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# Study on the formation mechanism of pore in the intersection of VPPA and FSW<sup>†</sup>

YU Yang<sup>\*</sup>, LI Baotian<sup>\*</sup>, JIANG Fan<sup>\*</sup>, CHEN Shujun<sup>\*</sup>

**KEY WORDS:** (VPPA) (FSW) (Porosity) (Oxide)

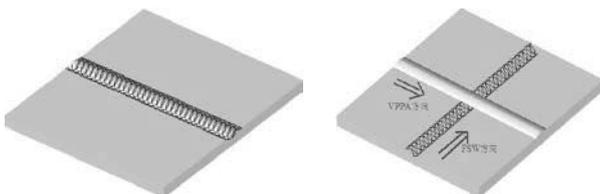
## 1. Introduction

Aluminium alloys are finding increased use in aerospace, transportation (automotive, shipbuilding) and chemistry industry due to their high strength-to-weight ratio, and remarkable ability to resist corrosion. The extensive application of aluminium alloys promotes the development of aluminium alloy welding technology; meanwhile the development of aluminium alloy welding technology extends the application of aluminium alloy.

Aluminum presents a high hydrogen solubility in the liquid and an important solubility gap between solid and liquid state. One of the major concerns during welding of aluminum alloys is the presence of porosity in the weld metal that can deteriorate mechanical properties, particularly tensile strength and elongation[1-3].

Variable polarity plasma arc welding (VPPAW) and Friction stir welding are two valuable welding processes for aluminum alloys. Compared with other arc welding processes, VPPAW can generate high weld quality and high productivity at relatively low cost. These attractive features are attributed mainly to a fully penetrated keyhole-mode weld pool, inside which hydrogen cannot be trapped, and to the removal of tenacious oxide film on the workpiece surface, which guarantees better fluidity of the metal in the weld pool[4]. Friction stir welding (FSW) is a relatively new solid state joining process[5] that offers the potential for joints with high fatigue strength, low preparation and little post-weld dressing. Other benefits include generally low defect populations (compared with fusion welding) and the ability to join dissimilar metals.

Joints without porosity can be produced by either VPPA or FSW. However complex structure can not be finished by one kind of welding process. Usually, space vehicle is produced with the support of several kinds of welding processes.



**Fig. 1** Overlapping welding specimens

There is a high possibility that sound joints will be obtained by either VPPA or FSW. However, only a limited number of studies have been done on defects in the intersection of VPPA and FSW. In this paper, several kinds of overlapping welding seam were prepared, and defects in the overlapping welding seam were detected. The mechanism of defects was further explored.

## 2. Experiment

The base metal used in this study was a 2219 aluminum alloy plate of 6 mm in thickness, whose chemical compositions are listed in **Table 1**.

**Table 1** Chemical compositions (wt.%)

Al	Cu	Mn	Fe	Si
Bal.	6.43	0.31	0.30	0.20

The plate was cut and machined into two kinds of rectangular welding samples: one is 400 mm in length and 200 mm in width; the other is 400 mm in length and 400 mm in width. After cleaned with acetone, two samples with dimension 400\*200mm were longitudinally butt-welded using an FSW machine, and stir-in-plate welding was performed on the middle of the 400\*400 samples. Then bead-on-plate welding was carried out on the plate with the butt-welded seam and plate with stir-in-plate welded seam by VPPA welding machine. Four kinds of overlapping joints were prepared. For the convenience, the sample with VPPA welded seam which is perpendicular to the butt-welded FSW seam is named BW+; the sample with VPPA welded seam in which the centerline is consistent with that of butted-welded FSW seam is named by BW-; the sample with VPPA welded seam which is perpendicular to the stir-in-plate welded FSW seam is named SIP+; and the sample with VPPA welded seam in which centerline is consistent with that of butted-welded FSW seam is named by SIP-. The schematic of overlapping welding is shown in **Fig. 1**.

Visual and X-ray radiography inspections of the overlapping joints were performed in order to reveal the weld defects on the surfaces and in the inner zones of the welded joint.

The configuration and size of the transverse tensile specimens were prepared with reference to China National Standard (GB2625-89), as shown in **Fig. 2**. The room

<sup>†</sup> Received on 30 September 2010

<sup>\*</sup> Beijing University of Technology, Beijing, China

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temperature tensile test was carried out at a crosshead speed of 1 mm/min using a computer-controlled testing machine and the tensile properties of each joint were evaluated using three tensile specimens cut from the same joint. After the tensile test, the fracture features of the joints were analyzed by OM and SEM mentioned above.

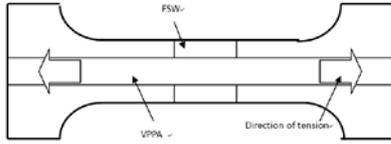


Fig. 2 Tension specimen

### 3. Results

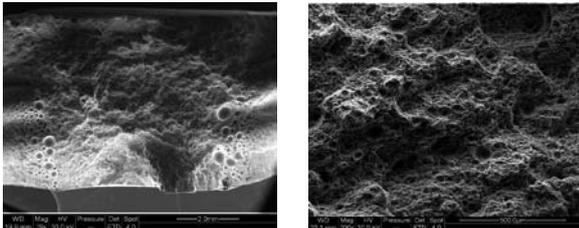
Table 2 shows the results of X-ray radiography inspections.

Table 2 Results of X-ray radiography inspections

	BW+	BW-	SIP+	SIP-
defect	Pores	No pore	No pore	No pore

Fracture surfaces of the tensile specimens are shown in Fig. 3(a). There are a lot of circular shape pores located in the neighborhood of fusion line at the root of the welding seam. The pores can be identified as hydrogen pores due to their smooth inner surface.

Figure 3(b) show the enlarged fusion-zone of the tensile fracture, and no pores but many dimples are observed.



(a) macrostructure (b) enlarging of fusion zone

Fig. 3 Tensile fracture surface

Typical microstructure of the cross-section of FSW joints is illustrated in Fig. 4. The micrograph was taken at the retreating side of the welded joint. The micrographs shown in Fig. 5 are for a specimen welded at welding speed of 180mm/min and tool rotational speed of 800 rpm. It is clear that, beside the BM, the macrostructure of the FSW alloy consists mainly of three distinct zones, typically, (i) fine grained dynamically recrystallised zone DRZ, (ii) thermo-mechanically affected zone (TMAZ) and (iii) heat-affected zone (HAZ). The TMAZ experiences both temperature and deformation during FSW and characterized by a highly deformed structure. The HAZ is the zone that is believed to be unaffected by any mechanical effects but only the thermal effects caused by the frictional heat generated by the shoulder and tool pin rotation.

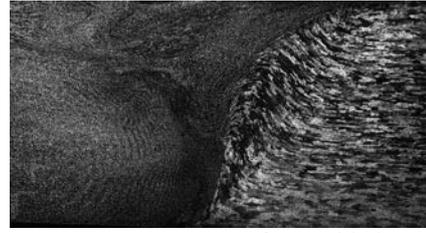


Fig. 4 Macrostructures of as-welded FSW

### 4. Discussion

Comparing the results of X-ray radiography inspections, pores can be found in the overlapping seam in the form of BW+, but there are no pores in the overlapping seam in the form of SIP+. The main difference between BW+ sample and SIP sample is that there are two initial surfaces of the BW+ sample. Conclusion that the oxide on the sample surface leads to the formation of porosity in the intersection of the BW+ sample can be drawn. With loosened structure, the oxide can adsorb water vapor easily. The water vapor can react with the molten metal, and produce hydrogen in the arc welding process.

Figure 5 is the enlarged picture of a tensile fracture, and it is obvious that some particles are located in some pores. The particles can be identified as aluminium oxide by EDX. Some fracture surfaces appeared as wave forms, as shown in Fig. 6, is identical with the fracture which tensile specimen bearing zigzag line [6]. Zigzag line is recently hypothesized to be due to entrapped oxide particles seeping from the specimen surface during welding [7], which can further confirm that the oxide is the source of hydrogen.

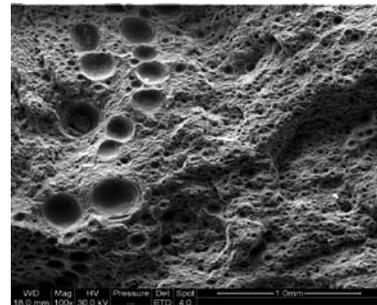


Fig. 5 pores with particle

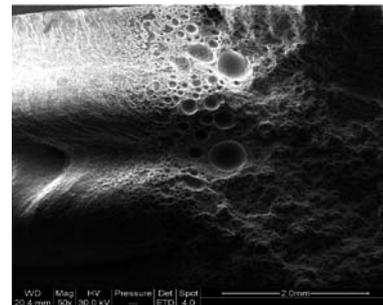


Fig. 6 Zigzag fracture

Although VPPA welding owing special process to avoid the formation of porosity, but if the hydrogen forms at the root of molten pool where temperature is low, the molten metal solid quickly. The hydrogen is trapped in the welding seam.

### 5. Conclusions

When an arc welding seam meets with the FSW seam, porosity is the usual defect in the intersection of above two different welding seams.

The entrapped oxide seeping from the specimen surface leads to the formation of porosity in the intersection of FSW with VPPA.

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