Investigation on the Process Parameters of Double-Sided Friction Stir Welded AA6082-T_6 Joints with Different Tool Pins Using Response Surface Methodology

S. Vignesh, P. Dinesh Babu, M. Nalla Mohamed, S. Martin Vinoth, G. Surya and S. Dinesh

Abstract Aluminium alloys are of much use in several vital areas including aerospace, marine, defence and railways, which becomes obligatory to have a welded joint of high strength. The input considerations of the friction stir welding process of double-sided type play an imperative part in identifying the performance and characteristics of the joints. This research is a novel approach to investigate the influence of weld input parameters on the output responses of aluminium 6082-T_6 alloy using tapered square and tapered pentagonal tool pin profiles. The double-sided friction stir welding (FSW) was chosen for the research work, as it gives better strength joint than single-sided ones. Response surface methodology (RSM) was used to establish the interactions through mathematical relationships, considering the FSW process parameters and output responses. The influence of tapered square (TSP) and tapered pentagonal pin (TPP) profiles on the welding

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characteristics was analysed. Also, an extended investigation was carried out in achieving the welding parameters in optimum level, so as to maximize the output responses.

Keywords Aluminium alloys · Double-sided friction stir welding Tapered square pin · Tapered pentagonal pin · Desirability approach Response surface methodology

1 Introduction

Al–Mg–Si alloy conforming to AA6082-T_6 is a common alloy for extrusions, plate and sheet from stock which has quite good weldability in comparison with high strength Al alloys [1]. It is increasingly used in the marine structures and aircraft applications with the fully heat-treated condition, as it has 0.2% proof stress (f_o) about equal to the yield of mild steel. Also, it can be readily welded with nearly 50% loss of strength in the heat-affected zone [2, 3]. Though these alloys are known for their weldability, they undergo problems such as softening, etc. in the heat-affected area. At the time of weld thermal cycle, Mg_2Si precipitate substances get reversed [4]. This mechanical disability is an important issue in the design aspects of engineering [5]. Friction stir welding (FSW) is chosen in spite of having many fusion welding processes, because it could be a solid-state welding approach where the material to be welded does not melt throughout the process [6]. This process is widely preferred due to the absence of parent metal melting [7]. The investigation on the improvement in double-sided friction stir welded joint in terms of strength is important for describing its performance. The main intention of any manufacturer is to select the welding process parameters that would yield a joint of high strength. Response surface methodology (RSM) is a type of approach that is used to predict the process parameters for producing a high strength joint with excellent characteristics. This particular method is widely preferred as it reduces the time required for the design of experiments and the effort needed from labours.

Ram Kumar et al. [8] made a comparative analysis on the improvement in the strength of aluminium joints using single- and double-sided friction stir welding processes and concluded that superior welds can be acquired by double-sided friction stir welded joints such that the welding regions are reachable from both sides for the process. Elatharasana et al. [9] conducted an experimental analysis and optimization of process parameter on FSW of AA 6061-T6 aluminium alloy using RSM. With the help of Taguchi design approach, Lakshminarayanan et al. [10] performed a study to investigate the influences of FSW process parameters on the tensile strength of AA7039 butt joints and concluded that the spindle speed, welding speed and axial force are the most significant parameters in deciding the tensile strength of the joint. Tiwari et al. [11] conducted a parametric analysis of FSW using RSM and suggested that it is necessary to investigate the mechanical aspects of the welded joint for describing its performance. Hence, in our research, the responses such as tensile strength, hardness, toughness were taken to assess the characteristics of double-sided FSW aluminium alloy 6082 joints. The main intention is to utilize RSM to establish mathematical relationships, considering the FSW input parameters such as spindle speed measured in rpm, welding speed measured in mm/s, two different pin profiles, and the output responses such as tensile strength measured in MPa, hardness in HV, toughness in kg(f) m. The other objective is to determine the optimal welding location which would maximize the output responses using desirability approach.

2 Experimentation

2.1 Materials

In this research, the aluminium 6082-T_6 alloy was chosen as the base metal due to its common usage in marine parts and aircraft structures [1]. In order to confirm the various elements present in as-received aluminium alloy, the chemical analysis test was conducted as per ASTM-E1251 standard. The chemical compositions of the base metal are formulated in Table 1. The base metal 6082-T_6 aluminium alloy has been cut into the required size (150 mm × 75 mm × 8 mm). The mechanical properties of the base material are given in Table 2. It is evident that when the tapered pin profile is used, it produces a higher welding force than the straight pin profile [12]. Hence, the welding of joints of 6082-T_6 aluminium alloy has been carried out in computer numerical controlled FSW machine using tools with two different pin profiles such as tapered square and tapered pentagonal. The tools which are made of tungsten carbide are used in experimentation due to its strength rather than steel with a Young's modulus of 550 GPa and maintains a sharp edge better than other tools. The process parameters such as spindle speed (N), welding speed (S) and tool pin profiles (tapered square or tapered pentagonal) were considered as an important aspect which influences the quality of the weld joint produced. The effects of tool pin profile on metallurgical and mechanical properties of the weldments were evaluated. The changes in the microstructure of the weld zones were observed using scanning electron microscope (SEM).

2.2 Methods

The welding process was performed using special friction stir welding equipment shown in Fig. 1. The machine is capable of welding 50-mm-thick Al alloys plates. The double-sided friction stir welding application is shown schematically in Fig. 3. The double-sided friction stir welded joints are found to have much better strength joints when compared with single-sided friction stir welded joints [13]. Thus, better

Table 1 Chemical composition of the 6082-T_6 alloy (wt%)

Reference	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Pb
Typical	0.7–1.3	$\leq$0.50	$\leq$0.10	0.4–1.0	0.6–1.2	$\leq$0.25		$\leq$0.20	$\leq$0.10	
Actual batch	1.0	0.20	<0.02	0.48	0.65	<0.01	<0.01	0.01	0.02	<0.01

Table 2 Mechanical properties of the 6082-T_6 alloy

Yield strength (MPa)	Ultimate strength (MPa)	Elongation (%)	Hardness (HRB)	Density (g/ cm^3)	Melting point (°C)
168.33	300	11.5	70	2.70	555

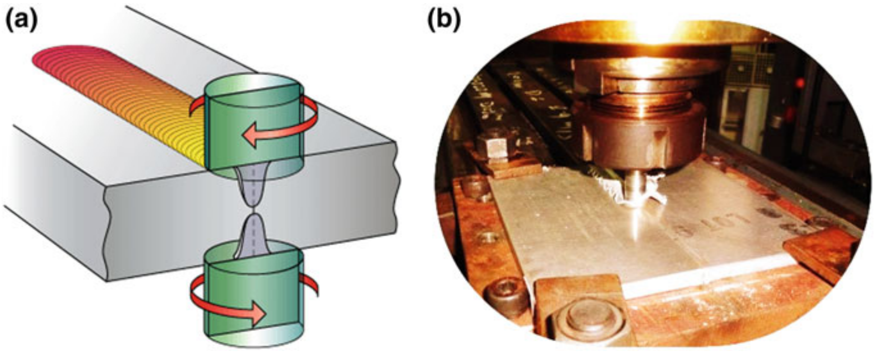

Fig. 1 Schematic illustration and equipment of double-sided friction stir welding

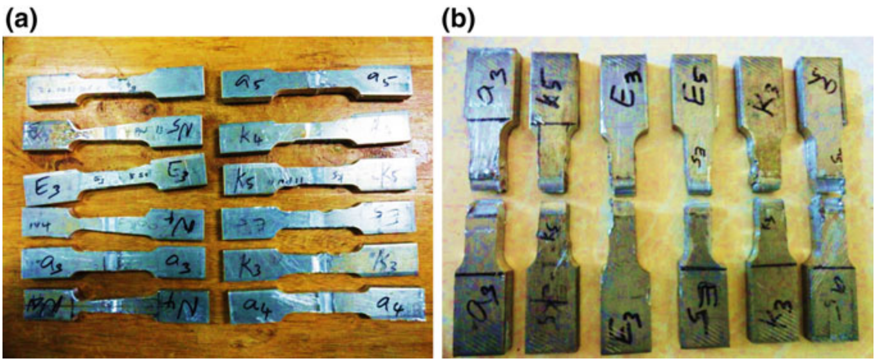

Fig. 2 Tensile specimens **a** before test and **b** after test

weld joints can be obtained in the case of double-sided FSW process [8, 13]. A rotating tool with a specially designed pin and shoulder is inserted into the butting edges of plates to be joined and then traversed along the joint line as shown in Fig. 1a. The test was performed by varying the various process parameters.

After performing the test, the tensile test specimen was cut as per ASTM standard. The tensile specimens before and after the tensile test are shown in Fig. 2. The Vicker’s micro-hardness testing machine was used for calculating the hardness of the weld portion. The specimens were prepared for the microstructure study with fine polishing and etching. The polishing of the specimens was done by successive grinding of specimens with the use of emery sheets of decreasing grain size. With the help of disc polisher, the specimens were polished to mirror finish by applying diamond polisher. For the sake of better visibility of the microstructural zones, the mirror-finished specimens were said to undergo etching with Keller's reagent for producing surface relief as well as contrast among the different phases and grains when viewed through the scanning electron microscope.

3 Approach

The acceptability of the developed mathematical relationship was tested using ANOVA methodology [14]. These test results for the improvement in mechanical properties of the two different pin profiles are shown in Tables 3 and 4, respectively. According to this methodology, if the *F*-ratio which is calculated for the developed model is less than the standard *F*-ratio at a preferred confidence level, the model is said to be satisfactory. The test results of tensile strength, hardness and toughness for the tapered square pin profile are shown in Table 3. The test results of tensile strength, hardness and toughness for the tapered pentagonal pin profile are shown in Table 4.

Table 3 ANOVA test results for tapered square pin profile

Terms involved	Tensile strength (TS)	Hardness (H)	Toughness (T)
Model			
Sum of squares	272.1016357	252.2086207	0.058931664
Degrees of freedom	5	5	5
Mean squares	54.42032714	50.44172414	0.011786333
F-value	258.2156543	107.9336987	35.30890499
Prob > *F*	<0.0001	<0.0001	<0.0001
Outcome	Significant	Significant	Significant

Table 4 ANOVA test results for tapered pentagonal pin profile

Terms involved	Tensile strength (TS)	Hardness (H)	Toughness (T)
Model			
Sum of squares	298.3174359	462.7658267	0.097357449
Degrees of freedom	5	5	5
Mean squares	59.66348718	92.55316534	0.01947149
F-value	58.05992728	52.65137613	27.19600323
Prob > *F*	<0.0001	<0.0001	0.0002
Outcome	Significant	Significant	Significant

4 Results and Discussion

The influence of double-sided FSW process and tool considerations on the micro-hardness is shown in Fig. 3. From the hardness trend, it is observed that the hardness in FSZ is less than the advancing and retreating side in all the different tool and process parameters due to the slow cooling occurred in the solid-state welding process. In the case of tapered pentagonal pin profile, the maximum hardness of

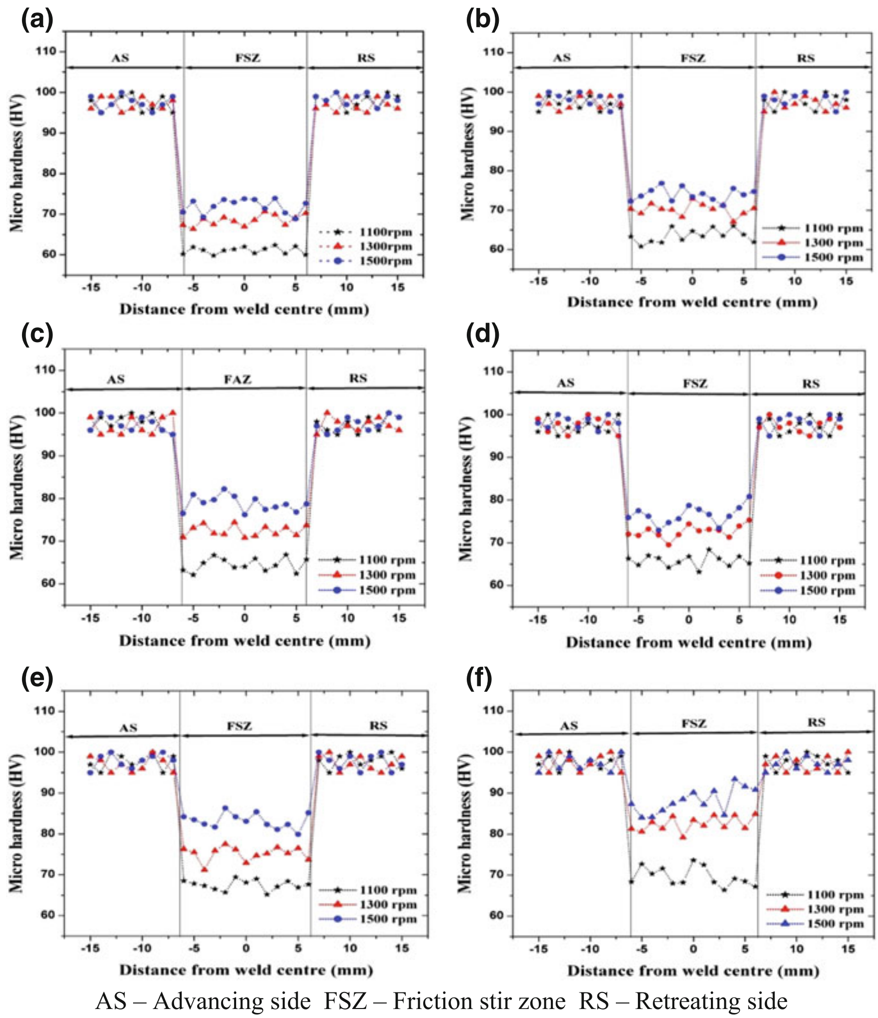

Fig. 3 Effect of process and tool parameters on micro-hardness of AA6082-T_6 aluminium alloy for the tool rotational speeds at 1100, 1300, 1500 rpm; **a** TSP; S = 2.4 mm/s, **b** TSP; S = 3.2 mm/s, **c** TSP; S = 4 mm/s, **d** TPP; S = 2.4 mm/s, **e** TPP; S = 3.2 mm/s, **f** TPP; S = 4 mm/s

88.1 HV is for the spindle and welding speeds of 1500 rpm and 4 mm/s, respectively. When the hardness for tapered square and tapered pentagonal pins is compared, the maximum hardness of 88.1 HV is obtained in the case of a tapered pentagonal pin.

4.1 Optimization using Desirability Approach

The tensile strength, hardness and toughness are related for developing an optimized model. The optimal range of the welding limits at which the preferred mechanical properties can be achieved is identified based on the optimization study carried out. Once the models are developed, we need to set the optimization criteria for which the optimum welding conditions can be achieved. The optimization criteria for two pin profiles have been implemented. In the event of tapered square pin tool, the criteria were set to achieve the maximum output responses with the input parameters spindle speed and welding speed at maximum limits. The developed optimization results show that for optimization criteria that is set to maximize, the input parameter spindle speed must be in the range of 1300 rpm for achieving the maximum tensile strength and hardness. The result gives the optimal welding conditions which would provide a maximum tensile strength of 149 MPa, maximum hardness of 75 HV and maximum toughness of 1.83 kg(f) m. The overlay plot is the result of the optimization obtained through graphical method. Figure 4 gives the overlay plot in which the yellow-shaded areas are the sections that come under the recommended criteria.

In the event of tapered pentagonal pin tool, the criteria were set to achieve the maximum output responses with the input parameters spindle speed and welding speed at maximum limits. The developed optimization results show that for optimization criteria that is set to maximize, the spindle speed must be in the range of 1400 rpm for achieving the maximum tensile strength and hardness. The result

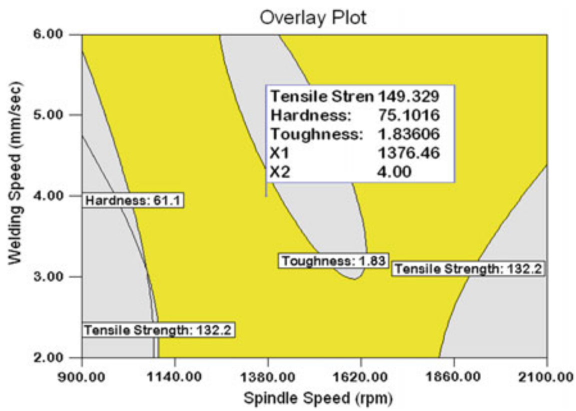

Fig. 4 Overlay plot shows the optimum working conditions for a tapered square pin profile

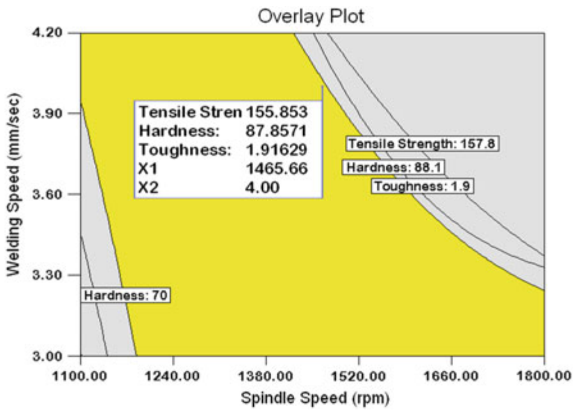

Fig. 5 Overlay plot shows the optimum working conditions for a tapered pentagonal pin profile

gives the optimal welding conditions which would provide a maximum tensile strength of 155 MPa, maximum hardness of 87 HV and maximum toughness of 1.91 kg(f) m. Figure 5 gives the overlay plot in which the yellow-shaded areas are the sections that come under the recommended criteria.

Now, when we compare the optimized results for tapered square and tapered pentagonal pin profiles, it is evident that the tensile strength, hardness, toughness are all maximum, when the pentagonal pin profile is adopted. Thus, we can conclude by using tapered pentagonal pin profile, the maximum tensile strength, hardness and toughness can be obtained. It is evident from the above results that the tapered pentagonal pin profile tends to produce a metallurgically defect-free weld compared with other type of tool pin profiles. It is evident that the determined results for the models are acceptable, and the predicted values are said to be in good agreement with the experimentally calculated results.

5 Conclusions

In this research, by using the double-sided FSW technique in the recommended input parameter limits considered in the work, the below-mentioned opinions can be concluded.

- Optimization using the desirability approach with the help of RSM is an advantageous approach for optimizing the double-sided FSW parameters to attain an improved model with good mechanical properties.
- When the tapered square pin profile is used, a spindle speed of 1375–1377 rpm is said to be the optimum range which will give an admirable welded module obtained from AA6082-T_6 aluminium alloy. When the tapered pentagonal pin profile is used, a spindle speed of 1464–1466 rpm is said to be the optimum range which will give an admirable welded module obtained from AA6082-T_6

aluminium alloy. Now, when comparing both, the maximum tensile strength, hardness and toughness can be obtained only when the tapered pentagonal pin profile is used.

- The tapered pentagonal pin profile with welding speed of 4 mm/s and spindle speed of 1500 rpm produces a better tensile strength than a square tool pin profile.
- Fine grains are observed in the FSZ when tapered pentagonal pin profile used, these grains are finer than the square tool pin profile.
- The spindle speed has been acknowledged as the most noteworthy factor. Further, it is followed by the influence of difference tool pin profiles and the welding speed. The monitoring of the interaction of welding speed with the spindle speed has to be done.

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