Fracture Energy in Friction Stir Welding Al6061-T6 by Micro Shear Punch Test

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Abstract. Fracture energy was analyzed for FSW (Friction Stir Welding) joint in accordance with the tool rotation speed and feed rate in the thermo-mechanically affected zone. Al6061-T6 sheet with thickness 5mm was welded with 9 conditions (tool rotation speed: 900, 1000, 1100rpm, feed rate: 270, 300, 330mm/min). Tool with shoulder diameter of 18mm and probe diameter of 5mm was used. Specimen size was 10×10×0.5mm. The MSP (Micro Shear Punch) test was carried out to evaluate the load-displacement properties of FSW sheet along the center line of cross section of weldment. The maximum fracture energy was 0.771 J at the tool rotation speed of 1000 RPM and the feed rate of 300 mm/min, which was about 35.9 % of the minimum value. The reason is considered to be that the shape and distribution of precipitates in the weld zone were different and affected the weld strength and ductility.

Introduction

Currently, the portion where FSW (Friction Stir Welding) is most often applied is the joint of aluminum alloy for aircraft fuselage or high speed train carriage requiring the reduction of weight. And studies are actively made in advanced countries\cite{1}\cite{2}.

Figure 1. shows the microstructure of joint section. The most distinctive characteristics are well-developed nugget (D) at the center of joint. It is the area of dynamic recrystallization. The joint of Al alloy frequently has distinctive onion-ring-type structure. The overall form of nugget varies widely depending on the applied materials and process conditions.

In general, nugget attachments with complex forms are frequently observed on the surfaces of welding and those attachments can extend to the end part of tool shoulder. Nugget diameter tends to be a little bit longer than that of probe, but much smaller than that of shoulder. Currently, it is impossible to predict nugget shape. They are dependent on various factors such as tool design, joint conditions and high-temperature strength of jointed base metal\cite{3}.

The microstructure outside of nugget is also very unique. The state around the nugget experiences severe plastic deformation, and elongated crystallized structure has area where it can rotate up to 90°. In FSW, this area is called thermo-mechanically affected zone (TMAZ:C) . This is where partial recrystallization occurs by plastic deformation.

Besides, though heat affected zone (HAZ:B) is not deformed, the joint of heat can affect the properties of the area. The base metal (A) at the outside place is not affected by heat or mechanical deformation. As such, heat and mechanical deformation affect them in complex method, so it is necessary to do research more deeply about the characteristics of microstructure of FSW joint\cite{4}.
To test mechanical characteristics of local structure, this study uses a small-scaled specimen and the metallography by Micro Shear Punch (MSP) test technique[5]. MSP test technique uses miniaturized specimen of the sizes of a few millimeters ~ hundreds of microns in size for big-size materials, and is the method evaluating mechanical characteristics of raw material in micro local area. Consequently, it can be used to evaluate microstructure of joint of FSW.

This study comparatively analyzes the fracture energy in order to comprehensively evaluate the mechanical properties of friction-stir-welded portion according to the tool rotation speed and feed rate of lightweight metal by using the MSP test technique.

**Figure 1. Macrostructure classification of friction stir welded.**

**FSW and MSP Test**

**FSW**

This study used Al6061-T6 alloy for aluminum alloy. Though Al6061-T6 alloy is lower in inferior material properties than Al 2000 Series, it is good in weldability and corrosion resistance. And, though it is lower in formability than T4, it is excellent in static strength. Thus, Al6061-T6 alloy is used for many mechanical parts. The chemical composition ratio and mechanical properties of Al6061-T6 were shown in Table 1. and Table 2.

Two sheets of 5mm thick were used as one unit in welding. The specifications and photograph of FSW machine were shown in Table 3. and Figure 3. The tool used in FSW is an element influencing weldability and the form of a tool greatly affects mechanical properties. This study used the circular screw tool as shown in Figure 2. The rotation direction of the tool was clockwise. The specifications and shape of the tool were shown in Table 3. and Figure 4.

**Figure 2. Photograph of rotation tool used in friction stir welding.**

Welding conditions were set referring to FSW conditions of Choi mentioned previously[5]. Tool rotation speed 900, 1000, 1100RPM and feed rate 270, 300, 330mm/min were considered as excellent conditions for weldability for Al 6000 series. This study adopted those conditions. Welding was done using the combination of nine methods. Welded specimen and welding conditions were shown in Figure 5.

| Table 1. Chemical compositions of Al6061(Wt.%). |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Mg              | Si              | Cu              | Cr              | Fe              | Zn              | Ti              | Mn              | Al              |
| 0.8             | 0.4             | 0.15            | 0.04            | 0.7             | 0.25            | 0.15            | 0.15            | Bal.            |
| ~               | ~               | ~               | 0.35            | ~               | ~               | ~               | ~               | ~               |
| 1.2             | 0.8             | 0.4             | ~               | 0.15            | 0.15            | 0.15            | 0.15            | Bal.            |
Table 2. Mechanical properties of Al6061-T6.

<table>
<thead>
<tr>
<th>Property</th>
<th>Yield stress (MPa)</th>
<th>Elongation (%)</th>
<th>Tensile stress (MPa)</th>
<th>Heat conduction coeff.</th>
<th>Density (g/cc)</th>
<th>E(kg/cm2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>55</td>
<td>25</td>
<td>240</td>
<td>0.40</td>
<td>2.7</td>
<td>7070</td>
</tr>
</tbody>
</table>

Figure 3. Photograph of friction stir welding machine.  Figure 4. Photograph of friction stir welding.

Table 3. Specification of the friction stir welding tool.

<table>
<thead>
<tr>
<th>Name</th>
<th>Property</th>
<th>Unit(mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoulder</td>
<td>Diameter</td>
<td>18</td>
</tr>
<tr>
<td>Probe</td>
<td>Length</td>
<td>4.8</td>
</tr>
<tr>
<td></td>
<td>Diameter</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Tilting angle</td>
<td>0°</td>
</tr>
</tbody>
</table>

Welding conditions 900RPM 1000RPM 1100RPM

<table>
<thead>
<tr>
<th>Welding conditions</th>
<th>900RPM</th>
<th>1000RPM</th>
<th>1100RPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>330(mm/min)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>300(mm/min)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>270(mm/min)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 5. Photograph completed friction stir welding.

MSP Test

The schematic diagram of MSP test method was shown in Figure 6. It consists of MSP jig composed of upper die, lower die and steel ball for load, temperature control device and data acquisition system, etc. The MSP test was performed by putting the Φ 2.4mm steel ball on top of the test specimen and putting load on it. It examined load behaviors by measuring central displacement (δ) of the specimen during the test period. As it can accurately measure the changes of the material up to 1 µm depending on applied load, it has very narrow error margin[6]. This study, to evaluate mechanical properties depending on welding conditions using the load-displacement data, compared fracture energy (Ψ).

In order to obtain sufficient ductility and brittleness characteristics for the microstructure of the weld, the area under the load-displacement curves was used for the test results up to a point 20% of the maximum load. Fracture energy was calculated from the following equation depending on each test condition.

\[
E_f = \int_{0}^{x_{\text{max}}} x \, dx .
\]  

(1)
Here, $t^*$: Minimum thickness of specimen at fracture

![Schematic diagram of the detailed MSP-jig(mm).](image)

**Figure 6. Schematic diagram of the detailed MSP-jig(mm).**

### Fracture Energy

#### Load Displacement Curves

![Load-displacement curves](image)

**Figure 7. The load-displacement curves at center: (a) 270mm/min, (b) 300mm/min, (c) 330mm/min.**

The MSP test was conducted to investigate the load and displacement caused by the deformation of the test specimen at a loading speed of 0.2 mm/min. Figure 7 was shown load-displacement according to the position of the weld. The center part was shown a large load-displacement behavior. Four-stage fracture behavior (elastic bending region, plastic bending region, plastic membrane stretching region, and plastic instability region) was observed under all welding conditions.

### Fracture Energy

**Figure 8.** was fracture energy ( Joule) graph depending on different welding conditions. The fracture energy showed a value increased up to 22% according to the feed rate increase at the tool rotation speed of 900 RPM. In the case of 1000 RPM, it decreased while it was increasing as the feed speed increased, but when it was 300 mm/min, it showed the largest value of 0.711 (J) among all the conditions. In the case of 1100 RPM, the fracture energy decreased as the feed rate increased. As the rotation speed of the tool increased at 270 mm/min, the value of the fracture energy increased, and when it was 300 mm/min, it showed a tendency to decrease while it was increasing. Also, at 330 mm/min, the increment of the tool rotation speed showed a continuous decrease in fracture energy, and the difference between the maximum value and the minimum value was 22%.

<table>
<thead>
<tr>
<th>Name</th>
<th>t</th>
<th>d1</th>
<th>d2</th>
<th>r</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small punch</td>
<td>0.5</td>
<td>2.4</td>
<td>4</td>
<td>0.2</td>
<td>2.4</td>
</tr>
</tbody>
</table>

| Specimen Size: 10 x 10 x 0.5 mm | Shear-punch Test System | MSP-tester |
Conclusion

This study carried out MSP test using small-scaled specimen in the central region of FSW. Al6061-T6 alloy plates which have 5mm thickness was welded to 9 conditions (tool rotation speed: 900, 1000, 1100RPM, feed rate: 270, 300, 330mm/min). The following results may be drawn from this study.

1. As a result of MSP test, the analysis of the fracture energy resulted in the improvement of the reliability in the existing life evaluation by deriving the displacement according to the load as the area until the fracture.

2. The maximum fracture energy was 0.771 J at the tool rotation speed of 1000 RPM and the feed rate of 300 mm / min, which was about 35.9 % of the minimum value. The reason is considered to be that the shape and distribution of precipitates in the weld zone were different and affected the weld strength and ductility.

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