EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
CERN - ACCELERATORS AND TECHNOLOGY SECTOR

CERN-ATS-2012-040

13 kA Superconducting Busbars Manufacturing Process

R. Principe, P. Fessia, E. Fornasiere
CERN, Geneva, Switzerland

Abstract

In the LHC, the superconducting Main Bending magnets and Quadrupole magnets are series-connected electrically in different excitation circuits by means of superconducting busbars, carrying a maximum current of 13 kA. These superconducting busbars consist of a superconducting Rutherford cable thermally and electrically coupled to a copper section all along the length. The function of the copper section is essentially to provide an alternative path for the magnet current in case of resistive transition. The production of these components was originally outsourced. The decision to import the technology at CERN led to a global re-engineering of the standard process. Although based on the procedures adopted during the LHC construction, a few modifications and improvements have been implemented, profiting of the experience gained in the last few years. This document details the manufacturing process of the 13 kA busbars as it is actually performed at CERN, emphasizing the new solutions adopted during the first months of production.

CERN-ATS-2012-040
20/02/2012

Presented at the 22nd International Conference on Magnet Technology (MT-22)
12-16 September 2011, Marseille, France

Geneva, Switzerland

February 2012

13 kA Superconducting Busbars Manufacturing Process

Rosario Principe, Paolo Fessia, Elvis Fornasiere

Abstract—In the LHC, the superconducting Main Bending magnets and Quadrupole magnets are series-connected electrically in different excitation circuits by means of superconducting busbars, carrying a maximum current of 13 kA. These superconducting busbars consist of a superconducting Rutherford cable thermally and electrically coupled to a copper section all along the length. The function of the copper section is essentially to provide an alternative path for the magnet current in case of resistive transition. The production of these components was originally outsourced. The decision to import the technology at CERN led to a global re-engineering of the standard process. Although based on the procedures adopted during the LHC construction, a few modifications and improvements have been implemented, profiting of the experience gained in the last few years. This document details the manufacturing process of the 13 kA busbars as it is actually performed at CERN, emphasizing the new solutions adopted during the first months of production.

Index Terms — 13 kA busbar manufacturing, tin-silver eutectic.

I. INTRODUCTION

INSIDE the cold mass of an LHC superconducting magnet, three sets of 13 kA superconducting busbars are present: one set for the dipole excitation, one for the focusing quadrupoles and one for the defocusing quadrupoles. In the LHC tunnel, they are connected to the corresponding sets of the neighboring cold masses. All these sets of busbars are immersed in superfluid helium.

II. BUSBAR MANUFACTURING

The busbar is made of a superconducting cable coupled to a copper section along the length and stabilized by the means of a Sn-Ag eutectic alloy.

The superconducting cable is the same Nb-Ti cable used for the outer coil layer of the main LHC dipoles and the quadrupoles.

The copper used for the hollow profile, is a typical oxygen free electronic standard, corresponding to oxygen content below 5 ppm. A high temperature annealing in a protective atmosphere is also performed to remove all oil traces from the section inner surface in view of the superconducting cable soldering. This final annealing treatment offers the advantage

of increasing the Residual Resistance Ratio (RRR) of the copper section. The LHC standard requires $RRR \geq 100$.

A single busbar can measure up to 17 meters and the total length of the 13 kA circuit in the LHC is close to 150 km. The busbars are submitted to temperature variations in the order of 300 K. The variations in the length generated by the temperature variation are compensated by lyra-shaped thermal compensation joints hereafter referred to as lyras. These lyras are designed in such a way as not to transfer any mechanical stress to the busbars once the machine is cold.

The first production step consists of inserting the standard Nb-Ti superconducting cable into the hollow copper profile while it is straight. The superconducting cable is sensitive to temperature; therefore the copper profile has been previously submitted to all the hard soldering and machining operations that might be harmful to the Nb-Ti strands.

Once the superconducting cable is inserted, the whole assembly undergoes bending and twisting operations, which are required to comply with the geometrical design.

Afterwards the correctly formed busbar is heated and filled with a Sn-Ag eutectic solder in order to ensure both thermal and electrical contact between the superconducting cable and the internal surface of the hollow copper profile. Finally the busbars are individually insulated with two layers of polyimide tape and a layer of fiberglass epoxy tape cured at 160 °C. The process is completed with the insertion of the busbars inside fiberglass protection profiles, ready to be tested and installed in the cold mass.

The LHC series busbar manufacturing process has been largely described in the literature [1] and will not be represented in this document.

III. NEW PROCESS REQUIREMENTS

The first LHC busbar facility was conceived for large scale production: depending on the busbar type, up to 2000 units were manufactured. Nowadays the CERN facility is foreseen for the production of spare busbars for the LHC and busbars for the new projects. Therefore the quantity per busbar type is smaller, while the installation must be flexible enough to produce a large number of different models, without major modifications of the process.

The convective technology adopted in the new process for the busbar heating, provide superior flexibility with respect to the geometry, if compared with the technology previously in use. Furthermore, the first convection oven could be made available by modifying existing CERN equipment. Recycling available tooling represented a clear advantage in terms of budget and schedule. Fig. 1 shows the convection oven originally used for the curing of the LHC cold bore tubes

Manuscript received 5 September 2011.

Rosario Principe, Paolo Fessia, Elvis Fornasiere, European Organization for Nuclear Research, CERN, Geneva 23, 1211 Geneva, Switzerland (phone: +41-22-76-73291; e-mail: Rosario.Principe@cern.ch).

insulation, which has been adapted to the new production requirements.

Fig. 1. Image of the 18 m convective oven for the cold bore tubes polymerization converted to the busbar production.

With the use of the convective oven, the Sn-Ag filling process had to be revised. In order to realize a suitable contact between the superconducting cable and the internal surface of the hollow copper profile, most of the related tooling had to be modified: the injection process and its control system, the injection and extraction devices and many other accessories like end-caps, busbar plugs, etc. Finally a relevant training period has been necessary to have an adequate understanding of all standard operations and technical results.

IV. SUPERCONDUCTING CABLE SOLDERING

The stabilization of the Nb-Ti superconducting cable inside the hollow copper profile is obtained by filling the gap between the cable and the hollow section with metallic filler. A filling factor of at least 95% in the busbar is needed in order to ensure a good electrical contact between the superconducting cable and copper profile in case of resistive transition. Such a filling also contributes to the overall mechanical stability of the busbar. Before inserting the superconducting cable, two holes are drilled at the extremities of the copper profile in order to connect it to the injection and extraction devices. At this stage the injection vessel is filled with an adequate amount of metallic filler. The quantity depends on the busbar dimensions and normally goes from 5 to 15 kg. The extraction device must be empty.

A. The eutectic alloy

The metallic filler is a Sn-Ag eutectic alloy, 96.5% tin and 3.5% silver, which has been chosen for its melting point of 221 °C. This value is “sufficiently low” (under 250 °C) not to alter the properties of the superconducting cable during the injection and “sufficiently high” not to be affected by the temperature during the polymerization (higher than 160 °C). The solder also presents favorable electrical and mechanical characteristics at low temperature and in a radioactive environment [4].

B. The solder flux

Before insertion in the hollow profile, the superconducting

cable and the copper are treated with a solder flux, in order to remove the oxides and promote an appropriate surface wetting. Fig. 2 represents a micrographic image of a busbar section at the interface between the Sn-Ag alloy and the copper profile in the case of a busbar which has not been treated with a flux. The absence of fluxing drastically reduces the contact between the Sn-Ag alloy and the copper surface. In Fig. 3 is represented the case of a busbar, which has been properly treated before injection. In this case the intermetallic compounds are correctly formed.

Fig. 2. Micrographic image of a busbar section at the interface between the Sn-Ag alloy and the copper profile. Case of a busbar which has not been treated with a flux, before filling with the Sn-Ag alloy. The black area between Cu and Sn-Ag alloy shows the absence of intermetallic (picture provided by the CERN Materials and Metrology section [3]).

Fig. 3. Micrographic image of a busbar section at the interface between the Sn-Ag alloy and the copper profile. Case of a busbar treated with a Kester 135 flux before filling with Sn-Ag alloy. A good contact between Sn-Ag and Cu can be noticed (picture provided by the CERN Materials and Metrology section [3]).

Nowadays the products in use are typical high purity rosin based fluxes. These fluxes are designed for “no-clean” technology: the small amount of residuals after soldering may be left without risk of corrosion. Furthermore, the flux viscosity remains reasonably constant around 250 °C, avoiding perturbations during the Sn-Ag injection. Moreover the presence of the flux strongly contributes to increase the

fluidity of the liquid alloy during the filling.

C. The end-caps

In order to prevent a liquid solder leakage at the extremities of the busbars, new solutions have been investigated to replace the existing water coolers originally foreseen during the design phase, or the sealing methods in use during the production of the busbars for LHC.

Several solutions have been developed and tested. The model which has been selected, see Fig. 4, combines technical efficiency with installation and operation simplicity, not requiring any external regulation in temperature.

Fig. 4. Illustration of the end-cap installed on the extremity of the copper profile during the busbar injection process. The metallic extension, which includes the Ni-Ti cable exceeding the copper profile, allows an appropriate evacuation of the residual gases and a complete filling of the busbar extremity.

The metallic extension including the superconducting cable on the left of the end-cap body allows an appropriate evacuation of the residual gases and a complete filling of the busbar extremity, see Fig. 5.

Fig. 5. Detail of a set of busbars produced at CERN. The picture shows the quality of the Sn-Ag filling at the extremity of the busbar after the injection process.

D. The configuration at the injection

Once the end-caps have been installed, the busbar is positioned inside the oven and connected to the injection and extraction devices by the means of heating metallic hoses,

following the scheme shown in Fig. 6.

The injection and extraction devices consist of stainless steel vessels positioned on a balance, in order to allow a real-time follow up and control of the injection process. The vessels are heated with standard electric resistors and appropriately insulated. The injection vessel is connected to a pressurized argon bottle. The extraction device is connected to a membrane vacuum pump.

Fig. 6. The injection scheme representing the copper profile positioned inside the filling oven, protected by the end-caps at the extremities and connected to the injection and extraction vessels.

Temperature sensors are positioned all along the busbars and at the injection and extraction in order to ensure a stable and homogeneous temperature between 245 °C and 260 °C during the process.

E. Lateral positioning of the busbar

The copper bar is positioned laterally in the oven, lying on its short edge, in order to decrease the size of the micro-bubbles produced by the residual gas.

After degassing, a number of micro-bubbles cannot be evacuated by the liquid metal during the Sn-Ag injection and remains in the copper bar. These micro-bubbles concentrate on top of the liquid stream at the copper section, degrading the quality of the electrical and mechanical contact between the Sn-Ag alloy and the copper.

When the copper profile is positioned on its short edge, the micro-bubble surface which reduces the contact between the filler and the copper is smaller, while the section opposed to the fluid stream is bigger, as shown in Fig. 7.

Fig. 7. The lateral positioning of the busbar during the injection process eases the micro-bubbles evacuation and reduces the surface interfering with the contact between the copper and the Sn-Ag for the residual gas.

F. The tin-silver filling process

The injection process starts once the temperature level is stable, which is achieved gradually and synchronously. The operating temperature must be high enough to ensure the efficient flow of the metallic filler during casting. A temperature above melting point of the solder is required; however it is important not to exceed a critical temperature of 260 °C, where the flux viscosity starts to change rapidly and contribute to the deterioration of the stream properties.

The operating temperature should be kept stable and homogeneous between 245 °C and 260 °C. Experience shows that a difference of 5 °C along the chain can strongly degrade the filling quality. The temperature control is a critical aspect of the process.

During the temperature ramp, the flux in the copper section is activated, producing gases which must be removed. The degassing process consists of reducing the pressure level in the busbar by a few tenths of kPa by the means of a vacuum pump connected to the extraction vessel. A bad circulation of the liquid solder with an increasing injection time, contribute to degrade the intermetallic and provoke locally cracks and failures, see Fig. 8.

When the filler has reached the extraction vessel, the vacuum pump can be stopped. The cycle is then maintained at a constant temperature for few minutes, to enable the filler level in the extraction and injection vessels to stabilize. The cool down phase is achieved by cooling from the centre to the extremities of the busbar. A cooling rate of some 10 °C per minute has proven to be satisfactory.

Fig. 8. Micrographic image of a busbar section at the interface between the Sn-Ag alloy and the copper profile. Case of a bad circulation of the SnAg liquid phase during the injection process. Several cracks and failures can be noticed (picture provided by the Materials and Metrology section [3]).

V. CONCLUSIONS

Nowadays the Busbar Facility is an integral part of the Large Magnet Factory at CERN and, even though the development phase is on-going, the facility is fully operational. Fig. 9 represents the first busbar set produced in 2011 for the cryostat prototype of the LHC warm collider.

Fig. 9. Image of the Busbar set QTC 01 produced at CERN and ready to be installed in the QTC prototype.

Converting and adapting existing tooling to the new process requirement, and to be faced with all technical aspects related to the facility construction and busbar production, has provided a deeper understanding of the process complexity. This know-how is now available in house and represents a considerable contribution for the future projects and new developments.

ACKNOWLEDGMENT

Special gratitude is addressed to L. Rossi for the constant attention to the project, to the CERN Engineering & Insulation Vacuum section and to the Materials and Metrology section for the active support and competence and to the CERN busbar team for the personal engagement and constructive attitude.

REFERENCES

- [1] The High Current Busbars of the LHC from Conception to Manufacture, L. Belova, M. Egorychev, BINP, J-L Perinet-Marquet, C. Urpin, CERN, RuPAC 2006, Novosibirsk, Russia.
- [2] Risk Analysis: Inventory of the Singular Points and First Risk Assessment for the 13 kA Circuits, R. Principe, S. Izquierdo, P. Fessia et al. CERN EDMS 1139345.
- [3] Observations MEB et analyses EDS de busbars, M. Scheubel, CERN EDMS 1146212.
- [4] The RRR of the Cu components of the LHC main bus bar splices, S. Heck., C. Scheuerlein, P. Fessia, R. Principe, CERN EDMS 1057918.