Electroslag Welding (ESW) -
A New Option for Welding Aluminum Bus Bars in Smelters

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Abstract

In recent years, a new welding process for aluminum bus bars, Electroslag Welding (ESW), has been developed, tested and used industrially, permitting significant productivity gains both in time and manpower. ESW offers among other advantages the possibility to modify or repair bus bars of an operating smelter with minimum power shutdown time (about 20 minutes per full bus bar cross-section weld) and to build a new rectifier room reducing the construction time and the costs by more than 50 %. The present paper will describe this new welding process and its optimization, discuss the weld quality and present a few industrial applications, such as factory construction of the bus bar network of a new smelter by assembly of sub-modules and the alteration of the bus bar network of a smelter in operation in order to add a new rectifier to the network for additional production capacity.

Keywords: Electroslag welding (ESW); aluminum bus bar welding; busbar sub-assembly; aluminum smelter capacity creep.

1. Introduction

When it comes to join two very thick metal plates, Electroslag Welding (ESW) is the most productive, single pass welding process available. Developed simultaneously in the 1940's in the United States by Kellog Co. and in the Ukraine by the Paton Institute, the ESW was used extensively with steel in the 1960's for railroad tracks, bridge beams, ship hulls, traction motor frames, etc.

In the meantime, the traditional method used by the aluminum industry to weld heavy aluminum bus bars was « staggered plate » method (Figure 1). With this approach, plates about 12 mm thick are piled in a staggered pattern one by one. Gas Metal Arc Welding (GMAW) is then done on each edge. The process is then repeated until the joint between the two bus bars is entirely filled.

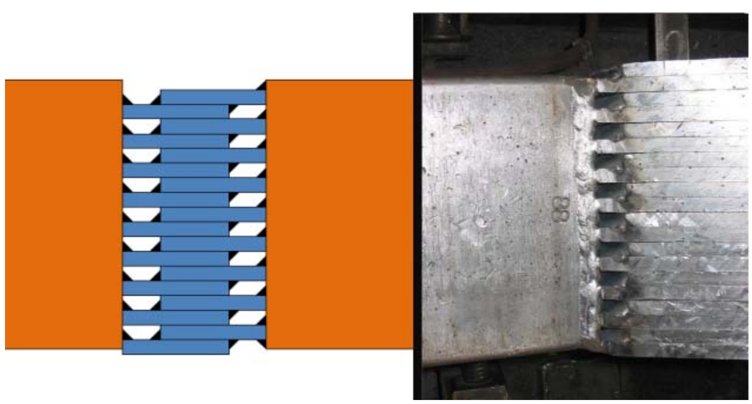

Figure 1. Staggered plate method for bus bar welding.

However, the resulting weldment has typically only about 80 % of full cross-section electrical conductance due to gaps that are left and weld quality issues; it is also very time-consuming and, in the case of a Greenfield plant, requires a great deal of competent workforce at the same time.

Trying to overcome those irritants, CANMEC developed the ESW for aluminum between 2003 and 2006, starting from the work achieved in the 1970's by the Union Carbide Company (UCC) through its subsidiary Linde.

A five head unit finally provided the ideal combination of electrode spacing. The Alcoa Fjarðaál Aluminum Smelter Iceland project [1] was then the ideal platform to test the new technology with the result that the bus bars were welded in two weeks only, compared to two months if the traditional method had been used. The welded area and the ESW provided better quality welded joints while reducing the welding time in total man hours per welded joint by half.

2. Principle of Operation

The principle of operation of the ESW process is shown in Figure 2. In summary, this process is initiated by an electric arc that is struck between a wire, fed into the location to weld and two slightly spaced vertical plates. A powdered flux is then added and it melts to form the slag that will shield the weld pool. Through a consumable guide that extends down the length of the joint, the wire is continually fed into the surfaces of the metal workpieces. With this method, the welding head remains at the top of the joint, while both the electrode and the guide tube are progressively melted by the slag. A retaining shoe, put into place before starting the process, is used to keep the coalesced metal between the plates. The result is a single pass welding joint obtained much more rapidly than with the conventional method (Fig. 2).

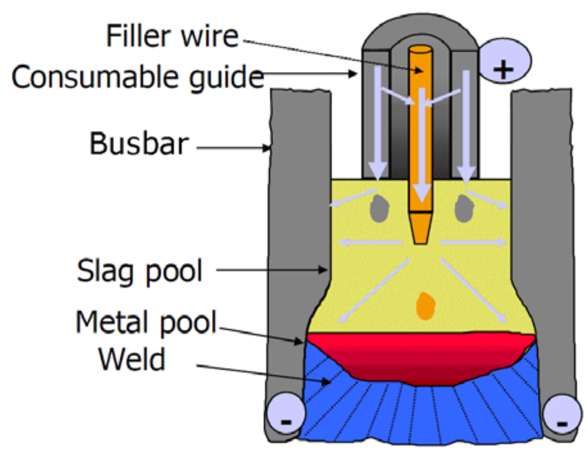

Figure 2. Sketch of Electroslag Welding process.

3. Process Description

The bus bars to weld are typically made from the 1 000 alloy series, and more specifically from 1350 or 1370 alloy. The main steps for the process are: the preparation of the joint, the bus bar assembly, the welding and the finishing.

3.1. Preparation of the joint

To ensure that the spacing between the bus bars will be maintained along all the length of the weld joint, it is important that the edges of the bus bars are cut at right angle and that the surface is relatively smooth (6.3 to 12 Ra). This can be achieved through saw cutting. Small asperities on each side (front, back and bottom) of the bars can also be polished by hand with a grinder or an appropriate tool in order to avoid leakage during welding.

3.2. Bus bar assembly

Bus bars are positioned end-to-end, separated by the specified 4 cm gap. This gap is required to insure that slag bath is large enough and to have good circulation as well as to avoid any contact between the guide tube and the bus bar wall. An excessively large gap would require a large quantity of metal non-economically justifiable and it would also compromise the fusion. When ready to proceed, surfaces are cleaned with adequate solvent to be free of oil, carbon deposits or humidity.

Figure 3 shows a typical arrangement of the materials to be Electroslag welded. A bottom extension or sump provides a place to start the weld so the flux is fully molten and fuses the weld start. Procedures were developed with satisfactory results to allow a very short sump (more likely to be used integrated in a bottom shoe because of the lack of space) approximately 25 mm high.

Figure 3. Bus bar assembly before using ESW.

As with the bottom of the weld, an area above the weldment is needed to carry the molten flux out of the joint. This is referred to as a top sump or run out.

Retaining shoes are then installed on both sides (front and back) of the gap to retain the molten slag and metal. For Consumable Guide Electroslag welding of steel, copper is generally used. However, for joining aluminum, the high thermal conductivity of copper does not produce adequate fusion at the weld edges. Another material, inert to the slag and having a lower thermal conductivity than copper is used instead, such as graphite.

Finally, the consumable guides are installed. Their number will vary with the width of the weld joint to do, but adequate spacing is important. Their primary function is to guide the aluminum wire down to the bottom of the joint and the electric current at the same time. These guides have to be isolated to prevent short circuit. As its name indicates, the guide will be consumed as the slag bath rises in the joint (Figure 4). The exterior diameter of the guide is generally half the gap width to the next guide and is chosen according to the diameter of the wire that will be used (up to 3.2 mm). The heat of the slag melts the guide but its chemical composition has little impact on the fused metal composition.

Figure 4. ESW welding system – view from the top showing the molten slag.

The maximum angle to the vertical position is ± 10° in order to avoid defects, such as inclusion of slag or lack of fusion. It can also be a nuisance to the proper alignment of the consumable guides.

The electrode wire is adjusted to be 5 - 8 cm longer than the guide in order to easily start the weld and it will always stay that way for the full welding time to avoid a situation that would cause operation instability (Figure 5).

Figure 5. Consumable guides and electrode wires.

In preparation for the welding, the welding head unit is put in place. This contains a powerful wire feeding motor (over 300 mm/s) for each welding head. Since aluminum conducts heat rapidly, it is essential to weld at a speed such that the heat generated in the molten Electroslag flux is contained in the welding area long enough to melt the base metal and is not conducted away too rapidly into its mass.

The head unit also contains all electrical connections to the power source and the instrumentation necessary to provide the desired electric current in the wire.

It is important that there is no interruption during the welding by lack of wire or flux since it will create imperfections in the welding joint. A good provision of flux is then added on the feeding plate. The flux used must be electrically conductive to allow the process to enter the Electroslag mode. It must have the correct resistivity to generate the temperatures required (approximately 650 °C) to melt the welding electrode and the base material. However, it must also be lighter than aluminum so that it floats on top of the molten puddle. This eliminates many of the typical oxides used in most fluxes. Optimizing the flux chemistry was part of the process development efforts.

There is no need for preheating since the process does it by itself. First an electric arc is established between the electrode and the bottom sump. Flux is added regularly. As the joint progresses and the slag and fusion bath gets higher, heat dissipates by the bottom, the sides and the metal walls. The molten metal in the weldment then gets colder and solidifies slowly in such a way that no cooling devices are required (Figure 4).

At the top of the welding, the speed of the wire feeding is slowed gradually until the slag can pour over the run-out.

The welding time for the joint is usually about 20 minutes for 280 mm x 1000 mm bus bars. The rest of the steps can be conducted during operation, meaning that the shutdown time is kept to a minimum when the assembly is done online (Figure 6).

Figure 6. ESW welding equipment.

3.3. Finishing

When the joint has cooled, all the assembly is stripped off (equipment, retaining shoes) as it can be seen in Figure 7. To clean the welded bars, the run-out is then cut when needed with a saw to insure a joint that covers the full length of the gap between the bus bars. If required, the external surfaces can also be polished by hand.

Figure 7. Complete ESW welding joint.

4. Innovation on the Industrial Unit

Since its debut in 2013, the ESW equipment has undergone some major improvements (Figure 8):

- The unit is now servo-driven; this has allowed a more reliable wire feeding and a more powerful wire dispenser. The weight of the dispenser was then lessened by removing the wire spools.
- The electrical connections and the electrical insulation of the wire dispenser were improved.

Figure 8. New improved industrial unit.

- The connection time between dispensers in the field while performing a welding sequence during an electrical shutdown was reduced.

- ESW trials in presence of strong magnetic fields were conducted in order to increase the range of possibilities for welding with ESW in magnetic fields greater than 45 Gauss. These trials are still in progress.

5. Weld Quality

The welding joint obtained with ESW is a full joint, with no gaps like in the staggered-plates method, where the plates are piled and welded one by one (as seen in Figure 1). The process with the retaining shoes mentioned previously ensures that the joint goes well beyond each extremity, leaving no void: This translates in a very good conductivity and low voltage drop. Figure 9 shows the weld surface at the end of the process.

Figure 9. ESW joint showing the solidified slag.

The quality of the welding joint can be verified by non-destructive methods (NDT) like ultrasound testing (UT). Taking into account the two welded surfaces, the worst cross section surface with a defect should be no more than 20 % of the total cross-section of the busbar. For example, the welded surface obtained in Figure 10 would be a 100 % cross-section surface without defect.

The alloy used typically for the bus bar is almost pure aluminum (99.5 %). The filler wire, for its part, has to be from a slightly different alloy, offering enough rigidity to guarantee easy feeding to the welding head. The 4043 alloy is usually chosen, which has a composition of 94.7 % Al and 5.2 % Si.

The mechanical properties of the alloy in the filler make the welded joint stronger (ultimate mechanical strength of 126 MPa) than the bus bar metal (84 MPa). If submitted to a major stress, the bus bar would crack before the joint. This is important, since it allows the transportation of preassembled modules without risking cracks or breakages as demonstrated in the next section.

Figure 10. Electroslag weld macroetch.

6. Applications of ESW of Aluminum Busbars

Two applications of the ESW will be discussed in this section: The first one is the use preassembled modules for bus bar assembly and the second is the possibility to modify the bus bar circuit while the potline is in operation.

6.1. Preassembled modules

The traditional welding method using staggered plates is not mechanically designed for transportation. Cracks could appear in those joints. Quality checks cannot be performed by NDT. Destructive tests have to be conducted during fabrication.

Excellent mechanical properties of the ESW joints, on the other hand, allow them to withstand all stresses implied by transportation, with no required bracing. This opens two options for the preassembly of modules, a method that saves a lot of time on site.

Depending on the transportation logistics implied, one can either chose to make minimal preassembly (Fjarðaál project) and will then have to perform the maximum number of welding joints in the field; or chose to preassembled modules. Two options are then possible: Assembly near the site in bigger modules which involve fewer ESW weld joints in the field (Rio Tinto Alcan AP-60 plant in Saguenay) or further from the site in smaller modules as was done for the Rio Tinto Alcan (RTA) Kitimat project (Figure 11).

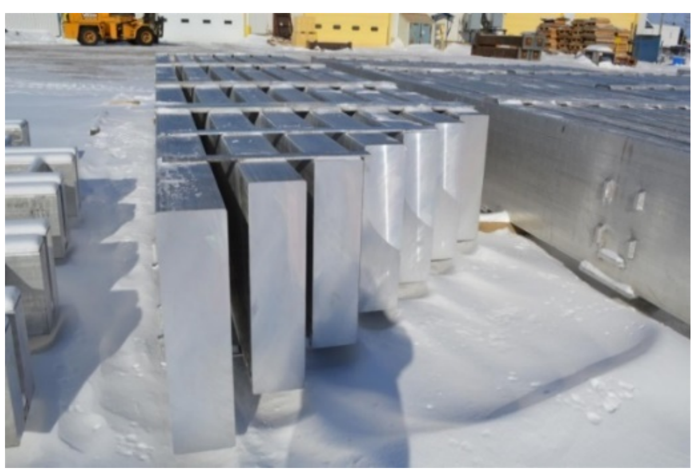
Figure 11. Preassembled modules.

The module preassembly allowed by ESW technology is then characterized by shorter deadlines for the plant construction and the presence of far less qualified welders on site than with the staggered plate method. The only limits for module dimensions with ESW are those set by the transportation specifications or the plant lifting capacity.

6.2. New method for the construction of a substation while reducing cost and shutdown time

When a new smelter is built, an electrical substation of great capacity should also be added with its associated network of conductors. The most recent built in Canada required the installation of five transformer-rectifier units with a bus bar network consisting of 28 modules (12 on the positive side and 16 on the negative side) as seen in Figure 12. This substation was designed by the engineering firm in collaboration with the provider ABB.

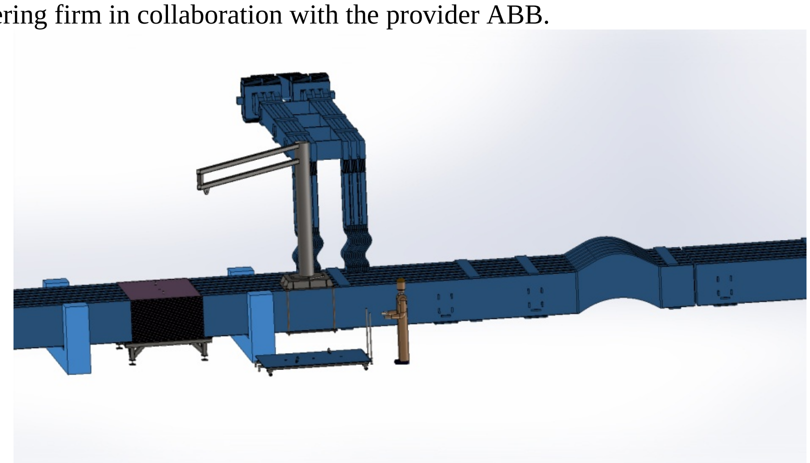

Figure 12. Sketch of the modules for the substation.

The modules were manufactured in the CANMEC shop. Those modules were complete (equipotential plate, sliding plates, secure key for lateral insulators, reference points as center of gravity and positioning marks, flexibles, etc.) (see Figure 13).

The total time of manufacturing plus delivery to Kitimat, was ten weeks.

Figure 13. Modules ready for delivery to Kitimat [2].

The installation of the modules required the addition of a railing system for logistical reasons (Figure 14) as well as the unloading and the positioning on site necessitated a crane.

Figure 14. Rail system used to move the modules on site [2]..

The onsite welding of the 157 ESW joints needed to assemble this impressive puzzle required a mobile unit and 12 weeks of work for five persons. This includes the welding operations, the cutting of run out as well as the joint cleaning and inspection (Figures 15 and 16).

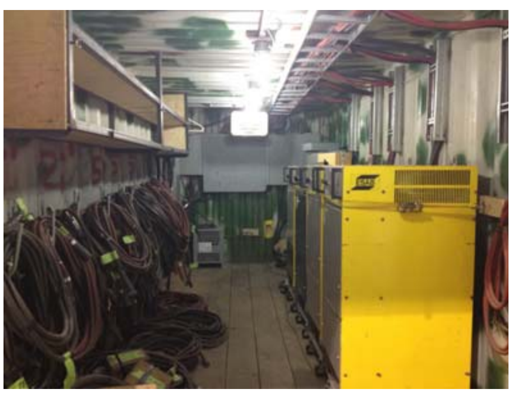

Figure 15. Inside the ESW mobile unit.

Figure 16. Run-out cutting.

Thus, once the design was completed, this revolutionary method with preassembled modules required (Figure 17):

- Manufacture: 8 weeks in the shop,
- Transport to Kitimat: 2 weeks,
- Installation: 3 weeks,
- Welding (ESW in the field, fixed points and corner flexibles): 12 weeks.

This method allowed the construction site to shorten its schedule by as much as 25 weeks while registering a 30 % gain in budget, due mainly to the hiring of non-specialized personnel instead of aluminum welders. A gain in quality was also noted because ultrasonic inspections could be performed frequently to monitor the welding.

Figure 17. Type of modules [2].

6.3. Modifying the bus bar circuit in operation

The other situation where the ESW offers a clear advantage on the staggered plate method is the modification of a bus bar configuration while the smelter is in operation (Figure 18).

Since every ESW weld joint takes only 20 minutes to complete approximately, the number of plant shutdowns necessary to perform the modification is minimal. Even more, many weld joints can be performed during each shutdown.

For example, in the Fjarðaál case, only two shutdowns were necessary (one for positive polarity and the other for the negative one). If the staggered plate method had been used, 40 shutdowns would have been required to perform the same task. This would not have been feasible economically and the delay would have been too long.

Figure 18. Design adapted to ESW process [3].

6.3.1. Example of bus bar installation in an operating plant

A plant wanted to increase its amperage capacity by a 100 kA circuit from 350 kA. This implementation would enable increasing production as well as give the opportunity to stop an existing operating rectifier for maintenance.

ABB and the plant technical team worked on a new circuit design based on modules, pre-assembled in the shop that could be installed in the field. Eight (8) negative polarity modules and three (3) positive polarity modules were then fabricated and installed (Figure 19). The switches were interlinked with the modules so that field welds were nor required anymore (Fig. 20 and 21). The manufacture of all eleven (11) modules in the shop required only 8 weeks.

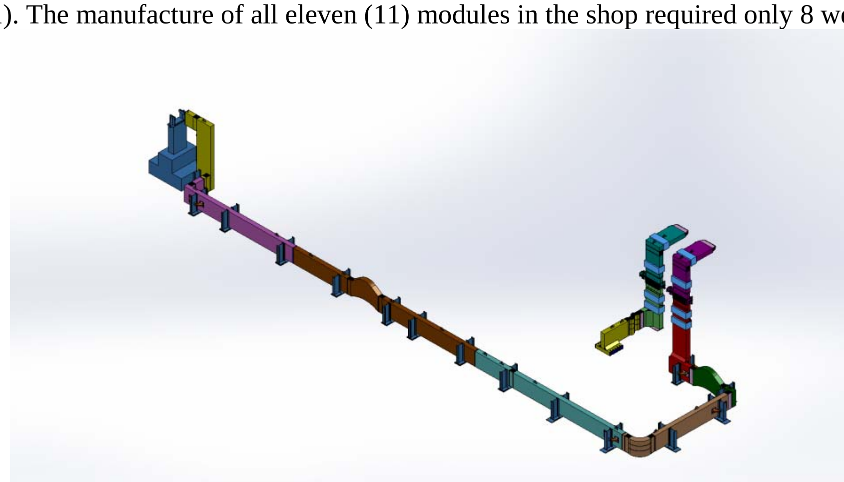

Figure 19. Modules for additional rectifier busbars.

Figure 20. Preassembled modules as fabricated [3].

Figure 21. Switch modules [3].

The installation of the modules on site took a little resourcefulness due to the restrictive space and difficult access. 12 weeks were necessary with the average presence of 6 workers to complete the work.

The magnetic field in the working area was 110 mT (millitesla). The welding had then to be performed through 6 operation shutdowns, each one being one hour long. It combined ESW and Gas Metal Arc Welding (GMAW) to achieve the results expected.

Connections to the existing network required adapted design (see Figures 22 and 23). In this case, an interlinked connection to 6 previously independent conductors proved necessary to distribute the 100 kA load.

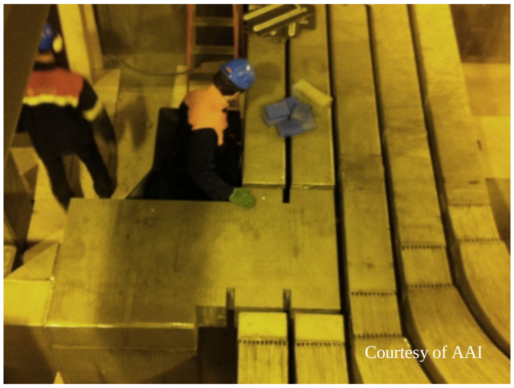

Figure 22. Interlinked connections used in Iceland.

Figure 23. Interlinked connections used in Sept-Îles.

In conclusion, this new way to proceed allows no compromise on interconnectivity, no overheating due to uneven current distribution, as well as an optimum quality of connection. It also permits very often to add extra staggered plates since the manual welding time allows it during a plant shutdown.

7. Conclusions

The Electroslag welding is an innovative method to join aluminum bus bars that allows significant gains both in manpower and time. It also makes possible the modification of the bus bar circuit while in production, a task that was impossible using the staggered plates welding method.

In summary, ESW shortens bus bar installation, improves electrical conductance of the joint to reduce the welded joint voltage drop by 22 %, provides welding joint of very high quality, and represent a significant gain of time (20 minutes for a standard joint).

CANMEC is now working on the Electroslag Welding in the presence of strong magnetic fields in order to save more power shutdown time during busbar modifications in an operating plant.

8. References

1. Bechtel, Fjarðaál Aluminum Smelter Iceland (2004 - 2007), online at http://www.bechtel.com/fjardaal_aluminum_smelter.html.
2. Pictures, 13, 14 and 17 are a courtesy of RTA Kitimat.
3. Pictures, 18, 20, 21, 22 and 23 are a courtesy of Aluminerie Alouette Inc.