OPTIMIZING THE PROCESS PARAMETERS OF FRICTION STIR WELDED AA 6061-T6 ALLOY USING TAGUCHI ORTHOGONAL TECHNIQUE

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Abstract

Friction stir welding is relatively a new solid state welding process in which no consumable materials are used. The main advantage is that it is pollution free. In the present study FSW of AA 6061 Aluminium alloy are used to improve the process parameters on 5 mm thickness plates. The process parameters are optimized by using the ANOVA technique based on L9 orthogonal array. Experiments have been conducted based on three and their percentage of contribution in producing a better joint is calculated, by applying the effect of the signal-to-noise ratio and analysis of variance. The results indicate that the tilt angle, tool process parameters, namely, rotational speed (rpm), D/d ratio and tilt angle at three different levels. The results indicate that rotational speed (RS), Shoulder diameter to pin diameter (D/d) ratio and tilt angle (TA) are the most significant factors, in deciding the mechanical properties of friction stir welding aluminum alloy. In addition, mathematical models were developed to establish relationship between different process variables and mechanical properties

Keywords— Aluminium alloy, Friction Stir Welding, Microstructure, Mechanical properties, Analysis of Variance; Signal-to-Noise ratio.

1. Introduction

Friction Stir Welding (FSW) is a solid–state joining technique invented and patented by The Welding Institute (TWI) in 1991 for butt and lap welding of ferrous and non–ferrous metals and plastics [1]. Since its invention, the process has been continually improved upon as its scope of application becomes expanded. FSW is a continuous process that involves plunging a portion of a specially shaped rotating tool between the abutting faces of a joint. The relative motion between the tool and the substrate generates frictional heat that creates a plasticised region around the immersed portion of the tool. In addition, the shoulder prevents the plasticised material from being expelled from the weld, therefore, the tool is moved relatively along the joint line, forcing the plasticised material to coalesce behind the tool to form a solid–phase joint [1]. The inserted picture also depicts the tool shoulder and the tool pin. The tool pin is sometimes referred to as the probe. The advancing side is on the right, where the tool rotation direction is the same as the tool travel direction (opposite the direction of metal flow), while the retreating side is on the left, where the tool rotation is opposite to the tool travel direction (parallel to the direction of the metal flow).

The tool serves three primary functions; the heating of the workpiece, the movement of material to produce the joint, and the containment of the hot metal beneath the tool shoulder [1]. The heat generated during the FSW process is often assumed to occur predominantly under the shoulder; due to its greater surface and to be equal to the power required to overcome the contact forces between the tool and the workpiece [3]. To an extent, the heat input into the welds increases as the shoulder diameter increases [4]. The three different shoulder diameters used in this research study were chosen to vary the heat input into the welds while varying the process parameter settings. The benefits of FSW process as a technology include: low distortion, greater weld strength compared to the fusion welding process, little or no porosity, no filler metals, no solidification cracking, no welding fumes or gases, improved corrosion resistance, and lower cost in production applications. Because of the many demonstrated advantages of FSW over the fusion welding techniques, the commercialization of FSW is progressing at a rapid pace [5]. FSW is considered to be the most significant development in metal joining techniques in decades; and it is, in addition, a "green technology" due to its energy efficiency, environmental friendliness and versatility. When compared to the conventional welding methods, FSW consumes considerably less energy and no harmful emissions are created during the welding process [6]. Different microstructural zones exist after FSW, this include: the Heat Affected Zone (HAZ) which is a region that lies closer to the parent materials, the materials have experienced a thermal cycle that has modified the microstructure and or the mechanical properties. The Thermo Mechanically Affected Zone (TMAZ) is a zone where the FSW tool has plastically deformed the material while the Stir Zone (SZ) also referred to as the Weld Nugget (WN) is a fully recrystallized region; it refers to the zone previously occupied by the tool pin. This microstructural characterization is credited to P. L. Threadgill [7]. Aluminum alloy 6061-T6 is widely utilize in aircraft, defence, automobiles and marine areas due to their good strength, light weight and better corrosion properties. But, they exhibits inferior tribological properties in extensive usage [8, 9].From the reported literature, it is observed that influence of AA 6061 alloys on mechanical properties was studied. Hence the objective of present investigation is to study the influence of process parameters on mechanical properties of AA 6061 alloys fabricated via FSW and obtain the optimum combinations using L_9 method was adopted to analyze the effect of each processing parameters (i.e rotational speed, D/d ratio and tilt angle) for optimum tensile strength.

2. Experimental procedure

The base material employed in this study is 5 mm thick Aluminum alloy on AA 6061-T6 plates having dimensions were cut to the required dimensions (240mm×60 mm×5mm) by wire cut Electric Discharge Machine. The chemical composition of base metal is AA 6061alloy plate shown in Table 1. Stainless steel tool having screwed taper pin profile with shoulder diameters The diameter of the tool shoulder (D) were 18 mm, 21 mm and 24 mm that of the insert pin diameter (d) and pin length (L) are 6 mm and 4.8 mm respectively.

Element	Mg	Si	Cu	Zn	Ti	Mn	Cr	Al
Amount (Wt %)	0.85	0.68	0.22	0.07	0.05	0.32	0.06	Balance

Table 1 Chemical composition of Aluminum 6061-T6 alloy (Wt. %)

The initial joint configuration was obtained by securing the plates in position using mechanical clamps. The direction of welding is normal to the rolling direction and single pass FSW used to fabricate the joints. The diameter of the tool shoulder (D) were 18 mm, 21 mm and 24 mm that of the insert pin diameter (d) and pin length (L) are 6 mm and 4.8 mm respectively.

After FSW, microstructural observations were carried out at the cross section of nugget zone (NZ) of Aluminum 6061-T6 alloy normal to the FSW direction, mechanically polished and etched with Keller's reagent (2 ml HF, 3 ml HCl, 20 ml HNO_3 and 175 ml H_2O) by employing optical microscope (OM).

Selection of Orthogonal Array

The experimental design proposed by ANOVA involves using orthogonal arrays to organize the parameters affecting the process and the levels at which they should be varies. Instead of having to test all possible combinations like the factorial design, the ANOVA techniques tests pairs of combinations.

According to the L9 orthogonal array, three experiments in each set of process parameters have been performed on AA 6061 alloy plates. The three factors used in this experiment are the rotation speed (rpm), D/d ratio and tilt angle. The factors and the levels of the process parameters are presented in Table.3 and these parameters are taken based on the trials to weld the FSW of AA 6061 alloy plates.

2.1 Planning of Experiments based on Taguchi's Method:

Rotational speed is the most important process parameter in FSW which has greater influence in uniform distribution of, grain refinement and heat input during the process [10].Trial experiments were conducted by varying the rotational speed, Did ratio and tilt angle of the joints and keeping the others constant to find the working range of parameters. Feasible levels of the process parameters were chosen in such a way that the welded joints should be free from defects.

Taguchi's Method is very effective to deal with responses influenced by many parameters. It is a simple, efficient and systematic approach to determine optimal process parameters. It is a powerful design of experiments tool which reduces drastically the number of experiments that are required to model and optimize the responses. Also, it saves lot of time and experimental cost [11]. The Taguchi method is devised for process optimization and identification of optimum levels of process parameters for given responses. In Taguchi method, the experimental values of various responses are further transformed to signal to noise (S/N) ratio. The response that is to be maximized is called 'Higher the better' and the response that is to be minimized is called 'Lower the better'. Taguchi uses the S/N ratio to measure deviation of the response from the mean value. S/N ratios for 'Higher the better' and 'Lower the better' characteristics are calculated using equations 1 and 2 respectively

$$\eta = -10\log_{10}\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^{\,2}}\right] \qquad (1)$$

$$\eta = -10\log_{10}\left[\frac{1}{n}\sum_{i=1}^{n} y_i^2\right] \qquad (2)$$

Where η denotes S/N ratio of experimental values, y_i represents the experimental value of the i^{th} experiment and n is total number of experiments.

In the present study, the Taguchi method was applied to experimental data using statistical software MINITAB-16. The number of process parameters considered under this study is three and the level of each factor is three. The degree of freedom of all the three factors is 6. Hence, L_9 (3^4) orthogonal array is selected. Each condition of experiment was repeated twice in order to reduce the noise/error effects.

The quality characteristic such as impact strength is evaluated for all the trials and then statistical analysis of variance (ANOVA) was carried out. Based on the ANOVA, the contribution of each element in influencing the quality characteristic is evaluated. The optimum element combinations were predicted and verified.

3. Results and discussions

3.1. Microstructure

The optical micrographs of all Aluminum 6061-T6 alloy (Exp.1-9) are shown in Fig.1.It show the optical micrographs of the nugget region of all the samples. Significant grain refinement can be noticed in the alloy on FSW in the second joint. Since the second phase particles were not discernible by optical microscopy. Density of precipitates has decreased as a result of coarsening; Grain boundary precipitates have also coarsened. The effects of process and tool parameters on macrostructure of the friction stir welded joints. It is generally known that the fusion welding of aluminum alloys accompanied by the defects like porosity, slag inclusion, solidification cracks, etc., deteriorates the weld quality and joint properties. Usually, friction stir welded joints are free from solidification related defects since, there is no melting takes place during welding and the metals are joined in solid state itself due to the heat generated by the friction and flow of metal by the stirring action. However, FSW joints are prone to other defects like pin hole, tunnel defect, piping defect, kissing bond, Zig-Zag line and cracks, etc., due to improper flow of metal and insufficient consolidation of metal in the FSP (weld nugget) region.

The particles of Mg and Si were observed to be dispersed uniformly in the NZ for all the conditions of composites made by FSP due to rotating tool gives sufficient heat generation and a circumferential force to distribute the reinforcement particles to flow in wider area [10-11]. It is found that the sample made at the optimum condition (i.e. A3B2C1) severe plastic deformation and frictional heating in the SZ during FSW resulted in generation of a recrystallized equiaxed microstructure.

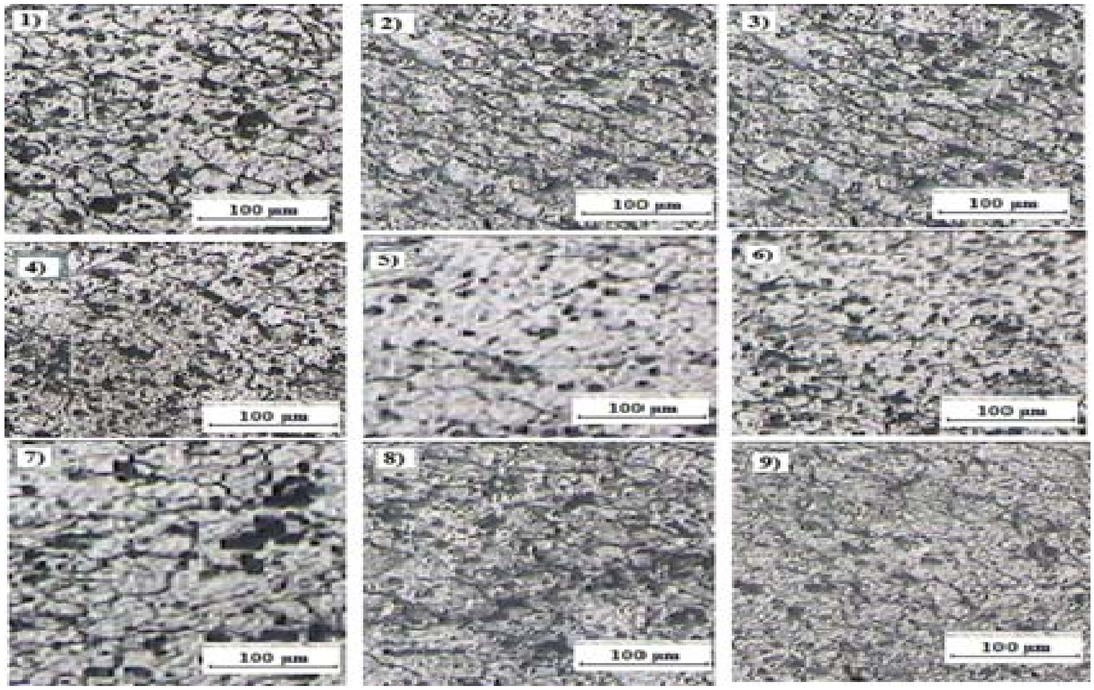


Fig. 1 Optical microstructures of all the Exp. 1 to 9 Aluminum 6061-T6 alloy

3.2 Mechanical properties

Mechanical properties such as UTS, YS, % of Elongation and Impact strength were evaluated and presented in Table.3

Mean and Signal to Noise ratio

The Mean and signal to noise ratio are the two effects which influence the response of the factors. The influencing level of each selected welding parameter can be identified. UTS, YS, % of Elongation and Impact strength of the FSW weld are taken as the output characteristic. The response table for the S/N ratio shows that the rotational speed (rpm) ranks first in the contribution of good joint strength, while tilt angle and D/d ratio take the second and third ranks. The same trend has been observed in the response table of the mean which is presented in Table respectively. The responses for the plot of the S/N ratio and Mean.

Statistical Analysis

The statistical analysis of the data was done in two phases. In the first phase, ANOVA was done to find the effect of process parameters and their contribution to responses, in the second phase, the relationships between the responses and the friction stir welding parameters were established.

Analysis of Variance

ANOVA (analysis of variance) is a statistical technique for determining the degree of difference or similarity between two or more groups of data. It is based on the comparison of the average value of common components. The percentage contribution of various process parameters to the selected performance characteristic can be estimated by ANOVA. Taguchi recommended a logarithmic transformation of mean square deviation called signal-to-noise ratio (S/N ratio) for analysis of the results. Signal-to-noise ratio (SNR) is utilized to measure the deviation of quality characteristic from the target. In this investigation, the S/N ratio was chosen according to the criterion, the “larger-the-better” in order to maximize the responses. The S/N ratio for the “larger-the-better” target for all the responses was calculated as follows.

The formula used for computing S/N ratio is given below. Larger the better:

$$S/N \text{ ratio } (\eta) = -10 \log 10 \frac{1}{n} \sum_{i=0}^{n} \left[\frac{1}{Y_i^2} \right] \qquad (1)$$

Where n is the number of experiments (for one set of parameters n=1) and Yi is the response for ith experiment. The experimental results were transformed into signal-to-noise (S/N) ratio using statistical software. The S/N ratio values of all levels are calculated for all properties and presented in Tables 2- 4.

The main effects plots for S/N ratio of tensile strength, and impact energy are shown in Fig 2. Larger S/N ratio corresponds to better quality characteristics. Therefore, the optimal level of process parameter is the level of highest S/N ratio [12].

Table 2 S/N Ultimate Tensile strength

Level	Rotation Speed	D/d ratio	Tilt angle
1	44.57	44.58	44.53
2	44.59	44.55	44.57
3	44.49	44.53	44.55
Delta	0.10	0.05	0.05
Rank	1	3	2

Table 4 S/N Yield strength

Level	Rotation Speed	D/d ratio	Tilt angle
1	42.69	42,83	42.73
2	42.85	42.77	42.80
3	42.63	42.58	42.64
Delta	0.22	0.25	0.16
Rank	1	3	2

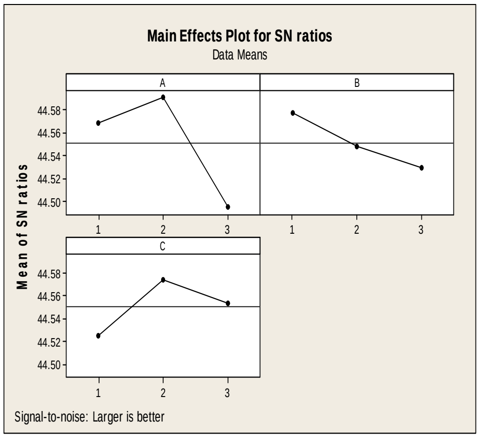
Table 3 S/N % Elongation

Level	Rotation Speed	D/d ratio	Tilt angle
1	18.33	18.29	17.95
2	18.46	18.27	18.33
3	17.67	17.90	18.18
Delta	0.79	0.39	0.39
Rank	1	3	2

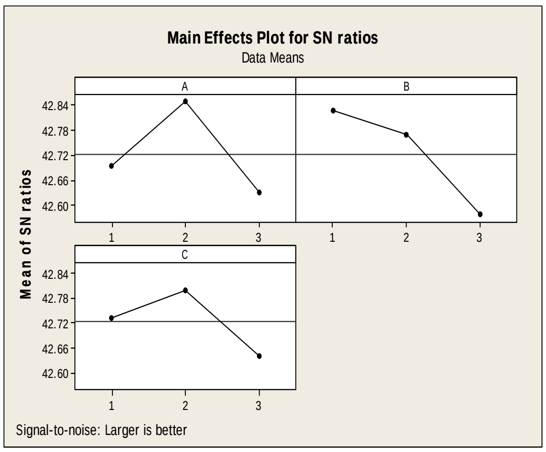
Table 4 S/N Impact Strengt

Level	Rotation Speed	D/d ratio	Tilt angle
1	26.13	26.15	26.02
2	26.02	26.02	26.30
3	25.87	25.72	25.37
Delta	0.58	0.43	0.73
Rank	2	3	1

Note: A- Rotational Speed, B- D/d ratio, C- Tilt Angle

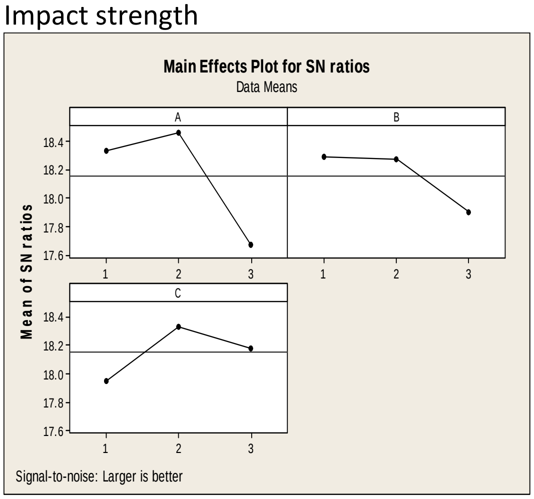


S/N ratio response graph for UTS

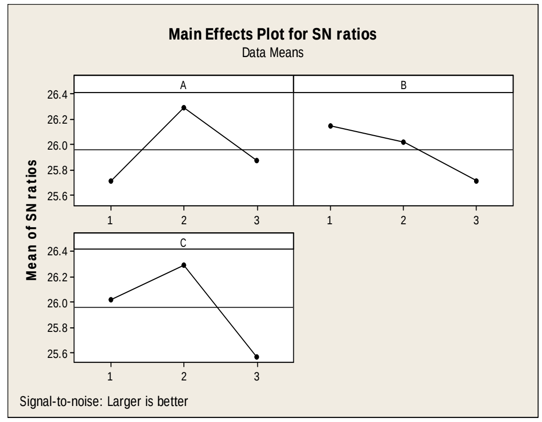


S/N ratio response graph for % of Elongation

Figure 2 Comparison of main effects plots for S/N ratio of UTS, YS, % of Elongation and Impact strength



S/N ratio response graph for YS



S/N ratio response graph for Impact strength

Table 5 ANOVA results

Source	DF	% Contribution Tensile strength	% of Contribution on YS	% of Contribution on Elongation	% of Contribution on Impact Energy
RS	2	67.00	34.19	64.74	32.08
D/d Ratio	2	15.85	46.21	17.21	17.53
TA	2	16.2	16.81	13.65	48.17
Error	2	4.30	2.76	4.38	2.19
Total	8	100	100	100	100

Table 5 shows the results of ANOVA with the properties of UTS, YS, % of Elongation and Impact strength. It is observed that the rotational speed (67.00%) and tool tilt angle (16.20%) have more statistical influence on the tensile strength. The D/d ratio (15.85%) presents low percentage of statistical significance contribution on tensile properties variation. The tool tilt angle has 48.17% has most statistical influence on the variance of impact energy followed by rotational speed (32.08%) and D/d ratio (17.53%).

4. Conclusion

The ANOVA techniques has been used to optimize the welding parameters of friction stir welding to weld a 5 mm plate the conclusions drawn from the present study are listed below:

The influence of rotational speed, D/d ratio and tool tilt angle on mechanical properties of Aluminum alloy 6061-T6 fabricated via FSW were investigated and the following conclusions are obtained.

- The practical benefit of this study is that, the use of obtained optimum condition improves the wear and mechanical properties of Aluminum alloy 6061-T6.
- Tensile properties at optimum condition (i.e. A3 B2 C1) were lower in small quantity as compare to the base material due to presence of Mg and Si particles which make the brittle.
- The rotational speed 1120 rpm D/d ratio 3 and tool tilt angle 2° is favourable to weld 6061 aluminium alloy with good mechanical properties.

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