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Study on the Weld Quality of the Friction Stir Welded Al-6063 Plates Using Square and Pentagonal Profiled Tools

P. Karthikeyan and K. Mahadevan
Department of Mechanical Engineering, Pondicherry Engineering College,
Puducherry-605014, India

Abstract: Friction stir welding process is used for joining materials such as aluminium, copper, magnesium etc., which are otherwise difficult to weld by the conventional welding processes. In friction stir welding, the tool profile plays a critical role in determining the end properties of the welded joint apart from the other parameters like rotational speed, welding speed and axial load. The aim of the present investigation was to compare the weld quality of the AA6063 plates joined using the square and the pentagonal friction stir welding tool profiles. From the test results it is observed that the square pin tool profile has yielded a good weld bead structure along with superior strength and hardness when compared with the pentagonal tool profile.

Key words: Friction stir welding, friction stir welding tool, tensile strength, hardness

INTRODUCTION

Friction Stir Welding (FSW) is a relatively new joining process that is presently attracting considerable interest among the researchers. The FSW is a solid state welding/joining process where a machine rotates, plunges and then traverses a specially shaped FSW tool along a joint/abutting edge to form a weld (Thomas, 1991). The rotation action and the specific geometry of the FSW tool generates friction and mechanical working of the material which in turn generates the heat and the mixing necessary to transport the material from one side of the joint line to the other for welding. As the friction stir welding tool plays a critical role in the formation of the weld, proper selection of the tool profile yields a good weldability. As pointed out by Mishra and Ma (2005), most of the tool designs are based on intuitive concepts. For example, the length of the shank is chosen in such a way that it must be held firmly by the machine during the welding process. Therefore, in this work, a systematic study of the effects of the tool pin profile on the strength and the hardness of the friction stir welded section of AA6063 alloy plates was investigated.

MATERIALS AND METHODS

AA6063 plates were prepared using standard procedures as per the dimensions shown in Fig. 1 for making butt joints. The factors/parameters chosen for the study were axial load, rotational Speed and welding speed at three levels along with the variation in the tool profile (square and pentagonal cross section).

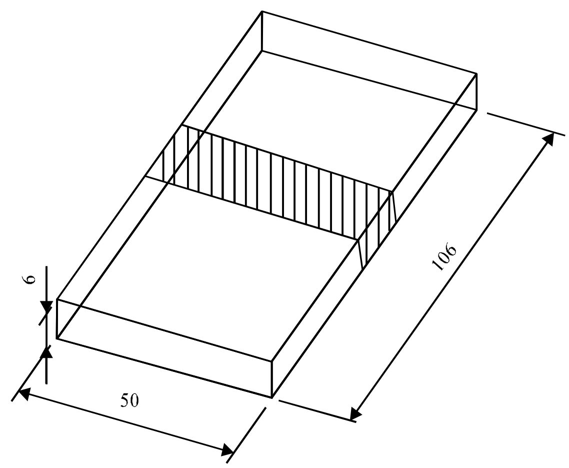

Fig. 1: Test plate after FSW, all dimensions are in mm

The details of the square and the pentagonal pin profile tools used for the welding are shown in Fig. 2a, b, respectively. The tool shoulder diameter was fixed as 18 mm based on the earlier studies (Elangovan and Balasubramanian, 2008a; Elangovan and Balasubramanian, 2007; Elangovan and Balasubramanian, 2008b). The length and the diameter of the tools were arrived by FEM analysis as per the details given in Karthikeyan and Mahadeven (2010). The friction stir welding was performed using a Czechoslovakian made vertical milling machine fitted with a specially designed

Corresponding Author: P. Karthikeyan, Department of Mechanical Engineering, Pondicherry Engineering College, Puducherry-605014, India

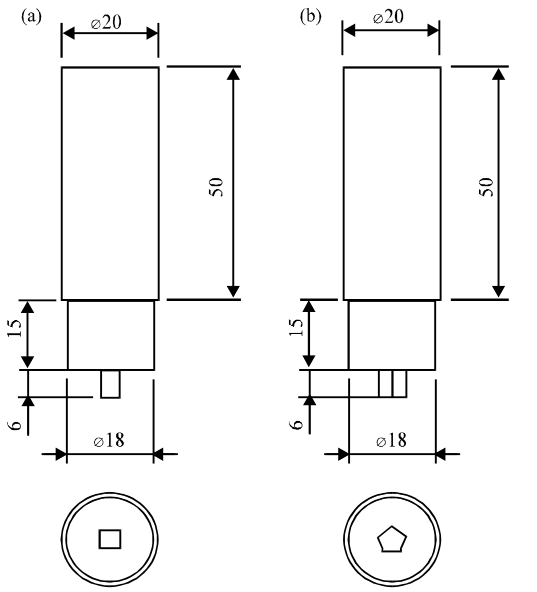

Fig. 2(a-b): Friction stir welding tools, (a) Square pin profile and (b) Pentagonal pin profile, All dimensions are in mm

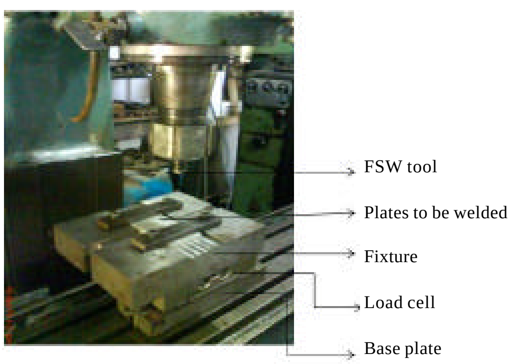

Fig. 3: FSW setup

retrofit as shown in the Fig. 3 (Minton and Mynors, 2006). The experiments were performed based on the Box-Behnken experimental design of response surface methodology. For three factors, the Box-Behnken design offers the advantages of requiring a fewer number of runs (Kim *et al*., 2006; Balasubramanian, 2008). The process parameters and the design matrix are given in Table 1 and 2, respectively.

RESULTS AND DISCUSSION

In the present study the hardness and the tensile strength at the welded section were taken as the responses parameters. The Hardness is was measured

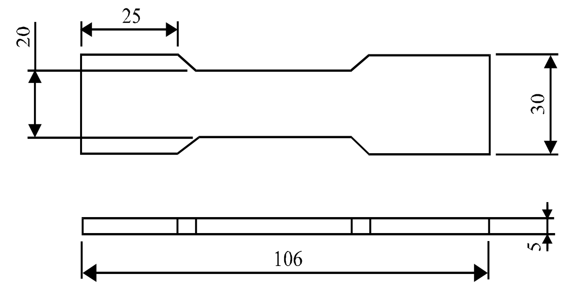

Fig. 4: Tensile test specimen, All dimensions are in mm

Table 1: The process parameters

Parameter	Units	-1	0	1
L	KN	1.1	1.5	2.2
S	RPM	710	1000	1400
F	MM/S	0.24	0.34	0.5

Table 2: Design matrix

REP	X1	X2	X3
1	-1	-1	0
1	+1	-1	0
1	-1	+1	0
1	+1	+1	0
1	-1	0	-1
1	+1	0	-1
1	-1	0	+1
1	+1	0	+1
1	0	-1	-1
1	0	+1	-1
1	0	-1	+1
1	0	+1	+1
3	0	0	0
Total runs = 15			

using Rockwell Hardness 'H' scale with the 3.125 mm ball indenter and under a load of 60 kgf. The tensile tests were carried out with the gradual application of the load in a Universal Testing Machine. Figure 4 shows the dimensions of the tensile test specimens cut out longitudinally from the welded plates. Fifteen experiments were carried out randomly for each tool profile as per the recommendations of the design matrix table in order to avoid any bias. The results of the hardness and tensile test are presented in Table 3.

Regression modelling: The response function representing the properties can be expressed as the function of the axial load, rotational speed and traverse speed for FSW operation as shown in Eq. 1:

$$Y = f(L, S, F) \quad (1)$$

For the second order relations, with 'k' number of factors, the model will be of the regression type given by the expression 2:

$$Y = b_0 + \sum_{i=1}^{k} b_i X_i + \sum_{ij=1}^{k} b_{ij} X_i X_j + \sum_{i=1}^{k} b_{ii} X_i \quad (2)$$

Table 3: Response tabulation

				Square pin		Pentagon pin	
Exp. No	L	S	F	HRH	Tensile (N mm^{-2})	HRH	Tensile (N mm^{-2})
1	1.1	710	0.34	74	52.94	75	19.91
2	2.2	710	0.34	74	54.00	78	14.30
3	1.1	1400	0.34	72	52.14	71	23.40
4	2.2	1400	0.34	70	53.65	84	42.54
5	1.1	1000	0.24	72	56.73	82	20.34
6	2.2	1000	0.24	72	55.72	81	18.71
7	1.1	1000	0.5	74	54.55	82	19.33
8	2.2	1000	0.5	70	29.04	80	20.14
9	1.5	710	0.24	75	23.72	75	34.52
10	1.5	1400	0.24	80	23.94	80	39.81
11	1.5	710	0.5	74	17.96	74	32.38
12	1.5	1400	0.5	78	19.67	84	42.00
13	1.5	1000	0.34	82	18.85	82	29.63
14	1.5	1000	0.34	84	15.43	84	24.52
15	1.5	1000	0.34	84	17.58	81	21.68

Table 4: Coefficient values

	Square pin profile tool		Pentagon pin profile tool	
	Hardness	Tensile strength	Hardness	Tensile strength
b_0	-61.9210	352.134	40.7369	82.7651
b_1	97.6591	-356.968	12.7872	74.4912
b_2	0.0652598	-0.0790800	0.0555978	-0.185918
b_3	176.348	55.1056	-22.7695	-178.783
b_{11}	-27.0922	116.502	-5.63812	-33.1864
b_{22}	-2.69843E-5	3.33130E-05	-3.90578E-5	6.69773E-5
b_{33}	-217.222	66.4608	4.80422	208.433
b_{12}	-0.00494973	0.00239507	0.0124186	0.0352121
b_{13}	-12.7678	-99.6957	-11.2309	5.02931
b_{23}	0.00157696	0.0149294	0.0377869	0.0167600

With three factors and three levels, the polynomial is expressed as Eq. 3:

$$Y = b_0+b_1 L+b_2 S+b_3 F+b_{11} L^2+b_{22} S^2+b_{33} F^2+b_{12} L S+b_{13} L F+b_{23} S F \quad (3)$$

where, b_0 is constant, b_1, b_2, b_3 are coefficients of linear terms, b_{11}, b_{22}, b_{33} are coefficients of second order terms, b_{12}, b_{13}, b_{23} are the coefficients of the interaction terms.

The linear and the second order terms provide the effect of the individual factors and the interaction terms provide the combined effect of the parameters.

Determination of the values of coefficients: The calculated values of the coefficients for different responses are presented in Table 4. After determining the coefficients, the regression models are developed.

Regression models: The second order regression equations developed to predict the hardness and the tensile strength at the weld section obtained by the two different tool profiles are given by the Eq. 4-7.

For square pin profile:

$$\text{Hardness (HRH)} = -61.9210+97.6591\,L+0.0652598\,S+176.348\,F-27.0922\,L^2-2.69843E\text{-}05\,S^2-217.222\,F^2-0.00494973\,L*S-12.7678\,L*F+0.00157696\,S*F \quad (4)$$

$$\text{Tensile strength} = 352.134-356.968\,L-0.0790800\,S+55.1056\,F+116.502\,L^2+3.33130E\text{-}05\,S^2+66.4608\,F^2+0.00239507L*S-99.6957L*F+0.0149294\,S*F \quad (5)$$

For pentagon pin profile:

$$\text{Hardness (HRH)} = 40.7369+12.7872\,L+0.0555978\,S-22.7695\,F-5.63812\,L^2-3.90578E\text{-}05\,S^2+4.80422\,F^2+0.0124186\,L*S-1.2309\,L*F+0.0377869\,S*F \quad (6)$$

$$\text{Tensile strength} = 82.7651+74.4912\,L-0.185918\,S-178.783\,F-33.1864\,L^2+6.69773E\text{-}05\,S^2+208.433\,F^2+0.0352121\,L*S+5.02931\,L*F+0.0167600\,S*F \quad (7)$$

Adequacy check: The adequacy of the models so developed was tested using the analysis of variance technique (ANOVA). The results of the ANOVA are

Table 5: Adequacy check for the square pin profile tool

	1st order terms		2nd order terms		Lack of fit		Error terms			
Response	SS	df	SS	df	SS	df	SS	df	F-ratio	R-ratio
Hardness	25.776	3	255.891	3	27.827	3	2.667	2	6.96	70.329
Tensile strength	214.84	3	3813.93	3	81.77	3	5.98	2	9.12	449.14

Table 6: Adequacy check for the pentagon pin profile tool

	1st order terms		2nd order terms		Lack of fit		Error terms			
Response	SS	df	SS	df	SS	df	SS	df	F-ratio	R-ratio
Hardness	44.713	3	80.603	3	62.237	3	4.667	2	8.89	15.28
Tensile strength	335.79	3	614.53	3	28.61	3	32.46	2	0.59	19.52

Table 7: Results of confirmation tests

				Hardness			Tensile strength		
Exp. for	L	S	F	Obtain value	Predicted value	Error (%)	Obtain value	Predicted value	Error (%)
Square pin	1.5	1000	0.34	84	83.33	0.8	18.85	17.287	9
Pentagon pin	2.2	1400	0.5	84	85.026	-1.20	43.25	45.45	-4.84

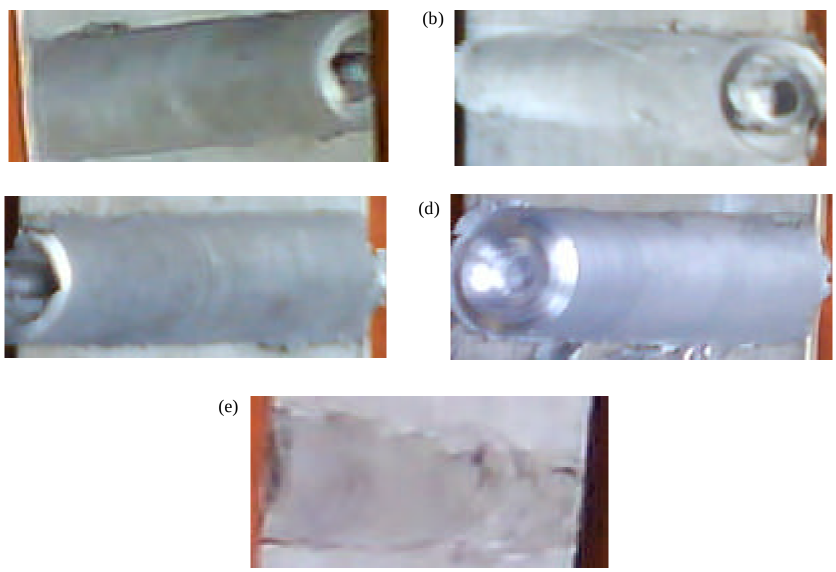

Fig. 5(a-e): Weld bead structures for square tool profile, (a) L: 1.5 KN, S: 1000 rpm, F: 0.34 mm sec^{-1}, (b) L: 1.5 KN, S: 710 rpm, F: 0.24 mm sec^{-1}, (c) L: 1.1 KN, S: 1000 rpm, F: 0.5 mm sec^{+}, (d) L: 1.5 KN, S: 1400 rpm, F: 0.24 mm sec^{-1} and (e) L: 1.1 KN, S: 710 rpm, F: 0.34 mm sec^{-1}

given in Table 5 and 6. From the tables, it was found that the calculated f-ratio (6.96) was lower than that from the statistical table f (3, 3, .05) = 9.27, indicating the adequacy for the models at a 95% confidence level. Hence, the developed models were considered to be adequate to predict the hardness and the tensile strength at the weld section for the square and the pentagon pin profiles.

Confirmation tests: Tests were conducted to verify the regression Eq. 3-6. The weld runs were made using the same values of the rotational speed, the welding speed and the axial force for each model; but in randomized combinations of the process parameters for square and pentagon pin profiles. The results obtained are presented in Table 7.

Comparison of weld bead, hardness and tensile strength for square profile and pentagonal tool profile: Figure 5 and 6 shows that the weld bead structures of the AA6063 alloy plates welded using the square profile and the pentagon profile tool respectively for the same process

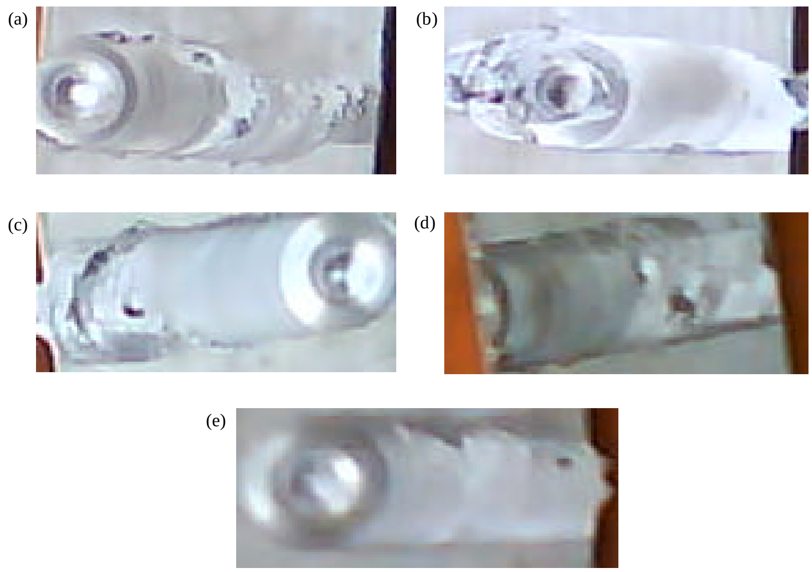

Fig. 6(a-e): Weld bead structures for pentagon tool profile, (a) L: 1.5 KN, S: 1000 rpm, F: 0.34 mm sec^{-1}, (b) L: 1.5 KN, S: 710 rpm, F: 0.24 mm sec^{-1}, (c) L: 1.1 KN, S: 1000 rpm, F: 0.5 mm sec^{-1}, (d) L: 1.5 KN, S: 1400 rpm, F: 0.24 mm sec^{-1}, (e) L: 1.1 KN, S: 710 rpm, F: 0.34 mm sec^{-1}

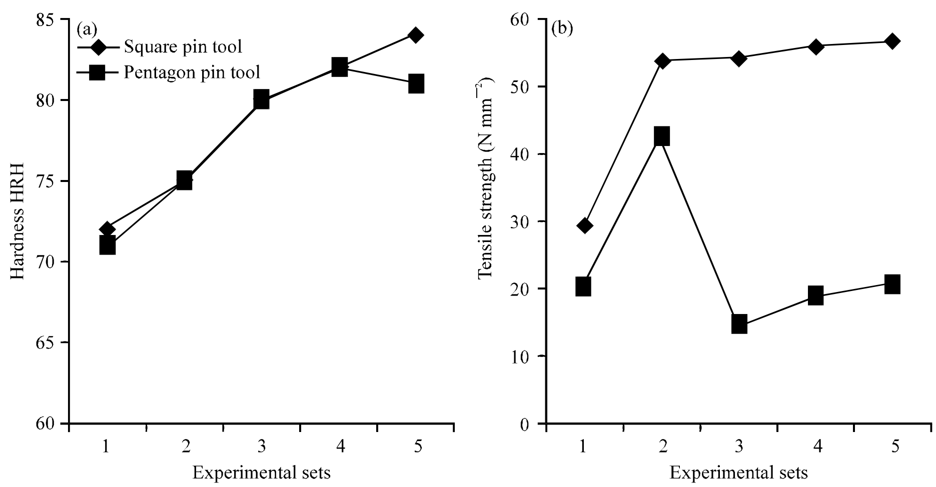

Fig. 7(a-b): Comparison graphs for tensile strength and hardness for both tools

parameters. From the figures it is observed that 6063 alloy plates welded using square profile pin has a good weld bead structure when compared to pentagon profile tool. From the experimental results shown in Fig. 7a the plates welded with the square profiled tool had a higher hardness value at the weld bead than the pentagonal profiled tool. Similarly, the tensile strength pertaining to the square profiled pin tool showed a constant improvement, while the plates welded with the pentagonal profiled tool fluctuated slightly depending upon the process parameters as shown in Fig. 7b.

CONCLUSIONS

Based on the experimental results, it is found that the friction stir welding on the Aluminium alloy 6063 using two different friction stir welding tools (i.e.) the square profiled tool and the pentagonal profiled tool, exhibits their individual effects on the mechanical properties. The following conclusions are arrived from the above study:

- The plates welded with the pentagonal profiled tool exhibits mechanical properties at certain process parameters and the results are satisfactory. Yet further study has to be done to on the pentagon profile tool to evaluate the bead structure and the mechanical properties
- The comparative evaluation of the results produced by the friction stir welding of AA6063 by the square and the pentagonal profiled tools reveal that the square profiled pin produces comparatively better results

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