CARE NED Work Package 3

Report on Alstom-MSA Production and Characterization

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Abstract

In the framework of the CARE-NED project CERN placed a contract with Alstom-MSA in France to develop a Nb_3Sn strand with a diameter of 1.25 mm to reach a high critical current J_c = 1636 A at 12 T and 4.2 K and to produce Nb_3Sn strand for a 580 m long superconducting cable made of 40 strands. This report describes the final strand production with the PIT technology and the characterization of the strand.

Acknowledgements

We acknowledge the support of the European Community-Research Infrastructure Activity under the FP6 "Structuring the European Research Area" programme (CARE, contract number RII3-CT-2003-506395)

1. Introduction

In the framework of the CARE-NED project CERN placed a contract with Alstom-MSA in France to develop a Nb_3Sn strand with a diameter of 1.25 mm to reach a high critical current J_c = 1636 A at 12 T and 4.2 K (corresponding to a non-copper critical current density J_c = 3000 A/mm^2 at 12 T and 4.2 K) and to produce Nb_3Sn strand for a 580 m long superconducting cable made of 40 strands.

The fabrication process of Alstom-MSA by the internal tin diffusion technology (IT) is based on a double stacking billet design in which the strand is fabricated in two steps: (1) fabrication of sub-elements in which a large number of Nb rods embedded in a copper matrix are arranged in concentric circles around a tin core, and (2) assembly of the sub-elements drawn to restacking dimensions in a billet which will be drawn by cold drawing to the required strand diameter.

Following CERN request, Alstom-MSA has started a development program made up of two R&D steps (referred to as Step 1 and Step 2) followed by the final production. The Step 1 was devoted to a Taguchi-type plan to study the influence of relevant parameters on workability and critical current density, while Step 2 was devoted to the influence of alloy composition on the performances and to optimize the initial strand design.

Alstom-MSA has followed two different roads for the fabrication of the sub-elements either by cold drawing (Road 1) or by warm extrusion (Road 2). During Step 1, only cold drawing was used by Alstom-MSA, both for the fabrication of the sub-elements and for the final billets. During Step 2, Alstom-MSA has continued the development to fabricate the sub-elements by cold drawing but also by warm extrusion. Alstom-MSA successfully manufactured a sub-element suitable for NED conductor by both processing roads. During this part of the conductor development program Alstom-MSA produced all the sub-elements with pure Nb filaments. Alstom-MSA has launched the final production of the NED conductor following both roads with NbTa filaments.

2. Results of the development program

2.1 Results achieved during Step 1

For Step 1, Alstom-MSA has launched into fabrication five different types of strands following Road 1 with the aim to determine the optimum design for the sub-elements in terms of workability and critical current. All the sub-element billets have suffered from a too large number of breakages due to a lack of cohesion between the different components. Alstom-MSA was able to draw to the diameter for restacking only one type of sub-element with a central Sn core. Alstom-MSA has investigated the possible reasons for breakages and has decided to produce a sub-element with a modified filament layout and with an improved manufacturing process. A final billet making use of this new sub-element has been assembled with 78 sub-elements and has been drawn to 1.25 mm and 0.8 mm with only few breakages showing a very good workability. At a diameter of 0.8 mm, the sub-elements of the strand had a diameter of 50 µm, as requested for the NED strand. Strand samples were sent by CERN to LASA-Milano for critical current measurements. A critical current value of 740 A was measured at 12 T and 4.2 K on the samples which corresponds to a non-copper critical current density J_c = 1500 A/mm^2, thereby doubling the value achieved by Alstom-MSA before starting the NED program. The non-copper critical current density achieved with this strand corresponds to the expected value calculated by Alstom-MSA as this sub-element has a large local Cu to Nb ratio. A sound sub-element design has been achieved by Alstom-MSA during the Step 1 with a manufacturing process following road 1. This design has been used for Step 2 keeping a very similar filament layout but increasing the amount of Nb and decreasing the amount of Cu in order to reach the non-copper critical current density requested in the NED specification.

2.2 Results achieved during Step 2.
The development plan for Step 2 was discussed in detail between CERN and Alstom-MSA. The decision was taken in 2006 to launch into fabrication two billets with two different sub-element designs following road 1. In parallel, Alstom-MSA has also launched into fabrication a sub-element billet following a warm extrusion process. It was also decided to go step by step to achieve 50 μm sub-element diameter starting with a final billet with 78 sub-elements and going to 114 sub-elements for the second final billet before to launch into production a billet with 246 sub-elements. Alstom-MSA has focused the development on the manufacturing process of the final billet.

For Step 2 following road 1, Alstom-MSA produced in 2007 a first final stage billet with 78 sub-elements (B1/14508) giving an effective filament diameter of 90 μm. This billet suffered from too many breakages which started already at a diameter of 15 mm. A lack of cohesion between the Nb barrier and the Cu can was the main reason for the breakages. This wire achieved a non-copper critical current density J_c = 1880 A/mm^2 at 4.2 K and 12 T, a value lower than expected. CERN performed a Scanning Electron Microscopy analysis to find an explanation. The average Sn content measured in the A15 phase (~ 24.3 at. %) is close to the stoichiometry as expected. On the other hand, the SEM examinations done both by CERN and by Alstom-MSA have shown the presence of big Nb_3Sn grains (300 nm to 500 nm) covering at least 40 % of the Nb_3Sn area. A significant amount of Nb filaments was not completely reacted, contributing also to the low critical current density. A piece length of the billet B1/14508 was drawn to a diameter of 0.825 mm in order to improve the microstructure and to decrease the sub-element diameter. The critical current density has increased up to J_c = 2090 A/mm^2 at 4.2 K and 12 T, which is quite good for a binary alloy. After the fabrication of the billet B1/14508, Alstom-MSA has taken several actions to improve the cohesion between the Nb barrier and the Cu can. These actions have been implemented for all the billets launched in production.

A second final stage billet (B1/21204) was produced with 114 sub-elements in order to reach step by step a sub-element diameter of 50 μm. Alstom-MSA encountered drawing problems with this billet starting already at a diameter of 36 mm. The reason for the breakages was identified. The layout of the sub-elements in the final stage billet is the main cause for the breakages. The wire drawn from the second final stage billet reached a critical current J_c = 1780 A/mm^2 at 4.2 K and 12 T, a value which is even lower than the value obtained with the billet B1/14508. The Nb barriers were severely damaged by the first drawing steps and the Nb filaments were even less reacted than those of the billet B1/14508 due to Sn leak through the Nb barrier damaged by the first drawing steps. Alstom-MSA has decided that the next final billet has to be mounted with 246 sub-elements.

In 2008, Alstom-MSA in agreement with CERN has launched into production, following Road 1, three sub-element billets with NbTa filaments and with the same design as for the sub-element used in the fabrication of the billet B1/21204. NbTa filaments have been used in order to reach higher critical current density. The drawing of the three sub-elements to the re-stacking diameter was very successful demonstrating that the actions taken by Alstom-MSA to improve the workability have been relevant. A first final billet mounted with 246 sub-elements is under fabrication and is being drawn to 1.25 mm in diameter. Six kilometres of strand are expected to be produced with the three sub-elements launched in production following the Road 1 and will be part of the final production.

During the Step 2, Alstom-MSA has continued the development of the NED strand following the Road 2 to fabricate the sub-element by warm extrusion. The sub-element billet extruded in April 2007 was used in December 2007 for the stacking of two final stage billets with 78 and 246 sub-elements, called respectively B1/20124 and B1/63468. The two billets were drawn to final diameter with only few breakages, which has allowed to get few very long piece lengths of 826 m and 402 m form the billet B1/20124 and of 1308 m, 154 m, 121 m, and 98 m form the billet B1/63468. The modifications implemented by Alstom-MSA in the manufacturing process were very successful in term of workability which was the main problem encountered by Alstom-MSA since the beginning of the program. The strand drawn to a diameter of 1.25 mm from the billet B1/63468 achieved only a critical current of 864 A at 4.2 K and 12 T corresponding to a non-copper critical current density of ~ 1500 A/mm^2. Several different types of heat treatments were tried without success by CERN to improve the critical current density. The critical current was measured at the Geneva University as a function of the longitudinal strain up to 0.35 % tensile strain to check the stress impact but the maximum critical current density reached did not exceed 1590 A/mm^2 at 4.2 K and 12 T. Scanning Electron Microscopy analysis was also performed at CERN to find an explanation for the low values of the critical current density. The examinations have shown the presence of bigger Nb_3Sn grains (average diameter around 500 nm) than those of the billet B1/14508. The main reason for the low value of the critical current density seems to be the presence of the big Nb_3Sn grains though the Sn content between 24.3 at % and 25.7 at % Sn could be slightly too high for a binary Nb_3Sn alloy. Solutions using Ta additions, which should limit grain growth, are being implemented by Alstom-MSA to overcome the limitation of binary Nb_3Sn alloy and to achieve the critical current density targeted for the NED strand.

3. Final strand production.

Alstom-MSA is launching into production two sub-element billets with NbTa filaments and NbTa barrier. The two sub-elements billets will be extruded in January 2009. The completion of the strand drawing is expected for March 2009. The material launched into fabrication should lead to the fabrication of at least 20 km of strand, which will be the main part of the final strand production. The remaining part of the final strand production will be completed by the sub-elements billets produced following Road 1.

4. Conclusion

Vigorous efforts were carried out by Alstom-MSA to develop the NED strand. The firm has concentrated the efforts in resolving workability issues to produce sub-elements of the desired geometry suitable for NED conductor. Two roads for the manufacturing processes of the sub-elements, either by cold working or by warm extrusion, have been investigated by Alstom-MSA. During the Step 2, Alstom-MSA was successful to manufacture a sub-element suitable for NED conductor by both processing roads. The main result of the Step 2 has been the production by Alstom-MSA of a billet including 246 sub-elements of 52 μm diameter with only three breakages. For the final production of the 25 km of strand, Alstom-MSA has launched into fabrication two sub-elements billets following Road 2, which can give at least 20 km of strand. In addition Alstom-MSA has also in production material following Road 1, which can give up to 5 km of strand.