

Contact Resistance Measurements in Two-Layer Spiral-Coated-Conductor Cable

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Abstract—We experimentally measured the tape-to-tape contact resistance distribution in two-layer spiral-coated-conductor cables. Current was injected at one end of the outer layer and extracted from the opposite end of the inner layer. In this case, the entire contact resistance of the cable can be measured using a simple four probe method, based on the voltage between the two coated conductors and current. Besides, we measured the current in each layer, distributed along the sample, using arrays of Hall sensors installed in the core of the cable. By combining the voltage between layers and the layer currents distributed along the cable, we determined the local contact resistance distributed along the cable. We also studied the influence of several fabrication conditions on contact resistance. Three samples were fabricated for each condition to investigate the variability.

Index Terms—cabling parameter, contact resistance, current sharing, Hall sensor, spiral-coated-conductor.

I. INTRODUCTION

IN spiral-coated-conductor cables consisting of coated conductors wound spirally on metal core in multiple layers, such as the CORC[®] cable and spiral copper-plated striated coated-conductor cable (SCSC cable), current-sharing among coated conductors in adjacent layers is facilitated by the tape-to-tape contact resistance [1-12]. The concept of current-sharing between layers is shown in Fig. 1. This phenomenon is expected to improve the robustness against the normal transition in coated conductors. The total resistance along the current path (red line in Fig. 1) comprises copper resistances and surface contact resistances. Typically, this total resistance is defined as the contact resistance between layers. The contact resistance depends on the contact pressure and surface conditions [13,14]. Measurements of the tape-to-tape contact resistance of the entire length of a piece of spiral-coated-conductor have been reported in [13-17], but very few studies investigated the factors that may affect contact resistance experimentally. Besides, note that the contact resistance is not always uniform along a cable. However, almost no study has reported the non-uniformity of contact resistance.

In this study, we proposed a method for determining the contact resistance distribution in spiral-coated-conductor cables. We focused on two-layer spiral-coated-conductor cables, which were much simpler than practical cables but were appropriate to clarify the fundamental natures of contact

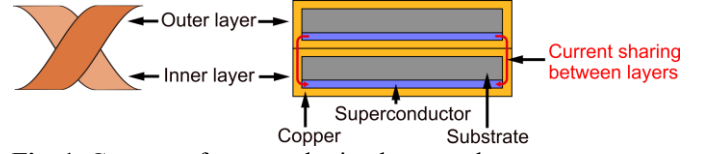


Fig. 1. Concept of current sharing between layers.

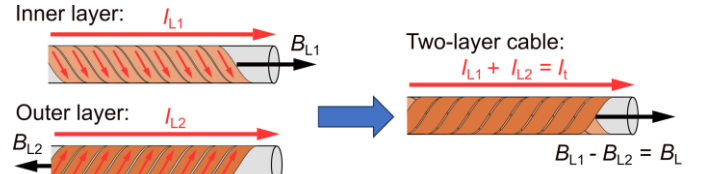


Fig. 2. Magnetic flux density generated by the two-layer spiral-coated-conductor.

resistance between layers. We measured the current distribution using arrays of Hall sensors installed in the core of the cable. By combining the voltage between the layers and layer currents distributed along the cable, we determined the local contact resistance distributed along the cable. Moreover, we fabricated and measured several cables under different conditions to study the influences of cable parameters, bending the cable, tape manufacturers, and thermal cycle(s) on contact resistance. We fabricated three samples for each condition to investigate the variability.

II. MEASUREMENT METHOD AND SAMPLES

A. Method to Determine Current Distribution

Fig. 2 shows a conceptual diagram of the magnetic flux density generated by a two-layer spiral-coated-conductor cable. Because the directions of the spiral windings in the first and second layers differ, the directions of the longitudinal magnetic flux density generated by the currents in the coated conductors in the inner and outer layer are different. Based on this condition, the following equations are obtained:

$$I_{L1} + I_{L2} = I_t, \quad (1)$$

$$B_{L1} - B_{L2} = k_1 I_{L1} - k_2 I_{L2} = B_L. \quad (2)$$

Here, I_{L1} and I_{L2} denote the currents in the coated conductors of the inner and outer layers, respectively; I_t represents the total current supplied to cable; B_{L1} and B_{L2} indicate the longitudinal magnetic flux densities generated by the inner and outer layers, respectively; k_1 and k_2 depend on the number of turns per unit length of the inner layer and outer layer N_1 and N_2 ($K_i = \mu_0 N_i$, $i = 1, 2$); B_L represents the longitudinal magnetic flux density generated by the cable. According to (1) and (2), measuring I_t and B_L allows determination of I_{L1} and I_{L2} . We conducted tests using a single-layer cable, and by comparing the calculated and measured magnetic flux values,

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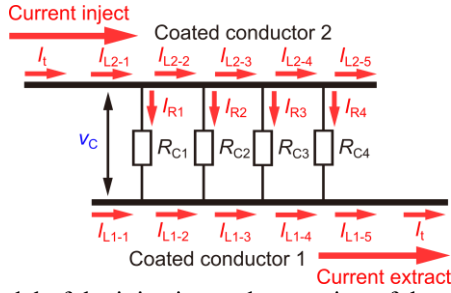


Fig. 3. Model of the injection and extraction of the current.

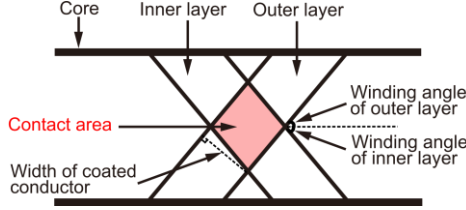


Fig. 4. Contact area of the two layers.

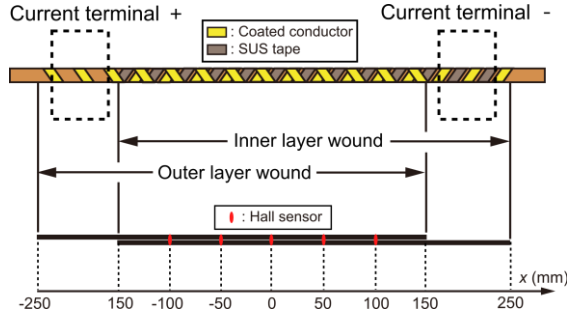


Fig. 5. Geometry of the sample.

we confirmed that they were in good agreement.

B. Method to Determine Contact Resistance Distribution

The conceptual diagram of the injection and extraction of the current is shown in Fig. 3. A current was injected into one end of coated conductor 2 (the left end of the cable in Fig. 3) and extracted from the opposite end of coated conductor 1 (the right end of the cable in Fig. 3). The current was kept below the critical current of the coated conductor to prevent voltage generation in each coated conductor and maintain each coated conductor at equipotential. In this condition, the local contact resistances (R_{Ci} , $i = 1, 2, \dots$) can be measured using a simple four probe method from the voltage between two coated

TABLE I
SPECIFICATIONS OF SAMPLES

Coated conductor		
Manufacture	Faraday Factory Japan	SuperPower
Width	4 mm	2 mm
Copper thickness	5 $\mu\text{m} \times 2$	10 $\mu\text{m} \times 2$
Entire thickness	$\sim 50\mu\text{m}$	
Critical current	130 A (@ 77 K)	
Cable		
Diameter of the hollow core	5 mm (outer diameter) 4 mm (inner diameter)	
Inner layer configuration	Coated conductor $\times 1$, 50- μm SUS tape $\times 1$ or 2	
Outer layer configuration	Coated conductor $\times 1$	
Winding angle of inner/outer layer	53.21° / 53.83°	
Spiral pitch of layers	12.31 mm	
Outer insulation of the cable	Polyimide tape	
Length of the entire cable	500 mm	

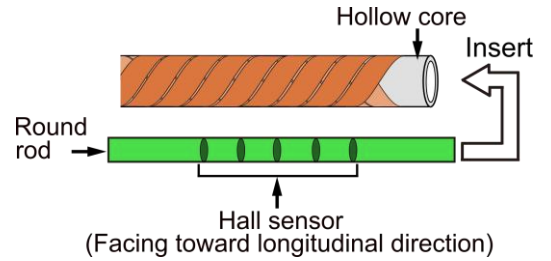


Fig. 6. Contact area of the two layers.

conductors (v_c) and currents flowing through the contact resistances (I_{Ri} , $i = 1, 2, \dots$) as follows:

$$R_{Ci} = v_c / I_{Ri}, \quad (3)$$

where I_{Ri} can be determined using I_{L1-i} or I_{L2-i} ($i = 1, 2, \dots$).

Note that the operating current in our experiments did not exceed the critical current of the coated conductor, the electrical potential along the tape can be regarded as uniform. Consequently, the voltage between the two coated conductors did not depend on the longitudinal position. Therefore, it was sufficient to install only one set of voltage taps to measure the voltage between the two coated conductors.

TABLE II
FABRICATION CONDITIONS

No.	Manufacturer of coated conductor ¹⁾	Tension of coated conductor ²⁾	Tension of outer insulation layer ²⁾	Straight or bent	Changed parameter compared with No. 0
0	Faraday Factory Japan	1	1	Straight	N/A (standard condition)
1	Faraday Factory Japan	1	0.5	Straight	Tension of polyimide tape
2	Faraday Factory Japan	1	N/A (no outer insulation layer)	Straight	
3	Faraday Factory Japan	2.5	1	Straight	Tension of coated conductor
4	Faraday Factory Japan	0.25	1	Straight	
5	Faraday Factory Japan	1	1	Bent ($\phi 200$)	Straight or bent
6	SuperPower	1	1	Straight	Manufacturer

¹⁾ A cable was fabricated by the coated conductors produced by the same manufacturer.

²⁾ Ratio to the tension of condition 0 (Values of the tension are not disclosed).

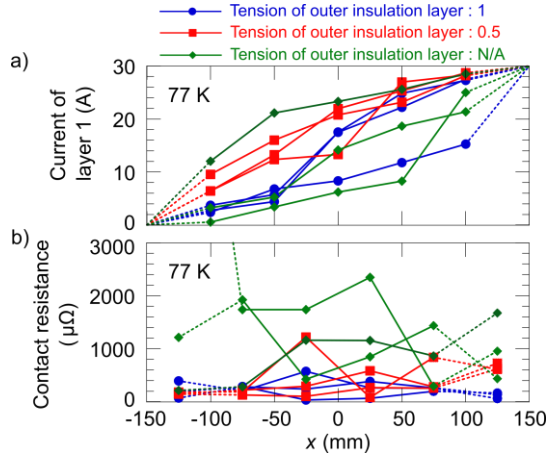


Fig. 7. Results of different tensions of polyimide tape. The three lines with identical markers refer to the three samples with the same cabling conditions. (a) Current distributions. (b) Contact resistance distributions.

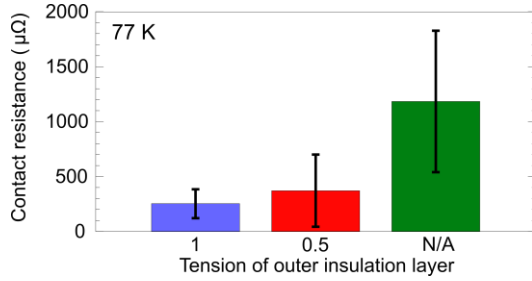


Fig. 8. Average and standard deviation of the contact resistance with different tensions of outer insulation layer.

C. Samples

The specifications of the coated conductors and cables are listed in Table I. The core of the cable was an aluminum hollow copper core. A polyimide tape was wound around the entire surface of the hollow core so that the core was electrically insulated from both the coated conductors and the terminals. The inner layer of the cable consists of one coated conductor and one SUS tape, and the outer layer consists of only one coated conductor. The conceptual figure of the contact areas between the two layers is shown in Fig. 4. In addition to these two layers, the exterior of the cable was wrapped with a 10-mm-wide polyimide tape without overlapping, leaving a small gap (< 0.5 mm) between adjacent spiral pitches. This layer is hereafter referred to as “outer insulation layer”. To implement the current injection and extraction method shown in Fig. 3, we fabricated spiral-coated-conductor cables as shown in Fig. 5. Current terminal + only contacted the coated conductor in the outer layer, whereas current terminal - only contacted the coated conductor in the inner layer.

As is shown in Fig. 6, five grooves, with an interval of 50 mm, were machined along the surface of a 3-mm-diameter round rod, and the Hall sensors were embedded in this groove. By inserting the sensor-mounted rod into the hollow core, the Hall sensors were positioned facing toward the axis of the spiral conductor, enabling measurement of the magnetic field

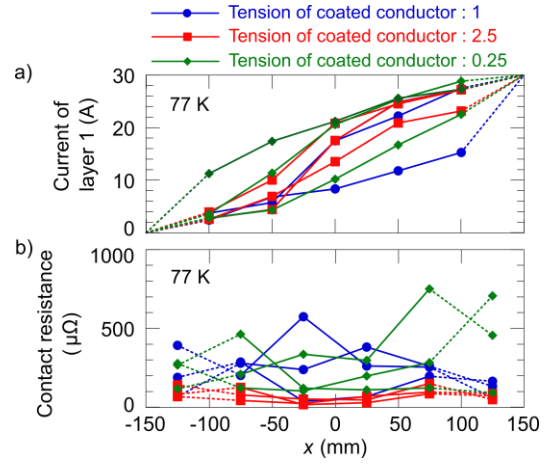


Fig. 9. Results of different tensions of coated conductors. The three lines with identical markers refer to the three samples with the same cabling conditions. (a) Current distributions. (b) Contact resistance distributions.

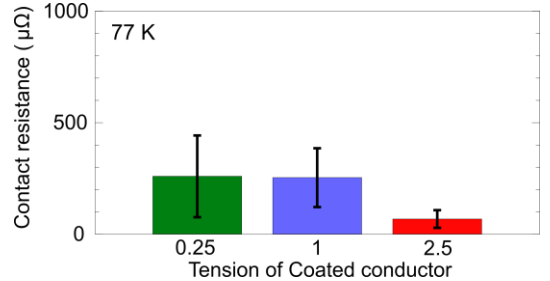


Fig. 10. Average and standard deviation of the contact resistance with different tensions of outer coated conductors.

generated by the transport current in the coated conductor. Type of Hall sensors we used were THS118 produced by Toshiba co., Ltd., which were single axis.

Based on the general Specifications in Table I, we fabricated several cables under different conditions (Table II) to study the factors that may affect contact resistance. The term “tension” in Table II refers to the applied force. For example, the “tension of the coated conductor” denotes the tensile force applied to the coated conductor during winding onto the core. During the cabling process, there were no surface cleaning or processing procedures before and during cabling. The coated conductors were wound in their original factory condition. However, during the cabling process, we made every effort to keep the coated conductor surfaces as clean as possible, for example by avoiding direct contact with the coated conductor surfaces by hand to prevent contamination.

III. MEASUREMENT RESULTS AND DISCUSSION

Three samples were fabricated for each cabling condition in Table II. In the experimental results in Fig. 7 – Fig. 16, the three lines with identical markers refer to the three samples with the same cabling conditions.

A. Effect of polyimide Tape Tension

The results of current and contact resistance distributions for different outer insulation layer tensions are shown in Fig. 7.

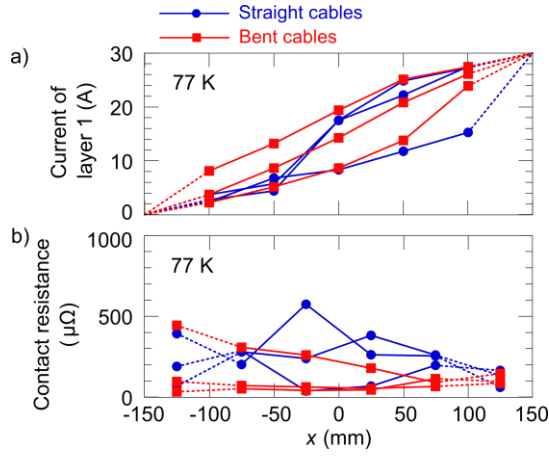


Fig. 11. Comparison of straight and bent cables. The three lines with identical markers refer to the three samples with the same cabling conditions. (a) Current distributions. (b) Contact resistance distributions.

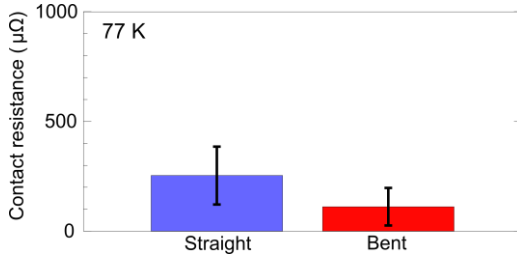


Fig. 12. Average and standard deviation of the contact resistance of straight and bent cables.

The average and standard deviations of the contact resistance for each measurement section are shown in Fig. 8. The results show that increasing tension of the insulation layer could effectively reduce both contact resistance and its variability. Besides, the contact resistance would be significantly higher without polyimide tape.

B. Effect of Coated Conductor Tension

The current and contact resistance distributions for different coated conductor tensions are shown in Fig. 9. The average and standard deviations of the contact resistance for each measurement section are shown in Fig. 10. Compared to tensions of 1 and 2.5, higher tension results in lower contact resistance. In contrast, contact resistances at tensions of 1 and 0.25 were nearly identical despite the difference in coated conductor tension. We speculate that this occurs because cables with a coated conductor tension of 0.25 have an outer insulation layer tension of 1, which exceeds that of the coated conductors; thus, the value of contact resistance depends on the tension of the outer insulation layer rather than that of the coated conductors.

C. Effect of Bending the Cable

The current and contact resistance distributions in the straight and bent cables are shown in Fig. 11. The averages and standard deviations of each measurement section of the contact resistance are shown in Fig. 12. In this experiment, the entire sample was bent, except for the sections in contact with

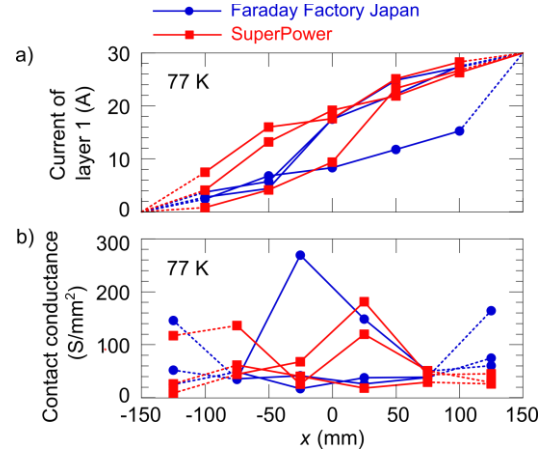


Fig. 13. Comparison of different manufactures. The three lines with identical markers refer to the three samples with the same cabling conditions. (a) Current distributions. (b) Contact resistance distributions.

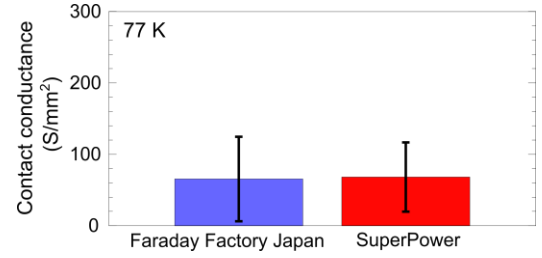


Fig. 14. Average and standard deviation of the contact conductance of different manufactures.

the current terminals. The sample was bent to a semicircle, along a $\phi 200$ bobbin (a polyvinyl chloride pipe). The results show that bending the cable reduces the contact resistance. The coated conductors might be squeezed during the bending process so that the contact resistance decreased.

In addition, the tension applied to the sample when bending along the bobbin was not controlled or measured in this experiment. It is considered that this tension may also affect contact resistance.

D. Difference of Coated Conductor's Manufacturer

We compared the contact conductance, defined as the conductance per contact area (S/mm^2), because the widths of the two manufacturers' coated conductor were different. The current and contact conductance distributions with different coated conductor's manufacturers are shown in Fig. 13. The averages and standard deviations of each measurement section of the contact conductance are shown in Fig. 14. The results show that there was almost no difference in the contact conductance between the two manufacturers, even though their copper thickness was different. The contact conductance consists of the copper conductance and the surface contact conductance. The two coated conductors with different copper thicknesses exhibited similar contact conductance, which may be because the surface contact conductance was more dominant than the copper conductance and their surface contact conductance was the same.

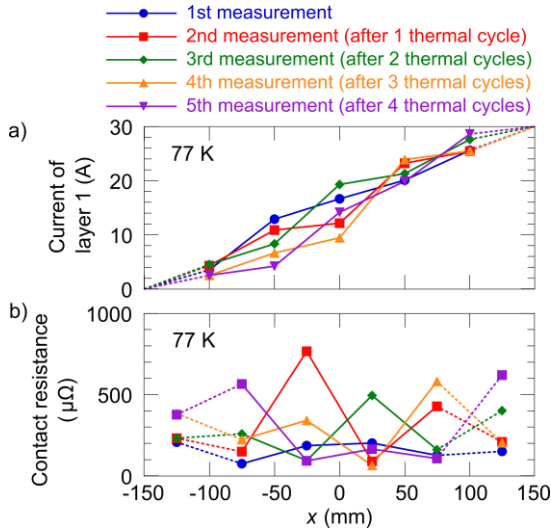


Fig. 15. Measurement results after thermal cycles. (a) Current distributions. (b) Contact resistance distributions.

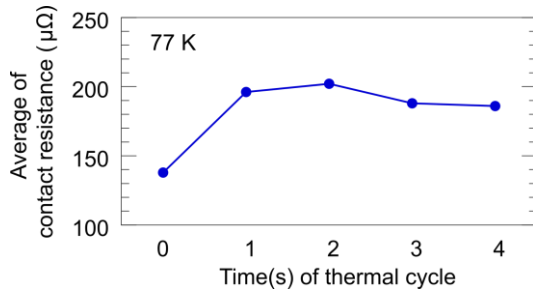


Fig. 16. Average of the contact resistance after thermal cycles.

E. Effect of Thermal Cycle(s)

The current and contact resistance distributions after the thermal cycle(s) are shown in Fig. 15. The averages of each measurement section of the contact resistance are shown in Fig. 16. The results show that the contact resistance increased after one thermal cycle, despite efforts to remove condensed moisture from the surface of the coated conductors. After the first thermal cycle, subsequent thermal cycles almost did not affect the average contact resistance. It was speculated that the surface oxidation is the most possible reason: the moisture oxidized the copper layer of the coated conductor during the first thermal cycle, which was irreversible, and caused the contact resistance to increase permanently. Subsequently, there were few changes in the surface condition of the coated conductor; therefore, the contact resistances remained nearly unchanged even after several thermal cycles. Addition to surface oxidation, stress redistribution during thermal cycles, changes in adhesion during thermal cycling (since a viscous polyimide tape was used for the outer insulation layer) may also lead to variations in the contact resistance.

F. Distribution of Contact Resistance

The contact resistance distributions shown in Fig. 7(b), Fig. 9(b), Fig. 11(b), Fig. 13(b), and Fig. 15(b) indicate that the contact resistance was not uniform in most cables. The contact resistance distribution of a cable can vary greatly among

different segments, by several or even several tens of times, which may be attributed to the nonuniform thickness and the surface condition of the coated conductor. This may result in a large amount of current-sharing being localized within a short segment of the cable.

IV. CONCLUSION

We measured the contact resistance distribution in two-layer spiral-coated-conductor cables. The distribution of contact resistance was not uniform in most cables. The contact resistance distribution can vary by several to tens of times along the cable due to nonuniform thickness and surface conditions, leading to local current-sharing. We also investigated factors that may affect contact resistance and their variability in each measurement section, which can be summarized as follows:

- 1) Increasing tension of polyimide tape reduces the contact resistance and their variability.
- 2) The tension of coated conductors can reduce the contact resistance when it exceeds that of the polyimide tape.
- 3) Bending the cable reduces the contact resistance compared with the straight configuration.
- 4) There was almost no difference in the conductance per contact area of cables fabricated with the coated conductor made by the two manufacturers.
- 5) Thermal cycles can lead to a permanent increase in contact resistance. Surface oxidation is considered to be the most possible reason.

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