Electrical Characteristics of Smart Insulation 2G HTS Coils Based on Three Fabrication Methods

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***Abstract*—This paper describes a technique for building smart insulation (SI) 2G high temperature superconductor (HTS) coils and investigates their electrical characteristics. The SI method utilizes the metal-insulated transition properties of V_2O_3. The V_2O_3 material acts as an insulator when the temperature is lower than a certain value. Above this temperature, the V_2O_3 material becomes a conductor. This transition can be used as a temperature switch between the turns of the 2G HTS magnets. The SI method is used to satisfy both the stability and charging/discharging time constant requirements of 2G HTS coils. We explain in detail how to make V_2O_3 paste using V_2O_3 powder and three different methods for installing V_2O_3 paste between the turns of the 2G HTS coil, which results in three different types of SI 2G HTS coils. These three types of SI 2G HTS coils are also discussed in terms of practical use.**

***Index Terms*—2G HTS coil, smart insulation method, V_2O_3 film, V_2O_3 paste.**

I. Introduction

WE HAVE, to the best of our knowledge, fabricated the first-of-its-kind smart insulation (SI) high temperature superconductor (HTS) coil, and further presented the results of experiments conducted on the coil over a span of two years [1]–[4]. The experimental results have revealed that SI 2G HTS coils have charging/discharging time constants similar to those of insulation coils before quench, and they exhibit increased stability owing to turn-to-turn current bypass after quench [2]. Furthermore, comparisons between the results of insulation, no-insulation, and SI coils have identified an increase in the output magnetic field of SI coils [1]. The sudden change of magnetic flux density in SI HTS coils after quench is termed the temperature switch function. This temperature switch function can definitively identify the occurrence of quench in the coil, and the switch can be further used to block the supply of electric power in order to protect the HTS coils when quench occurs. Thus, this temperature switch function is expected to contribute to the commercialization of HTS coils.

In the SI method, materials with metal-insulated transition (MIT) characteristics are inserted between turns of the HTS coil. The property of the MIT material, namely the rapid reduction of electrical resistivity due to temperature rise, is used. This study used V_2O_3, among various MIT materials [5].

This paper describes the V_2O_3 paste fabrication method. In addition, the details and results of experiments conducted using three types of 2G HTS coils, fabricated through the proposed method, are presented such that researchers requiring the SI method can apply it.

Manuscript received October 30, 2018; accepted February 15, 2019. Date of publication February 20, 2019; date of current version March 22, 2019. This work was supported by the Korea Electrotechnology Research Institute (KERI) Primary Research Program through the National Research Council of Science and Technology (NST) funded by the Ministry of Science, ICT, and Future Planning (MSIP) under Grant 18-12-N0101-07. *(Corresponding author: Young-Sik Jo.)*

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Digital Object Identifier 10.1109/TASC.2019.2900557

II. V_2O_3 Paste and V_2O_3 Film Fabrication Method

Fig. 1 presents a schematic of the process used to fabricate V_2O_3 paste. The process is as follows: (a) prepare polyvinylidene fluoride (PVdF) 10 wt% solution; (b) combine zirconia ball, PVdF 10 wt% solution, and N-Methyl-2-Pyrrolidone (NMP) with V_2O_3 powder using the Thinky mixer; and (c) obtain the fabricated V_2O_3 paste.

PVdF-HFP Kynar 2801 powder, serving as a binder, is mixed with NMP employed as a solvent at 10:90 wt% using a stirrer at 150 rpm for 12 h to prepare PVdF 10 wt% solution.

V_2O_3 is provided in the form of powder with particle size approximately 180 to 200 mesh. This size can be converted into approximately 123 μm to 141 μm for practical use. However, this large and irregular size is inappropriate for preparing the paste. Thus, ball milling is performed for 40 min by using 15 zirconia balls with 3-mm diameter, as well as 10 zirconia balls with 5-mm diameter. The particle size was not significantly reduced by ball milling over 40 min.

V_2O_3 paste was prepared by adding NMP, which serves as a solvent facilitating the mixture of PVdF 10wt% solution and V_2O_3. The mixing ratio of V_2O_3 to PVdF was 98:2, as a weight percentage, for preparation.

In this study, 20 g per session was prepared by considering the characteristics of the Thinky mixer device. At a ratio of 19.6 g of V_2O_3, 4 g of PVdF 10 wt% solution, and 8 g of NMP 20 g of V_2O_3 paste was prepared. Because NMP evaporates during

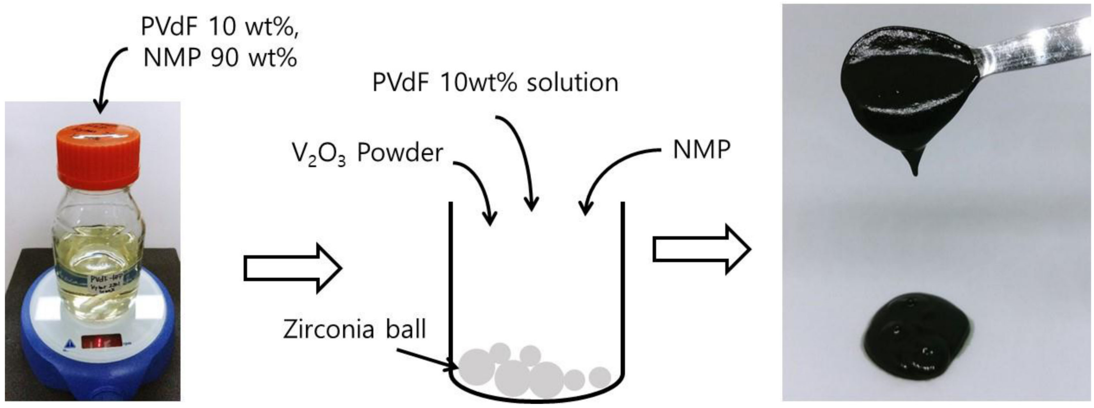


Fig. 1. Preparation steps for V_2O_3 paste. (a) PVdF 10 wt% solution. (b) Mixed in Think mixer. (c) V_2O_3 paste.

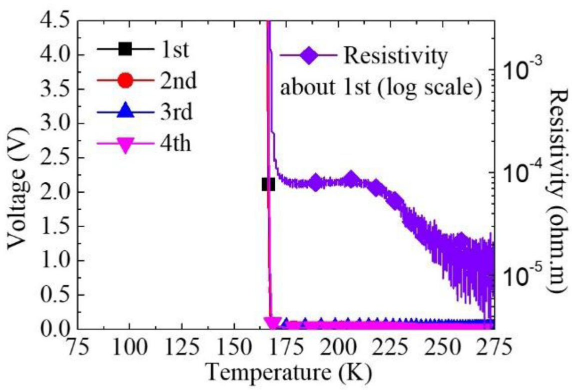


Fig. 2. Experimental result of voltage and resistivity at different temperatures of V_2O_3 paste.

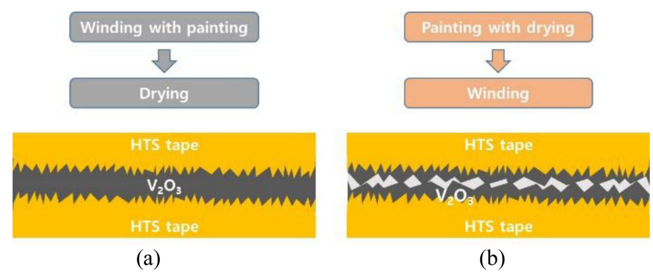


Fig. 3. Flow of application of V_2O_3 paste to (a) Coil 1 and (b) Coils 2 and 3, and diagram of contact section between the turns of the coil.

the drying process, the viscosity control suitable for painting the 2G HTS tape, as well as the volume reduced after drying, was considered in this process.

The rotation speed of the Thinky mixer was 1800 rpm. The mixture was stirred first for 3 min, and further stirred after the V_2O_3 paste had sufficiently cooled. This step was repeated four times to obtain the V_2O_3 paste. This step was applied to prevent the drying and phase variation due to frictional heat, which occurs during rotation.

Fig. 2 presents the experimental results of voltage and resistivity corresponding to various temperatures of the V_2O_3 paste. The most notable results of the repeated experiments performed using numerous manufactured short samples are presented. The transition temperature of the V_2O_3 paste was approximately 160 K, and the resistivity was 10^{-4}–10^{-5} ohm.m [2].

The V_2O_3 film was fabricated by coating V_2O_3 paste at a thickness of 50 μm onto 10 μm thick and 12 mm wide copper tape via the doctor blading method. In fabricating the V_2O_3 film via the doctor blading method, the target mixture was dried at a temperature of 100 °C for 2 h. The V_2O_3 film was fabricated because 1) it is more productive than when it is coated directly onto HTS tape, and 2) it can be applied to various types of superconducting wires, such as circular superconducting wire, in addition to tape-shaped materials.

III. Fabrication and Experimental Results for Three Types of SI HTS Coils

Three types of SI HTS coils were manufactured using three different V_2O_3 paste application methods. The first method (Coil 1) is "drying after winding," in which the coil is wound by painting V_2O_3 paste with a brush between the turns of the coil and further drying the painted coil. The second method (Coil 2) is "winding after drying," in which the coil is wound after HTS tape is coated with V_2O_3 paste and further dried. Finally, in the third method (Coil 3), the coil is fabricated by co-winding the coil with V_2O_3 film and HTS tape.

Fig. 3 presents the flow of the respective application method for applying V_2O_3 paste to Coil 1 (Fig. 3(a)) and Coils 2 and 3 (Fig. 3(b)), as well as a diagram of the resulting contact section when the coils are wound. Both coils have advantages and disadvantages. In Coil 1, the liquid V_2O_3 paste is painted onto the HTS tape while winding the coil. Because the coil is dried after being wound, the contact resistance between the turns is likely to be small. However, this method has the following disadvantages. The drying time is excessive in this case because it is necessary to dry the coil in the oven for approximately 12 h at 120 °C to dry the NMP present between the turns. Furthermore, as the size of the coil is increased, drying equipment with larger space is required to accommodate the larger coil. Given that this occurs before solidification, the thickness depends on the winding tension; thus, controlling the thickness is difficult.

TABLE I
SPECIFICATIONS OF SI 2G HTS COILS ACCORDING TO FABRICATION METHOD

Parameters	Coil 1	Coil 2	Coil 3
2G HTS tape	ReBCO (SuperPower, SCS12050-AP)		
Width of tape (mm)	12		
Thickness of tape (mm)	0.064		
Thickness of stabilizer (μm)	Cu, 10, enclosed		
Thickness of substrate (μm)	50		
Ic @ 77 K, self-field (A)	335–342		
V2O3 paste	With winding	Before winding	V_2O_3 film
Number of turns	8		
Inner diameter of coil (mm)	80		
Winding tension (N)	39.2		

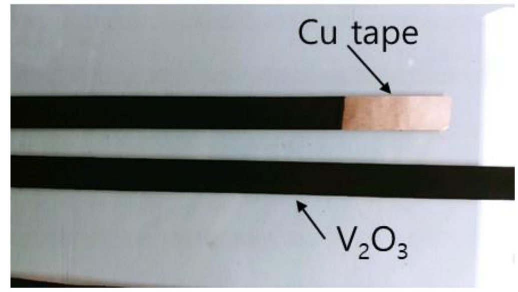
In Coil 2, the method of painting and drying V_2O_3 paste onto the HTS tape and winding the coil with the painted tape after completion of drying is applied. This method is advantageous in that the thickness can be controlled, and the tape dries quickly because the V_2O_3 layer that is exposed to the outside is dried. However, given that the turns are in contact with each other while the V_2O_3 paste is in the solid state, the contact resistance is high. This is a disadvantage.

Table I shows the specifications of the three types of SI HTS coils according to fabrication method. Other conditions, such as application of HTS tape, equal number of turns, and the V_2O_3 paste application method, were varied. The thickness between turns are 50 μm and 100 μm for Coil 1, 100 μm for Coil 2, and 50 μm for Coil 3. The HTS tape used in all three coils was manufactured by SuperPower, and a length of approximately 200 cm was used for each coil. After winding, the outside of the coil was sealed using a special silicone adhesive (Addisil8108 model of MOMENTIVE).

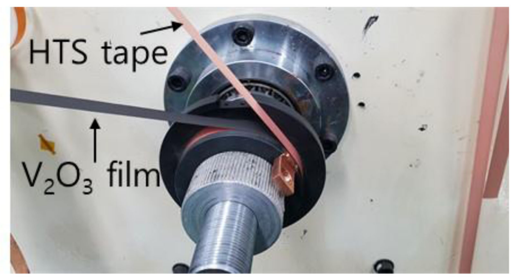
Fig. 4 shows images of the fabricated V_2O_3 film, as well as the co-winding step of HTS tape and the V_2O_3 film. A length of 2 m of V_2O_3 film was, and the total thickness was as small as 50 μm; thus, extra care was required when winding the coil.

Fig. 5 shows the results of the critical current test for the three types of coils. The critical current was measured at 77 K (LN_2) based on 1 μV/cm, and a current of 1 A/s was applied. The critical currents were 179.9 A for Coil 1, 264 A for Coil 2, and 203.9 A for Coil 3.

Fig. 6 shows the overcurrent test results for Coil 1. At 215 A, a quench occurred in the coil, and the coil burned out at 230 A. Although the critical current of the coil was 179.9 A, the output magnetic field was continuously raised while maintaining the number of turns up to 215 A. After the quench, a rapid current bypass occurred, and the output magnetic flux density of the coil sharply dropped. In the figure, Δt represents the time taken from the occurrence of quench to the time when the coil burned out. Here, quenching indicates a phenomenon in which the output magnetic field rapidly decreases. The recorded Δt was 15.1 s. The burn out was referenced at the open circuit point, in which the electrical current becomes zero in an instant, as the experimental result suggests. A protective circuit of a superconducting coil is produced using a semiconductor, and it sufficiently acts within a few milliseconds. Therefore, one second is a



(a)



(b)

Fig. 4. Image of (a) V_2O_3 film and (b) co-winding step of HTS tape and V_2O_3 film.

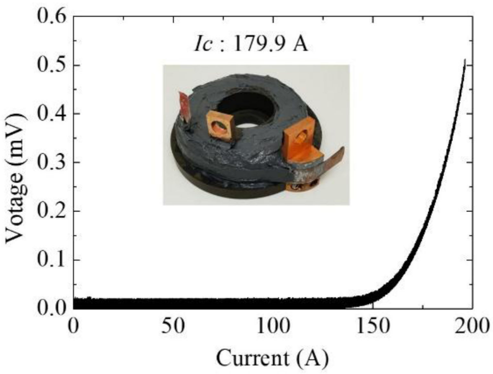
sufficient time to protect the superconducting coil from burning out.

Fig. 7 shows the overcurrent test results for Coil 2. Fig. 7(a) presents the overall experimental results, whereas Fig. 7(b) provides a magnified view of the time interval during which quenching occurred. The critical current of the coil was 264 A; however, quenching occurred at 298 A. The recorded Δt was 3.1 s.

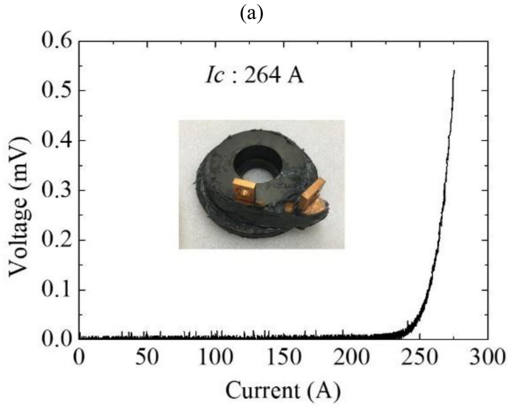
Fig. 8 shows the overcurrent test results for Coil 3. Fig. 8(a) presents the overall experimental results, whereas Fig. 8(b) provides a magnified view of the time interval during which quenching occurred. Quenching occurred at 236 A, and Δt was 4.2 s. Coil 1 displays a larger Δt than Coils 2 and 3 because, as explained in Fig. 3, Coil 1 utilizes the winding after dry method, which results in better contact resistance between turns. In contrast, Coils 2 and 3 utilize the dry after winding method, which results in larger contact resistance between turns compared to Coil 1.

All three SI HTS coils burned out near the current lead located on the outside. During the winding process, the HTS tape is joined to the current lead part located on the outside. The current lead located on the outside is produced as a copper block with a sufficient volume that a current with a large magnitude can flow through. Therefore, when the HTS tape is connected to the current lead, a section where there is no contact between the last turns between coils exists. That section is a weak point as the path through which the current flows to the current lead is only the HTS tape. After winding, the two HTS tapes are joined together at this section; however, this point is susceptible to burnouts.

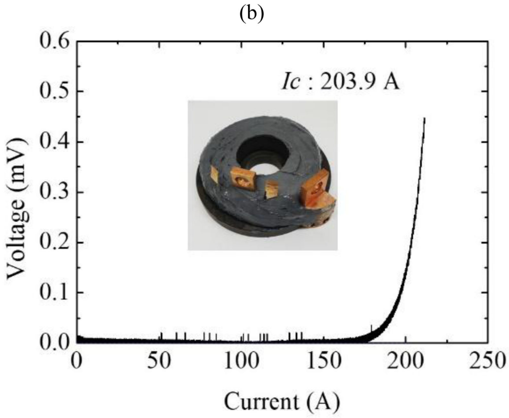
The critical currents of three coils, the maximum magnetic flux density, the quench current, and the time at which the current bypass occurred after quenching all differed. It is difficult to



(a)



(b)



(c)

Fig. 5. Critical current test results for the three coils: (a) coil 1, (b) coil 2, and (c) Coil 3.

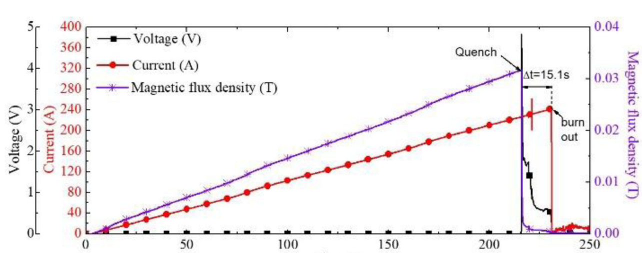
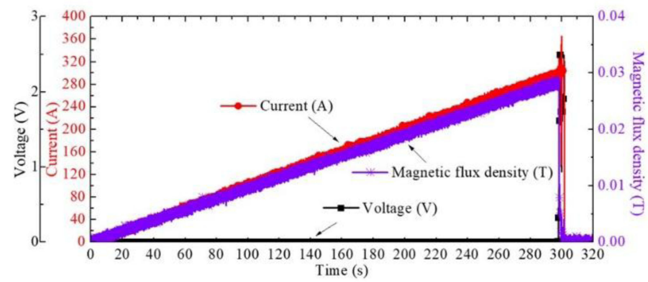
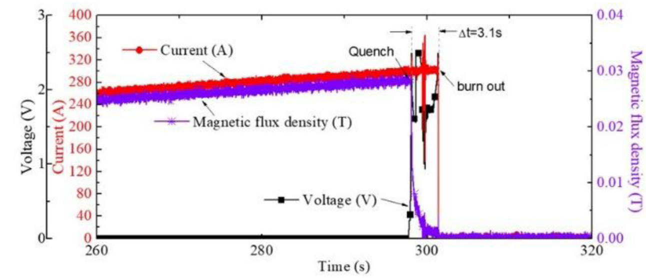


Fig. 6. Overcurrent test results for Coil 1.

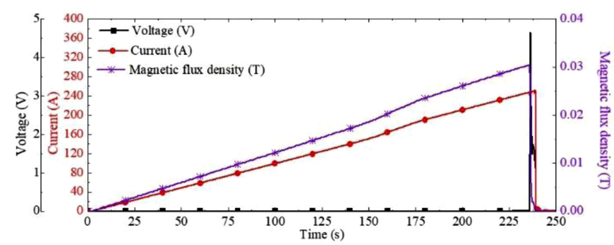


(a)

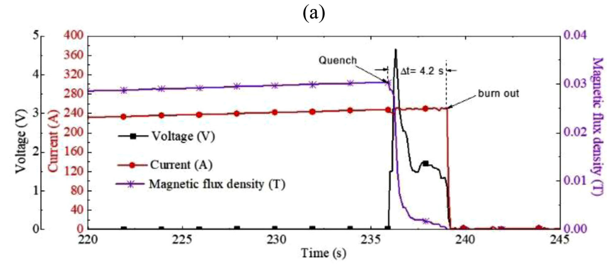


(b)

Fig. 7. (a) Overcurrent test results for Coil 2 and (b) magnified view for the time interval near the occurrence of the quench.



(a)



(b)

Fig. 8. (a) Overcurrent test result for Coil 3 and (b) magnified view for the time interval near the occurrence of the quench.

precisely describe the reasons for each case. Among the reasons, it could be that the HTS tape may have had a different critical current along the length, or it may have had a defect. It could also be that there were differences in the manufacturing processes, or the positions of the hall sensor were different.

However, it is certain that the V_2O_3 paste described in this paper can be used to fabricate SI HTS coils using three different methods. Before the coil is quenched, the number of turns, as in the insulation coil, is maintained, and after the quench, a current bypass occurs, which allows sufficient time to protect the coil from burning out.

IV. Conclusion

In this paper, the V_2O_3 paste fabrication method was examined in detail. Further, experiments and results for three types of SI 2G HTS coils fabricated by applying three different fabrication methods using V_2O_3 paste specifically, 1) drying after winding, 2) winding after drying, and 3) V_2O_3 film co-winding were presented and analyzed.

All three types of HTS coils showed typical SI HTS coil characteristics because the number of turns is maintained before quenching, and a current bypass occurs after quenching. An additional advantage of the SI method is that the number of turns is maintained and the output magnetic field is raised above the critical current of the HTS coil.

The Coil 1 method is better for taking large Δt, but it has difficulty in the drying process after winding. The Coil 2 method has an advantage when producing large coils, and the V_2O_3 film is applicable even to circular superconducting wires.

SI HTS coils will be applied in field coil development for several MW-class superconducting rotors in the future.

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