Original Article

Microstructures and mechanical properties of micro friction stir welding (μFSW) of 6061-T4 aluminum alloy

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Micro friction stir welding (μFSW) was successfully performed to join the ultra-thin 6061-T4 sheet with the thickness of 0.5 mm. The optimum plunging depth of 0.05 mm was obtained and reduction ratio was lower than 0.2%. Based on better dynamic flow induced by the triflat pin, the good surface appearance at the wider process window was obtained, while the grain size at the nugget zone was finer than that by the taper pin. Increasing welding speed caused that tensile property increased firstly and then decreased with high welding speed than 500 mm/min. The maximum values of tensile strength and elongation of the μFSW joint using the triflat pin reached 220.3 MPa and 11.7%, which were 91.9% and 54.4% of base material, respectively.

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1. Introduction

Micro friction stir welding (μFSW), as an extension of friction stir welding (FSW), was firstly proposed by TWI in 2003 to prepare lap joint of ultra-thin sheet with the thickness 1 mm or less (TWI, 2003 and 2005) [1,2]. Compared with micro resistance spot welding [3], the μFSW can also perform longer butt joint. μFSW has been reported to possess the huge potential advantages at the manufacturing of the ever smaller components such as joining thin walled structures in electrical, electronic, micro-mechanical assemblies and in the packaging industry [4–6].

Up to present, μFSW has attracted more attentions from scientists and engineers in scientific communities and industrial sectors [7–9]. Scialpi et al. [10,11] and Cerri et al. [12] performed the μFSW of 0.8 mm thick sheets of 2024-T3 and 6082-T6 alloys and proved that the feasible and desirable of the μFSW in the joining of ultra-thin sheets. They elaborated that μFSW joint showed excellent mechanical properties. However, tensile specimen fractured at the nugget zone (NZ) due to the irregular thickness rather than the presence of defects. Kim et al. [13] used pinless tool with the shoulder diameter of 6 mm to join 0.5 mm thick 430M2 steel sheet and
stated that no reduction of effective thickness attributed to the high joint strength. Galvão et al. [14] performed μFSW of 1 mm thick sheets of aluminum, copper, copper–zinc and zinc alloys, and found that the increase of welding speed enhanced process productivity and raised the degree of grain refinement, improving mechanical properties. Papaefthymiou et al. [15] also performed μFSW of titan zinc sheet with thickness of 0.7 mm and stated that μFSW was more comparable to the joining of sheets than TIG. Sattari et al. [16] carried out the μFSW in the butt configuration of 5083 alloy with the thickness of 0.8 mm and expounded that sound joint was obtained between 430 °C and 510 °C. However, high welding speed easily resulted in microscopic defects at the NZ. Klobčar et al. [17] performed the μFSW of electrical contacts with selected welding parameters and tools, and higher strength was achieved compared with base material (BM). Yusof et al. [18] joined ultra-thin sheets of 5052 alloy and pure copper. They expounded that no intermetallic compounds were found at NZ, resulting in the maximum tensile strength of 49.9 MPa.

The limitation of thickness reduction of joint for friction stir butt welding of ultra-thin sheet is not still systematically investigated, which significantly reduces mechanical properties of 1 mm or less thick sheets. In this study, ultra-thin 6061-T4 alloy sheet with the thickness of 0.5 mm was chosen as research object, which has been widely used in electronic packaging, battery cover plate, thermal insulation project, and so on. From the viewpoints of good surface, small thickness reduction and high joint quality, μFSW process was investigated and analyzed in details.

2. Experimental procedure

6061-T4 aluminum alloy was chosen as BM used in this experiment, whose sheet dimension was 150 mm × 80 mm × 0.5 mm. The ultimate tensile strength, elongation and microhardness of the BM are 239.6 MPa, 21.5% and 74 Hz, respectively. Welding tool is made of H13 tool steel containing concave shoulder with taper pin or triflat pin (Fig. 1). The diameter and concave angle of the shoulder of welding tool are 6 mm and 3°. The bottom diameter, top diameter and length of the taper pin are 2 mm, 1.65 mm and 0.3 mm, respectively. The triflat pin owns the pin length of 0.3 mm and bottom diameter of 2 mm, while the cutting distance of three flats is 0.3 mm. According to the results of Elangovan et al. [19], it was stated that a square pin profile produced more pulse/sec compared to the pin without squares. The square pin profile produced 80 Hz (pulses per second) (pulses/sec = rotational velocity in one second × number of flat faces) and triangular pin profile produced 60 pulses per second at the tool rotational velocity of 1200 rpm. While such pulsating action was observed in cylindrical, tapered and threaded pin profiles. In this study, the taper and triflat pins are employed. According to the followed formula

\[
\psi = \frac{V_{\text{Dynamic}}}{V_{\text{Static}}} = \frac{\pi (d^2/4)}{\pi (d_2/4)^3} = \frac{(d^2/4) \times \sqrt{bd - b^2((d/2) - b)}}{(d_2/4)^3}
\]  

where \( \psi \) presents the ratio of dynamic volume/static volume; \( V_{\text{Dynamic}} \) indicates the area occupied by the pin in dynamic condition; \( V_{\text{Static}} \) is the area occupied by the pin in static condition; \( b \) presents the cutting edges distance of the pin; \( d \) is the bottom diameter of the pin; \( c \) means the angle occupied by the cutting edge. By calculating, the ratios of dynamic volume/static volume for the taper pin and the triflat pin are 1 and 1.8. Welding tool rotated anticlockwise. During μFSW process, the existence of tilting angle always results in the thickness reduction, deteriorating mechanical property, especially for 0.5 mm thick ultra-thin sheet. Therefore, the tilting angle with respect to Z-axis was 0°. Rotational velocity of 1500 rpm was constant, while welding speeds were 300 mm/min, 400 mm/min, 500 mm/min, 600 mm/min and 800 mm/min, respectively. All the experiments were performed using the FSW machine (W3-FSW-B1). Meanwhile, in order to reduce the heat loss and avoid lack of root penetration defect, the titanium alloy with low thermal conductivity was chosen as backing plate.

Surface appearance was observed using a digital camera. Microstructural and mechanical specimens were cut perpendicular to welding line by an electrical discharge cutting machine. The microstructural specimen was etched by anode coating (5 g H3BO3, 15 ml HF and 438 ml H2O) whose discharge, current and etching time were 25 V, 0.5 A and 60 s, respectively. Macrostructural and microstructural specimens were observed using optical microscopy (OLYMPUS, GX71). Tensile specimen was prepared for each joint with reference to GB/T 2651-2008 (ISO 9016: 2001) to evaluate tensile strength of joint [20]. Tensile test at room temperature was carried out under a constant crosshead speed of 0.5 mm/min. Fracture surface morphology of tensile specimen was characterized using scanning electron microscopy (SEM). Microhardness of μFSW joint was measured by a micro-hardness tester at a load of 200 g for 10 s. The tested layer on the cross-section of joint was measured, which was 0.25 mm distances away from the
Fig. 2 – Tensile property of the μFSW joints using different plunging depths.

Top surface, while the interval between two adjacent points was 0.25 mm.

3. Results and discussion

3.1. Plunging depth

Fig. 2 displays the tensile strength and elongation of the μFSW joints under different plunging depths. With the increase of plunging depth, the tensile properties increase firstly and then decrease, which are attributed to the welding defect or severe softening degree of joint. For butt joint of μFSW, an important influencing factor is the plunging depth of rotational shoulder, which significantly affects heat input and thermal-mechanically behavior, and consequently control thickness reduction and tensile property of ultra-thin sheet [5,12]. At the plunging depth of 0.02 mm, lack of root penetration defect appears at the bottom of joint, resulting from that insufficient frictional heat results in limited thermal-mechanically behavior. With plunging depth increasing to 0.05 mm, the tensile strength and elongation reach the maximum values of 210.4 MPa and 10.2%, respectively. As plunging depth further increases to 0.08 mm, tensile strength gradually reduces, which is attributed to the big softening degree induced by increasing frictional heat and stress concentration formed at the borders of shoulder. The optimum plunging depth of 0.05 mm for the 0.5 mm thick ultra-thin 6061-T4 sheet can be obtained, which is beneficial to obtain better frictional heat and thermal-mechanically behavior, and consequently attain high-quality μFSW joints.

3.2. Joint formation

Table 1 exhibits surface appearances of μFSW joints. Good surface appearances without defects can be obtained using the taper and triflat pins. With the increase of welding speed, the coarsen degree of surface appearance gradually increases. At the welding speeds of 300 mm/min and 400 mm/min, sufficient frictional heat and material flow can effectively soften and transfer plasticized materials from the pin bottom to the pin tip, obtaining smooth surface appearance. For the taper pin, when welding speed increases to 500 mm/min or 600 mm/min, the reductions of heat input and stirring time weaken the efficiency of material transfer and then result in the partial plasticized material overflowing out of NZ, forming flash defect and coarse surface. With increasing welding speed to 800 mm/min, the surface quality is severer, which perhaps deteriorates thickness reduction and reduces mechanical property. Compared with the taper pin, sound joint without obvious flash defect is attained using the triflat pin. It is attributed to that the triangle pin can produce more pulsating action and then improve material transfer.

Fig. 3 shows the reduction ratio of the μFSW joint, in which the reduction ratio is defined as the ratio of the thickness of NZ reduction and the thickness of BM. With the increase of

| Table 1 – Surface appearances of joints using the both welding tools. |
|-------------------------|-------------------------|-------------------------|
| Welding speed (mm/min)  | The taper pin            | The triflat pin          |
| 300                     | ![Image](image1.png)     | ![Image](image2.png)     |
| 400                     | ![Image](image3.png)     | ![Image](image4.png)     |
| 500                     | ![Image](image5.png)     | ![Image](image6.png)     |
| 600                     | ![Image](image7.png)     | ![Image](image8.png)     |
| 800                     | ![Image](image9.png)     | ![Image](image10.png)    |
welding speed, the reduction ratio increases in general, while the increasing tendency using the triflat pin is lower than that by the taper pin, resulting from the better material transfer. The ratios of thickness reduction of joints at the low welding speeds of 300 mm/min and 400 mm/min for the both welding tools are all lower than 2%, due to the sufficient frictional heat and material flow as well as no flashes. Moreover, for the triflat pin, reduction ratio at 500 mm/min is smaller than 2%, which indicates that the triflat pin owns wider process window. As the welding speed is higher than 500 mm/min, the reduction ratio severely increases. For the μFSW joint, the main factors influencing the reduction ratio contains three respects: (1) the plunging depth of shoulder; (2) welding defects, which easily results in the loss of plasticized materials, causes the big thickness reduction; (3) resistance between shoulder and plasticized materials, in which the bigger resistance causes the smaller thickness reduction, and vice versa. In this study, when the welding speed is relatively high, insufficient frictional heat and material flow are attained, which are difficult to drive plasticized material flow into NZ. Although the resistance between shoulder and plasticized materials is bigger, the flashes defect appears at the surface, resulting in the higher reduction ratio. To obtain sound joint with smaller reduction ratio, sufficient heat input and material flow are very essential by regulating and controlling rotational velocity and choosing more suitable welding tool such as the triflat pin.

3.3. Macrostructures and microstructures

Macrostructures of the typical μFSW joints are shown in Fig. 4. The μFSW joint in cross-section is divided into NZ, thermomechanically affected zone (TMAZ) and heat affected zone (HAZ). With the small sizes of welding tool of μFSW, the NZ is significantly dominated by the rotational pin, and the shoulder has no obvious influence on NZ. Increasing welding speed can reduce the widths of NZ, TMAZ and HAZ. The decrease of heat input induced by increasing welding speed to 600 mm/min results in the occurrence of kissing bond defect at the NZ, as shown in Fig. 5a. When the welding speed reaches 800 mm/min, the lack of root penetration also appears, as indicated in Fig. 5b. These defects at the NZ easily become initiation and propagation of crack, reducing tensile property [21]. Compared with the taper pin, the widths of NZ and TMAZ of joint by the triflat pin are bigger due to better stirring actions.

Microstructures in different welding zones are listed in Table 2. The microstructure at the HAZ only experiences thermal cycle without mechanical stirring, indicating coarse morphology compared with BM. The microstructure of TMAZ presents bended and deformed morphologies, resulting from
Table 2 – Microstructures at different welding regions of the typical joints.

<table>
<thead>
<tr>
<th>Welding tool</th>
<th>Welding speed (mm/min)</th>
<th>TMAZ of AS</th>
<th>NZ</th>
<th>TMAZ of RS</th>
</tr>
</thead>
<tbody>
<tr>
<td>The taper pin</td>
<td>300</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>800</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The triflat pin</td>
<td>300</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>800</td>
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</table>

the occurrence of thermal cycle and mechanical stirring. It is worth mentioning that interface between TMAZ and NZ on the AS indicates sharp morphology, while interface between TMAZ and NZ that on the RS exhibits unclear interface, which are attributed to the differences of both shear stress and material flow. The dynamic recrystallization due to high peak temperature and big strain rates happens at the NZ, resulting in fine and equiaxed grains. In addition, compared with the taper pin, the microstructure of NZ by the triflat pin is finer because of severe stirring actions, which is propitious to the augment of hardness and tensile property.

3.4. Mechanical property

3.4.1. Microhardness

Microhardness distributions of the typical $\mu$-FSW joints are displayed in Fig. 6. The microhardness distributions of the $\mu$-FSW joints all present typical W-shape. The lowest hardness value lies at the HAZ of AS and the highest value of NZ is

![Microhardness distribution](image)

Fig. 6 – Microhardness distributions of the typical joints with different welding tools: (a) the taper pin and (b) the triflat pin.

![Tensile properties](image)

Fig. 7 – Tensile properties of the typical joints using both different welding tools: (a) tensile strength and (b) elongation.
lower than BM. Hardness are related to distribution and size of strengthening phases and grain size. The materials in the HAZ experience high thermal cycle and then easily result in the redistribution of β precipitates and coarse grain, deteriorating hardness value. The fine and equiaxed grains appear at the NZ due to dynamic crystallization. According to the Hall–Petch formula, the smaller the grain size, the higher the hardness. Moreover, for the both welding tools, the same tendency of hardness distribution is obtained. With the increase of welding speed, the hardness value gradually raises due to the reduction of the coarsen degree of grain size, further dissolution and redistribution of β precipitates induced by the decrease of heat input. The average hardness value obtained by the triflat pin is slightly higher than that by the taper pin, which is attributed to that grain size by the triflat pin is finer than that by the taper pin.

3.4.2. Tensile property

Fig. 7 exhibits the tensile properties of joints under different welding speeds and welding tools. With the increase of welding speed, the tensile strength and elongation gradually increase firstly and then decrease from 500 mm/min to 800 mm/min. At the low welding speeds, the lower tensile property is attributed to the severe softening of HAZ of joint. With welding speeds increasing to 400 mm/min and 500 mm/min, the softening degree of HAZ reduces. As welding speed further increases to 600 mm/min and 800 mm/min, the formation of lack of root penetration defect causes the initiation of source and propagation of crack, deteriorating joint quality [22]. For the triflat tool, the maximum values of tensile strength and elongation of joint at the welding speed of 500 mm/min reach 220.3 MPa and 11.7%, which are 91.9% and 54.4% of BM, respectively. The maximum tensile strength of 208.4 MPa and elongation of 10.2% of joint by the taper pin are obtained at the welding speed of 400 mm/min. The tensile properties of joints by the triflat pin are higher than those by the taper pin, resulting from the finer grain size.

Fig. 8 exhibits the typical fracture locations of the μFSW joints using the taper pin at the welding speeds of 400 mm/min, 600 mm/min and 800 mm/min, respectively. Welding speed exerts a significant influence on fracture location of joint. At the welding speed of 400 mm/min, the minimum hardness values in the HAZ lead to the fracture at the HAZ (Fig. 8a). With increasing welding speed to 600 mm/min, the kissing bond defect appeared at the NZ.

Fig. 9 – Fracture surface morphologies: (a) BM; the typical μFSW joints using different welding speeds at a rotational velocity of 1500 rpm, (b) 300 mm/min, (c) 600 mm/min and (d) 800 mm/min.
easily becomes the crack source and then causes the joint failure. As shown in Fig. 8b, the crack initiates from the kissing bond and then propagates upward to the surface with the small load bearing area or downwards the HAZ with the minimum hardness values. When welding speed reaches 800 mm/min, the lack of root penetration defect forms at the bottom, which not only becomes the crack source, but also decreases effective load bearing area, leading to joint fracture (Fig. 8c).

Fracture surface morphologies of BM and typical joints are exhibited in Fig. 9. Many large and deep dimples with tearing edges associated with micropores appear at the fracture surface of BM, indicating the typical ductile fracture (Fig. 9a). When welding speed is 300 mm/min, the smaller dimples can be observed relative to BM, which results from the softening of joint in the HAZ, as shown in Fig. 9b. Observing Fig. 9c, the fracture surface morphology contains the lower and shallower dimples due to the rapid propagation of crack induced by kissing bond defect at the NZ, which is detrimental to the ductility. As the welding speed increases to 800 mm/min, no obvious dimples can be found, which also indicates no effective bonding (lack of root penetration, Fig. 8c) at the NZ, as shown in Fig. 9d. This is induced by the severe decrease of heat input compared with other welding speeds.

4. Conclusions

In this study, μFSW of ultra-thin 6061-T6 alloy sheet with the thickness of 0.5 mm was performed. Based on the present investigation, the following conclusions can be attained.

- Joint formation and mechanical properties were significantly influenced by plunging depth. Relative low plunging depth of 0.02 mm resulted in the lack of root penetration and reduced tensile property. High plunging depth of 0.08 mm produced stress concentration and severe softening degree. The suitable plunging depth of 0.05 mm was attained, obtaining the maximum tensile strength.

- With increase of welding speed, the reduction ratio gradually increased, resulting from the insufficient material transfer and stirring times. Compared with the taper pin, the surface appearance was better and the reduction ratio by the triflat pin was smaller due to better dynamic flow.

- When the welding speed was lower than 500 mm/min, defect-free joint could be obtained. As the welding speed increased to 600 mm/min and 800 mm/min, kissing bond and lack of root penetration defect formed at the NZ.

- The maximum tensile strength of 220.3 MPa and elongation of 11.7% of the μFSW joint by the triflat pin were achieved, which were 105.7% and 114.7% of those by the taper pin, while the triflat pin produced the wider process windows. All the benefits were attributed to the finer grain size induced by severe dynamic flow.

Conflicts of interest

The authors declare no conflicts of interest.

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