Investigation of Microstructure and Mechanical Properties of Friction Stir Lap-Jointed A6061/HT590 Alloys

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In this study, the mechanical properties of friction stir lap-jointed A6061/HT590 alloys were evaluated. Friction stir welding was conducted at a tool rotational speed of 500 rpm and a traveling speed of 300 mm/min, where Ar gas was introduced to prevent the materials from corroding during the welding process. Electron back-scattering diffraction was used to characterize the microstructural parameters such as the grain size, misorientation angle, and crystal orientation. The evolution of intermetallic compounds in A6061 during the process was examined in terms of the morphology, size, and aspect ratio in three distinct zones in the Al base material, the heat affected zone, and the stir zone, where transmission electron microscopy was used. It was revealed that friction stir welding gave rise to grain refinement as well as the growth of intermetallic compounds in A6061. The morphological changes in the intermetallic compounds influenced the mechanical properties, resulting in the occurrence of fracture in part of the base material instead of the jointed parts (heat affected zone and stir zone). This study systematically evaluated the microstructural evolution during the friction stir welding for joining A6061 with HT590 and its effect on the mechanical properties.

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1. Introduction

The A6061 alloy, which is age hardenable, is widely used in the parts of automobiles, ships, aircraft, and machinery owing to its excellent toughness, formability, and corrosion resistance¹,². In addition, Al alloys are significantly lightweight relative to Fe-based alloys and have a density that is approximately 1/3 that of steel. Furthermore, their applications in industry are gradually increasing. In particular, to decrease the carbon emissions from vehicles, which consequently increases the fuel efficiency, automobile makers are adopting Al alloys as a lightweight material, and many studies have been carried out³,⁴. The joining technology between dissimilar materials for the creation of a lightweight vehicle has received significant attention. However, studies on the lap joints consisting of thin plates of steel and Al alloys have not been reported so far.

Friction stir welding (FSW) has several advantages for defect suppression, such as a blow hole, segregation, and cracking, which mainly occur in fusion welding⁵,⁶. The notable grain refinement in the stir zone due to FSW results in an outstanding increase in the mechanical properties of the welds. On the other hand, dissimilar materials that are welded can be used in many ways. FSW as a welding method between dissimilar materials is a promising new welding process, and many studies on the welding of dissimilar materials have been reported⁷–⁹. In particular, joining techniques are certainly applied to produce an automobile, and the FSW of several different materials is actively being studied. Therefore, this work was carried out to evaluate the thin plates of dissimilar materials welded together and investigate the development of microstructures and mechanical properties during FSW.

2. Experimental Procedures

The materials used in this study were A6061 and HT590 (high tension steel with a 590 MPa class of tensile strength manufactured by KOBELEC) alloys, and the chemical compositions are listed in Table 1. To carry out FSW lap joining, samples were prepared in thin plates with dimensions of 100 mm × 150 mm × 1 mm (A6061, the upper side) and 100 mm × 150 mm × 1 mm (HT590, the lower side). FSW was conducted using a WC–Co tool with a 15-mm-diameter shoulder, a 6-mm-diameter probe, and a length of 1.8 mm. To obtain a sound welds, the tool was tilted 1° forward from the vertical, and argon gas was utilized to prevent surface oxidation during welding. FSW was performed at a tool rotational speed of 500 rpm, a tool down-force of 19 kN, and a traveling speed of 300 mm/min.

In order to evaluate the microstructure of the welds, scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) were employed. An evaluation of the grain shape, size, and grain misorientation of the welds was carried out using electron backscattering diffraction (EBSD). For this work, specimens were machined to dimensions of 2 mm × 20 mm, mechanically ground, and then electropolished at 20 V and −40°C at the surface with a solution comprising 100 ml of perchloric acid and 900 ml of methanol. The sample surfaces were then analyzed by an orientation image mapping (OIM) system incorporated with SEM.

Table 1 Details of chemical compositions of the materials used in this work.

<table>
<thead>
<tr>
<th>Material</th>
<th>Si (wt%)</th>
<th>Fe (wt%)</th>
<th>Cu (wt%)</th>
<th>Mn (wt%)</th>
<th>Mg (wt%)</th>
<th>Cr (wt%)</th>
<th>Zn (wt%)</th>
<th>Ti (wt%)</th>
<th>Al (wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A6061</td>
<td>0.60</td>
<td>0.66</td>
<td>0.35</td>
<td>0.08</td>
<td>1.22</td>
<td>0.07</td>
<td>0.04</td>
<td>0.02</td>
<td>Bal.</td>
</tr>
<tr>
<td>HT590</td>
<td>0.08</td>
<td>0.23</td>
<td>1.55</td>
<td>0.03</td>
<td>0.002</td>
<td>Bal.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Furthermore, to evaluate the dispersed precipitates in the welds, transmission electron microscopy (TEM) was employed. For the TEM analysis, discs with a diameter of 3 mm were prepared, mechanically polished to 80 μm, and then thinned to <10 μm using ion milling. They were examined by TEM at 200 kV. For evaluation of the mechanical properties, the Vickers microhardness and a tensile test were employed. The Vickers hardness was obtained from the cross section of the weld zone with a load of 1.96 N and a dwell time of 10 s. For the tensile test, the tensile test specimen, in which HT590 is located on the retreating side, was used to evaluate the transverse tensile strength of the friction stir lap joints.

3. Results and Discussion

Top and cross-sectional views of the macrostructures of friction stir lap-jointed A6061 and HT590 are shown in Fig. 1. From the top view, the materials were soundly lap-jointed without any defects such as cracks, voids, and grooves in the weld surface, as shown in Fig. 1(a). From the cross-sectional view of the macrostructure, the interface exhibited a soundly jointed state without voids and cracks, as shown in Fig. 1(b). However, a hook with a height of 800 μm was observed on the retreating side and the A6061 side originating from the HT590 alloy. The EDS results for the hook are shown in Fig. 2, which indicates that it is formed by the HT590 alloy owing to the presence of Fe in the spectrum.

The orientation image maps and grain-size distributions of the base material and friction stir lap joints (A6061 side) acquired by EBSD are shown in Fig. 3. In the initial state, the base material consisted of grains ranging between 8 μm and 80 μm in size, as shown in Figs. 3(a) and (b), with an average size of 42 μm. For friction-stir-welded A6061, the stir zone exhibited a significantly refined grain size relative to the base material, with a grain size ranging between 2 μm and 22 μm and an average size of 11 μm, as shown in Figs. 3(c) and (d). Moreover, the grains in the base material were primarily arranged along <001> // ND; however, the stir zone showed the primarily exhibited the arrangement of <111> // ND.

The orientation image maps and grain-size distributions of the base material and friction stir lap joints (HT590 side) are shown in Fig. 4. The base material consists of the grains ranging from 2.5 μm to 12 μm in size, as shown in Figs. 4(a) and (b), with an average size of 6 μm. For friction-stir-welded HT590, the stir zone consisted of grain sizes ranging from 0.1 μm to 0.9 μm with an average size of 0.75 μm, which is a notably refined size relative to the base material, as shown in Figs. 4(c) and (d). On the other hand, the grain orientation was primarily arranged along <111> // ND in the base material and <101> // ND in the stir zone.

The changes in the distributions of the grain misorientation angle in the base materials and friction-stir-welded joints are shown in Fig. 5. The high-angle grain boundaries in the base materials comprised 92% (A6061) and 94% (HT590) of the entire grain boundaries, as shown in Figs. 5(a) and (c), respectively. The stir zone also exhibited similar distributions as the base materials. As a result, the high-angle grain boundaries comprised over 87% (A6061) and 92% (HT590) of the entire grain boundaries, as shown in Figs. 5(b) and (d), respectively.

Fig. 1  (a) Top-view and (b) cross-sectional macrostructures of the friction stir lap joints. Adv., Ret., and SZ in the figure indicate the advancing side, retreating side, and stir zone, respectively.

Fig. 2  SEM image and EDS results of friction stir lap-jointed interfaces between the A6061 and HT590 alloys.

Fig. 3  Orientation image maps and grain-size distributions of the base material and stir zone of the A6061 alloy. (a and b) Base material and (c and d) stir zone.
The orientation image maps of the base material, thermo-mechanically affected zone (TMAZ), and stir zone of HT590 are shown in Fig. 6. In the analyzed zone, the changeable aspect of grain size on each zone indicated in direct, as shown in Fig. 6(a). In case of the TMAZ [indicated by the dashed rectangle in Fig. 6(a)], elongated grains due to significant deformation were observed, as shown in Fig. 6(b). Furthermore, the grains near the stir zone in the TMAZ exhibited a more refined and elongated shape relative to those near the base material.

![Fig. 4](image)

**Fig. 4**  Orientation image maps and grain-size distributions of the base material and stir zone of the HT590 alloy. (a and b) Base material and (c and d) stir zone.

![Fig. 5](image)

**Fig. 5**  Misorientation angle distributions in the base materials and stir zones of A6061 and HT590 alloys. (a) Base material and (b) stir zone of the A6061 alloy and (c) base material and (d) stir zone of the HT590 alloy.

![Fig. 6](image)

**Fig. 6**  (a and b) Orientation image maps of the BM, SZ, and TMAZ acquired by EBSD. BM, SZ, and TMAZ in this figure indicate the base material, stir zone, and thermo-mechanically affected zone, respectively. Subfigure (b) shows a magnification of the TMAZ (dashed rectangular) in subfigure (a).
The distributions of the cross-sectional Vickers microhardness for A6061 and HT590 are shown in Fig. 7. The A6061 base material has a value ranging from 75 Hv to 88 Hv. However, the friction-stir-welded zone exhibited slightly lower values relative to the base material, with the values ranging from 50 Hv to 82 Hv, as shown in Fig. 7(a). Moreover, the hardnesses (dashed ellipse) with significantly higher values were observed in the A6061 stir zone, which was identified by the hook formed on the retreating side. For HT590, the base material exhibited values ranging from 180 Hv to 205 Hv, and friction-stir-welded zone had significantly higher values relative to the base material, which ranged from 275 Hv to 320 Hv, as shown in Fig. 7(b).

The tensile properties of the base materials and friction stir lap joints are shown in Fig. 8. The tensile specimen was first deformed and fractured in the base material zone without any delamination at the lap-jointed interface, as shown in Fig. 8(a). At initial materials, A6061 and HT590 exhibited yield strengths of 217 MPa and 227 MPa, tensile strengths of 352 MPa and 512 MPa, and elongations of 32% and 29%, respectively, as shown in Fig. 8(b). However, the friction stir lap joints have yield and tensile strengths of 195 MPa and 263 MPa, respectively, which were slightly lower than those of the initial A6061 material. Furthermore, the lap joints have a notably decreased elongation compared to the initial material.

The distributions of the intermetallic compounds analyzed in the base material zone in the initial state and after FSW were acquired by TEM, and the results are shown in Fig. 9. In the initial state, the intermetallic compounds were dispersed with a size in the range of 0.05–0.25 μm, a comparatively homogeneous distribution, which was identified as α-Al13(Fe, Mn, Cr)3Si2, as shown in Fig. 9(a). However, the base material zone after FSW exhibited more coarsened intermetallic-compound sizes relative to the initial base material, with a size in the range of 0.1–0.5 μm, as shown in Fig. 9(b). In addition, the fraction of intermetallic compounds was significantly decreased compared to the initial base material.

A6061 and HT590 were soundly lap jointed by FSW. In general, FSW has a lower heat input relative to fusion welding such as gas tungsten arc welding, laser welding, and electron-beam welding, which can effectively suppress the formation of weld defects\(^{10}\). As mentioned earlier in the discussion of Fig. 1, the lap joints exhibited a soundly welded state without defects such as cracks, blow holes, and delamination at the surface and interface. However, the hook [Figs. 1(b) and 2] from the HT590 side was formed on the retreating side by the tool downforce, which could maintain the mechanical properties such as the tensile and peel strengths\(^{11}\).

The application of FSW led to a significant grain refinement. In the initial base material, A6061 and HT590 consisted of grains with average sizes of 42 μm and 6 μm, respectively, as seen in Figs. 3(a) and 4(a). However, the stir zones of A6061 and HT590 consist of significantly refined grains with average sizes of 11 μm and 0.75 μm, respectively, as seen in Figs. 3(c) and 4(c). Thus, the grain refinement obtained by FSW can be explained in terms of dynamic recrystallization. FSW induces heat due to friction caused by the
Friction stir lap joints using thin plates of A6061 and HT590 were soundly carried out without outstanding weld defects in the jointed area. The application of FSW led to dynamic recrystallization in the stirred zone, resulting in a significantly refined grain size relative to the base material. The refined grain size resulted in an increase in the micro-hardness of the HT590 alloy. In contrast, the A6061 alloy did not exhibit an outstanding increase. However, the coarser size and decreased fraction of precipitates in the A6061 alloy caused a decrease in the tensile strength relative to that of the initial material, which resulted in fracture in the base material zone. Therefore, the application of FSW to A6061 and HT590 lap joining can effectively develop the mechanical properties, accompanied with the development of microstructures.

### Acknowledgements

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### REFERENCES

6) C.J. Dawes: An introduction to friction stir welding and its development, (Welding And Metal Fabrication, 1995)