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Transport Characteristics of CVD-YBCO Coated Conductor under Hoop Stress

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***Abstract*—Transport characteristics of IBAD/CVD-$YBa_2Cu_3O_7$ (YBCO) coated conductor were measured at 4.2 K under hoop stress. The conductor was fabricated by a multi-stage metal-organic chemical vapor deposition (CVD) method. The YBCO layer was deposited on Hastelloy substrate with PLD-CeO_2 and IBAD-$Gd_2Zr_2O_7$ buffer layers. A 20-μm silver layer was sputtered as a protective and stabilizing layer. The hoop stress test coils were fabricated by winding the conductor on a 250-mm diameter stainless-steel bobbin by five turns. Two coils, denoted as coils A and B, were fabricated. The Hastelloy substrate located outside for coil A and inside for coil B. Both coils were tested in magnetic field at 4.2 K under hoop stresses. Coil A and B experienced 1028 and 777 MPa at 11 T, 4.2 K. The measured stress-strain curves provided that the Young's modulus of the conductor was 190 GPa. The tolerable stress of ~1000 MPa and the Young's modulus of 190 GPa are consistent with the values obtained by a tensile test. The hoop stress test results indicates that the YBCO coated conductor is promising for application under huge hoop stress.**

***Index Terms*—Coated conductor, hoop stress, magnetic field, transport characteristics, YBCO.**

I. Introduction

STRESS in superconducting magnets is estimated from a magnetic pressure

$$p_{\mathrm{m}} = \frac{B^2}{2\mu_0},$$

where B and μ_0 are magnetic field and the permeability in vacuum [1]. The equation indicates that the magnetic field of 20 T results the magnetic pressure of 159 MPa. The 160 MPa hoop stress deteriorates the critical current (I_{c}) of conventional Nb_3Sn superconductors, although the I_{c} degradation is not irreversible. However, the magnetic field of 30 T results in the magnetic pressure of 358 MPa, which leads an irreversible I_{c} degradation in conventional Nb_3Sn superconductors. It deteriorates I_{c} by 20–40% even in high strength Nb_3Sn superconductors [2].

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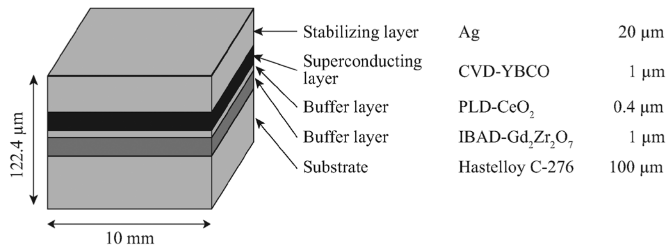

Fig. 1. Schematic architecture of CVD-YBCO coated conductor. YBCO layer was deposited by the multi-stage MOCVD technique on PLD-CeO_2 /IBAD-$Gd_2Zr_2O_7$/Hastelloy C276 substrate. Ag layer was sputtered on the YBCO layer as a protective and stabilizing layer.

The authors have started the case studies of a 30 T superconducting magnet and a 20 T large bore superconducting magnet [3], [4]. High-T_{c} superconducting materials are necessary to generate 30 T. Bi-2212 $(Bi_2Sr_2CaCu_2O_8)$ round wire is one of the candidates for a high field insert winding, although there are several critical issues to fabricate a practical coil [5].

Hastelloy C-276, which is Ni-Cr-Mo-W alloy, is usually used as a substrate for coated conductors because of its thermal stability at high temperature. Its yield strength at low temperature is ~800 MPa [6]. The 800 MPa yield strength is much larger than that of high-strength Nb_3Sn conductors. From a mechanical point of view, Hastelloy substrate supports and dominates the mechanical strength of coated conductors. Furthermore, I_{c} of coated conductors exceeds 200 A/cm-width [7]. Thus, coated conductors are promising material from not only a mechanical point of view but also a superconducting point of view.

In the present work, the mechanical characteristic of YBCO coated conductor was explored by the electromagnetic hoop stress test.

II. Sample Preparation

Fig. 1 shows the schematic architecture of the CVD-YBCO tape. The YBCO layer was deposited by a multi-stage metal-organic chemical vapor deposition (CVD) technique on a Hastelloy C-276 substrate with PLD-CeO_2 and IBAD-$Gd_2Zr_2O_7$ buffer layers [8]. A silver layer was sputtered on the YBCO layer as a protective and stabilizing layer.

The YBCO conductor is insulated by a 25-μm thick polyimide tape wrapping. Fig. 2 shows a photograph of the YBCO coil and a schematic illustration of the insulation wrapping. A 0.1-mm thick Polytetrafluoroethylene (PTFE, Teflon) sheet was

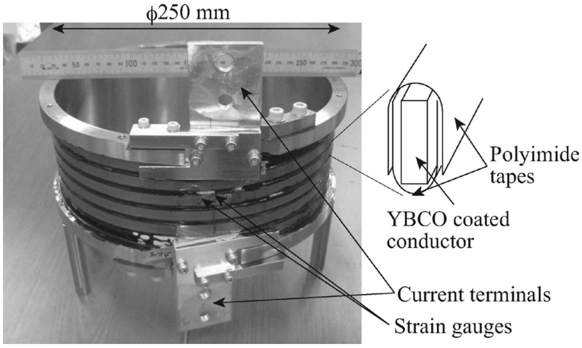

Fig. 2. Photograph of YBCO coil. The YBCO conductor, which was insulated by polyimide tapes, was wound five turns on a 250-mm diameter stainless-steel bobbin. An epoxy resin was painted to fix the conductor.

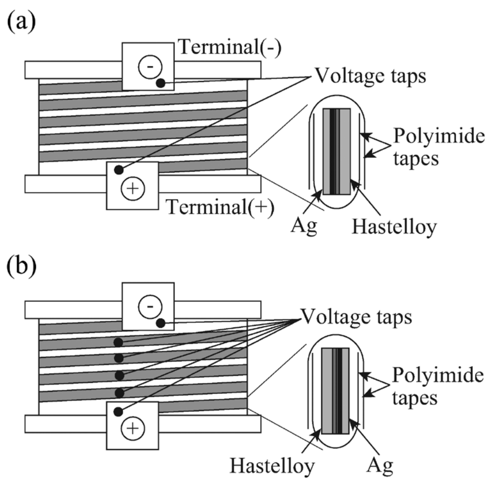

Fig. 3. Schematic illustration of coils A and B. Coils A and B are "Hastelloy outside" and "Hastelloy inside."

wound onto a 250-mm diameter stainless steel bobbin. The insulated conductor was wound by five turns on the insulated bobbin. An epoxy resin (Stycast 2850 FT) was painted to fix the conductor windings.

Two kinds of coils, denoted as coil A and B, were fabricated. Coil A is wound that Hastelloy is outside and coil B is wound that Hastelloy is inside, i.e. Ag is outside. Schematic illustration of the two coils are shown in Fig. 3. The coated conductor coils are usually wound like coil A. The coil A method is convenient to utilize a mechanical stiffness of Hastelloy substrate.

III. Experimental Procedure

Transport characteristics were explored in 77.3 K (liquid nitrogen immersion) and in 4.2 K (liquid helium immersion). In the 77 K test, the coil was immersed in liquid nitrogen and evaluated in a self field. In the 4.2 K test, the coil was immersed in liquid helium in a large bore cryostat. The cryostat was set in superconducting outsert of the hybrid magnet. The experimental setup at 4.2 K is shown in Fig. 4. A transport current was supplied linearly by using a DC power supply. Current and voltages were measured by a data acquisition system. Strain gauge signals were measured by a data logger.

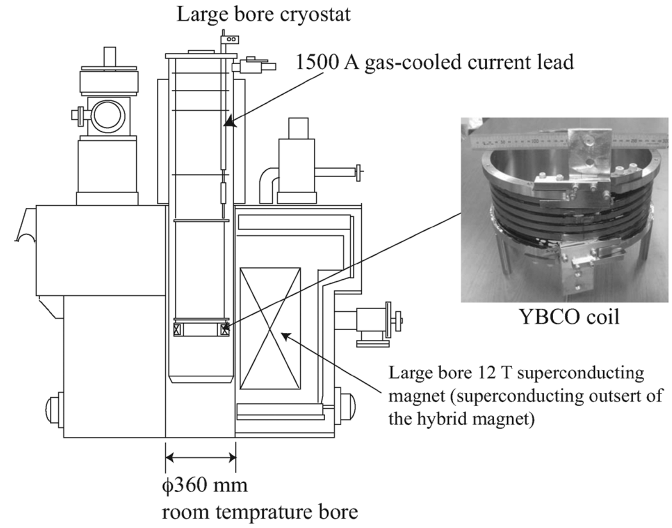

Fig. 4. Experimental setup for 4.2 K test in large bore superconducting magnet.

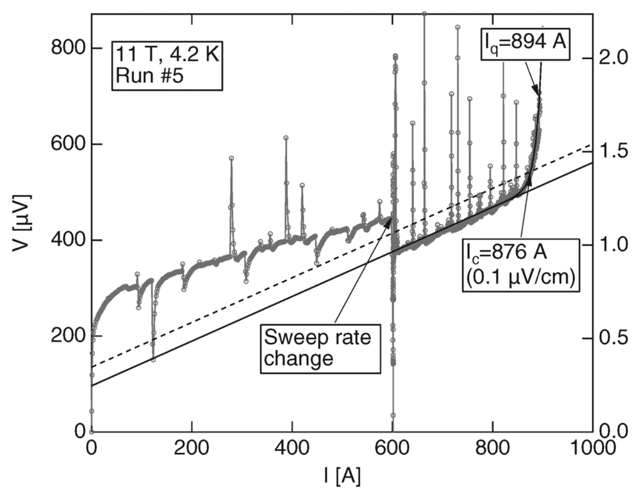

Fig. 5. $V-I$ characteristic of the YBCO coil A at 11 T, 4.2 K. Voltage spikes came from epoxy-resin cracks. The conductor burned out at the current terminal after this run.

IV. Results and Discussion

A. Coil A (Hastelloy Outside)

The 77 K test provided that I_c and n-value were evaluated to be 112.7 A and 26, indicating that the winding did not deteriorate the conductor performance. The 4.2 K test result is shown in Fig. 5. One can find a lot of spikes in the $V-I$ characteristic. The spikes were caused by epoxy-resin cracks, and thus the number of the spikes increased with the increasing current, which is proportional to the electromagnetic hoop stress.

I_c of the conductor was 876 A at 11 T, 4.2 K. The hoop stress $(\sigma_{\rm hoop})$ is calculated by using a product relation, $\sigma_{\rm hoop} = BJR$, where B, J and R are magnetic field, transport current density and coil radius, respectively. The equation provided that I_c of 876 A corresponds to $\sigma_{\rm hoop}$ of 1007 MPa. The I_c-stress curve, which was obtained from the tensile test at 77.3 K, provides that ~1000 MPa tensile stress deteriorates the I_c by 10%, although the I_c deterioration is not irreversible [9], [11].

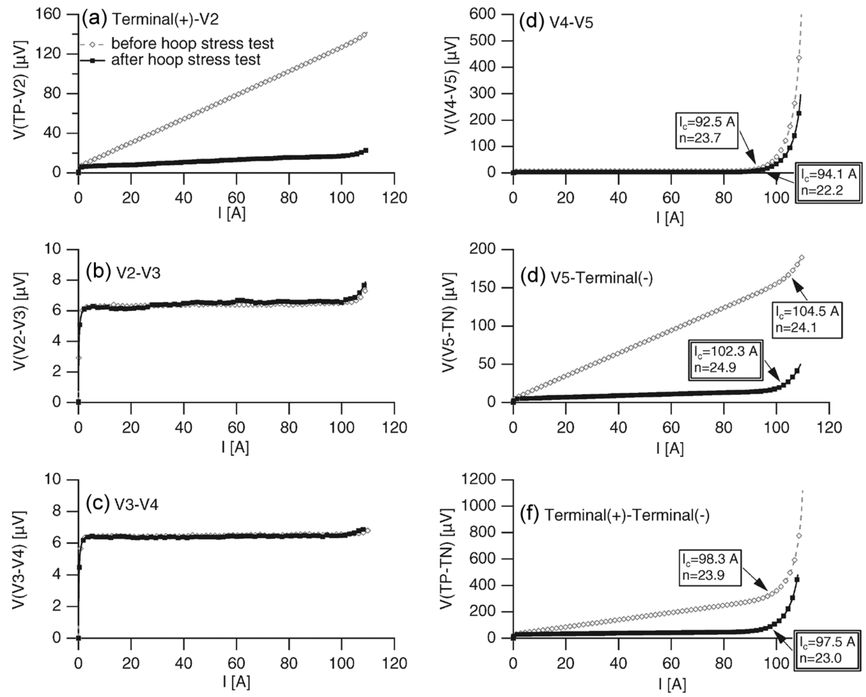

Fig. 6. $V-I$ characteristics of the YBCO coil B at 77 K, self-field; (a) terminal(+)-V2, (b) V2-V3, (c) V3-V4, (d) V4-V5, (e) V5-terminal(-), and (f) total voltage, respectively. The open and soild markers represent the $V-I$ characteristics *before* and *after* the hoop stress test. Two $V-I$ curves are almost overlapping in (b) and (c).

The quench current (I_q) was 894 A, indicating that the maximum applied hoop stress was 1028 MPa. The conductor burned out after this quench. The burned-out position was the terminal(+). The result imply that a local I_c degradation occurred by the strain concentration near the terminal(+).

B. Coil B (Hastelloy Inside)

Fig. 6 shows the $V-I$ characteristics of coil B at 77 K for each voltage tap pairs. The open and solid markers represent the $V-I$ characteristics *before* and *after* the hoop stress test.

Fig. 6(f) provides that I_c and n-value of the whole conductor are 98.3 A and 23.9 *before* the hoop stress test. The local I_c of V4-V5 section was 92.5 A (Fig. 6(d)), which indicates that the section influenced the conductor I_c.

One can find that the joint resistance at both terminals decreased by 1/10 from Figs. 6(a) and 6(e). The joint resistance at terminal(+) was 1.2 $\mu\Omega$ *before* the hoop stress test. It decreased to 0.11 $\mu\Omega$ *after* the test.

Figs. 6(b) and 6(c) provide that $V-I$ characteristics of V2-V3 and V3-V4 *after* the hoop stress test and *before* the test are in good agreement. It indicates that the V2-V4 section did not get any degradation by the test.

Fig. 7(a) shows the $V-I$ characteristic of coil B at 11 T, 4.2 K. I_q achieved 676 A (run #8), then it decreased to 601 A (run #13). $V-I$ traces of runs #9–#12 were not plotted because they were similar to that of run #13. Observed voltage spikes caused by epoxy-resin cracks are similar to coil A. The maximum applied hoop stress was calculated to be 777 MPa.

Voltage measurement results provided an information of the quench initiation. Figs. 7(b) and 7(c) show the $V-I$ characteristics of V4-V5 and V5-terminal(-). The current sharing voltage was not measured in V4-V5, on the contrary, voltage arose in

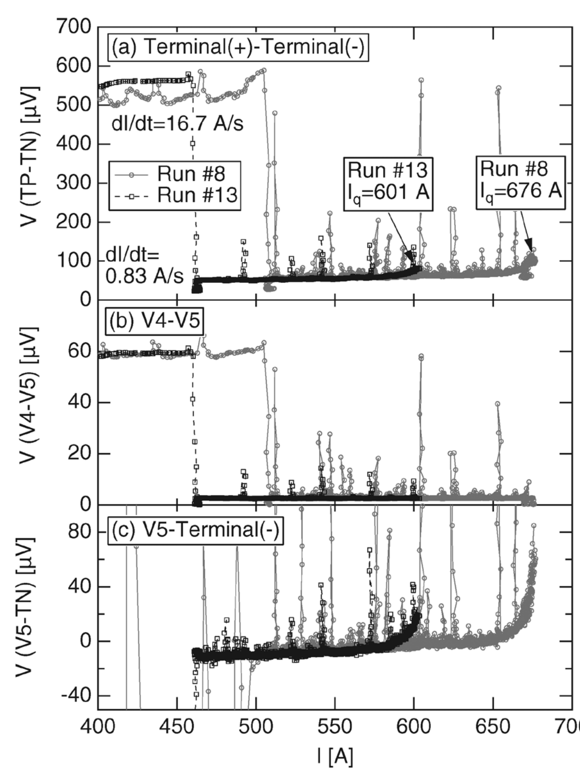

Fig. 7. $V-I$ characteristics of the YBCO coil B at 11 T, 4.2 K; (a) total voltage, (b) V4-V5, and (c) V5-terminal(-), respectively.

V5-terminal. The 77 K test result (Fig. 6) provided that performance of V4-V5 is the worst along the conductor. However the 4.2 K test result indicated that performance of V5-terminal(-) is the worst under the hoop stress at 4.2 K.

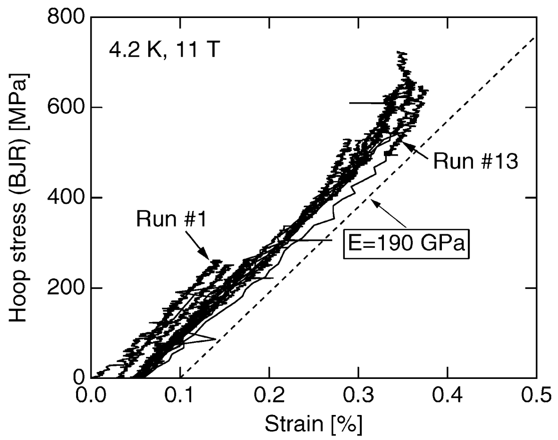

Fig. 8. Stress-strain (SS) traces for coil B at 4.2 K, 11 T. Evaluated Young's modulus is 190 GPa. The SS traces show negative curvature when the hoop stress exceeds 400 MPa, which implies the occurrence of the local stress/strain concentration.

The transverse tensile stress, which is calculated from the Lorentz force, is evaluated to be 0.74 MPa in the case of $I_q = 676$ A at 11 T. It was reported that the delamination occurs at 10 MPa transverse tensile stress for MOD-RABiTS YBCO coated conductors [10]. The present result suggests that 0.74 MPa transverse tensile stress does not induce the delamination for the MOCVD-YBCO coated conductor.

Fig. 8 shows the measured stress-strain curves for coil B at 11 T, 4.2 K. The Young's modulus is evaluated to be 190 GPa, which is consistent with the tensile test result at 77.3 K [11]. The strain-axis intercept of the stress-strain curve shifted from 0 to 0.05% strain with increasing the run number, suggesting that there was an accumulation of the plastic deformation in the conductor. The stress-strain curves show negative curvature when the hoop stress exceeds 400 MPa. It implies the occurrence of the local stress/strain concentration.

The voltage measurement and the strain measurement results suggest that the mechanical bending by the Lorentz force deteriorated I_c in V5-Terminal(-) section. The I_c degradation was not irreversible because the 77 K test results did not show any degradation. An improvement of the terminal structure mitigates the local degradation near the terminals, which improves the test coil performance.

V. Summary

Two coils were fabricated using CVD-YBCO coated conductor. One was the usual winding, i.e. Hastelloy substrate located outside, the other was that Hastelloy located inside. The coils were tested under the large electromagnetic hoop stress at 4.2 K. The "Hastelloy outside" coil was exposed the maximum hoop stress of 1028 MPa. Before the burn-out, the conductor I_c was evaluated under the hoop stress of 1007 MPa. The "Hastelloy inside" coil was exposed the maximum hoop stress of 777 MPa. The results indicate that the coated conductor is applicable for large stress use in high magnetic fields.

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