Industrial Practice of Special Welding Technology for Aluminium Electrolysis Cells

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Abstract

In the aluminium electrolysis industry, electrical conductors are primarily connected through welding. This paper investigates direct welding between dissimilar metals such as steel and aluminium, as well as full-section welding of steel sections with very large cross-sections.

The physical properties of steel and aluminium differ significantly, making direct welding susceptible to the formation of brittle compounds and cracks. This study demonstrates that a special welding process, utilizing an auxiliary flux, and selecting effective welding materials and parameters can effectively inhibit compound formation and reduce cracking. Through extensive testing and optimization of welding process conditions and parameters, excellent weld joints with high electrical conductivity and weld strength are achieved. Industrial practice has proven that this technique is suitable for current applications in the aluminium electrolysis industry.

To address the shortcomings of traditional large-section welding between steel sections, this paper proposes a special welding method that achieves joints with properties comparable to those of the base metal. Practical application demonstrates that this technology is effective for current applications in the aluminium electrolysis industry.

Keywords: Welding parameters, Auxiliary flux, Full-section, Intermetallic compound, Electrical conductor.

1. Introduction

With the continuous development and advancement of aluminium electrolysis technology, electrolysis cells are becoming increasingly larger, and the corresponding conductors, such as anode rods, cathode collector bars, aluminium busbars, and aluminium flexibles, are also becoming larger in size. Due to production, processing, and transportation, these workpieces often require welding before use. This paper investigates a steel-aluminium direct welding technique and a narrow-gap full-section welding technique for large-section workpieces. These techniques are applied to direct welding of dissimilar steel and aluminium materials and narrow-gap full-section welding of same materials of large cross-section, respectively. These techniques are primarily used in the aluminium electrolysis industry and are discussed below.

1.1 Research Background on Steel-Aluminium Direct Welding Technology

In the aluminium electrolysis industry, explosion welding clads are currently primarily used for transitional connections between dissimilar metals, such as the welding of anode aluminium rods and steel yokes in anode rod assemblies, and the welding of cathode aluminium flexibles and cathode steel collector bars. Due to the high production cost and inconsistent quality of explosion welding blocks, aluminium smelters invest heavily in developing steel-aluminium dissimilar metal welding.

The physical properties of steel and aluminium are very different, as shown in Table 1, and steel is almost insoluble in aluminium. Therefore, it is easy to generate excessive amounts of brittle intermetallic compounds such as FeAl, $FeAl_3$, and Fe_2Al_5 using ordinary fusion welding technology. When the thickness of the interface compound layer is controlled below 10 µm, the obtained joint can meet the use requirements [1]. As the thickness of the intermetallic compound layer increases, the mechanical properties of the welded joint will decrease sharply. Therefore, controlling the generation of intermetallic compounds is the biggest obstacle to achieving good direct steel-aluminium welding.

Table 1. Comparison of physical properties of steel and aluminium.

Material	Melting Point, °C	Thermal Conductivity W/m·K	Density g/cm^3	Coefficient of Linear Expansion, 10^{-6}/K
Carbon steel Q355	1534	77.5	7.86	11.76
Pure aluminium 1060	660	217.7	2.70	24

Although there are currently some methods that can achieve direct welding of steel and aluminium, they are often costly, inefficient, and difficult to apply in batches in actual production due to high costs, poor operability, and the requirement that the weldment must reach a specific shape.

1.2 Research Background of Narrow-Gap Full-Section Welding Technology for Large-Section Workpieces of the Same Metal Material

In aluminium electrolysis cells, cathode steel collector bars are welded using steel connecting plates, which are manually welded layer by layer into the joint. The high ambient temperature and strong magnetic field during collector bar steel welding significantly impact welding efficiency and quality, they also pose safety risks. Furthermore, the varying welding skills of workers make inspection of completed joints difficult, leading to potentially serious accidents during the cell operation caused by poor welding quality.

Traditional anode steel stub welding is often manual arc welding with a groove. The effective welding area at the joint is far less than the effective cross-section of the base material. The strength and conductivity of the weld are quite different from those of the base material. The welded joint has a short service life after grooving, requires frequent repairs, and has a high cost of use.

In response to the traditional welding repair method of large-section workpieces of the same material, this paper proposes a narrow-gap full-section welding technology. By controlling the heat input, the weld and the base material are completely fused. Protective agents are added during welding to refine the grains and to prevent high-temperature oxidation of the base material. Welded joints with good performance were obtained in the experiment. This method was tested in a magnetic field and it was not affected by it. At present, this method has been widely used on construction sites, which can significantly improve welding quality and efficiency, reduce personnel workload, and reduce voltage drop at the joint and production operation costs.

2. Welding Methods Developed in this Work

2.1 Welding Method of Steel-aluminium Direct Welding Technology

The huge difference in physical properties between steel and aluminium is the main reason why they are difficult to weld directly. In general, there are the following problems when welding steel and aluminium directly [2, 3]:

(1) Using ordinary fusion welding technology, when both steel and aluminium are melted, the molten aluminium will float on the molten steel. After cooling and crystallization, the difference in density will make the weld composition uneven, and brittle intermetallic compounds will easily form at the joint. Excessive intermetallic compounds will cause the performance of the weld joint to drop sharply. Steel and aluminium can form solid solutions and intermetallic compounds, or they can form eutectics [4, 5].

(2) Welded joints are prone to cracks: There are two main reasons for the occurrence of cracks: First, the intermetallic compounds produced during welding increase the brittleness of the weld, reducing the plasticity and toughness of the weld. Second, large welding stresses are easily generated under restraint conditions, increasing the cracking tendency of the joint.

(3) Slag inclusion: When welding steel and aluminium, an insoluble oxide film will form on the aluminium base material. As the temperature of the molten pool increases, the thickness of this oxide film will continue to increase, eventually forming slag inclusions, which will affect the welding quality.

Based on the above analysis, we found that if we want to obtain a weld joint with good performance, we must avoid the production of brittle compounds. Perhaps one can make one of the two base materials melt and the other not melt, to avoid melting each other and producing negative compounds. Obviously, from the difference in melting points, it can be seen that aluminium should be melted while steel should not melt during welding in this proposed approach.

If one wants to obtain a welded joint with good performance, the following two things must be done: first, achieve the wetting and spreading of the brazing filler metal on the steel surface to obtain good joint formation; second, control the growth of the brittle intermetallic compound layer at the interface to improve the joint performance.

To address the wetting and spreading of the brazing filler metal, a composite coating compatible with both materials should be applied to the aluminium and steel prior to welding. Different coating compositions can significantly affect welding performance and results, and a coating with the appropriate composition facilitates wetting and spreading of the brazing filler metal. Secondly, the heat input during welding must be addressed to prevent excessive heat input from forming excessive intermetallic compounds.

In this case, by selecting a coating with a suitable ratio, controlling the heat input during welding, and avoiding the generation of excessive intermetallic compounds, a weld joint with good performance can be obtained. Based on this idea, we have conducted a large number of experiments and obtained weld joints with good performance.

2.2 Narrow Gap Full-Section Welding Method for Large-Section Workpieces

Large-section workpieces used in electrolysis cells, such as butt welds in cathode collector bars steel and anode steel stubs (where the base metal at both ends of the weld are the same material), have large cross-sections and are difficult to weld across their entire length. However, if the welding wire can penetrate into the centre of the butt weld gap and sufficient heat is applied to the weld area to melt both the base metal and the filler material while preventing oxidation in the weld area, narrow gap welding of large workpieces can be achieved.

In our research, we drew on existing box girder welding methods, optimizing and extending them to achieve simultaneous control and welding of multiple welding wires, along with appropriate cooling measures to optimize weld quality. This technology now meets the welding requirements for anode steel stubs and cathode collector bars of all sizes in China and has been widely adopted by domestic aluminium smelters.

3. Process Parameters and Performance Testing

3.1 Steel-Aluminium Direct Welding Technology Process Test

3.1.1 Basic Process Parameters and Performance Testing of Steel-Aluminium Direct Welding Technology

The materials used in this experiment were 1060 pure aluminium and Q355B carbon steel plates. The aluminium plate dimensions are 100 × 100 × 200 mm, and the steel plate dimensions are 80×80×100 mm. The joints used in this experiment were butt-jointed, with a V-groove on the aluminium plate and no groove on the steel plate. The chemical composition of the base materials in this test are listed in Table 2 and Table 3 respectively.

Table 2. Chemical composition of 1060 pure aluminium (mass fraction, %).

Base material	Si	Fe	Cu	Mg	Mn	V	Zn	Ti	Others	Al
1060	0.25	0.35	0.05	0.05	0.03	0.05	0.05	0.03	0.02	Balance

Table 3. Chemical composition of Q355B steel plate (mass fraction, %).

Base material	C	Si	Mn	P	S	Ni	Cr	Cu	Others	Fe
Q355B	0.24	0.55	1.6	0.035	0.035	0.3	0.3	0.4	0.01	Balance

Before welding, one must polish the aluminium and steel materials used in the test until they are shiny. Then one must remove any oil and rust from the workpiece surfaces to avoid defects such as pores and slag inclusions, ensuring that the weld joints are not affected by surface impurities. Also, one has to secure the cleaned aluminium and steel plates to the test platform and weld according to the set process parameters.

3.1.2 Selection and Determination of Basic Process Parameters

The experiment used the special flux JW-05A6 as the matrix component, along with auxiliary element powders. The choice of coating composition was crucial during the experiment, requiring an appropriate coating composition and thickness. Extensive testing was conducted on coatings with varying compositions. Welding process parameters, such as welding voltage, welding current, wire feed speed, arc length correction, pulse size, and shielding gas flow, significantly influence the microstructure and mechanical properties of the welded joint. Therefore, optimal welding parameters were crucial to achieve high-quality welds, and we conducted extensive testing on these parameters.

We welded multiple groups of samples under different coating compositions and coating thicknesses, as well as different welding process parameters, and conducted mechanical property tests and microstructure analyses. The experiment used 99.999 % high-purity argon as the shielding gas, and the welding experiment was carried out by adjusting different welding voltages, currents and coating compositions.

Some of the process parameters determined in the experiment are given in Table 4:

Table 4. Welding process parameters.

No.	Basic Parameter	Parameter Value
1	Welding wire diameter	1.2 mm
2	Welding wire brand	Pure aluminium welding wire with alloy added
3	Welding torch movement mode	Oscillation mode
4	Distance from welding torch nozzle to workpiece (mm)	15
5	Welding wire extension (mm)	12
6	Angle between welding torch and forward direction (°)	105
7	Set current (A)	110–150
8	Arc starting current (%)	150
9	Arc extinguishing current (%)	60
10	Shielding gas	Ar
11	Gas flow setting value (L/min)	20
12	Pre-purge time (s)	1
13	Post-purge time (s)	2
14	Arc length correction value	0

3.1.3 Performance Testing of Welded Joints

We took samples of the welded specimens for tensile and shear tests. The specimen with the highest tensile strength presented 95.6 MPa. The macroscopic appearance of the tensile specimen and the fracture of the specimen are shown in Figure 1 (the length of the tensile specimen in the figure is 200 mm, and the cross-sectional size at the weld is 25 × 25 mm). There are no defects such as slag inclusions and pores at the fracture position. The specimen with the highest shear strength reached 116 MPa. The macroscopic appearance of the fracture of the shear specimen and the specimen is shown in Figure 2 (the length of the shear specimen in the figure is 60 mm, and the diameter is 10 mm). Obvious fracture marks of the aluminium base material can be seen at the fracture position.

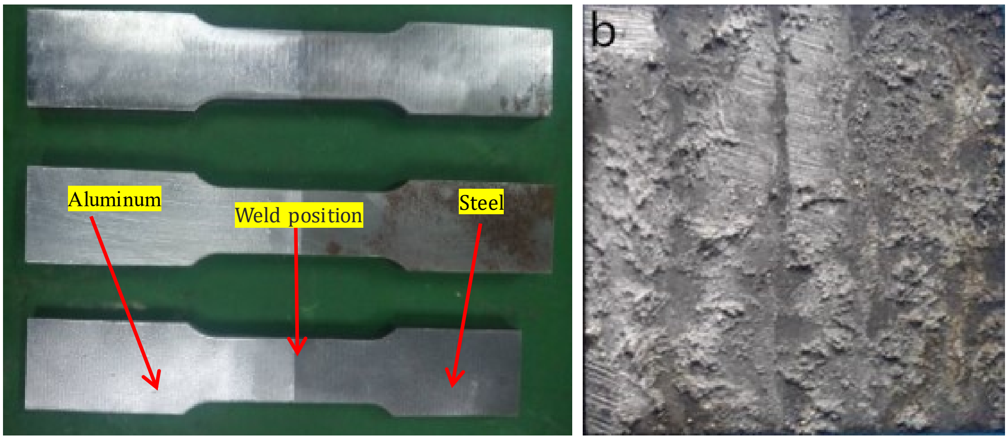

Figure 1. Left: Tensile specimen. Right: The macroscopic morphology of the tensile specimen's fracture surface.

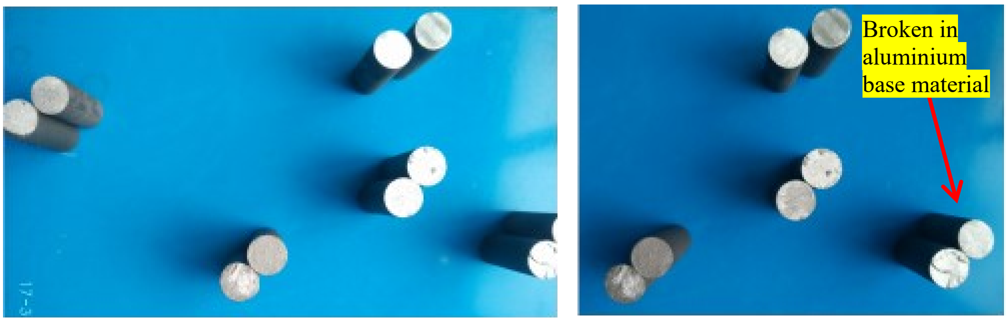

Figure 2. The macroscopic morphology of the shear specimen's fracture surface.

3.1.4 Section Testing

During the test, we performed direct welding of the anodized aluminium rod to the steel yoke, and direct welding of the cathode collector bar to the cathode aluminium flexibles. We then sectioned the welds to test the weld quality, as shown in the following Figure 3.

The Figure 3 (left) clearly shows that the weld joint between the steel and aluminium is well fused, with no defects such as slag inclusions, pores, or unfused components. Compared to the conventional method of Figure 4, the developed method eliminates the explosion weld block, reducing the amount of explosion weld block material and the weld joint between the explosion weld block and the steel yoke.

The Figure 3 (right) clearly shows that the aluminium flexibles and cathode collector bars are not transitioned using the explosion welding clad. Compared to conventional method of Figure 5, the developed method not only eliminates the explosion weld block, but also eliminates the steel connecting piece and its two welds.

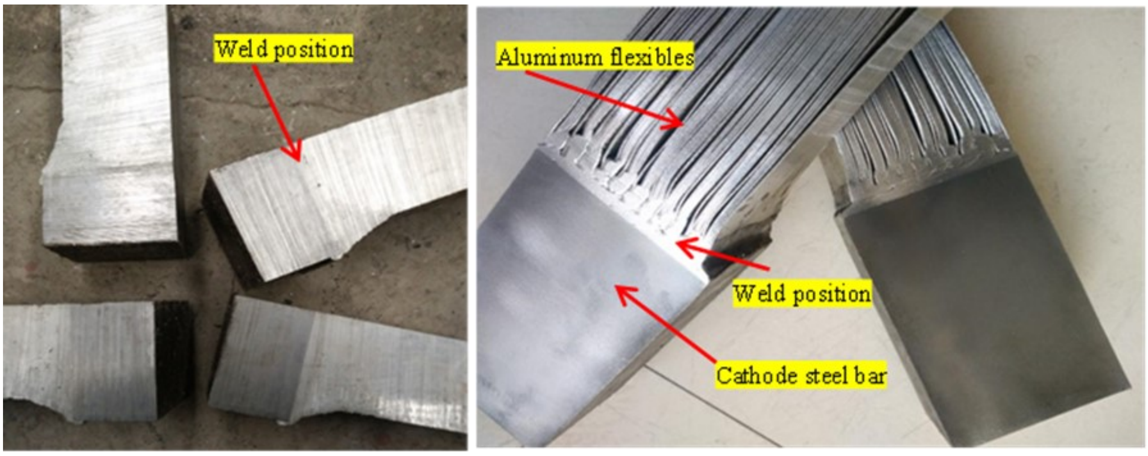

Figure 3. Left: Inspection of anode steel-aluminium welding section. Right: Inspection of cathode steel-aluminium welding section.

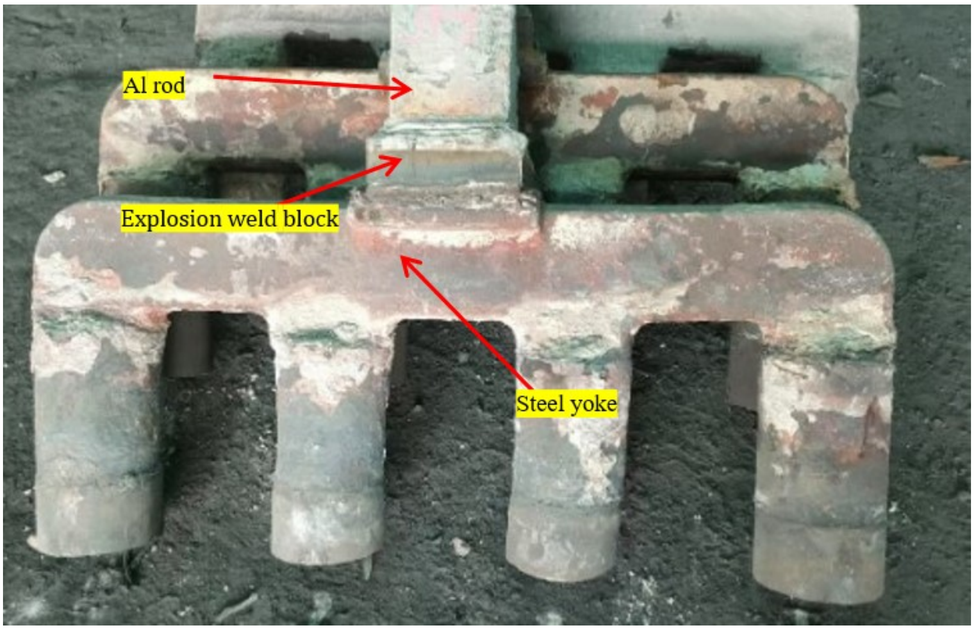

Figure 4. Traditional method—aluminium rod and steel yoke are connected by explosion welding blocks.

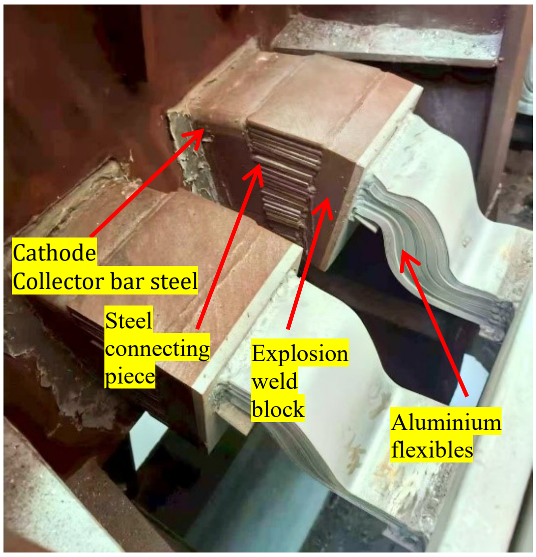

Figure 5. Traditional method—aluminium flexibles and cathode steel collector bar are connected by explosion weld block.

3.1.5 Weld Microstructure Analysis

Metallographic specimens were obtained by wire cutting of the welded workpiece. The sample surface was abraded with sandpaper to remove the oxide layer and contaminants, resulting in a smooth and even surface. The sample was then cleaned with alcohol to remove residual abrasive and impurities. EDS (Energy Dispersive Spectroscopy) analysis was then performed and shown in Figures 6–9.

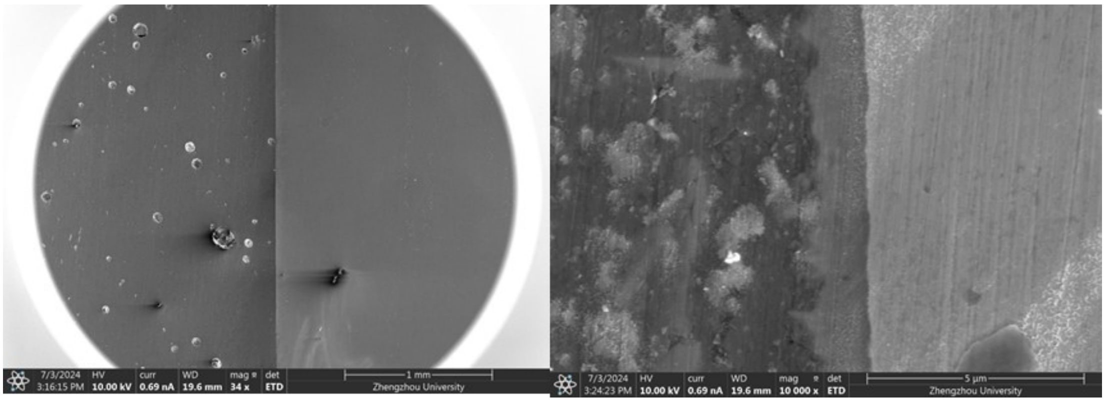

Figure 6. Left: Appearance of the weld joint under 34× magnification. Right: Line scan appearance of the weld joint under 10 000× magnification.

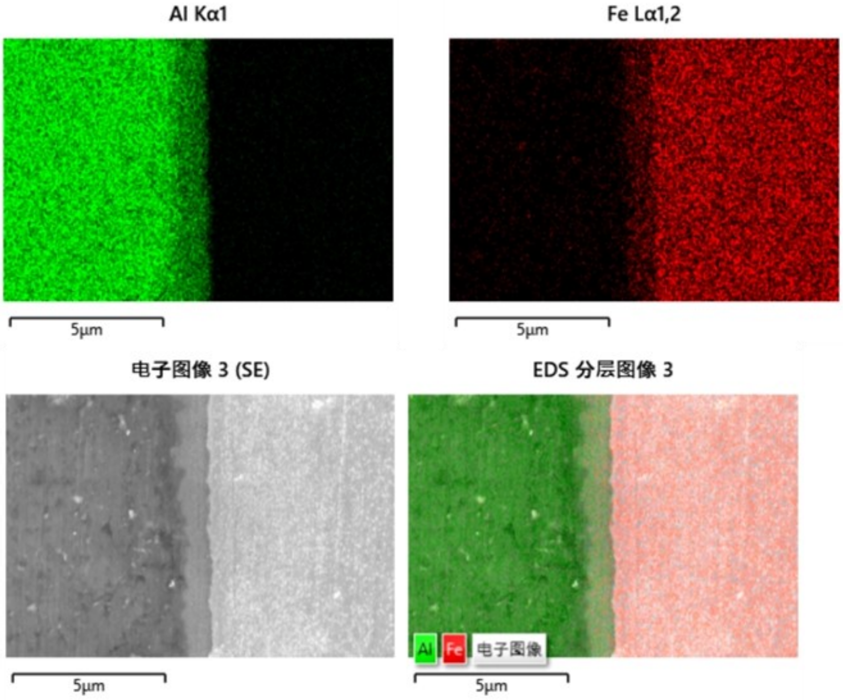

Figure 7. Surface scan morphology and structure of the weld joint.

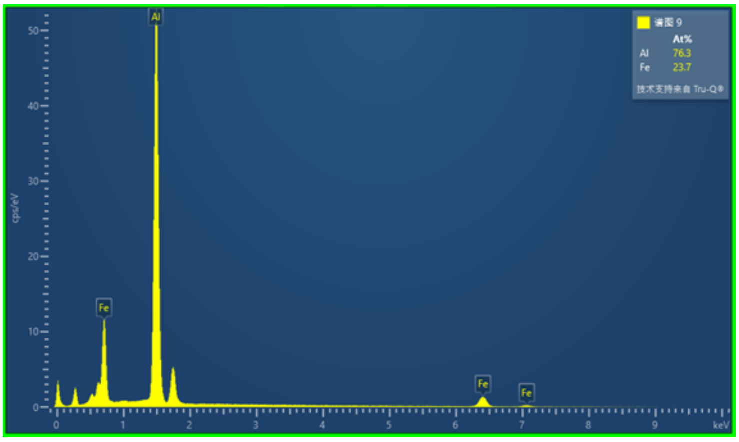

Figure 8. Energy dispersive spectroscopy (EDS) analysis diagram of the weld joint position.

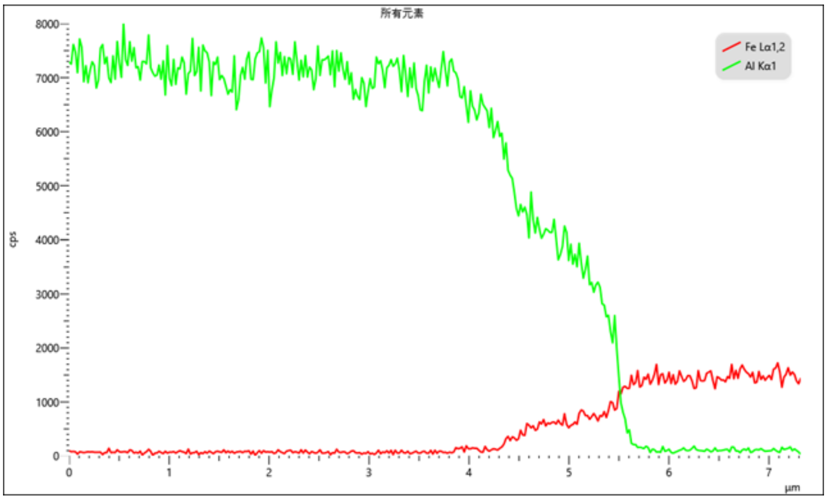

Figure 9. Energy spectrum analysis diagram of intermetallic compound aggregation area.

It can be seen from the results of energy spectrum analysis that the thickness of the intermetallic compound is 1.4 μm. This area is mainly composed of Fe and Al. The intermetallic compounds generated in this area may be $FeAl_3$, $FeAl_2$, Fe_2Al_5, Fe_3Al and $FeAl_6$, but the thickness of the intermetallic compound is controlled within a good range and the weld brittleness is low.

3.2 Narrow-Gap Full-Section Welding Process Test for Large-Section Workpieces

3.2.1 Selection and Determination of Process Parameters for Narrow-Gap Full-Section Welding of Large-Section Workpieces

For the narrow-gap full-section welding of large-section workpieces, we started with the principles of the welding method of box beams, optimized and improved it on this basis, realizing the synchronous control and simultaneous welding of multiple welding wires, thus increasing the size range of weldable workpieces. The test material was cathode steel collector bar (Q235B); cross-sectional dimensions: 198 × 120 mm, length 300 mm. The two workpieces to be welded have the same specifications and dimensions. Before welding, the surface of the workpieces was firstly cleaned of slag to avoid the formation of defects such as slag inclusions and pores.

First, the steel collector bar pieces to be welded are aligned. The steel can be formed into a vertical surface, eliminating the need for bevelling. An arc-starting device is installed at the bottom of the steel, and moulds are placed on either side of the weld seam. The workpiece and mould form a sealed welding cavity with an open top and surrounding edges. During welding, a protective agent is applied to prevent high-temperature oxidation of the metal in the weld seam. For the test, two welding wires are used simultaneously (depending on the size of the cathode steel, there is no upper limit on the number of wires that can be welded simultaneously).

The main parameters of this experiment are: welding voltage, welding current, wire feed speed, assembly gap, slag pool depth, number of welding wires, etc. These parameters play a decisive role in the stability of the welding process and the welding quality. The test found that for the test workpiece, when the welding current was less than 350 A, the weld width increased with increasing welding current. When the welding current exceeded 350 A and above, the weld width decreased. This range of variation varied with different welding conditions. Among all parameters, welding voltage, slag pool depth, assembly gap, and wire swing speed had the greatest impact on weld width, with welding voltage having the most significant influence. In the test, the welding voltage was adjusted within a range of 20–40 V. Adjusting the welding voltage was the most effective way to change the weld width.

The parameter that has the most significant effect on the depth of the molten pool is the welding current. In the experiment, as the welding current increases, the depth of the metal molten pool increases sharply. The adjustment range of the welding current in the experiment is 200–650 A. In the test, the welding wire diameter was selected as 2.5 mm. According to different workpiece specifications, multiple welding wires can be used for simultaneous welding. Coiled welding wire was used for welding cathode steel collector bar, and barrelled welding wire was used for welding anode steel yokes.

3.2.2 Mechanical Properties Testing

We commissioned a third-party testing agency to test the tensile, flexural, and impact strength of the welded joints (testing standards: GB/T228.1-2010; GB/T232-2010; GB/T229-2007). Some of the results are as follows (Table 5):

Table 5. Mechanical properties test results.

<table>
<tr><th colspan="5">Tensile test results</th></tr>
<tr><th>Specimen number</th><th colspan="2">Tensile strength, Rm MPa</th><th>Fracture location</th><th>Remarks</th></tr>
<tr><td>SQ1-A-1</td><td colspan="2">393</td><td>Broken in the base material</td><td>Q235</td></tr>
<tr><td>SQ1-A-2</td><td colspan="2">386</td><td>Broken in the base material</td><td>Q235</td></tr>
<tr><td>SQ1-A-3</td><td colspan="2">382</td><td>Broken in the base material</td><td>Q235</td></tr>
<tr><td colspan="5">Bending test results</td></tr>
<tr><td>Test number</td><td colspan="2">Cold bend d = 4a ≥ 120°
The diameter of the bending centre (d) is 4 times the thickness of the specimen (a)</td><td colspan="2">Remarks</td></tr>
<tr><td>SW1-B-1</td><td colspan="2">Qualified</td><td colspan="2">Q235</td></tr>
<tr><td>SW1-B-2</td><td colspan="2">Qualified</td><td colspan="2">Q235</td></tr>
<tr><td>SW1-B-3</td><td colspan="2">Qualified</td><td colspan="2">Q235</td></tr>
<tr><td colspan="5">Impact test results</td></tr>
<tr><td rowspan="2">Test number</td><td rowspan="2">Notch location</td><td rowspan="2">Test temperature ℃</td><td colspan="2">Impact energy KV2 （J）</td></tr>
<tr><td>Unit value</td><td>Average value</td></tr>
<tr><td>SIT1-C-1</td><td>Heat-affected zone</td><td>23 ±5</td><td>17</td><td rowspan="3">19.3</td></tr>
<tr><td>SIT1-C-2</td><td>Heat-affected zone</td><td>23 ±5</td><td>21</td></tr>
<tr><td>SIT1-C-3</td><td>Heat-affected zone</td><td>23 ±5</td><td>20</td></tr>
</table>

3.2.3 Microstructure Analysis

During the experiment, we determined two welding parameters that achieved mechanical properties equivalent to those of the base material. We also compared the grain size of each Specimen. Figure 10 clearly shows that Specimen 1 has a smaller and more uniform grain size than Specimen 2. Therefore, the welding parameters for Specimen 1 were ultimately selected as the final parameters.

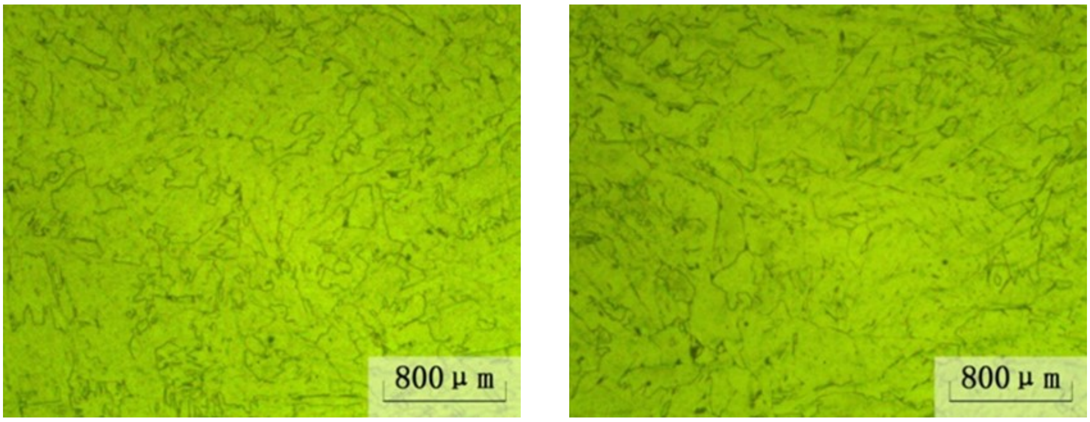

Figure 10: Left: Specimen 1, 12.5X. Right: Specimen 2, 12.5X.

4. Industrial Applications

4.1 Industrial Applications of Steel-Aluminium Direct Welding Technology

At present, the steel-aluminium direct welding technology has been applied to the direct welding of anode rods and steel yokes, and has begun to take shape in industrial applications. The following Figure 11 shows the on-site application situation.

Figure 11. Industrial application of direct welding technology for steel and aluminium.

4.2 Industrial Application of Narrow-Gap Full-Section Welding Technology for Large-Cross-Section Workpieces

Currently, narrow-gap full-section welding technology for cathode steel collector bars and anode steel yokes has been implemented in the vast majority of domestic aluminium smelters, significantly improving welding quality and results compared to traditional methods, as shown in Figure 12 and Figure 13.

Figure 12. Industrial application of cathode steel collector bar narrow-gap full-section welding.

Figure 13. Industrial application of narrow-gap full-section welding of anode steel stubs.

5. Conclusions

5.1 Steel-Aluminium Direct Welding Technology

(1) This technology is the first in China to directly weld anode aluminium rods and steel yokes, and aluminium flexibles and cathode collector bars, replacing the traditional explosion welded transition joint method.
(2) This steel-aluminium direct welding technology has been industrialized for the first time in China. Field data testing shows that the weld voltage drop in a 400 kA electrolysis cell is approximately 10 mV lower than that of explosion block welding, as shown in Figure 14.

To date, this technology has shown positive results, reducing the weld voltage drop by approximately 10 mV compared to traditional welding methods.
(Note: The traditional explosive welding method requires replacement every five years. The replacement frequency is around six years after adopting aluminium-steel direct welding.)

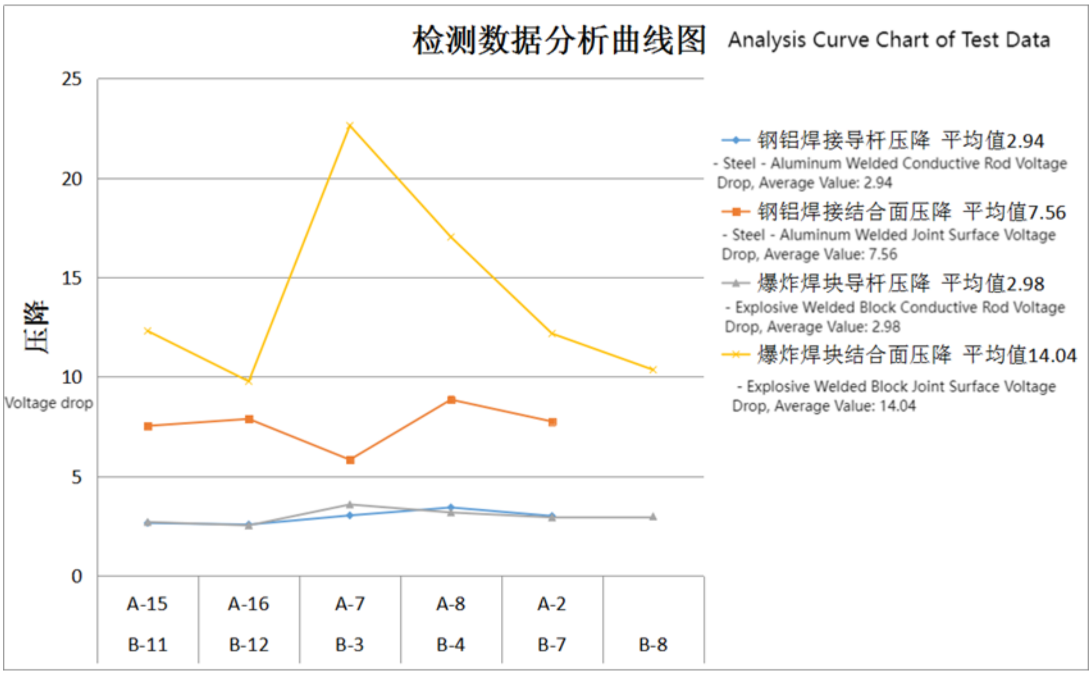

Figure 14. Measured voltage drop at connections. Traditional versus present work.

5.2 Narrow-Gap Full-Section Welding Technology for Large-Cross-Section Workpieces

(1) The narrow-gap full-section welding method changes the welding method for large-section steel connectors, enabling full-section welding. The entire process is automated, eliminating human interference and significantly improving welding efficiency. The mechanical properties of the finished welded joint are comparable to those of the original base material, and its electrical conductivity is comparable to that of the base material. This effectively reduces the voltage drop across the welded joint, which is of great significance for energy conservation and consumption reduction in aluminium electrolysis production.
(2) The narrow gap full-section welding of cathode steel collector bars can be applied to the welding of cathode collector bars with different specifications and sizes in various potlines under strong magnetic field environments. It has been applied in most domestic aluminium smelters with positive field results.
(3) Full-section welding of anode steel stubs significantly improves welding efficiency, ensuring that the finished joints can reach the lifespan of the new steel stubs, significantly reducing production and operating costs.

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