Influence of Welding Parameters on Mechanical Properties of Friction Stir Welded 6061-T6 Launch Box

Hsing-Ta Hsieh$^{1,2,*}$ and Jahau Lewis Chen$^1$

$^1$Department of Mechanical Engineering, National Cheng Kung University, Tainan, Taiwan 701, R. O. China
$^2$Metal Industry Research & Development Centre, Kaohsiung, Taiwan 811, R. O. China

Friction stir welding (FSW) is a welding process which deals with joining parts in a solid state at low temperature to result in welded parts with excellent mechanical performance, such as low distortion and high tensile strength. Additionally friction stir welding is applicable to aluminum alloy products with precision dimensions. By using friction stir welding parameters, this research studies the tensile strength, hardness, elongation rates, and shrinkage of extruded 6061-T6 alloy. Results indicate that the joining strength of the extruded 6061-T6 alloy can reach 78% of the base metal after friction stir welding. Meanwhile, welding parameters can accurately predict and control the welding distortion of welded products. This research applies these results in the manufacturing of launch boxes to arrive at a technology that can be directly applied to welded products without expensive as-welded modifications. [doi:10.2320/matertrans.L-MRA2008829]

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1. Introduction

Missile and rocket systems play vital role in the modern military equipment. The systems have strong mobility and high reliability. Additionally these missile systems are well equipped with air seals, pressure resistance, heat resistance and corrosion resistance to facilitate daily storage and long distance transportation. The box must be able to sustain the missile weight, recoil and high temperature after launching.

Aluminum alloy has a high strength/weight ratio and enough stability to effectively reduce the weight of a launch box. Additionally, aluminum alloys can be repeatedly used and recycled.

Since the design of a launch box has to take internal dimensions and housing strength into account, the feasible manufacturing methods include machining, extrusion and assembly. (1) Machining: Machining has limitations of processing equipment and cost. (2) Aluminum extrusion: The launch box can be easily and rapidly formed using extrusion, but the required extrusion equipment and molds are very expensive. After launch box is formed, it is very difficult to modify the inner dimension and distortion. (3) Welding assembly: The four sides of a launch box are separately processed using welding methods and assembly. Material distortion produced by high fusion temperatures in the weld is hard to modify and predict in advance. However above mentioned methods are not economical or practical. As a result, this research introduces FSW to demonstrate a new manufacturing method for launch boxes.

FSW is a joining process and was developed by TWI of the United Kingdom in 1991. FSW uses spinning of a tool to produce heat on the surface of the work piece along with mechanical stir to generate material plasticization and to achieve joining through extrusion and a forging mechanism. Since alloy materials have low heat input, the joining temperature of a work piece does not reach melting point. Therefore, FSW is classified as a low temperature/solid state joining process. The resulting weld has low distortion, low shrinkage, without porosity and cracking that are commonly occurred in traditional arc welding. FSW is especially effective in the use of joining aluminum alloys. Basic study and industrial applications of FSW are gradually and rapidly developed. For the last few years, many in-depth FSW studies have been conducted about materials, welding parameters, microscopic structure, mechanical property and the design of stir tools. Comparison of the related studies indicates that differences in materials, experimental equipment and the designs of stir tools will change the relationship between operational parameters and mechanical properties. However it is difficult for above mentioned researches in the practical application.

6061-T6 aluminum alloy is chosen as material for launch box, this research conducts the study of necessary welding parameters, including rotation speed, traveling speed, shoulder diameter, pin diameter and mechanical properties, such as tensile strength, weld hardness, elongation rate and shrinkage. Additionally this research hopes to locate properly applied parameter combinations to achieve desired mechanical properties and to control joining shrinkage change to reach a net joining of the inner box without as-welded treatment.

2. Experimental Procedures

The research adopts extruded 6061-T6 aluminum alloy with a composition analysis of 0.59±Si, 0.12±Fe, 0.23±Cu, 0.009±Mn, 0.99±Mg, 0.027±Zn, 0.007±Ni, 0.09±Cr, 0.007±Ti, 0.007±Pb and balance Al (in mass%). The FSW experiment uses a Makino Milling Machine with mandrel power of 3.75 KW. Figure 1 displays experimental positioning and sampling to show a welding specimen with a size of 250 × 80 × 9 mm, while the specimen is fixed on one side and the other side of the specimen is applied with a fixed torque to make two pieces of specimen to be tightly held together. At both sides of weld, flat blocks are used to
prevent the specimen from warping. The leading plates are added at the front and rear ends of the specimen to serve as the beginning and ending of the weld and to maintain specimen stability during the welding process.

Using a selected material, Table 1 shows the values of the welding parameters in the FSW which may affect the mechanical properties of the work piece. In the beginning, the research sets basic reference parameters that are established through experience. Each set of experiment changes one parameter; the rest remains at the original basic settings among which pins use columns with standard threads that are shown in Fig. 2. At the beginning of the welding process, the pause of 8 seconds is set in the boundary between the leading plate and the work piece.

This research analyzes the influence of tensile strength, hardness, shrinkage and elongation rate on the weld when welding parameters change. According to ASTM E8M, tensile strength analysis adopts the MTS 810 system 1000KNC with testing conditions at 0.2% initial speed of 2.0 mm/min and a secondary speed 6.0 mm/min are used. The measuring distance of the elongation rate is 50 mm. Micro-hardness distribution tests on the weld using 100 g load, the testing location is a 3 mm distance under surface and hardness data is taken every 1 mm. In terms of shrinkage measurement, linear scale is used to measure the dimensional change between pre-weld and as-welded at the same location on the experimental machine. In the welding process, the work piece is limited by normal grip; the research does not consider the influence of as-welded warp.

This research results apply feasible welding parameters to the joining of aluminum alloy launch box parts. Through material preparation, machining and joining, the dimension and performance of the finished product is also tested. In the actual manufacturing of a launch box, the box is divided into four units based on cross-sectional shape, as shown in Fig. 3. Each unit adopts a single cross-sectional extruded 6061-T6 alloy. Through machining, the extruded unit is made to conform to pre-assembly dimensions. Afterwards this research conducts assembly welding after obtaining feasible welding parameters. Finally, this research carries out welding quality testing and precision measurements of important dimensions to verify the feasibility of FSW.
3. Results and Discussion

Research results indicate that the sampling points are the average of data taken from three sets of specimens. For the base metal of the extruded 6061T-6 alloy, the average tensile strength is 316 MPa, yielding strength is 253.8 MPa, elongation rate is 16.2% and hardness is Hv 120 respectively.

3.1 Tensile strength

These research results indicate when shoulder diameter progressively increases from φ16 to φ28 mm, the tensile strength decreases from 247.9 MPa to 225.4 MPa. As soon as pin diameter gradually increases from φ6 to φ10 mm (the pin diameter φ3 mm & φ4 mm broke in experiment), tensile strength decreases from 235.2 MPa to 227.4 MPa. However, applied side force from 0 to 14.125 Nm does not remarkably affect tensile strength. Its value remains around 230 ± 4.9 MPa.

Stir rotation speed changes from 560 to 1800 rpm; the result indicates that a peak of 235.7 MPa is shown at 900 rpm. However at 900 rpm, tensile strength shows a slow decrease.

Change of traveling speed has significant influence on tensile strength. The corresponding changes are shown in Fig. 4(a). The result demonstrates that a translation scope of 350~550 mm/min has better tensile strength. In Fig. 4(a), a maximum tensile strength value of 247.9 MPa is shown around 450 mm/min.

Figure 5 exhibited the average grain size for low traveling speed was significantly bigger than high traveling condition. It was implied the ultimate tensile strength decreased at low traveling speed. But the distribution of precipitates for these specimens displayed very much alike.

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Fig. 4 The mechanical behaviors are relative to the welding parameters (a) strength to travelling speed, (b) hardness distribution to shoulder diameter, (c) hardness distribution to travelling speed, (d) elongation rate to travelling speed.

Fig. 5 Microstructure of Thermo Mechanically Affected Zone, 100X (a) traveling speed 50mm/min (b) traveling speed 550 mm/min.
On the other way, the linear heat input is small for high traveling speed; it will cause insufficient fusion and create some defects in nugget (Fig. 6). If the defect is occurred on the fusion zone, it also reduces the tensile strength. Result indicates that traveling speed is increasing, linear heat input is then decreasing. Furthermore more fine grain size on welded zone and get higher strength are the results, yet a peak is occurred at different traveling speeds.

3.2 Micro hardness

Measurements of weld hardness indicate that changes in rotation speed, pin diameter and side force have no significant difference on weld hardness distribution. However when shoulder diameter enlarges, hardness changing area expands as well. In Fig. 4(b), the expanding area is in direct proportion to changes of diameter.

The influence of traveling speed on hardness distribution is shown in Fig. 4(c). As soon as traveling speed is decreasing, the hardness decreases and hardness changing area expands.

3.3 Elongation

In terms of elongation rate, the results indicate that changes of pin diameter, shoulder diameter, rotation speed and side force do not affect elongation rates too much. The average changes fall between 5.5 and 6.8%. When stir traveling speed is slow, the elongation increases. However 650 mm/min speed shows a tremendous elongation decrease of 3.1%, the result shows in Fig. 4(d). Weld microscopic structure indicates that unfilled porosity is occurred in the advancing side of the weld at a speed of 650 mm/min, shown as Fig. 6.

3.4 Shrinkage

With regard to side shrinkage, when shoulder diameter increases, the sidewise shrinkage produced by as-welded specimens increases at the same time. When pin diameter changes, the same situation is also occurred as shown in Fig. 6(a) and (b). However welding traveling speed changes, an increase of traveling speed produces smaller shrinkage as shown in Fig. 7(c). The higher rotation speeds generate more shrinkage, as Fig. 7(d). From Fig. 7(c)–(d), traveling speed is much more sensitivity than rotation speed on the effect of width shrinkage. The side force does not show significant influence on shrinkage.

Figure 7(a)–(d) shows specimen shrinkage under different parameters relating to different slope. The slopes are nearly linear, increase at beginning stage and gradually reach stable conditions. For welding procedure, the specimen temperature will increase from room temperature to a high and stable temperature situation. The experimental specimen length

![Fig. 6 The macrograph of porosity exists in advancing side (travelling speed is 650 mm/min).](image)

![Fig. 7 The shrinkage distribution relates to the welding parameters (a) width shrinkage to shoulder diameter, (b) width shrinkage to pin diameter, (c) width shrinkage to travelling speed, (d) width shrinkage to rotation speed.](image)
cannot indicate the complete shrinkage situation. To further confirm the shrinkage-free area, a shrinkage test of the specimen at 600 mm in length is conducted at two separate traveling speeds. The result indicates when welding starts and the process moves to a certain distance, the shrinkage gradually stabilizes and fluctuation remains within 0.1 mm as shown in Fig. 8.

3.5 Parameters application
To summarize the relationship between welding parameters and mechanical properties, this research selects a feasible and stable parameter combination and applies in the welding process. Figure 9 shows the work pieces that are machined extruded parts before joining. This research conducts the welding is conducted after necessary assembly in a Cincinnati Milacron milling machine. Figure 10 illustrates the completed launch box. After external milling, the welded launch box is completed. Furthermore, this research conducts an important internal dimension measurement and an X-ray inspection of the weld. The inspection unit is every meter. The checking positions are shown as Fig. 11 and the results are displayed on Table 2.

Weld at each point in the assembly goes through X-ray non-destruction tests so that corner angles of as-welded distortion within the launch box and as-welded central diameters can be precisely estimated and controlled to achieve the expected results without post machining on internal launch box.

4. Conclusions
(1) In FSW, changes in shoulder diameters affect weld quality than those in pin diameters. Hardness distribution and cross-sectional microscopic structure observation indicate that enlargement of shoulder diameters will expand the heat affected zone of welds and enlarge as-welded side shrinkage.
(2) Proper grip is a necessary process for FSW. Research indicates as long as a grip mechanism or fixture constraint stiffness is sufficient, it is not necessary to apply additional force.
(3) Changes in traveling speeds demonstrate significant influence on the mechanical properties of welds. At low speeds, unit weld lengths have high input heat

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**Table 2 Examinations of as-welded box.**

<table>
<thead>
<tr>
<th>Test Items</th>
<th>Designed Valve</th>
<th>As Welded Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nugget X-ray</td>
<td>—</td>
<td>Accept</td>
</tr>
<tr>
<td>Main Circle</td>
<td>ϕ252 + 0.3 mm</td>
<td>ϕ252.164 mm</td>
</tr>
<tr>
<td>Corner</td>
<td>90°</td>
<td>89.90°</td>
</tr>
<tr>
<td>Angle/m</td>
<td>90°</td>
<td>89.97°</td>
</tr>
<tr>
<td></td>
<td>90°</td>
<td>90.13°</td>
</tr>
</tbody>
</table>
which enlarges the heat affected zone, affect the changes in hardness distribution, produce bigger grain, reduce joining strength and increase as-welded shrinkage. The high speed area has higher tensile strength and low shrinkage.

(4) Research and application indicate that FSW can precisely control the quality and dimension of finished products in the welding process to achieve precision joining without post machining.

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