TAGUCHI OPTIMIZATION OF PROCESS PARAMETERS IN FRICTION STIR WELDING OF ALUMINIUM 2014 & 6061 ALLOYS

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Abstract
In present study, Dissimilar Friction Stir Butt Welds made of 2014 and 6061 Aluminium alloys were performed with various welding parameter. The present study deals with the influence of process parameters on Friction Stir Welded joint. FSW parameter such as welding speed, tool profile and D/d ratio plays a significant role in the assessment of mechanical properties. Using ANOVA and Signal to Noise ratio, influence of FSW process parameters is evaluated and optimum welding condition for maximizing mechanical properties of the joint is determined.
Keywords— Aluminium alloy, Friction Stir Welding, Microstructure, Mechanical properties, Analysis of Variance; Signal-to-Noise ratio.

I. 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. Threading [7]. Aluminum alloy 6061-2014 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 6061-2014 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 6061-2014 alloys fabricated via FSW and obtain the optimum combinations using L9 method was adopted to analyze the effect of each processing parameters (i.e Tool design, welding speed and D/d ratio) for optimum tensile strength.

II. Experimental procedure

The base material employed in this study is 5 mm thick Aluminum alloy on AA 2014 and 6061 plates having dimensions were cut to the required dimensions (300mm×60 mm ×5mm) by wire cut Electric Discharge Machine. The chemical composition of base metal is AA 6061alloy plate shown in Table 1. H13 tool steel 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

Table 1 Chemical composition of Aluminum 2014-6061 alloy (Wt. %)

ELEMENT	**AA6061**	**AA2014**
Al	95.50	93.50
Cu	0.40	4.40
Mg	0.15	0.50
Si	0.80	0.80

After FSW, microstructural observations were carried out at the cross section of nugget zone (NZ) of Aluminum 2014 and 6061 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).

III.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 parametershave been performed on AA 6061-2014 alloy plates. The three factors used in this experiment are the Tool design, welding speed, D/d ratio. 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 6061-2014 alloy plates

Process Parameters	Tool Design	Welding Speed (Mm/Min)	D/D Ratio
Notations Levels	A	B	C
1	I	25	3
2	Ii	40	3.5
3	Iii	75	4

I Taper thread.II Taper cylindrical III Straight Cylindrical

IV. Planning of Experiments based on Taguchi's Method:

D/d ratio 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 Tool design, welding speed and D/d ratio 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 away dthat 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, L9 (34) 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

V. Results and discussions

A Microstructure

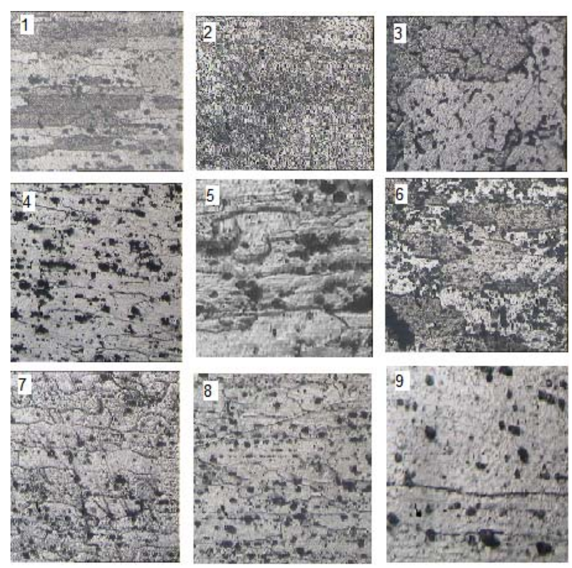

Fig. 1 Optical microstructures of all the Exp. 1 to 9 Aluminum 2014 - 6061 alloy

The optical micrographs of all Aluminum 6061-2014 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 FSW 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.

***B Mechanical* properties**

Exp No	UTS/MPa		YS/MPa		Impact strength (Jouls)		%EL	
	Trail 1	Trail 2	Trail 1	Trail 2	Trail 1	Trail 2	Trail 1	Trail 2
1	169.894	165.191	134.158	131.355	4.58	4.24	16	28
2	156.180	122.304	123.917	97.812	4.02	3.64	28	20
3	153.066	142.077	117.609	125.319	10.72	9.80	14	36
4	119.520	132.269	95.36	104.826	1.10	2.52	18	8
5	71.257	66.535	56.525	52.654	1.20	0.58	4	3
6	186.371	181.513	149.036	145.118	6.70	6.18	10	18
7	139.809	139.510	110.24	111.186	3.36	3.18	6	18
8	117.785	97.897	94.108	78.191	2.74	2.64	16	4
9	104.626	144.519	1.62	1.96	1.62	1.76	16	20

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

C 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.

D 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.

E 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 3- 5. The main effects plots for S/N ratio of tensile strength, micro hardness 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 3 S/N Ultimate Tensile strength

Level	Tool Design	Welding speed	D/d ratio
1	41.70	39.95	41.60
2	41.20	40.86	9.71
3	38.58	40.67	40.17
Delta	3.12	0.92	1.89
ank	1	3	2

Table 4 S/N Yield strength

Level	Tool Design	Welding speed	D/d ratio
1	40.80	39.04	41.21
2	38.99	39.40	40.45
3	37.72	39.06	35.84
Delta	3.08	0.36	5.37
Rank	2	3	1

Table 5 S/N of Elongation

Level	Tool Design	Welding speed	D/d ratio
1	21.46	15.98	20.61
2	17.07	20.11	13.54
3	11.50	13.93	15.87
Delta	9.96	6.18	7.07
Rank	1	3	2

Table 6 S/N Impact Strength

Level	Tool Design	Welding speed	D/d ratio
1	25.41	20.86	26.44
2	19.50	23.40	21.20
3	20.50	21.14	17.76
Delta	5.91	2.54	8.67
Rank	2	3	1

Note: A- Tool design, B- welding speed, C- D/d ratio

Table.6 Comparison of main effects plots for S/N ratio of UTS, YS, % of Elongation and Impact strength

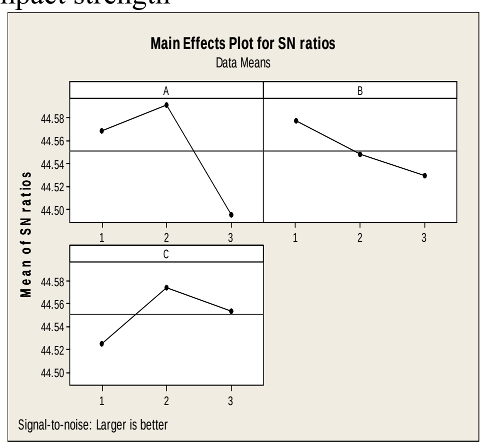

Fig. 2 S/N ratio response graph for UTS

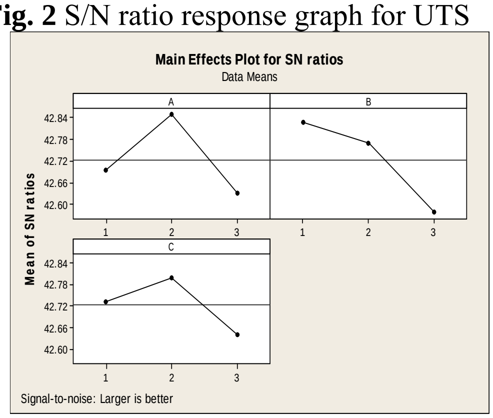

Fig. 3 S/N ratio response graph for YS

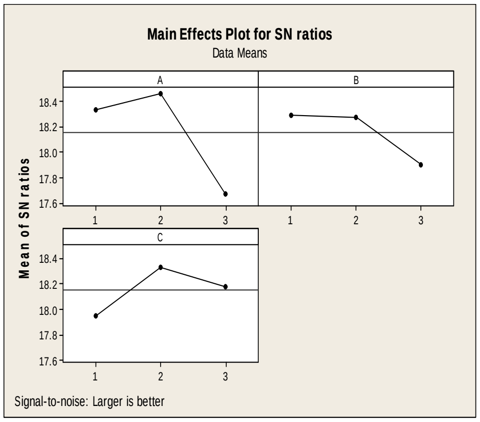

Fig. 4 S/N ratio response graph for % of Elongation

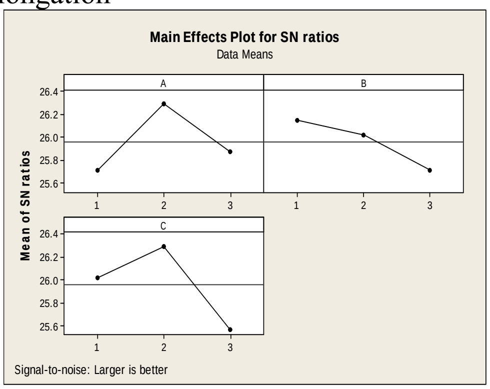

Fig. 5 S/N ratio response graph for IS

Source	DF	% Contribution Tensile strength	% of Contribution on YS	% of Contribution on Elongation	% of Contribution on Impact Energy
Tool Design	2	67.91	20.40	50.48	38.12
WS	2	5.65	0.31	20.07	0.033
D/d Ratio	2	23.53	76.48	26.26	58.60
Error	2	2.88	2.79	3.17	3.23
Total	8	100	100	100	100

VI. 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:

1. The Analysis of Variance for the ultimate tensile strength result concludes that the tool design is the most significant parameter with a percentage of 67.91%, followed by the D/d ratio is 23.53% and welding speed of 5.65%.

2. The Analysis of Variance for the yield strength result concludes that the tool design is the most significant parameter with a percentage of 20.40%, followed by the D/d ratio is 76.48% and welding speed of 0.31%.

3. The Analysis of Variance for the % of elongation result concludes that the tool design is the most significant parameter with a percentage of 50.48%, followed by the D/d ratio is 26.26% and welding speed of 20.07%.

4. The Analysis of Variance for the Impact Strength result concludes that the tool desion is the most significant parameter with a percentage of 38.12%, followed by the D/d ratio is 58.60% and welding speed of 0.033%.

5. The optimum combination of parameters obtained from the main effect plot for mean is process parameters of
Tool design of taper cylindrical, 40 welding speed (mm/min), and D/d ratio of 3 has been predicted to give the Impact Strength of 80.80.

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