Micro friction stir welding of ultra-thin Al-6061 sheets

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ABSTRACT
The plunging depth of 0.05 mm was optimum for joint formation of 0.5 mm thick Al-6061 sheet by micro friction stir welding. Increasing rotational velocity from 1500 rpm to 2000 rpm was beneficial to sound surface formation, while the taper pin with three flats owned wider process window than the single taper pin. The minimum ratio of thickness reduction of 2% was attained, which enhanced the area of load bearing. The taper pin with three flats owing to the severe stirring actions resulted in the finer grain size, improving tensile property. The maximum tensile strength by the taper pin with three flats reached 217 MPa, equivalent to 90% of base material.

1. Introduction
Nishibara and Nagasaka (2004) investigated the feasibility of the micro friction stir welding (µFSW) on AZ31 magnesium alloys. Sattari et al. (2012) carried out µFSW in the butt joint configuration of 5083 alloy with the thickness of 0.8 mm. They expounded that microscopic defects easily formed at the nugget zone (NZ) under high welding speed, while sound joint could be obtained under temperature ranges from 430 °C to 510 °C. Scialpi et al. (2008a,b) studied µFSW of 0.8 mm thick 2024-T3 and 6082-T6 sheets, and elaborated that these joints showed excellent mechanical properties. However, the irregular thickness induced by shoulder plunge caused that tensile failure occurred at the NZ, rather than by the presence of defects. In addition, Vijayan et al. (2012) carried out µFSW of 0.8 mm Al-6061-T4 sheet with the thickness of 0.5 mm was chosen as research base material.

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2. Experimental procedure
Base material (BM) was 6061-T4 aluminum alloy, whose sheet dimension was 150 mm × 80 mm × 0.5 mm. Chemical compositions and mechanical properties of the BM are listed in Table 1. Schematic diagram of the µFSW process is shown in Fig. 1. Welding tool is made of H13 tool steel containing concave shoulder and taper pin or taper pin owning three flats, as shown in Fig. 2. In this study, in order to illustrate conveniently, the welding tool with taper pin and welding tool with taper pin owning three flats are named welding tool one and welding tool two, respectively. The diameter and concave angle of shoulder are 6.0 mm and 3°, respectively. The bottom diameter, top diameter and pin length of the welding one are 2.0 mm, 1.65 mm and 0.3 mm respectively. The welding tool two owns the pin length of 0.3 mm and pin bottom diameter of 2.0 mm, while the cutting distance is 0.3 mm. The rotational pin rotated anticlockwise and the tilting angle relative to Z-axis was 0°, which could reduce thickness reduction induced by tilting angle. Rotational velocity varied from 1000 rpm to 2000 rpm at an interval of 250 rpm, while welding speed of 400 mm/min was kept constant. Because of heavy heat loss of the ultra-thin sheet, insufficient material flow is easy to take place, resulting in lack of root penetration defect. To reduce the heat loss, the titanium alloy with lower thermal conductivity was selected as the backing plate.

Surface appearance was observed by super depth field microscopy (VHX-1000E). Microstructural and mechanical specimens were cut perpendicular to the welding line using an electrical discharge cutting
3. Results and discussion

3.1. Plunging depth

Surface appearances of µFSW joints obtained by different plunging depths using the welding tool one are shown in Fig. 3. The unfilled groove defect appears at the advancing side (AS) of joint, as shown in Fig. 3a. Under the low plunging depth of 0.02 mm, contacting area between shoulder and welded workpieces is insufficient, which leads to inadequate material flow and then forms the groove defect. As plunging depth increases to 0.05 mm, the groove defect is eliminated and good surface appearance without big flashes is attained (Fig. 3b). The reason is that rotational shoulder owns adequate contacting area with welded workpieces, resulting in better material flow. As plunging depths increase to 0.08 mm and 1 mm, frictional heat gradually increases, which not only results in big flashes defect, but also easily leads to big thickness reduction, deteriorating tensile properties (Fig. 3c and d). Additionally, when plunging depth is 0.1 mm, the bigger heat input causes that irregular shoulder marks appear at the surface of joint, as shown in Fig. 3d. In summary, the plunging depth of µFSW should be chosen based on following principles. Firstly, sufficient frictional heat guarantees better material flow. Secondly, smaller welding defects at the beginning of rotational shoulder avoids the dilaceration of BM (Sithole and Rao, 2016). Lastly, smaller flashes and thickness reduction increase the effective loading area, improving joint quality of µFSW.

3.2. Surface appearance

Surface formations of µFSW joints using the both welding tools are listed in Table 2. With the raise of rotational velocity, the surface appearance of the joint becomes smooth, resulting from the improvements of frictional heat and material flow. When rotational velocity is 1000 rpm or 1250 rpm, the small shoulder is difficult to produce sufficient material flow, resulting in the coarse surface. With increasing rotational velocity from 1500 rpm to 2000 rpm, both frictional heat and material flow velocity are enhanced, which are propitious to smooth surface appearance. Interestingly, when using the welding tool one at the rotational velocity of 2000 rpm, the groove defect occurs at the end of joint, while the welding tool two with three flats does not have such phenomenon. The reason is attributed to that the welding tool two can produce severer material flow compared with the welding tool one, and then make more plasticized materials flow into the joint. With the advancement and rotation of the welding tool, heat accumulation is heavy at the location far away from the beginning of joint, leading to the deformation of sheet and formation of big flashes. The instantaneous cavity behind the welding tool cannot be filled with sufficient plasticized materials due to big flashes, forming the groove defect. The welding tool two is beneficial to the transfer of plasticized materials, resulting in joint formation and broadening the welding process windows.

3.3. Thickness reduction

For the butt joint of µFSW, an important limitation is thickness reduction due to the forging effect of rotational shoulder, which always significantly reduces tensile property of ultra-thin sheet joint (Sithole and Rao, 2016). Moreover, another main characteristic of FSW is shoulder marks featured by the uniform concave and convex alternating arc, in which the concave is called as trough of wave and the convex is named as wave crest (Mishra and Ma, 2005). The partial enlarged photos of shoulder marks under different welding parameters are exhibited in Table 3. The thickness reduction is also closely correlated

### Table 1

**Chemical compositions and mechanical properties of BM.**

<table>
<thead>
<tr>
<th>Nominal chemical composition (wt.%)</th>
<th>Mechanical properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>Si</td>
</tr>
<tr>
<td>Bal.</td>
<td>0.4</td>
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</tbody>
</table>

### Fig. 1.

Schematic diagram of µFSW process.

### Fig. 2.

Welding pins: (a) the taper pin and (b) the taper pin with three flats.

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machine. The microstructural specimens were etched by anode coating (5 g H3BO3, 15 ml HF and 438 ml H2O), in which the discharge, current and etching time were 25 V, 0.5 A and 60 s, respectively. Macro and microstructures were observed using optical microscopy (OLYMPUS, GX71). Tensile specimen was prepared for each joint with reference to GB/T 2651-2008 (equivalent to ISO 9016: 2001) to evaluate tensile property of joint. Tensile test at room temperature was performed at a constant crosshead speed of 0.5 mm/min. Fracture surface of tensile specimen was observed by scanning electron microscopy (SEM). Microhardness distribution of joint was measured by a micro-hardness tester at a load of 200 g for 10 s. The tested layers on the cross-section of joint were measured, which were 0.25 mm distances away from the top surface. The interval between two adjacent points was 0.25 mm.
Fig. 3. Effect of plunging depth on surface appearance of μFSW joint: (a) 0.02 mm, (b) 0.05 mm, (c) 0.08 mm and (d) 0.1 mm.

Table 2
Surface appearances of joints using the both welding tools.

<table>
<thead>
<tr>
<th>Rotational velocity (rpm)</th>
<th>Welding tool one</th>
<th>Welding tool two</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td>1250</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td>1500</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td>1750</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td>2000</td>
<td>![Image]</td>
<td>![Image]</td>
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</tbody>
</table>

Table 3
Characteristics of surface appearances using the both welding tools.

<table>
<thead>
<tr>
<th>Welding tool</th>
<th>Morphology</th>
<th>Welding parameters</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td>1750 rpm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2000 rpm</td>
</tr>
</tbody>
</table>

Welding tool one
- Surface appearance
- 3D morphology

Welding tool two
- Surface appearance
- 3D morphology
with the shoulder marks. Scialpi et al. (2008a,b) also stated that tensile failure easily occurred at the NZ induced by the irregular thickness rather than by the presence of defects. To investigate the shoulder marks, the related characteristic value of shoulder marks is as \( h \) to describe the distance between wave crest and trough of wave. Table 4 presents the characteristic values of shoulder marks under different welding parameters. All the surface appearances of \( \mu \)FSW joints are sound and uniform. Moreover, for the both welding tools, with the increase of rotational velocity, the \( h \) gradually decreases, which may be attributed to the expansion with higher frictional heat at high rotational velocity. It should be noticed that the \( h \) obtained by the welding tool two is far smaller than that using the welding tool one. This is attributed to that the drastic stirring action provided by the welding tool two can make more plasticized materials flow into the NZ and scanty materials adhere to the shoulder. It can be concluded that the welding tool two is not only beneficial to the reduction of thickness reduction, but also lessens the procedure of surface treatment, which is more suitable for the \( \mu \)FSW of ultra-thin sheet.

Here, in order to evaluate the thickness reduction, a formula was established, which was designed as the ratio of thickness reduction as follows.

\[
\eta = \frac{a_1}{a} \times 100\%
\]  

(1)

Where, \( a_1 \) presents thickness reduction whose unit is mm; \( a \) indicates the thickness of BM. In fact, the main factors influencing the ratio of thickness reduction are divided into three respects: (1) the plunging depth of shoulder; (2) welding defects easily lead to the loss of plasticized materials, causing the big thickness reduction; (3) resistance appears between shoulder and plasticized materials, in which the bigger the resistance, the smaller the thickness reduction, and vice versa. With the increase of rotational velocity from 1000 rpm to 2000 rpm, the ratio of thickness reduction gradually reduces up to 1500 rpm and then presents no obvious variations from 1500 rpm to 2000 rpm, as exhibited in Fig. 4. When rotational velocity is lower than 1500 rpm, insufficient frictional heat and material flow are attained, which are difficult to drive plasticized material flow into NZ and then overflow out of NZ. Although the resistance between shoulder and plasticized materials is bigger, the flashes defect appears at the surface, resulting in the higher ratio of thickness reduction. When rotational velocity is higher than 1500 rpm, all the ratios of thickness reduction are smaller than 2%. These are attributed to the improvements of both frictional heat and material flow, which are beneficial to reduce the loss of plasticized materials, while no obvious flashes appear. The synthesis effects attribute to the smaller ratio of thickness reduction. It is postulated that frictional heat and material flow play significant influences on the ratio of thickness reduction, which can be improved by regulating and controlling rotational velocity.

### 3.4. Macrostructure

Fig. 5 shows macrostructures of the typical joints using the both welding tools under low rotational velocity of 1250 rpm and high rotational velocity of 2000 rpm. The \( \mu \)FSW joint is mainly divided into three regions: NZ, thermo-mechanically affected zone (TMAZ) and heat affected zone (HAZ), as shown in Fig. 5. Increasing rotational velocity significantly improves the widths of NZ, TMAZ and HAZ, which results from the augment of frictional heat. Moreover, the width of NZ obtained by the welding tool two owning better stirring actions is bigger than that by the welding tool one at the same rotational velocity. In

### Table 4

<table>
<thead>
<tr>
<th>Welding tool</th>
<th>Rotational velocity (rpm)</th>
<th>( h/\mu )m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Welding tool one</td>
<td>1750</td>
<td>28.0</td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>18.0</td>
</tr>
<tr>
<td>Welding tool two</td>
<td>1750</td>
<td>4.4</td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>3.2</td>
</tr>
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</table>
addition, the partial enlarged photos of the joints using the welding tools under the rotational velocity of 1250 rpm are exhibited in Fig. 6. The kissing bond defect appears at the NZ due to insufficient frictional heat and material flow, which is detrimental to mechanical property.

3.5. Microstructure

Fig. 7 indicates the microstructure of BM and the microstructures at different positions of the μFSW joint are shown in Table 5. The microstructure of BM exhibits elongated grains due to the rolling direction, as shown in Fig. 7. The microstructures of TMAZ present bended and deformed morphologies, resulting from the occurrence of thermal cycle and mechanical stirring. It is worth mentioning that the interface between TMAZ and NZ at the AS indicates sharp morphology, while the interface between TMAZ and NZ at the retreating side (RS) exhibits unclear interface. This phenomenon is attributed to the differences of both shear stress and material flow on the two sides, as stated by Huang et al. (2016). The dynamic recrystallization due to high peak temperature and big strain rates happens at the NZ, resulting in fine and equiaxed grains. The microstructure at the HAZ only experiences thermal cycle without mechanical stirring, presenting coarser morphology than BM. In addition, compared with the welding tool one, the grain size of NZ by the welding tool two is smaller because of severe stirring actions, which benefits from the augments of hardness and tensile property.

3.6. Microhardness

Fig. 8 shows microhardness distributions of the μFSW joints using the both welding tools. It is clearly observed that hardness distributions of the μFSW joints all present typical W-shape. The lowest hardness value locates at the HAZ of AS and the highest value lies at BM. 6061-T4 alloy belongs to precipitate strengthening alloy, whose hardness is not only connected with distribution and size of strengthening particles, but also influenced by grain size (Jonckheere et al., 2013). The material in the HAZ experiences high heat input, which leads to redistribution of β precipitates and coarse grain and then reduce mechanical property. The hardness in the TMAZ is higher than HAZ, which results from smaller grain size and higher dislocation density induced by thermo-mechanically action. According to the Hall-Petch formula, the smaller the grain

### Table 5

<table>
<thead>
<tr>
<th>Welding tool</th>
<th>Rotational velocity (rpm)</th>
<th>TMAZ of RS</th>
<th>NZ</th>
<th>TMAZ of AS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Welding tool one</td>
<td>1250</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
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<tr>
<td></td>
<td>2000</td>
<td>![Image]</td>
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<td>![Image]</td>
</tr>
<tr>
<td>Welding tool two</td>
<td>1250</td>
<td>![Image]</td>
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<td>![Image]</td>
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<tr>
<td></td>
<td>2000</td>
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</tbody>
</table>
size, the higher the hardness (Zhu et al., 2014). Therefore, the hardness of NZ featured by fine and equiaxed grains is higher than those at the HAZ and TMAZ, but lower than BM. Moreover, for both welding tools, the same tendency of hardness distribution is that with the increase of rotational velocity, the hardness value gradually decreases. The average hardness value obtained by the welding tool two is slightly higher than that by the welding tool one, attributing to smaller grain size, as indicated in Table 5.

3.7. Tensile property

Fig. 9 exhibits the experimental results of tensile specimens of the μFSW joints. Tensile strength and elongation all firstly increase and then decrease with the augment of rotational velocity. At the rotational velocity of 1500 rpm and welding speed of 400 mm/min, the tensile strength and elongation using the welding tool one are respectively size, the higher the hardness (Zhu et al., 2014). Therefore, the hardness of NZ featured by fine and equiaxed grains is higher than those at the HAZ and TMAZ, but lower than BM. Moreover, for both welding tools, the same tendency of hardness distribution is that with the increase of rotational velocity, the hardness value gradually decreases. The average hardness value obtained by the welding tool two is slightly higher than that by the welding tool one, attributing to smaller grain size, as indicated in Table 5.

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210 MPa and 10.4%, while the maximum tensile strength and elongation using the welding tool two are 217 MPa and 12.3%, respectively. The tensile property using the welding tool two is slightly higher than that by the welding tool one, which may be attributed to smaller grain size caused by severe plastic deformation. Moreover, for the both welding tools, when rotational velocity is lower than 1500 rpm, the cavity or kissing bond defect may appear at the NZ, decreasing tensile property. When rotational velocity is higher than 1500 rpm, the increase of welding heat input leads to the coarser grain size and bigger softening degree, deteriorating tensile property.

Fracture locations of the µFSW joints using both the welding tools are divided into two modes. One is fracture along the welding defect such as cavity or tunnel defect, the other is fracture at the location with the minimum hardness value. The fracture locations of the µFSW joints by the welding tool two are exhibited in Fig. 10. When rotational velocity is lower than 1500 rpm, the fracture location of joint locates at the defect of NZ, which results from insufficient frictional heat and material flow, as shown in Fig. 10a. As rotational velocity exceeds 1500 rpm, the augments of frictional heat and material flow eliminate welding defect, but deteriorate hardness of joint, as indicated in Fig. 8. And consequently, the fracture location of joint locates at the HAZ (Fig. 10b). In addition, the effect of rotational velocity on fracture location of joint using the welding tool one is the same as the welding tool two.

Fig. 11 shows the fracture surface morphologies of BM and joints using the welding tool two. In Fig. 11a, many large and deep dimples with tearing edges associated with micropores appear on the fracture surface of BM, indicating the typical ductile fracture. When rotational velocity is 1000 rpm, the welding defect appears at the NZ, which easily becomes the initiation of crack, resulting in bad ductility. As shown in Fig. 11b, there is no obvious dimples appearing at the fracture surface. As rotational velocity increases to 2000 rpm, sound joint can be obtained, which can bear bigger force and plastic deformation under tensile test. The fewer and shallower dimples relative to BM form at the joint at the rotational velocity of 2000 rpm. Meanwhile, there are also some cracked second-phase particles with a larger size at the bottom of dimples (Fig. 11c), indicating the precipitation and coarsen of the strengthening phase during µFSW process.

4. Conclusions

In this study, the µFSW of ultra-thin Al-6061 sheet was investigated, which provides technical support and then expands the application of µFSW. Based on the present investigation, the following conclusions can be extracted.

1. The optimum plunge depth of 0.05 mm was obtained for 0.5 mm thick Al-6061 sheet. Lower or higher plunging depth relative to 0.05 mm all easily produced welding defects such as the unfilled groove, bigger flashes and thickness reduction.
2. Increasing rotational velocity improved surface appearance and eliminated kissing bond defect. The ratios of thickness reduction of joints were lower than 2% under rotational velocities higher than 1500 rpm. The welding tool two produced severer stirring actions, broadening process windows relative to the welding tool one.
3. The maximum tensile strength of 217 MPa was obtained. The fracture location of joint with higher tensile property lied at the HAZ owning minimum hardness value, presenting the typical ductile fracture.

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References


