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Title: Inter-strand Resistance of Prototype SIS300 Dipole Cable

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Inter-strand Resistance of Prototype SIS300 dipole cable

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This report summarizes the measurements of adjacent inter-strand resistance, R_A in a prototype SIS300 cable. Cable samples were pre-reacted in air to oxidize the surface of the strand, which were then insulated and assembled in 6-stacks. These stacks were cured at 195C for various applied pressures. Measurements show that with pre-reactions of several hours at 200C, the R_A of the cable can be adjusted to a value ~ 200 μΩ.

Introduction

GSI plans to use a cored Rutherford NbTi cable for the SIS300 dipole, and a prototype cable **A0345B** was fabricated by Alstom using strands similar to that used for the outer layer of the LHC dipole magnets. The cable has 36 strands of diameter 0.825 mm which are coated with Sn-4%Ag solder. The average coating thickness quoted by Alstom is 0.34 μm. The core material is 304-SS and is 25 μm thick. Past measurements have shown that the inter-strand coupling losses of cored cables are dominated by the adjacent inter-strand resistance R_A [1]. It is also well known that the contact resistance of strands which are coated with Sn-4%Ag solder can be controlled by the solder layer thickness and reacting the cable at 190-200 ^{o}C to oxidize the strand surface [2]. In fact this technique has been used to control the cross-over resistance $R_{C,}$ in the cable for LHC dipole magnets. In this report we focus on measurements of R_A for the cable which are pre-annealed at 200C and then cured under various conditions.

Sample Preparation

Initially a 5 m section of the cable A0345B was annealed at 200 C for 8 hours in a large furnace with circulating air. Subsequently 2 m long sections were annealed for 2 hrs and 4 hrs in a smaller oven without the air being circulated. It is quite easy to see visually the effect of the time duration for annealing on the oxidation of the strand surface.

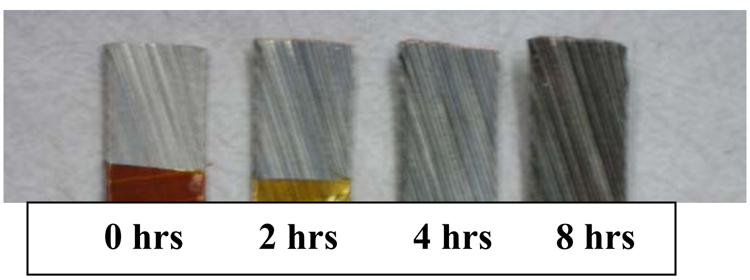

Fig. 1 Cable surface after annealing at 200C for 2, 4 and 8 hrs.

The temperature profiles during the annealing are shown in Fig. 2. In hind-sight it would appear that the annealing duration for the second cycle was not very precise as the oven door was opened after the cable had reached the desired temperature. In future greater care has to be taken to ensure the duration and temperature both of which affects the inter-strand resistance.

After annealing, the cable was insulated by hand as follows: 50% overlap wrap using 25 μm Kapton™, followed by a 50% overlap wrap using Apical™ with adhesive (PIXEO® BP55) on the outer surface [3]. The Apical™ polyimide film thickness was 57 μm. The adhesive thickness is ~ 4-6 μm.

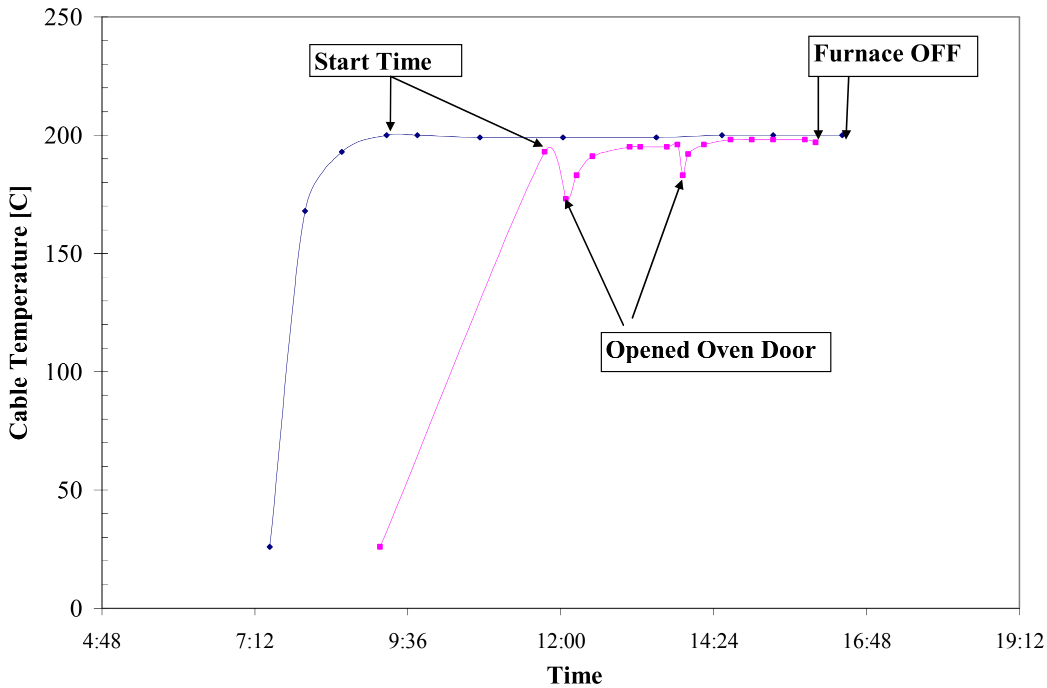

Fig. 2 Annealing cycles for the cable samples

6-Stack Fabrication

The insulated cable was cut into sections and stacked with the minor-edge keystone side alternated to provide a rectangular package. The third and fourth layer pieces are longer than the others to facilitate attaching the current leads and the voltage taps. The stack is then assembled in a curing fixture shown in Fig. 3. Vertical pressure can be applied to the cable during curing with a hydraulic press, and it can also be heated to the desired temperature. Since the cable lay-pitch is 100 mm, the active length of compression in the fixture was also 100 mm.

Initial information from GSI indicated that the adhesive bonds adjacent film layers at 190 C under a relatively low pressure of 7 MPa. A first test of curing a pair of samples under this condition did not bond at all. Following that we tried two cure-cycles of the RHIC type where the bonding temperature was 195C instead of 225C. At 7 and 15 MPa for 10 min, the cable stack bonded very poorly. Eventually we tried one in which the stack was reacted at 195C for 30 min under a pressure of 78 MPa. In this case the samples bonded together very well. Hence for the time and temperature we picked 195C for 30 min and used a pressure of 17, 39 and 78 MPa. At 17 MPa, the bonding of the cable was not very good, meaning it was easy to de-laminate the layers with minimal force. No precise measurement of bonding strength was made.

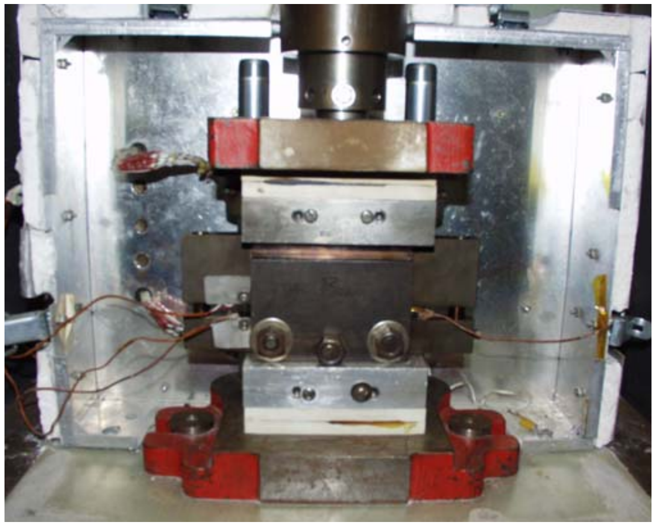

Fig. 3 Curing Fixture

For the measurements described below, a RHIC-type cycle was used:

1. At 20 C apply 15 MPa
2. 20 C to 135 C ramp up in 50 min under 15 MPa,
3. At 135 C, apply pressure of 76 MPa and hold 30 min
4. Release pressure and ramp up to 195 C in 30 min.
5. Apply (17, 38 or 76) MPa and hold for 30 min.
6. Release pressure and ramp down to 135 C in 30 min.
7. Re-apply 76 MPa and hold for 30 min.
8. Cool down under 76 MPa.

A typical cure cycle is shown in Fig. 4.

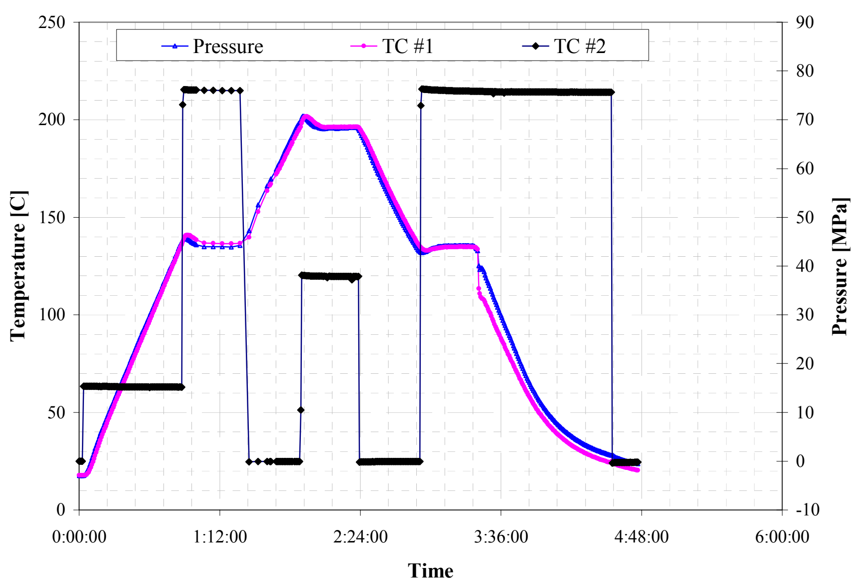

Fig. 4 Record of a cure cycle.

We should note that the high temperature set-point varied somewhat from run to run. This has to be taken into account when interpreting the results. During the ramp up to and down from 135 C to 195C, the cable surface continues to oxidize. This is different from the standard LHC dipole magnet cure cycle where the high pre-load on the coil is not relaxed during the curing cycle.

R_A Measurements

After the 6-stacks are prepared, the sample is assembled in the test fixture and pre-loaded (over a length of 100 mm) at room temperature to 54 MPa. The third and fourth layers are instrumented with current leads at strand 1 and 19, and voltage taps are connected to strands 2, 4, 6, 8, 10, 12, 14 and 16. A picture of the sample in the test fixture is shown in Fig. 5.

Fig. 5 Test Fixture with a 6-stack cable sample.

Since the cross-over resistance R_C is high due to the SS-core, the voltage profile is expected to be a straight line. This is the ideal case for uniform R_A. However, previous experience shows that this is not the case, with the R_A being dominated by the contact at the cable edge [2]. Hence, the voltage profile differs from the idealized case. However, we use the following to calculate R_A:

$$R_A = 8(V/I)(Ls/L_p)$$

where V is the voltage drop between taps 1 and 19, I is the current, Ls is the sample length (defined by the sample length under compression during curing) and Lp is the cable pitch length, which is 100 mm.
A typical voltage profile is shown below in Fig. 6.

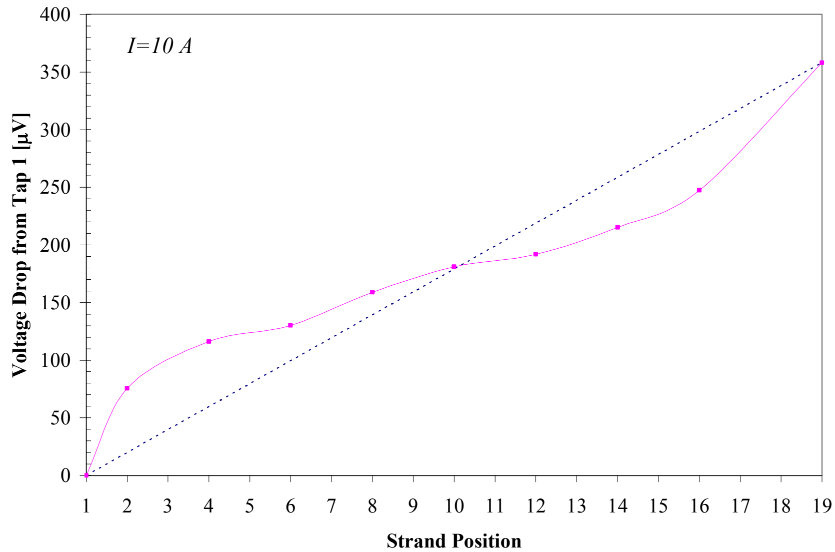

Fig. 6 Voltage profile measurement.

Table I

Run #	Pre-anneal		Temp	Pressure	R_A (μΩ)			
	Temp, C	Time, h	°C	MPa	Sample1	Sample 2	Average	Range
2419	200	8	198	76	309	293	301	16
2422	200	8	198	39	310	332	321	22
2423	As-Cabled	0	196	39	33.7	30.5	32.1	3.2
2426	200	4	192	39	127	131	129	3.7
2429	200	8	196	17	177	188	183	11
2430	200	2	193	39	100	94	97	6
2434	As-Cabled	0.01			14		14	
2434	200	8			147		147	
2438	200	2			48		48	
2438	200	4			62		62	
2454	200	2	195	39	92	121	106.5	29
2461	200	4	196	38	134	139	136.5	5
2462	200	8	188	15	239	287	263	48

Table I is a summary of the R_A results of samples taken from the cable **A0345B**. Except for the non-cured samples, each stack yields two results of R_A. The temperature and pressure are that recorded at the high temperature bonding stage. The temperature is given as the average of the temperatures at either ends of the sample.

Discussion

The cable as fabricated has a fairly low adjacent resistance of 14 μΩ. When pre-annealed at 200C, it increases with duration of anneal, however, there is insufficient data to predict R_A. One will have to measure many samples to get a statistical average of R_A that reflects the average coating thickness of the strands. LHC experience has shown that to control inter-strand resistance, the coating thickness has to be well controlled to be able to get predictable results. What is also evident from the data is that the cure cycle followed in these experiments always increases R_A. This comes from the fact that there is no pressure during the ramp from 135C to 195C, an application of pressure after the sample reaches the bonding temperature and also releasing it during the ramp down to 135C. These steps promote further re-oxidation. Results can be very different if a different temperature/pressure cycle is used to cure the magnet coils.

The bonding of the insulation seems to require at least a pressure greater than 17 MPa. Also the duration has to be greater than 10 min. This can be compared to the LHC dipole coil curing cycle where the pressure of 120 MPa is applied throughout the cure cycle. To see the effect of the pre-anneal duration on R_A, the data for curing at 37 MPa are compared in Fig. 7. The data show that to achieve a R_A of ~ 200 μΩ, this cable needs to be pre-annealed for 6 hours. This duration would depend on the average Sn-Ag coating thickness, so would be different for another cable. The dependence of R_A on coating thickness needs to be established.

These preliminary experiments show the following:

1. Using the Apical™ film with the adhesive, a bonding temperature of 195C and pressure of 35 MPa-70 MPa is recommended for duration of 30 min.
2. Based on the coating thickness, the cable should be pre-annealed at 200C for duration of several hours to increase the R_A to ~ 100 μΩ in the uncured state.
3. A cure cycle that has been tried here can then increase the inter-strand resistance to the desired level of 200 μΩ.

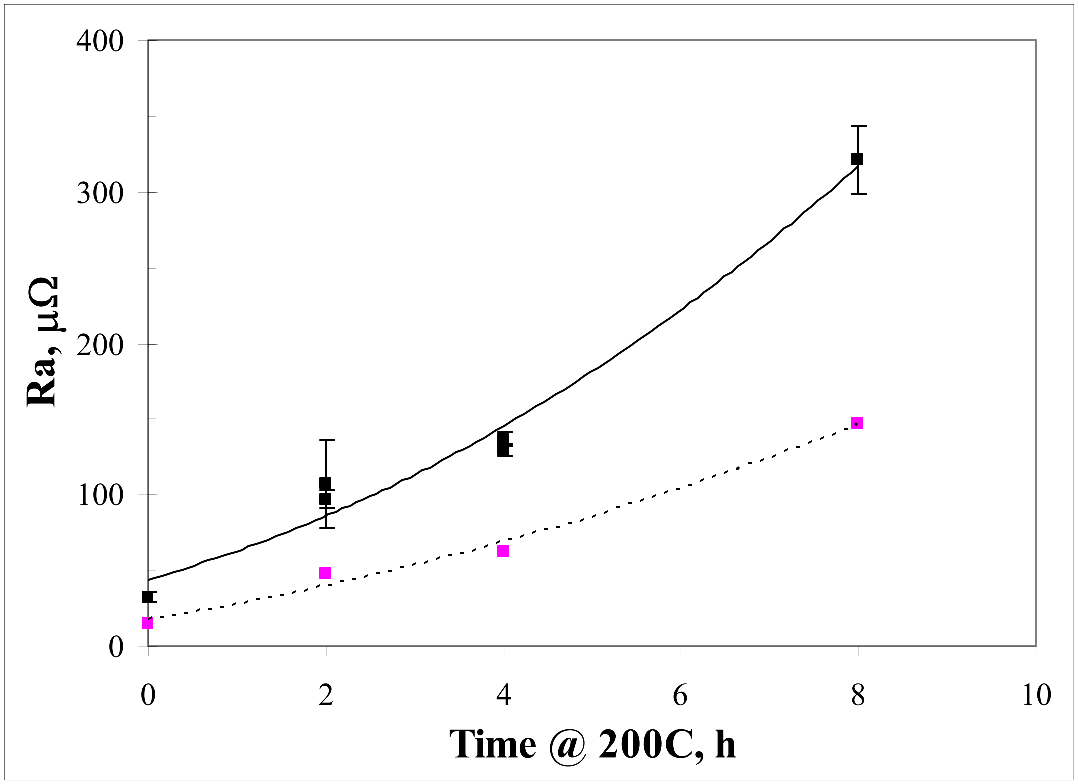

Fig. 7 RA for samples pre-annealed for different durations at 200C. For comparison, the data for samples which were not cured are also shown.

References

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3. http://www.kanekahightech.com/feature.html