Interstrand Contact Resistance and AC Loss of a 48-strands Nb_3Sn CIC Conductor with a Cr/Cr-oxide Coating

Arend Nijhuis, Herman H. J. ten Kate, *University of Twente, Faculty of Applied Physics, P.O. Box 217, 7500 AE Enschede, The Netherlands*

Victor Pantsyrny, Alexander K. Shikov, *VNIINM, Moscow 123060, Russia*

Marco Santini, *Duralloy AG, Oberflächentechniek, CH-4624 Härkingen, Switzerland*

***Abstract*-- The interstrand contact resistance (R_c) between crossing strands in Cable-In-Conduit Conductors (CICC's) determines the coupling loss and the stability against local disturbances. The surface oxidation, surface roughness and micro-scale sliding of the contact surfaces are key parameters in the R_c. The level of surface oxidation is influenced by manufacturing parameters in the strand and cable production, the plating procedure determining the crystalline structure and by the heat treatment. A new process of making a more stable oxide has been developed and characterised. The Cr coating is actually build up out of two different layers. The first layer is a hard Cr coating, identical to the standard Cr layer previously used. On top of this a layer of black Cr oxide is deposited electrolitically. The coupling loss time constant and R_c are measured on a 48-strands CIC Conductor with this double-coated strand material. The void fraction amounts to 36 % and the strand, cabling and jacketing are identical to those used in the previous chrome vendor comparison action.**

The results, presented in terms of R_c, time constant $n\tau$, and the atomic concentration of oxygen (*acO*) in the peripheral region of the strand, are compared to previous results from single coated strands.

***Index terms*—interstrand contact resistance, chromium oxide coating, cable-in-conduit, ac losses**

I. Introduction

The interstrand contact resistance R_c is a critical parameter for the design of CICC's applied in fusion magnets and magnetic energy storage. The strands in multistage cables are coupled in regular and irregular patterns creating different current loops, which can contribute significantly to the AC losses. The resistance of the strand crossover contacts determines the interstrand coupling loss and must therefore be controlled keep the generated heat below acceptable limits. On the other hand the R_c strongly affects the stability of a cabled conductor by determining the level of current redistribution among strands. Therefore, R_c is not allowed to exceed a certain maximum value, in order to guarantee sufficient margin for current redistribution.

The R_c depends on a variety of factors, but besides the internal strand lay-out, the resistance of the oxidised surface crossover contact mostly causes the dominant contribution to the R_c [1]-[9]. The surface layer properties and in particular the level of oxidation and the crystalline structure are considered to be key parameters in the R_c and so in the stability of CICC's [8,11]. The level of surface oxidation and surface roughness is influenced by manufacturing parameters in the strand and cable production but above all by the strand coating process.

The Nb_3Sn strands are often plated with a Cr layer mostly having a typical thickness of ~2 μm. This is an effective method to avoid inter-metallic diffusion at the strand crossovers of CICC's during the reaction heat treatment and it also acts as an electrical resistance barrier in reducing the interstrand coupling loss [2]-[9].

In a previous study the effect of oxidation on the R_c for a substantial number of Cr plated strands have been examined with Auger (AES) analyses [8]. Non heat-treated strand material was taken from samples used in a study of the effect on AC loss and R_c of different Cr plating vendors with identical Nb_3Sn strand material [4,5]. The surface of the strands taken from the Cr vendor study was analysed with Auger technique. The atomic concentration of oxygen (*acO*) in the surface layer of non-heat treated strand correlated well with the R_c of CICC manufactured with the same strand.

For natural oxidation the oxide growth rate depends on temperature and grain orientation. [8]. Fine-grained polycrystalline oxide thickens most rapidly and can easily reach a thickness of hundreds of nanometers.

Manuscript received September 27, 1999. These investigations are part of NET contract No. 98/479 between the European Union and the University of Twente. A. Nijhuis, +31.53.489.3889, fax +31.53.489.1099, a.nijhuis@tn.utwente.nl.

1051-8223/00$10.00 © 2000 IEEE

Monocrystalline oxide thickens very slowly and reaches a thickness in the order of 10 nm. Using different surface pretreatments or oxidation procedures can change the oxide grain size. In the case a high R_c is desired it would be useful to develop a coating with a larger chromium oxide thickness. The Swiss company Duralloy AG (Härkingen) has developed a process to deposit directly from the electrolytic bath a thick black Cr oxide layer on top of an also electrolytically deposited polycrystalline hard Cr layer which is the standard patented process. The Cr layer on top is amorphous and has a black color. This layer is tested recently for AC loss by Kwasnitza on a 147 strands cable manufactured with NbTi strand [10]. From this test it appeared that the total coupling loss is suppressed to the level of intra-strand coupling loss.

During the conductor heat treatment in vacuum or inert gas, the oxygen at the micro-contacts, diffuses from the contact surface deeper inside the coating (or strand) [9]. Consequently the concentration of oxygen in the contact drops and so the R_c decreases. It is observed that during the heat treatment the R_c may drop by over two orders of magnitude [6]. The cables manufactured from NbTi strand with the double coating technique were not subjected to a heat treatment, possibly affecting the concentration of oxygen at the strand contact surfaces. In order to investigate the stability of this additional amorphous Cr oxide layer against a heat treatment, a CICC is manufactured from Nb_3Sn strands coated with the new Durally double Cr layer.

The results of the analyses of the double Cr layer in terms of R_c, coupling loss and atomic concentration of oxygen in the strand peripheral region is compared to some previously obtained results on other similar conductors as described in Refs. [4,5,8].

It should be mentioned that loading such conductors mechanically or electromagnetically leads to an increase of the R_c during the first several tens of loading cycles. The interstrand contact surfaces interfere by micro-sliding which results into friction and anomalous contact resistance versus force behaviour [8]. Therefore the virgin conductor is eventually subjected to slight bending in order to create some interstrand micro-sliding effects as a simulation of a Lorentz force.

II. CONDUCTOR SAMPLES

The conductor is exactly identical to the ones used in the Cr vendor tests [4,5]. The strands in the previous samples were the same except for the Cr plating, which was applied by different vendors. The main strand and conductor data are summarised in Table I, a more detailed specification can be found in Ref. [4].

The new double coating exists of two layers. The thickness of the first standard process Cr layer varies between 2.0 and 2.5 μm. The thickness of the amorphous chromium oxide layer varies from 1.0 to 1.5 μm.

The samples for coupling loss are straight sections of conductor, cut by electronic erosion, with lengths of 420 mm. The contact resistances are investigated on 560 mm long samples: twelve strands at one end are untwisted and attached to a support. After the heat treatment, the current leads and voltage taps are soldered to the strands. The strands are selected in order to measure the contact resistance within a triplet (first cable stage) and between strands belonging to succeeding cable stages.

TABLE I. STRAND AND CONDUCTORS DATA

Strand manufacturer	VNIIM (Bochvar)
Strand diameter (incl. Cr layer)	0.813 mm
Twist pitch	9 mm
Strand coupling loss time constant, nτ	1.2 ms
Diffusion barrier	Ta + Nb
Cable configuration	3 x 4 x 4
Number of strands	48
Cable pitches	27 / 55 / 95 mm
Void fraction	36.2 %

III. EXPERIMENTAL RESULTS

A. *Interstrand Resistance*

The resistance between a selected pair of strands, R_c, (μΩm) is derived from the measured voltage, divided by the sample current and multiplied by the jacketed sample length. The R_c results are independent of the sample current in the range below 100 A, far below I_c.

The R_c is slightly increased at about 0.2 T when the background magnetic field is raised from zero to 2 T. This is due to the critical field of the Nb foil buffering the Ta diffusion barrier in the strand. The inner diffusion barrier is made of Ta and the outer is of Nb and is superconducting up to ~0.2 T, but the critical current is low (Fig. 1). The R_c has been measured also before the heat treatment (2Cr-nonHT) in order to estimate its effect on R_c. In Fig. 2 can be seen that at a current of 10 A, there are still superconducting paths inside the strands, even at a background field of 2 T. The Nb barrier is not expected to provide a superconducting path at fields higher than 0.2 T. The superconducting state at 2 T can be explained by the presence of microscopic areas of NbTi located inside the Nb filaments, which are formed during the manufacturing process.

After the heat treatment, the R_c is measured again in the virgin state (2Cr-HT) and thereupon the sample is subjected to 10 times a bending strain of 0.4 % in opposite directions (2Cr-HT-bend).

Table II shows a summary of the average values of the

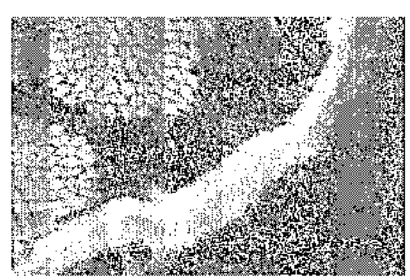

Fig. 1. Part of the cross-sectional area of the Bochvar strand showing filament bundles, the inner Ta and the outer Nb barrier.

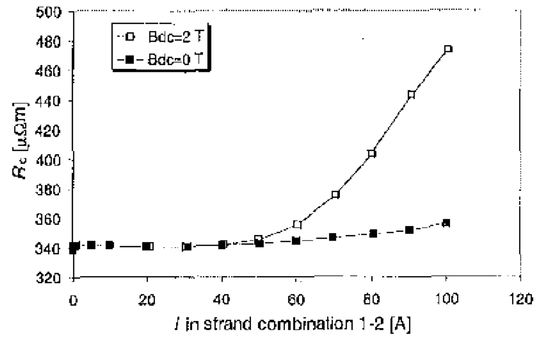

Fig. 2. The R_c versus current with zero and 2 T DC background field.

measured R_c's for various strands from different cabling stages. The results from Ref. [4] (bare copper and standard single Cr layer) are included for a direct comparison. The average R_c of the virgin conductor with new double Cr oxide layer amounts to 4 μΩm. The R_c is a weak function of the cable stages and the background field. On average, the first stage interstrand resistance is about 400 times larger than for the standard single Cr layer.

TABLE II. SUMMARY OF AVERAGED R_C VALUES

Conductor type	R_c [μΩm] 1st stage		2nd stage		3rd stage	
B_{dc}=	0 T	1 T	0 T	1 T	0 T	1 T
2Cr-nonHT	310	-	320	-	290	-
2Cr-HT-bend	59.7	59.7	52.3	-	52.6	-
2Cr-HT	4.09	4.13	5.77	5.81	5.83	5.88
Standard 1Cr	$9\cdot10^{-3}$	$13\cdot10^{-3}$	$12\cdot10^{-3}$	$17\cdot10^{-3}$	$15\cdot10^{-3}$	$21\cdot10^{-3}$
Bare copper	$0.36\cdot10^{-3}$	$2.5\cdot10^{-3}$	$0.52\cdot10^{-3}$	$3\cdot10^{-3}$	$0.54\cdot10^{-3}$	$3.9\cdot10^{-3}$

B. Coupling Loss

The coupling loss can be represented by the energy loss per cycle versus frequency:

$$Q_{cpl} = \frac{\pi \cdot B_a^2 \cdot \omega \cdot n\tau}{\mu_0} \qquad [\mathrm{J/m^3 \cdot cycle}]. \qquad (1)$$

The applied field is $B_a sin(2\pi ft)$. The $n\tau$ value can be used for AC loss calculations of magnets operating at low ramp rates. The loss measurements are performed in a calorimeter. A sinusoidal field of amplitude B_a=0.4 T transverse to the conductor axis, is applied with or without a background DC field of 1 T, generated by a dipole magnet.

To avoid non-linearity of the loss curve (screening effects), the frequency is is kept below 0.1 Hz. The results are presented in Fig. 3.

The initial slope of the loss curves (giving the nτ value) is calculated by linear regression of the measured loss points. The interfilament coupling loss constant is estimated to be about 1.2 ms [4]. The nτ value for the conductor with double Cr layer is 4.2 ms. For the standard compared with the "Cr vendor study" [4] because the strand, cabling and jacketing are identical for all conductors. Optically mostly dark but some light tinted areas can be distinguished on the surface of the non-heat-treated strand. Auger analyses is carried out on both a dark and a light area and the results are presented in Fig. 4. The total amount of oxygen (*acO*) is expressed as the summation of the atomic concentration along the depth (Δ*d*). The *acO* at the dark areas appears to be one order of magnitude higher than in the lighter areas. On the heat-treated strand no color tones can be clearly distinguished and the *acO* appears to be higher and deeper than in the non-heat-treated strand. During the heat treatment the oven was flushed with high purity argon gas.

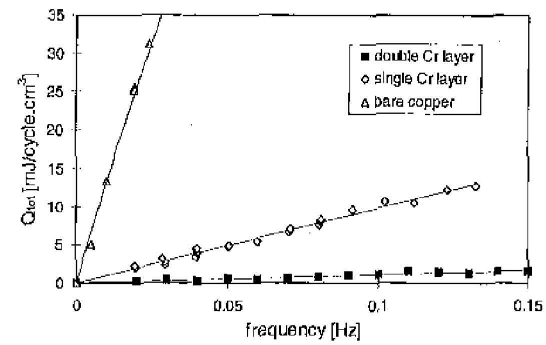

Fig. 3. Total loss minus the hysteresis loss versus the frequency of the applied AC field, B_a=400 mT and B_{dc}=0 T.

The oxygen depth profiles of all samples of the Cr vendor series have been gathered in Fig. 5. Sample RF-1 has bare copper strands showing a low atomic concentration of oxygen as compared to the average of the Cr coated specimen. Most of the coatings are oxidised by natural

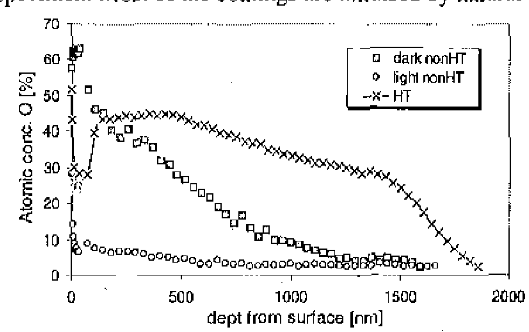

Fig. 4. Profiles of the atomic concentration of oxygen of: a dark and a light spot on a non heat treated strand and of a heat treated strand.

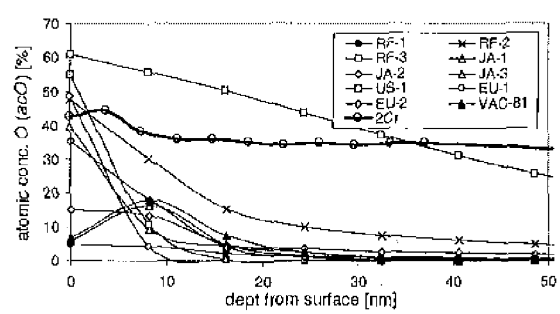

Fig. 5. Profiles atomic concentration oxygen of all samples of the Cr vendor series with Nb_3Sn strand compared to the Cr/Cr-oxide layer, 2Cr (lines are drawn as a guide to the eye).

way except RF-3 being artificially oxidised by using a special coating process. In Fig.6 the R_c is plotted versus the atomic concentration acO (oxygen) on a logarithmic scale. In general small Cr scales with fine grains and an amorphous polycrystalline structure result into a high R_c. Fig. 7 shows two SEM micrographs of the polycrystalline surface.

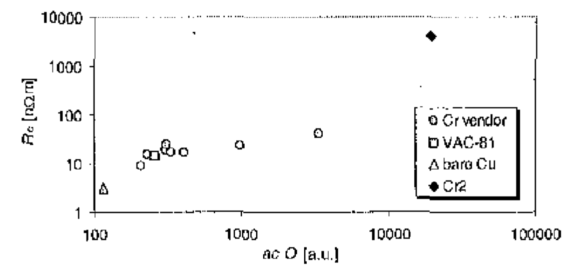

Fig. 6. The interstrand contact resistance R_c versus the atomic concentration of oxygen, acO.

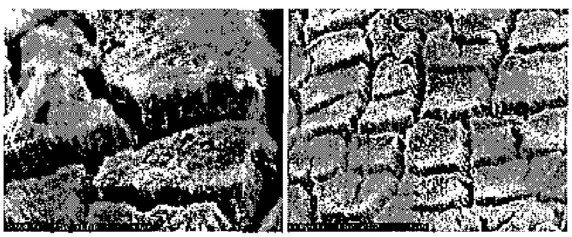

Fig. 7. SEM micrographs of the oxidised surface (12000 and 5000 times magnification).

IV. Discussion

The R_c in the virgin state after the heat treatment of the new (double) Cr/Cr-oxide layer is large enough to reduce the cable interstrand coupling loss ($n\tau$=4.2 ms) down to about the level of the intrafilament loss ($n\tau$=1.2 ms). The average R_c of the virgin conductor with new double Cr oxide layer amounts to 4 μΩm and is about 400 times larger than for the standard single Cr layer (virgin state).

After applying some artificial strand micro-sliding by way of bending the conductor, to simulate the effect of a pulsed Lorentz force, the R_c increases by more than one order of magnitude (60 μΩm). Without a heat treatment, which approaches the practical case for Cr/Cr-oxide coated NbTi CICC's, the R_c reaches a level of 300 μΩm. The final value of the R_c after several magnet loading cycles is presumably between the 60 and 300 μΩm [7,8]. The Cr-oxide layer is stable regarding the heat treatment.

The values found with the R_c measurements correlate well with the results obtained with the AC loss measurements and the determination of the atomic concentration of oxygen. However, it appears that the relation between $n\tau$ and R_c is not simply reciprocal.

The oxide layer on Cr coated strands, which mostly determines the R_c, has a thickness of less than ~10 nm. The double Cr layer with a very thick Cr-oxide layer is suggested to withstand a possible deterioration due to wearing of the resistive surface layer during the life time of a magnet.

V. Conclusions

The average R_c of the virgin 48-strands conductor with the new (double) Cr/Cr-oxide strand coating amounts to 4 μΩm and the $n\tau$ is about 4 ms (void fraction 36 %). The R_c in the virgin state of the CICC is ~400 times larger than for the standard single Cr layer.

The R_c after cyclic electromagnetic loading is expected to be between the 60 and 300 μΩm.

The Cr-oxide withstands the heat treatment and appears to be stable.

The new double Cr/Cr-oxide coating technique offers a very low interstrand coupling loss although the ability of current redistribution may be seriously affected.

VI. References.

[1] Nijhuis, A., ten Kate, H.H.J., Bruzzone, P., Botture, L., 'Parametric study on coupling loss in sub-size ITER Nb_3Sn cabled specimen', *IEEE Trans. on Magn.*, vol. 32, no.:4, July 1996, pp. 2743-2746.

[2] Mower, T. M. and Y. Iwasa, 'Experimental investigation of AC losses in cabled super conductors', *Cryogenics*, vol. 26, 1986, pp. 281.

[3] Dolgosheev, P.L, G.G. Svalov, V.E. Sytnikov, I.V. Podyablonskaya, 'Transversal conductivity in conductors of cable in conduit type', IEEE Trans. on Appl Superc., Vol. 5, No. 2, 1995, pp. 749-752.

[4] Bruzzone, P., Nijhuis, A., ten Kate, H.H.J., 'Effect of Cr plating on the coupling current loss in Cable-in-Conduit conductors', *Proc. ICEC-16*, Elsevier 1997, pp. 1243.

[5] Nijhuis, A., H.H.J. ten Kate, and P. Bruzzone, 'Effect of Cr plating on the coupling current loss in Cable-in-Conduit conductors', *Proc. EUCAS'97*, Applied Superconductivity, IOP Publishing Ltd., 1997, pp. 921-924.

[6] Bruzzone, P., Nijhuis, A., ten Kate, H.H.J., 'Contact resistance and coupling loss in CIC of Cr-plated strands', *MT-15 Proceedings.*, Science Press, Beijing, China, 1998, pp. 1295-1298.

[7] Nijhuis, A., N.H.W. Noordman and H.H.J. ten Kate, N. Mitchell and P. Bruzzone, 'Electromagnetic and Mechanical Characterisation of ITER CS-MC Conductors Affected by Transverse Cyclic Loading, Part 2: Interstrand Contact Resistances', *IEEE Trans. on Supercond.*, vol. 9, no.:2, June 1999, pp. 754-757.

[8] Nijhuis, A. and H.H.J. ten Kate, 'Surface oxidation and interstrand contact resistance of Cr-coated Nb_3Sn and bare NbTi strands in CICC's', presented at the ICMC'99, Montreal, Canada, July 1999.

[9] Kimura, A., T. Shintomi, A. Terashima, S. KawaBata, F. Sumiyoshi, 'Interstrand Coupling Losses of Rutherford Cables in Various Curing Conditions', *Cryogenics, Vol.: 36*, 1996, pp. 681-690.

[10 Kwasnitza, K. and St. Clerc., 'Coupling current loss reduction in cable-in-conduit superconductors by thick chromium oxide coating', *Cryogenics*, vol. 38, 3,1998, pp. 305-308.

[11]Amemiya, N., 'Influence of current re-distribution on minimum quench energy of superconducting triplex cable against local disturbance', *Cryogenics vol. 38*, (1998), pp. 559-568.