Aluminum Strand Coating for Increasing the Interstrand Contact Resistance in Rutherford Type Superconducting Cables

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***Abstract*—The interstrand contact resistance (R_c) in Rutherford type cables for fast cycling superconducting magnets must be sufficiently high in order to limit eddy current losses. The required value for R_c depends on the cable and magnet geometries and on the foreseen cycling rate, but is typically of the order of one $m\Omega$. Such values can be reached with a dedicated strand coating or with a resistive internal cable barrier. As a possible candidate Al strand coatings have been tested. For a Rutherford type inner conductor cable of the Large Hadron Collider (LHC) made of Al coated strands R_c values higher than 500 $\mu\Omega$ are achieved. The native Al_2O_3 oxide layer formed at ambient temperature in air is sufficient to reach this high contact resistance. A 6 h-200°C oxidation heat treatment in air with 100% relative humidity further increases R_C to values above 600 $\mu\Omega$. Due to the high thermal and mechanical stability of Al_2O_3 only a relatively moderate R_c drop of about 40% is obtained during a 190°C heat treatment under 50 MPa pressure (the so-called curing cycle of the coil insulation) subsequent to the 6 h-200°C oxidation heat treatment.**

***Index Terms*—Contact resistance, superconducting cables.**

I. Introduction

THE contact resistance of the crossing strands in Rutherford type cables for high field magnets must be controlled in order to reduce coupling currents between the strands and at the same time allow sufficient current sharing for the superconductor stability [1]. R_c within the cables of the LHC main magnets, as an example, should be between 20 and 100 $\mu\Omega$ at operating conditions. Eddy current effects, i.e. losses and field harmonics, are proportional to dB/dt and, therefore, for future fast cycling magnets R_c values must be strongly increased with respect to the R_c values obtained with the standard LHC cables.

In order to achieve the needed R_c values in the LHC superconducting cables a $Sn_{95\ wt.}Ag_{5\ wt.}$ coating is deposited onto the copper matrix of the strands by a continuous hot dip process. Subsequently the cable made of $Sn_{95wt.}Ag_{5\ wt.}$ coated strands is submitted to a 200°C heat-treatment (HT) in air, lasting typically a few hours [1], [2]. In this case the contact resistance increase is due to the Cu_2O oxide layer that remains on top of a Cu_3Sn intermetallic layer that is formed on the strand during the 200°C HT in air [3], [4].

Unlike most native metal oxides, the air formed Al oxide, Al_2O_3, is a good electrical insulator, whose electrical resistivity is several orders of magnitude higher than for instance that of the native Cu-oxide, which is a semi-conductor. Thus, it should be expected that Al coated strands exhibit a comparatively high contact resistance, even without any high temperature HT in oxidizing atmospheres. Al oxide films also exhibit good mechanical and thermal stability and are widely used for protection against wear and corrosion [5]. In this article we present for the first time R_c measurements on a LHC inner conductor cable made from strands that have been coated with a 0.5 μm thick Al layer. R_c results are compared with those obtained for cables made of strands with various strand coatings that have been previously measured at CERN under similar experimental conditions.

II. Experimental

A. The Samples

The Al coating has been applied onto the Cu matrix of a LHC type 01 Nb-Ti/Cu composite strand with a nominal diameter of 1.065 mm and a length of 40 m. The Al coating is deposited by an electrochemical process. This process is based on metal deposition from an organometallic complex electrolyte, which consists essentially of Al alkyl complexes in a nonaqueous solution. All process steps are performed within a closed unit under inert gas atmosphere, which assures excellent Al coating adhesion to the substrate.

The thickness of the galvano-aluminum coatings can be varied over a large range. The coating thickness on the strands used for the fabrication of Rutherford type cable studied here is 0.5 μm. In order to obtain entirely non porous films, a minimum thickness of about 7 μm is needed. The Vickers hardness reported for a 30 μm thick galvano Al coating is $HV_{0.015} = 20$. The coatings have a very high ductility and no crack formation in the Al due to the plastic deformation during cabling is expected to occur. More information about the galvano Al coatings can be found in reference [6].

Pure Al is a good electrical conductor. By conversion of the Al into the Al oxide Al_2O_3 an insulating layer can be obtained. This can be achieved for instance by oxidation in air or other oxidizing atmospheres at room or high temperatures. For Al coatings that are thick enough, anodic oxidation can be applied to increase the Al_2O_3 layer thickness. The samples used in the

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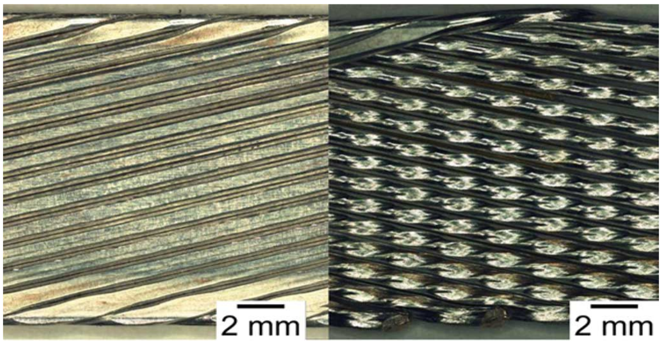

Fig. 1. Inner LHC superconductor cable, consisting of 28 Nb-Ti/Cu strands with a nominal diameter of 1.065 mm. The right image shows the cross contacts inside the cable made of Al coated strands.

present study were either oxidized at room temperature in ambient air, or at 200°C in air with 100% relative humidity.

A LHC inner conductor cable has been fabricated at CERN from the Al coated strands (see Fig. 1). The Rutherford type cable, made out of 28 strands, has a mid thickness of 1.9 mm, a width of 15 mm, a keystone angle of 1.25° and a transposition pitch of about 115 mm. The cable compaction factor is about 90%. Due to the cable key stone angle the cross contact areas increase from the thick cable edge (top) towards the thin edge (bottom).

B. R_c Measurements

Throughout this article the interstrand contact resistance (R_c) is defined as the resistance of one cross-over of two strands in the Rutherford cable. R_c is measured at 4.2 K under a pressure of 50 MPa applied to the broad face of the cable sample. As can be seen in Fig. 1, the interstrand cross contact areas vary across the cable width from about 0.7 mm^2 to 1.5 mm^2 from the thick to the thin cable edge, respectively. The R_c results presented are average values obtained for cross contacts distributed over the whole cable width. R_c measurements have been performed on as-received cable samples and after a 0.5 h-190°C cable HT under 50 MPa pressure. This HT simulates the influence of the coil curing in superconducting magnets on R_c. More details about the R_c measurement method can be found in [2].

In the present study R_c of an inner (01 type) LHC cable has been measured. From previous experience it is known that R_c of (02 type) LHC outer conductor cables, made of 36 strands with a nominal diameter of 0.825 mm, is more than twice the R_c measured for 01 cables with identical coating and oxidation HT. The resistance of adjacent contacts (R_a) cannot be measured with the used experimental set-up. As a rough estimate it may be assumed that R_a is about 8 times higher than R_c [7].

C. Surface Analysis by X-Ray Photoelectron Spectroscopy

The surfaces of the Al coated strands after different HT have been analysed by X-ray Photoelectron Spectroscopy (XPS). The characteristic electrons that are detected by XPS are emitted from the topmost some 10 nm of the surface analysed. In addition to the identification of the surface elements, XPS also yields chemical specificity, provided that photoelectron peak shifts are accurately measured and compensated for sample charging effects.

TABLE I
R_c MEASURED FOR LHC TYPE 01 CABLES MADE OF Al COATED STRANDS. MEASUREMENTS HAVE BEEN PERFORMED ON AS-RECEIVED CABLE SAMPLES AND AFTER A 6 h-200°C HT IN AIR WITH 100% REL. HUMIDITY. EACH HT WAS FOLLOWED BY A SO-CALLED CURING HT (0.5 h-190°C HT UNDER 50 MPa)

No HT	After curing	6 h-200 °C, 100% rel. humidity	After curing
528±265 μΩ	87±53 μΩ (-83%)	640±223 μΩ	377±141μΩ (-41%)

XPS measurements are performed using an ESCA 5400 series instrument from Physical Electronics. For the acquisition of survey and high resolution spectra the PHI model 10–360 spherical capacitor electron spectrometer is operated with a fixed pass energy of 89 eV and 35 eV, respectively. A non-monochromated Mg K_α X-ray source ($hv = 1253.6$ eV) is used to excite photoelectrons. Prior to the measurements, the binding energy (BE) scale has been calibrated using *in-situ* sputter-cleaned Au and Cu samples.

III. RESULTS

A. Contact Resistance Measurement Results

R_c measurements have been performed using cable samples as received after cabling (no HT) and after different 200°C heat treatments. 200°C heat treatments in ordinary laboratory air have been found to have only a minor influence on R_c. Temperatures exceeding 200°C are not compatible with Nb-Ti strands, since they would cause a degradation of the critical superconductor properties. Therefore, a 200°C HT has been performed in air with 100% relative humidity.

The R_c results are summarized in Table I. The standard deviation indicates the scatter of the different R_c measurement results that have been obtained for the different cable samples. During a HT lasting 6 h at 200°C in air with 100% rel. humidity, R_c increases to about 640 $\mu\Omega$, which is about 25% higher than the R_c of the as-received cable. In order to simulate the influence of the so-called curing HT of magnet coils, after each R_c measurement the cable is submitted to a 0.5 h-190°C HT at 50 MPa pressure and afterwards R_c is re-measured again. During the curing HT R_c is reduced by about 40%.

B. Surface Analysis Results

Due to the high $\mathrm{Al_2O_3}$ resistivity the strand sample surface is electrically charged during the measurements and the photoelectron peaks are shifted by about 5 eV. For charge compensation the C 1 s peak position of adventitious carbon is used as a reference.

Survey and Al 2p high resolution photoelectron spectra are presented in Fig. 2 for a strand heat treated at 200°C in air with 100% relative humidity. Some metallic signal is still detected through the Al oxide layer, indicating that the $\mathrm{Al_2O_3}$, thickness does not exceed 10 nm (the attenuation length of the Al 2p photoelectrons is about 2.5 nm [8]).

As can be seen in the high resolution spectrum, the detected Al is mainly in the form of $\mathrm{Al_2O_3}$. Traces of Cu are also detected, indicating some porosity of the coating. A rough esti-

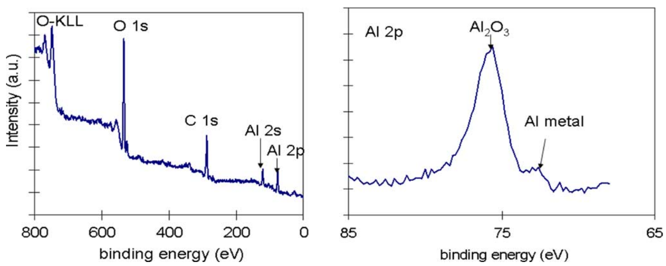

Fig. 2. XPS survey spectrum (left) and Al 2p high resolution spectrum (right) acquired for the Al coated strand extracted from the LHC 01 cable after 6 h-200°C HT in 100% relative humidity.

TABLE II
INTERSTRAND CONTACT RESISTANCE IN TYPE 01 LHC CABLES WITH DIFFERENT COATINGS. THE FOLLOWING OXIDIZING HEAT TREATMENTS IN AIR HAVE BEEN PERFORMED: *5 min-200°C, **30 min-190°C, ***6 h 200°C 100% REL. HUMIDITY

	As received	**After curing**	**HT in air (*,**,***)**	**After HT + curing**
Al	530 μΩ	90 μΩ	640 μΩ ***	380 μΩ
Sn95-Ag5 [2,9]	1.7–30 μΩ	0.5-4.5 μΩ	100-200 μΩ	17–23 μΩ
Bare Cu [2]	80-700 μΩ	0.5-1.6 μΩ	-	-
Ni [2]	320 μΩ	55 μΩ	>300 μΩ **	-
Sn65-Ni35 [1]	65 μΩ	12 μΩ	-	-
Cu55-Sn45 [1]	90 μΩ	2.2 μΩ	600 μΩ *	130 μΩ

mate of the Al_2O_3 oxide thickness can also be obtained by combined electron spectroscopy and sputter depth profiling measurements, assuming that the sputtering speed for Al_2O_3 is identical to that of the reference material Ta_2O_5. An Al_2O_3 thickness of about 9 nm (Ta_2O_5 equivalent) has been measured after a 10 h-200°C HT in ordinary laboratory air.

IV. DISCUSSION AND CONCLUSION

The R_c of Rutherford type cables can be strongly increased when the strands are coated with a thin Al layer instead of the LHC type Sn-Ag layer. The relatively thin Al_2O_3 layer formed in air at ambient temperature is sufficient to achieve a contact resistance above 500 $\mu\Omega$.

200°C heat treatments in air with 100% relative humidity can further increase R_c. The Al_2O_3 thickness after this treatment is about 10 nm. In Table II, R_c values obtained for the Al coated LHC type 01 cable are compared with R_c of type 01 Nb-Ti cables with other coatings that have been measured under similar experimental conditions at CERN. All cable samples were first measured "as received" and after subsequent 0.5 h-190°C HT under a pressure of 50 MPa (so-called curing HT). R_c of some cable samples was also measured after HT in air and again after subsequent 0.5 h-190°C HT under a pressure of 50 MPa.

It can be seen that the Al coated cable exhibits a relatively high R_c and that the curing treatment has a relatively small influence on R_c of the Al coated cable. This can be explained by the high mechanical and thermal stability of Al_2O_3 as compared to other native metal oxides.

R_c of identically treated cables increases with decreasing strand diameter. As an example, for LHC type 02 cables (strand diameter 0.825 mm) it is estimated that R_c is at least twice that of R_c of type 01 cables after identical HT. Thus, for cables made of smaller Al coated strands, the high contact resistance that is needed in order to limit eddy current losses in fast cycling magnets may be provided.

The ductile galvano-aluminum coatings are well adhesive to the Cu strand matrix and have a uniform thickness, which can be controlled in tight tolerances. Unlike other coatings like Cr or Ni that can be used to increase the contact resistance in superconducting cables, Al coatings are very soft, which facilitates the production of Rutherford type cables.

The thermal-electromagnetic stability of a LHC type 01 cable made of Al coated strands against local heat depositions has been tested at the FRESCA test facility at CERN and evaluation of these results is underway.

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