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Behaviors of turn-to-turn contact resistance (R_c) of various REBCO CC tapes according to applied contact pressure

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Abstract

No-insulation (NI) pancake magnets are fabricated using Rare earth-Barium-Copper Oxide (REBCO) coated conductor (CC) tapes, which enabled a very compact magnet in the aspects of high critical current density (J_c) and high mechanical strength by removing insulation and allowing thinner stabilizer. They have also advantages such as self-quench protection. Therefore, it does not need quench detection and protection that can be very challenging in a high critical temperature (T_c) superconducting magnet technology. Recently, it was reported that the NI REBCO CC magnets have some drawbacks of long charging time and high field ramp loss which will be a concern in the operation of cryocooled magnets. These issues are related to the turn-to-turn contact resistivity and can be released by managing it. This is also closely related to the activity of reducing the contact joint resistance in the case of CC joints for long length CC fabrication. Therefore, in this study, the turn-to-turn contact resistance (R_c) at the CC contact part of differently stabilized CC tapes was measured. The behaviors of R_c at CC contact parts according to the applied contact pressure were investigated. The range of R_c measured for CC tapes adopted will provide fundamental data for design and fabrication of the CC NI coils.

Keywords: coated conductor, No-insulation, contact resistance, mechanical contact pressure, contact part structure

1. INTRODUCTION

High-temperature superconducting (HTS) second-generation (2G) Rare earth-Barium-Copper Oxide (REBCO) coated conductor (CC) tapes have excellent mechanical properties, high current density (J_c), and excellent electrical properties under magnetic field [1-3]. It is expected that CC tapes can be applied to high-field power devices and magnets. Recently, it has been found that magnets and coils with no insulation (NI) using HTS 2G REBCO CC tapes have been developed and have many advantages over conventional epoxy-impregnated insulation magnets and coils [4-6]. NI CC coils have a self-quenching protecting structure that does not require a key detection and protection system which is essential in the 2G REBCO CC magnets. In addition, it is possible to make high J_c and high strength by directly making turn-to-turn contact of CC wires without any insulation, making it possible to fabricate a compact magnet with high magnetic field over 25 T [4,7]. In this case, it is known that the turn-to-turn electrical contact resistance (R_c) between the CC tapes in the NI coil is directly related to the charging delay and the ramp loss of the coil [8]. Thus, the measurement of the R_c value depending on the contact structure of CC tapes is necessary in the design of NI pancake magnets. On the other hand, Lu et al. showed the variation of R_c according to contact pressure applied on the CC tape and investigated the R_c values on the CC tape contact parts due to additional treatments to the CC tape surface. The results can be used as design data for the NI magnets [9, 10]. In this study, we investigated the turn-to-turn contact resistance, R_c for various CC contact structures which adopts differently processed CC tapes under mechanically controlled contact pressure conditions. The behavior of R_c according to the

TABLE 1
SPECIFICATIONS OF CC TAPES SUPPLIED.

Fabrication process	MOCVD	RCE-DR
Type	Cu layer stabilized	Cu layer/Sn-Cu-double layer stabilized
Structure	Ag/HTS/LMO/ IBAD MgO/ Hastelloy substrate	Ag/GdBCO/$LaMnO_3$/ IBAD MgO/ Y_2O_3/Al_2O_3/ Stainless steel substrate
I_c @ 77 K & *s.f.*	100 ~ 120 A	200 – 240 A / 250 - 270 A
Dimension, t x w	0.09mm x 4 mm	0.150 mm x 4 mm /0.170 mm x 4.1 mm
Stabilizer	Cu Electroplating	Cu/Sn Electroplating
Manufacturer	Superpower-INC	SuNAM Co. Ltd.
Hardness (HV)	Cu : 127	Cu : 115 Sn-Cu 15.4

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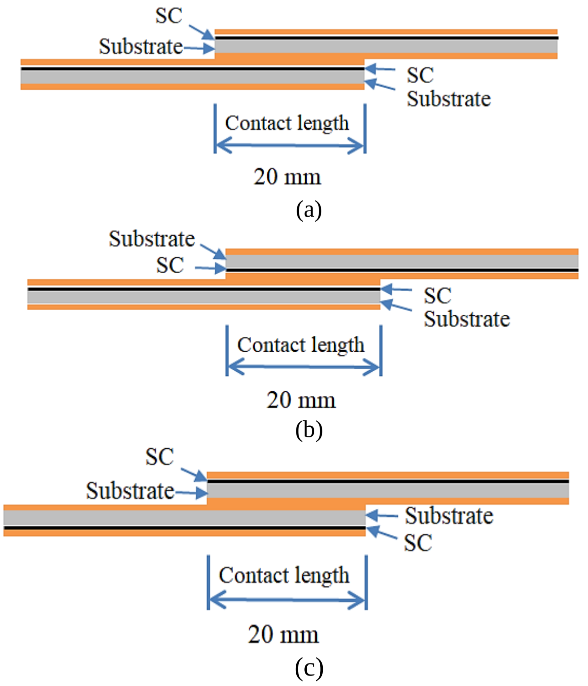

Fig. 1. Contact configurations of turn-to-turn CC tapes (a) face-to-substrate, (b) face-to-face, and (c) substrate-to-substrate.

applied contact pressure was investigated. And it was tried to provide fundamental data for the design and manufacturing of NI coils through understanding of the range of R_c obtained for REBCO CC tapes.

2. EXPERIMENTAL PROCEDURES

2.1. CC tape samples and preparation

In this study, Cu layer and Sn-Cu double-layer stabilized CC tapes which were manufactured by RCE-DR process and a MOCVD processed Cu-stabilized CC tapes were used, respectively. Specifications of CC tapes supplied are shown in Table. 1.

The CC tapes used in coil winding usually forms a turn-to-turn contact. Therefore, to measure the R_c which can be expected at the NI coil winding, three kinds of contact structures are prepared, as shown in Fig. 1. Figure 1 (a) shows the face-to-substrate contact structure of the CC tape samples with substrate-to-superconducting layer (SC), (b) SC-to-SC and (c) substrate-to-substrate configuration, respectively. In addition, to examine the effect of surface condition on the contacting area of the CC tapes, for the contact structure of face-to-substrate, the surface of the contacting part was polished using a sand paper of #1,000. The surface hardness of the CC tapes measured in Vickers hardness (under P = 0.49 N load) was added to Table 1.

2.2. Measurement of R_c under mechanical contact pressure

In this study, the R_c was measured at liquid nitrogen temperature (77 K) with mechanical contact pressure applied to the overlapped CC tapes. For this purpose, a universal material testing machine (Model: Shimadzu AG-IS, Loadcell capacity: 5 kN) [11] was used. Fig. 2 shows

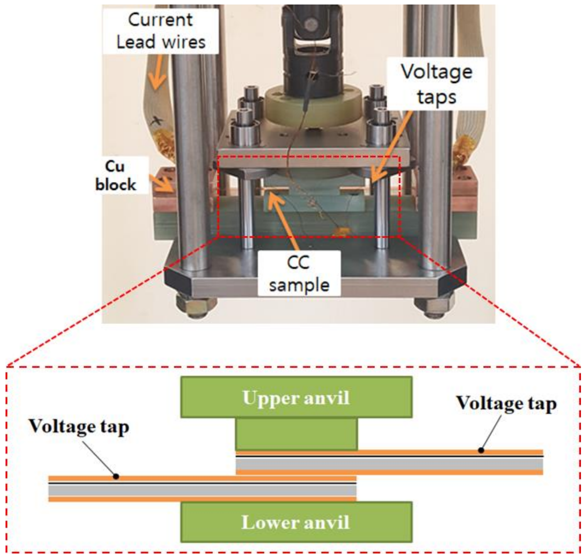

Fig. 2. Sample holder and fixture installed for contact resistance measurement of overlapped CC tapes.

the test jig and holder for measuring the R_c including the upper and lower anvils for applying mechanically a contact pressure to the overlapped CC tapes. In measuring the R_c of the overlapped CC tapes, we used a four-probe method which is the same method used in measuring the critical current, I_c of a single CC tape. The R_c was derived from the slope of the initial part of the I-V curve. In this case, the length of the overlapped CC contact part is 20 mm, and the voltage tap separation for the voltage measurement is 30 mm which includes the overlap contact portion. At that time, the voltage taps were installed on the upper surface of the respective CC tape on the overlapped structure, as shown in Fig. 2. In the case of the R_c and I_c measurement, both upper and lower anvils were made of GFRP (G10) material for electrical insulation. Copper blocks were used to clamp both end parts of the overlapped CC contact sample and which also served as the current terminal too. In this study, it is most important thing to apply a uniform contact pressure onto the overlapped CC contact part which is closely related to the reproducibility of the data during the R_c measurement. Therefore, both a steel ball and a universal joint were introduced on the load-axis to apply the compressive contact load which can resultantly maintain a uniform pressure distribution on the overlapped CC contact. On the other hand, in order to ensure assembled upper and lower anvils which need to maintain its parallelism to give a uniform pressure distribution on the CC contact part, a fixture including four-linear bushes is employed, as shown in Fig. 2.

The I-V behaviors for respective contact structure were measured as the contact pressure was increased from 1 MPa to a maximum of 60 MPa, in which the current was flowed up to 50 A. R_c was calculated from the slope at the initial part of the I-V curve. Also, at the maximum contact pressure adopted of 60 MPa, the critical current of the CC contact part was measured, in order to confirm whether any I_c degradation occurred due to the damage which might be induced on the superconducting layer at the highest contact pressure of 60 MPa.

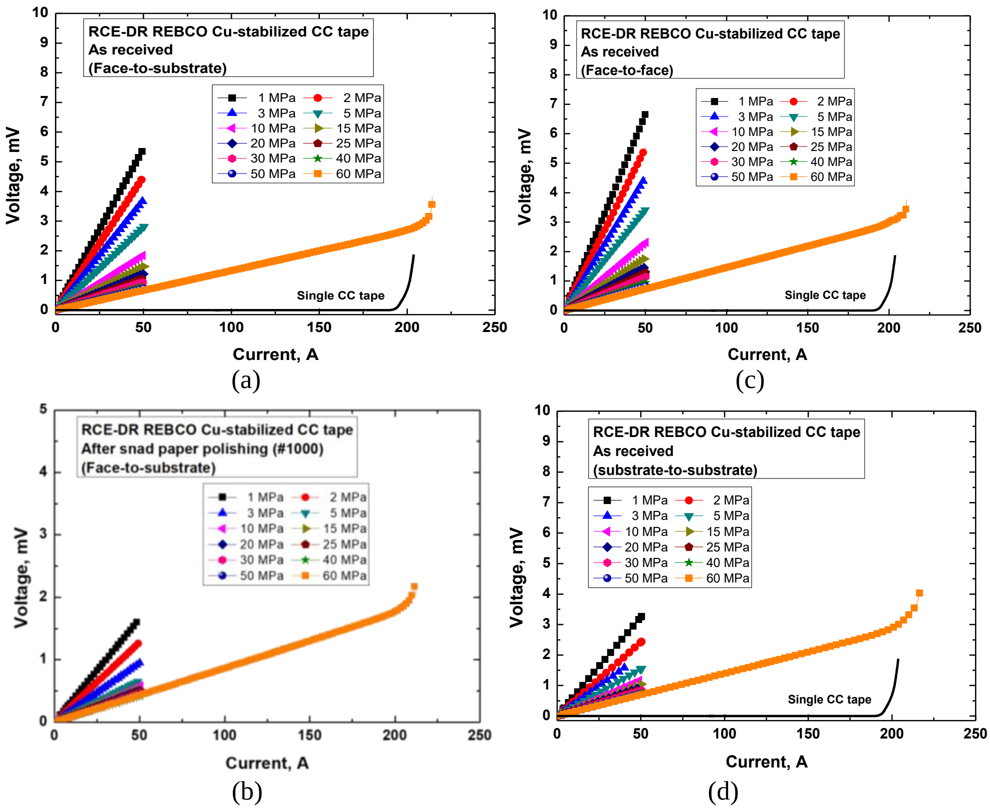

Fig. 3. *I-V* curves of RCE-DR processed Cu-stabilized CC contact structures under mechanical contact pressure (a) face-to-substrate, (b) face-to-substrate (after polishing), (c) face-to-face and (d) substrate-to-substrate.

3. EXPERIEMETAL RESULTS AND DISCUSSION

3.1. Measurement of R_c under pressure

Figures 3 to 5 show the I-V curves obtained under respective mechanical contact pressure for various contact structures using CC tapes supplied. Regardless of contact structures tested, as the contact pressure increases, the slope of the I-V curves decreased and the R_c decreased. When the applied contact pressure exceeds 10 MPa, the decrease of the slope reduced remarkably and saturated to a characteristic R_c value for the CC tapes used. Also, it can be seen that even at the contact pressure of 60 MPa, there occurred no I_c degradation; which means that no damage was caused by on the superconducting layer. This is because the test fixture used in this study was well aligned giving a uniform contact pressure to the contact part while keeping the horizontal position between the upper and lower anvils during the contact experiment. If the both anvil's parallelism did not maintain properly, damage due to localized indentation of anvil edges will occur resulting in a drop of I_c. On the other hand, in the case of the RCE-DR processed Sn-Cu double-layer CC tape shown in Fig. 4, the behaviors of I-V curves are similar to that of the Cu-stabilized CC tapes although the Sn layer existed on the contacting surface. Figure 5 shows the case of MOCVD processed Cu stabilized CC tape, where the slope of I-V curves converged rapidly as the contact pressure increases. Especially, in the substrate-to-substrate structure, I-V curves with much higher slope were observed.

For CC tapes supplied, the R_c was calculated from the slope of I-V curves under respective contact structures and its behavior according to the contact pressure is shown in Fig. 6. As a whole, the R_c showed a relatively large value at low contact pressure and it decreased remarkably at the beginning with the contact pressure increase, and then gradually decreased when the contact pressure exceeded 5 MPa and converged to a constant R_c value. At high contact pressure, there existed a characteristic R_c corresponding to the CC tape used regardless of the contact structure.

Fig. 6 (a) shows the behavior of R_c according to the contact pressure of RCE-DR Cu stabilized CC tape; for the face-to-substrate contact structures, R_c was in a range of 11 to 57 μΩcm^2, it was 5.5 to 28 μΩcm^2 after surface polishing, 11~115 μΩcm^2 for the face-to-face contact structure, and it was in a range from 11 to 70 μΩcm^2 for the substrate-to-substrate one. Fig. 6 (b) shows the R_c behavior of RCE-DR Sn-Cu double-layer stabilized CC tape against the contact pressure. R_c behaved similarly to the case of RCE-DR Cu-stabilized CC tapes, showing similar R_c range at respective contact structure. Finally, Fig. 6 (c) shows the R_c behavior of the MOCVD Cu stabilized CC tape against contact pressure. The R_c at the face-to-substrate contact structure was in a range from 36 to 46 μΩcm^2. R_c of the face-to-substrate after polishing was from 6.5 to 24 μΩcm^2, and R_c of the face-to-face contact structure was 16 ~32 μΩcm^2. However, the R_c of the substrate-to-substrate contact structure was in the range of 580 to 2,000 μΩcm^2.

Particularly, in all three CC tapes used, the R_c at the face-to- substrate contact structure after polishing contact surface showed a lower R_c below 30 μΩcm^2 than other contact structures, it was soon converged to a characteristic value when the contact pressure exceeded 10 MPa. This is

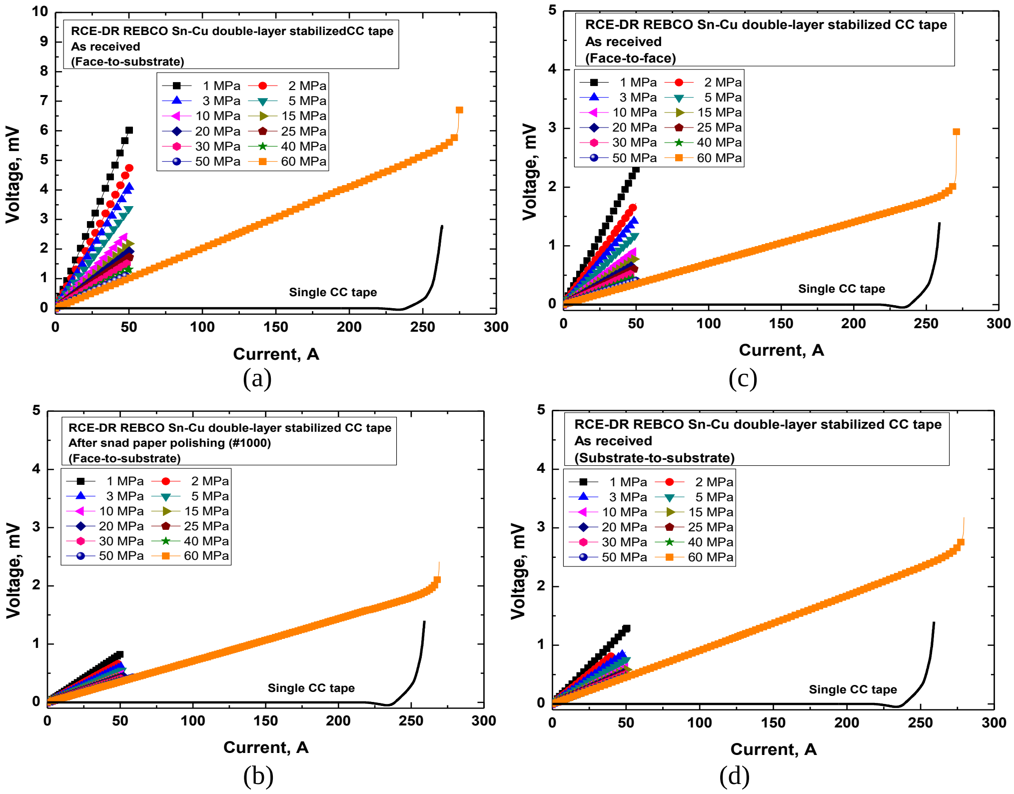

Fig. 4. *I-V* curves of RCE-DR processed Sn-Cu double layer stabilized CC contact structures under mechanical contact pressure (a) face-to- substrate, (b) face-to-substrate (after polishing), (c) face-to-face and (d) substrate-to substrate.

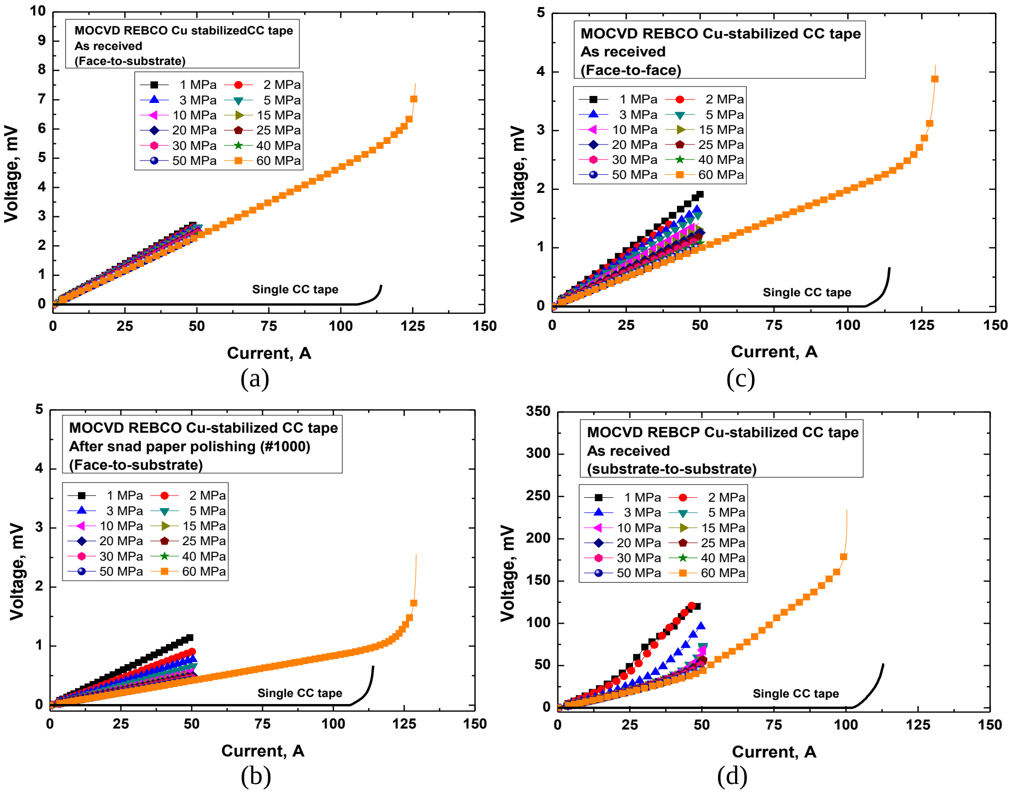

Fig. 5. *I-V* curves of MOCVD processed Cu-stabilized CC contact structures under mechanical contact pressure (a) face-to- substrate, (b) face-to-substrate (after polishing), (c) face-to-face and (d) substrate-to substrate.

deformed plastically and produced a complete contact at the interface under a high contact pressure which resulting to a saturation to a characteristic R_c value.

In the case of the RCE-DR Cu stabilized CC tape of Fig. 6(b), the face-to-substrate contact structure showed a higher R_c but other cases showed similar and lower R_c behavior. In the case of MOCVD processed Cu-stabilized CC tape shown in Fig. 6 (c), unlike RCE-DR CC tapes, when the contact pressure reached 5 MPa, it started to saturate to a constant R_c. It showed a somewhat large difference in the R_c depending on the contact structure adopted. Particularly, the substrate-to-substrate structure showed a much higher value of 750 μΩ-cm^2 and it can be explained using 3D surface topology observations followed in the next section.

3.2. Observations of surface contours of CC tapes

Fig. 7 shows three-dimensional surface contours measured at both the superconducting layer and substrate layer sides along the width direction of CC tapes. Three-dimensional surface contours were obtained by scanned process using a usual surface measuring instrument (Mitutoyo Co., Model: SURFTEST SV-400). Upper part figures show the surface profiles at the as-received state and the lower part indicates the surface profiles after polishing for RCE-DR and MOCVD processed Cu-stabilized CC tapes, respectively. The surface contours at the as-received state of the Cu and Sn-Cu double-layer stabilized CC tapes fabricated by the RCE-DR process showed that the central part of the superconducting layer side was higher than that at both ends, showing a little bulged in the middle. On the other hand, in the case of the substrate layer side, the central part is shallower than at the both ends having a shallow valley shape. It can be thought that the difference in the surface contour produced the difference in the R_c behavior observed depending on the contact structure for respective CC tapes used.

In the case of the MOCVD processed Cu stabilized CC tape, the superconducting layer side showed that the central and the both ends parts are convexly protruded, but the substrate layer side has a surface profile in which both ends are only protruded. These surface contour observations can be used to explain the result that a much higher R_c behavior observed in the case of the substrate-to-substrate contact structure in Fig. 6 (c). In the contact structure of substrate-to-substrate, the local contact was only maintained at both ends, consequently brought a much higher R_c during the contact resistance test.

On the other hand, the surface morphologies after polishing showed that the both surfaces at the superconducting layer and the substrate layer sides became flat. Which indicates that the most part of the interface under contact pressure became in contact. Therefore, as observed in Fig. 6, all CC tapes after polishing showed the lowest R_c as compared to other contact structures. It is

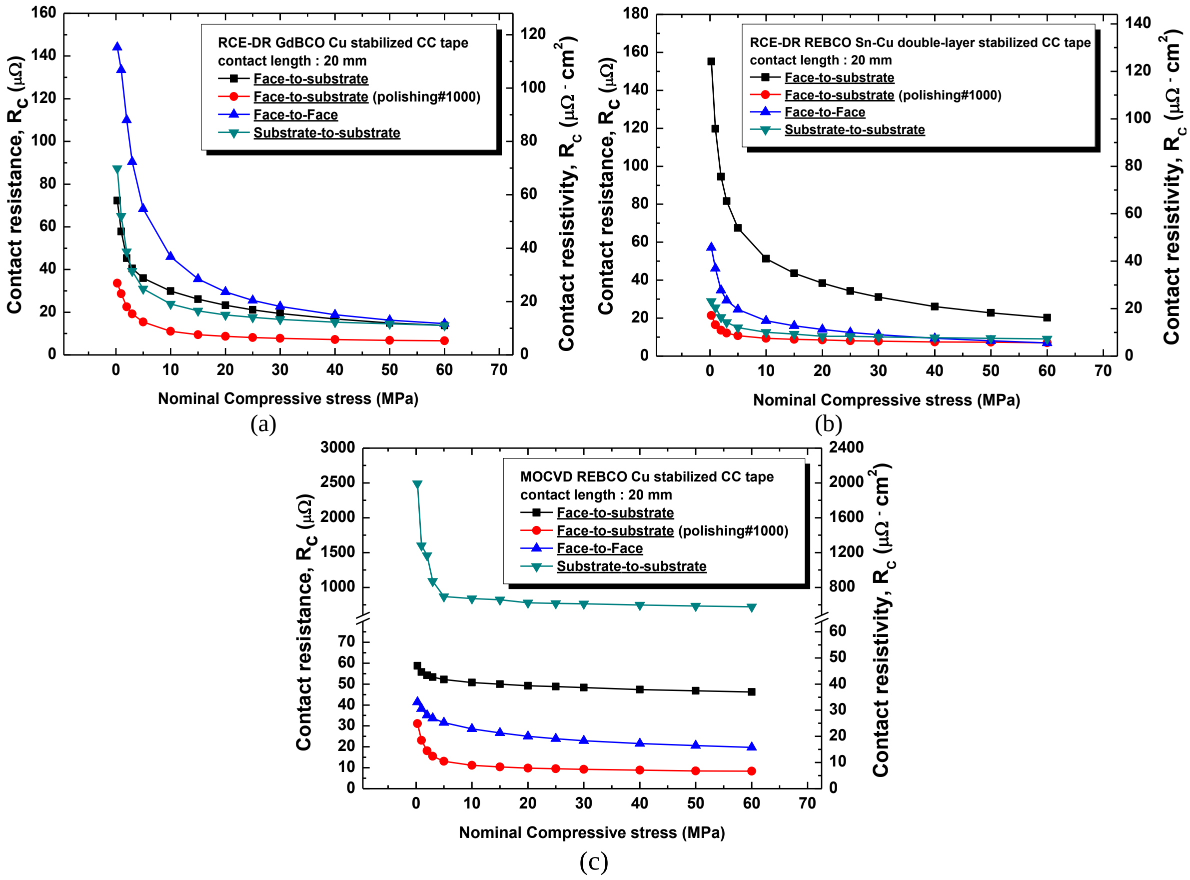

Fig. 6. Behaviors of R_c with contact pressure for (a) RCE-DR processed Cu-stabilized, (b) RCE-DR processed Sn-Cu double-layer stabilized and (c) MOCVD processed Cu-stabilized REBCO CC tapes.

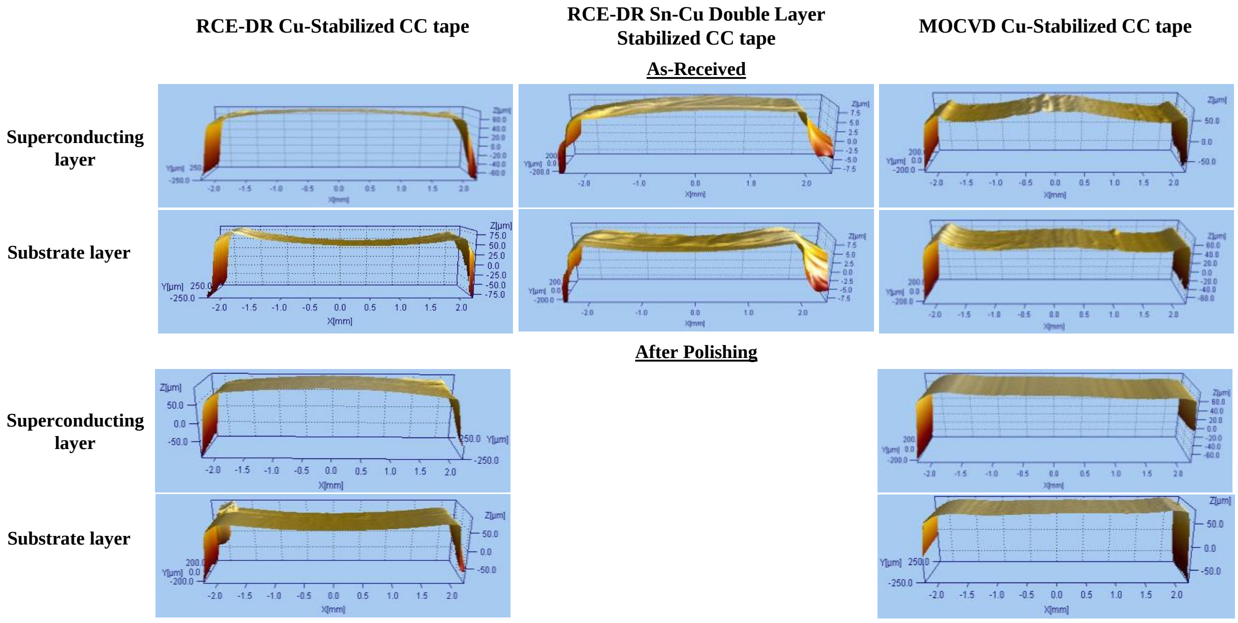

Fig. 7. 3-dimensional surface contours of differently stabilized REBCO CC tape samples along the width direction at as-received and after polishing.

considered that the polishing of the stabilizer layer surface of the CC tape resulted in the removal of the oxide layer from the surface of the CC tapes and a complete contact at the beginning of the contact, resultantly showing a significantly lower R_c behavior.

4. CONCLUSION

The turn-to-turn contact resistance (R_c) of REBCO CC tapes showed some differences depending on the contact structure. As a whole, as the contact pressure increased, it rapidly decreased from a high value at the beginning, then gradually decreased after 5 MPa and saturated to a constant value. It can be explained that the difference observed in the R_c behavior depending on the contact structure was resulted from the initial surface contour of the CC stabilizing layer of CC tapes. Therefore, the lowest R_c was obtained at the cases after polishing for all CC tapes used. The R_c of REBCO CC tapes used in this study was usually in the range of 5~2,000 $\mu\Omega cm^2$ depending on the contact structure, surface condition and contact pressure. Both fine and coarse adjustment of R_c for the design and fabrication of NI CC coils is possible.

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