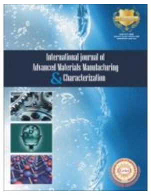

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Application of Taguchi Method for Optimization of Friction Stir Welding Process Parameters to Joining of Al Alloy

Saurabh Kumar Gupta[1] K.N. Pandey[2]

Department of Mechanical Engineering, Motilal Nehru National Institute of Technology Allahabad, 211004, India[1& 2]

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ABSTRACT

In this study, the joining of 6061-T4 Al alloy plates are carried out using friction stir welding (FSW) process and the process parameters are optimized using Taguchi method. The rotational speed, welding speed and axial force are the process parameters taken into consideration. The optimum process parameters are determined with reference to tensile strength of the joint. The results indicate that the rotational speed is highest significant parameter to deciding the tensile strength of the joint. The result shows that optimal values of process parameters are to get a maximum tensile strength of friction stir welded AA 6061 is 162 MPa.

Introduction

Friction stir welding (FSW) is a solid state joining process that invented at The Welding Institute (TWI) United Kingdom in 1991, is a viable technique for joining aluminium alloys that are difficult to fusion welding [1]. No defects are observed in FSW like porosity, alloy segregation and hot cracking, and welds are produced with good surface quality and thus no post weld cleaning is required [2]. There have been a lot of efforts to understand the effect of process parameters on material flow behavior, microstructure formation and mechanical properties of friction stir welded joints. The effect of some important process parameters on weld properties is major area for researchers [3-5]. In order to study the effect of FSW process parameters, most of follow the traditional experimental techniques, i.e. varying one parameter at a time while other parameters are constant, this conventional parametric design of experiment approach is time consuming. Taguchi statistical design is a powerful tool to identify significant factor from many factors by conducting relatively less number of experiments.

- Corresponding author: Saurabh Kumar Gupta
- E-mail address: saurabhguptanit@gmail.com
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Though research work applying Taguchi method on various processes have been reported in literatures [6-11], it appears that the optimization of FSW process parameters of 6061-T4 aluminium alloy using Taguchi method has not been reported yet. Considering the above facts, the Taguchi method is adopted to analyse the effect of each processing parameters (i.e. rotational speed, welding speed and axial force) for optimum tensile strength of friction stir welded joints of 6061-T4 aluminium alloy.

Taguchi method

Taguchi, a Japanese quality engineer widely recognized as the father of quality engineering [12], addresses quality in two main areas: off-line and on-line quality control. Both of these areas are very cost sensitive in the decisions that are made with respect to the activities in each. Off-line quality control refers to the improvement in quality in the product and process development stages. On-line quality control refers to the monitoring of current manufacturing processes to verify the quality levels produced [13]. The most important difference between a classical experimentaldesign and a Taguchi method-based robust design technique is that the former tends to focus solely on the mean of the quality characteristic, while the later considers the minimization of the variance of the characteristic of interest. Although the Taguchi method has drawn much criticism due to several major limitations, it has been able to solve single response problems effectively.

The Taguchi method attempts to optimize a process or product design and is based upon three stages, as follows:
1. Concept design or system design
2. Parameter design
3. Tolerance design
The following are the steps to be followed for process parameter optimization [14]:
Step 1: Determine the quality characteristic to be optimized.
Step 2: Identify the noise factors and test conditions.
Step 3: Identify the control factors and their alternative levels.
Step4: Design the matrix experiment and define thedata analysis procedure.
Step 5: Conduct the matrix experiment.
Step 6: Analyze the data and determine optimum levels for control factors.
Step 7: Predict the performance at these levels

FSW process parameters

It has been clearly shown in the literature [15–18] that FSW process parameters such as tool geometry rotational speed, welding speed and axial force significantly influence the process and play a major role in deciding the quality of the weld.

The detailed list of FSW process parameters are listed below:
1. Rotational speed of the tool (rpm)
2. Welding speed (mm/min)
3. Axial load (KN)
4. Tool geometry
(i) D/d ratio of tool
(ii) Pin length
(iii) Tool shoulder diameter, D (mm)
(iv) Pin diameter, d (mm)
(v) Tool inclined angle (◦)

In the present investigation, three process parameters, i.e. rotational speed, welding speed and axial force are considered. Trail experiments are carried out using thick rolled plates of 6061 AA to fix the working range of FSW process parameters. When the rotational speed is lower than 800 rpm, low frictional heat is generated which results in poor plastic flow of the material during welding and contain defects like pinhole or tunnel in weld zone; when the rotational speed is higher than 1000 rpm causes excessive release of stirred material to the upper surface, which resultants left voids in the weld zone and poor surface quality.

Table1: Process parameters with their range and three levels

Level	**Rotational Speed(A) RPM**	**Welding Speed (B) mm/min**	**Axial Force (C) KN**
Range	**800-1000**	**60-100**	**6-8**
Level 1	800	60	6
Level 2	900	80	7
Level 3	1000	100	8

Similarly, when the welding speed is lower than 60 mm/min, pin holes type of defects are observed due to excessive heat input per unit length of the weld; when the welding speed is higher than 100 mm/min associated with low heat input, poor plastic flow of the material which causes some defects are observed at the weld zone. When the axial force applied on the tool by machine head is lower than 6 KN, sufficient heat is not generated which causes tunnel and crack like defect at the weld zone are observed; when the axial force is higher than 8 KN, large mass of flash and excessive thinning are observed due to higher heat input.Hence, the range of process parameters such as tool rotational speed is selected as 800-1000 rpm, the welding speed is selected as 60-100 mm/min and axial force is selected as 6-8 KN. The FSW process parameters along with their range and values are given in Table 1.

Table 2: Chemical composition of Al alloy

Material	Mg	Si	Fe	Ca	Cu	Al
6061-T4	0.92	0.6	0.33	0.2	0.06	Bal.

Selection of orthogonal array (oa)

Before selection of particular OA following points must be considered.

1. The number of factors and interactions of interest
2. The number of levels and interactions of interest

As three levels and three factors are taken into consideration, L9 OA is used in this investigation. Only the main factor effects are taken into consideration and not the interactions.The degrees of freedom (DOF) for each factor is 2 (number of levels − 1, i.e. 3 − 1 = 2) and therefore, the total DOF will be 6(= 3 × (3-1)). As per Taguchi method, the total DOF of selected OA must be greater than or equal to the total DOF required for the experiment. So an L9 OA having 8 (=9-1) degrees of freedom are selected for the present analysis**.**

Experimental procedures

The material used in this study is 5 mm thick sheets of 6061-T4 aluminium alloy. Chemical composition of base metal is given in Table 2. The rolled plates are cut into required dimension (300 mm long and 150 mm wide) for friction stir welding. Welding is carried out in butt joint configuration using friction stir welding machine. The butt joints are fabricated normal to the rolling direction. The experiments are conducted using parameters of the designed L9 OA table 3.

The American Society for Testing and Materials (ASTM E8) standard is used for preparing the tensile test specimens. The wire cut electro discharge machine (EDM) is used for prepared the smooth profile tensile test specimens. To minimize the machining error (noise), three specimens are prepared at each set of parameters in the designed matrix. The 27 prepared tensile specimens are subjected to tensile testing and ultimate tensile strength of each specimen is evaluated.

Results and discussion

Signal to Noise Ratio

The signal to noise S/N ratio is calculated based on the quality of characteristics intended. The objective function described in this investigation is maximization of the tensile strength, so the larger the best S/N ratio is calculated. The formula for S/N ratio is given below.

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

Where n is number of experiments and y is observed response value.

In this study, the tensile strength value of the FSW joints is analyzed to study the effects of the FSW process parameters. The experimental results are then transformed into means and signal-to-noise (S/N) ratio.In this work, 9 means and 9 S/N ratios are calculated and the estimated tensile strength, means and signal-to-noise (S/N) ratio are given in Table 4.The main effects of average mean and S/N ratio values of all levels are calculated and listed in Table 5 and 6.It is clear that a larger S/N ratio corresponds to better quality characteristics. Therefore, the optimal level of process parameter is the level of highest S/N ratio. Based on both mean and S/N ratio, indicated that the tensile strength at maximum when rotational speed, welding speed and axial force are at level 2. The main effects for mean and S/N ratio are plotted in Fig. 1 and 2.

Table 3: Experimental layout – L9 Orthogonal Array

Sl.No.	Rotational Speed (A)	Welding Speed (B)	Axial Force (C)
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

Table 4: Mean value and S/N Ratio

Input Parameters			Tensile strength (MPa)			Mean (MPa)	S/N Ratio
A	B	C	T1	T2	T3		
800	60	6	130	127	131	129.33	42.2340
800	80	7	142	144	141	142.33	43.0659
800	100	8	120	122	120	120.67	41.6320
900	60	7	150	154	153	152.33	43.6557
900	80	8	155	153	158	155.33	43.8251
900	100	6	145	148	147	146.67	43.3268
1000	60	8	135	137	135	135.67	42.6497
1000	80	6	140	138	141	139.67	42.9021
1000	100	7	125	128	127	126.67	42.0535

Table 5: Main effects of the process parameters

Process Parameter	Level	Means			S/N Ratio		
		A	B	C	A	B	C
Average value	L1	130.7	139.1	138.6	42.31	42.85	42.82
	L2	151.4	145.8	140.4	43.60	43.26	42.93
	L3	134.0	131.3	137.2	42.54	42.34	42.70
Main effects	L2-L1	20.7	6.7	1.8	1.29	0.41	0.11
	L3-L2	-17.4	-14.5	-3.2	-1.06	-0.92	-0.23

Table 6: Response table for Means and S/N Ratio

Level	Means			S/N Ratio		
	A	B	C	A	B	C
L1	130.7	139.1	138.6	42.31	42.85	42.82
L2	**151.4**	**145.8**	**140.4**	**43.60**	**43.26**	**42.93**
L3	134.00	131.3	137.2	42.54	42.34	42.70
Delta	20.7	14.4	3.2	1.29	0.93	0.22
Rank	1	2	3	1	2	3

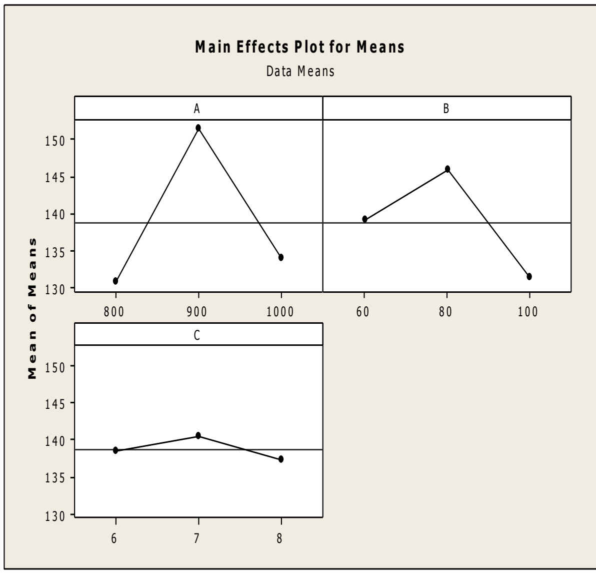
Table 7: ANOVA for Tensile Strength (Means)

Source	DF	Seq SS	Adj SS	Adj MS	F	% of Contribution
A	2	741.68	741.68	370.84	20.62	67
B	2	313.38	313.38	156.69	8.71	28.3
C	2	15.71	15.71	7.85	0.44	1.4
Error	2	35.97	35.97	17.99	-	3.3
Total	8	1106.74	1106.74			100

Table 8: ANOVA for S/N Ratio

Source	DF	Seq SS	Adj SS	Adj MS	F	% of Contribution
A	2	2.85892	2.85892	1.42946	16.10	67
B	2	1.29297	1.29297	0.64648	7.28	28.3
C	2	0.07455	0.07455	0.03728	0.42	1.4
Error	2	0.17752	0.17752	0.08876	-	3.3
Total	8	4.40396	4.40396			100

DF=Degrees of freedom, Seq SS=Sequencial sum of squares, Adj SS=Adjusted sum of square, Adj MS=Adjusted mean square, F=Fisher ratio



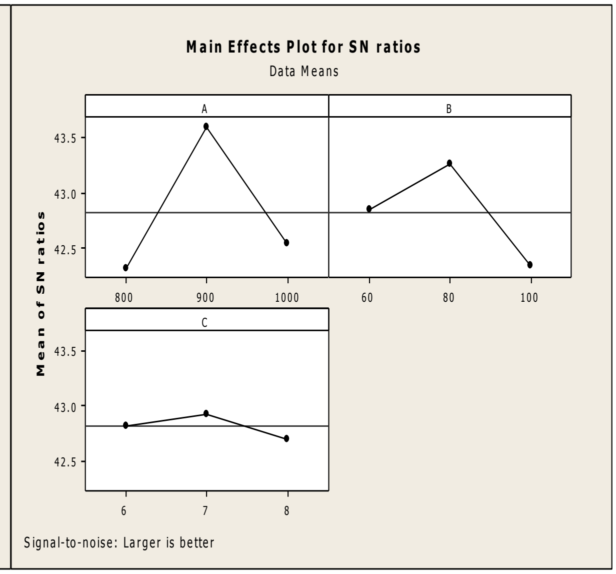


Fig.1 Main Effects Plot for MeansFig.2 Main Effects Plot for S/N ratio

Analysis of Variance (ANOVA)

ANOVA test is performed to find out the significant factor statistically. The purpose of ANOVA is to find out the significant process parameters which affect the tensile strength of FSW joints. The ANOVA result for both mean and S/N ratio is calculated and given in table 7 and 8 respectively. The F-test is being carried out to study the significances of process parameters. The high F value shows that the, factor is highly significant to affecting the response of process. In this study, results of ANOVA show that the rotational speed is highly significant factor and plays an important role to affecting the tensile strength of FSW joints.

Predicted Value of Tensile Strength

Based on the experiments, the optimum level setting is $A_2B_2C_2$.The additive model to evaluate the predicted tensile strength is taken from the literature [10]. The average values of parameters are taken from table 6 and predicted the value of tensile strength.

Tensile strength (predicted)
$= A_2+B_2+C_2-T(2)$
$= 151.4 + 145.8 + 140.4 - 2\ (138.7)$
$= 160.2$ MPa

Where,
A_2= average value of tensile strength at second level of rotational speed
B_2= average value tensile strength at second level of welding speed
C_2= average value of tensile strength at second level of axial force
T= overall mean of tensile strength

Confirmation Run

The confirmation experiments are carried out by setting the process parameters at optimum levels. The rotational speed, welding speed and axial force are set at 900 RPM, 80 mm/min and 7KN respectively. Three tensile specimens are subjected to tensile test and the average value is 162 MPa of the friction stir welded AA 6061.

Conclusion

1. The L9 Taguchi orthogonal designed experiments of FSW on aluminium alloy AA 6061 are successfully conducted.
2. The FSW process parameters are optimized to maximize the tensile strength of joint. The optimum level levels of the rotational speed, welding speed and axial force are found to be 900 RPM, 80 mm/min and 7 KN respectively.
3. The rotational speed plays an important role and contribution 67 % of the overall response, welding speed and axial force contribute 28% and 1.4 % respectively of the overall response.

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