Original Article

Preliminary study of friction stir overlap welding on variable polarity plasma arc weld

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\textbf{A R T I C L E  I N F O}

Article history:
Received 23 August 2019
Accepted 24 October 2019
Available online 8 November 2019

Keywords:
VPPA
FSW
Overlap weld
Mechanical properties
Metallurgical processes

\textbf{A B S T R A C T}

The friction stir overlap welding on variable polarity plasma arc (FSOW-VPPA) weld was first proposed for a complete girth weld in 2219 aluminium alloy. The mechanical properties, microstructures, and metallurgical processes of FSOW-VPPA in comparison to single-FSW and VPPA welded joints were studied in this paper. The FSOW-VPPA welded joint was characterized by the modified nugget zone (NZ), thermo-mechanically affected weld zone (WZ), heat affected fusion zone (FZ), and double heat affected zone (HAZ). The modified NZ was characterized by “onion-rings” without the porosity that appeared in the VPPA weld. The grains in the thermo-mechanically affected WZ were finer than that of the VPPA weld. In the second thermal cycle, the angle of the direction of crystal growth from the horizontal decreased from 38 degrees in the VPPA weld to 22 degrees. In contrast with the single-FSW weld, there was no serious deformation on the advancing side (AS). In general, the second thermal cycle did not degrade the quality of the weld. The elimination of pores and grain refinement improved both the tensile strength and elongation of the FSOW-VPPA weld compared to the VPPA and single-FSW welds. The tensile strength increased to 84.0% compared to 79.8% for the VPPA weld. In addition, the metallurgical processes were analysed and compared.

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1. Introduction

Aluminium alloy is one of the most widely used materials in the industry. Due to the good weldability of 2219 aluminium alloy, it has become the preferred material in many manufacturing processes such as the tank dome of launch vehicles \cite{1,2}. Compared to other types of welding processes, Variable Polarity Plasma Arc (VPPA) welding presents many advantages, such as ease of automation and higher efficiency \cite{3,4}. However, VPPA welding alone is not sufficient to complete the whole process for the girth welding of a pipeline, because it...
requires keyhole closure to achieve the circumferential weld [5–7]. A keyhole usually remains after the arc is extinguished and needs to be repaired by other welding processes.

To this date, much published research focuses on producing a stable keyhole [6,7]. This benefits the weld formation and quality but not the keyhole closure. Two technical approaches have been proposed for keyhole closure by controlling the current and welding speed [5]. This successfully closes the keyhole, but the mechanical properties of the overlap weld such as hardness and tensile strength are weaker than that of the single pass weld. Consequently, the overlap weld becomes a source of trouble for the whole weld. Thus, it is necessary and significant to study the modification process of refining this overlap weld, as a basis for improving the performance of girth welds.

Recently, Friction Stir Welding (FSW) has been proposed to improve the aluminium weld performance [8–10]. FSW is a new technology of solid phase joint by the advantages of small heat input and deformation. This process can eliminate the side-effects associated with re-solidification in fusion welding, although some defects exist, such as cold traps and gas cavities in the orthogonal cross joints of FSW and VPPAW. Compared with the VPPA weld, the microstructure of the intersection weld is characterized by asymmetry and inhomogeneity in the orthogonal cross joints [11]. Besides, the method to solve the keyhole left by FSW has been reported in the previous researches [12,13]. There are two methods to solve the hole left after FSOW. First, the stirring pin was lifted out slowly in the final stage of FSW, and the hole would be filled with the base metal. Second, a guide plate should be used at the end of the FSOW weld, the final hole left after FSOW will be left on the guide plate to ensure the integrity of the FSOW-VPPA weld. If an FSW was conducted on VPPA weld, the keyhole left by VPPAW could be solved by FSW while the keyhole left by FSW could be solved with the above methods. Thus, the synclastic overlap weld of FSW on VPPAW was proposed in this research. To the authors’ best knowledge, the reports focusing on this issue was limited.

In this paper, the friction stir overlap welding on VPPA weld (FSOW-VPPA) was first proposed to complete the girth welding of aluminium alloys. Experimental simulation of girth welding was conducted using plate butt welding to study its mechanical properties and metallurgical processes. The optimized parameters of FSOW-VPPA were proposed. The micro- and macro-structure and mechanical properties of the FSOW-VPPA welds were tested in comparison with those of single-FSW and single-VPPA. Finally, metallurgical processes for the FSOW-VPPA were discussed and analysed.

### Table 1 – Chemical compositions of base metal 2219 and filler wire ER2319 (wt%).

<table>
<thead>
<tr>
<th>Elements</th>
<th>Cu</th>
<th>Mg</th>
<th>Si</th>
<th>Zn</th>
<th>Mn</th>
<th>Ti</th>
<th>Ni</th>
<th>Fe</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base metal</td>
<td>5.8–6.8</td>
<td>0.2–0.4</td>
<td>&lt;0.2</td>
<td>&lt;0.1</td>
<td>0.2–0.4</td>
<td>0.02–0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.3</td>
<td>Balance</td>
</tr>
<tr>
<td>Filler wire</td>
<td>5.8–6.8</td>
<td>&lt;0.2</td>
<td>&lt;0.2</td>
<td>&lt;0.1</td>
<td>0.2–0.4</td>
<td>0.1–0.2</td>
<td>&lt;0.1</td>
<td>&lt;0.3</td>
<td>Balance</td>
</tr>
</tbody>
</table>

2. **Materials and methods**

2219 aluminium alloy with a thickness of 6 mm and ER2319 with a diameter of 1.6 mm are selected as the welding plates and filler wire. The standard chemical compositions of both materials are listed in Table 1 [14,15]. Before welding, several steps such as acid pickling and oxide removal are required to eliminate the influence of external factors on the welding results.

Using FSOW to complete the VPPA girth welding, an overlap weld is inevitable. Experimental simulation of FSOW-VPPA on plate welding was conducted to study the weld performance and mechanical properties. A schematic diagram to show how the FSOW-VPPA works was shown in Fig. 1. First, vertical-up VPPA butt welding was adopted to butt joint the plates using an independently developed VPPA-S00 power source. During VPPA, the welding process and the wire feed speed was controlled to reduce the reinforcement height and penetrated backside height. Then, to ensure the rigor of tooling during FSOW process, a milling cutter was used to remove the reinforcement and penetrated backside height caused by VPPA welding process, since the reinforcement couldn’t be totally avoided with controlling the welding parameters. Finally, the FSOW process was carried out on the VPPA weld. For both FSOW and single-FSW welds, flat welding was used, single-FSW as a reference. The equipment (FSW-TS-08) and stirring head (HM3) were provided by China FSW Centre. Generally, the weakest links of the welded joint in VPPA and single-FSW are the area near the heat affected zone and advancing side (AS), respectively. If they combine together in overlap welding, the quality of this area will be worse. That is, if the FZ of VPPA weld was completely consumed by the nugget of FSOW weld, the double heat affected zone may be worse. So the present paper selected the welding tool with a shoulder of 15 mm diameter and a probe tilted 1.5° with a root diameter of 5.91 mm, a tip diameter of 2.69 mm and length of 5.81 mm. This setup can make the nugget zone of the single-FSW smaller than the fusion zone of the VPPA weld by separating the weakest link in the two welding processes. As a result, the nugget zone was completely consumed by the fusion zone. The welding sources and welded platforms used in both welding processes are shown in Fig. 1. Both the welding parameters of VPPA and FSW were the result of many initial tests, and the parameters are shown in Table 2.

The present paper is a preliminary study of friction stir overlap welding on variable polarity plasma arc weld with the goal of studying the weld performances and mechanical properties of FSOW-VPPA process. Weld performances, mechanical properties, and microstructures of the WZ and FZ were studied after a series of experiments, as shown in Fig. 2. Fig. 2(a) is a schematic diagram of a FSOW-VPPA weld. The clamping accuracy of FSOW is seriously affected by the large weld reinforcement on the surface and root surface. Consequently, the weld reinforcement must be removed before the FSOW-VPPA welding process. The microhardness was measured with Vicker’s method under a load of 100 g for 15 s. The sampling points are shown in Fig. 2(b). Tensile tests were carried out at room temperature using the universal testing machine.
Table 2 – The welding parameters for VPPA and FSW.

<table>
<thead>
<tr>
<th>VPPA</th>
<th>FSW</th>
</tr>
</thead>
<tbody>
<tr>
<td>DCEN (A)</td>
<td>Rotation speed (rpm)</td>
</tr>
<tr>
<td>165</td>
<td>700</td>
</tr>
<tr>
<td>195</td>
<td></td>
</tr>
<tr>
<td>140</td>
<td></td>
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</table>

Fig. 3 is the weld performances and welded joints, Fig. 3(a)–(c) are the front view and back view of welds of VPPAW, single-FSW, and FSOW-VPPA, respectively. All the weld beads were

3. Results
3.1. Weld performances and welded joints
Fig. 3 – Weld performances and welded joints, (a)–(c) are the weld performances of VPPAW, single-FSW and FSOW-VPPA, (e)–(f) are the welded joints of VPPAW, single-FSW and FSOW-VPPA.

Table: Weld seam and welded joint

<table>
<thead>
<tr>
<th>VPPA</th>
<th>Weld seam</th>
<th>Welded joint</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>Front view</td>
<td>BM HAZ WZ HAZ B</td>
</tr>
<tr>
<td>(b)</td>
<td>Back view</td>
<td>3mm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FSW</th>
<th>Front view</th>
<th>TMAZ AS HAZ NZ AS</th>
</tr>
</thead>
<tbody>
<tr>
<td>(c)</td>
<td>Front view</td>
<td>10mm</td>
</tr>
<tr>
<td>(d)</td>
<td>Back view</td>
<td>BM HAZ WZ HAZ</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>VPPA + FSW</th>
<th>Front view</th>
<th>Double HAZ NZ HAZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>(e)</td>
<td>Front view</td>
<td>10mm</td>
</tr>
<tr>
<td>(f)</td>
<td>Back view</td>
<td></td>
</tr>
</tbody>
</table>

excellent without obvious welding defects. Fig. 3(d)–(f) are the welded joints of VPPAW, single-FSW, and FSOW-VPPA. In general, the weld of VPPA is divided into three zones: WZ, FZ, and heat affected zone (HAZ). The single-FSW weld is divided into the nugget zone (NZ), thermo-mechanically affected zone (TMAZ), and HAZ. Fig. 3(d) is cross section of VPPA weld shown in Fig. 3(a), the cutting position is marked as red line. In the welded joint of VPPA, the weld widths of the surface and root-surface were about 9.3 mm and 5.4 mm. The diameters of the root and tip of the stirring pin were 5.91 mm and 2.69 mm, and the weld widths of surface and root-surface of single-FSW were almost equal to the diameter of the stirring pin. In the FSOW-VPPA welded joint, the FSOW weld was within the WZ of the previous VPPA weld. The FSOW-VPPA weld had both the characteristics of VPPA and single-FSW, and both widths of weld surface and root-surface were equal to that of the VPPA. Under the second thermal cycle process, the weld was divided into the modified NZ, thermo-mechanically affected WZ, heat affected FZ, and double HAZ. The TMAZ was not noticeable in the FSOW-VPPA welded joint, because the materials in the WZ of the previous weld were softer than that of the BM.

3.2. Microstructure

Fig. 4 depicts the microstructure of the weld zone; Fig. 4(a)–(c) are VPPAW, single-FSW, and FSOW-VPPA respectively. In general, the grains are smaller in the WZ of VPPAW, but the performance and mechanical properties of the joint were reduced due to porosity, as shown in Fig. 4(a). The porosity was also an inevitable defect in the arc welding of aluminium alloy. The NZ consisted of fine equiaxed grain in conventional FSW, as shown in Fig. 4(b). During the process of FSOW-VPPA, recrystallization occurred in the WZ of VPPAW under the high-speed mechanical agitation and high-temperature thermal cycle, forming a modified NZ, as shown in Fig. 4(c). The grain and structure in this zone had both the characteristics of a VPPA and single-FSW weld. During recrystallization, the pores in the WZ disappeared, the grain was obviously refined, and the microstructure was similar to the “onion-rings” of single-FSW. It can be seen that FSOW had a great influence on the microstructure of the WZ.

Generally, the weakest links of the welded joint in VPPAW and single-FSW are the FZ and advancing side (AS), respectively. It is closely related to the structure and direction of crystal growth. Fig. 5 is the microstructures of the FZ in VPPAW, TMAZ of AS in single-FSW, and AS of FSOW-VPPA. Fig. 5(a) is the typical FZ of VPPAW. The grain and structure were greatly affected by the thermal cycle due to its proximity to the welding arc. The grain size was obviously larger than that of the WZ. In addition, there existed noticeably directional columnar crystal growth within this region. Dendrite growth was perpendicular to the direction of the temperature gradient during weld solidification at an angle of 38 degrees between the direction of crystal growth and the horizontal direction. In the TMAZ of AS in single-FSW, the bending deformation of microstructure was more obvious. The relative velocity and shear rate at the interface between the stirring pin and the workpiece on the AS were higher than those of the retreating side (RS), resulting in a higher temperature at the AS. Both the higher temperature and relative velocity contributed to the bending deformation of the structure. The affected TMAZ in FSOW-VPPA is shown in Fig. 5(c), the transitional region of WZ to BM and NZ to WZ are shown in Fig. 5(e) and (f). In the second thermal cycle, the angle between the direction of crystal growth and the horizontal direction in the heat affected FZ of VPPA weld decreased to 22 degrees. This indicates that the stress was released during the second thermal cycle, and the grain structure was still columnar. The TMAZ in the FSOW-VPPA weld was quite different from that of the single-FSW. There was no bending deformation near this zone. Fine grain
zone formed instead of the bending deformation. Both of those characteristics are beneficial to the weld’s performance and mechanical properties.

3.3. Mechanical properties

Fig. 6 is the hardness distribution of the whole welded joints. Fig. 6(a) is the hardness of VPPA weld, ranging from 77.41 HV to 120.77 HV. The hardness was evenly distributed from the weld surface to the root-surface. The porosity in the WZ reduced the hardness, and the average value of the WZ was about 90.91 HV, which was lower than the FZ and BM. For the single-FSW, the lowest hardness appeared in the AS and RS. The average hardness at AS was 91.39 HV, and 93.60 HV at RS. The hardness was lower at the AS owing to serious compressional deformation of the microstructure. And the hardness at the NZ gradually decreased from the top-surface to the root-surface of the welded joint, as shown in Fig. 6(b). The average value at NZ was about 98.21 HV, which was higher than that of the weld in VPPA because of the fine equiaxed grain distribution in the NZ of single-FSW. The hardness distribution of FSOW-VPPA weld was more complex and had both the characteristics of single-FSW and VPPA but was different from them, as shown in Fig. 6(c). The average value of the hardness in the modified NZ was about 89.49 HV and close to the value of VPPA weld, but lower than that of single-FSW. The hardness distribution at the modified NZ did not vary with depth, in contrast to the distribution in the single-FSW weld, which was harder at the surface. The lowest hardness in the FSOW-VPPA weld was distributed in the affected FZ of AS, with an average value around 85.49 HV. The distribution gradient at the FSOW-VPPA welded joint was flatter and more even than the single-FSW and VPPA welds.

The fracture positions of the tensile specimens were also different because of different heat treatment processes, as shown in Fig. 7. The VPPA weld joint fractured at the
FZ under the tensile load, which was caused by the coarse grains and direction of dendritic growth near the FZ, as shown in Fig. 5(a). Both the welds of single-FSW and FSOW-VPPA fractured at the HAZ of AS as a result of the inherent characteristics of the single-FSW welding process, as shown in Fig. 5(b)-(c). The coordination of AS during deformation affected by thermomechanical treatment processing was poorer than that of RS. This also revealed that the weld of FSOW-VPPA had the fracture characteristics of the single-FSW.

The tensile strengths are shown in Fig. 8. Fig. 8(a) is the average ultimate tensile strength of two tensile samples located in the middle of the weld seam and (b) shows the elongation and reduction of area. The average ultimate tensile strength of the VPPA welded joint was 286.9 MPa, and the tensile strength was 359.3 MPa in the BM; thus, the tensile strength of the VPPA weld reached about 79.8% of that of the BM. As to the single-FSW weld, the tensile strength was 330.6 MPa, 92.0% of that of BM. Welding defects easily appeared in the FZ of VPPAW due to the higher temperature gradient and cooling rate, consequently, the ultimate tensile strength was lower than that of the single-FSW. The tensile strength of the FSOW-VPPA welded joint was 301.7 MPa, 84.0% of that of BM. The tensile strength was increased by 4.2% in comparison with that of VPPAW. Both elongation and reduction of area improved significantly, as shown in Fig. 8(b). The average elongation and reduction of area in the FSOW-VPPA welded joint was 5.2% and 20.3% respectively, which was higher than the 3.2% and 6.4% in the single-FSW weld and higher than the 2.2% and 7.5% in the VPPA weld. The second thermal cycle did not reduce weld performance but instead improved it for the FSOW-VPPA weld.

4. Discussion

The mechanical properties are greatly influenced by the metallurgical process and thermal cycles. The HAZ at the AS of single-FSW weld was the softest area due to the following two reasons. HAZ could probably be attributed to the dissolution of precipitates induced by the thermal cycle during the welding process [16]; serious extrusion deformation of the material appeared during the thermal cycle, as shown in Fig. 5(b). The porosity in the VPPA welded joint was one of the main reasons for its poor mechanical properties, and the reduced hardness and tensile strength in the FZ also resulted from the deterioration of constituents during the thermal cycle [17]. This was consistent with the research of Shinoda et al. [18]. In this study, the mechanical properties of FSOW-VPPA are shown to be superior to the VPPA weld. The characteristics of fracture surface were studied using SEM for further analysis, as shown in Fig. 9.

The fracture surface was characterized by cracked second-phase particles and shallow dimples; this would suggest that an extensive plastic deformation occurred during the tensile test and the failure mode of BM was ductile failure [19,20], as shown in Fig. 9(a). Fig. 9(b) is the fracture surface of single-FSW
Fig. 8 – The mechanical properties, (a) tensile strength, (b) elongation and reduction of area.

Fig. 9 – The characteristics of fracture surface, (a) BM, (b) single-FSW, (c)-(d) VPPA, (e)-(f) FSOW-VPPA.
weld, with a large number of deep dimples of different sizes and tearing ridges. It fractured at the HAZ of AS, as shown in Fig. 7(b), and the failure mode was also ductile failure. Some pores appeared at the fracture surface of VPPA weld, as shown in Fig. 9(c)–(d). Due to the higher temperature gradient and cooling rate at the FZ of VPPA weld, the gas in the melting metal had no time to dissolve or escape, resulting in porosity, as shown in Fig. 4(a). This was the main reason for the reduced hardness and tensile strength of the VPPA weld. The tensile strength of the FSOW-VPPA weld was higher than that of the VPPA weld but lower than single-FSW and fractured at the HAZ of AS, the area with the lowest hardness, as shown in Figs. 6(c) and Fig. 7(c). The fractured surfaces are shown in Fig. 9(e)–(f). This revealed that the poor mechanical properties and porosity at the FZ of the VPPA were improved, and the stress caused by dendrite deformation was also relieved during the second thermal cycle. The fracture surface had deep dimples and tearing ridges with no porosity, suggesting that extensive plastic deformation occurred during tensile test similar to that of single-FSW. The tensile strength of FSOWVPPA weld was increased by 4.2%. The plastic deformation of it was also improved with the high tensile strength of the FSOW-VPPA welded joint. In comparison to the results of single-FSW and VPPAW, the elongation of FSOW-VPPA was increased by 2.0% and 3.0%.

The weld performance was affected by the metallurgical processes during the thermal cycles, as shown in Fig. 10. The BM of 2219 is composed of an α phase and strengthening phase (Cu-Al solid solution and CuAl2) according to the Al – Cu binary phase diagram [21,22]. The strengthening phase in the WZ was dissolved at the higher temperatures of VPPA and formed the low melting point eutectic, resulting in a reduced hardness [5] as shown in Fig. 6(a). Single-FSW is a solid phase joining process with the advantage of low heat input, the distribution of strengthening phase during this process was less than VPPAW, so the hardness distribution of single-FSW was higher than that of the VPPA weld.

The grain size in the modified NZ of FSOW-VPPA was finer than that of VPPA, as shown in Fig. 4, and smaller grain size led to increased hardness according to the Hall-Petch relationship [23]. In fact, the hardness of FSOW-VPPA was lower than that of VPPA weld. Wang et al. found that they could hardly precipitate the second phase particles, but could easily dissolve them in the process of overlap welding [5]. This may be the main reason there exists a reduced hardness in the modified NZ and thermo-mechanically affected WZ. The porosity also disappeared during that period, as shown in Fig. 5(c). The temperature at the FZ reached a certain value to dissolve the gas during the overlap welding process, as shown in Fig. 3(c). The weld performance was improved greatly after eliminating the porosity defects, as shown in Fig. 8, but it still cannot reach the strength of the single-FSW weld. Wang et al. pointed out that some low melting point strengthening phases (CuAl2) located at the crystal boundaries and in the crystals when the HAZ temperature near the weld pool reached a certain value [5]. The solubility of Cu in Al decreases with decreasing temperature according to the Al–Cu binary phase diagram [21,22], so the Cu in Cu–Al solid solution precipitated in the form of CuAl2 and diffused to the crystal boundaries in the area of HAZ. With further decreases in temperature, the low melting point eutectic (α phase + CuAl2) increased, resulting in a lower hardness at the double HAZ. As to the AS of the FSOW-VPPA, the lower cooling rate led to a long-time diffusion of the strengthening phase [24], resulting in a lower hardness distribution (Fig. 6(c)). HAZ softening was an unavoidable defect in the FSOW-VPPA process. Besides, the fractured position of FSOW-VPPA was at double HAZ at AS, conforming to the theory that the tensile strength decreases with decreasing hardness [23,25].

5. Conclusions

The friction stir overlap welding on variable polarity plasma arc (FSOW-VPPA) weld was first proposed to complete the circumferential weld joining end-to-end in 2219 aluminum alloy. Experimental simulation of welding processes was conducted to study the mechanical properties and metallurgical processes during girth welding. The following conclusions can be drawn:

1. The modified NZ of FSOW-VPPA was characterized by “onion-rings” without the porosity that appeared in the VPPA weld. Furthermore, the grains in the modified NZ were refined in comparison to that in VPPAW. The angle of the direction of crystal growth from the horizontal decreased from 38 degrees in the VPPA weld to 22 degrees during the second thermal cycle.

2. The average hardness in the FSOW-VPPA welded joint was 89.49 HV, close to the value of 90.91 HV for the VPPA weld but lower than that of 98.21 HV for the single-FSW weld. The lowest hardness in FSOW-VPPA was distributed in heat affected FZ of AS, with an average value of about 85.49 HV.
(3) The tensile strength of the FSOW-VPPA weld reached about 84.0% of that of the BM compared to 79.8% in the VPPA weld. However, it was still lower than the 92.0% of the single-FSW weld. The average elongation and reduction of area in the welded FSOW-VPPA joint was 5.2% and 20.3%, which was higher than the 3.2% and 6.4% in single-FSW weld and higher than the 2.2% and 7.5% in VPPA weld.

(4) Metallurgical analysis of the WZ and HAZ during the second thermal cycle has been carried out. The mechanical properties of the double HAZ decreased due to the precipitation of low melting point strengthening phases. However, the gas at the heat affected FZ can be dissolved during the second thermal cycle, resulting overall in enhanced mechanical properties of the welded joint.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was funded by the Natural Science Foundation of China, grant number: 51704013 and the Beijing Municipal Education Commission Fund, grant number: KM201810005016.

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