Pinless tool for FSSW of AA 6061-T6 aluminum alloy

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A B S T R A C T

Pinless tools have been proposed to eliminate pinhole problems during friction stir welding; while strength of the joint could be decreased. Two probe tools with pin lengths of 2 and 3 mm and two pinless tools with the scroll groove and L-shaped grooves were used for lap welding of 2 mm thick 6061-T6 aluminum alloy sheets. The average tensile shear strength of the weld created by the long probe tool was about 3 times larger than that of the joint fabricated by the short probe tools. This difference was related to the larger stir zone and higher volume of the displaced metal resulted from the higher plunge depth, the higher heat input and more severe stirring induced by the long probe tool. The pinless welds were stronger due to the larger effective cross section area and absence of the keyhole. The application of the proposed pinless tool with L-shaped grooves produced welds with the average tensile shear strength of 2595 N in comparison to 2222 N of the welds created by the pinless tool with the scroll groove. This slight improvement was resulted from the larger stir zone and more severe stirring caused by the grooves with sharp corners.

1. Introduction

Friction stir spot welding (FSSW) is a solid-state welding method that is developed for lap joints. A rotating tool plunges into the upper sheet in the overlapping area until it reaches a certain plunge depth in the lower sheet. Then the rotating tool is held for a few seconds in order to mix the materials. Then, the rotating tool retracts and a solid-state spot weld is created. These steps are called plunging, dwell and retracting, respectively. The tool consists of a cylindrical shoulder and a pin. At the end of the plunging step, the tool shoulder plunges slightly into the upper sheet. This method was invented by Mazda (Iwashita, 2003) and sometimes is called conventional FSSW.

Aluminum alloys are increasingly being used in automotive and aerospace industries due to weight reduction and fuel efficiency enhancement (Piccini and Svoboda, 2017). Resistance spot welding (RSW), which is used for joining aluminum sheets, has some disadvantages like thermal distortion, high electric power consumption, limited electrode life span and low weld strength. Another joining process is self-piercing riveting (SPR). The main limitation of SPR is cost of rivets. FSSW can be an alternative and competent process to reduce cost (Sekhar et al., 2018).

The biggest limitation in the conventional FSSW is the keyhole. It causes reduction of the effective cross sectional area of the joint. Several methods have been proposed to fill the keyhole. For example, one of the best methods is refill FSSW, which can fill the keyhole, but it needs very complicated equipments (Chen et al., 2017). Another solution in preventing formation of the keyhole is application of pinless tool.

Fiction stir spot welding is a fairly new and developing method, So many researchers have studied the effect of tool geometry and process variables on microstructure and mechanical properties of the friction stir spot welds. Shen et al. (2013) reported that increasing the tool rotational speed and the dwell time increased the tensile shear strength and there was a direct correlation between the effective weld width and the weld strength. Song et al. (2014) found that the pin-plunging speed had almost no effect on the hook geometry and the tensile shear strength. By contrast, increasing the shoulder-plunging speed increased the effective sheet thickness and decreased the effective weld width; therefore there was an optimum shoulder-plunging speed for the highest tensile shear strength. Badarinarayan et al. (2009) pointed out that the cross tension strength of welds made with the triangular pin was twice that of welds made with the cylindrical pin, which was attributed to the finer grain size as well as the tensile failure mode. Gadakh and Kumar (2018) have proposed a new tool geometry which combines aspects of both conical and square tool pin profile. Tozaki et al. (2007) concluded that increasing the pin length increased strength of the friction stir spot welded sheets with thickness of 2 mm. However, Bakavos and Prangnell (2009) investigated the influence of the pin length and a pinless tool on FSSW of 0.9 mm thick sheets and claimed that the optimum pin length was in the range of 0.7–1 mm, which was...
considerably shorter than conventionally used. They also reported that successful welds were produced using the pinless tool; and strength values were comparable to the highest values measured with the optimum conventional tool. Therefore, effects of pin length are unclear.

On the other hand, Bakavos et al. (2011) pointed out that it is possible to achieve high shear strength in FSSW of thin sheets using a novel long flute wiper pinless tool. Chiou et al. (2013) found that a pinless embedded tool can improve strength of the joint. Kuang et al. (2015) observed that the rotation speed played a more important role during friction stir welding when the pinless tool was applied. Xu et al. (2016) showed that the concave shoulder of pinless tool increased the joint strength compared to the tools with the convex and the flat shoulders. Tozaki et al. (2010) proposed a newly developed pinless tool with a scroll groove on its shoulder and they reported that the scroll tool yielded comparable or superior performance to a conventional probe tool. Liu et al. (2016) showed that the geometry of grooves on the pinless tools can affect the formation of kissing bond defect. It seems that it is possible to design new pinless tools to achieve better performance in FSSW.

In this research, two probe tools with pin lengths of 2 and 3 mm and two pinless tools with a scroll groove and L-shaped grooves were investigated in FSSW of 2 mm thick 6061-T6 aluminum alloy sheets. The welds structure, strength, microhardness profile and fractured surface were examined to determine the potential of the proposed pinless tool design and the effect of pin length.

2. Experimental procedure

The 6061-T6 aluminum alloy sheet with thickness of 2 mm was used as the base material. The chemical composition and tensile properties of the base metal is listed in Tables 1 and 2, respectively.

Four tools were used in this research. First pinless tool was made with the scroll groove and the tool concavity angle of 10°. The diameter of the shoulder and the middle flat part were 10 and 4 mm, respectively. This scroll pinless tool design has been proposed by Tozaki et al. (2010). Here, it is designated as LS (Fig. 1(a)). The new pinless tool design was proposed which contained five L-shaped grooves with depth of 0.5 mm on its shoulder surface (designated as LL, Fig. 1(b)). All grooves were spark eroded. It was assumed that sharp corners of the L-shaped grooves could induce more plastic deformation during FSSW. Probe tools were P2 and P3 with pin lengths of 2 and 3 mm, respectively (Fig. 2). They had a standard M4 threaded pin. All tools were made of quenched and tempered AISI H13 tool steel.

Friction stir spot welds were created using a Tos Olomouc FGU32 manual vertical milling machine. Welding parameters were chosen based on preliminary trials. The tool rotational speed, dwell time and plunging/retracting speed were fixed at 1400 rpm, 6 s and 18.6 mm/min, respectively. Other welding parameters are presented in Table 3. The sheets were fixed using two clamps on both sides of the weld, which were tightened by bolts and nuts. Each welding condition was repeated four times.

Tensile-shear test was used to evaluate the performance of joints. Test coupons with dimensions of 138 × 60 mm were prepared according to DIN EN ISO 14,273. The overlap area was 46 × 60 mm for the lap shear specimen and spot welds were created in the center of this part. Two shims (62.5 × 60 × 2 mm) were attached to the two end sides of the specimens. Tests with a displacement rate of 1 mm/min were carried out using a Zwick Z250 universal testing machine. Three tensile-shear specimens were tested for each welding condition. Vickers microhardness profile of each weld was obtained in a line 0.7 mm above the interface with a load of 0.5 kgf and a loading time of 10 s.

The longitudinal section of the welds were cut and mounted. Samples were ground and polished, and then they were etched with Keller’s reagent (2.5 ml HNO₃, 1.5 ml HCl, 1 ml HF and 95 ml H₂O). The macrostructure and fracture surfaces were examined using an Olympus SZX9 stereo microscope, while the microstructure was studied using an Olympus BX60 M metallurgical microscope and a LEO 1450 VP scanning electron microscope (SEM). The fracture mechanism and bonding quality were also investigated via SEM.

3. Results and discussion

3.1. Microscopic characterization of the welds

Fig. 3 shows macrostructure of specimens welded with the probe tools. By using a short pin (P2), there was smaller keyhole due to the
lower plunge depth (Fig. 3(a)). The SZ was shallow and the effective weld width ($W_{ef}$; the shortest distance between the interface of the keyhole and the hook [5]) was very small. In other word, the weld nugget was not developed completely. The volume of the extruded and displaced metal was much less, so the sheets were not compressed together well. Tozaki et al. (2007) also have reported that the amount of the lower sheet that flowed upward was increased with increasing pin length.

In the case of P3 (Fig. 3(b)), hook (a kind of lap FSW or FSSW geometrical defect) originated in the sheets interface (unbonded region), spread upward and outward from the weld before reaching the stir zone (partially bonded region), and finally arrested in the upper part of the stir zone (completely bonded region). In fact, the partial metallurgical bond was the interface between the upper and the lower sheets. A part of the lower sheet that was displaced upward but has not been stirred was between the stir zone (SZ) and the partially bonded region. This hook behavior was somehow similar to those in other studies (Yang et al., 2010). Yin et al. (2010) stated that tool shoulder penetration into the surface of the upper sheet and pin penetration into the lower sheet during the dwell period provided the driving force for the displacement of lower sheet material upward, the formation of hook regions and increasing the stir zone and the bond width. They also stated that when lower sheet material was displaced upward, hook regions were moved outward from the axis of the rotating tool.

Fig. 3 shows the hook region of specimen P2. The hook was mainly flat and $W_{ef}$ was very small. As mentioned before, the upward flow of the lower sheet material for specimen P2 was negligible due to the low plunge depth (insufficient stirring). For specimen P3, the unbonded and partially bonded regions of the hook were observed as shown in Fig. 4(b). The formation of regions with different degree of bonding was associated with degree of the interfacial oxide break-up (Shen et al., 2013). In the partially bonded region, the oxide layer was not broken and dispersed completely; and there was an array of discontinuous oxide fragments (Fig. 4(c)).

Fig. 5 shows the typical microstructure of different weld zones for specimens welded with the probe tools. According to Fig. 5(a), microstructure of the base metal consisted of equilibrium phases of $\beta$ (Mg$_2$Si) in the form of dispersed dark tiny particles within the matrix. Some grey irregular shaped particles were also found. Kaufman (2000) reported that these grey precipitations were Fe$_5$SiAl$_{12}$. Deformation of precipitates can be observed in the thermomechanically affected zone (TMAZ) of the upper sheet (Fig. 5(b)). This was caused by the pin stirring in the SZ beside the TMAZ. The dynamic recrystallization, breaking and dissolution of the precipitates occurred in the SZ which were caused by the pin stirring and friction thermal cycle (Fig. 5(c)). This finding was in conformity with the results of Zhang et al. (2011). Large elongated Fe$_5$SiAl$_{12}$ precipitates were deformed to smaller equiaxed ones in the SZ.

Macrostructures of pinless welds are shown in Fig. 6. There was not any keyhole and the SZ did not reach the interface of sheets. This behavior was somehow similar to that observed by Tozaki et al. (2010). On the other hand, Bakavos et al. (2011) have reported expansion of the SZ to the lower sheet, formation of the hook and a more severe
deformation of the interface in FSSW of 0.9 mm thick sheets. The formation of hook was also observed by Li et al. (2014).

In the case of specimen LL (Fig. 6(a)), a doughnut-shaped ring is observed in the SZ. Similar patterns in the SZ of friction stir spot welds have been observed by Bakavos et al. (2011) using the long flute wiper tool. On the other hand, there was not any doughnut-shaped ring in the SZ of weld LS (Fig. 6(b)) and the SZ structure was simpler in this joint. It seems that the scroll groove stirred material more uniformly compared to L-shaped grooves. The SZ of the weld LL was deeper and wider. This could be a result of grooves with sharp corners that caused severe stirring in the SZ.

Although the microstructural constituents of specimens welded with the pinless tools were similar to that of the probe tools welds, the microstructure of the SZ inside the doughnut-shaped ring for weld LL was studied carefully (Fig. 7(a)). High plastic deformation and stirring resulted in the breaking and dispersing of precipitations. Fig. 7(b) shows the close-up view of the ring in the SZ. High density of precipitates was located on the rim of the ring. Also, the density of precipitates inside the ring was a little higher compared to the outside. Therefore, the ring was a region with the highest material flow. According to the high density of precipitates and results of other researchers (Bakavos et al., 2011), it could be concluded that direction of the material flow in the lower part of the weld nugget was from the center of the joint to the outside (from right to left in Fig. 7(b)). In other words, first the material flowed from the outside to the center in the upper part of the weld nugget. Then, it flowed downward near the weld center; and finally, it flowed outward in the lower part of the weld nugget. Fig. 7(c) shows onion ring-like patterns in the upper part of the SZ which revealed severe stirring of the material in the vicinity of the tool. These observations clearly revealed the rule of L-shaped grooves and their sharp corners on the microstructure.

Fig. 8(a) shows a part of weld LL which consisted of the completely bonded and partially bonded regions. It might be said that the hook was formed in a flat shape. The completely bonded regions were formed as discontinuous segments at the interface and the oxide layer has been eliminated in these regions. As shown in Fig. 8(b), the partially bonding was also observed in the case of specimen LS.

For a comparison between spot welds created by different tools; the bond width ($W_b$) for pinless welds can be defined as the maximum width of the weld without unbonded regions. $W_{eff}$ for probe welds was defined as half of the weld nugget due to the symmetry; and hence $W_b$ can be defined by $2W_{eff}$ in these welds. $W_b$ values for welds LL, LS, P3 and P2 were 7321, 6860, 1778 and 698 μm, respectively. In probe welds, $W_b$ for specimen P3 was about 2.5 times of that for specimen P2. This could be related to the fact that the weld nugget in joint P2 has not been developed completely. In the case of pinless welds, $W_b$ for specimen LL was a bit larger than that for specimen LS. It could be a result of the wider and deeper SZ in weld LL. This was an advantage for the pinless tool (LL) proposed in the present study. It is clear that in pinless welds there was not any keyhole, so the cross sectional area or $W_b$ was much higher compared to probe welds.
3.2. Mechanical properties

The Vickers microhardness profiles for probe welds are shown in Fig. 9(a). Hardness was decreased by moving toward the SZ. This may be due to the gradual dissolution of the metastable strengthening precipitates (mainly $\beta''$) (Heinz and Skrotzki, 2002), and reduction in the dislocation density (Murr et al., 1998). Also, overaging could decrease hardness in the heat affected zone (HAZ) according to the results of Heinz and Skrotzki (2002). This reduction in the microhardness for specimen P3 was more pronounced and occurred in a wider region due to the higher heat input produced by longer pin and the higher plunge depth. Local hard spots in the SZ (and sometimes in the TMAZ) were attributed to a high density of equilibrium precipitates and effects of strain hardening. The microhardness profiles were similar to those obtained by Shen et al. (2013). However, it has been reported that no hardness reduction could be observed when low rotation speeds were applied during FSSW of 6061-T6 aluminum alloys (Sun et al., 2018).

Fig. 9(b) shows the microhardness profile for pinless welds. Similar to probe welds, a gradual decrease in the microhardness was observed from the HAZ towards the SZ. There was not much difference between hardness profiles of pinless welds which indicated a similar heat input. Generally, softening has been occurred in the SZ due to the same mentioned reasons for probe welds. The homogeneous hardness profile and more uniform SZ were particularly obvious for specimen LS. On the other hand, a relative increase of the hardness in the SZ of specimen LL was notable in regions with high density of equilibrium precipitates (the doughnut-shaped ring of the SZ).

The average strength of welds made by P3 was about three times of that for weld P2 (1.7 kN vs. 0.6 kN). This could be related to the lower $W_{tip}$ in specimen P2. Tozaki et al. (2007) also observed an increase in tensile-shear strength with increasing pin length which was attributed to the increase in the nugget size. As mentioned before, Bakavos and Prangnell (2009) obtained different results for thin sheets (0.9 mm) and found the optimum pin length in the range of the sheet thickness. This shows that the optimum pin length for FSSW of thin and thick sheets is probably different; however, this needs further investigations.

The average tensile-shear strength of welds made by pinless tools was higher than those made by probe tools (2.6 kN for specimen LL and 2.2 kN for specimen LS). It seems that the larger cross sectional area of pinless tools and the absence of the keyhole outweighed the lower bonding quality (the partial bonding). According to the results, specimen LL showed the highest strength among the welds fabricated by different tools.

Fig. 10 shows the relationships between the tensile-shear strength...
Fig. 9. Microhardness profile for welds made by: (a) probe tools; (b) pinless tools.

Fig. 10. The relationship between the tensile-shear strength and the bond width ($W_b$).

Fig. 11. The fracture surface of: (a) weld P3-the bottom surface of the upper sheet; (b) weld P3-the top surface of the lower sheet (the fracture initiated from the left side); (c) weld LL-the bottom surface of the upper sheet; (d) weld LL-the top surface of the lower sheet. The loading direction has been indicated by arrows.
and the bond width. There was a direct correlation between tensile-shear strength values and $W_b$. The larger $W_b$ in weld LL was the result of wider and deeper SZ. In this specimen, the $i$-shaped grooves of the tool caused more plastic deformation. This could be the possible reason for the increased strength value.

3.3. Fracture surface appearances

Shear fracture of the nugget occurred for any welds made by probe tools. The macrograph of the fractured weld P3 is shown in Figs. 11(a) and (b). It is observed that the faying surfaces between sheets were completely sheared off. Shen et al. (2013) also observed this type of fracture. They found that the crack nucleated and propagated along the hook and the nugget circumference, and finally passed towards the keyhole. According to the hook geometry (Fig. 4(b)), it could be said that the unbonded region acted as the initial crack. Song et al. (2014) stated that two cracks may initiate from the hook region. One of these cracks spread through the upper sheet vertically and the other spread towards the keyhole horizontally; but in the shear fracture mode, the latter reached the keyhole before the former reached the top of the upper sheet. As shown in Fig. 11(a), the depression area indicated the vertical propagation of the crack. Similar fracture behavior was observed for weld P2.

In the case of welds made by pinless tools (LL and LS), the bonded surface was sheared off. Fig. 11(c) and (d) show the macrograph of fracture surfaces in specimen LL. Spiral marks, which were resulted from stirring caused by grooves, were observed in both specimens welded by pinless tools (notably in weld LL). Bakavos et al. (2011) demonstrated that a spiral-like pattern was formed during welding with the long flute wiper tool by using a gold marker on the bottom sheet surface. They clarified that sticking between the top and bottom sheet surfaces first occurred locally at high spots on the sheet surfaces. Contrary to the results of Li et al. (2014), the nugget pullout fracture mode was not observed in this research.

Fig. 12(a) shows SEM micrograph of the shear fracture surface in the probe specimen (weld P3). There were small and dispersed dimples which indicated ductile fracture and proper bonding quality. This could be attributed to the propagation of the crack through the SZ. Regions close to the keyhole (the right upper part of the micrograph) contained smaller dimples which were result of the severe stirring and the refining phenomenon. Shen et al. (2013) also observed elongated dimples of various sizes with the same direction. The SEM micrograph of the fracture surface in the pinless specimen (weld LL) is presented in Fig. 12(b). The ductile fracture mode with elongated dimples was observed. Comparing to weld P3, the amount of dimples was lower and their size was larger in pinless specimens. However, stronger welds were obtained by pinless tools due to the higher cross sectional area.

Fig. 13 shows load-displacement curves of welds obtained from tensile-shear tests. The tensile behavior of welds made by pinless tools was different from those made by probe tools. Pinless welds failed almost immediately after reaching the peak load and demonstrated very little deformation after that; while probe welds exhibited a significant deformation after the peak load. This indicated a difference in fracture mechanism of pinless and probe welds. For pinless welds, it seems that the fracture has occurred at points with a weaker bonding (partial bonding), then it has propagated to stronger points and two sheets have been separated finally with void coalescence mechanism. Therefore, the load dropped rapidly after reaching the peak load. On the other hand, the crack propagated along the hook in probe welds, and then it moved towards the SZ and the nugget circumference (around the keyhole). After that, the effective contact area reached a critical value, and the fracture caused a gradual drop in load. However, the pinless welds yielded higher strength values compared to the probe welds.

4. Conclusions

Friction stir spot welding was done on 2 mm thick 6061-T6 aluminum alloy sheets using probe tools (with 2 and 3 mm pin length) and pinless tools (with a scroll groove and L-shaped grooves). According to the microstructural investigations and mechanical tests, following conclusions were made:

1. For the pinless welds, the stir zone did not reach the interface. The stir zone in the weld made by the pinless tool with L-shaped grooves was slightly wider and deeper that can be attributed to sharp corners of grooves. For the probe welds, the size of the keyhole and the stir
zone, the volume of the displaced metal, and the effective weld width were higher in the weld made by the long probe tool.

2 The doughnut-shaped ring and onion ring patterns were observed in the weld made by the pinless tool with L-shaped grooves that contained a higher density of precipitates due to more severe stirring. The deformation of precipitates was observed in the thermomechanically affected zone.

3 The bond width of the specimens welded by pinless tools was much higher than that of the probe welds. The problems caused by the remained keyhole could be solved by application of the grooved pinless tools without a decrease in joint strength.

4 The highest average tensile-shear strength was achieved for welds made by pinless tools, which was the result of higher bonded surface area. The pinless tool with L-shaped grooves yielded the best result (2.6 kN comparing 2.2 kN for the tool with scroll groove), which was attributed to more effective bonding, larger stir zone and more sever deformation. The average tensile shear strength for welds made by the long and short probe tools were 1.7 kN and 0.6 kN respectively.

References


