Multi Optimization of Friction Stir Welding of Aluminium AA 6061 Alloy using Grey based Taguchi Method

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Abstract

In this paper an experimental investigation has been carried out to determine the optimal parametric setting during Friction Stir Welding (FSW) of Aluminium AA 6061 alloy. The FSW process parameters considered are welding speed, axial force and tool rotational speed whereas the quality characteristics considered are tensile strength and tensile elongation. The Taguchi method was applied in designing the experiments involved in this study to optimize the welding parameters. Following the Taguchi quality design, an L9 (3 3) orthogonal array was chosen to design the experiment. The process parameters that were taken and their levels incorporated in the array were chosen after conducting pilot experiments and also through literature survey. The significant process parameters that affect welding performance were determined by making use of Analysis of Variance (ANOVA) and the F-test values along with the experimental results obtained. By considering the significant parameters so obtained, the verification of the improvement in the quality characteristics for the FSW of Aluminium AA 6061 was done and the results obtained were found out to be an improvement over the results obtained while using the original parameters (original setup). Apart from the optimization of each process parameter taken individually, multi response optimization has also been performed on both the process parameters that have been mentioned above by making use of the Taguchi-Grey relational analysis.

Keywords: *Design of Experiments, Multi Optimization,ANOVA, Orthogonal arrays, Aluminium 6061*

1. Introduction

Friction stir welding is one of the solid state welding process where two components are rubbed together at a controlled rotational speed to induce friction. That friction is used to generate enough heat that allows both components to reach a state of plasticity, helping to generate a bond when both the components are forced together. The force is laterally applied and is termed as 'up-set' which is used to fuse the components. The bond is created when layers of plastic material from both components interwine and create new layers of combined material [1]. Friction welding can replace conventional welding and one piece construction as one of the most economical welding processes available. It also gives benefits in design, strength and cost reduction. The process can provide increased design flexibility, superior strength and significant cost savings over other conventional welding processes. Heat treatable wrought Aluminium- Magnesium-Silicon alloy AA 6061 has very good welding characteristics among high strength Aluminium alloys. These types of alloys are used extensively in pipelines, marine frames, storage tanks and aircraft applications among others. Defects in welding such as large distortion, solidification cracking, porosity and oxidation are not observed in FSW compared to several other fusion welding processes that are generally used for joining structural alloys [2,3]. In order to produce an excellent quality welded joint, it is necessary to optimize the process parameters. In the present research an experimental

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investigation is done on the FSW of Aluminium AA 6061 alloy taking into account Tensile strength and tensile elongation as the quality characteristics. The experimentation process is designed using the Taguchi method where the process parameters considered are Welding speed, axial force and tool rotational speed. Multi optimization is done by making use of the Grey co relational analysis while ANOVA is made use of to determine the significance of the process parameters with respect to the outcome.

2. METHODOLOGY

In this study 6mm thick plates of 6061 Aluminium alloy was used as the base metal. The chemical composition of the alloy and its properties are shown in Table 1 and Table 2 respectively. The configuration used is of the butt type and the welding was carried out by using a vertical milling machine. The process parameters under investigation were selected based on literature survey. The respective levels were selected based on preliminary experiments. Each experiment was run thrice and the average values for the quality characteristics were taken in order to account for variance

Table 1: Chemical composition for base metal (%wt)

Material	Mg	Fe	Cu	Cr	Si	Al
6061-T6	0.8- 1.2	0.33	0.25	0.18	0.4- 0.8	Rest

Table 2: Properties of base metal

Property	Metric
Density	2.7 g/cc
Brinell Hardness	95
UTS	310 MPa
Modulus of elasticity	68.9 GPa
Poisson’s ratio	0.33
Thermal conductivity	167 W/mK

The experimental investigation is conducted with the aim of optimizing the FSW process in order to improve the above discussed quality characteristics namely Tensile strength and Tensile elongation, Several researches have been carried out by researchers showcasing the techniques involved in the selection of the optimal parametric values for Tensile strength and Tensile elongation [4,5]. Taguchi method has been widely used in the selection of the process parameters. Taguchi method makes use of Orthogonal Arrays (OAs) [6] for designing the experiments. The predominant advantage of this technique lies in its simplicity and adaptability. They provide the required information making use of only the least possible number of trials. However they still yield results which have good precision and are reproducible.

In order to determine the performance characteristics corresponding to the optimal machining parameters, a specially designed experimental methodology is imperative. A full factorial experimental design will cover all the possible arrangements possible for a particular experimental setup. However as the number of factors and levels increases, the total number of experiments also increases. Making it unviable both financially and in terms of time taken. Hence Taguchi's orthogonal arrays are made use of to reduce the number of experiments required. The experiment includes three process parameters each of three levels.

Therefore each process parameter will contribute 2 degrees of freedom each. Therefore there are 6 degrees of freedom in total. The interaction between the parameters is neglected [6-9]. The levels of the individual process parameters/factors are given in Table 3. While selecting an Orthogonal Array it should be noted that the degrees of freedom of the Orthogonal Array must be greater than or equal to those of the process parameters. [10]. An L9 array will have 8 degrees of freedom (i.e.: 9-1=8). It has already been specified that the process parameters used here have 6 degrees of freedom. The degree of freedom for the Orthogonal Array is less than the degrees of freedom of the process parameters. Hence it is possible to use an L9 for the experiments in this study. The experimental layout for the process parameters in terms of an L9 Array is given in Table 4.

Table 3: Factors and their levels

Factor	Unit	Level 1	Level 2	Level 3
Welding speed (A)	mm/min.	60	80	100
Axial force (B)	kN	5	6	7
Tool rotational Speed (C)	RPM	900	1000	1100

Table 4: Experimental layout

Experiment No.	A	B	C
1	60	5	900
2	60	6	1000
3	60	7	1100
4	80	5	1000
5	80	6	1100
6	80	7	900
7	100	5	1100
8	100	6	900
9	100	7	1000

3. Results and Discussions

The experiments were conducted as per the arrangement of the orthogonal array in Table 4. Three sets of experiments are conducted for each run and the average values of the quality characteristics are calculated and tabulated as shown in Table 5.

The experimental results are obtained by conducting the experiments are shown in Table 5. The results showcase the effect of the four control parameters on the 2 quality characteristics. The S/N ratios are also displayed in the same table. Once the calculations are made, the graphs for the particular control parameters at their three levels of application are plotted. For maximizing each response, the main effect plot for S/N ratio (Fig. 1 and 2) gives different factor levels as shown in Table 6.

Table 5: Experimental results

Exp. No.	Tensile Strength (MPa)	S/N ratio for Tensile Strength (dB)	Tensile Elongation	S/N ratio for Tensile Elongation (dB)
1	154	43.7504	5.41	14.6639
2	164	44.2969	5.22	14.3534
3	170	44.6090	5.33	14.5345
4	163	44.2438	5.86	15.3580
5	171	44.6599	5.79	15.2536
6	157	43.9180	5.74	15.1782
7	168	44.5062	6.35	16.0555
8	157	43.9180	6.37	16.0828
9	165	44.3497	6.29	15.9730

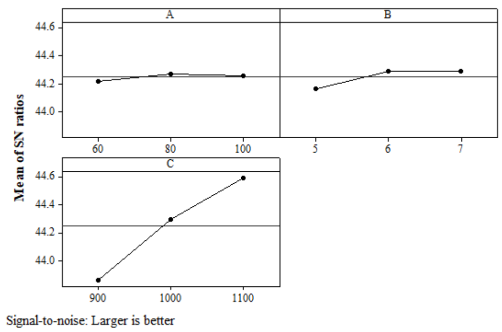

Figure 1: Main effects plot for S/N ratio of Tensile Strength

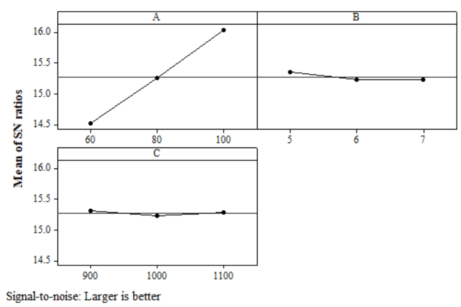

Figure 2: Main effects plot for S/N ratio of Tensile Elongation

Table 6: Optimised levels of corresponding quality characteristic

Factors	Quality characteristic	
	Tensile Strength (MPa)	Tensile elongation (%)
A	80	100
B	7	5
C	1100	900

The analysis of variance method (ANOVA) is made use of to determine the relative influence of each factor and these results are presented in Table 7 and Table 8 for tensile strength and tensile elongation respectively.

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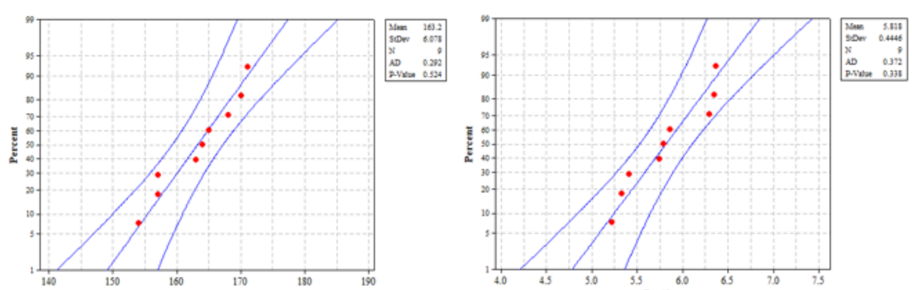
Table 7: ANOVA for Tensile strength

Factor	DOF	SS	V	F-value	P- value
A	2	1.556	0.778	7	0.125
B	2	10.889	5.444	49	0.020
C	2	282.889	141.444	1273	0.001
Error	2	0.222	0.111		
Total	8	295.556			
R^2 = 99.92%; R^2(adj) = 99.70%					

Table 8: ANOVA for Tensile elongation

Source	DOF	SS	V	F-value	P- value
A	2	1.55242	0.776211	140	0.007
B	2	0.01396	0.006978	1.26	0.443
C	2	0.00389	0.001944	0.35	0.740
Error	2	0.01109	0.005544		
Total	8	1.58136			
R^2 = 99.30%; R^2(adj) = 97.20%					

It is clearly observed from Table 6 and Fig. 1 and Fig. 2 that optimum factors for the highest tensile strength are A_2, B_3 and C_3 and for the highest tensile elongation are A_3, B_1 and C_1 respectively. From ANOVA Table 7 and 8, it is observed that with respect to Tensile Strength, the significance of the input parameters are the tool rotation speed, axial force and welding speed with the tool rotation speed being the most significant and the welding speed being the least significant. Whereas for Tensile elongation it is observed that the welding speed is the most significant parameter and the tool rotation speed is the least significant parameter. The adequacy of the analysis is carried out using the Anderson–Darling (AD) test and results are illustrated in Fig. 3. It clearly shows that that the data obtained follows normal distribution. This developed procedure is thus suitable to explore the design.



(a) (b)

Figure 3: Normal probability plot of residue at 95% of confidence: (a) Response is tensile strength and (b) Response is tensile elongation

4. Multi Optimization Using Grey Co-Relation

Taguchi method cannot be used directly to optimize the multi-response problems. The data which was observed for each response using Taguchi designs can be analyzed by different methods to obtain a solution for a multi response problem. Here we attempt to perform a multi response optimization for all three quality characteristics taken all at once. The Taguchi Grey relational analysis is used to perform this multi optimization [11,12].

The value of the grey relational grade is directly proportional to the corresponding factor combination to the optimal value. The results of grey relational grade calculations are summarized in Table 9.

Table 9: Gray relational grade

Grey relational generation			Grey relational coefficient		Grey relational grade
Exp. No.	TS	IE	TS	IE	
1	0	0.179565	0.333333	0.378663	0.355998
2	0.600833	0	0.55607	0.333333	0.444702
3	0.943988	0.104739	0.89926	0.358356	0.628808
4	0.542423	0.580869	0.522151	0.543992	0.533072
5	1	0.520511	1	0.51047	0.755235
6	0.184252	0.47695	0.380012	0.488735	0.434373
7	0.830967	0.984206	0.747348	0.969379	0.858363
8	0.184252	1	0.380012	1	0.690006
9	0.658889	0.936523	0.594452	0.887348	0.7409

Table 10: ANOVA Table for Grey Relational Grade (GRG)

Source	DF	SS	V	F	P
A	2	0.127351	0.063676	43.66	0.022
B	2	0.003432	0.001716	1.18	0.459
C	2	0.101308	0.050654	34.73	0.028
Error	2	0.002917	0.001459		
Total	8	0.235008			

5. Confirmation Experiment

A confirmation experiment is executed to validate the results obtained from the aforementioned analysis. The levels of process parameters made use of for the confirmation test are given in Table 9 and the responses obtained for the levels are presented in Table 11. It is observed that the results are in good agreement with those predicted mathematically and are within expected range at 95% of confidence.

Table 11: Confirmation test results

Response	**Optimal factor combination**			**Significant factors**	**Predicted value**	**Experimental value**	**Absolute error (%)**
	A	B	C				
Tensile Strength (S/N ratio) (db)	2	3	3	B, C	44.63	44.66	0.067
Tensile Elongation (S/N ratio) (db)	3	1	1	A	16.04	16.16	0.74
GRG	3	2	3		0.763	0.831	8.2%

6. Conclusions

An attempt was made to optimize the FSW process with respect to the selected quality characteristics. The necessary levels at which the process parameters have to be set to obtain an optimized result for the quality characteristics have been obtained. From them, we come to the following conclusions.

- For optimum Tensile strength, the recommended parametric combination is A2B3C3 where A2 is 80 mm/min, B3 is 7kN and C3 is 1100 RPM whereas for optimum tensile elongation the recommended parametric combination is A3B1C1 where A3 is 100 mm/min, B1 is 5kN and C1 is 900 RPM.
- It is observed that the Tool rotation speed is the most significant parameter that affects the Tensile strength of Aluminium 6061 followed by axial force and welding speed whereas welding speed is the most significant parameter that affects the tensile elongation of Aluminium 6061 followed by axial force and tool rotation speed.
- Multi optimization has been performed for both quality characteristics and the optimal level of the parametric arrangement is found to be A3B2C3.
- By conducting the conformational experiments we can see that the results so obtained are in close line with the theoretical models that were obtained.

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