Effect of Pin Shapes on Joint Characteristics of Friction Stir Spot Welded AA5J32 Sheet

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The joint strength of friction stir spot welded 5J32 Al alloy was investigated according to the tool shape (threaded pin tool: TPT; cylindrical tool: CT; cylindrical tool with projection: CTP) and tool penetration depth. With increasing tool penetration depth, the vertical joint deformation increased in TPT and CT, whereas the joint diameter increased in TPT. The tensile shear load of the joint using TPT and CT did not vary with tool penetration depth, because the decreased upper plate thickness impeded the increase of the tensile shear load. That of CTP, however, rapidly increased with increasing tool penetration depth to produce a maximum tensile shear load of 4.6 kN. CTP, with its shoulder comprising a slight, broad projection, retarded the vertical joint deformation and produced good mechanical properties. [doi:10.2320/matertrans.M2009405]

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1. Introduction

With its many advantages such as lower energy consumption, no shielding gas or filler wire, no welding fumes or spatter hazards and superior mechanical properties, friction stir welding (FSW) can be applied to join various metal materials with superior joint properties.1,2 Friction stir spot welding (FSSW) is a new, solid-state, joining process that uses a cylindrical tool with a pin tip. The rotating tool is plunged into the upper and lower sheets of the lap joint configuration at a pre-determined penetration depth, which generates friction heat in the specimen. Subsequently, the heated and softened material adjacent to the tool deforms plastically, and a solid state bond is formed between the upper and lower sheets.3,4 As the joint material does not melt, similar to FSW, FSSW has many advantages such as superior mechanical properties, and, in particular, low energy consumption compared to electrical resistance welding. Although some research results for FSSW have been reported in recent years, insufficient detail remains on the effect of welding variables such as tool penetration depth, duration time and downward force.5,6)

In general, a threaded pin tool (TPT) is used for severe plastic deformation in FSSW. In a previous report,7) Tozaki et al. indicated that the length of the threaded probe strongly affected the strength of FSSW joints. However, TPT has been reported to decrease the joint volume and the upper plate thickness, owing to the deep tool penetration.8,9) Therefore, a new tool without threaded pin has recently been developed.

In order to develop a new welding tool for a satisfactory FSSW joint, the effect of the tool shape and tool penetration depth on the joint strength of FSSW 5J32 Al alloy was investigated. The joint deformation and upper plate thickness were observed from the external shape and cross-sectional macro-images, respectively.

2. Experimental Procedure

Commercial A 5J32 alloy with a nominal composition of Al-5.54 Mg-0.03 Si-0.07 Fe-0.32 Cu-0.03 Ti-0.01 Zn (mass%) was selected. A schematic diagram showing the specimen dimensions and the FSSW process used is presented in Fig. 1. In order to investigate the effect of the tool shape on the FSSW joints, three kinds of tool with different geometry were investigated: a general FSSW tool consisted of a shoulder with a larger diameter and a threaded pin projected from the shoulder (Threaded Pin Tool: TPT), a simple cylindrical shape (Cylindrical Tool: CT) and a cylindrical shape with small projection (Cylindrical Tool with Projection: CTP). The three tools are shown in Fig. 2. The specimens fastened firmly with clamps on the anvil were joined under several welding parameters, which are summarized in Table 1.

After FSSW, the variation of joint diameter and thickness deformation of the joint were observed by macro-images. The microstructure of the weld zones was observed by optical
microscopy (OM). The specimens were micro-polished using 0.3 μm Al₂O₃ powder and etched by a Keller’s reagent for 15~20 s at room temperature. The tensile shear tests were conducted with a cross-head speed of 1.67 × 10⁻⁴ m s⁻¹ to evaluate the mechanical properties of the joints. Plates of the same thickness were used to minimize the effect of eccentricity in the tensile shear test. To investigate the effect of tool penetration depth on the failure mode, the fractured specimens were observed by OM after tensile testing.

3. Results and Discussion

The weld nugget diameter is closely related to the mechanical properties of the joint. Generally, joints with a large weld nugget area have a higher shear strength. Therefore, observation of the weld nugget diameter in the joint is essential.

Figure 3 presents the variation of weld nugget diameter in the upper plate according to the tool penetration depth and tool geometry. Figure 3(a) shows the measurement location. In Fig. 3(b)–(d), the weld nugget diameter variation of the joints is very small, regardless of tool penetration depth and tool geometry, except for the outer CTP diameter, which increased linearly with increasing tool penetration depth, as shown in Fig. 3(d). At the deepest pin penetration depth of 0.6 mm, the weld nugget diameter was increased to above 16 mm, which was larger than the shoulder diameter of 13.5 mm. These results suggested that the increase of the weld nugget was related with the tool shape.

After FSSW, the joint thickness is closely related to the gap between the upper and bottom plates around the weld nugget. To investigate the vertical joint deformation, the joint thickness after FSSW was measured, the amount of deformation was calculated by the following simple formula, and the results are shown in Fig. 4.

\[ A (\%) = \frac{(B - 2C)}{2C} \]  

Where, A is the amount of thickness deformation, B the final joint thickness of the upper and bottom plates after FSSW, and C the initial plate thickness before FSSW. Figure 4(a) shows the location of measurement from a side view of the joint. As shown in Fig. 4(b) and (c), the amount of deformation increased with increasing tool penetration depth for TPT and CT, respectively. For CTP, however, no increase of deformation was observed in Fig. 4(d). This suggested that the variation of deformation is related with the tool shape. In the case of TPT, a shoulder was also inserted in the upper plate during welding, suggesting that the inserting of this shoulder caused the extreme joint deformation. On the other hand, in the case of CTP, the shoulder was almost not inserted in the upper materials during welding, which

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<tr>
<th>Duration Time [s]</th>
<th>Tool Rotation Speed [rpm]</th>
<th>Tool Penetration Depth [mm]</th>
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Fig. 2 Details of tool geometry: (a) TPT, (b) CT and (c) CTP tools.

Fig. 3 Variation of joint diameter according to the tool penetration depth and tool geometry: (a) location of measurement, (b) TPT, (c) CT and (d) CTP.

Fig. 4 Variation of thickness deformation according to the tool penetration depth and tool geometry: (a) location of measurement, (b) TPT, (c) CT and (d) CTP.
suggested that the deformation was less than that of CTP. From these results, we considered that the slight and broad projection of the CTP shoulder impeded the vertical growth of the welding burr.

Figure 5 presents the macro-images of the cross-section after FSSW according to the tool penetration depth and tool geometry. No welding defect was observed in the weld nugget adjacent to the pin mark in Fig. 5(a)–(c). As mentioned above, the gap between the upper and bottom plates due to vertical deformation increased with increasing tool penetration depth. In Fig. 5(a), a white zone was observed in the region facing the welding tool, and its size did not change with variation in tool penetration depth. This plastically deformed zone was attributed to the stirring effect of the threaded pin and was similar to the stir zone in linear FSW. In the case of CTP in Fig. 5(c), a white line in the joint, which was considered to represent the weakly bonded region, was observed at a tool penetration depth of 0.4 mm (see the white dashed line). A broken piece was observed at a tool penetration depth of 0.6 mm (see the white dotted line). This was considered a fragment separated from the joint due to the high load at the deepest tool penetration depth. From these microstructural observations, the deformation structure, weakly bonded region and fragment separated from the joint were assumed to affect the mechanical strength of the joint.

Figure 6 presents the tensile shear load according to the tool penetration depth and tool geometry. Fractured specimens showing the fracture location at each condition are presented together. In the case of TPT in Fig. 6(a), fracture occurred across the weld nugget until a tool penetration depth of 1.55 mm. At a greater tool penetration depth, fracture occurred on the side of the weld nugget (Fig. 7(a)). However, the tensile shear load was restricted within the range between 3000 and 4000 N. In general, as the size of the fully bonded area in electric resistance spot welding (ERSW) increases, the joint strength improves. In this case, however, the tendency was slightly different, indicating that the plastically deformed structure observed in the macrostructure was the dominant factor affecting the tensile shear load. An increase to 0.4 mm in the tool penetration depth
slightly increased the tensile shear load, but beyond 0.4 mm there was no further increase in the tensile shear load and fracture occurred with an identical shear-type mode under all applied conditions in the case of CT in Fig. 6(b) and Fig. 7(b). In the case of CTP in Fig. 6(c), as the tool penetration depth increased to 0.4 mm, the tensile shear load slightly increased and a shear-type fracture mode was observed similarly to that of CT (Fig. 7(c)). However, at tool penetration depths of 0.5 and 0.6 mm, the tensile shear load increased to above 4500 N and the fracture type was changed to weld nugget pull mode (Fig. 7(c)). These result suggested that the tensile shear strength of the joint is related with the tool penetration depth, role of the shoulder and thickness of the upper plate in the joint. These three effects are considered next. Firstly, with increasing tool penetration depth the tool exerted greater pressure on the joint. In the low-pressure condition, a weakly bonded region was formed in the joint. However, in the high-pressure condition, the upper and lower plates were fully bonded in the joint. This suggested that the increase in the fully bonded area with increasing tool penetration depth affected the tensile shear strength of the joint. Secondly, regarding the role of the shoulder in FSSW, CT and CTP showed very different tensile shear strength according to the presence or absence of a shoulder, even under the same welding condition. The joint for CT had a widened gap between the upper and bottom plates, suggesting, as aforementioned, that more deformation had occurred in the joint during FSSW. On the other hand, there was almost no gap between the upper and bottom plates in the joint for CTP, because the upper plate was pressed by the shoulder. Therefore, the deformation was decreased and the bonded area was increased due to the shoulder pressure exerted during FSSW. Thirdly, Fig. 8 shows the change of the upper plate thickness in the joint according to the tool penetration depth and tool geometry. In the case of TPT, the upper plate thickness was decreased with increasing tool penetration depth, suggesting that the decrease of thickness is related with the shoulder penetra-
tion. When the tool penetration depth was over 1.5 mm, the shoulder penetrated into the upper plate, which decreased the upper plate thickness. Therefore, in spite of the increased tool penetration depth, the tensile shear load did not increase owing to the decreased upper plate thickness. On the other hand, in the case of CTP, the upper plate thickness increased with increasing tool penetration depth. This indicated that the fracture line length increased, which in turn increased the tensile shear strength.

Consequently, the joint for CTP had a wider bonded area and a longer fracture line, which provided it with better mechanical properties than the two other tool shapes.

4. Summary

The joint characteristics of FSSW 5J32 Al alloy were investigated according to three tool shapes (TPT, CT and CTP) and the tool penetration depth. The study conclusions are summarized as follows.

(1) The vertical joint deformation increased with increasing tool penetration depth for TP and CT, whereas the tensile shear load of the joint did not increase because the decreased upper plate thickness impeded the increase of the tensile shear load.

(2) In the case of CTP, the joint diameter and the tensile shear load rapidly increased with increasing tool penetration depth, because CTP, comprising a shoulder with a slight, broad projection, retarded the vertical joint deformation.

(3) The maximum tensile shear load for TPT, CT and CTP in the tensile shear testing was about 4000 N, 2800 N and 4600 N, respectively. Under the various welding parameters applied in this study, CTP demonstrated superior mechanical properties to those of the other two tool shapes.

Acknowledgment

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REFERENCES


