was confirmed that the heat generation phenomenon under SC-coil vibration was strongly affected by the elastically twisting and bending deformation of the SC-coil^{2) 3)}. The results of the SC-coil vibration test were applied to the arrangement of SC-coil support-columns for SCMs on the Yamanashi Maglev Test Line, which minimized the elastically twisting deformation in the eigen-mode of the SC-coil⁴⁾. In addition, heat generation areas were evaluated by an FEM stress analysis of the SC-coil which given elastic deformation

at the eigen-mode^{5) 6)}.

The dual aims of this study were to elucidate and then to control directly the relation between friction and heat generation between the structural components of the SC-coil.

A fretting test was performed by immersing samples in liquid helium to evaluate the friction-generated heat inside the SC-coil.

Firstly, frictional properties were evaluated to confirm the material combination that generated the maximum frictional heat in the SC-coil. Secondly, the surface condition in the area that was expected to show the maximum heat generation was controlled to reduce frictional heat. Finally, a frictional heat control method to be applied to actual SC-coils was considered and the effect to reduce frictional heat demonstrated by a fretting test by using liquid-helium-cooled specimens.

2. SCM and SC-coil structures

Figure 1 shows the structure of the SCM used on the Yamanashi Maglev Test Line. The SCM consists of four SC-coils, an outer vessel, insulated support columns (between the SC-coils and the outer vessel), a radiation shield plate and liquid helium and nitrogen tanks⁴⁾. Structure of the outer vessel is designed to have mechanical properties with a rigidity that enables it to act as a vacuum bulkhead for cryostat, and electrical properties it to enable act as an electromagnetic shield. The SC-coils which are insulated by vacuum and insulated support columns, are primarily cooled by liquid helium and secondarily

*) In this paper, the term "SC-coil" is used to refer to the assembly comprising an epoxy-impregnated superconducting coil, spacers and coil fasteners as well as an inner vessel.

Fig. 1 SCM structure

cooled by liquid nitrogen in the radiation shield plate. Helium is reliquefied from evaporated refrigerant by an on-board helium refrigeration system. The electromagnetic force generated by the superconducting coil is transmitted to the outer vessel through the insulated support columns and turned into power to finally operate the vehicle.

Figure 2 shows the structure of one example of an SC-coil. The SC-coil consists of an epoxy resin-impregnated Nb-Ti superconducting coil, an inner vessel, and coil fasteners. The epoxy resin-impregnated superconducting coil is installed in the inner vessel with intermediate coil fasteners and spacers that are arranged on the race track shaped superconducting coil at equal intervals. In this paper, "SC-coil" means an assembly of epoxy-impregnated superconducting coil, spacers and coil fasteners, and an inner vessel.

Figure 3 shows the cross section of one example of an SC-coil. Polyimide tape was inserted between the coil fastener spacers and the epoxy-impregnated superconducting coil in order to minimize the heat shrinkage stress caused by the change from room to cryogenic temperatures. The coil fastener spacers act as a relief in the event of a rise in the heat on the surface of the epoxy-impregnated superconducting coil, therefore aluminum or copper was applied to the coil fastener spacers to provide high thermal conductivity⁴⁾. It was presumed that when the SC-coil vibrates, friction occurs at the boundaries between the polyimide tape and the coil fastener spacers,

Fig. 2 SC-coil structure

Fig. 3 Cross section of an SC-coil

or between the spacers and the coil fastener, or between the coil fastener and the inner vessel.

3. Experiment

3.1 Experimental rig

Figure 4 shows the experimental rig used to immerse specimens in liquid helium for the fretting test. In a previous vibration test using actual SC-coils, the amount of heat generation had increased at frequencies of approximately 150 Hz and 200 Hz^{2) 3)}. On the other hand, the SC-coils vibrate at 0 to 308 Hz, corresponding to vehicle speeds from 0 to 500 km/h on the JR maglev¹⁾. Therefore, test specimens were vibrated at frequencies up to 300 Hz in this fretting test. A reciprocating sliding provided between sliding and fixed specimens at a displacement level of 10 μm was obtained from the vibration tests of using an actual SC-coil²⁾. The experimental rig consisted of sliding and fixed specimens, a Dewar vessel, a vibration generator, an outer frame, as well as thermally insulated vibration and fixed rods. The sliding and fixed specimens were connected to the vibration generator and the outer

Fig. 4 Experimental rig used for liquid helium-cooled fretting test

frame, which was arranged outside the Dewar vessel, by the thermally insulated vibration rod and fixed rod, respectively. The contact surfaces at both ends of the vibrating specimen were curved to a radius of 30 mm, the contact surfaces of the fixed specimens being flat. Accelerometers were mounted at the base of the fixed and vibration rods, and a load cell installed between the vibration rod and the vibration generator.

3.2 Experimental procedure

After setting up the specimens in a holder, the Dewar vessel was filled with liquid helium, vibration starting when the amount of helium evaporation had stabilized (indicating that the devices inside the Dewar vessel were sufficiently cooled).

Displacements were calculated from the accelerometer output by double integration, and the relative displacement between the fixed and sliding specimens was indicated by the difference in displacement. Normal and frictional forces that act on the boundary between the sliding and fixed specimens were measured by setting up load cells adjacent to the specimens. The amount of helium gas which evaporated from the Dewar vessel was measured by using a mass flowmeter during vibration. The heat generation caused by vibration was indicated by the increase in the volume of helium evaporation when a specimen vibrated.

The validity of the heat generation measurement that was converted from the amount of helium evaporation was confirmed by setting up a heater adjacent to the specimens. Moreover, it was confirmed that, no heat generation was detected under vibration when the specimens were not installed.

4. Results and discussions

4.1 Properties of frictional heat in each material combination

A fretting test was performed in liquid helium by combining several materials to determine where frictional heat was generated⁷⁾. Table 1 shows the combinations of fretting test specimens and corresponding the SC-coil structural components. The boundaries between an epoxy-impregnated superconducting coil and a coil fastener spacer, between a coil fastener and coil fastener spacer, and between a coil fastener and an inner vessel were simulated by the contacts between copper-based polyimide tape and copper, copper and stainless steel, and between stainless steels, respectively. Applied load for the specimen contact was set at 50 N, which corresponded to the initial tightening load to fit the coil fastener on the epoxy-impregnated superconducting coil.

Figure 5 shows the correlation between the amplitude of frictional force and the amount of frictional heat. This experiment was performed under constant vibration power, using several frequency and material combinations.

In the case of friction between copper and stainless steel and between two stainless steel specimens, the frictional heat was hardly ever measured when frictional forces

Table 1 Combinations of fretting test specimens and corresponding SC coil structural components

Combination of specimens		Corresponding SC-coil components	
Fixed	Sliding	Fixed	Sliding
Polyimide tape	Copper	Epoxy-impregnated superconducting coil	Coil fastener spacer
Stainless steel	Copper	Coil fastener	Coil fastener spacer
Stainless steel	Stainless steel	Coil fastener	Inner vessel

Fig. 5 Correlation between amplitude of frictional force and amount of frictional heat

increased. On the other hand, frictional heat was measured in frictional forces over 10N in the copper-based polyimide tape and copper combination under the same conditions as a metal versus another metal. Relatively sliding occurred readily in fretting copper-based polyimide tape versus copper, which compared a metal-to-metal condition, since the contact pressure decreased as the contact area increased. Meanwhile, relatively slip was almost never because stick (that is to say only elastic deformation in boundary area without sliding) were occurred in fretting of a metal versus another metal. From this consideration, it is possible that specimens slip relatively in the fretting of polyimide tape versus copper. In contrast, specimens do not slip relatively in the fretting of metal against metal.

Therefore, it is assumed that when the SC-coil was vibrated in train running operation, frictional heat was generated at the boundary between the epoxy-impregnated superconducting coil and coil fastener spacers.

4.2 Frictional heat properties in the fretting of polyimide tape versus copper

The frictional heat properties in the fretting of liquid-helium cooled copper-based polyimide tape versus copper were examined in order to eliminate the factor that influences frictional heat.

Various thicknesses of polyimide-tape were pasted on copper for the fixed specimens, and copper was used for the sliding specimen. The normal force that acts on the boundary between specimens was lowered to 20 N to increase frictional heat detection sensitivity. Sliding specimens were vibrated at 300 Hz with a relative sliding displacement of about 10 μm .

Table 2 shows the list of test conditions. The correlation between the thickness of the polyimide tape and the amount of frictional heat is shown in Fig. 6. Zero thickness denotes the result of copper versus copper. Frictional heat decreased when the thin polyimide tape was inserted. However, frictional heat showed a tendency to increase gradually when tape thickness was increased. The amount of frictional heat exceeded that of copper when 82 μm -thick tape was used, and that was almost constant in tape thicknesses over 82 μm .

The hardness of a film-coated bulk body is influenced by that of both materials. When the film is thin, the influence of the base material becomes significant. However, the influence of the hardness of a film increases as the thickness of the film increases. Then the hardness of a film-coated bulk body shows an asymptotic tendency in the hardness of the film ^{8) 9)}.

Figure 7 shows the correlation between the thickness of polyimide tape and hardness for various thicknesses of polyimide tapes pasted on copper. These data were measured at 30 K by using the Vickers-type hardness tester for cryogenic temperatures ¹⁰⁾. Test specimens were cooled directly by refrigerator in a vacuum chamber. The indenter depth was shallow and the Vickers hardness value high when a thin tape was pasted on, because the hardness of the copper was dominant. However, both indenter depth and the Vickers hardness value decreased incrementally according the thickness of the tape, because of the growing influence of the polyimide on hardness.

Frictional heat increased incrementally according to the thickness of the polyimide tape (as seen in Fig. 6). On the other hand, increments in the thickness of the tape caused the hardness in copper-based polyimide tape to decrease (as seen in Fig. 7). These results suggest that the frictional heat strongly relates to surface hardness. It was assumed that frictional heat was strongly affected by the growth of the sliding area caused by the decrease in contact pressure that accompanies a decrease in hardness. In addition, it is possible that the frictional heat increases because of the change in the frictional drag owing to the elastic deformation of the polyimide tape.

It was confirmed that there was a possibility that frictional heat would be reduced by an incremental increase in the surface hardness of polyimide tape-coated epoxy-impregnated superconducting coils.

Table 2 Test conditions in fretting of copper-based polyimide tape versus copper

Condition of the fretting test			
Polyimide tapes		Vibration	
Thickness (μm)	Number of tape layers	Normal force (N)	Frequency (Hz)
-	0	20	300
36	1		
56	1		
82	1		
112	2		
168	3		
280	5

Fig. 6 Correlation between polyimide tape thickness and amount of frictional heat

Fig. 7 Correlation between hardness and tape thickness at 30 K for copper-based polyimide tape

4.3 Control method to reduce frictional heat inside SC-coil

4.3.1 Consideration of frictional heat control method

In the structure of an SC-coil, polyimide tape is placed between the epoxy-impregnated superconducting coil and coil fastener spacers. Frictional heat is assumed to be generated here. A control method for frictional heat here was considered from the results of the fretting test for various thicknesses of polyimide tapes.

Frictional heat can be restricted by inserting a metal thin film between the polyimide tape and the epoxy-impregnated superconducting coil. Figure 8 shows an example of an application to reduce the frictional heat in an SC-coil.

It was expected that inserting the metal thin film would increase the equivalent hardness (total hardness of the film-coated material) of the polyimide tape-coated epoxy-impregnated superconducting coil. Moreover, it was possible that the frictional heat load on the epoxy resin layer would be reduced by improving the cooling efficiency

Fig. 8 Example of application to reduce the frictional heat in SC-coil.

on the frictional surface. The thermal conductivity of resins such as epoxies and polyimide are 1/100 or less when compared with metals such as copper and aluminum. Furthermore, the specific heat of these resins at 4 K is about 1/600 that at room temperature. Consequently, the temperature of the resins at 4 K would rise immediately under a slight heat load. The hardness of materials at cryogenic temperatures decreases as the temperature rises^{10) 11)}. Therefore, there was a possibility that the temperature of the epoxy resin layer would rise slightly when fretting was occurring. Then there would be a decrease in the hardness of the epoxy resin layer. Inserting the intermediate metal thin film would prevent the temperature from rising and hardness from decreasing by providing high-performance hardness and thermal conductivity.

4.3.2 Verification of heat-reducing effect

Figure 9 and Table 3 show the test specimens used to verify the heat-reducing effect. In former experiments, the epoxy-impregnated superconducting coil was simulated by copper-based polyimide tape. Nevertheless, the epoxy resin layer was simulated in this experiment to reproduce the frictional environment of the epoxy-impregnated superconducting coil. In the case of fixed specimens, metal thin film was inserted between the epoxy resin layer and polyimide tape. A 150 μm -thick aluminium thin film and a 40 μm -thick stainless steel thin film were prepared. The normal force acting on the boundary between the specimens was set at 20 N. Test specimens were vibrated at 300 Hz under constant vibration power.

A comparison of the amount of frictional heat for simulated conventional and simulated heat-reducing specimens is as shown in Fig. 10. The amount of frictional heat was about 0.65 W when simulated conventionally. It was the same as that of tape thicknesses over 80 μm or three times that when using the same tapes pasted on copper with no epoxy resin layer (compare Fig. 6). The epoxy resin layer affected the amount of frictional heat.

(a) Simulated conventional SC-coil
(b) Simulated to reduce the frictional heat
Fig. 9 Schematic diagrams of test specimens used to verify heat-reducing effect

Table 3 Test specimens used to verify heat-reducing effect

Structure of fixed specimen (simulated surface of epoxy-impregnated superconducting coil)				
Simulational object	Top coat	insert	Epoxy-impregnated superconducting coil	
Conventional surface	Polyimide tape (36 μm)	—	epoxy resin layer	Copper
Frictional-heat reducing surface		Aluminium thin film Stainless steel thin film

Fig. 10 Comparison of amounts of frictional heat for simulated conventional and simulated heat-reducing specimens

On the other hand, the amount of frictional heat was reduced to approximately 0.3 W and 0.2 W when 150 μm -thick aluminium thin film and 40 μm -thick stainless steel thin film were inserted, respectively. The amount of frictional heat decreased to half that of the simulated con-

ventional specimen by inserting the intermediate metal thin film between the polyimide tape and the epoxy resin layer. This result demonstrates the heat-reducing effect in fretting coil fastener spacer versus epoxy-impregnated superconducting coil.

It was confirmed that there is a possibility that frictional heat can be reduced by an intermediate metal thin film inserted between polyimide tape and an epoxy-impregnated superconducting coil. It can be said that the increment of surface hardness of an epoxy-impregnated superconducting coil is an effective method for reducing the frictional heat that occurs on the surface of an epoxy-impregnated superconducting coil.

5. Conclusions

In the JR maglev system, the SCMs are vibrated by the electromagnetic disturbance when trains are operated. This phenomenon generates frictional heat inside the SC-coil. The dual aim of this study was to elucidate and then to control the relation between friction and heat generation inside the SC-coil.

A fretting test was performed by immersing specimens in liquid helium to evaluate the heat generated by friction between the SC-coil's structural components.

From the test results gained from respective material combinations, it is assumable that the frictional heat generated at the boundary between the epoxy-impregnated superconducting coil and a coil fastener spacer arose from SC-coil vibration.

From the test results gained from fretting copper-based polyimide tape versus copper, it was confirmed that there is a possibility that frictional heat will be reduced by increasing the surface hardness of a polyimide tape-coated epoxy-impregnated superconducting coil.

Finally, a control method to reduce the frictional heat that occurs on the surface of polyimide tape-coated epoxy-impregnated superconducting coil was considered. In this method, an intermediate metal thin film was inserted between the polyimide tape and an epoxy-impregnated superconducting coil to increase the equivalent hardness of the polyimide tape-coated epoxy-impregnated superconducting coil.

By verifying the heat-reducing effect, it was confirmed that there is a possibility that frictional heat will be reduced by an intermediate metal thin film inserted between the polyimide tape and the epoxy-impregnated superconducting coil. It can be said that the increment of surface hardness of epoxy-impregnated superconducting coils is an effective method to reduce the frictional heat that occurs on the surface of epoxy-impregnated superconducting coils.

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