Fatigue Strength of Friction-Welded 6061 Aluminum Alloy Joints*

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The Ono’s rotary bending fatigue test and the cantilever rotary bending fatigue test were carried out on friction-welded 6061 aluminum alloy joints, and the relationship between the deformation heat input in the upset stage or the upset burn-off length and fatigue strength was examined. In the Ono’s type test, sound joints, which fractured in the heat affected zone in the tensile test, fractured in the heat affected zone also and the fatigue limit of these joints was slightly lower than that of 6061 aluminum alloy base metal. This is because joints fractured in the softened area in both tensile test and Ono’s type test using smoothed test specimens. While, in the cantilever type test, the fatigue limit of sound joints was a little more than or a little less than that of 6061 aluminum alloy base metal. It seems that a weld and a structure at the weld interface softened area in both tensile test and Ono’s type test using smoothed test specimens. While, in the cantilever type test, the fatigue limit of sound joints was slightly lower than that of 6061 aluminum alloy base metal. This is because joints fractured in the heat affected zone in the cantilever type test using notched test specimens. Judging from the fatigue limit obtained, sound joints could be produced when either the deformation heat input in the upset stage or the upset burn-off length exceeded a certain value.

Keywords: friction welding, 6061 aluminum alloy, evaluation of joint performance, joint strength, fatigue strength

1. Introduction

Friction welding is used in many fields because the procedure is easily automated and it is possible to weld dissimilar materials.1 However, there are still unresolved issues in this method, such as the difficulty in setting the appropriate welding conditions for some materials, and the variance of optimum welding conditions depending on the different friction welding machines. Although the changes in the strength of friction-welded joints with the variation of each friction welding factor have been reported, there are no reports that joint strength can be evaluated by a parameter comprising various factors. Recently, the authors began examining a method of evaluating joint strength by analyzing heat input, which is the mechanical work done during friction welding, in order to logically set the appropriate welding conditions.

2. Experiment

The material used in this study is 6061-T6 aluminum alloy (A6061-JIS). The chemical composition and mechanical properties of the base metal are listed in Tables 1 and 2. A cylindrical alloy bar of 16 mm in diameter was cut to 100 mm in length, and a 20 mm length of bar on the welding end was machined down to 14 mm in diameter. Friction welding was conducted using a brake-type friction welding machine. The friction welding factors and the tensile strength of used joints are shown in Table 3. The joints B-E had a stable tensile strength and fractured in the heat affected zone, while the joint A fractured near the weld interface and the tensile strength of this joint was somewhat lower than those of the joints B-E.

The fatigue tests were carried out using an Ono’s rotary bending test machine using smoothed round bar test specimens.

<table>
<thead>
<tr>
<th>Material</th>
<th>Si</th>
<th>Mn</th>
<th>Cu</th>
<th>Cr</th>
<th>Fe</th>
<th>Mg</th>
<th>Zn</th>
<th>Ti</th>
<th>Al</th>
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<tbody>
<tr>
<td>A6061-T6</td>
<td>0.60</td>
<td>0.02</td>
<td>0.19</td>
<td>0.07</td>
<td>0.15</td>
<td>0.97</td>
<td>0.01</td>
<td>0.01</td>
<td>Re</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material</th>
<th>Tensile strength $\sigma_t$/MPa</th>
<th>Elongation $\epsilon/%$</th>
<th>Reduction of area $\phi/%$</th>
<th>Hardness $HV$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A6061-T6</td>
<td>287</td>
<td>13.6</td>
<td>66.8</td>
<td>118</td>
</tr>
</tbody>
</table>

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mens and a cantilever rotary bending test machine using notched round bar test specimens. The shape and dimensions of the test specimens are shown in Fig. 1. The fatigue test specimens of the latter were notched at the welding interface and the stress concentration factor for grooved shafts in bending is about 1.6. For comparison, an A6061 base metal test specimen of the same shape as the joint was tested. The hardness distribution of joints was measured 3.5 mm from the axial center at intervals of 0.5 mm from the weld interface to the original material zone, using a Vickers hardness tester.

3. Results and Discussion

3.1 Hardness Distribution of Joints

The hardness distribution of joints is shown in Fig. 2. All of joints softened in this investigation and the softened area decreased with increasing in upset pressure except the joint A. The distance from the weld interface to the most softened division increased when the softened area expands. It appears that in the joint A, the softened area was narrow, because the generated heat at the friction stage was small due to comparatively low friction pressure and low friction speed. It appears that in the joints B-E, the friction heat was sufficiently generated and the softened area was extended in the friction stage due to large friction pressure and high friction speed. However, the softened area decreased with an increase in upset pressure because the softened material adjacent to the weld interface was displaced with the burr by high upset pressure.

3.2 Fatigue Strength

3.2.1 Ono’s rotary bending fatigue test

S-N curves of joints and the A6061 base metal are shown in Fig. 3. The typical sections of fractured paths after fatigue test and appearance of fatigue-fractured surfaces of joints and the A6061 base metal are shown in Figs. 4 and 5, respectively. A crack grew from the upper part to the lower in Fig. 4. In the joint A, the fatigue strength was considerably low compared with that of the A606 base metal. Also, the joint A fractured rectilinearly along the weld interface, although thin A6061 adhered on the fractured surface. In contrast, in the joints B-E, although there was a little difference in fatigue strength between these joints, the fatigue strength and the fatigue limit of these joints was a little less

<table>
<thead>
<tr>
<th>Joint</th>
<th>Friction pressure $P_1$/MPa</th>
<th>Upset pressure $P_2$/MPa</th>
<th>Friction time $t_1$/s</th>
<th>Friction speed $N$/s$^{-1}$</th>
<th>Unit deformation heat input in upset stage $q_{fu}$/J/s</th>
<th>Upset burn-off length $\delta_2$/mm</th>
<th>Tensile strength $\sigma_s$/MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>10</td>
<td>30</td>
<td>2</td>
<td>33.3</td>
<td>13</td>
<td>0.3</td>
<td>196</td>
</tr>
<tr>
<td>B</td>
<td>25</td>
<td>75</td>
<td>2</td>
<td>66.7</td>
<td>1136</td>
<td>9.8</td>
<td>216</td>
</tr>
<tr>
<td>C</td>
<td>30</td>
<td>90</td>
<td>2</td>
<td>50.0</td>
<td>1452</td>
<td>10.5</td>
<td>233</td>
</tr>
<tr>
<td>D</td>
<td>40</td>
<td>120</td>
<td>2</td>
<td>66.7</td>
<td>2770</td>
<td>15.0</td>
<td>243</td>
</tr>
<tr>
<td>E</td>
<td>45</td>
<td>135</td>
<td>2</td>
<td>66.7</td>
<td>3566</td>
<td>17.2</td>
<td>250</td>
</tr>
</tbody>
</table>

Fig. 1 Shape and dimensions of test specimens (unit: mm).

(a) Ono’s rotary bending fatigue test specimen

(b) Cantilever rotary bending fatigue test specimen

Fig. 2 Hardness distribution of joints.

Fig. 3 S-N curves in Ono’s rotary bending fatigue test.
than that of the A6061 base metal. These joints fractured in a zigzag manner at apart from the weld interface, which is the softened area. Also, thick A6061 adhered and there was no welding surface on the fracture surface of the joints B-E.

### 3.2.2 Cantilever rotary bending fatigue test

In the Ono’s rotary bending fatigue test using smoothed test specimens, the fatigue fractured occurred in the weakest area in joints. Therefore, the cantilever rotary bending fatigue test was carried out using notched test specimens in order to examine the fatigue strength at the weld interface. S-N curves of joints and the A6061 base metal are shown in Fig. 6. The typical sections of fractured paths after fatigue test and appearance of fatigue-fractured surfaces of joints and the A6061 base metal are shown in Figs. 7 and 8, respectively. The S-N curve of the joint A could not be obtained due to the large dispersion of data and the fact that its fatigue strength was considerably lower than that of the A6061 base metal. Also, the joint A fractured rectilinearly along the weld interface and thin A6061 adhered on the fractured surface. It is clear that the weld at the weld interface was poor. In the joints B-E, although the fatigue limit was almost equivalent to the A6061 base metal, the fatigue strength of all joints at high repeated stress was low in comparison with that of the A6061 base metal. This difference decreased with a reduction in repeated stress. The fatigue strength of both joints B and D was relatively larger than that of both joints C and E. Although the fatigue limit of both joints B and D was slightly higher than that of the A6061 base metal, that of both joints C and E was slightly lower than that of the A6061 base metal. Both joints B and D, which had high fatigue strength, fractured in a zigzag manner near the boundary between fine structure layer and deformation zone. It appears that the weld at the weld interface was good. The joint C fractured rectilinearly to the weld interface. This seems to be because the weld at the weld interface was somewhat poor. In the joint E, there was narrow fine structure layer at the weld interface. Also, there was a deformation zone, which showed that the lamellar structure of the base material was twisted to the periphery, near the weld interface. It is known that strength of friction-welded joints decrease when the fracture occurs in some structure (e.g., deformation structure, fluidized structure) of the heat affected zone. It appears that the joint E fractured along the lamellar structure and this caused a slight decrease in fatigue strength.

The fatigue strength of the joint A, which fractured near the weld interface in the tensile test (joint efficiency in the tensile test: 68%), was considerably lower than that of the A6061 base metal, and joint efficiencies for the fatigue limit of the A6061 base metal in the Ono’s rotary bending fatigue test and in the cantilever rotary bending fatigue test were 24% and 50%, respectively. In contrast, in the joints B-E, which
fractured in the heat affected zone in the tensile test (joint efficiencies in the tensile test: 75–87%), there was a little difference in fatigue strength between joints and joint efficiencies for the fatigue limit were 92–98% in the Ono’s rotary bending fatigue test. This is because smoothed test specimens fractured in the softened area, or more precisely, the weakest area in both the tensile test and the Ono’s rotary bending fatigue test. In the cantilever rotary bending fatigue test, the fatigue strength of both joints B and D (joint efficiencies for the fatigue limit: 106%) was relatively larger than that of both joints C and E (joint efficiencies for the fatigue limit: 100% and 94%). It seems that a weld and a structure at the weld interface affected fatigue strength in the cantilever type test because test specimens fractured at the weld interface due to the presence of the notch.

3.2.3 Evaluation of fatigue strength

It is difficult in the field to calculate the deformation heat input because various friction phenomena need to detect. It is convenient in the field if joint strength could be evaluated in terms of burn-off length. In the friction welding of 6061 aluminum alloy, the authors revealed that the deformation heat input in the upset stage correlated with the upset burn-off length under the same stopping time, and tensile strength could be evaluated by the deformation heat input in the upset stage or the upset burn-off length.5) The relationship between fatigue limit and deformation heat input in the upset stage or upset burn-off length was examined in order to evaluate the fatigue strength of joints. These relationships are shown in Figs. 9 and 10. The fatigue limit of the A6061 base metal in the Ono’s rotary bending fatigue test and in the cantilever rotary bending fatigue test were 127 MPa and 80 MPa, respectively. It was possible to obtain joints that have a fatigue limit which is almost equivalent to the A6061 base metal when the deformation heat input in the upset stage exceeded 1000 J/s or the upset burn-off length exceeded 9 mm. These findings show that the fatigue strength can be evaluated by deformation heat input in the upset stage and by upset burn-off length, as judged from the fatigue limit.

4. Conclusion

Friction-welded 6061 aluminum alloy joints were examined by Ono’s rotary bending fatigue test and cantilever rotary bending fatigue test, and the fatigue strength of joints were evaluated by the deformation heat input in the upset stage and upset burn-off length. The results are as follows: (1) The fatigue strength of the joint, which fractured near the weld interface in the tensile test, was considerably lower than that of the A6061 base metal in the Ono’s rotary bending test.
(2) In the Ono’s rotary bending fatigue test, there was a little difference in fatigue strength between joints, which fractured in the heat affected zone in the tensile test, and the fatigue limit of these joints was a little less than that of the A6061 base metal. The similar tendency was shown in the tensile test. This is because smoothed test specimens fractured in the softened area in both the tensile test and the Ono’s rotary bending fatigue test.

(3) In the cantilever rotary bending fatigue test, there was a difference in fatigue strength between joints, which fractured in the heat affected zone in the tensile test. This is because a weld and a structure at the weld interface affected fatigue strength because test specimens fractured at the weld interface due to the presence of the notch.

(4) Judging from the fatigue limit, sound joints could be produced when the deformation heat input in the upset stage or the upset burn-off length exceeded a certain value in the fatigue test as well as in the tensile test.

REFERENCES