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Analyzing the effect of tool pin design and process parameters on the microstructural and mechanical properties of Friction Stir Welded 6061 Aluminium alloy

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Abstract. Present work investigates the effect of tool pin design and process parameters in Friction stir welded 6061 Al alloy. The three pin designs selected were the square, circular and triangular type. It was seen that the triangular pin tool was generating a defective joint area containing flash and pores. SEM and microhardness analysis showed that square tip tool produced a good quality weld with high strength and elasticity comparing with circular and triangular pin tools. High tool rotation and low travel speed were generating a uniform weldment. Finally, tensile testing results showed a maximum value of 107.2 MPa ultimate tensile strength.

1. Introduction

Friction Stir Welding (FSW) is considered as one of the best environmental friendly processes since it consumes very less power and successfully generates a joint without any addition of shrouding environment or filler material. Key benefits of FSW include solid-phase process, low distortion of the workpiece, good dimensional stability, repeatability, excellent metallurgical properties in the joint area etc. FSW joints usually consist of four different regions namely unaffected base metal, heat affected zone (HAZ), thermomechanically affected zone (TMAZ) and friction stir processed (FSP) zone (nugget). The formation of above regions is affected by the material flow behaviour under the action of rotating non-consumable tool. However, the material flow behaviour is predominantly influenced by the FSW tool profiles, FSW tool dimensions and FSW process parameters [1]. The main metallurgical advantage of FSW is that problem associated with the liquid/solid phase transformation is eliminated. The alloy composition is also preserved, and hence there is no loss of alloying elements due to evaporation.

From the date of invention by Wayne Thomas, the friction stir welding process being a main interest of research for many scholars. Stephen and Jayakumar [2] investigate the impact of process parameters on mechanical properties FSW of 6061 aluminium. It has been revealed that the welding parameters such as tool rotational speed and welding speed play a major role in deciding the joint characteristics. Lakshminarayanan and Balasubramanian [3] have used two methods, response surface methodology and artificial neural network to predict the tensile strength of friction stir welded AA7039 aluminium alloy. Jawdat et al [4] investigated the appearance and the mechanical properties of the friction stir welded plates with different parameters. Similarly, other researchers also studied the effect of process parameters like welding speed on FSW welded joint qualities[5-8].Some of them studied the effect of tool geometry on welded samples of FSW [9-11]. Elangovan and Balasubramanian [12] studied the effect of tool pin profile and tool shoulder diameter on the formation of a friction stir processing zone in AA6061 Aluminium alloy. Rodrigues et al [13] conducted an investigation on the effect of conical and scrolled shouldered tools on very thin plates. Shigeki [14] states that the friction stir welding tool geometry has a significant influence on the material mixing and hence eventually influences the static strength of resultant spot welds.

In the present study, the effect of tool pin profile, tool rotation speed and welding speed on the formation of the weld was investigated. The quality of the weld was analysed by conducting an optical inspection, SEM analysis, microhardness and tensile testing of welded samples.

2. Materials and Methods

Thin 6061 aluminium alloy sheet has been cut into desired dimensions of 75mm x 60mm x 4mm. Elemental composition (weight %) of workpiece material AA6061 Al alloy is given in table 1. No pre-processing treatment was carried out before the experiment. Non-consumable tools made of high carbon steel have been used to join the thin Al sheets.

Table 1. Elemental composition (wt. %) of AA6061 Al alloy for the experiment.

Elements	Cu	Mg	Si	Fe	Mn	Ti	Ni	Al
Wt. (%)	0.2	0.2-0.6	6.5-7.5	0.5	0.3	0.2	0.1	Balance

Universal milling machine (HMT FN1U) has been used to conduct the experiment.Fig. 1(a) shows the fixture developed for the experiment and fig. 1(b) shows the tools prepared for the experiment. Three different tool pin geometries were developed as shown in fig. 1(b). Single-pass welding procedure had been used to perform friction stir welding with different pin geometries and effect of different tool pin geometries and process parameters on mechanical properties of FSW joints were investigated. The Friction Stir Welding experimental parameter set is as per table 2.

Table 2. Experimental parameter set for the experiment

Exp. No.	1	2	3	4	5	6	7	8	9
Tool pin	Circular			Triangular			Square		
Tool speed (rpm)	700	1000	1300	700	1000	1300	700	1000	1300
Tool travel speed (mm/min)	72	86	112.5	86	112.5	72	112.5	72	86

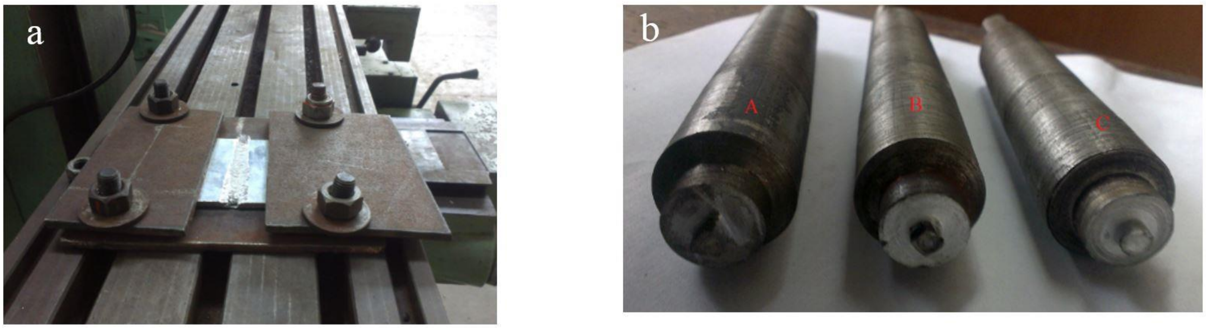

Fig. 1(a) Fixture developed for FSW process **(b)** Tools with different pin arrangements used for the experiment: (A) Triangular profile (B) Square profile (C) circular profile

3. Results and Discussion

3.1 Optical images of the welded joints

The optical images of the welded samples are shown in Fig. 2.In sample 1 with circular pin tool working at 700 rpm and 72 mm/min tool speed, due to the low tool and welding speed, it was observed that there is a formation of voids and tunnel defects. This may have taken place due to insufficient heat generation. No other samples show any sign of defects by visual inspection. There was too much flash formation as seen in Fig. 2(b) where a triangular pin tool was used for the welding. We can observe that the excessive heat generation can lead to thermal softening of the workpiece material beyond the boundary of tool shoulder. Therefore, the tool shoulder, rather than actively participating as a means for material containment, gives rise to material expulsion in the form of the excessive flash formation. The sample prepared with square pin tool at 700 rpm and 112.5 mm/min tool speed showed very good surface appearance. The sample prepared pin with a square pin has shown some voids at lower tool rotation values.

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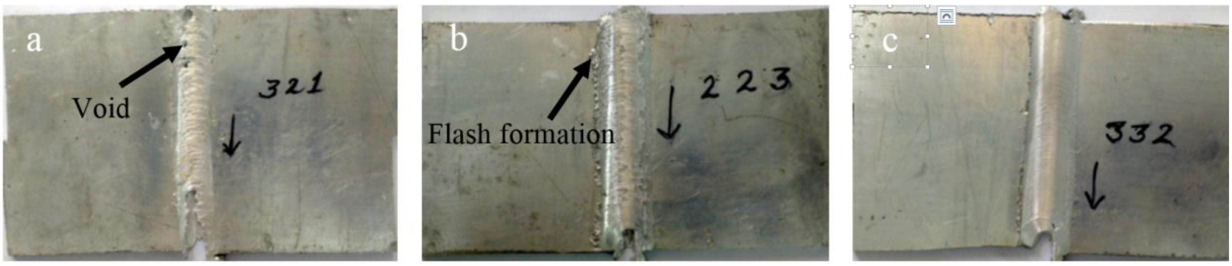

Fig. 2 FSW joint with (a) Square pin with tool rotation of 1000 rpm and welding speed of 72 mm/min (b) Triangular pin at tool rotation of 1000 rpm and welding speed of 112.5 mm/min ((c) Square pin with tool rotation of 1300 rpm and welding speed of 86 mm/min.

3.2 SEM Analysis of the FSW joints

Fig. 3 shows the SEM image of some samples. There has been some improper consolidation of material in the sample prepared with square pin tool with tool rotation of 1000 rpm and a welding speed of 72 mm/min. There also has been some pitting defect on the surface. Square pin tool used as in Fig. 3(c) shows excellent surface appearance, there has been good material consolidation and the grain structures were uniform and fine due to efficient heat generation and proper material flow. The best result in terms of surface appearance and consolidation of weldment has been attained with square pin tool followed by a circular pin tool and then triangular pin tool.

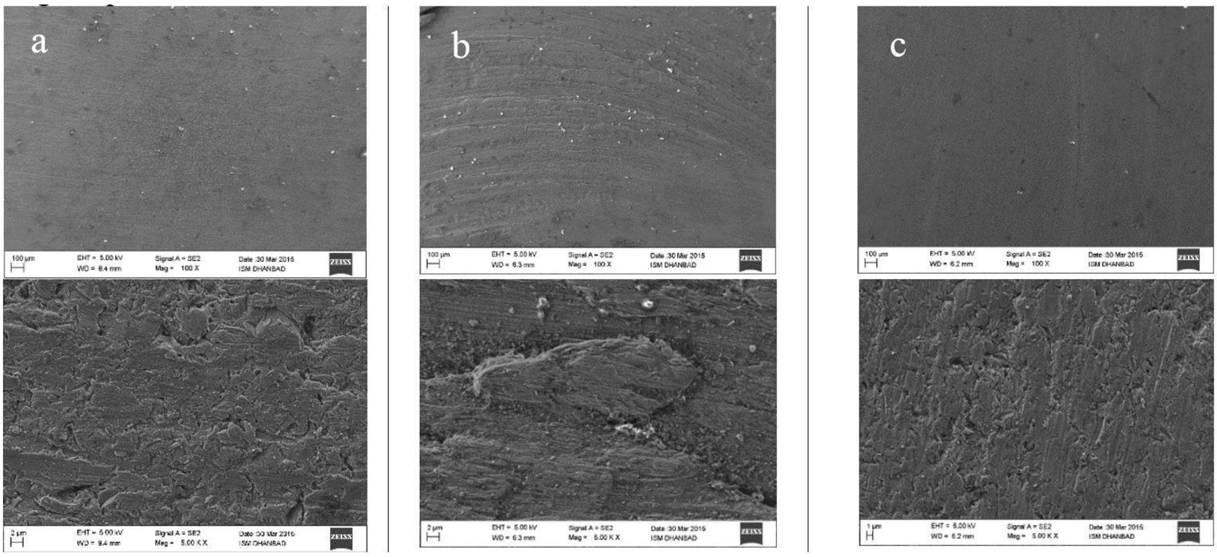

Fig. 3 SEM image of FSP region of joint formed with (a) Circular pin tool at tool rotation speed of 1300 rpm and a welding speed of 112.5 mm/min at 100X and 5KX magnification. (b) Triangular pin tool at tool rotation speed of 1300 rpm and a welding speed of 72mm/min at 100X and 5KX magnification (c)Square pin tool at tool rotation speed of 1300 rpm and a welding speed of 86 mm/min at 100X and 5KX magnification.

3.3 Microhardness

Microhardness testing has done on Vicker's microhardness testing apparatus Economet VH-1 MD. Vickers's microhardness was measured with a load of 20 gm.f (0.2 kg) with a dwell time of 10 sec. The microhardness schematic diagram, as well as the microhardness values of some of the samples, are shown in Fig. 4(a) and Fig. 4(b) respectively. It was observed that the microhardness value does not follow a linear trend. This is obvious as the mixing action done by the pin of the tool results in non-uniform hardness across the bead. Due to some thermal gradient present between the centre of the weld bead and the tool boundary we can see that the microhardness is slightly low at the centre. Probably it happens due to the low cooling rate at centre with respect to the boundary area. The microhardness value drops down when the distance from weld centre increases towards the retreating side, but after a sudden drop in microhardness values its value increases towards thermo-mechanically affected zone. Further, towards heat affected zone, its value reduces and reaches to that of the parent material. The variation in hardness value in advancing side is different to that of the retreating side as the value was uniformly decreasing from weld centre to heat affected zone. The hardness variation in this zone has been uniform. The micro-harness value at the retreating side of the weld was higher than that in advancing side. Table 3 gives the microhardness value of the centre of the weld for the experimental samples.

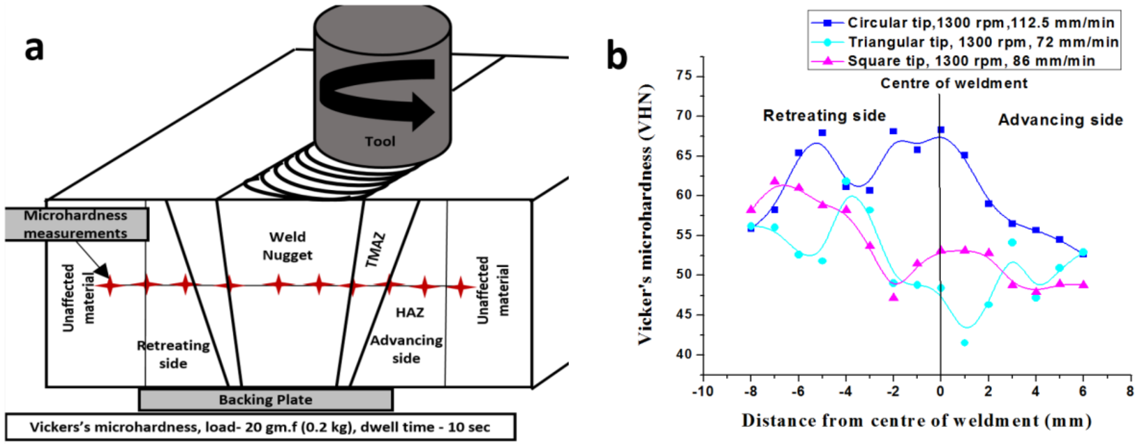

Fig. 4(a) Schematic diagram of microhardness measurement **(b)** Variation of hardness across the weldment plotted against the distance of the point from the weld centre.

Table 3.Microhardness value of the centre of weld for the experimental samples.

Exp.no	1	2	3	4	5	6	7	8	9
$VHN_{0.2}$	61.0	52.6	68.3	49.8	44.1	48.4	57.4	65.7	53.1

3.4. Tensile test of the welded specimens

The tensile test has been carried out in 20 KN, electro-mechanical controlled Universal Testing Machine. The specimen is loaded at the strain rate of 2 mm/min as per ASTM specifications and extensometer is attached to the specimen, so that tensile specimen undergoes deformation. The gauge length of the test sample is 25 mm.The ultimate tensile strength of AA6061 Aluminium alloy is 150.8 MPa and the percentage elongation (strain) is 17.6%. Joint efficiencies of 31 to 71 percent have been obtained. We know from the literature review that joint efficiency above 50 percent is considered satisfactory. The samples after conducting the tensile testing are shown in Fig. 5(a). We can see that there are a clear cup and cone shape for the Exp. no. 9 which also occurs in parent aluminium alloy which is absent in most of the other joints. Fig. 5(b)shows the stress vs strain plot for Square tip tool,1300 rpm and 86 mm/min tool travel speed. From this observation, we can infer that the weakest section in friction stir welded joint is occurring at the advancing side. Therefore, most of the test samples fail on the advancing side of the weld. Table. 4 gives Ultimate tensile stress, percentage elongation and joint efficiency of welds. Fig. 6(a) shows the Ultimate Tensile strength(UTS) and Fig. 6(b) shows the % elongation variation plotted for various experimental conditions.From the result, it can easily be concluded that square pin tool with 1300 rpm and 86 mm/min tool travel speed is giving the best result.

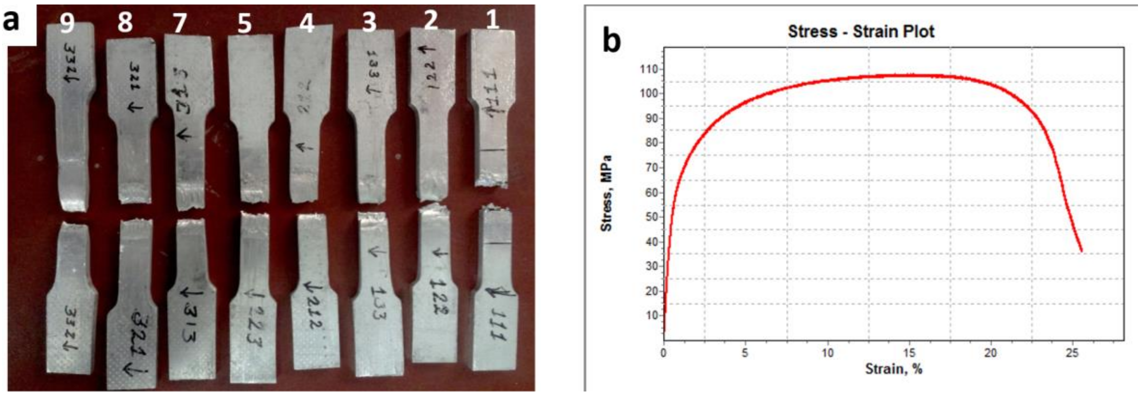

Fig. 5(a) Test specimens after the tensile test **(b)** Stress versus strain plot for Square tip tool,1300 rpm and 86 mm/min tool travel speed.

Table. 4 Ultimate tensile stress, percentage elongation and joint efficiency of welds.

Exp. No.	UTS(MPa)	% Elong.	Joint Eff.	Exp.No	UTS (MPa)	% Elong.	Joint Eff.
1	46.8	0.6	31.03	**6**	70.8	1.25	46.95
2	55.4	1.75	36.73	**7**	82.3	1.1	54.57
3	68.0	3.0	45.09	**8**	94.2	3.75	62.47
4	68.4	1.8	45.36	**9**	107.2	18.8	71.09
5	57.2	1.75	37.93				

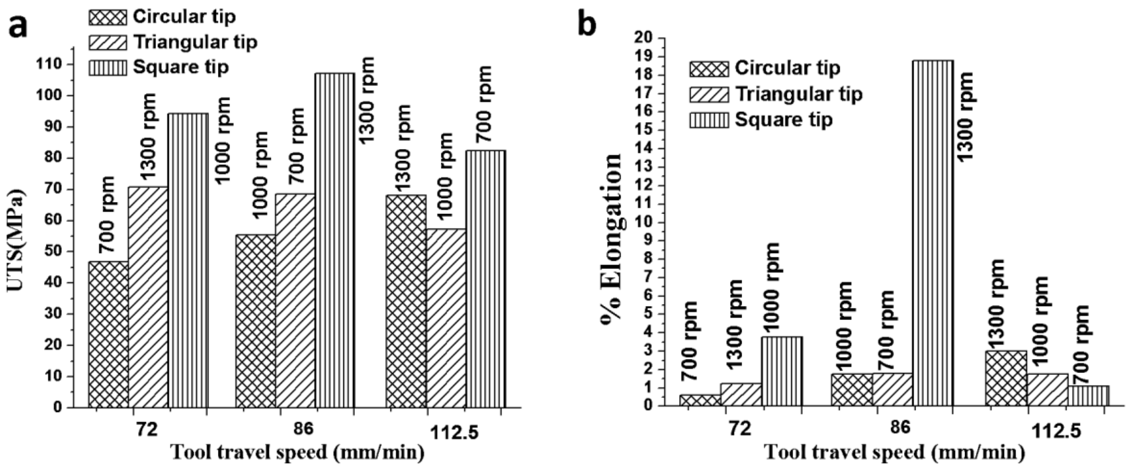

Fig. 6(a) Ultimate Tensile strength (UTS) and **(b)** % elongation variation plotted for various experimental conditions

4. Conclusion

Following conclusions are obtained from this investigation:

- The joint efficiency, tensile strength and elasticity of the weld joints have increased with the tool rotation speed for all three tool profiles.
- The Square pin tool produced a good quality weld with high strength and elasticity comparing with circular and triangular profiled tools.

- Weld produced by the square profiled tool at tool rotation speed of 1300 rpm and weld speed of 86 mm/min produced the best quality joint. The same has shown the maximum joint efficiency of 71.09 %.
- There has been no clear relation between process parameters and the microhardness of the weld zone, the retreating side has been showing an increase in hardness value as we move away from weld centre and finally decreases to that of parent material hardness in heat affected zone. The microhardness variation in advancing side shows linear decrement.

5. References

[1] Elangovan K, Balasubramanian V. Influences of tool pin profile and welding speed on the formation of friction stir processing zone in AA2219 aluminium alloy. Journal of materials processing technology. 2008 May 8; 200(1):163-75.
[2] Leon JS, Jayakumar V. Investigation of mechanical properties of aluminium 6061 alloy friction stir welding. American Journal of Mechanical Engineering and Automation. 2014 Apr 2;1(1):6.
[3] Lakshminarayanan AK, Balasubramanian V. Comparison of RSM with ANN in predicting tensile strength of friction stir welded AA7039 aluminium alloy joints. Transactions of Nonferrous Metals Society of China. 2009 Feb 1; 19(1):9-18.
[4] Al-Jarrah JA, Swalha S, Mansour TA, Ibrahim M, Al-Rashdan M, Al-Qahsi DA. Welding equality and mechanical properties of aluminum alloys joints prepared by friction stir welding. Materials & Design. 2014 Apr 30; 56:929-36.
[5] Liu HJ, Hou JC, Guo H. Effect of welding speed on microstructure and mechanical properties of self-reacting friction stir welded 6061-T6 aluminum alloy. Materials & Design. 2013 Sep 30; 50:872-8.
[6] Yong-Jai KW, Seong-Beom S, Dong-Hwan PA. Friction stir welding of 5052 aluminum alloy plates. Transactions of Nonferrous Metals Society of China. 2009 Sep 1; 19:s23-7.
[7] Milčić D, Živković A, Mijajlović M. An Overview on Friction Stir Welding of the Al 2024 T351. In34th International Conference on Production Engineering, Niš, Serbia University of Niš, Faculty of Mechanical Engineering 2011.
[8] Lakshminarayanan AK, Balasubramanian V. Process parameters optimization for friction stir welding of RDE-40 aluminium alloy using Taguchi technique. Transactions of Nonferrous Metals Society of China. 2008 Jun 1;18(3):548-54.
[9] Elangovan K, Balasubramanian V. Influences of tool pin profile and welding speed on the formation of friction stir processing zone in AA2219 aluminium alloy. Journal of materials processing technology. 2008 May 8;200(1):163-75.
[10] Sung-Ook YO, Myoung-Soo KA, Yong-Jai KW, Sung-Tae HO, Dong-Hwan PA, Kwang-Hak LE, Chang-Yong LI, Jong-Dock SE. Influences of tool plunge speed and tool plunge depth on friction spot joining of AA5454-O aluminum alloy plates with different thicknesses. Transactions of Nonferrous Metals Society of China. 2012 Dec 1; 22:s629-33.
[11] Kwon JW, Kang MS, Yoon SO, Kwon YJ, Hong ST, Park DH, Lee KH, Seo JD, Moon JS, Han KS. Influence of Tool Plunge Depth and Welding Distance on Friction-Stir-Lap-Welding between AA5454-O Aluminum Alloy Sheets with Different Thicknesses. Transactions of Nonferrous Metals Society of China. 2012 May: 156-.
[12] Elangovan K, Balasubramanian V. Influences of tool pin profile and tool shoulder diameter on the formation of friction stir processing zone in AA6061 aluminium alloy. Materials & design. 2008 Dec 31; 29(2):362-73.
[13] Rodrigues DM, Loureiro A, Leitao C, Leal RM, Chaparro BM, Vilaça P. Influence of friction stir welding parameters on the microstructural and mechanical properties of AA 6016-T4 thin welds. Materials & Design. 2009 Jun 30;30(6):1913-21.

[14] Hirasawa S, Badarinarayan H, Okamoto K, Tomimura T, Kawanami T. Analysis of effect of tool geometry on plastic flow during friction stir spot welding using particle method. Journal of materials processing technology. 2010 Aug 1;210(11):1455-63.