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Effect of Tool-Pin Profile on Weld Zone and Mechanical Properties in Friction Stir Welding of Aluminium Alloy

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ABSTRACT

This article presents the experimental analysis of tool pin-profile effects on the weld zone shape, mechanical properties and microstructure of the friction stir welding (FSW) process. To determine tool pin-profile effects on weld zone shape, mechanical properties and microstructure, four different pin-profile tools were used namely, the cylindrical pin, conical pin, cylindrical-conical pin and stepped-conical pin. The results of the experiment showed that weld-zone shape thickness of the cylindrical-conical tool near the shoulder was the highest and the conical pin-profile tool was the lowest near the bottom of the tool pin with respect to all other tool pin-profiles. Fine grain structure was produced by the stepped-conical pin-profile tool in the weld zone compared with the other three pin-profile tools. Yield strength, ultimate tensile strength, ductility and joint efficiency of the stepped-conical tool were the highest among all the tool pin-profiles. Additionally, this article also explains the effect of weld-zone shape on mechanical properties, showing that the small basin shape of the weld-zone shape produces high yield strength, ultimate tensile strength, ductility and joint efficiency.

Keywords: Friction stir welding, mechanical properties, microstructure, tool pin-profiles, weld-zone shape

INTRODUCTION

Currently, the friction stir welding (FSW) process is gaining wide acceptance for joining alloy components used in the aerospace, automobile and shipbuilding industries because the friction stir welding process has several advantages compared with fusion welding. The FSW process reduces weld defects, residual stresses and distortion and improves the dimensional stability of the welded structure (Gibson et al., 2014). It is also known as an eco-friendly welding process because the friction stir

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welding process does not produce smoke, fumes and arc glare (Thomas, Johnson, & Wiesner, 2003). In the friction stir welding process, the tool used has a specially designed shoulder and pin profile that rotates and plunges into the workpiece edges to be joined and moved along the weld direction. Heat is created from friction between the tool and the workpiece. At an elevated temperature, the workpiece material undergoes extreme plastic deformation and material flows around the tool (Mishra & Ma, 2005). Most of the plasticised material flows from the advancing side (AS) to the retreating side (RS) and deposited plasticised material behind the tool creates a weld zone, joining the workpiece material (Kumar & Kailas 2008; He, Gu, & Ball, 2014). Performance of the welded joint is evaluated by the weld-zone mechanical properties, which depend on various process parameters like tool welding speed, rotational speed, tool pin-profile and axial force, among others.

Several attempts have been made to identify pin-profile effect on weld-zone shape, mechanical properties and microstructure. Lorrain, Favier, Zahrouni and Lawrjaniec (2010) described the effect of the tapered cylindrical pin as producing three flat surfaces and a straight cylindrical surface in the shape of the weld zone. They observed that the weld size was larger in the straight cylindrical surface than in a TC3F pin. Su, Wu, Bachmann and Rethmeier (2015) analysed pin-profile effect on the behaviour of material flow using conical and triflat pin-profile tools. It was concluded that the weld zone caused by a conical pin-profile tool was smaller than that caused by a triflat pin-profile tool. Hasan, Bennett and Shipway (2015) predicted the effect of unworn and worn tool geometries on the shape of the weld zone. Their results showed that worn tools produced the conical shape of the weld zone.

Marzbanrad, Akbari, Asadi and Safaee (2014) analysed cylindrical and square pin-profile tool effects on the microstructure of the weld zone of AA5083. They observed that using a square pin-profile tool produced smaller recrystallised grains in the weld zone compared to when using the cylindrical pin profile. Gadakh and Kumar (2014) analysed the effect of tapering cylindrical and straight cylindrical pin-profile tools on weld joints. They observed that fine microstructure in the stir zone and higher hardness and strength of the weld joint were developed by using a tapering cylindrical pin-profile tool. Zhao, Lin, Wu and Qu (2005) explained pin-profile effects on mechanical properties and weld shape. They concluded that plastic material flow and mechanical properties of the weld joint are strongly affected by pin profile. Elangovan, Balasubramanian and Valliappan (2008) studied the various tool pin-profiles and rotation speed effects on mechanical properties of FSW AA6061 aluminum alloy. They found that pin-profile effects on mechanical properties were significantly large with respect to rotation speed. Suresha, Rajaprakash and Upadhya (2011) analysed square and conical pin-profile effects on the joint efficiency of welds of 7075–T6 aluminum alloy. They observed that joint efficiency produced by the conical tool was better than that produced by the square tool.

Previous works on this subject showed that tool pin-profile effect on the weld-zone shape, mechanical properties and microstructure are significant. However, the relationship between the weld-zone shape and mechanical properties has not been discussed extensively. The objective of this article was to investigate tool pin-profile effects on weld-zone shape, mechanical properties and microstructure and also to show the relationship among them. Experiments were conducted using four different tool pin-profiles; two of the tools are commonly used (cylindrical and conical), while the two other were combinations: cylindrical-conical and stepped-conical pin-profile tools. These tools were used to find the effect of tool geometry on weld-zone shape along with thickness. Weld zone, mechanical properties and microstructure were determined with each tool pin-profile. This work also showed the weld-zone shape effect on the mechanical properties of the weld joint.

MATERIALS AND METHOD

To investigate tool pin-profile effects on weld-zone shape, mechanical properties and microstructure, experiments were conducted on a vertical milling machine as shown in Figure 1(a). Four different types of fabricated tool pin-profile were used namely, the cylindrical pin (T1), conical pin (T2), cylindrical-conical pin (T3) and stepped-conical pin (T4) as shown in Figure 1(b). The schematic diagram of the FSW tool is shown in Figure 1(c). The length and shoulder diameter of all the tool pins were 5.7 mm and 18 mm, respectively. The other dimensions of the tool are given in Table 1.

Table 1
Dimensions of the tool pin-profile

Tool	Tool Pin Profile	Upper Pin Diameter (mm)	Lower Pin Diameter (mm)
T1	Cylindrical pin	6	6
T2	Conical pin	6	4
T3	Cylindrical-Conical pin	6	4
T4	Stepped-Conical pin	6	3

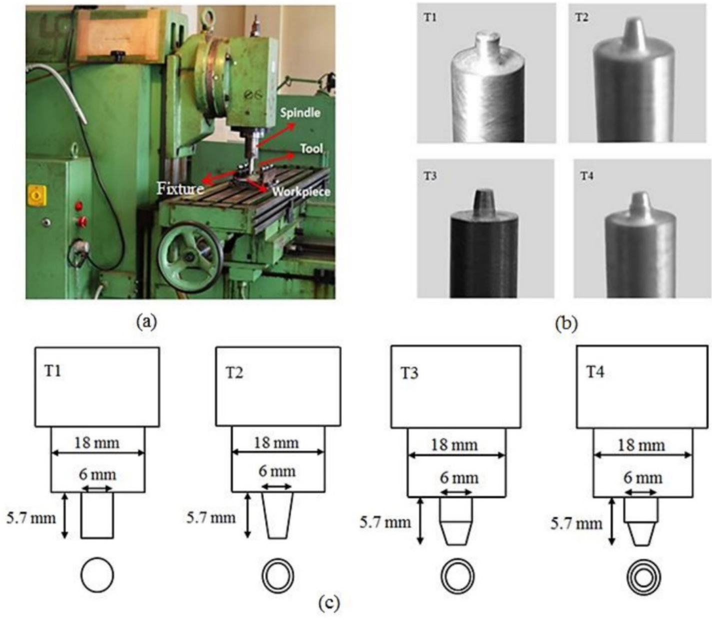

Figure 1. (a) Experimental setup; (b) Tool pin-profiles: Cylindrical pin tool (T1), conical pin tool (T2), cylindrical-conical pin tool (T3), and stepped-conical pin tool (T4); (c) Schematic diagram of the FSW tool

The workpiece material was 6061 aluminium alloy rolled plates with the dimensions 100 x 50 x 6 mm. The experiment was conducted at 1120 rpm of tool rotation and 80 mm/min of welding speed at zero tool tilt angle. For the microstructural characterisation of the weld zone, the specimens were cut in perpendicular to the weld direction by wire electro-discharge machining (WEDM). The specimens were polished using abrasive disks (600, 800, 1000 and 2000 grade), followed by a final polishing diamond on tissue disk and etched by Keller's reagent (Muthukumaran & Mukherjee, 2008). The chemical composition of Keller's reagent is nitric acid (3 ml), hydrochloric acid (2 ml), hydrofluoric acid (1 ml) and water (94 ml). The weld-zone shape and microstructure were measured along the thickness of the workpiece by an optical microscope. To determine tool pin-profile effect on weld-zone shape, four characteristic lengths were defined as shown in Figure 2. In Figure 2, L_r, L_1, L_2 and L_3 represent the four characteristic lengths at the bottommost portion, 1.5 mm away from the bottommost portion, 3 mm away from the bottommost portion and 4.5 mm away from the bottommost portion of the weld, respectively.

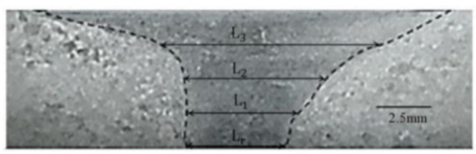

Figure 2. Weld-zone macrostructure

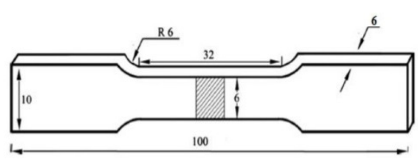

Figure 3. Workpiece dimension (mm) for testing tensile strength

Mechanical properties such as yield strength, ultimate tensile strength, ductility and joint efficiency were measured. For this purpose, three specimens were prepared per joint according to 'ASTM: E8 M' as given in Figure 3. The tensile tests were conducted at 1 mm/min cross head speed in a universal testing machine (UTM).

RESULTS AND DISCUSSION

Tool Pin-Profile Effect on Weld-Zone Shape

Tool pin-profile effect on the shape of the weld zone was determined by macrostructure of a cross section of the weld joint. In the macrostructure, the weld zone was shown by a dashed line as given in Figure 4. Weld zone includes the thermo-mechanical affected zone (TMAZ) and the nugget zone (NZ). It was observed that all pin-profile affected the basin shape of the weld zone. A similar result was found in the literature (Mishra & Ma, 2005). The weld zone is larger near the shoulder compared to the bottom because the shoulder stirring effect was large at the top surface of the workpiece and its value decreases from top to bottom. It was also observed that the weld zone shape in the advancing and retreating side was not symmetric. The reason for the asymmetric shape was deposition of material in the retreating side from the advancing side during the welding process (Kumar & Kailas, 2008).

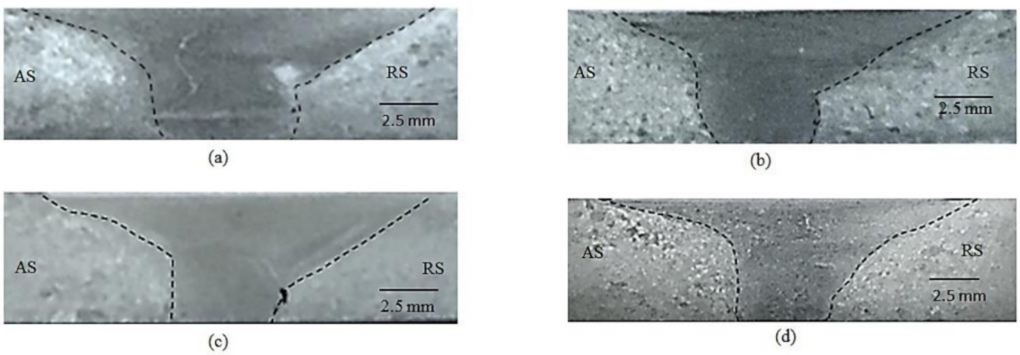

Figure 4. Experimental weld zone: (a) T1: Cylindrical pin tool; (b) T2: Conical pin tool; (c) T3: Cylindrical-Conical pin tool and; (d) T4: Stepped-Conical pin tool

However, the thicknesses of the weld zone of all the tool pin-profiles were different, as shown from top to bottom in Figure 5. It can be observed from the figure that cylindrical-conical tool weld zone thickness was large at the top of the workpiece in comparison with all the other tools.

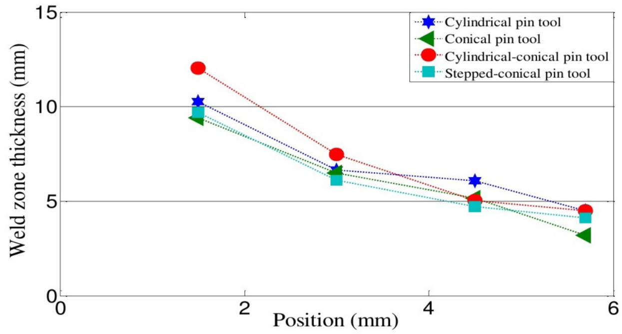

Figure 5. Experimental weld zone along with the thickness of the workpiece from top to bottom for all the tools

At the mid-point of the pin length for the conical, cylindrical-conical and stepped-conical tool weld zones, the thickness decreased gradually but for the cylindrical tool, the weld zone thickness did not decease gradually. The weld-zone thickness of the conical pin-profile tool was small near the bottom of the tool pin compared with all the other tools. The difference in the weld-zone thickness between top and bottom of the pin length was lowest in the stepped-conical tool. This means that the small basin shape was produced by a stepped-conical tool rather than the other tools.

Tool Pin-Profile Effect on Microstructure of FSW Joint

In the friction stir welding process, the workpiece material undergoes extreme plastic deformation at elevated temperatures and grain is recrystallized; this affects the microstructure of the weld zone. The pin geometry affects the microstructure greatly. Figure 6 shows four different tool pin-profile effects on the microstructure of the weld zone.

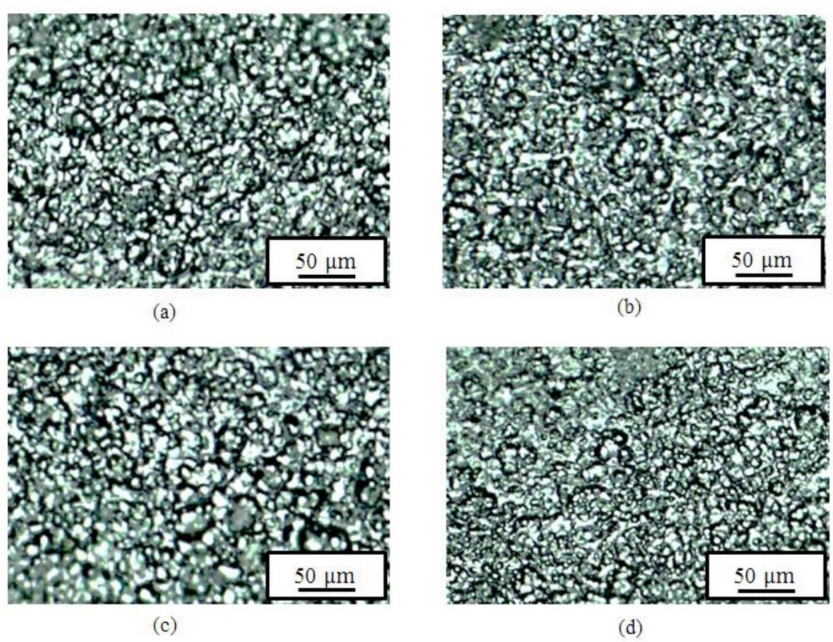

Figure 6. Microstructure in the weld nugget zone: (a) Cylindrical pin profile tool (T1); (b) Conical pin profile tool (T2); (c) Cylindrical-Conical pin profile tool (T3); (d) Stepped-Conical pin profile tool (T4)

Fine-grain structure was produced by the stepped-conical pin profile tool in the weld zone as shown in Figure 6(d). The largest grain structure was observed in the cylindrical-conical pin-profile tool as shown in Figure 6(c). Figure 6(a) and 6(b) show that grain structure produced by the conical tool was smaller than that produced by the cylindrical tool. It was found that using the stepped-conical and conical pin-profile tool weld-zone microstructure produced finer grain, which improved the mechanical property, as described in the following section.

Tool Pin-Profile Effect on Mechanical Properties

The mechanical properties of the weld joint were measured by tensile test on the universal testing machine. Table 2 shows the fracture locations of the FSW joints obtained by the different tool pin-profiles. It was observed that fractures occurred at two locations.

Table 2
Fracture location of tensile test specimens

Tool	Fracture Location	Photograph of Fractured Specimen AS RS
T1	HAZ, RS	
T2	HAZ, RS	
T3	NZ	
T4	HAZ, RS	

The first location was inside the weld zone and the second was outside the weld zone in the retreating side (RS). The fracture occurred inside the weld zone in the cylindrical-conical pin-profile tool (T3). It was also observed from Figure 4(c) that a void existed inside the weld zone that weakened the weld joint. This revealed that a low stirring effect was produced by the cylindrical-conical pin profile. Three other tool pin-profile fractures occurred outside the weld zone on the retreating side (RS). The weld zones produced by the three tools did not form a void as shown in Figure 4(a, b, d). This showed that the weld zone produced by the three tools using the stirring effect was strong. A similar result was also observed by Yuqing, Liming, Fencheng, Yuhua and Li (2017). The results were further evaluated by comparison of mechanical properties with respect to the base metal (B). Tool pin-profile effects on yield strength, ultimate tensile strength, ductility and joint efficiency are shown in Figure 7.

It can be observed from the figure that yield strength, ultimate tensile strength, ductility and joint efficiency of the weld joint produced by the stepped-conical pin profile were superior compared with those produced by the cylindrical-conical tool pin. The joints produced by the cylindrical and cylindrical-conical pin-profile tools showed equivalent yield strength and ultimate tensile strength. Ductility produced by the cylindrical-conical pin-profile tool was significantly lower compared with that produced by the cylindrical pin-profile tool.

Salari, Jahazi, Khodabandeh and Ghasemi-Nanesa (2014) explained that pin profile influences plastic deformation and material mixing during the welding process; consequently, volume and material flow vary as a function of tool geometry. It was predicted that the stepped-conical pin-profile tool would improve material mixing and enhance material movement in the weld zone, increasing the mechanical properties of the structure.

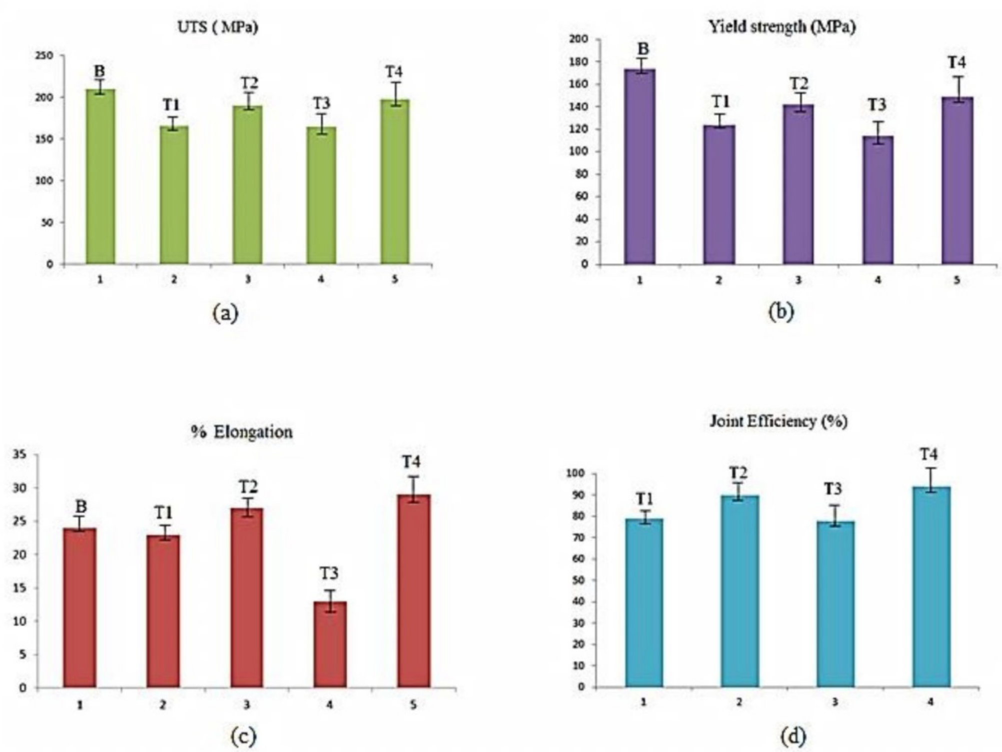

Figure 7. Tool profile effect on mechanical properties: (a) Ultimate tensile strength; (b) Yield strength; (c) Ductility (percentage of elongation); (d) Joint efficiency

It was also observed from the figure that the weld joint fabricated using the stepped-conical tool pin-profile had a high value of ductility (percentage of elongation) compared with the base metal (B). The stepped-conical tool produced maximum joint efficiency (94%), while the cylindrical-conical tool had minimum joint efficiency (78%).

This analysis also showed that size and shape of the weld zone significantly affected the mechanical properties. In the cylindrical-conical pin-profile tool, the mechanical properties were inferior and the basin shape of the weld zone was large compared with the other pin-profile tool. The mechanical properties produced by the stepped-conical pin-profile tool were superior and the basin shape of the weld zone was small compared with the other tool pin-profiles. Finally, it could be concluded that the small basin shape of the weld zone produced high yield strength, ultimate tensile strength, ductility and joint efficiency.

CONCLUSION

Tool pin-profile effects on mechanical properties and weld zone were experimentally investigated and the following conclusions were made:

1. Weld-zone thickness of the cylindrical-conical tool near the shoulder was highest but lowest for the conical pin-profile tool near the bottom of the tool pin compared with all the other tool pin-profiles.
2. The conical, cylindrical-conical and stepped-conical tool pin profiles produced weld-zone thickness that decreased gradually in the middle of the workpiece but the weld-zone thickness produced by the cylindrical tool did not decease gradually.
3. The stepped-conical and conical pin-profile tool weld-zone microstructure produced finer grain compared with that produced by the cylindrical and cylindrical-conical pin-profile tools.
4. The stepped-conical pin tool exhibited higher mechanical properties compared with the other tool pin-profiles.
5. The small basin shape of the weld zone produced higher mechanical properties.

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