Contact resistance between two REBCO tapes under load and load cycles

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Received 22 November 2016, revised 10 January 2017
Accepted for publication 20 January 2017
Published 21 February 2017

Abstract
No-insulation (NI) REBCO magnets have many advantages. They are self-protecting, and therefore do not need quench detection and protection, which can be very challenging to implement in a high $T_c$ superconducting magnet. Moreover, by removing the insulation and allowing thinner copper stabilizers, NI REBCO magnets have significantly higher engineering current density and higher mechanical strength. On the other hand, NI REBCO magnets have the drawbacks of long magnet charging time and high field ramp loss. In principle, these drawbacks can be mitigated by managing the turn-to-turn contact resistivity ($R_c$). Evidently, the first step toward managing $R_c$ is to establish a reliable method of accurate $R_c$ measurement. In this paper, we present experimental $R_c$ measurements for REBCO tapes as a function of mechanical load up to 144 MPa and load cycles up to 14. We find that $R_c$ is in the range of 26–100 $\mu\Omega\cdot$cm$^2$, and that it decreases with increasing pressure, and gradually increases with the number of load cycles. The results are discussed in the framework of Holm’s electric contact theory.

Keywords: contact resistance, mechanical load, no-insulation, REBCO

(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, 2]. They are self-quench-protecting, which eliminates the need for a quench detection and protection system, which can be very challenging to implement in a high $T_c$ superconducting magnet [3]. NI coil technology also eliminates the insulation and reduces the copper stabilizer volume. This results in magnet coils with very high engineering critical current density and significantly higher engineering mechanical strength, which enables a very compact magnet to reach a field well above 30 T.

Long charging delay [4–6] and high ramp losses, which are a concern in the operation of cryo-cooled magnets, are some of the obstacles that need to be overcome in NI magnet technology. These issues are directly related to turn-to-turn contact resistivity ($R_c$) and can be mitigated by increasing $R_c$. On the other hand, too high $R_c$ jeopardizes the self-protection ability. Therefore it is highly desirable to have an engineered $R_c$ that minimizes the charging delay and ramp loss while retaining reliable self-protection ability. The first step of $R_c$ engineering is to develop a reliable method to measure it accurately.

It is conceivable that $R_c$ varies with variations of conductor surface conditions, such as roughness, native oxide chemistry and thickness. $R_c$ is also expected to vary with contact pressure and temperature. The turn-to-turn contact pressure in a coil is equal to the coil radial stress, which can be calculated based on the coil winding tension, thermal stress and electromagnetic stress for a specified case. A few useful examples are given in [7], where the winding and thermal stress in a REBCO pancake coil are calculated, and [8], where the electromagnetic stress is calculated for a 35 T REBCO magnet. In these cases, the turn-to-turn compressive pressure is below 30 MPa.

The $R_c$ of NbTi and Nb$_3$Sn wires under mechanical load and load cycles has been studied extensively for superconducting cable applications [9–12]. The $R_c$ between REBCO tapes has also been studied by a few research groups [13–20]. It should be noted that the REBCO layers of most REBCO conductors are grown on a substrate that has an insulating oxide buffer layer. A conductive stabilizer layer is subsequently deposited or laminated around the REBCO/...
substrate. Therefore the contact resistivity \( R_c \) depends strongly on the contact configuration, i.e. whether it is a face-to-face (REBCO-to-REBCO) or face-to-back (REBCO-to-substrate) contact. In mechanical joints for fusion applications [13–15], where a minimum \( R_c \) is desired, a REBCO-to-REBCO configuration is used. In addition, the conductor surfaces are usually ground and cleaned to reduce resistance. In [13–15], \( R_c \) of the order of 0.1 \( \mu \Omega \cdot \text{cm}^2 \) was obtained. On the other hand, for the turn-to-turn contacts of REBCO pancake coils, conductors are in a REBCO-to-substrate configuration. The \( R_c \) of a SuperPower conductor was measured indirectly via the charging time constant at 77 K [18], and a value of 70 \( \mu \Omega \cdot \text{cm}^2 \) was reported. By contrast, a direct measurement for an AMSC conductor [20] reported an \( R_c \) of 0.7–10.6 \( \mu \Omega \cdot \text{cm}^2 \) as a function of pressure. Since the reported \( R_c \) values vary considerably, a comprehensive study of \( R_c \) in the REBCO-to-substrate configuration is still needed. In this paper, we measured \( R_c \) in the REBCO-to-substrate configuration under load and load cycles at 77 K and below. We discuss our experimental results in the framework of Holm’s electrical contact theory.

2. Theory of contact resistance

The properties of electrical contacts are a special electrical engineering topic and are generally well understood in the context of Holm’s electrical contact theory [21, 22]. The roughness of the surface of contacts means that only a very small fraction of a surface makes good electrical contact, as shown in figure 1. These contact spots are called asperity spots. Consequently, electrical current flow is constricted to these asperity spots, which causes additional resistance compared to the case of unrestricted current flow. This is called constriction resistance. In addition, surface contamination, such as from native oxide film, albeit very thin if in series connection with asperity spots, may make a significant contribution to \( R_c \), which can be written as [22],

\[
R_c = \frac{\rho}{2aN} + \frac{\rho f d}{\pi a N},
\]

where \( \rho \) and \( \rho f \) are the resistivity of the contact material (Cu in our case) and the surface contamination film (Cu oxides in our case), respectively, \( a \) and \( N \) are the average radius and number density (in m\(^{-2}\)) of the asperity spots, and \( d \) is the thickness of the oxide film. The first term in equation (1) represents the constriction resistance and the second term is the contribution from the contamination film. This holds true for large numbers of contact situations. However, in the case of sub-micron thin films, some deviation from this theory has been observed [23, 24].

Based on the assumption that the pressure at the asperities is equal to the conductor’s plastic flow stress or hardness \( H \) [22], the radius of the asperity spots \( a \) can be related to the nominal contact pressure \( P \) via the hardness \( H \) of the contact material,

\[
H = \frac{\rho}{\pi a^2 N}.
\]

Here \( \pi a^2 N \) corresponds to the fraction of the surface that actually made contact. So equation (1) becomes

\[
R_c = \frac{\rho}{2N} \left( \frac{a}{H} \right) + \frac{\rho f d}{\rho},
\]

In equation (3), the relative contribution of the second term depends on the resistivity and thickness of the film. For example, if the film has been pierced at the asperity spots, the film thickness is zero, so the second term is zero. If we assume \( H \) and \( N \) to be independent of load, the \( R_c (P) \) curve will be proportional to either \( P^{-1/2} \) or \( P^{-1} \), depending on which term is dominant.

In practice, under increasing mechanical load, one has to consider the change in \( H \) due to work hardening, especially at cryogenic temperatures, as well as the change in the number of asperity spots \( N \). Furthermore, when an oxidized surface surrounds asperity spots, the size of the asperity spots is likely to increase much more slowly than is suggested in equation (3), because the asperity spots have to compete with oxides for contact area. When the size of the asperity spots can no longer increase with pressure, the \( R_c (P) \) curve becomes flat.

3. Experimental setup

The samples used in this experiment are REBCO conductors made by SuperPower (SCS4050AP). They are cut from a 4 mm wide tape with a thickness of about 95 \( \mu \)m, including a 20 \( \mu \)m layer of copper stabilizer deposited on each side by electroplating. The nominal critical current in self-field at 77 K is 80 A. The residual resistivity ratio of the copper stabilizer layer has been measured on similar SuperPower conductors to be about 50.

For the conductor surface morphology and contact cross-section characterization, we use an optical microscope (Olympus BX60M), a scanning electron microscope (Zeiss...
and a laser confocal microscope (Olympus OLS 3100).

For $R_c$ measurement, a test probe is designed and constructed, as shown in figure 2. In this probe, a 25 mm long lap contact in a REBCO-to-substrate configuration is placed on a flat G-10 bottom plate. An alignment tool is used to align two REBCO tapes and the alignment is then checked by a microscope. The centering of the G-10 block on top of the sample is adjusted to ensure that the thin gaps between the G-10 block and the bottom G-10 plate on either side of the sample are even. The mechanical load is provided by a 6" diameter air cylinder (FABCO-AIR, HP6X4FF) driven by pressurized nitrogen gas whose pressure is measured by a PX209-300G5V pressure transducer (Omega Engineering, Inc.). The load as a function of gas pressure is calibrated by a 10 kN MTS load cell. The designed maximum load for this probe is 15 kN.

The $R_c$ is obtained by linear fits of $V-I$ curves measured between 0 and 15 A. The current source is a PowerTen P63C-51000 (0–5 V, 0–1000 A) and the voltage meter is a National

Figure 2. (a) A schematic drawing of the $R_c$ measurement configuration with a 25 mm long contact area. (b) A photograph of the experimental probe. The stainless steel push rod with a spherical end provides the load. The G-10 block has a concave top surface to match the spherical end of the push rod. The voltage taps are soldered ~25 mm outside the contact area.
Instruments SCXI-1125 with a SCXI-1325 terminal block, which has a typical noise level of $1 \times 10^{-7}$ V. The voltage tap length is about 75 mm, which is about 25 mm outside the contact area on each side (figure 2(b)).

As-received samples are cut and wiped clean with ethanol and mounted on the sample holder. Then a 24 N load is applied at room temperature to check the centering of the G-10 block under load. This load is maintained during the transportation and cooldown of the probe. For 77 K tests, the sample is immersed in liquid nitrogen. For helium temperature tests, a Cernox temperature sensor is attached to the top of the G-10 bottom plate with GE 7031 varnish. The probe is cooled down to 4.2 K and then allowed to warm up naturally at a typical rate of 10 mK s$^{-1}$. In this case, $R_c$ is measured automatically during the temperature rise by applying $+/-1.00$ A current from a Keithley 2400 bipolar DC current source and measuring the voltage with a Keithley 2010 digital multimeter. The error for all $R_c$ measurements is estimated to be less than 0.1 $\mu\Omega$·cm$^2$.

4. Results and discussions

4.1. Morphology of contacting surfaces

$R_c$ is largely determined by the number of contact asperity spots and their size. Therefore it is very important to characterize the morphology of contacting surfaces. The low-magnification micrograph in figure 3(a) illustrates the surface morphology of our sample. The longitudinal lines on the surface are likely to be scratches made during the conductor spooling process. The bright spots seem to be 10–20 $\mu$m sized knolls on the copper stabilizer layer, and one of them is shown in figure 3(b) at higher magnification. These copper knolls were probably formed during the copper electroplating process. The surface roughness $R_a$, as measured by laser confocal microscopy in a $50 \times 50$ $\mu$m$^2$ area, is 0.196 $\mu$m.

The nominal thickness of our samples is 95 $\mu$m. However, it is expected that the copper stabilizer layer will not be very uniform due to the edge effect in the copper electroplating process. The thickness obviously varies, with three local maximums at the center and both edges of the tape. Consequently, when pressed by the flat G-10 block, the center and edges will take most of the load. This load distribution is confirmed by a pressure-recording film inserted between two contacting surfaces (25.4 × 4.0 mm$^2$ area) under different nominal pressures at room temperature, as shown in figure 5, where the darker (red) color indicates higher pressure. Figures 5(a) and (b) correspond to the test by two types of films with different sensitivity ranges (9.7–49 MPa and 49–128 MPa). It is evident that the pressure is higher at the
center and both edges, which is consistent with the thickness profile shown in figure 4.

In order to observe contacts under pressure directly, a cross-sectional sample is prepared with a 150 MPa nominal pressure that is applied by a pair of G-10 plates compressed by two UNC 8-32 screws tightened with a torque wrench. As shown in figure 6, due to the surface roughness, even at such high pressure at room temperature, only a small fraction of the area (asperity spots) has intimate contact (labeled ‘A’ in figure 6).

5. Contact resistance

A typical $V-I$ curve for a REBCO contact measured under a 2.4 MPa pressure at 77 K is shown in figure 7. It is linear except in the region near the critical current of about 80 A (figure 7(a)). When a linear component, obtained by fitting $V-I$ data below 15 A, is subtracted from raw data, the residual as plotted in figure 7(b) reveals non-linearity above 20 A. For this reason, all $R_c$ values presented in this paper are obtained from linear fits of $V-I$ data below 15 A. High linearity below 15 A also indicates that joule heating at the contact is negligibly small.

$R_c$ as a function of pressure is measured up to 144 MPa, as shown in figure 8. As expected, $R_c$ decreases with increasing pressure. However, it decreases much more slowly than $P^{-1/2}$ (a simulation with $P^{-1/2}$ is also shown in figure 8) and obviously has a non-zero asymptotic level. In fact, $R_c$ versus $P$ data can be fitted well with

$$R_c = \frac{A}{P^{1/2}} + B,$$

where $A = 15.0$ and $B = 25.4$ are the fitting parameters. As a
comparison, a REBCO-to-substrate soldered lap joint prepared using the method described in [25] has a resistivity of 0.95 μΩ·cm² (shown as a horizontal dashed line in figure 8), which is much smaller than the measured $R_c$.

As mentioned above, special care should be taken in analyzing a REBCO-to-substrate contact. Due to the insulating buffer layer, the electrical current must flow from the REBCO to the surrounding edges of one conductor before entering the other conductor. The electrical current distribution is very different from that for a REBCO-to-REBCO contact, and can only be simulated numerically [26]. However, since the resistance of a soldered REBCO-to-substrate joint is only a few per cent of $R_c$, it may be concluded that contact resistance as described by Holm’s theory is dominant.

The $R_c(P)$ curve in figure 8 is significantly flatter than $P^{-1/2}$ or $P^{-1}$, as predicted by equation (3). This discrepancy might be explained as follows. Firstly, the contact copper surface is usually covered with a thin layer of native oxides, which are essentially insulating at 77 K [27, 28]. The thickness of the surface oxides, and whether they are pierced by asperities, depends on the local pressure. Therefore the proportionality between the nominal pressure and the size of the asperities as described by equation (2) is no longer strictly valid. Under increasing load, the increase in size of the asperity spots is hindered by neighboring oxide-covered areas, so $R_c$ decreases much more slowly than in equation (3).

Secondly, in a REBCO-to-substrate contact, the transport current distribution within the copper stabilizer layer is not uniform and might be pressure-dependent. So it is conceivable that the $R_c(P)$ curve deviates from equation (3), which is derived assuming a uniform current distribution outside the immediate vicinity of the contacting surface. Finally, the copper hardness is expected to increase with load and load cycles due to the work hardening at cryogenic temperatures. This effect will also make the $R_c(P)$ curve flatter according to equation (3).

Cyclic load is also applied up to 144 MPa for up to 14 cycles. $R_c$ is measured during load cycle numbers 1, 2, 3 and 14, as shown in figure 9. Small hysteresis is noticeable in $R_c$ for each cycle, where unloading $R_c$ is slightly lower than loading $R_c$, which is indicative of some degree of plastic deformation at the asperities. It is also observed that after the first load cycle the $R_c(P)$ curves can no long be fitted with equation (4). Furthermore, under a given load, $R_c$ increases gradually with the number of load cycles, as shown in figure 10. At 2.4 MPa pressure, $R_c$ seems to level off after only two cycles, while at higher loads $R_c$ is still increasing after 14 cycles. This gradual increase of $R_c$ with the number of load cycles has been observed in NbTi CICC [8], but is not very well understood. Based on the results of this experiment,
we attribute this effect to cryogenic work hardening of copper under cyclic load.

A similar behavior of $R_c$ versus load and load cycles is observed in three other samples tested. However, there is significant variation in $R_c$ from sample to sample. For instance, under 144 MPa pressure $R_c$ spreads from 26 to 60 $\mu\Omega$·cm$^2$ from sample to sample. This appreciable spread is likely due to variations in sample surface morphology and surface chemistry.

Since most of NI REBCO magnets operate at 4.2 K [1–8], measuring $R_c$ at liquid helium temperatures is also important for practical purposes. In addition, the temperature dependence of $R_c$ may shed light on the nature of the contact, as temperature-dependence is material-specific. We measured $R_c$ versus $T$ under a nominal contact pressure of 2.4 MPa. As shown in figure 11, $R_c$ was almost constant below 20 K. Above 20 K, $R_c$ initially increased slowly until it showed a rapid upturn with an onset at $\sim$85 K consistent with a sharp increase in longitudinal resistance at the $T_c$ of REBCO. The $R_c$ versus $T$ curve below 77 K is generally consistent with the behavior of copper resistivity [29]. This implies that the constriction resistance, which is proportional to copper resistivity, made the dominant contribution in the measured $R_c$. However, the ratio of $R_c$ between 77 K and 4.2 K was about 2, as compared to the ratio of 7 measured from the Cu stabilizer peeled-off from similar REBCO conductors. This discrepancy may be explained by assuming a $T$-independent contribution of 25 $\mu\Omega$·cm$^2$. Once this $T$-independent contribution has been subtracted, the remaining $R_c$ has a resistance ratio of 7, which is consistent with the copper resistance ratio.

6. Conclusions

Turn-to-turn contact resistance in a NI REBCO coil is directly related to the coil charging delay and ramp losses. The contact resistivity $R_c$ of SuperPower REBCO samples is measured at 77 K and 4.2 K under a mechanical load of between 2.4 and 144 MPa and for up to 14 load cycles. We find that $R_c$ is in the range between 26 and 100 $\mu\Omega$·cm$^2$ and decreases with load, but gradually increases with load cycles. The $R_c$ versus load and load cycle behavior can be understood using Holm’s electrical contact theory. In subsequent experiments, we will measure the $R_c$ of a REBCO conductor coated with different thin films with the aim of tailoring $R_c$ for different NI magnet design options.
Acknowledgments

We thank Dr Roland Timsit for helpful discussions on interpretation of the results, and Brent Jarvis, Vince Toplosky, Jeremy Levitan, Kolby McDaniel and Deven Heard for assistance in experiments. The NHMFL is supported by NSF through NSF-DMR-1157490 and the State of Florida.

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