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Contact resistance between two REBCO tapes: the effects of cyclic loading and surface coating

Jun Lu, Jeremy Levitan, Dustin McRae and Robert Walsh

National High Magnetic Field Laboratory, Tallahassee, FL 32310, United States of America

E-mail: junlu@magnet.fsu.edu

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Abstract

No-insulation (NI) superconducting REBCO magnets have advantages of self-quench-protection, a very high engineering current density and high mechanical strength, and the potential to reach very high magnetic fields. However, NI REBCO magnets have drawbacks of a long magnet charging time and high field ramp losses. These can be mitigated by controlling the turn-to-turn contact resistivity (R_c). In an effort to control R_c, we consider two approaches. One is coating a REBCO conductor with various resistive thin films, and the other is to use a stainless steel (SS) tape as an interlayer which is also coated with different metallic films. We present experimental results of R_c of an as-received sample under cyclic contact pressure of 2.5–25 MPa up to 30 000 cycles. After an initial increase in R_c for the first 10–20 cycles, R_c decreases to about one tenth of its initial value after a few hundred cycles. A warm-up and cool-down thermal cycle does not significantly change the low R_c resulting from a previously high number of load cycles. We also studied R_c of REBCO tapes that are coated with different resistive layers and interlayers. In order to increase R_c, we experimented with electro- and electroless plating of Ni, Cr, and Ni–P. We also measured R_c with a thin metallic interlayer as a coil co-winding material which included Cu, SS, and SS plated with Ni and Cu. A SS interlayer increases R_c by about three orders of magnitude; while the Cu plated SS interlayer only increases R_c by one order of magnitude. Finally, we treated the as-received REBCO surface by oxidation using an Ebonol® C solution. This controlled oxidation allowed the R_c to be controlled over a wide range.

Keywords: coating, contact resistance, no-insulation, REBCO, cyclic loading

(Some figures may appear in colour only in the online journal)

1. Introduction

No-insulation (NI) REBCO pancake magnet coils have several advantages over conventional insulated coils [1–3]. Due to low turn-to-turn electrical resistance, when a magnet quench happens in a NI REBCO coil, the quench current automatically bypasses the normal zone, and a hot spot is avoided. This self-quench-protection ability eliminates the need for a quench detection and protection system that can be very challenging and costly in a large high field REBCO magnet [4]. Consequently, a NI REBCO coil is very stable which allows for a thinner copper stabilizer to be used on the REBCO conductor. The thinner stabilizer and the elimination of insulation make the engineering critical current density and the effective mechanical strength of the coil very high. These suggest that this technology enables very compact magnets to reach a very high magnetic field.

There are, however, drawbacks with the current state of the NI REBCO coil technology. NI coils typically have long charging delay times [5–7] as well as high field ramp losses [8] which is a concern especially for cryo-cooled magnets where the cooling power is limited. These issues are directly related to low turn-to-turn contact resistivity (R_c) which is defined as contact resistance multiplied by contact area, and can be mitigated by somehow increasing R_c. However, very high R_c compromises the turn-to-turn current transfer

Table 1. REBCO coating methods.

Coating	Electrolyte	T (°C)	Current density (A dm^{-2})	Growth rate (μm min^{-1})
Ni	Caswell Ni	40	1	0.12
Ni–P	Caswell electroless Ni–P	90	—	0.5
Cr	Cr_2O_3: H_2SO_4 : H_2O = 45 : 200 : 0.45	22	2.5	0.03
Cu on SS	$CuSO_4{\cdot}5H_2O$: H_2O = 7 : 250 (add H_2SO_4 until pH = 1)	22	0.3	0.05

capability therefore jeopardizes the coil's self-protection ability. In principle, R_c can be optimized to achieve a relatively short charging delay time and low ramp losses without jeopardizing the coil's self-protection ability. Many theoretical analyses have been done to predict the quench behaviors of NI magnet coils and the effect of R_c [9–12]. These studies suggest that R_c values ranging from 1000 to 100 000 $\mu\Omega$ cm^2 might be suitable, which is significantly higher than about 70 $\mu\Omega$ cm^2 in the current NI coils [6]. Therefore it is critical to develop a technology to control R_c to this desirable level. To this end, the effect of 'insulation' by a metallic co-winding interlayer is also explored [13–15]. In addition, it is proposed that the conductor with graded R_c is used to reduce the ramp loss [8] as well as to improve stability and recovery speed after a quench [16] in large NI REBCO magnets.

Evidently R_c is a very critical parameter in the development of NI coil technology. In our previous paper on this subject, we reviewed REBCO R_c studies in the literature and reported our measurements and analysis of R_c between two SuperPower REBCO samples as a function of temperature and contact pressure for several load cycles [17]. In this paper, considering the fact that a practical superconducting magnet typically experiences a few thousand charge–discharge cycles in its lifetime, we study the effect of a large number of pressure cycles on R_c. Moreover, we performed a large number of experiments in order to develop a technology to control R_c. Here we present the effects on R_c of a thin layer of metal deposited on REBCO, various metallic interlayers, and oxidation of REBCO tape. Based our experimental results, we propose a practical method to control R_c. The implications of our results on NI REBCO coil applications will be discussed.

2. Experimental

2.1. Samples

Samples used in this experiment are REBCO conductors made by SuperPower (SCS4050AP) and SuNAM, both are surrounded by electroplated copper stabilizers. The SuperPower conductor is 4 mm wide with overall thickness of 95 μm which includes a 20 μm copper stabilizer on each side. The nominal critical current in the self-field at 77 K is 80 A. The resistivity ratio between room temperature and 4.2 K for the copper stabilizer layer is measured on similar SuperPower conductors to be about 50. Since SuperPower conductors were used for the majority of our experiments, the data in this paper are all from SuperPower SCS4050AP samples unless stated otherwise. The SuNAM conductor is 4 mm wide with an overall thickness of 135 μm which includes a 30 μm laminated copper stabilizer. The nominal critical current in the self-field at 77 K is 105 A. One SuNAM sample has 1 μm stainless steel (SS) cladding.

2.2. Thin film coating and surface oxidation

In order to control R_c, various kinds of surface coatings were made. The surface coating methods chosen in this experiment are relatively low cost, and easy to scale up to high volume production. Due to these reasons, a more sophisticated process such as physical vapor deposition (PVD) was not considered. It should be noted, however, a REBCO conductor manufacturer is typically equipped with a PVD system with reel-to-reel operation capabilities. Therefore, for a REBCO manufacturer to coat a thin film using PVD on a REBCO tape may not be very expensive.

Cr, Ni and Ni–P films were deposited on REBCO conductors directly. Cr film was electroplated on REBCO samples using an electrolyte made of 200 ml deionized water, 45 g Cr_2O_3, and 0.45 g sulfuric acid. Ni film was electroplated using a commercial nickel plating solution (Caswell Inc., USA). Ni–P with 5%–7% phosphorus is a high resistivity material with a high hardness and good wear resistance, and all these properties potentially lead to high contact resistance. Therefore several samples were plated with Ni–P on Ni plated REBCO using a commercial electroless Ni–P plating solution (Caswell Inc., USA). All these plating processes resulted in dense, uniform and adherent metallic coatings. In addition, Ni and Cu were plated on 316 SS tape, which was then used as an interlayer between two REBCO tapes. For Cu electroplating, a $CuSO_4$ solution was used. The detailed electrolytes and other conditions used for these plating processes are summarized in table 1.

In addition, we experimented with oxidation of the REBCO surface. In the oxidation experiments, we used Ebonol® C, a mixture of sodium hydroxide and sodium chromate [18] and dissolved it in deionized water at a weight ratio of Ebonol® C: water = 18: 80. The REBCO surface was oxidized in Ebonol® C solution at 98 °C for various durations. The thicknesses of the oxide layer on the copper strips were measured by weight loss after removing the oxide layer with a solution of HCl: H_2O = 1: 10, and assuming the density of the oxide is 6.31 g cm^{-3} for CuO. As shown in figure 1, the oxide thickness increases almost linearly with the logarithm of time. Depending on the thickness of the oxides, the color of the oxidized REBCO surface changed from dark brown after 10 s to black after 30 s.

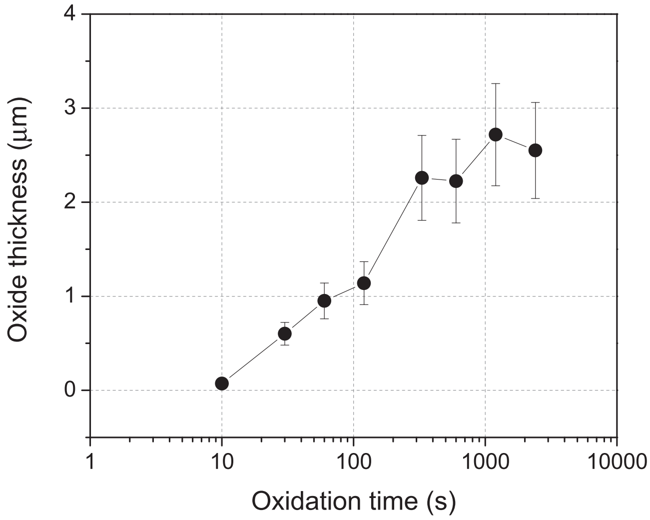

Figure 1. CuO layer thickness versus Ebonol® C oxidation time. Ebonol® C concentration is about 18 wt%, temperature was 98 °C.

2.3. Transverse load cycling and R_c measurement at cryogenic temperatures

For R_c measurement, a probe used in our previous experiment [17] was modified to fit to a Material Test System tensile machine which enables fast load cycling at a rate up to 10 Hz at 77 K or 4.2 K, load cycles of 2.5–25 MPa being applied. More details of the experimental setup are described in our previous paper [17]. R_c was measured during the load cycling by applying ± 1.00 A current from a Keithley 2400 bipolar DC current source, and measuring voltage with a Keithley 2010 digital multimeter. The instrument error for resistance measurements was estimated to be less than 0.1 $\mu\Omega$ cm^2, obtained from a measurement of a REBCO solder joint sample using otherwise the same experimental conditions.

3. Results and discussions

3.1. R_c variation due to surface conditions

It is known that surface conditions such as slight oxidation or other contamination, as well as roughness, have a significant effect on contact resistance. Since the surface condition of a commercial REBCO conductor is usually not specified, it is expected that R_c from different manufacturers and different production batches varies widely. We investigated this variation by measuring R_c of REBCO with different surface conditions at 25 MPa contact pressure at 77 K. As shown in table 2, R_c varied drastically from sample to sample. We observed a systematic difference in R_c between SuperPower and SuNAM conductors, which might be contributed to their respective surface flatness and roughness. Because while a SuperPower conductor has a rough finish with increased thickness at the center and the edges [17], a SuNAM conductor has a smooth and shiny finish with a relatively uniform thickness. After slightly polishing the surface of the SuperPower conductors with an abrasive (Scotch-Brite) or chemical etching it with a solution of HCl: H_2O = 1: 1, R_c was reduced by a factor of about ten. When the conductor surface was handled by ungloved hands, R_c increased by a factor of two to six. When a consistent surface cleaning method was applied, e.g. by wiping with an ethanol soaked tissue, the measured R_c values became much more consistent. Variation along the conductor length of the same piece was also observed.

3.2. Effect of contact load cycling

We reported in our previous paper [17] that R_c increases with contact load cycling up to 14 cycles of 140 MPa at 77 K. In order to simulate a user magnet with frequent field ramps, in this paper we measured R_c of the SuperPower conductor with a larger number of load cycles between 2.5 and 25 MPa. This contact pressure range was chosen because it seems to be a reasonable range for radial stresses in a coil. Admittedly, the radial stress in a coil which depends on winding tension, thermal stress, and electromagnetic load during the coil's operation, is not uniform and very difficult to calculate precisely.

Figure 2(a) shows a series of curves of R_c versus contact pressure P measured after different numbers of load cycles at 77 K. Each R_c (P) curve shows the expected behavior where R_c decreases with transverse load. It is also evident that R_c increases within the first 10–20 cycles then decreases quickly. After a few hundred cycles, R_c levels off to a value only about one tenth of its initial value. This trend is presented more clearly in figure 2(b) where R_c at 25 MPa pressure is plotted against load cycles in a semi-logarithm scale. After only about 200 cycles, R_c decreases to about 4 $\mu\Omega$ cm^2 from the initial value of 40 $\mu\Omega$ cm^2 then levels off. This experiment was repeated a few times, and similar results were obtained. Since we are interested in a high field REBCO magnet operating at 4.2 K, the load cycling effect was studied at 4.2 K as well. The results are presented in figure 3 and compared with the 77 K data. Despite the difference between the 77 K and 4.2 K data which can be partly attributed to the variation from sample to sample, a similar trend was observed. The initial higher R_c at 4.2 K is likely due to random variations in surface conditions. The significant decrease in R_c seems to occur after a few hundred cycles, somewhat later than that at 77 K. At the end of 20 000 load cycles at 4.2 K, R_c is only 0.85 $\mu\Omega$ cm^2 which is significantly lower than 4 $\mu\Omega$ cm^2 at 77 K. The lower asymptotic R_c value at 4.2 K is likely due to the lower resistivity of copper, consistent with [17]. After these load cycling experiments, the sample surfaces were examined with a light microscope up to 1000× magnification. No discernable surface morphology changes were observed.

This significant decrease in R_c upon a large number of contact pressure cycles was not discovered in our previous experiment [17] because the number of cycles was limited to 14. In order to understand this load cycling effect, we review the Holm theory of contact resistance where R_c is related to mechanical and electrical properties of the contacting surface by [17]

$$R_C = 0.886\rho\sqrt{\frac{HV}{PN}} + \frac{\rho_f dHV}{P} \tag{1}$$

Table 2. R_c of samples with various surface conditions.

Sample ID	Surface	Number of samples	R_c at 25 MPa ($\mu\Omega$ cm^2)
SuNAM	Ethanol wiped	2	5.9–7.5
SuperPower-1	Ethanol wiped, beginning of the spool	13	16–58
SuperPower-2	Ethanol wiped, end of the spool	7	47–180
SuperPower-3	Ethanol wiped then finger handled	1	100
SuperPower-4	Scotch-Brite wiped	5	0.8–7.3
SuperPower-5	HCl etched	6	3.4–22

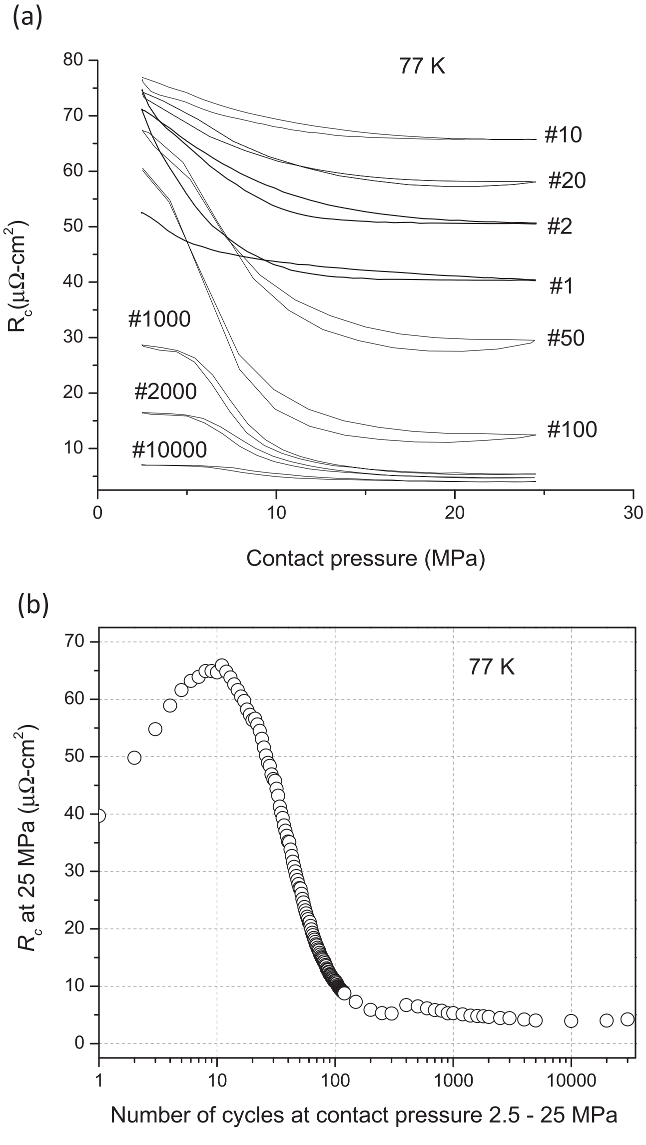

Figure 2. R_c of as-received SuperPower SCS4050 at 77 K. (a) R_c versus contact pressure curves for different numbers of load cycles. (b) R_c measured at 25 MPa as a function of number of load cycles.

where ρ and ρ_f are resistivity of the contact material (Cu in our case) and the surface contamination film (probably Cu oxides) respectively, HV the Vickers hardness of the contact material, N the number density (in m^{-2}) of contact spots, and d the thickness of the oxide film. According to equation (1), under a given contact pressure, the harder the contacting material, the smaller contact spot radius, therefore higher R_c.

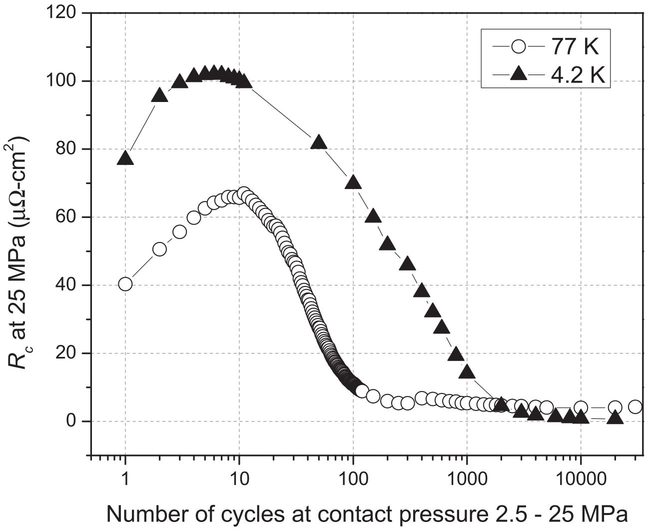

Figure 3. R_c measured at 25 MPa as a function of number of load cycles at 77 K and 4.2 K.

So we speculate that initially the surface cold-work hardened the material and increased its resistivity, and both led to higher R_c as explained in our previous paper [17]. However, the cold-working effect reached its saturation at a few tens of cycles. The quick decrease in R_c after that might be explained by gradual wear-out of the oxide layer on the copper surface. The fact that there is a ten-fold difference in R_c between as-received and freshly HCl etched samples seems to be consistent with the existence of a thin resistive oxide layer.

This appreciable load cycling effect has very important implications for NI magnet coil technology. Because a user magnet usually undergoes at least a few thousand charging/discharging cycles in its lifetime. R_c of a magnet coil measured without significant load cycling might considerably underestimate the charging delay time, which, in some cases, could be ten times longer than its initial value after only a few hundred charging cycles. It should also be noted that during operation the contact pressure in a NI coil is not uniform and depends on the specific magnet design. Therefore the result from these experiments may not fully represent the situation in a real magnet coil.

3.3. Effect of thermal cycling

In its lifetime, a superconducting magnet is usually warmed up to room temperature many times. Therefore it is very

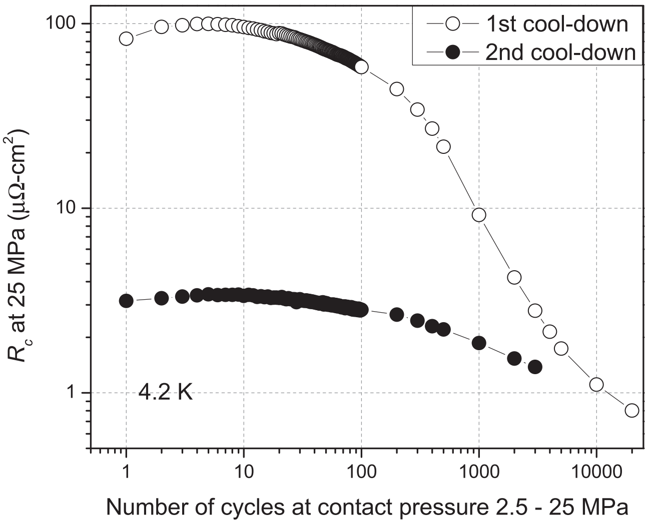

Figure 4. Effect of thermal cycling. R_c versus number of load cycles at 4.2 K measured after first and second cool-down. During warming up to 273 K, the contact pressure was kept at 2.5 MPa.

relevant to investigate the effect of thermal cycling on R_c. In the following experiment, R_c of a sample was tested for up to 20 000 load cycles at 4.2 K. Then the sample was allowed to naturally warm up inside the cryostat overnight under a 2 MPa constant pressure to 273 K. The sample was cooled down to 4.2 K again and R_c was measured again. The measured R_c versus number of cycles for both the first and the second cool-downs are shown in a log–log plot in figure 4. As shown in the figure, thermal cycling does not reset R_c to its initial value before load cycling. After thermal cycling, R_c only increases moderately from 0.8 $\mu\Omega$ cm^2 to about 3.1 $\mu\Omega$ cm^2, still much less than the initial value of nearly 100 $\mu\Omega$ cm^2. This suggests that in a magnet coil the drastic decrease in R_c due to load cycling cannot be reset by warming the coil up to room temperature.

3.4. Control of R_c

For NI magnet applications, it is highly desirable to control R_c so the coil charging delay time is relatively short without compromising the coil's self-protection ability. Our study on the load cycling effect suggests that it is also important for R_c to be insensitive to load cycling. To this end, two approaches are considered. The first one is coating the conductor surface with a thin resistive film so R_c is increased and may be controlled by either the chemical composition or the thickness of the film. The second one is winding the coil with a resistive co-winding tape, and coating the co-winding tape with various resistive films to control R_c. The results of these efforts are presented in the following subsections.

3.4.1. Metallic cladding. One of the earliest efforts to control R_c was made by the REBCO manufacturer SuNAM [19]. REBCO conductors were coated with up to 1 μm SS cladding (MC-REBCO). The charging delay of the test NI coils using MC-REBCO conductors reduced considerably. We measured R_c of a SuNAM MC-REBCO as a function of load cycles at both 77 K and 4.2 K. The results are plotted in figure 5 together with data from as-received SuperPower samples. Evidently SuNAM's MC-REBCO sample has higher R_c than the as-received SuperPower sample. Furthermore, R_c does not decrease drastically with load cycles especially at 77 K. It might be possible to further control R_c by changing the thickness of the SS cladding layer.

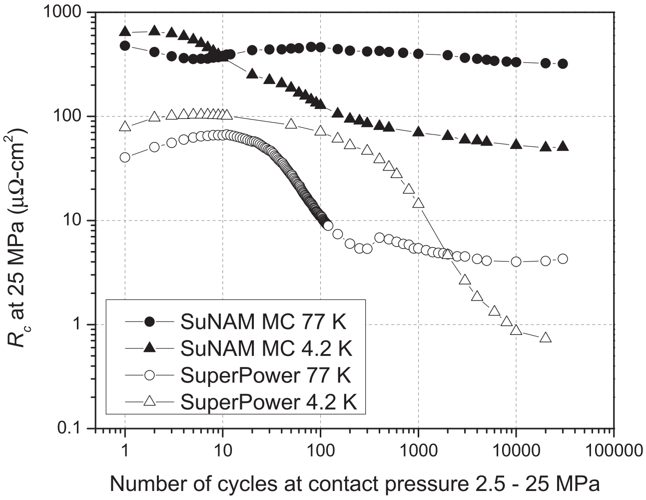

Figure 5. R_c versus load cycles of the SuNAM metallic cladded sample as compared with the SuperPower as-received sample.

Encouraged by this result, we experimented with depositing metallic layers on REBCO by electroplating, which is more economical and easier to scale up compared with the magnetron sputtering method used by SuNAM [10]. In these experiments, short samples of SuperPower conductor were plated with Ni or Cr films of different thicknesses. However, the plated Ni thin films did not seem to increase R_c significantly as shown in table 3, where R_c under first load at 25 MPa for different surface coatings are listed. Cr plating and the native oxide layer on the Cr surface seem to have the potential to significantly increase R_c, but our results on three Cr plated samples vary widely, therefore are not presented in table 3. Further investigation is needed to understand the formation of the native Cr oxides and their effect on R_c. On the other hand, the environmental concerns of the hexavalent Cr plating makes it a less attractive option.

Ni5-7wt%P is a highly electrical resistive, wear and corrosion resistant material that can be plated to metal surfaces by an electroless process [20]. Therefore in order to increase the R_c, Ni–P of various thicknesses was plated on SuperPower samples which were already plated with a 1 μm pure Ni layer. The 77 K R_c measurements on Ni–P plated samples show a near linear increase in R_c with Ni–P thickness, as shown in figure 6(a). This demonstrates a certain level of R_c control by varying the Ni–P thickness. However, the Ni–P sample seems to be sensitive to load cycling. As shown in figure 6(b), after only a few hundred load cycles, R_c of a 1 μm Ni–P plated sample drops down almost two orders of magnitude and becomes lower than that of an as-received uncoated sample before load cycling.

Table 3. R_c of REBCO with different coatings.

Sample	Surface	Number of samples	R_c at 25 MPa ($\mu\Omega$ cm^2)
SuNam	1 μm SS cladding	2	180, 224
SuperPower	1 μm Ni plating	3	19–64
SuperPower	Graphite sprayed	1	180

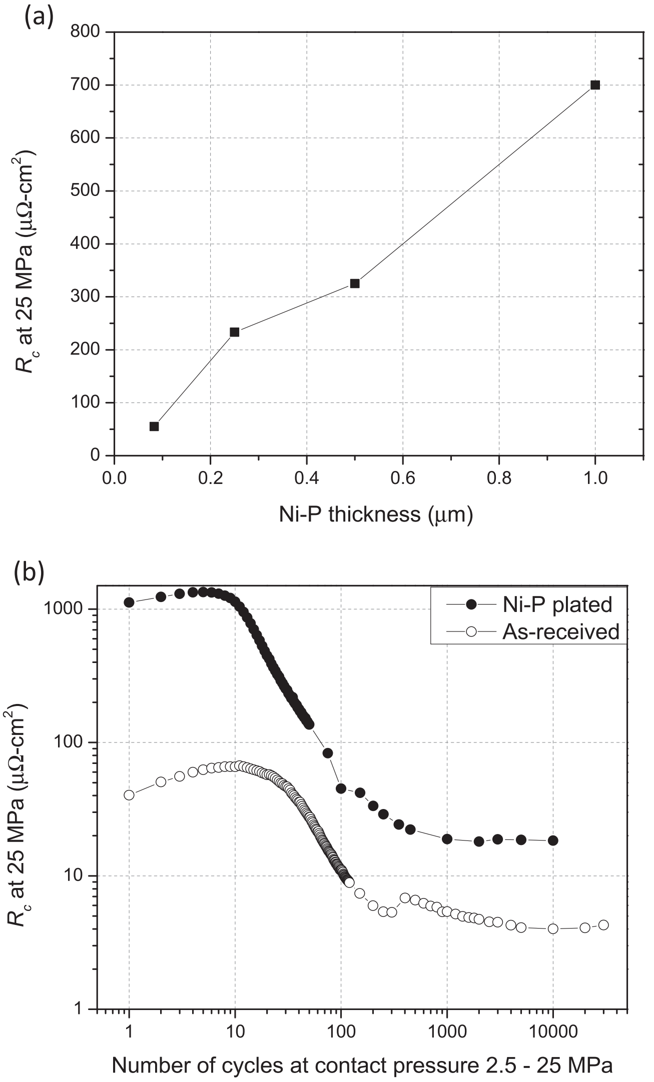

Figure 6. Effect of Ni–P plating. Ni–P is plated on REBCO with a 1 μm pure Ni buffer layer (a) R_c versus Ni–P thickness. (b) R_c versus load cycles for 1 μm Ni–P plated sample with an as-received sample for comparison.

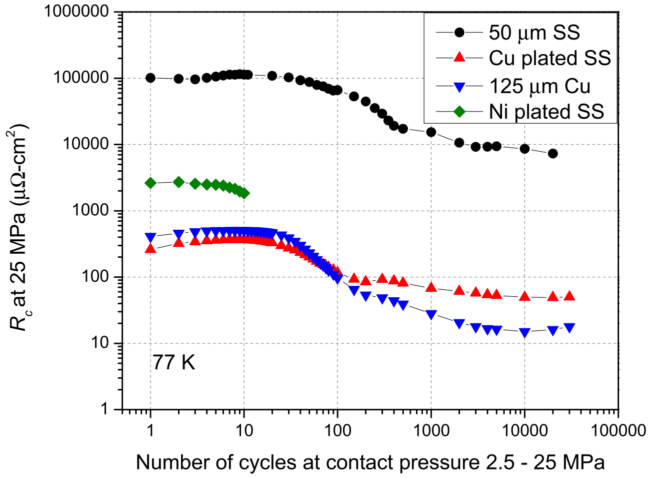

Figure 7. Effect of co-wind tape. R_c versus load cycles for REBCO inserted with SS tape, Cu tape, Ni plated SS tape and Cu plated SS tape.

3.4.2. Co-wind tape and its coating. Co-winding a REBCO pancake coil with 316 SS tape is another attractive option for a NI coil. Here the co-winding 316 SS tape is used as mechanical reinforcement as well as a metallic interlayer to increase R_c. The properties of 316 SS co-wound REBCO coils have been analyzed [21] and experimental results reported in [14, 22, 23]. In order to verify the R_c values reported in these works, we measured R_c of two SuperPower REBCO conductors which have a 50 μm thick 316 SS tape placed in between them. As shown in figure 7, R_c is in the order of 10 000–100 000 $\mu\Omega$ cm^2 which is much higher than $\sim$1000 $\mu\Omega$ cm^2 reported in [14] and about three orders of magnitude higher than measured without the 316 SS interlayer. Since the resistance of 50 μm SS tape in its thickness direction is only in the order of 1 $\mu\Omega$ cm^2 at 77 K, the high R_c is likely due to the native oxide layer on the SS surface as well as its appreciable hardness compared with copper. This is consistent with equation (1) where high native oxide resistivity ρ_f and high hardness HV make R_c higher. With such high R_c, the self-protection ability of such an NI coil becomes questionable, especially for the coils with large stored energy. So in an effort to reduce and control such high R_c, about 1 μm of pure nickel or copper was plated on the SS tape. As also shown in figure 7, these thin films of pure metals on SS tape reduced R_c dramatically. The remarkable effect of these thin films on R_c demonstrates the importance of the native oxide resistivity and contact material hardness. This moderation of R_c by a thin film on SS co-wind tape seems to be a viable option for controlling R_c in a NI magnet coil. It is also very interesting to see that with a 125 μm thick Cu tape between REBCO tapes, as plotted in figure 7, R_c is similar to that with the Cu plated SS. This further demonstrates the dominant role surface materials play in controlling R_c.

3.4.3. Surface treatment by Ebonol® C oxidation. Since electroplating pure metals on REBCO seems to have limited potential in controlling R_c, an alternative is to deposit a layer of highly resistive material on REBCO, so R_c may be controlled reliably by changing the thickness of the deposited layer. Copper oxide (CuO), being a semiconductor, is an obvious option. We used a commercial copper blackening agent Ebonol® C to oxidize the Cu surface of REBCO tapes

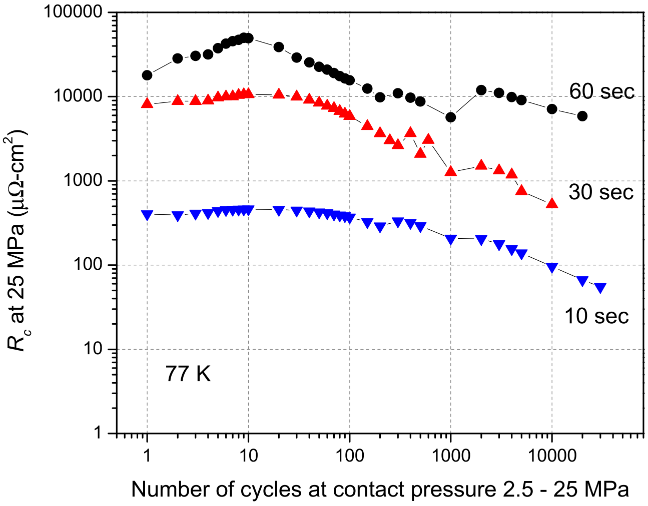

Figure 8. R_c versus load cycles for REBCO oxidized by Ebonol® C for 10, 30, and 60 s.

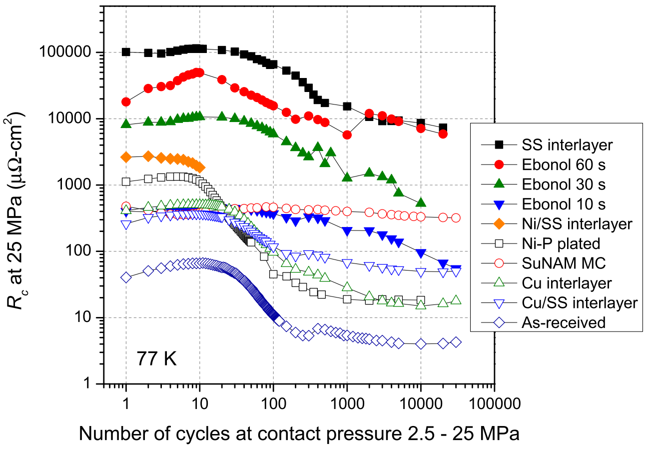

Figure 9. A summary of all the R_c versus load cycle curves measured at 77 K from samples of different surface and interlayer conditions.

and calibrated the oxide thickness as a function of oxidation time (figure 1). Figure 8 shows the R_c as function of load cycle for samples oxidized for 10, 30 and 60 s. The R_c of these samples ranges for two orders of magnitude and are significantly higher than for the as-received REBCO. Furthermore, they do not seem to decrease too much with load cycling. Therefore by controlling the oxidation time, R_c can be easily controlled and be tailored to different NI coils for different applications. This Ebonol® C oxidation process is also economical and easy to be scaled up to have a reel-to-reel surface treatment process which allows industry to manufacture REBCO tapes with customized R_c at a low cost. Figure 9 summarizes all 77 K R_c versus load cycle curves presented previously. This covers large variety of R_c from different surface conditions. Among them, the most controllable cases are the Ebonol® C treated surfaces.

Finally, it should be noted that our R_c measurements are on small stamp samples. Although our technique has the advantages of being versatile and able to perform fast measurements under a large number of load cycles, as well as the ability to reveal the underlying physics of the contact resistance, the results of these experiments need to be confirmed with a coil test such as those performed in [1]. This is because, for the applications in magnet coils, the contact pressure varies from turn to turn, so the effect of the load cycling cannot be predicted precisely. An R_c test by a small coil would bring us one step closer to the real situation in a magnet coil. For these reasons, we are developing a reel-to-reel Ebonol® oxidation system, so we can oxidize the surface of long length of REBCO tapes in order to make small coils for R_c tests.

4. Conclusions

The contact resistance R_c between two REBCO tapes was measured at 77 K and 4.2 K under mechanical load between 2.5 and 25 MPa up to 30 000 cycles. We found that R_c reaches a maximum at 10–20 cycles and then decreases. After about 1000 cycles, R_c decreased to about one tenth of its initial value. After 20 000 load cycles, thermal cycling was performed by warming the sample from 4.2 K to 273 K under 2.5 MPa pressure and cooling down to 4.2 K again. This increased R_c slightly which was still much lower than its value before load cycling. Both electroplating of Ni, Cr, and Ni–P directly on REBCO, and using a Cu or Ni plated SS co-wind tape were able to control R_c to a certain degree. A SS interlayer increases R_c by about three orders of magnitude; while the Cu plated SS interlayer only increases R_c by one order of magnitude. Controlled REBCO surface oxidation by an Ebonol® C solution results in an easily controlled R_c that covers a wide range by varying oxidation time. This oxidation technique can be easily scaled up to meet the needs of large NI magnet coils.

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ORCID iDs

Jun Lu https://orcid.org/0000-0001-8521-489X

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