EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
CERN - ACCELERATORS AND TECHNOLOGY SECTOR

CERN-ATS-2011-067

ELECTRICAL INTERCONNECTION OF SUPERCONDUCTING STRANDS BY ELECTROLYTIC CU DEPOSITION

C. Scheuerlein[1], D. Schoerling[1], S. Heck[1], A. Ams[2]
1 CERN, Geneva, Switzerland
2 Technische Universität Bergakademie Freiberg, Germany

Abstract

The electrical interconnection of Nb_3Sn/Cu strands is a key issue for the construction of superconducting devices such as Nb3Sn based insertion devices for third generation light sources. As an alternative connection method for brittle superconducting strands like Nb_3Sn/Cu, test joints have been produced by electrolytic deposition of Cu. The resistance of first test joints produced by electrolytic Cu deposition with a strand overlap length of 3 cm at 4.2 K is about 10 nΩ, similar to the resistance measured for joints produced by soft soldering with the same strand overlap length. Interconnection by electrolytic Cu deposition can be done before or after the reaction heat treatment, and it produces a mechanically strong connection. Simulations have been performed with Comsol multiphysics in order to estimate the influence of deposit imperfections on the joint resistance, and to compare the resistance of joints made with different techniques.

Presented at : Applied Superconductivity Conference 2010 (ASC'2010)
1-6 August 2010, Washington, USA

Geneva, Switzerland

August 2011

Electrical interconnection of superconducting strands by electrolytic Cu deposition

C. Scheuerlein, D. Schoerling, S. Heck, A. Ams

***Abstract*— The electrical interconnection of Nb_3Sn/Cu strands is a key issue for the construction of superconducting devices such as Nb_3Sn based insertion devices for third generation light sources. As an alternative connection method for brittle superconducting strands like Nb_3Sn/Cu, test joints have been produced by electrolytic deposition of Cu. The resistance of first test joints produced by electrolytic Cu deposition with a strand overlap length of 3 cm at 4.2 K is about 10 nΩ, similar to the resistance measured for joints produced by soft soldering with the same strand overlap length. Interconnection by electrolytic Cu deposition can be done before or after the reaction heat treatment, and it produces a mechanically strong connection. Simulations have been performed with Comsol multiphysics in order to estimate the influence of deposit imperfections on the joint resistance, and to compare the resistance of joints made with different techniques.**

***Index Terms*—superconducting wires and filaments, Nb_3Sn, joint resistance**

I. INTRODUCTION

THE electrical interconnection of superconducting strands and cables is a crucial part in the manufacturing process of superconducting magnets.

Ultrasonic (US) welding is the state-of-the-art technology for the electrical interconnection of ductile Nb-Ti/Cu composite superconducting strands. About 35 000 joints with resistances below 10 nΩ have been routinely achieved during the construction of the Large Hadron Collider (LHC) [1]. Such a low joint resistance and high mechanical strength can be obtained with a strand overlap length as short as 1 cm.

Soft soldering is another technique commonly used for the electrical interconnection of low T_c superconducting strands with a Cu matrix. Due to the low solubility of Ag in Sn, the Sn96Ag4 solder alloy has practically the same electrical resistance as pure Sn, and it is the solder which has the lowest resistivity of typically used solders [2]. The resistivity of the Sn96Ag4 solder at 4.2 K is only about 10 times higher than that of high purity Cu with a residual resistivity ratio (RRR) of 200. Lap joints with low resistance and high strength can be produced by soft soldering, when the strand overlap length is somewhat increased with respect to that of US welded joints.

As compared to the ductile Nb-Ti/Cu alloy conductors, the interconnection of Nb_3Sn/Cu strands is more difficult. Soft soldering before reaction is not possible since the solder would diffuse into the strand matrix during the reaction heat treatment at typically 700 °C. Special care has to be taken for soft soldering after reaction, because the fragile A15 phase is easily damaged when the strand is subjected to mechanical stresses.

An example of electrical interconnection of brittle Nb_3Sn/Cu strands that is today routinely achieved is the strand connection on critical current measurement barrels. The strand length that is soldered to the Cu cylinders on either side of the barrel is typically 200 mm, which assures very low joint resistance.

Lap joints of Nb_3Sn/Cu strands are notoriously difficult to make. Nb_3Sn/Cu lap joints are for instance a key issue for Nb_3Sn based insertion devices for third generation light sources. There is an increasing interest in these Nb_3Sn superconducting insertion devices as they may provide the means to generate hard x-ray light with high brilliance.

The joint specifications are set by the heat load from the electrical power dissipated in the resistive Nb_3Sn/Cu joints and the mechanical strength of the joints. The cooling of the insertion devices installed in light sources is usually achieved by cryocoolers, which provide very limited cooling power at 4.2 K, and therefore low joint resistances are mandatory.

Horizontal racetrack wiggler magnets, as they are developed for the Compact Linear Collider Study are another example where many Nb_3Sn/Cu lap joints are required. A two meter long wiggler magnet with a period length of 50 mm requires more than 160 joints and it is of paramount importance to be able to produce reliable and repeatedly each of these Nb_3Sn/Cu joints.

In order to exclude Nb_3Sn/Cu strand damage, either a connection method that can be performed prior to the reaction is needed, or a well reproducible and reliable interconnection procedure has to be applied that does not harm the brittle conductor. Here we describe first tests of lap joints produced by electrolytic Cu deposition. The joints have been characterized by optical metallography and the joint resistance has been measured with a dedicated set-up at the CERN Cryolab, which measures the current decay time in a superconducting test loop [3].

II. LAP JOINTS MADE BY ELECTROLYTIC CU DEPOSITION

Two Internal Tin Nb_3Sn/Cu strands of the Restack Rod Process (RRP) design [4] with a nominal diameter of 0.8 mm have been interconnected by electrolytic deposition of Cu with an overlap length of 50 mm. A study for finding optimum deposition parameters using DC and pulse plating is ongoing. The joints shown here have been produced by pulse plating. The nominal twist pitch length of the RRP strand is 12 mm. A cross section of the reacted RRP strand is shown in Fig. 1. It

Manuscript received 1 August 2010

C. Scheuerlein, D. Schörling and S. Heck are with CERN, CH-1211 Geneva 23, Switzerland.

A. Ams is with Technische Universität Bergakademie Freiberg, Germany.

can be seen that the thickness of the Nb-Ta barriers is roughly 0.5 µm, and locally less than 0.1 µm.

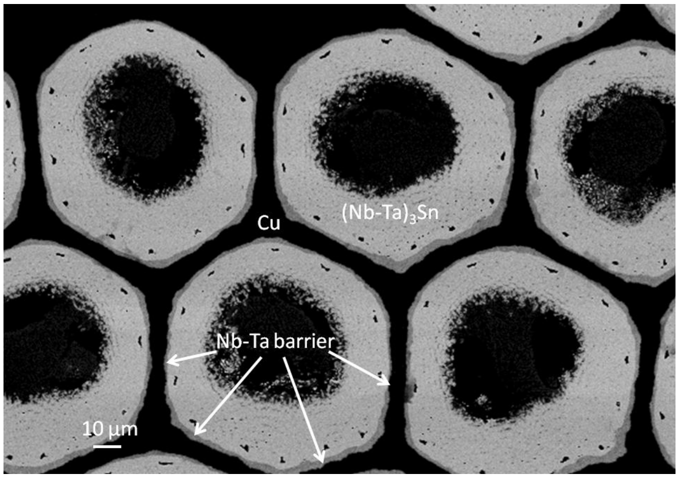

Fig. 1. Backscatter Electron Scanning Electron Microscope image of sub-element cross section in RRP strand after 17 h-695 °C treatment.

A metallographic cross section of the joint is shown in Fig. 2. Through deposition of an about 1.2 mm thick Cu layer intimate contact between both strands is achieved over the entire cross section, except in the center part, where a gap of approximately 0.6 mm length is present between the two strands. The minimum distance between the superconducting filaments in the opposing strands is about 0.4 mm and the width of the gap between both strands is 0.6 mm.

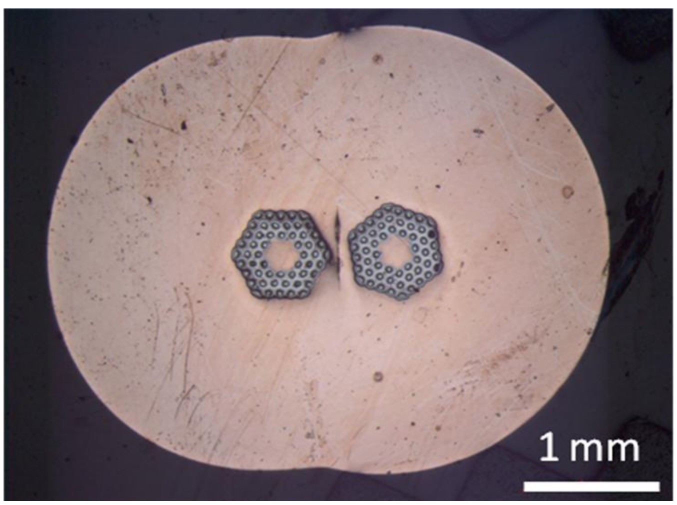

Fig. 2. Metallographic cross section of an un-reacted Nb_3Sn/Cu lap joint produced by electrolytic deposition of a 1.2 mm-thick Cu layer on top of two Nb_3Sn/Cu RRP strands (Ø=0.8 mm).

During a 695 °C heat treatment the Vickers hardness of the Cu deposit changes from $HV_{2.0}$=120±2.7 to $HV_{2.0}$=33.6±1.5. The Cu annealing is very likely accompanied by a strong increase of the RRR.

First resistance measurements have been performed with a test loop made of a Nb-Ti/Cu strand (see Fig. 3) that was joined at both ends by electrolytic Cu deposition. A Nb-Ti/Cu test loop has been used for the ease of resistance measurements.

From the measured decay constant of 60 seconds and the loop inductance of 610 nH, a resistance of 10 nΩ at 4.2 K has been determined for the joint produced by electrolytic deposition of a 1.1 mm thick Cu layer with a strand overlap length of 3 cm.

Fig. 3. Nb-Ti/Cu test loop for the measurement of the joint resistance. The joint has been produced by electrolytic Cu deposition.

This joint resistance has been achieved despite the comparatively large gap width of about 2.3 mm remaining between both strands (see optical micrograph in Fig. 4).

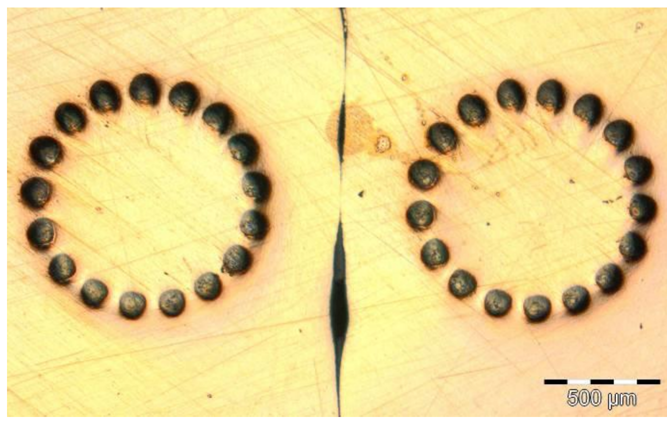

Fig. 4. Metallographic cross section through a Nb-Ti/Cu lap joint produced by electrolytic deposition of a 1.1 mm Cu layer on top of tow Nb-Ti/Cu strands (Ø=1.6 mm). A gap with a width of about 2.3 mm remained between the opposing strands. The minimum distance between the superconducting filaments is about 0.5 mm.

III. JOINT RESISTANCE SIMULATIONS

Simulations of joint resistances have been performed with the Comsol Multiphysics software in order to estimate the influence of different deposit imperfections on the joint resistance, and to compare the resistances achievable with joints produced by different methods. For all simulations a Cu RRR of 100 has been assumed. The resistance of the RRP strand Nb-Ta diffusion barriers has been neglected.

A Resistance of lap joints by electrolytic Cu deposition

The first test joints made by electrolytic Cu deposition that are presented here have gaps between the opposing strands. These imperfections restrict the current flow and, therefore, cause an increased joint resistance. The influence of the gap size on the resistance has been simulated and is shown in Fig. 5 for a joint produced by electrolytic deposition of a 1.2 mm-thick Cu layer on top of 0.8 mm-diameter RRP strands. The resistance that can be obtained in the best case (no gap) with 1 cm strand overlap is about 6 nΩ.

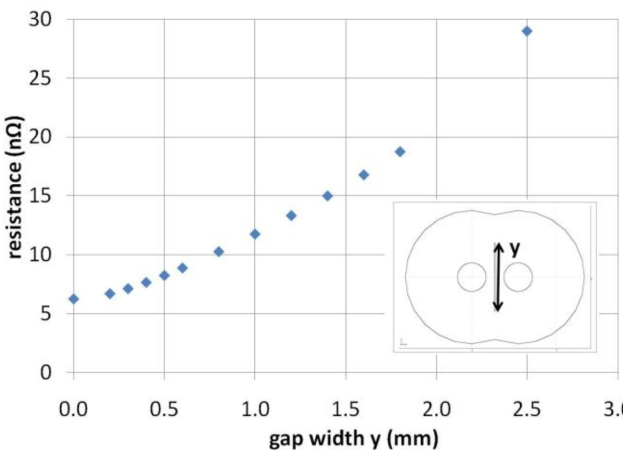

Fig. 5. Lap joint resistance at 4.2 K as a function of the gap width between two RRP strands (Ø=0.8 mm) on which a 1.2 mm-thick Cu layer has been deposited. Simulation results are normalized to a strand overlap length of 1 cm.

The influence of the Cu deposit thickness on the joint resistance at 4.2 K is presented in Fig. 6. It can be seen that increasing the deposit thickness above 1 mm does not have a strong influence on the resistance of a defect free joint.

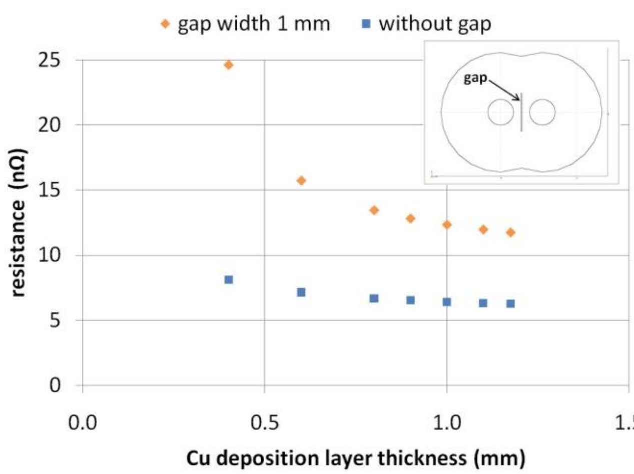

Fig. 6. Resistance at 4.2 K of the RRP strand (Ø=0.8 mm) lap joint as a function of the deposited Cu layer thickness. Simulations have been performed for a defect free joint and a joint with a 1 mm-wide gap between the strands. Results are normalized to a strand overlap length of 1 cm.

The simulated resistance for the lap joint produced by electrolytic Cu deposition onto Ø=1.6 mm Nb-Ti/Cu strands (see Fig. 3 and Fig. 4) is 18 nΩ (with a 2.3 mm wide gap between the opposing strands). The simulation result for the same joint without defect is 6 nΩ.

B Resistance of US welded and soft soldered lap joints

As can be seen in the metallographic cross section shown in Fig. 7, US welding can produce lap joints without any porosity visible in the optical micrograph. A low joint resistance of about 3 nΩ at 4.2 K has been measured for the US welded joint with 1 cm strand overlap. The simulated resistance at 4.2 K for the same joint is 8 nΩ per cm strand overlap length.

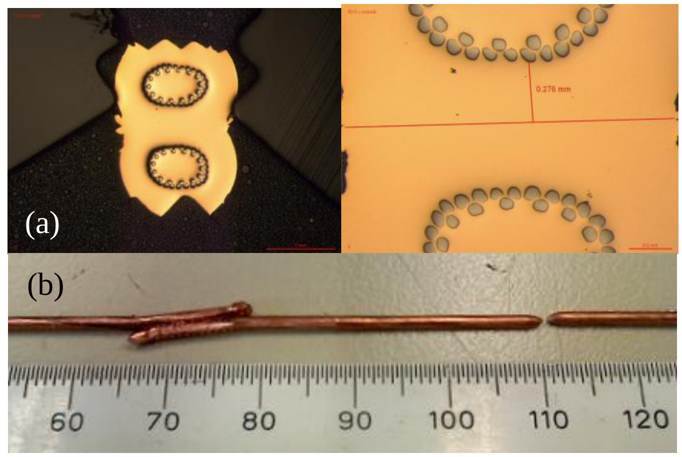

Fig. 7. (a) Metallographic cross section of US welded lap joint of Nb-Ti/Cu strands (Ø=1.6 mm). The strand to strand contact width and the minimum distance between the opposing superconducting filaments are 1.7 mm and 0.53 mm, respectively. (b) US welded joint after tensile test at RT. The joint strength exceeds the strength of a single strand (618±5.6 N).

Due to the plastic deformation of the initially round strand during the US welding process, a comparatively large contact area can be formed, and the distance between the superconducting filaments of the opposing strands is reduced simultaneously. Therefore, US welded joints can have comparatively low resistances. Simulation results for the influence of the contact width on the joint resistance are summarized in Fig. 8. An increase in the contact width in the range 0.68 to 1.7 mm that is caused by a transverse compression of the strands causes a reduction of the minimum distance between the superconducting filaments in the opposing strands from 0.93 to 0.53 mm. The combination of both effects has a strong influence on the joint resistance.

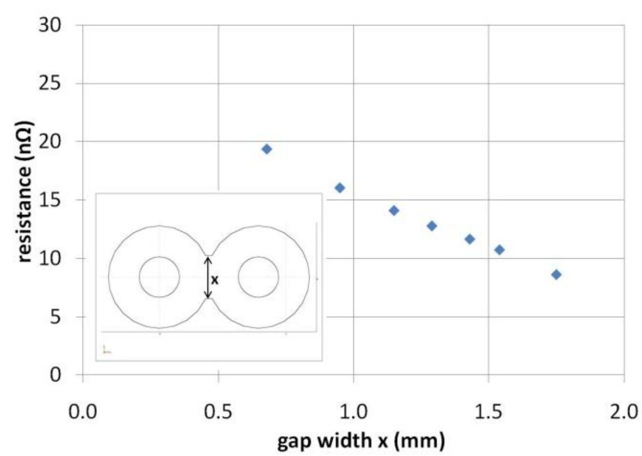

Fig. 8. US welded lap joint resistance as a function of contact width between the two initially round Nb-Ti/Cu strands (Ø=1.6 mm). Simulation results are normalized to a strand overlap length of 1 cm.

Simulations indicate that the resistance of lap joints made of round strands produced by soft soldering with a Sn96Ag4 solder, is roughly twice the resistance of an US welded joint with the same overlap length (see Table 1). The influence of the plastic deformation of the Cu matrix during the US welding process on the Cu RRR has not been determined, and is therefore a main uncertainty in the simulations of the joint resistance.

TABLE 1 Comparison between simulated resistance for lap joints made of Nb-Ti/Cu strands (Ø=1.6 mm) by electrolytic Cu deposition, soft soldering and US welding (at 4.2 K, normalized to 1 cm overlap length, assuming a Cu RRR=100, *1.1 mm deposit thickness, ** Sn96Ag4 resistivity=1.05 nΩ m).

Electrolytic Cu	Soldered	US welded
18 nΩ*	19 nΩ**	8 nΩ

IV. Discussion and Conclusion

Experimental and simulation results show that of the three techniques compared here, US welding can produce joints with the lowest resistance. Because of the strong plastic strand deformation involved, US welding can only be used for the electrical interconnection of ductile superconductors.

Both, soft soldering and electrolytic Cu deposition can be used for connecting brittle superconductors like Nb_3Sn/Cu. An important advantage of the interconnection by electrolytic Cu deposition is that it can be done with the ductile precursor strand, thus avoiding any mechanical straining of the brittle A15 phase.

The Cu deposit can also provide a mechanical reinforcement of the joint, preventing strand damage under high Lorentz forces. Adding additional Cu to a single strand may however increase the axial Nb_3Sn pre-compression during cool down to 4.2 K due to the thermal contraction mismatch between Cu and Nb and Nb_3Sn, which may cause some critical current reduction in the joint [5]. However, since in accelerator magnets joints are usually placed in low field areas, there is sufficient critical current margin.

The main disadvantage of the electrolytic deposition process is the comparatively long deposition duration in the order of one hour, which limits the application of this technique to installations that require not more than some hundreds of joints. Before application of electrolytic Cu deposition it has to be excluded that the use of corrosive electrolytes can cause any corrosion problem during the entire life time of the device.

The deposition process needs to be further optimized in order to avoid or at least minimize gaps between the strands that constrict the current flow. More tests are also needed to determine optimum process parameters for different strand diameters and joints with different geometries, and in order to proof the reproducibility of the process.

For the simulations it has been assumed that the resistance of the diffusion barriers in the Nb_3Sn/strands can be neglected. It can be seen in Fig. 1 that the Nb-Ta barrier thickness in the RRP strand is about 0.5 µm, and locally less than 0.1 µm. Therefore, it is assumed that the Nb-Ta barrier resistance on the overall joint resistance is relatively small. Other Nb_3Sn strand types have several µm-thick diffusion barriers, which resistance can have a strong influence on the joint resistance. In bronze route strands the resistance of the bronze matrix has to be considered as well.

When the barrier resistance can be neglected, the resistance of an Internal Tin Nb_3Sn/Cu lap joint is determined by the bulk resistance of the Cu between the superconducting filaments, the constriction resistance in case of porosity or other constrictions of the current flow, and contact resistances. In case of soft soldering the resistance of the typically 50-100 µm-thick solder layer has to be taken into account as well, while the resistance of the roughly 1 µΩ-thick intermetallics is comparatively small [6].

Simulations predict that by defect free electrolytic Cu deposition with a strand overlap length of 6 cm, joints with resistances in the order of 1 nΩ can be achieved with the RRP Nb_3Sn/Cu strand shown in Fig. 1, assuming a Cu RRR of 100. The exact RRR of the electrolytic deposit remains to be measured.

Acknowledgements

We are grateful to M. Malabaila, CERN/TE-VSC for the electrolytic Cu depositions, to S. Prunet, CERN/TE-CRG for joint resistance measurements, to L. Favier and M. Pozzobon, CERN/TE-MSC, for production of the soldered and US welded connections and to A. Gerardin, CERN/EN-MME for metallographic characterization of the soldered and US welded samples.

References

[1] J. Ph. Tock, D. Bozzini, F. Laurent, S. Russenschuck, B. Skoczen, "Electro-Mechanical Aspects of the Interconnection of the LHC Superconducting Corrector Magnets", CERN, LHC Project Report 724, 2004.

[2] F. Heringhaus, T.A. Painter, "Magnetoresistance of selected Sn- and Pb-based solders at 4.2 K", *Materials Letters* vol. 57, pp. 787– 793, 2002

[3] R. Herzog, D. Hagedorn, "Inductive method to measure very small joint resistances of superconducting wires", *17th International Cryogenic Engineering Conference*, Bournemouth, UK, 1988, pp. 495-498, IOP, Bristol, 1998

[4] J. A. Parrell, Y. Zhang, M.B. Field, P. Cisek, S. Hong, "High Field Nb3Sn Conductor Development at Oxford Superconducting Technology", *IEEE Trans. Appl. Supercon.* vol. 13, no. 2, pp. 3470-3473, 2003

[5] C. Scheuerlein, U. Stuhr, L. Thilly, "In-situ neutron diffraction under tensile loading of powder-in-tube Cu/Nb_3Sn composite wires: effect of reaction heat treatment on texture, internal stress state and load transfer", *Appl. Phys. Lett.*, vol. 91, no. 4, 042503, 2007

[6] C. Scheuerlein, Ph. Gasser, P. Jacob, D. Leroy, L. Oberli, M. Taborelli, "The effect of CuSn intermetallics on the interstrand contact resistance in LHC superconducting cables", *J. Appl. Phys*. vol. 97, no. 3, 2005