Development of Radiation-Resistant Magnet Coils for High-IntensityBeam Lines: Part II-completely inorganic insulated coils

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Abstract--We report here on R/D work concerning two types of radiation-resistant magnet coils, which were insulated using completely inorganic materials. Regarding the first coil, the electric insulator employed was a alumina long fiber and a ceramic binder. A new combination of adhesive agent, inorganic filler and alumina long fiber was found, which enabled us to form a strong insulation layer which does not peel off from a copper conductor. The magnet coil for 2000A excitation current was produced using this insulation method. The second coil is a mineral insulated cable (MIC) with a 3000A excitation current. This 3000A-class MIC has been manufactured as a short sample, and was tested concerning its electric insulation both before and after bending.

I. INTRODUCTION

In Japan some big projects are being carried out concerning intensity-frontier sciences which require high intensity and high energy beams. For the transmutation of high-level radioactive waste [1], Thorium molten-salt nuclear energy synergetics [2] and the Japanese Hadron Facility (JHF) project [3] are well-known examples. The beam lines of these facilities will have to handle primary proton beams of more than 1GeV-10mA. The very high radiation level around the primary beam will diminish the lifetimes of the beam-line magnets assembled using conventional organic insulation materials. Therefore, the production of highly radiation-resistant magnets is essential to realize the primary beam lines of those big projects. It is well known [4] that inorganic materials (e.g. MgO, Al_2O_3, and SiO_2) should be employed as electric insulators in order to increase the radiation resistance. We have already constructed magnets using inorganic insulation materials comprising high alumina cement (HAC) and compacted magnesium oxide (MgO) [5]. We have found, however, that an HAC insulator is weak against humidity. Therefore, a coil using HAC had to be hermetically sealed in a stainless-steel casing filled with dry nitrogen. On the other hand, it is known that ceramic materials are very hard against radiation destruction. There are several methods to form a ceramic insulation layer on a conductor surface, e.g. chemical-vapor deposition and plasma thermal-sprayed coating. However, there are several serious disadvantages in using such methods. For example, a coated layer peels off easily upon bending a conductor, and an insulation layer can not be formed at the inter-conductor position. We therefore developed a new coating method using the combination of a completely inorganic gelatinous binder and a pure continuous alpha-alumina fiber.

The other cable insulated by a complete inorganic material we are developing was a mineral insulated cable (MIC), which was covered by a compacted MgO powder. We have already produced an MIC of 2000 A-30 m class in Japan. The test results of a coil assembled with this MIC were reported at MT13[6]. We intend to prepare a larger size MIC of 3000 A class for assembling large-scale and higher field magnets for future high-energy/high intensity projects.

II. COIL WITH NEW ELECTRIC INSULATION MATERIALS

A. Ceramic Insulator

The radiation life of an organic material never exceeds 10^9 Gy, even in the strongest case. The electrical insulation formed with mineral materials resists higher radiation destruction. Usually, the ceramic insulation on a coil conductor is formed by plasma thermal spraying and/or by chemical-vapor deposition. However, such methods can not be applied to a copper conductor. It is known that the thermal-expansion coefficient of the usual ceramic binder is $6\text{-}14\times10^{-6}$. This value is very close to those of steel (11×10^{-6}), stainless steel (15×10^{-6}) and nickel metal (13×10^{-6}). It is, however, slightly far from copper (19×10^{-6}). Therefore a simple ceramic layer on a copper substrate always peels off after a thermal cycle. We have subsequently found a combination of a completely inorganic ceramic binder and a pure alumina long fiber. Both materials have recently become available as new industrial materials. Since a ceramic binder was combined with an alumina long fiber, the electric insulation layer on a copper conductor maintained its shape after curing and baking. In this case, a ceramic binder does not coat the complete plane of the copper substrate surface, and sticks at many points on the substrate.

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A ceramic binder under wet conditions was wrapped on a conductor just before winding, and was dried and baked. Therefore an electric insulation layer using both new materials came to be easily applied on an ordinary oxygen-free copper (OFC) hollow conductor as a traditional fiber reinforced plastic (FRP) insulator.

B. Adhesive Agent and Inorganic Filler

The role of a ceramic binder was as an adhesive agent and an inorganic filler between alumina long fibers. We tried several combinations of compositions for the ceramic binder. The requirements of insulation materials of a copper conductor are summarized as follows:

(1)A ceramic binder can dry and bake under 200 °C, because a copper conductor is oxidized at over 200 °C.

(2)An electric insulation layer never peels off due to thermal cycling, and should keep its shape on a conductor, i.e. the thermal-expansion coefficient of the binder should be nearly equal to that of a copper conductor.

(3)After being baked, the electric resistance should be more than 1000 MΩ-cm, even in a high-humidity environment.

We first used two types of binders: the usual commercial-base adhesive agent and an inorganic filler (samples A and B of Table I). Table I gives the compositions of ceramic adhesive agents. Aluminum oxide (Al_2O_3), which is most commonly used as a coating material, was chosen as the main part of the adhesive agent. It is known that coating oxide materials provides underlying metals with protection against oxidation at elevated temperatures and with a high degree of thermal insulation. The melting point of aluminum oxide is about 2070 °C. Both samples A and B contained an organic binder. After curing at 200 °C, although sample A was not completely carbonized in the binder, the carbon in sample B was burned away, and completely disappeared. The alumina sol was used as a plasticizer in order to increase the viscous property.

TABLE I

Compositions of the ceramic adhesive agent and inorganic filler

	A	B	C	D
Alumina Powder: Al_2O_3	62 wt%	43	43	53
Dimethyl Phthalate: $C_{10}H_{14}O_4$	11	--	--	--
Alumina Sol: $Al(OH)_3$-Al_2O_3,AlOOH	--	0	29.4	11
Basic Aluminum Chloride: $Al_2Cl(OH)_5$ liq.	--	22	22	33
Poly Vinyl Acetate	--	33	3.6	0
Epoxyline Resin Solution:	11	--	--	--
Water	--	2	2	3
Methyl Ethyl Ketone	16	--	--	--

The electric insulation of sample A reached over 1000MΩ-cm against the A.C. 500V peak-to-peak voltage after curing at 100°C for 4 hours and 150 °C for 2 hours. It was, however, broken down to 500M ohm-cm after extra curing at 200 °C for 2 hours. Sample B reached over 1200 MΩ-cm after curing at 100 °C for 4 hours and at 150 °C for 2 hours and maintained electric insulation after extra curing at 200 °C for 2 hours.

We then tried to obtain an organic binder from the compositions of sample B, i.e. poly vinyl acetate (PVA) as a plasticizer material. In samples C and D, we increased the fraction of alumina sol in the plasticizer and decreased the PVA. These samples can be diluted with water. The slurry of both samples C and D easily settles out of solution. Therefore, before dipping and brushing with a slurry binder, these have to be thoroughly stirred. In order to harden the ceramic binder, it was baked at over 200°C for 2 hours. The results of an electrical-insulation test for samples C and D reached 1200MΩ-cm. However, we found that sample D included not a small fraction of PVA, and was not suitable for brushing and spraying on conductors. We therefore decided to use sample C as a ceramic binder.

C. Pure continuous alpha-alumina fiber

The pure alpha-alumina fiber that we used was ALMAX [7] which was used as the base tape of a new wrapping insulator instead of glass tape or asbestos tape. The pure alumina tape was a ribbon cloth of 25 mm width and 0.5 mm thickness, woven from long alumina yarn. When a ribbon cloth was woven, a polyester thread was used as a sizing material. However, the woven ribbon was desized by an incinerator at 1000 °C, and the organic materials were removed. The physical constants of ALMAX tape are listed in Table II. From the thermal-expansion coefficient of ALMAX, we can expect that the maximum shearing temperature of sticking ALMAX fibers onto a copper surface is 287 °C.

TABLE II

Pure alpha-alumina long fiber

Chemical composition(%)	Al_2O_3 : 99.5 wt% purity	
Crystal phase	alpha-Al_2O_3	
Filament diameter	10	μm
Filaments/yarn	1000	
Density	3.6	g/cm^3
Tensile modulus	33000	kgf/mm^2
Tape width	25	mm
thickness	0.5	mm

D. Coil Fabrication

In order to compare with 2000A class MIC, which had been made before 1993 (we had already reported on it. [6]), we chose the cross-section of the conductor to be 15x15 mm^2. The conductor was wound as a race-track coil with 2 rows x 7 layers x 2 pancakes. The cross-section of the fabricated coil was 139 mm in width and 82 mm in thickness. The surface of conductors must be chemically cleaned before brushing and taping in order to utilize the mutual-diffusion between the oxides of the metal surface and alumina ceramics. It is, however, more important that the surfaces of the substrates are mechanically slightly rough in order to adhere to the binder. The actual fabrication procedure of the magnet coil is as follows:

(1)We first cleaned the outside surfaces of a copper conductor so as to be free from any dirt, oil or scales.

(2)Secondly, the ceramic binder(i.e. sample C) was painted using a brush. At the same time, an alumina ribbon tape was wrapped around the copper conductor in a double layer with a 2/3 overlap. Therefore, the insulation thickness was 2 mm. The ceramic binder plays the role of an adhesive agent and an inorganic filler between alumina long fibers.

(3)In order to maintain the ground insulation, all of both pancakes was wrapped with alumina ribbons.

(4)While curing the conductor the ceramic binder was dried and baked. A flow chart of baking and curing coils as well as ceramic binder is shown in Table III.

TABLE III

time	curing temperature	
4 hours	room temperature	
48 hours	45°C	preliminary drying
4 hours	100°C	curing
2 hours	150°C	
1 hours	180°C	baking
1 hours	200°C	

E. Results

A newly ceramic-insulated magnet coil was tested using the same magnet assembly as that for the 2000A-class MIC coil. One coil of the test magnet was replaced by the ceramic coil, as shown in Fig.1. The insulation resistance between ceramic-insulated pancakes and between the coils and ground was measured using a mega-ohm-meter with 1000V A.C. Each resistance exceed 1000MΩ. The long-term operation results of the 2000A-class ceramic-insulated coil are listed in Table IV. The results for a 2000A-MIC coil are also listed as references. No defect in the ceramic insulation was observed, even under a high-humidity environment, for more than two years (since MT13).

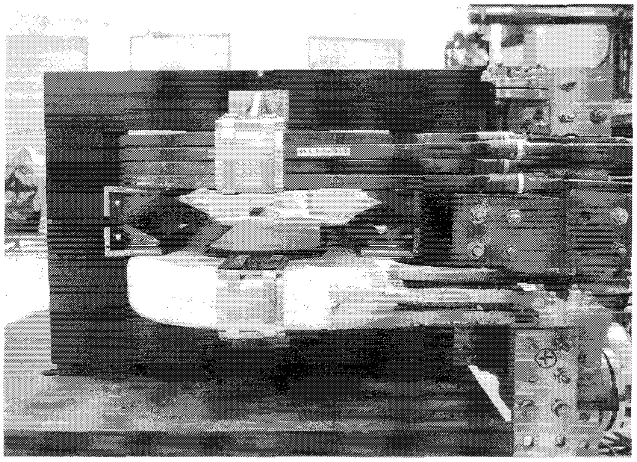

Fig.1 Test magnet assembled using the new ceramic-insulated coil and 2000A-class MIC.

III. 3000A CLASS MIC

We have already developed a 2000A-class MIC which has a square cross-section hollow conductor in Japan [6]. As mentioned before, we intend to obtain larger size MIC in Japan in order to assemble large-scale higher-field magnets for higher-energy/high-intensity accelerator facilities. We therefore started R and D work on a 3000A-class MIC.

TABLE IV

Operation results of the ceramic-insulated coil and 2000A MIC

	CERAMIC	2000A MIC	
D.C. resistance/cooling circuit (room temperature = 20°C)	5.23	6.50	mΩ
Total number of turns	28	28	
	2 rows x 7 layers x 2 pancakes		
Insulation thickness/coil	2	1.75	mm
Magnet voltage/cooling circuit	12.7	14.8	Volts
Magnet power/cooling circuit	25.4	29.6	kWatts
Pressure drop	10	10	kg/cm2
Water flow/cooling circuit	0.283	0.200	litter/sec
Conductor temperature rise	21.4	35.4	°C
Coil surface temperature rise	40.4	43.7	°C
Specific heat	0.88	0.96	J•g-1•K^{-1}

TABLE V

Dimensions and basic parameters

Outside diameter	28.00	mm2
Insulation wall thickness	2.50	mm
Conductor outside diameter	20.00	mm2
inner diameter	10.00	mm2
Cross sectional area conductor	293.1	mm2
hollow	99.1	mm2
Test coil length	30	m
Material sheath	PDC, C1220(JIS)	
conductor	OFC, C1020(JIS)	
Nominal current	3000	A

TABLE VI

Expecting conductor parameters (at 3000 A-60 m)

Mass electrical resistance(t=20°C)	d20=0.15328 Ω-g/m2	
Conductor length/cooling circuit	60	m
Magnet voltage/cooling circuit	10.23	volts
Magnet power/cooling circuit	30.7	kWatts
Pressure drop	10	kg/cm2
Water flow/cooling circuit	0.3163	litter/sec
Conductor temperature rise	23	°C

A. Cable design

The basic design constraints of the 3000A-class MIC are summarized below. The pressure drop of cooling water is 10 kg/cm^2 and the maximum allowed temperature rise is below 35°C. In order to realize a sufficient water-path length without connecting the MIC conductor in one coil pancake, it is desired that the length of the conductor should be more than 60 m. The materials employed for the 3000A class MIC were the same as those of the 2000A class MIC, i.e. a hollow conductor was made of oxygen-free copper (OFC) and the outside sheath was made of phosphorus deoxidized copper (PDC). Compacted magnesium oxide (MgO) was inserted between the hollow conductor and the sheath for the electrical insulator. The dimensions and parameters of the 3000A class MIC are listed in Table V. The expected conductor parameters of the 3000A/60m MIC are listed in Table VI.

B. Present Status

A short sample (2 m) of the 3000A MIC was just recently fabricated. The manufacturing process of the MIC that we employed was the conventional drawing of a multilayered coaxial insulator/conductor assembly. Fig.2 shows the cross section of the 3000A MIC. The results of electrical insulation tests before and after bending the conductor were satisfactory, and reached over 1000 MΩ-cm at 1000VA.C.. The electrical insulation between the conductor and outside sheath remained on after bending at a radius of 90mm.

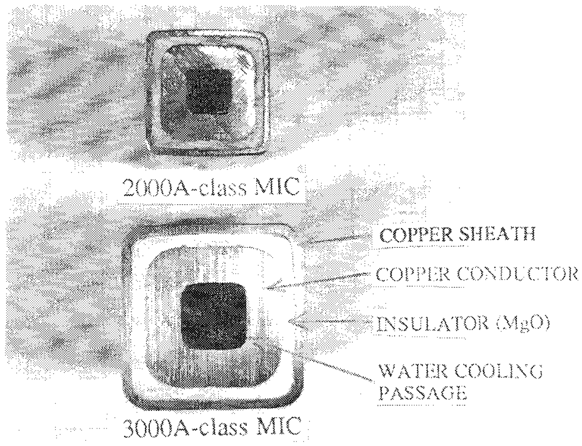

Fig.2 Cross-section of a 3000A mineral insulated cable.

IV. SUMMARY

In order to realize future high-intensity/high-energy beam lines, we have developed two kinds of radiation-hard coils. The first coil, with a ceramic insulator (i.e. alumina binder and alumina long fiber), was tested and fabricated successfully. The new-ceramic which we successfully employed insulated the magnet coil under both high-radiation and high-humidity environments. The second coil was designed using 3000A class MIC. Short samples were successfully produced in Japan. By the end of this fiscal year, this coil will be fabricated in lengths of more than 30m.

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