Ongoing Development of Aluminium Welding in Strong Magnetic Fields

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Abstract

The development of higher amperage aluminium electrolysis potlines has resulted in industrial environments with significantly stronger magnetic fields. These stronger magnetic fields present operational challenges and they also directly impede the arc welding of aluminium components. Indeed, the electric arc of the welder can be deflected and destabilized, and the molten aluminium pool can be displaced during the welding process. In weak to medium magnetic fields these phenomena can be mitigated by experienced welders and the use of simple general magnetic shields. For the more intense magnetic fields encountered in high amperage electrolysis potlines, specific magnetic attenuation equipment is required, in addition to a specialized understanding of magnetic fields and welding physics. Rio Tinto Aluminium developed the required knowledge and experience at the AP5X experimental cells in LRF (Laboratoire de Recherche des Fabrications) in France and at the Arvida - AP60 Technology Center in Saguenay, Canada. Welding activities are required in the electrolysis potlines for equipment maintenance, cell replacement and conductor modification projects. These led to the development of methods and technologies to control the magnetic field intensity at the welding position. The use of these technologies has already saved several hours of potline shutdown to perform welding work. The technology is also being further developed for welding on energized busbars. This next generation of the technology represents a large potential to further reduce the number of potline shutdowns even more and contributes to the overall productivity goals.

Keywords: Aluminium reduction technology, Aluminium welding, Magnetic fields, Magnetic fields control, Welding in magnetic fields.

1. Introduction

Arc welding in aluminium smelter potlines has always been a very challenging activity. The high magnetic fields generated by the high DC currents destabilize the electric welding arc and often make the welding process impracticable. These constraints have become greater as the electrical current applied in modern cell technologies has increased.

The startup of the Arvida - AP60 Technology Center [1] posed new magnetic challenges and indeed required an extensive magnetic field study program to validate the behavior of numerous parts and practices before startup. This demonstration plant has always provided a supportive environment for further testing and development, particularly with respect to magnetic fields. A great deal of knowledge and expertise was hence developed and is in the process of being applied to all the Rio Tinto plants.

To compensate or attenuate the effect of the magnetic fields on the arc welding process, several solutions have been presented in the past and are detailed in their respective patents. The most common solutions induce electrical currents in the welded part to attenuate the magnetic fields at the weld location [2, 3]. However, these solutions do not work on parts that are not ferromagnetic, such as aluminium conductors. In aluminium smelters, magnetic field control has been developed using electrically induced counter magnetic fields with some success [4]. However, simpler non-powered solutions are required to overcome this difficulty in a wide range of situations in the potlines.

This paper aims to present the work carried out at Rio Tinto in recent years to achieve better welding results in potlines with increasing magnetic fields.

2. Arc Welding and Magnetic Field Interactions

The arc welding process involves creating an electric arc between the welding tip and the welded part. This arc is in fact an electrical conductor. In the presence of magnetic field, a conductor carrying an electric current will be subject to an electromagnetic force, given in Equation (6). The force is perpendicular to the electric current and to the magnetic field. The orientation of the force is illustrated in Figure 1.

$$\mathbf{F} = \mathbf{J} \times \mathbf{B} \tag{1}$$

where:

F Force on the conductor (N/m^3)
J Current density in the conductor (A/m^2)
B Magnetic field (T)
x Vector cross product

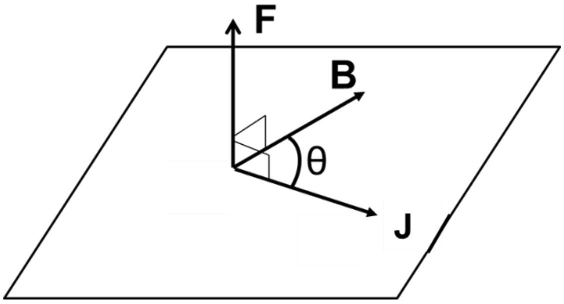

Figure 1. Vector product of current density and magnetic field gives a force perpendicular to the current density and the magnetic field.

Equation (1) can be simplified in scalar form for a given straight conductor to Equation (2):

$$F = I \times L \times B \sin\theta \tag{2}$$

where:

F Force acting on the conductor (N)
I Current in the conductor (A)
L Length of the conductor in magnetic field (m)
θ Angle between the current and the magnetic field direction.

The conductor subjected to this force will be displaced if not restrained. For this reason, the busbar supports must be designed to prevent their displacement due to this electromagnetic force. An electric arc of the welding torch which carries current cannot be restrained and will move in the direction of the force. Since the arc if flexible it continuously changes the direction in a dynamic way, making it extremely unstable. Stronger magnetic fields and increased welding currents amplify this detrimental behavior.

For typical welding currents, a magnetic field of 5 mT (50 Gauss) will begin to destabilize the electric arc, reducing weld quality, because the arc is blown away and does not stay attached long enough to the molten weld pool to melt deep enough the busbars being welded. Greater magnetic fields will completely inhibit the possibility of making a satisfactory weld.

3. Magnetic Field Welding Setup

Work on welding in magnetic fields started at Rio Tinto with an assessment of the domain where welding was possible. Bench tests were set up to reproduce simple weld geometries in various magnetic field magnitudes and orientations. These tests were carried out with plant welders who were well qualified and experimented in welding in magnetic fields and with good workshop welding preparations. The different welding conditions were categorized according to the resulting quality of the welds. A good weld has a stable arc and weld pool throughout the welding process, a regular surface structure and no surface defects. The structural advantage of a stable arc is the creation of a weld with increased penetration.

The results of these tests define a weldable domain that depends on the magnetic field strength and on its direction relative to the welding arc (Figure 2).

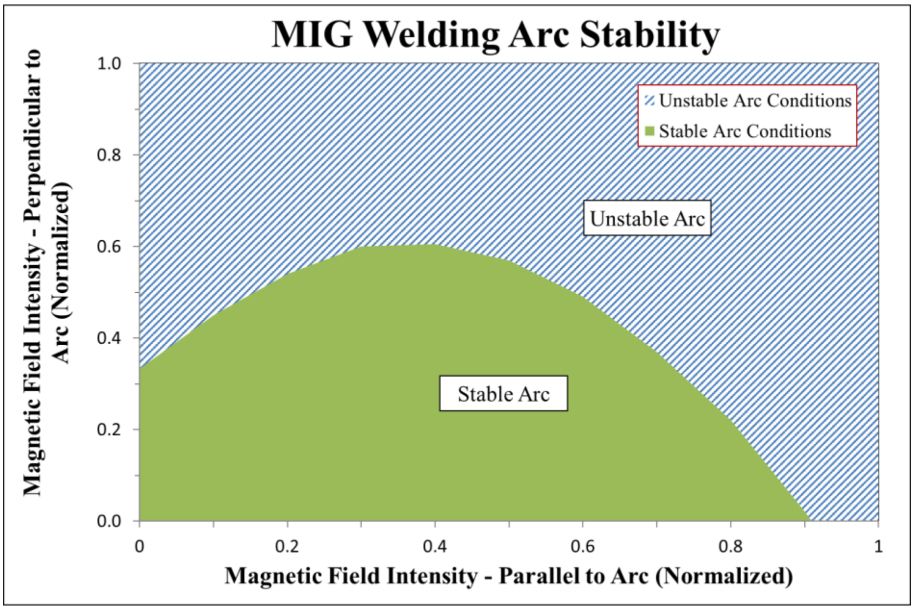

Figure 2. Example of metal inert gas (MIG) arc stability mapping.

The objectives of the subsequent magnetic field attenuation tests were to develop methods to reduce one or both magnetic field components to the stable arc zone.

3.1 Cell Anode Riser Welding During Replacement

Cell anode risers use a bolted connection as the main structural link which also allows good current transfer. A peripheral weld bead on the connection provides additional mechanical stability and reduces electrical resistance. These welds must be performed during the cell replacement operations on a short-circuited cell in the energized potline. The weld quality can vary from poor to good depending on the welder's expertise and the cell electrical and magnetic condition. A poor weld produces a weaker initial electrical contact and may fail during the cell operating life (Figure 3).

Figure 3. Example of weld damage resulting from initial poor quality

Trials to improve the quality of these welds have helped identify four important factors to control:

1. Surface preparation
2. Welding procedure
3. Magnetic shield
4. Current carried in the riser

Factors 1 and 2 are inherent to all welding operations. They are critical when welding in magnetic fields as all imperfections are amplified in these adverse conditions.

Factor 3 is the magnetic shield that is comprised of an iron ring, which provides magnetic field attenuation inside its contours. In its most basic form this ring can be a simple geometry designed from practical considerations, which will result in an average performance. For the riser welding operation, based on the magnetic field measurements in the welding zone, shield geometries were modelled using a finite element magnetic calculation software. Several geometries were tested in the software to result in the largest zone possible with the lowest magnetic field inside the shield ring. The result is a geometry compromise between the ideal magnetic shielding and the practical welding considerations. An example of a tested magnetic shield ring and the resulting calculated magnetic field are shown in Figures 4 and 5.

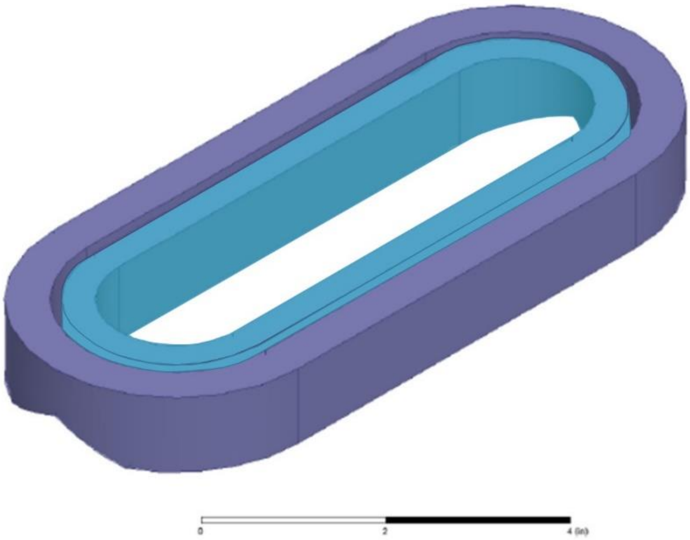

Figure 4. Magnetic shield ring example.

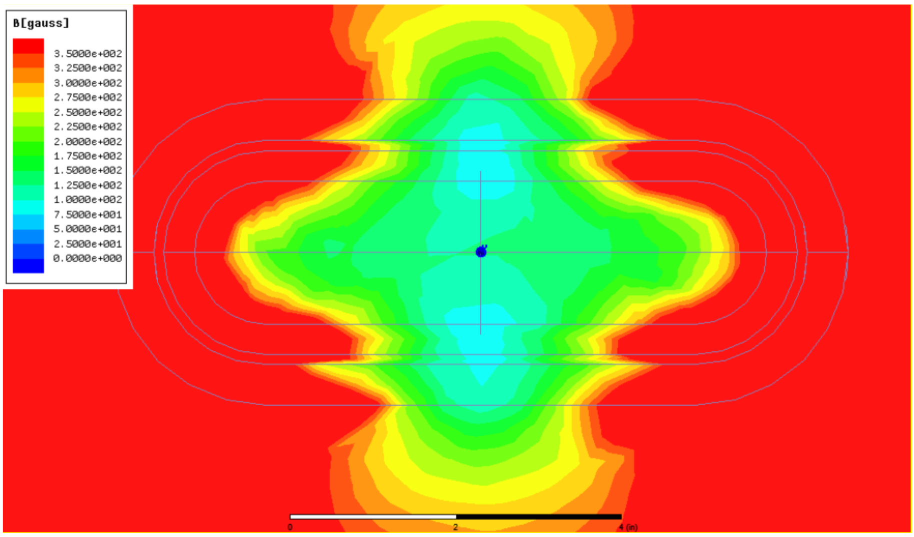

Figure 5. Calculated magnetic field inside the ring shield (1 Gauss = 0.0001 Tesla).

Factor 4 is the control of the electrical current in the riser. Risers will have a residual electrical current even if the cell is cut-out. The specific current magnitude depends on the conductor network design and on the quality of all the contact resistances involved. It was experimented that some risers were more difficult to weld, even with good control of factors 1 to 3. The study showed that these risers were carrying more current than the others. This caused a magnetic field of greater and more varied magnitude than the shield was designed to attenuate. Improving the quality of the electrical contacts on all parallel conductor lines in the cell was necessary to minimize the current in the riser at the time of welding.

These tools and methods were developed in one plant and were implemented in the work procedures to weld the anode risers during cell replacement. The initial quality of the riser welds as well as their durability in operation was improved by these developments. This was confirmed by visual inspection (Figure 6) and by measuring the voltage drop across the electrical contact surfaces (Figure 7).

Figure 6. Example of good weld quality using the magnetic field attenuation.

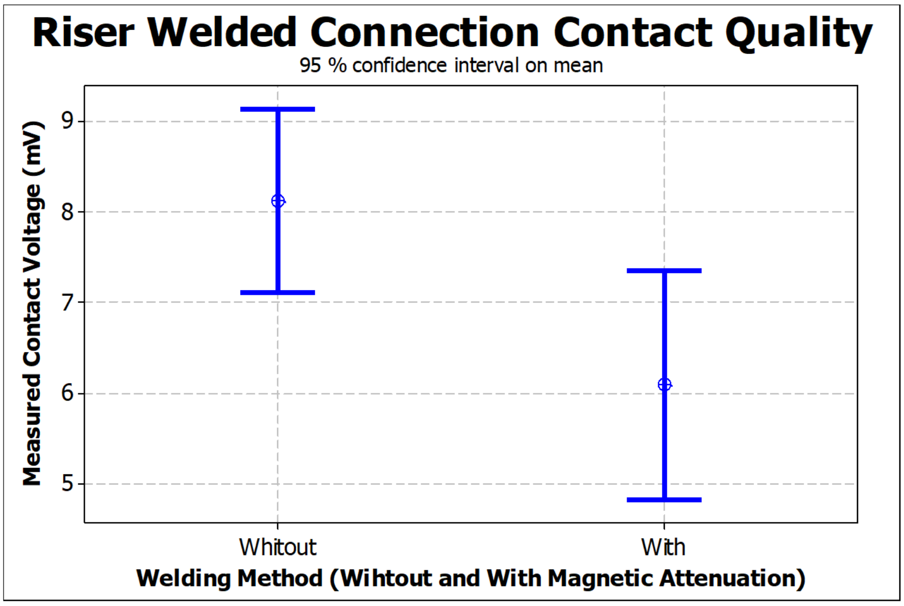

Figure 7. Riser connection contact quality without and with magnetic attenuation.

The tools and methods have been in service at the plant since 2018. A quantitative quality control procedure, implemented during the magnetic field welding trials, shows that welds in recent pot replacements are still done with the magnetic attenuation solution and produce good quality welds.

3.2 Conductor Network Modification Projects

Conductor networks sometimes require modification work involving welding. The weld configuration and complexity depend on the joint design, its accessibility and the magnetic field orientation. A new magnetic attenuation solution was developed using powerful permanent magnets. These generate their own stable magnetic fields and they can be positioned to effectively attenuate the environmental magnetic field effectively. This solution has proven to provide greater positional flexibility and better magnetic attenuation coverage than ring shields.

The magnet impact zone is controlled by adjusting its position relative to the welding arc. Numerical modelling is a powerful tool to assess the local impact of the magnet on the magnetic field around the welding zone. It enables the definition of the ideal magnet position with its greatest attenuation capability while including the constraints dictated by the accessibility required for the welding operation. It also allows the evaluation of simultaneous use of two or more magnets, which can become very complex, as illustrated in Figure 8.

For most joint types, a typical magnet configuration was calculated and then tested on the work site. Once proven to be satisfactory it was replicated on all similar joints. However new joint configurations and opportunities often require a rework of the setup to adjust to the magnetic environment and the practical accessibility.

This solution was used in a recent project that would have required 14 potline shutdowns without the developed solution. A review of the welding operations showed that all the welds could be performed while keeping the potline energized if the magnetic attenuation solution was used. The potline shutdowns were then reduced to only three activities where a connection had to be made between the new conductors and the existing circuit.

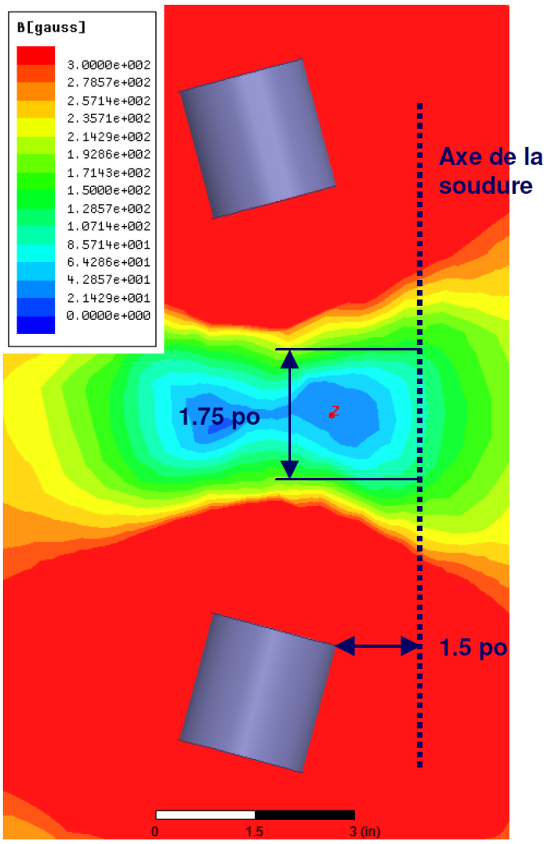

Figure 8. Example of magnet configuration to counter an ambient magnetic field along a weld (1 Gauss = 0.0001 Tesla).

4. Upcoming Development

The previous results were obtained when welding on conductors that were not energized. Welding on energized conductors poses additional constraints. When welding on an energized conductor the newly deposited welds create a change in the conductor geometry and a corresponding change in the electrical current paths and local magnetic fields. This alters the attenuation required to continue welding and limits the stable conditions to tiny areas. Rio Tinto has directed the development activities accordingly and believes this challenge will be overcome soon. These future developments will lead to further opportunities to build or repair energized conductors on the operating smelter potline.

5. Conclusions

High magnetic fields have a critical impact on electric arcs that deteriorates or inhibits arc welding. Solutions need to be found to allow arc welding in high amperage potlines without stopping the aluminium production. Based on its extensive work on magnetic fields in the AP60 technology, Rio Tinto has developed two sets of tools to improve weld quality. An iron ring shield is used for welding anode risers during the cell replacement procedure in the operating potline. A permanent magnet attenuator is used for conductor welding during conductor modification projects near the potlines. Both technologies were successfully developed and tested and were submitted in patent applications. They are now operational in one plant and are being replicated in other Rio Tinto plants with adjustments made for each situation. The development of these solutions had benefited from the collaboration of highly experienced personnel and enterprises in both welding and magnetic fields. Further development work is needed to identify and deploy practical solutions which will address the challenges of welding directly on energized conductors.

6. References

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