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Optimization of Process Parameters on Friction Stir Welding of AA 6082-T6 Butt Joints Using Taguchi Method

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Friction Stir Welding (FSW) was carried out on Aluminum Alloy 6082-T6 plates with dimensions of 200 x 70 x 2 mm. Design of Experiment (DOE) was applied to determine the most important factors which influence the Ultimate Tensile Strength (UTS) and Hardness (HV) of AA 6082-T6 joints produced by Friction Stir Welding (FSW). Effect of two factors which include tool rotational speed and welding speed on (UTS, HV) were investigated by Taguchi method using L9 orthogonal array to find the optimum process parameters. An analysis of variance (ANOVA) was carried out to determine which of the selected factors are more significant on both of responses, the optimum parameters for the higher UTS it found by using a rotational speed of 1400 rpm and 125 mm/min for the welding speed, also 1400 rpm and 160 mm/min to maximize Hardness (HV).

Keywords: Friction Stir Welding, AA 6082-T6, Taguchi Method, ANOVA Analysis.

1. Introduction

Friction stir welding (FSW) is a solid state welding process invented by Thomas et al (1991) at TWI, UK. In this process [1]. The tool is comprised of two parts: the shoulder and pin. The shoulder has two major roles in FSW. One of these is to produce frictional heat, and the other is to apply force to the surface. The pin also plays a role in both helping the production of frictional heat and trans-versing the plasticized material on either side of the joint line [2]. The plastic deformation capability of the material increases with the effect of the rotation of both shoulder and pin. Hence, the plasticized material replaces itself around the tool [3] and transverses along the joint line [4]. Aluminum material was profitably developed and the welding plates from 1 to 75 mm thickness can be welded in a single pass by the FSW process [1].

The main applications of FSW are the welding of long lengths of material in the aerospace, shipbuilding and railway industries. This process has the advantages over conventional fusion-welding processes such as good mechanical properties, safety and no consumables material used. It can operate in all positions [5].

Al-Mg-Si alloys (6xxx series) are widely used as medium-strength structural alloys, which have the additional advantages of good formability, corrosion resistance, immunity to stress corrosion cracking, and low cost [6-8]. Different from high strength aluminum alloys (2xxx and 7xxx series), 6xxx alloys can be welded by traditional fusion welding techniques like tungsten inert gas (TIG) and metal inert gas (MIG). Nevertheless, friction stir welding (FSW) joints are usually stronger [9-11] and less expensive [12] than fusion welds. This is why FSW is attracting an increasing amount of interest in automotive and shipbuilding industries where 6xxx alloys are extensively used [13].

The conventional parametric design of experiment approach is time consuming and calls for enormous resources. Taguchi statistical design approach is a powerful tool to identify significant factor from many by conducting relatively less number of experiments [14]. In this study, 9 sets of FSW joint were produced using two process parameters (tool rotational speed and welding speed). The tensile strength and Hardness of the welded specimen were taken into account to determine the optimum process parameters with the impact rate of the input parameters on output responses (UTs, HV). Thereby a Taguchi L9 orthogonal design of experiments accompanied by the S/N and the Analysis of Variance were used.

2. Experimental work and conditions

2.1. *Materials*

This study carried out using ALMO 1.5 milling machine, which had 5 kW spindle motor. The work-pieces materials used were AA 6082-T6 aluminum alloy plates in the form of 200 x 70 x 2 mm clamped on the machine milling table as shown in Fig. 1a. The chemical composition and mechanical properties of the base material are presented in Table 1 and 2. The longitudinal direction of the FSW was perpendicular to the rolling direction of AA 6082-T6. Butt welding configuration was followed to fabricate the joints Fig. 1b.

The welding tool made of tool steel with conical unthreaded pin profile and concave shoulder was used in this work Fig. 1c. The dimensions of the tool are shown in Table 3.

Nine [09] welds were performed with the use of several combination speeds. Welding speeds [80, 125, 160] mm/min and rotational speeds [1000, 1400, and 2000] rpm. Then a tensile specimen (ALTER) and a sample for the measurement of HV micro-hardness were extracted for each weld joint in order to mechanically characterize the FSW solder joints.

Table 1 Chemical compositions in% of 6082 aluminum alloy

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
0,7-1,3	Max 0,5	0,1	0,4-1,0	0,6-1,2	Max 0,25	Max 0,2	Max 0,1	Rest

Table 2 Mechanical properties of the base metal AA6082-T6

Re (MPa)	Rm (MPa)	A%	E (GPa)	HV	$T_{melting}$ (°C)
249	310	11	67	107	650

Table 3 Tool dimensions

Tool characteristic	Values
Tool shoulder diameter D (mm)	12
Pin diameter d (mm)	4
Degree of taper pin (°)	2°
Pin length L (mm)	1,86

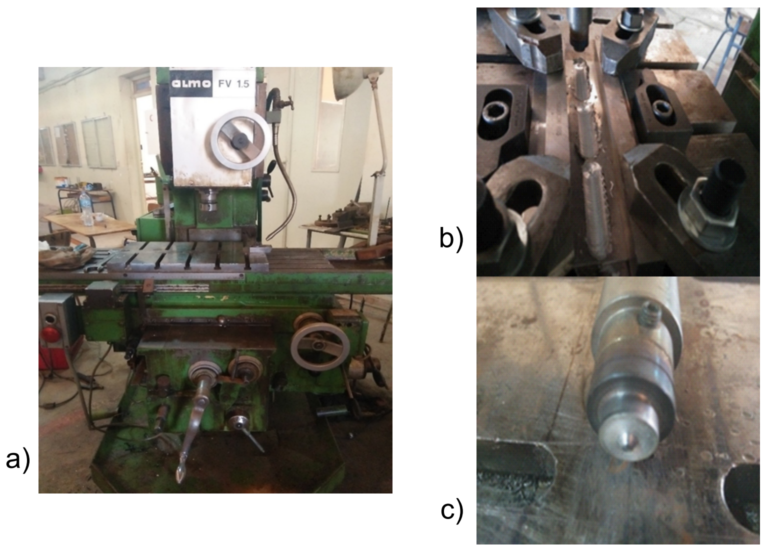

Figure 1 a) Friction stir welding machine, b) the clamping devices and work-pieces with welds, c) welding tool

2.2. *Parameters and their levels*

The parameters selected for experimentation are tool rotational speed [N], welding speed [WS] Table 4.

Table 4 Friction stir welding parameters and their levels

Parameters	Unit	Notation	Levels		
			1	2	3
Rotational speed	rpm	N	1000	1400	2000
Welding speed	mm/min	WS	80	125	160

3. Results and discussions

3.1. *Analysis of experimental data*

The Taguchi method is an experimental method used in to minimize the number of test compared with traditional techniques. It provides a predictive model for finding optimal configurations and the possibility to suggest quickly experimental results [15].

3.1.1. *Orthogonal arrays (Taguchi method)*

Two factors were studied in this research rotational speed [N], Welding speed [WS]. Three levels of each factor were considered for optimum the ultimate tensile strength and the hardness of weld joints of AA 6082-T6 aluminum alloy. An L_9 Orthogonal Array was selected for this study using Minitab 17, Table 5.

Table 5 Experimental conditions and results

N° Trial	N (rpm)	WS (mm/min)	UTs (MPa)	S/N (UTs)	HV	S/N (HV)
1	1000	80	196,86	45,8831	61,1	35,7208
2	1000	125	193,94	45,7533	65,5	36,3248
3	1000	160	165,19	44,3597	58,7	35,3728
4	1400	80	193,79	45,7466	74,5	37,4431
5	1400	125	202,05	46,1092	69,3	36,8147
6	1400	160	201,06	46,0665	82	38,2763
7	2000	80	162,19	44,2005	70,1	36,9144
8	2000	125	198,23	45,9434	68,5	36,7138
9	2000	160	143,45	43,1340	63,5	36,0555

The goal of this research was to produce maximum arithmetic mean heights of the ultimate tensile (UTs) and the hardness (HV) of the friction stir welded joints. A higher value of UTs and HV represent the best mechanical resistance. In order to evaluate influence of input parameters (N, WS) on responses (UTs, HV); the performance indicator correspondent for this study is the S/N ratio with a Larger-is-better characteristic developed by Taguchi. The ratio is given by the Eq. (1):

$$\frac{S}{N} = -10 \log_{10}\left(\frac{1}{n}\sum \frac{1}{y_i^2}\right) \tag{1}$$

y_i is the value of responses (UTs, HV) for the ith test and n is the total number of the tests.

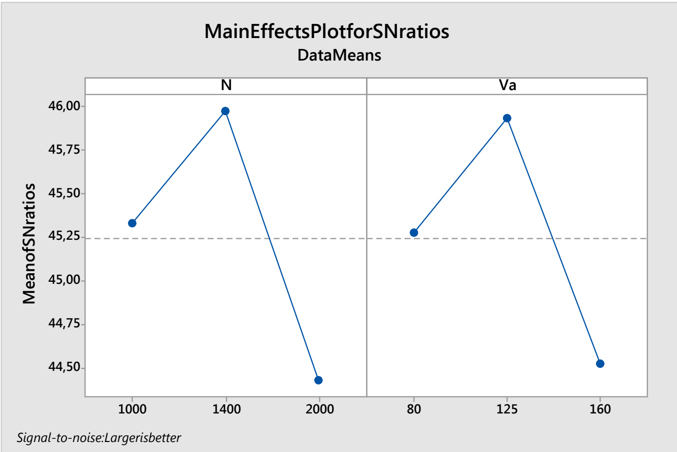

Figure 2 S/N ratio plot for UTs response

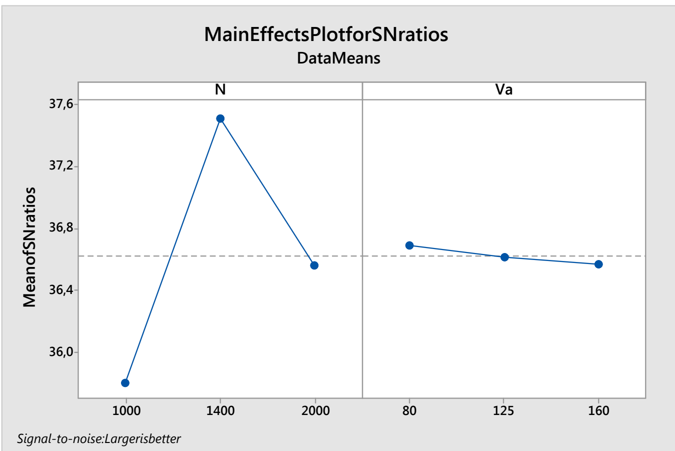

Figure 3 S/N ratio plot for HV response

The obtained tensile strength and hardness were converted into S/N ratio. The experimental results and calculated S/N ratio values are tabulated in Table 5. S/N ratio against the design factors as obtained by the Minitab Software is shown in Fig. 2 and Fig. 3. Therefore, optimal level of process parameter is at the level of highest S/N ratio, which indicate that the tensile strength was maximum while using the parameters level of 1400 rpm spindle speed, and a welding speed of 125 mm/min. Also for a maximum hardness of the joint by using parameters of 1400 rpm spindle speed and a welding speed of 160 mm/min.

3.1.2. *Analysis of variance (ANOVA)*

The main purpose of the ANOVA test is to identify the effect of individual factors on the process response [16]. The Analysis of variance ANOVA for responses has been performed to identify statically significant process parameters that affect tensile strength and hardness of FSW joints as shown in Table 6. The Taguchi experimental method could not judge the effect of individual parameters on the entire process. In this study, the analysis of variance is conducted at a confidence level of 95%. The significance of control factors in ANOVA is determined by comparing the F values of each control factor.

The results of the analysis of variance for the tensile strength and the hardness show that the rotational speed is the factor which represents the great effect on the total variation of the tensile limit and hardness. The F-ratio for tensile strength was 2.86 for the rotational speed followed by welding speed F-ratio = 2.35. Also the analysis of variance for the hardness show that the both factors have an effect on the response with the highest significant is by the rotational speed F-ratio = 4.31 and 0.02 for the welding speed.

Table 6 ANOVA results for Tensile Strength and Hardness

Source	Sum of squares	Df	Mean square	F-Ratio	P-Value
For the tensile strength (UTs)					
N	1449	2	724.7	2.86	0.169
WS	1191	2	595.4	2.35	0.211
Error	1013	4	253.2		
Total	3653	8			
R^2= 72.27 %			R^2(Adj)= 44.55 %		
For the hardness (HV)					
N	276.020	2	138.010	4.31	0.100
WS	0.980	2	0.490	0.02	0.985
Error	128.040	4	32.010		
Total	405.040	8			
R^2= 68.39 %			R^2(Adj)= 36.78 %		

The R-squared statistic indicates that the model as fitted explains 72.27% of the variability in (UTs) and 68.39% in (HV). The adjusted R-squared statistic, which more suitable for comparing models with different numbers of independent variables, is 44.55% for the (UTs) and 36.78% for (HV).

The Fig. 4 shows the normal probability of the model residues for the tensile strength (UTs), it is found that the residuals adjust a little randomly in a straight line, which explains an abnormal distribution of errors and consequently the model is less significant. Also Fig. 5 shows the normal probability of model residuals for hardness (HV), we find that the residuals fit reasonably in a straight line, which allows us to conclude that the errors have a normal distribution and therefore the model is significant.

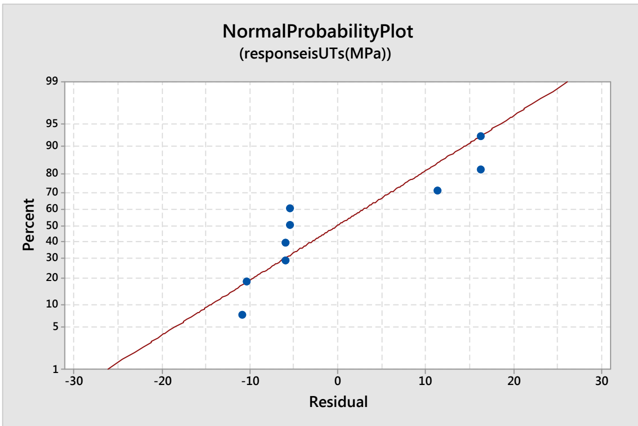

Figure 4 Normal probability curve of (UTs)

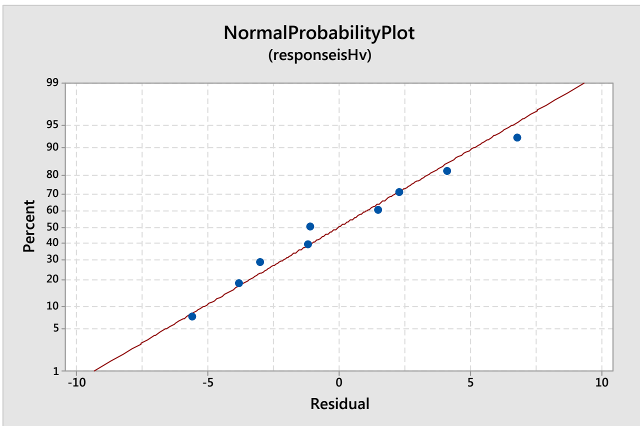

Figure 5 Normal probability curve of (HV)

3.2. *Effect of process parameters on (UTs) and (HV)*

Contour plots play a very important role in the study of the responses analysis, it was a mean for optimizing the parameters of friction stir welding. At first we can observe that the best Tensile Strength and Hardness values are in the dark green colored areas in the both contour plots Fig. 6, Fig. 7.

3.2.1. *Effect on Tensile Strength (UTs)*

The Fig. 6 shows that the optimum values of the Tensile Strength (UTs) is exhibited for values of (N) around [1300 to1950] rpm and for values of (WS) around [110 to160] mm/min. we notice that with increasing rotation speed, the Tensile Strength increases. Indeed, at a higher rotational speed, the heat generated by friction is higher. This heat gives rise to more intense agitation and mixing of metal flow, which gives strengthening to the joint. An increase in the welding speed affects the tensile strength of the joint, this may be associated with the decrease in heat input into the HAZ.

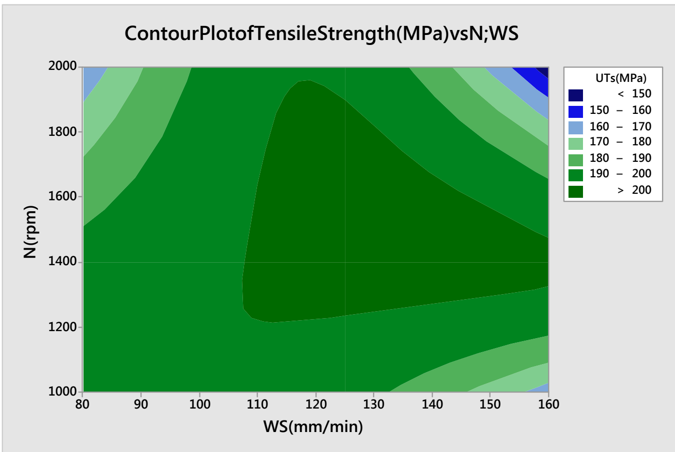

Figure 6 Contour plot for the effect of rotational speed and welding speed on tensile strength

3.2.2. *Effect on Hardness (HV)*

The Fig. 7 shows the effect of the rotational speed (N) and welding speed (WS) on the Hardness of the joint, it was found that with the increase of the rotational speed the hardness increase due to a grain refining which result a structural hardening. Thus the increase of the welding speed results in a decrease in the thermal exposure which increase in the hardness and strength of the welded joint. The optimum values of the Hardness (HV) is exhibited for values of (N) around [1300 to1650] rpm and for values of (WS) around [130 to160] mm/min.

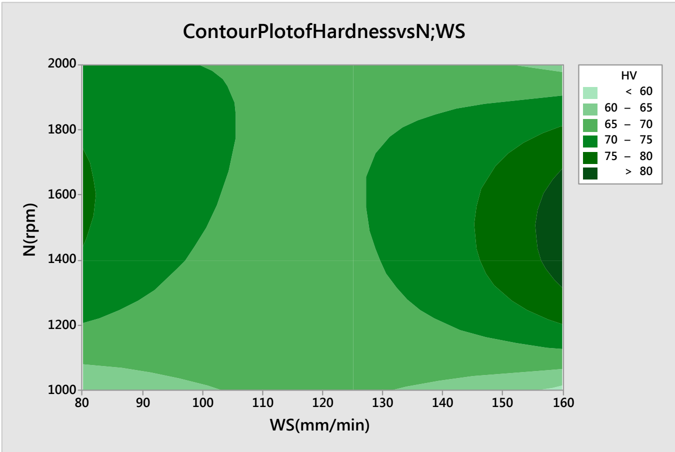

Figure 7 Contour plot for the effect of rotational speed and welding speed on hardness of the joints

4. Conclusion

Experiments were conducted for various combinations of tool rotational speed and welding speed at three levels in Taguchi's orthogonal array. The strength of the joints was analyzed by tensile and hardness test.

The following observations were made from the studies:

1. Taguchi's orthogonal array has been successfully used to find the optimum level setting of process parameters

2. The optimum process parameters levels which are found to achieve greater tensile strength are such, 1400 rpm tool rotational speed and 125 mm/min welding speed. It was found that the combination of 1400 rpm tool rotational speed and 160 mm/min result a maximum hardness values.

3. According to the Analysis of Variance results, both of rotational speed and the welding speed significantly affect the mechanical properties of the friction stir welded joints, with the most influencing parameters is the rotational speed followed by the welding speed, also the ANOVA test for Hardness response show that the rotational speed have the most influence more than the welding speed.

4. Contour plots are drawn to study the interaction effect of the welding speed and the rotational speed on the Tensile Strength and the Hardness of the friction stir welded joints.

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