1. Introduction

The use of zinc-coated steels for the automotive body construction has increased significantly in the last 2 decades to enhance the durability of vehicle structures. The automotive industries are currently working to develop lighter and more fuel-efficient vehicles. A significant proportion of this effort is currently being directed toward the substitution of aluminum for steel in the body structure. Aluminum is considerably lower in strength and stiffness than steel, and the design of the spaceframe coupled with the use of thicker material sections, successfully compensates for this.

Nevertheless, the replacement of material presents a vital challenge with respect to the methods of joining to be used for fabrication in volume production. Over the last decade, friction stir welding (FSW) has offered excellent welding quality to the joining of aluminum, magnesium, titanium, copper, and Fe alloys. Recently, some trials have been made to join the dissimilar materials, for examples dissimilar Al alloys and aluminum to steel joints. However, most of the FSW efforts to date have not involved joining aluminum to zinc-coated steel. From an industrial point of view, there seems to be considerable interest in extending the process to this joint. Therefore, this research has been aimed at investigating the performance of aluminum-to-zinc coated steel (Al/Zn-coated steel) lap joint by friction stir welding and metallurgical factors controlling the performance.

2. Experimental Details

The materials used were a plate of commercially pure aluminum A1100H24 2.0 mm thick and a plate of low carbon Zn-coated steel 1.0 mm thick. The steel had Zn coating of 10 \( \mu \)m thickness. The chemical compositions of base metals are shown in Tables 1 and 2. The microstructures of the base metals are shown in Fig. 1. The aluminum base metal presented grains elongated in the rolling direction, and the steel base metal showed ferritic structure due to its very low carbon content. The base metals were cut into specimens of 250 mm x 100 mm for welding. Lap welding was made by a FSW machine as schematically shown in Fig. 2. Rotation and travel speeds of the tool employed are listed in Table 3. The depth of the pin tip from the upper surface of the aluminum plate was fixed at 2.0 or 2.1 mm (0.0 and 0.1mm from the surface of the zinc-coated steel plate).

The tool of steel SKD61 was comprised of a shank, shoulder and pin as shown in Fig. 3. The tool axis was tilted by \( 3^\circ \) with respect to the vertical axis of the plate surface. The FSW tool, fixed to the holder, was slowly pushed into the aluminum plate to the specified pin depth and then forcibly traversed along the joint until the end of the weld was reached. The welding tool was then...
retracted while the tool continued to turn.

The surface for the observation of microstructure was etched by 3% Nital to reveal the steel microstructure and subsequently by 1% HF aqueous solution to reveal the aluminum microstructure.

Table 3  Welding parameters.

<table>
<thead>
<tr>
<th>Rotation</th>
<th>Travel mm/s</th>
<th>Pin depth mm</th>
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The microstructure was observed with an optical microscope and SEM (Scanning Electron Microscope) for closer observations. A peel test was employed to estimate the fracture load of the obtained joint. The schematic view of the specimen for the peel test is shown in Fig. 4.

Temperature measurements at positions close to the zinc-coated steel surface (0.3 mm down from the surface) were carried out by using a thermocouple (K-type) percussion-welded to the bottom of holes drilled from the back surface of the steel specimen. X-ray diffraction analyses were carried out to identify phases present on the fracture surfaces of joint after peel tests.
3. Experimental Results and Discussion

3.1 Characteristics features of joints

The macroscopic views of traverse sections of joints welded at pin depth of 2.1 mm are shown in Fig. 5. It should be noted that a great change in the steel microstructure was observed in the area below the pin tip when the rotation speed was not less than 25.0 s\(^{-1}\). Meanwhile, at a rotation speed of 16.7 s\(^{-1}\) the change in steel microstructure at the interface was quite small, but a remarkable change was observed in the aluminum stir zone to the direction of advancing side. The figure showed no clear onion ring structure or thermo-mechanically affected zone in contrast to the general stir zone reported in many previous papers\(^{14-16}\) about FSW of aluminum alloys.

A few characteristic regions can be identified in both aluminum side and zinc-coated steel side of the joints as shown in Fig. 6 (a). The microstructure of the aluminum corresponding to the stir zone was characterized by equiaxed fine grains as shown in Figs. 6 (b) and 6 (c). The grain size near the bond interface (area II) was slightly coarser than the upper surface of aluminum (area I), suggesting the effect of heat generated by friction between the pin tip and Zn-coated steel on the grain size of the aluminum. Several authors suggested that the equiaxed fine grain in the stirred zone was formed through the dynamic recrystallization followed by the static grain growth for a short period during the cooling process\(^{17-19}\).

Between the stir zone and the base metal, narrow heat-affected-zones (areas III and IV) were observed which were characterized by slightly coarse grain size as shown in Figs. 6 (d) and 6 (e). Area V in the zinc-coated steel side was characterized by much finer equiaxed-grains than the base metal as shown in Fig. 6 (f). The average grain size of this zone was approximately 3 \(\mu m\) at a rotation speed of 25.0 s\(^{-1}\) at a traveling speed of 3.3 mm/s, while it was 7 \(\mu m\) at a rotation speed of 41.7 s\(^{-1}\). The grain size was reduced with an increase in traveling speed from 3.3 mm/s to 5.0 mm/s. In the transition zone between area V and zinc-coated steel substrate, as shown in Fig. 6 (g), a coarser grain structure representing the Zn-coated steel HAZ was observed (area VI).

The very fine grain size in the steel close to the Al/Zn-coated steel interface (area V) can be attributed to the recrystallization of the area deformed heavily by the friction with the rotating pin, since the maximum temperature measured with thermocouples, at points 0.3 mm down from the steel surface was about 779 K, much lower than \(\alpha \rightarrow \gamma\) transformation of the steel. The size of the recrystallized grains depends mainly on the strain which took place in the grains and the temperature relative to the melting point of the material. It can be expected that the deformation of the steel fine grain zone was smaller than that of aluminum, since the tool pin tip does not reach this zone. Therefore, the much smaller grains size of the steel fine grain zone can be attributed to the higher melting point of the steel than the aluminum.

In the aluminum stir zone close to the interface, some iron-
rich particles were observed as shown in Fig. 6 (a). These particles were separated from the steel surface by the stirring effect of the pin which pulled them from the zinc-coated steel surface and scattered in the aluminum substrate.

With an increase in the rotation speed, grains of both aluminum and zinc-coated steel in all characteristic areas were coarsened. This is probably due to the increase in heat input which increases the maximum temperature of the area and decreases the cooling rate. This result agrees with many previous papers. In contrast to the rotation speed, increasing the travel speed decreased the heat input, which in turn decreased the grain size and decrease the steel fine grain zone area as obviously seen in Fig. 7.

Close observations with a SEM of the Al/Zn-coated steel interface revealed that layered structures containing high percentage of aluminum, from 20 to 40 %, formed in the Zn-coated steel fine-grain zone adjacent to the weld interface at rotation speeds higher than 16.7 s⁻¹. The layer structure was more developed in size and thickness at higher rotation speeds as shown in Fig. 8. Meanwhile, at a rotation speed of 16.7 s⁻¹, a layer involving Al, Fe, and Zn was formed at the interface as shown in Fig. 9, and it extended to the advancing side. The chemical composition of this Al-Fe-Zn layer was well above the solid solubility of Fe in Al, as shown in Table 4. This suggests that the Al-Fe-Zn layer involved Al-Fe or Al-Fe-Zn intermetallic compounds.

The hardness value of the aluminum was almost constant (∼30 Hv) in the equiaxed fine grain zone, HAZ, and base metal. The hardness of the zinc-coated steel showed the highest value in the layer structure, reaching 584 Hv. This could be related to the formation of intermetallic compounds within this structure as

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**Fig. 7** Effect of travel speed on fine grain area of Zn-coated steel: (a) Weld No. 20, (b) Weld No. 22, and (c) Weld No. 24.

**Fig. 8** Layered structure observed at the Zn-coated steel interface: (a) weld No. 20 and (b) weld No. 14.

**Fig. 9** Layer of deformed Al/Fe/Zn observed at the Al/Zn-coated steel interface. Weld No. 2.

**Table 4** Chemical analyses at points 1 to 5 indicated in Fig. 9 (at %).

<table>
<thead>
<tr>
<th>Elements</th>
<th>Points</th>
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<td>Al</td>
<td>1</td>
</tr>
<tr>
<td>Fe</td>
<td>17</td>
</tr>
<tr>
<td>Zn</td>
<td>6</td>
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suggested by EDX analyses and X-ray diffraction analyses of the fracture surfaces of the joints (see Fig.16). The very fine grain area in the steel close to interface was higher in hardness than the base metal. Hardness values of different areas at Al/Zn-coated steel interface are shown in Fig. 10.

At a rotation speed of 16.7 s⁻¹, as shown in Fig. 11, the Al-Fe-Zn layer observed at the interfacial region (see Fig.9) showed hardness higher than the aluminum and zinc-coated steel base metals, suggesting the presence of intermetallic compounds. The extension of this layer to the advancing side in the aluminum stir zone showed a similar hardness level to those at the interface. The extension of this layer was surrounded by areas diluted with aluminum showing hardness of 34 Hv.

The fracture load of joints on peel test is shown in Fig. 12. It seems that increasing travel speed from 3.3 to 5.0 mm/s slightly decreased the fracture load. Meanwhile, increasing the rotation speed from 16.7 to 25.0 s⁻¹ raised significantly the fracture load, while further increase from 25.0 to 41.7 s⁻¹ exhibited a slight positive effect on the fracture load.

For most joints bonded at rotation speeds of 25.0 to 41.7 s⁻¹, the fracture on the peel test occurred along the path as shown in Fig. 13 (a). Iron-rich fragments stuck to the fractured surface of the aluminum side which contained mainly layer structure, similar to those observed in Fig. 8. Results from point analyses of the layered structure are listed in Table 5. The Fe and Al contents of the layered structure suggest the presence of intermetallic

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compounds. It can be considered that the crack propagated either in the aluminum substrate or layer structure.

It was frequently noted that the fracture path developed into the aluminum substrate in the areas indicated by arrows in Fig. 14. These joints achieved higher fracture loads than others.

SEM micrographs of the fracture surfaces corresponding to the fracture path shown in Fig. 13 are shown in Fig. 15. The fracture surfaces were mainly ductile with some brittle areas. The ductile morphology was more prominent in joints that showed higher fracture loads. Meanwhile, ductile fracture morphologies were observed in the area where the crack propagated in the aluminum substrate as shown in Fig. 14.

In order to identify the intermetallic compounds formed in the layered structure of the joint bonded at higher rotation speeds (25.0-41.7 s⁻¹), X-ray diffraction patterns from fractured surfaces of the aluminum and steel sides were analyzed as shown in Figs. 16 (a) and 16 (b). As can be seen from these, diffraction lines that were attributable to intermetallic compounds of Al₃Fe₄ and Al₅Fe₂ were detected from both aluminum side and steel side. This suggests that these intermetallic compounds were involved in the layer structure and responsible for the brittle fracture on peel test.

The pin depth of 2.0 mm was not deep enough to penetrate the pin tip to the zinc-coated steel side. It only reached the top surface of zinc layer and hence, there was no evidence for fine grain zone and layered structure in the zinc-coated steel.

3.2 Comparison with joint of aluminum to steel without zinc coating

The fracture loads of Al/Zn-coated steel joint at 2.1 mm pin depth were higher than those of similar joints of aluminum to steel without Zn coating (Al/steel) in spite of similarity in microstructure of joints. It should be also mentioned that while the Al/Zn-coated steel joint exhibited considerable fracture load at pin depth of 2.0 mm, Al/steel joints were so week that they fractured during preparation of the specimen for metallurgy at the same pin depth. In fact, the zinc-coated layer is the only reason for this improvement in the fracture load of the joint.

There were two main factors controlling the performance of the solid-state bonded joint of dissimilar metals. One of them is the intimate contact between aluminum and steel, and the other is the microstructure, particularly the formation of brittle intermetallic compounds. In regard to the microstructure, the amounts of the layer structure and intermetallic compounds in Al/Zn-coated steel joints decreased in comparison with those observed in the Al/steel joint. According to Al-Fe-Zn ternary phase diagram, Zn increases the solid solubility of Fe in Al, which probably contributed to decrease the intermetallic compounds in the layer structure. Moreover, it is conceivable that the zinc layer acted as lubricant during the FSW process because zinc itself is softer than aluminum and steel. Moreover, aluminum becomes softer by alloying with zinc owning to the decrease in its melting point (the lowest melting point in the Al-Zn system is 654 K much lower than the peak temperature of the fine grain
The intimate contact will be enhanced by increasing the heat input, viz. increasing the rotation speed or decreasing the traveling speed, since it facilitates the materials flow in the stir zone through lowering the flow stress, and increases the period held at high temperatures. On the other hand, it enhances the formation of intermetallic compounds, through the promotion of the mechanical mixing of the two metals and the diffusion of elements forming the intermetallic compound. In the present investigation, as shown in Fig. 12, the bond strength was increased with the heat input. The bond strength of the joint of aluminum to steel without Zn coating was also increased with the heat input. These results suggest that the bond strength of these joints was controlled mainly by the attainment of intimate contact at the interface. Therefore, the effect of Zn coating on the bond strength can be attributed mainly to the enhancement of the intimate contact at the bond interface. As mention above in the explanation of the effect of zinc coating on the layer structure, the zinc coating can be considered to introduce a softened zone in the zone close to the weld interface. Meanwhile, the steel just under the tool pin showed a very fine grain zone that involved a hard layer structure in the area close to the weld interface.

These effects of the Zn coating on the attainment of intimate contact and the formation of layer structure are probably responsible for the improvement of the bond strength observed in the Al/Zn-coated steel joint. This result also suggests that further improvement can be obtained by applying a zinc intermediate layer to the joining of aluminum to steel.

4. Conclusions

1. The feasibility of the FSW lap joint of a commercially pure aluminum plate to a zinc-coated steel plate was exhibited. The Al/zinc-coated steel joint showed higher fracture strength than the Al/steel joint, suggesting that the zinc coating had a beneficial effect on the bond strength.

2. The Al/zinc-coated steel joint welded at 2.1 mm pin depth were much stronger than that welded at 2.0 mm pin depth, and its fracture strength showed a general tendency to decrease with an increase in traveling speed.

3. The aluminum microstructure of the joint consisted of the stir zone and the heat affected zone on the retreating and advancing sides of the stir zone. The stir zone consisted of equiaxed fine-grains, and the heat affected zone was characterized by coarser grains than the base metal and stir zone. Meanwhile, the steel just under the tool pin showed a very fine grain zone that involved a hard layer structure in the area close to the weld interface.

4. Fracture of joints bonded at rotation speeds of 25.0 - 41.7 s⁻¹ occurred mainly in the aluminum substrate and the layer structure where intermetallic compounds such as Al₃Fe₂ and Al₁₁Fe₂ were formed. The joints having higher fracture strength showed more ductile fracture morphology which corresponds to the fracture in the aluminum substrate.

References


