The published version of this preprint appeared in IEEE Transactions on Applied Superconductivity 23, 4601204 (June 2013).

Development of High Strength Pancake Coil with Stress Controlling Structure by REBCO Coated Conductor

Shigeo Nagaya, Tomonori Watanabe, Tsutomu Tamada, Mitsuhito Naruse, Naoji Kashima, Toshio Katagiri, Naoki Hirano, Satoshi Awaji, Hidetoshi Oguro and Atsushi Ishiyama

***Abstract*—High strength against electromagnetic force is required for high magnetic field and large capacity coil in order to develop large-capacity superconducting magnetic energy storage (SMES) system for electric power system control. And suppression of delaminating of Yttrium (Y) based coated conductor in a coil is also required to manufacture the highly reliable and durable superconducting coil. Insulating coating, using liquid resin of low-temperature-curable-polyamide, was developed and showed durability at very low temperature without deterioration of transport properties of superconducting wire in a coil. Combining paraffin molding, delaminating and deterioration of transport properties of superconducting wire were not also observed in a coil. These insulating techniques were applied to the pancake coil, in which superconducting wire and the reinforcing outer plates of the coil withstand electromagnetic force. The double pancake coil of this coil structure, called "Yoroi-coil; Y-based oxide superconductor and reinforcing outer integrated coil" was prepared and verified durability against electromagnetic force by hoop stress test. The coil achieved 1.5 kA transporting at 4.2 K in 8 T back-up magnetic field without the degradation of transport properties. Maximum hoop stress at the hoop stress test reached 1.7 GPa, based on the calculations. This result was confirmed that Yoroi-coil structure has a capability to withstand the large hoop stress, which exceeded the tensile strength of Y-based coated conductors, and bring out highly durable and reliable superconducting coils.**

***Index Terms*— Hoop stress, Yoroi-coil, SMES coil, Yttrium based coated conductor.**

I. Introduction

TOWARD the realization of GJ (giga-joule) class large capacity superconducting magnetic energy storage (SMES) system for power system control, high reliability and durability of superconducting coil is essential [1], [2]. High strength and high field coil is needed to increase the electric power capacity. But strong electromagnetic stress affects to the coil according to the increase of magnetic field (*B*), current density (*J*) and the coil radius (*R*).

Coated conductors, in which Hastelloy is used as substrates, have high tensile strength exceeding 1 GPa, calculated in the condition that the stress is only given to the Hastelloy substrates [3]-[6]. Therefore, coated conductors were considered that they can construct high field and high strength coil owing to their own mechanical strength. It was confirmed that the single pancake (SP) coil using coated conductors could withstand a hoop stress of over 600 MPa [7]. However, the coil structure depending on only the strength of coated conductor has risks because delaminating would occur in the impregnation molded coil. So, novel design of coil construction is required to achieve high strength and high field coil without dependence on only the strength of coated conductors themselves.

In this paper we report about the development of the insulating coating technology that uses liquid resin and also the novel structure of high strength pancake coil by REBCO coated conductor.

II. Insulating Coating Technology by Liquid Resin for Coated Conductor in Coil

Conventional insulating coating technique using formal enamel resin needs high temperature treatment, which might cause degradation of transport properties in coated conductors. Insulation of wrapping resin tapes around coated conductor might degrade insulation performance by inclination of tapes in winding into a coil and/or impregnation molding. The inclination of wrapping tape also causes stress concentration and inclination of impregnating resin, so that it causes degradation of transport property. Therefore the development of continuous flat insulation coating with high insulation performance, flexibility at low temperature and low cost is required. And its process must be simple and have high manufacturing speed. Then, liquid resin, curing at lower temperature than 150 °C, was introduced to insulating coating technique for coated conductors.

In the superconducting wire, a buffer layer was formed using the ion beam assisted deposition (IBAD) method and a Y-based oxide superconducting layer was formed using the chemical vapor deposition (CVD) method on a Hastelloy substrate with a width of 10 mm and thickness of 100 μm. The wire was then plated with 50 μm-thick layer of stabilizing

Manuscript received 5 October 2012. This work was supported by the New Energy and Industrial Technology Development Organization (NEDO) as the Technological Development of Yttrium-based Superconducting Power Equipment.

S. Nagaya, T. Watanabe, T. Tamada, M. Naruse, N. Kashima, T. katagiri and N. Hirano are with the Chubu Electric Power Co., Inc., Nagoya, 459-8522, Japan (phone: +81-50-7772-3041; fax: +81-52-624-3994; e-mail: Nagaya.Shigeo@chuden.co.jp).

S. Awaji and S. oguro are with the Institute for Material Research, Tohoku University, Sendai, Japan.

A. Ishiyama is with the Waseda University, Tokyo, Japan..

The published version of this preprint appeared in IEEE Transactions on Applied Superconductivity 23, 4601204 (June 2013).

copper on all over. A long coated conductor was insulated by the liquid resin, named low-temperature-curable-polyamide, and heated to cross-link below 150 °C. Fig. 1 shows the cross-section of coated conductor insulated by low-temperature-curable-polyamide. The heat conductivity of the liquid resin after heat treatment is about 2 W / K m, which is about 10 times higher than the performance of conventional insulating resin tape. This means the liquid resin has capability to apply conduction cooling for coil system. A.C. break down voltage of 10 kV / 25 μm (thickness) is comparable to conventional insulating resin tape. Coated conductor insulated by the liquid resin was coiled into SP coil and the coil was molded by paraffin to play roles of insulator, spacer, thermal conductor, coil shape fixer and stress absorbing by cracking itself. The specification of the SP coil is shown in table I. The *I-V* characteristics of the coil before and after winding and molding, and after several times of cooling cycles between room temperature and liquid nitrogen temperature were measured to verify the influence of insulation and molding. There was no difference in critical current (I_c) and *n*-value of all *I-V* curves, as shown in Fig. 2. These results indicated that liquid resin insulation and paraffin molding are available to form pancake coils without degradation of transport property.

III. High Strength Pancake Coil

A. *Concept of Design*

Hoop stress is the electromagnetic forces acting on the circumference of a superconducting coil, and tends to elongate the superconducting wires within the coil. When only the superconducting wire itself withstands against the hoop stress, electric current can flow through the coil to the extent strength and uniformity of the superconducting wire permit. We developed novel coil structure, in which whole structure

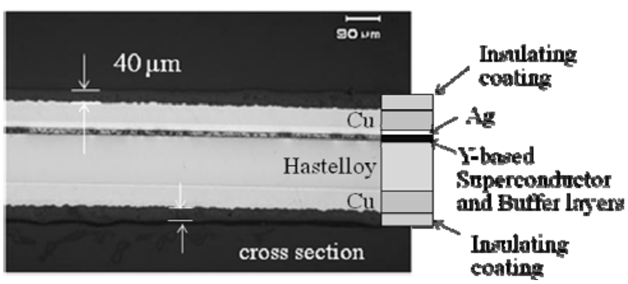

Fig. 1. Cross-section of coated conductor insulated by liquid resin called low-temperature-curable-polyamide

TABLE I Specifications of The SP Coil for Hoop Stress Tests

Superconducting wire type	Copper plated IBAD/ CVD - (Y, Gd)BCO tape coated conductor
Wire length	22 m
Insulated wire width	10.3 mm (maximum)
Insulated wire thickness	315 μm (maximum)
Coil figure	single-pancake coils
Inner/ Outer diameter	143 / 171 mm
# of total turns	45

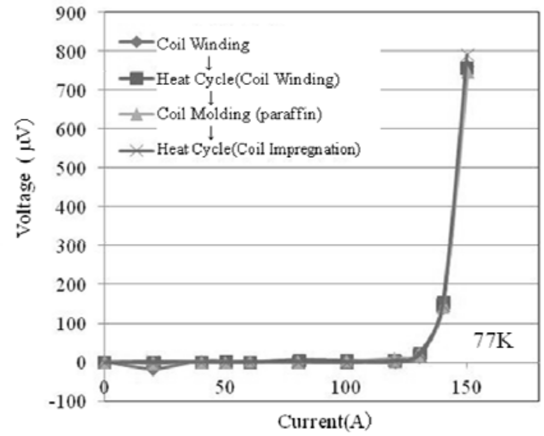

Fig. 2. *I -V* characteristics of SP coil measured before and after winding and molding, and after several times of cooling cycles

materials including superconducting wire can withstand the hoop stress. Fig. 3 describes the schematic of the new coil structure. We call it "Yoroi-coil" (Y-based oxide superconductor and reinforcing outer integrated coil). Yoroi means "SAMURAI armor" in Japanese. The coil winding of superconducting wire was set into the reinforcing outer plates and frames. In current flowing, electromagnetic force would make coil winding of superconducting wire expand and make superconducting wire elongate. Then stress affects to the frame through the superconducting coil winding situated inside to expand the whole structure of the superconducting coil. But the reinforcing outer plates, connected to the frame, support the coil to suppress the deformation of the coil against electromagnetic forces. In Yoroi-coil structure, a part of electromagnetic force is shift from the coil winding to the reinforcing outer plates situated at the surface of the coil, and not only with the strength of superconducting wire but also the integration of whole structure materials withstand the electromagnetic force. Yoroi-coil wears armor of reinforcing outer plates and frames, so that it can withstand far larger electromagnetic forces than strength of superconducting wire itself can

B. *Hoop Stress Test*

In order to verify the capability of Yoroi-coil structure to withstand the electromagnetic force, we examined hoop stress

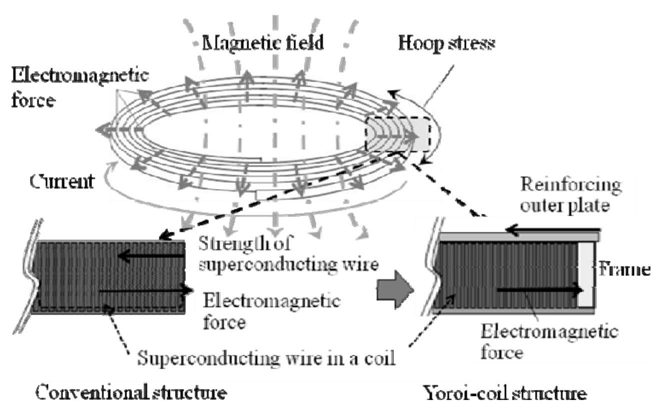

Fig. 3. A schematic of supporting mechanism of "Yoroi-coil" structure against electromagnetic force

test using a small coil. Table II shows the specifications and Fig. 4 shows an outlook of the double-pancake (DP) coil. The superconducting wire, insulating coating and paraffin molding were already mentioned. The reinforcing outer plates and frames were made of fiber reinforced plastic (FRP). After the DP coil was cooled down to 4.2 K using liquid helium immersion cooling, external magnetic field of 8 T was applied, and then current was flowed. Fig. 5 shows the *I-V* measurement results. The current increases were carried out several times as shown in Fig. 5. The maximum current was 1,500 A, which is a limit of D. C. power source for this test. And flow resistance was not observed. As a result, no deterioration was observed, even when the highest stress was applied to the coil. Fig. 6 shows the calculated hoop stress distribution in the coil at coil transport current of 1,500 A, in the condition that the stress is only given to the hastelloy substrate. The stress specifically indicated the σ_θ^{BJR} calculated from $B \times J \times r$, when wires are completely independent. The σ_θ^{Wilson} is calculated from a Wilson formula using an infinite length coil [8], assuming the coil winding is integrated. The maximum hoop stress reached 1.7 GPa from $B \times J \times r$ calculation and about 1.6 GPa from a Wilson formula [8]. Both values were far exceeding the irreversible stress of coated conductors ranging from 1 GPa to 1.3 GPa. Our novel

TABLE II Specifications of The DP Coil with "Yoroi-coil" structure for Hoop Stress Tests

Superconducting wire type	Copper plated IBAD/ CVD - (Y, Gd)BCO tape coated conductor
Wire length	52 m
Insulated wire width	10.2 mm (maximum)
Insulated wire thickness	315 µm (maximum)
Coil figure	single-pancake coils
Inner/ Outer diameter	219 / 240 mm
Height	30 mm (height of armature = 24 mm)
Insulation	Low-temperature-curable Polyamide
Mold	Paraffin mold
# of total turns	34 each (upper and lower coil)

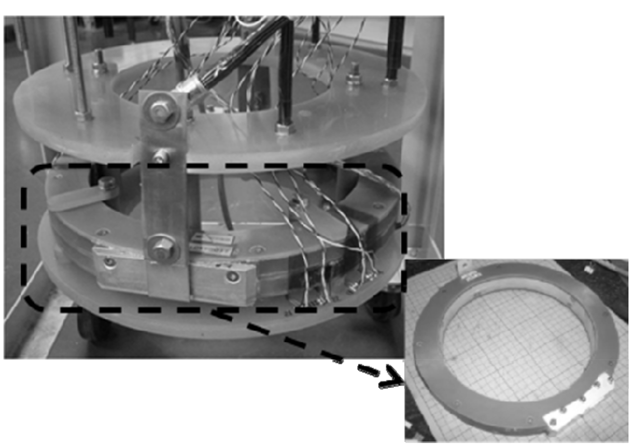

Fig. 4. An outlook of the double-pancake (DP) coil with "Yoroi-coil structure. for hoop stress test

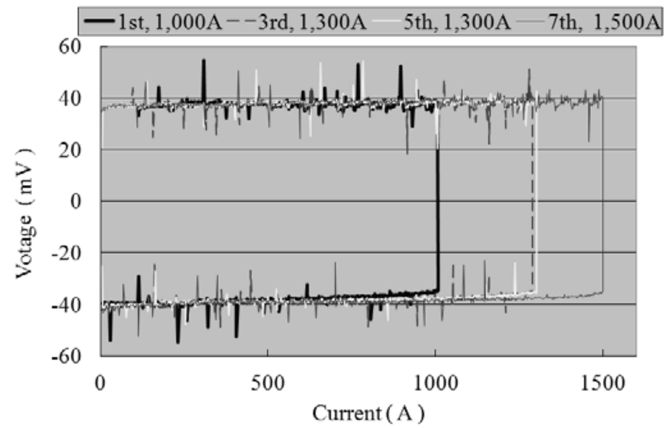

Fig. 5. *I-V* characteristics of the DP coil with "Yoroi-coil structure excited in 8 T magnetic field.

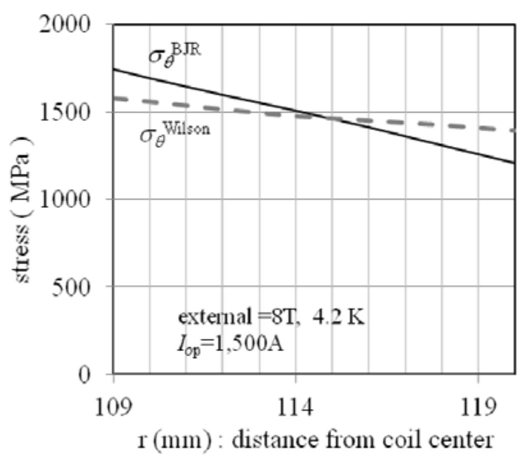

Fig. 6. Hoop stress distributions of DP coil at coil transport current of 1,500 A in 8 T back-up field. Hoop stresses were calculated based on the thickness of Hastelloy substrate.

design makes it possible that coil can withstand higher stress than strength of coated conductor alone. The strains of superconducting wire in the coil winding were measured by strain gauges. Every three strain gauges were stuck on the outermost and innermost wire of the upper and lower coils. The total number of gauges was 12. Fig. 7 shows the changes of strains with varying of transport current. The strains of the innermost wire were larger than those of the outermost wire because the hoop stress became smaller as distant from the coil center, as shown in Fig.6. The maximum strain is about 0.4 % at coil transport current of 1,500 A. Though the irreversible strain of coated conductors is about 0.7 % [5], [6] at the tensile stress of about 1 GPa. Strains are quite small even affecting stress was about 1.7 GPa from the calculation in the Yoroi-coil structure. These results of strains described that the stress affecting to superconducting wire was quite smaller than 1 GPa, and the residual force are managed by reinforcing outers. In fact, the frames of FRP were elongated by electromagnetic force according to the increase of excitation current flow. Fig. 8 indicates current dependence of the strain of the FRP frame and superconducting wire. The strain of the FRP frame indicated the same tendency, but is slightly small compared with the strains of the outermost wire. At the beginning of current increase, strains didn't show the

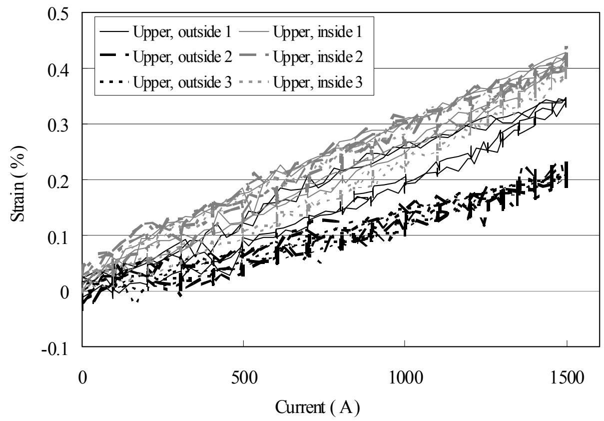

Fig. 7. Current dependence of the strains of superconducting wire in DP coil winding with "Yoroi-coil structure

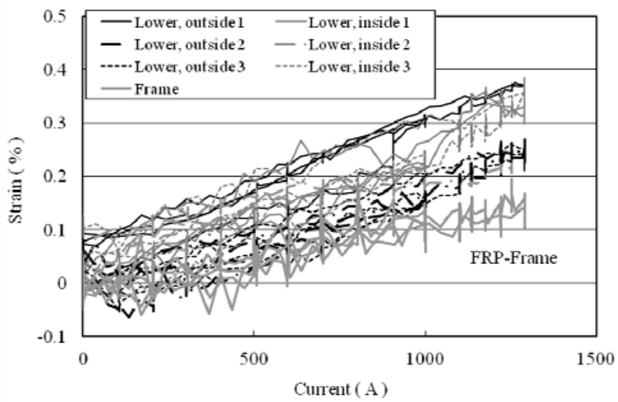

Fig. 8. Current dependence of the strains of superconducting wire in DP coil winding and FRP frame of the DP coil with "Yoroi-coil structure

same tendency, but they showed similar tendency at every gauges according to the increase of current. It was considered that the superconducting coil winding and the reinforcing outers withstand electromagnetic force by gradual integration according to the increase of hoop stress. After hoop stress test, we measured *I-V* characteristics of this coil in liquid nitrogen. There was no deterioration in the *I-V* characteristics comparing before and after hoop stress test as shown in Fig. 9. These results also showed that insulating coating using low-temperature-curable-polyamide had flexibility against stress and in the liquid helium without deterioration of transport property of superconducting wire in the coil. Therefore this insulating coating is available to use superconducting coil in cryogenic temperature.

The strain of about 0.4 % was given by the maximum hoop stress of 1.7 GPa derived by $B \times J \times r$ calculation, so that this coil was guessed to withstand stronger hoop stress more than 2 GPA easily considering 0.4% was quite smaller than the irreversible strain of a coated conductor.

IV. Conclusion

In order to achieve high strength and high magnetic field for large capacity SMES, coiling technology has been developed.

Insulating coating by liquid resin of low-temperature-curable-polyamide has capability to be flexible and shows

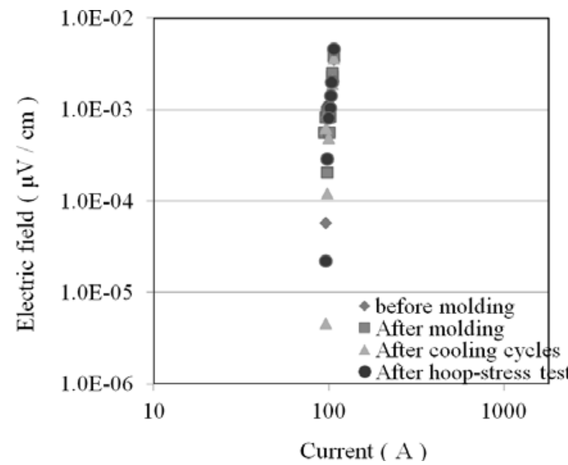

Fig. 9. Comparison of *I-V* characteristics of the DP coil with "Yoroi-coil" structure before and after hoop stress test.

insulation performance at liquid nitrogen and liquid helium. Combining this insulating coating by liquid resin with paraffin molding, insulating technique without delaminating and deterioration of transport properties of superconducting wire in a coil was established. This insulating technique was available to form an coil winding for high magnetic field coil.

Highly durable coil structure of "Yoroi-coil" achieved to withstand a hoop stress of 1.7 GPa not only by the strength of superconducting wire but also by the integration of whole structure themselves. The maximum strain of superconducting wire in the DP coil was 0.4 % when maximum hoop stress of 1.7 GPa affected to the coil, so that this coil structure is guessed to withstand a hoop stress of 2 GPa.

These coiling technologies can mitigate the restriction of mechanical property of coils and would realize high field and large capacity coil with high durability and reliability.

References

[1] K. Higashikawa, T. Nakamura, M. Sugano, K. Shikimachi, N. Hirano, S. Nagaya, "Performance Improvement of YBCO Coil for High-Field HTS-SMES Based on Homogenized Distribution of Magnetically-Mechanically Influenced Critical Current," *IEEE Trans. Appl. Supercond.*, vol. 18, pp. 758-761, 2008..

[2] K. Shikimachi, N. Hirano, S. Nagaya, H. Kawashima, K. Higashikawa, T. Nakamura, "System Coordination of 2 GJ class YBCO SMES for Power System Control, " *IEEE Trans. Appl. Supercond.*,vol. 19, pp. 2012-2018, 2009.

[3] M. Sugano, T. Nakamura, K. Shikimachi, N. Hirano, S. Nagaya, "Stress tolerance and fracture mechanism of solder joint of YBCO coated conductor," *IEEE Trans. Appl. Supercond.*, vol. 17, pp. 3067-3070, 2007.

[4] M. Sugano, K. Shikimachi, N. Hirano, S. Nagaya, "Simultaneously Bending and Tensile Strain Effect on Critical Current in YBCO Coated Conductors," *Physica C* 463-465 (2007) 742-746.

[5] M. Sugano, Y. Yoshida, M. Hojo, K. Shikimachi, N. Hirano, S. Nagaya, "Two different mechanisms of fatigue damage due to cyclic stress loading at 77 K for MOCVD-YBCO coated conductors," *Supercond. Sci. Technol.* 21 (2008) 054006.

[6] M. Sugano, T. Nakamura, T. Manabe, K. Shikimachi, N. Hirano, S. Nagaya, "The intrinsic strain effect on critical current under a magnetic field parallel to the c axis for a MOCVD-YBCO-coated conductor," *Supercond. Sci. Technol.* 21 (2008) 115019..

[7] K. Shikimachi, T. Tamada, M. Naruse, N. Hirano, S. Nagaya, S. Awaji, G. Nishijima, K. Watanabe, S. Hanai, S. Kawashima, Y. Ishii, "Unit Coil Development for Y-SMES", *IEEE Trans. Appl. Supercond.*, 21, pp. 1348-1353, 2011.

[8] M. Wilson "Superconducting magnets", Oxford Sci. Pub., 1983