Effect of Welding Process Parameters on Mechanical Property of FSW Lap Joint between Aluminum Alloy and Steel

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This paper investigated the effect of a tilt angle and a pin diameter of the tool on the tensile shear load of lap joints between A5083 aluminum alloy and SS400 steel produced by Friction Stir Welding. The main results obtained are as follows:

The joint shear strength could not be increased with the increase of a tool tilt angle due to the formation of intermetallic compound at the joint interface. The increase of a tool tilt angle caused the concentration of aluminum in the intermetallic compound increased, resulting in the decrease of the joint strength. The increase of a pin diameter of a tool also could not increase the shear strength of the joint due to a void defect and a thicker intermetallic compound formed at the interface. The size of the void increased as the pin diameter increased. The effect of a pre-hole, which was opened at the pin inserting position of an aluminum plate before welding, was investigated to obtain the higher shear strength of the joints. It was concluded that the joint interface temperature was slightly decreased and the thickness of the intermetallic compound at the interface decreased with the increase of pre-hole diameter. The optimal pre-hole indicated the shear strength of about 77% that of the aluminum base material. The interface microstructure examination showed no intermetallic compound was formed at the joint interface.

(Received March 7, 2005; Accepted August 11, 2005; Published October 15, 2005)

Keywords: lap joint, aluminum alloy, steel, friction stir welding, tilt angle, pin diameter, pre-hole

1. Introduction

The use of a combination of aluminum alloy and steel has been introduced to the automobile industry for reducing the weight of automobiles to improve fuel efficiency and energy preservation.¹ However, it is very difficult to join the aluminum alloy and steel by fusion welding because the brittleness intermetallic compound (IMC) phase is inevitably formed at the joint and there is another difficulty that the large different in thermal expansion between them also introduce large residual stresses in the joint after fusion welding.²

Friction Stir Welding (FSW) has been widely applied for joining the materials difficult to weld such as aluminum alloy.³,⁴ Since this welding is a solid-state welding process, it is expected to provide a practical solution for joining aluminum alloy to steel, and some studied has applied this FSW to produce the butt⁵,⁶ and lap joint⁷⁻⁹ between the aluminum alloy and steel.

The FSW of an aluminum alloy/steel lap joint has many welding process parameters that affect the joint strength such as rotating speed, traverse speed, pin depth, tool geometry and so on. Recently, it has been reported that the effect of some welding process parameters on the joint strength. Elrefaey et al.⁸ studied the effect of rotating and traverse speed on the lap joints of A1100-H24 and low carbon steel, and reported that the fracture load increased when the rotating speed was increased and the traverse speed was decreased. Authors⁹ produced the lap joint of A5083/SS400 by FSW and found that the tensile shear load of a joint increased with decreasing in a rotating speed and a pin depth, and with increasing in a traverse speed.

However, other important welding process parameters such as the tilt angle and the pin diameter of a tool have not yet been studied. In this study, we investigated the effect of the tilt angle and the pin diameter of a tool on the joint tensile shear load. Additionally, in order to reduce IMC formed on the joint, we pre-set a hole (hereafter, pre-hole.) at the starting point of an aluminum plate before welding (shown in Fig. 8) and investigated the effect of the pre-hole on the interface microstructure and the tensile shear load of a joint.

2. Experimental Procedure

Plates of 3 mm thick A5083-O aluminum alloy (hereafter, Al) and SS400 mild steel (hereafter, Fe) were used in this study and had chemical compositions as listed in Table 1. The plates were cut to rectangular shape and have the dimension of 100 mm in length and 55 mm in width. The surfaces of both plates were polished with 240-grit emery paper, cleaned with acetone, and then were mounted in a jig to make a lap joint that Al plate overlapped Fe plate by 30 mm as shown in Fig. 1(a).

The rotating tool made of JIS-SKH57 tool steel had a shoulder (20 mm diameter) with an unthreaded pin (4–7 mm diameter and 3.0 mm long). The tilt angle of the rotating tool

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<th>SS400</th>
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<tr>
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<td>—</td>
</tr>
<tr>
<td>C</td>
<td>—</td>
<td>0.15</td>
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<tr>
<td>P</td>
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</tr>
<tr>
<td>S</td>
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</tr>
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</tr>
<tr>
<td>Fe</td>
<td>0.21</td>
<td>Balance</td>
</tr>
</tbody>
</table>

*Graduate Student, Niigata University
with respect to Z-axis of the milling machine was 1 degree as shown in Fig. 1(a). The welding process parameter was a rotating speed of 225 rpm, a traverse speed of 0.73 mm/s, a pin depth of 3.1 mm from upper surface of Al plate as shown in Fig. 1(a). The rotating tool was plunged into the plate of Al at speed of 0.01 mm/s. The temperatures during welding were measured by K-type thermocouples. The thermocouples were welded in the Fe plate, as shown in Fig. 1(b). Temperatures were measured at 3 points along the welding line at the distances of 30, 50 and 70 mm from the end of the plate.

A tensile shear test was investigated and the tensile shear specimens were prepared perpendicular to the X-axis from the welds. The welded area was located in the center of the tensile shear specimen. The dimension of the tensile shear specimen is shown in Fig. 1(c). Samples for metallographic examination were produced from the welds and mechanically polished. The polished samples were observed and analyzed using a scanning electron microscope (SEM) with X-ray energy-dispersive spectroscopy (EDS).

3. Results and Discussion

3.1 The effect of tool tilt angles on the shear strength of a joint

Joints were made using a tool with a tilt angle of 0 to 4° and a pin diameter of 5 mm. Figure 2 shows the relationship between the shear strength, IMC thickness and the tool tilt angle.

At a tool tilt angle of 0°, an imperfect weld in appearance occurred as shown by the arrow in Fig. 3(a) and a defect occurred on the aluminum side as shown by the arrows in Fig. 3(b). During the production of the shear test specimen the joint broke, therefore the shear strength of the joint was zero.

The cross sectional structures of the joints made under a tool tilt angle of 1–4 are shown in Fig. 4. The rectangular areas in the schematic were examined. The quantitative analysis by EDS was performed to reveal the phases observed at the interface of the joints and the results as listed in Table 2 were compared to the chemical composition of the IMCs on the Fe–Al phase diagram.10)

At a tool tilt angle of 1°, a sound joint could be produced and indicated average shear strength of about 112 MPa as shown in Fig. 2. The interface structure of the joint showed that the FeAl phase was formed along the interface as shown in Figs. 4(a) to (c) and the FeAl₃ phase observed in Fig. 4(b) was also formed around the Fe particles scattered in the Al alloy matrix. The thickness of the IMC that was obtained by calculating the average at 20 points at the interface of retreating and advancing sides was approximately 1.11 µm as shown in Fig. 2. Thickness was measured at the interface of retreating and advancing sides because, firstly, these locations indicated the maximum stress when the lap joint was subjected to the shear load test11) and, secondly, the IMC thickness between the retreating and advancing sides was not uniform.

At a tool tilt angle of 2°, the cross sectional structure indicated that Fe₂Al₅ formed around the interface of the joint as shown in Figs. 4(d) to (f). The Fe₂Al₅ phase was also found at the interface of the center side and around the Fe particle scattered on the Al side as shown in Figs. 4(e) and (f). The average shear strength of this joint was lower than that of a 1° tool tilt angle joint due to the formation of a Fe₂Al₅ phase, which indicated the brittle property of the joint when compared to a FeAl phase.12,13)
At a 3° tool tilt angle, the formation of the Fe$_2$Al$_5$ phase on the interface and the Fe particle on the Al side as shown in Figs. 4(g)–(i) was the same as that in the case of a 2° tool tilt angle. However, the average shear strength was lower than that of a 2° tool tilt angle. This decrease seemed to occur due to the formation of the void defect on the interface of the retreating side as shown in Fig. 4(g) and the increase in IMC thickness as shown in Fig. 2.

At a tool tilt angle of 4°, a void defect was observed at the interface of the retreating and the advancing sides as shown in Figs. 4(j) and (l) and Fe$_2$Al$_5$ IMC also formed on the joint interface as shown in Figs. 4(j) to (l). Comparing this result with the tool tilt angle of 3°, the decrease in shear strength seemed to occur because this condition produced a thicker IMC and the void defect along the joint interface.

The decrease in the shear strength when the tool tilt angle...
increased seemed to mainly occur due to void formation and an increase in the thickness of IMC formed at the interface of the joint. Furthermore, as the tool tilt angle increased, the Al concentration in the IMC phase increased as shown in Table 2. This implies that the IMC property becomes more brittle, resulting in a decrease in the shear strength of a joint. This relationship was noted in the work of Rathod and Kutsuna\(^\text{14}\) who studied the joining of AA5052 and low carbon steel using the laser rolled welding process. The findings of this work reported that when IMC thickness increased, the amount of Al increased while the amount of Fe decreased in the weld interface. They also found that an increase in Al-rich brittle IMC thickness at the interface drastically reduced the strength of the joint. The increase in IMC thickness and the increase in Al concentration seemed to be because a larger tool tilt angle gave rise to a higher temperature at the interface. The average peak temperatures at the interfaces of the joints made under tool tilt angles of 1\(^\circ\) to 4\(^\circ\) were 728, 755, 761 and 768 K, respectively. (These temperatures were measured at locations close to the joint interface. Heat conduction was ignored in this study.) However, the reason for the increase of IMC phase with slightly increased average peak temperature of about 40 K is still unclear. According to the above results, a tool tilt angle of 1\(^\circ\) was adopted thereafter as the optimal tool tilt angle for the welding experiments.

### 3.2 The effect of pin diameter on the shear strength of a joint

Joints were made using a tool with a pin diameter of 4 to 7 mm and the tilt angle of 1\(^\circ\). Figure 5 shows the relationship between the shear strength, IMC thickness and the pin diameter and shows that the joint shear strength increased with the increase of the pin diameter from 4 to 5 mm but the shear strength decreased when the pin diameter was 6 and 7 mm. The variation in the shear strength is attributed to various characteristics of an interface structure as following results.

Figures 6(a) to (c) show the interface structure at retreating, center and advancing sides of the 4 mm pin diameter and the void defect which was observed on the joint interface as shown in Figs. 6(a) to (c). The FeAl IMC phase was formed along the joint interface and had an average thickness of about 0.91 μm. The shear strength was slightly lower than that of the 5 mm pin diameter, which indicated a maximum shear strength of approximately 112 MPa. Comparing the interface of this joint to a pin diameter of 5 mm as shown in Figs. 4(d) to (f), the decrease of the shear strength of the 4 mm pin diameter seemed to be due to the void that was formed on the joint interface.

Using larger pin diameters of 6 and 7 mm resulted in incomplete joints with void defects as shown in Figs. 6(d) to (i). The larger amount of Fe fraction was swept to the aluminum side as shown by A in Figs. 6(e), (f), (h) and (i) and a thicker IMC was observed around the interface between the Fe fraction and the Al matrix. The EDS analysis indicated that these IMCs had chemical compositions that were close to the FeAl\(_2\) phase listed in Table 3. The average thickness of IMC also increased compared to that of a 5 mm pin diameter, IMC thicknesses were 6.57 and 6.77 μm for pin diameters of 6 and 7 mm, respectively as shown in Fig. 5. The formation of the FeAl\(_2\) IMC phase occurred because the larger pin diameter produced a high interface temperature. The average peak temperatures of the joints made with pin diameters of 4 to 7 mm were 719, 728, 778 and 797 K, respectively. In this study, the variation of IMC phase with an increase in average peak temperature of approximately 80 K is still unclear. Since the FeAl\(_2\) IMC phase is harder and more brittle than that of FeAl IMC phase\(^{13,14}\) and the void defect formed on the interface, it attributes that the shear strength of the pin diameter of 6 and 7 mm was lower than that of the pin diameter of 4 and 5 mm. As pin diameter increased, the shear strength of the joint decreased. A pin diameter of 5 mm indicated the maximum shear strength of about 112 MPa.

### 3.3 The effect of a pre-hole at the starting point on the shear strength load of a joint

Previous study\(^9\) and the results in section 3.1 and 3.2 suggested that the formation of a thicker IMC was the cause of the deterioration of the joint strength and it was possible to reduce the IMC amount by decreasing the interface temperature. In this section, an investigation for reducing the interface temperature was carried out. Recently, Song and Kovacevic\(^{15}\) reported that the interface temperature could be reduced by decreasing the rotating speed, and increasing the traverse speed and also increasing the pin insertion rate. However, in this study, the decrease of the rotating speed and increase of traverse speed were limited because the present speeds are the speeds that give the maximum shear strength.
Therefore, in order to increase only the pin insert rate and to reduce the frictional heat between tool surface and materials, authors attempted to allocate a pre-hole at the start point of the lap joint as shown in Fig. 7. Welding was done under the conditions of a pre-hole of 0.0 to 20.0 mm, 1° tool tilt angle and 5 mm pin diameter.

Surface appearances of the welds for 0.0 to 10.0 mm pre-holes showed a complete surface as seen in Fig. 8(a), however, when the pre-hole diameter was 15.0 and 20.0 mm, an incomplete part occurred at the commencement point indicated by the arrows in Figs. 8(b)–(c). This was because the aluminum amount seemed to be insufficient to form the weld at the commencement point.

Figure 9 shows the increase of shear strength with the increase in size of the pre-hole diameter, and the maximum shear strength of about 130 MPa was achieved. The thickness

<table>
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<th>Pin diameter</th>
<th>Al</th>
<th>Fe</th>
<th>Mg</th>
<th>O</th>
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<td>7 mm</td>
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<td>38.74</td>
<td>2.89</td>
<td>5.62</td>
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Figure 9 shows the increase of shear strength with the increase in size of the pre-hole diameter, and the maximum shear strength of about 130 MPa was achieved. The thickness
of IMC formed on the joint interface also decreased, as expected, and no IMC was observed for 10.0 to 20.0 mm pre-holes. Table 4 shows the results of EDS analysis of IMC formed on an interface of 0.0 to 7.5 mm pre-hole and indicates that the IMCs are close to FeAl and the concentration of Al in IMC decreased with the increase of the pre-hole. These results are attributed to the fact that the interface temperature decreased with the increase of the pre-hole diameter. The average temperatures for the pre-holes of 0.0 to 20.0 mm were 728, 723, 706, 691, 678, 672 and 666 K, respectively.

Figure 10 shows the cross sections perpendicular to the traverse direction of the weld with a 10 mm pre-hole, which attained the maximum shear strength. Figures 10(a) to (c) correspond to retreating, center and advancing sides, respectively. No voids were observed along the joint interface. EDS line analysis was performed for the parts of rectangular A to C in Figs. 10(a)–(c). The results in Figs. 10(d)–(f) reveal no IMC existed on the interface of this joint.

SEM photographs of the fracture surfaces of the joint produced under the pre-hole of 10 mm, are shown in Fig. 11. Figure 11(a) shows the macro-photographs of fracture surface of Al and Fe sides and the dotted line corresponding to the location where the specimen started to break. The enlarged rectangular on the uneven fracture surface are shown in Figs. 11(c) and (d) and a dimple pattern indicating ductile features in both aluminum was observed. The points I to VI in Fig. 11(b) were analyzed by EDS. It was indicated from the analysis that the dimple surface contained high amounts of aluminum as shown in Table 5. This fact suggests that the fracture of the selected area as seen in Fig. 11(b) occurred in the aluminum base metal.
As mentioned in this section, we successfully improved the shear strength and the interface microstructure of the joint by putting a pre-hole at the starting point of the Al plate.

4. Conclusion

Authors investigated the effects of a tool tilt angle and a pin diameter on the shear strength and interface microstructure of FSW lap joint between A5083 aluminum alloy and SS400 mild steel. The effect of a pre-hole at the pin inserting location was also investigated. The following results were obtained.

(1) Increasing of the tool tilt angle decreased the shear strength of the joint because the larger tool tilt angle formed a thick Fe$_2$Al$_5$ IMC at the joint interface, which directly related to the decrease of the joint shear strength.

(2) Increasing of the pin diameter decreased the shear strength of the joint because the larger pin diameter such as 7 mm gave a thicker FeAl$_3$ IMC and large voids along the interface. An optimum pin diameter of 5 mm attained the maximum shear strength.

(3) The application of the pre-hole on the Al plate could increase the shear strength of the joint because the amount of IMC phase formed on the interface decreased with the increasing of the size of the pre-hole diameter. The optimum pre-hole to obtain the maximum shear strength of the joint was 10 mm.

REFERENCES


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