ELSEVIER
Available online at www.sciencedirect.com
ScienceDirect
Procedia Engineering 64 (2013) 1227 – 1234
Procedia Engineering
www.elsevier.com/locate/procedia

International Conference On DESIGN AND MANUFACTURING, IConDM 2013

Comment [S1]: Elsevier to update with vo and page numbers.

An experimental analysis and optimization of process parameter on friction stir welding of AA 6061-T6 aluminum alloy using RSM

G. Elatharasan[a],V.S. Senthil Kumar[b] *

[a]*Research Scholar, Department of Mechanical Engineering, CEG, Anna University, Chennai– 600025.Tamilnadu,India*
[b]*Associate Professor, Department of Mechanical Engineering, CEG, Anna University, Chennai – 600025.Tamilnadu,India*

Abstract

Friction stir welding (FSW) process is an emerging solid state joining method in which the material that is being welded does not melt and recast. The welding parameters such as tool rotational speed, welding speed and axial force plays a major role in deciding the joint characteristics. In this investigation central composite design technique and mathematical model was developed by response surface methodology with three parameters, three levels and 20 runs, was used to develop the relationship between the FSW parameters (rotational speed, traverse speed, axial force,) and the responses (tensile strength, Yield strength (YS) and %Elongation (%E) were established.

*Keywords:*FSW; aluminium alloy; response surface methodology;tensile strength;ANOVA

1. Introduction

Friction Stir Welding (FSW) has emerged as a new solid state joining technique. FSW was invented by The Welding Institute (TWI) in 1991 [1], especially for aluminum alloys [2,3]. The process as shown in Fig. 1, requires lower energy than conventional fusion welding processes [4,5] and no consumables such as electrodes and

* Corresponding author. Tel.: 944495248;
*E-mail address:*vssk70@gmail.com

doi:10.1016/j.proeng.2013.09.202

protecting gases are needed [6,7] and have been successfully applied to the aerospace, automobile, shipbuilding industries, etc. In this process a rotating tool is inserted into the butt of the workpiece due to the action of the axial pressure it produces a highly plastically deformed zone through the associated stirring action. Studies report that the maximum temperature in the material being welded is usually less than 80% of its melting temperature [8]. Jayaraman et al. [9] developed an empirical relationship to predict the tensile strength the friction stir welded cast aluminium alloy using RSM Rajakumar et al. [10] proposed models using RSM to predict tensile strength of FSW joints of AA 7075 Al alloy. Lakshminarayanan et al. [11] also studied the effect of FSW welding parameters on the tensile strength of butt joints made of AA7039 aluminium alloys using Taguchi parametric design approach. Therefore in this paper to employ RSM to develop empirical relationships relating the FSW input parameters rotational speed, welding speed, axial force[12] and the three output responses ultimate tensile strength (UTS), Yield strength (YS) and %Elongation(%E) to find the optimal operating parameters.

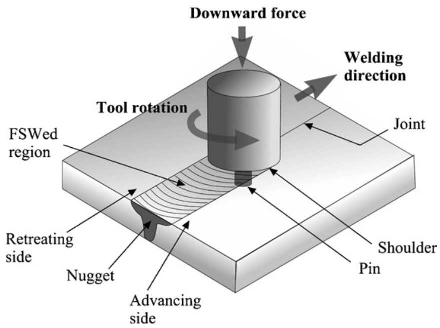

Fig 1. The friction stir welding process.

2. Experimental work

2.1. Fabricating the joints and preparing the specimens

The material used in this investigation was AA6061-T6. The chemical composition of base metals are presented in Table 1.The rolled plates of 6 mm thickness were machined to the required size (100 mm X 50 mm) welding was carried out in butt joint configuration using friction stir welding machine. The welding direction was aligned normal to the rolling direction, the welded joints were machined to the required dimensions as shown in Fig. 2. Tensile specimens were fabricated as per the American Society for Testing of Materials (ASTM E8M-04) standards [13] to evaluate the tensile properties of the joints. As prescribed by the design matrix, totally twenty joints of each alloy were fabricated in this investigation. The photographs of some of the fabricated joints are displayed in Fig. 3.

Table 1- Nominal chemical composition of alloys used in this investigation.

Element	Mg	Mn	Zn	Fe	Cu	Si	Cr	Al
AA6061-T6	0.84	0.01	0.06	0.40	0.24	0.54	0.18	Bal

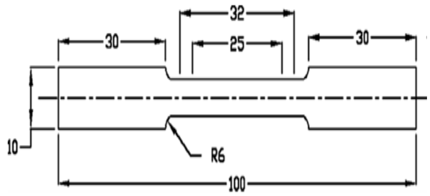

Fig 2. Dimensions of tensile specimen

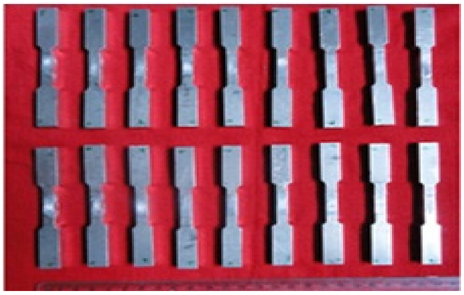

Fig 3. Photograph of tensile specimens

2.2 Design of experiments

Response surface methodology (RSM) [14] is an interaction of mathematical and statistical techniques for modelling and optimizing the response variable models which several independent variables influence a dependent variable or response and the goal is to optimize the response [15] Experiments have been carried out according to the experimental plan based on central composite rotatable second-order design (CCD)matrix with the star points being at the center of each face of factorial space was used,. The upper limit of a factor was coded as +1, and the lower limit was coded as –1. The "face-centered CCD" involves 20 experimental observations at three independent input variables. The experimental Friction stir welding parameters and their levels in this study in the actual form is given in Table 2

Table 2. An example of a table.

Parameter	Level		
	-1	0	-1
A:Axial Load (kN)	6	8	10
B:Welding Speed (rpm)	800	1000	1200
C: Traverse speed (mm/min)	30	60	90

3. Results and Discussion

3.1 Developing the mathematical model

The adequacy of the developed empirical relationship for the response variables UTS, YS and %E was tested using the analysis of variance (ANOVA) technique [15]. The experimental Friction stir welding parameters and their levels in this study in the actual form is given in Table 3. The fit summary reveals that the fitted quadratic model is statistically significant to analyze the response variables. It is found that the calculated F ratios are larger than the tabulated values at a 95% confidence level; hence, the models are considered to be adequate. Another criterion that is commonly used to illustrate the adequacy of a fitted regression model is the coefficient of determination (R^2). Which compares the range of the predicted value at the design point to the average prediction error, the values form of analysis of variance (ANOVA) obtained are given in the table 4.

$$\mathbf{UTS} = +166.39 + 3.80 * \mathbf{A} + 8.30 * \mathbf{B} - 13.70 * \mathbf{C} - 1.00 * \mathbf{A} * \mathbf{B} - 6.75 * \mathbf{A} * \mathbf{C} - 5.00 * \mathbf{B} * \mathbf{C} - 14.45 * \mathbf{A}^2 - 7.95 * \mathbf{B}^2 + 11.05 * \mathbf{C}^2 \quad (1)$$

$$\mathbf{YS} = +149.56 + 4.10 * \mathbf{A} + 5.70\mathbf{B} - 12.20 * \mathbf{C} + 0.37 * \mathbf{A} * \mathbf{B} - 5.38 * \mathbf{A} * \mathbf{C} - 3.63 * \mathbf{B} * \mathbf{C} - 13.41 * \mathbf{A}^2 - 12.41 * \mathbf{B}^2 + 15.09 * \mathbf{C}^2 \quad (2)$$

$$\%\mathbf{E} = +6.40 - 0.080 * \mathbf{A} - 0.11 * \mathbf{B} - 0.99 * \mathbf{C} + 0.31 * \mathbf{A} * \mathbf{B} - 0.41 * \mathbf{A} * \mathbf{C} + 0.26 * \mathbf{B} * \mathbf{C} - 0.15 * \mathbf{A}^2 + 0.50 * \mathbf{B}^2 - 0.70 * \mathbf{C}^2 \quad (3)$$

Table 3 Design layout and Experimental results

Exp.No	A:Axial Load (kN)	B:Rotational Speed (rpm)	C:Traverse speed (mm/min)	UTS (Mpa)	YS (Mpa)	% E
1	8	1000	60	138	129	6.9
2	8	1000	60	142	130	7.3
3	6	800	90	135	125	4.2
4	6	1200	90	148	136	5.8
5	10	1200	30	198	178	7.2
6	10	800	90	137	130	5.0
7	8	1000	60	153	145	6.2
8	8	1000	60	159	146	6.8
9	8	800	60	137	130	5.0
10	6	800	30	130	122	4.8
11	8	1000	90	145	132	4.5
12	10	1200	90	191	154	6.3
13	8	1200	60	190	159	6.5
14	6	1200	30	193	151	6.4
15	10	800	30	158	142	4.5
16	10	1000	60	163	151	5.5
17	8	1000	30	176	163	6.4
18	6	1000	60	190	159	6.5
19	8	1000	60	145	135	7.3
20	8	1000	60	140	130	7.0

3.1. Effect of Process Parameters on UTS

The plot for the response UTS of joint is illustrated in Fig. 4. This plot provides the response surface and shows the change of UTS while each FSW parameters moves from the reference value. Fig. 4a–c illustrates the counter plots presenting the interaction effect of any two input parameters on the UTS where the other parameters are on their center level. The increase in tool rotational speed, and tool axial force result in the increase in UTS of the FS welded joints up to a maximum value, where the decrease in welding speed result in the increase in UTS.

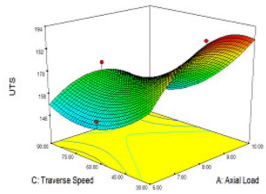

Fig. 4(a)

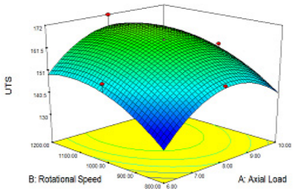

Fig. 4(b)

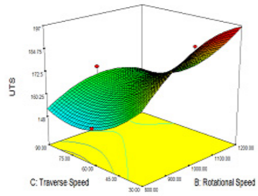

Fig. 4(c)

Fig. 4 (a), (b) and (c) shows the response of Rotational Speed, Welding Feed and Axial Load on UTS

3.2. Effect of Process Parameters on YS

The plot for the 3D response YS of joint is illustrated in Fig.5. Fig. 5 a–c illustrates the counter plots presenting the interaction effect of any two input parameters on the YS. The higher rotational speeds, lower welding speeds and higher axial forces result to elimination of the defects in WZ of the joints due to enough friction and plastic flow of material and so the YS is higher.

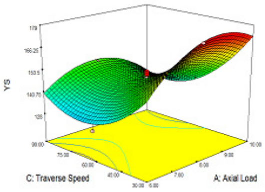

Fig.5 (a)

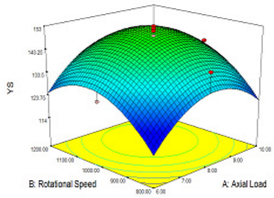

Fig. 5(b)

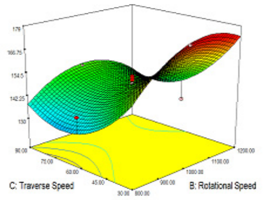

Fig. 5(c)

Fig. 5 (a), (b) and (c) shows the response of Rotational Speed, Welding Feed and Axial Load on YS

3.3. Effect of Process Parameters on %E

The response %E of joints is illustrated in Fig 6 As can be seen from Fig 6a–c, the increase in tool rotational speed and tool axial force result in the increase in TE of the FS welded joints continuously where the decrease in welding speed result in the increase in TE. Increasing the tool rotational speed and axial force, and decreasing the welding speed lead to elimination of the defects in WZ of the joints due to enough friction and plastic flow of material and so, the TE is higher.

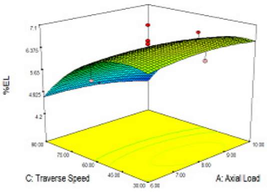

Fig. 6(a)

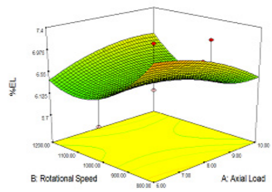

Fig. 6(b)

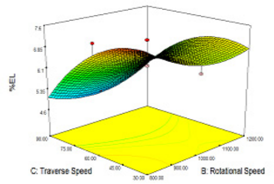

Fig. 6(c)

Fig. 6 (a), (b) and (c) shows the response of Rotational Speed, Welding Feed and Axial Load on % E

3.4 Optimization of parameters of FSW on responses

One of the most important aims of this investigation was to maximize the UTS, YS and % E of FS welded joints of AA 6061-T6 and also, find the optimum process parameters[16] from the mathematical model developed. Derringer and Suich describes a multiple response method called desirability this method used to solve multiple-response optimization problems, combines multiple responses into a dimensionless measure of performance called the overall desirability function. In which the desirability ranges between 0 and1.The predicted optimal results from above technique are UTS,YS and TE that can be obtained, are 197.50MPa,175,25 MPa and 6.96% respectively. Using Design Expert software gives the combined desirability value of 0.91.

Table-4ANOVA table for response surface model

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
For UTS						
Model	4458.52	9	495.39	44.36	< 0.0001	significant
Residual	111.68	10	11.17			
Lack of Fit	108.35	5	21.67	32.50	0.0008	
Pure Error	3.33	5	0.67			
Std. Dev.	3.34			R-Squared	0.9756	
Mean	160.70			Adj R-Squared	0.9536	
C.V. %	2.08			Pred R-Squared	0.8676	
PRESS	605.11			Adeq Precision	23.486	
For YS						
Model	3787.05	9	420.78	13.48	0.0002	significant
Residual	312.15	10	31.22			
Lack of Fit	268.82	5	53.76	6.20	0.0334	
Pure Error	43.33	5	8.67			
Cor Total	4099.20	19				
Std. Dev.	5.59			R-Squared	0.9239	
Mean	144.20			Adj R-Squared	0.8553	
C.V. %	3.87			Pred R-Squared	0.4876	
PRESS	2100.55			Adeq Precision	13.654	
For %E						
Model	13.40	9	1.49	7.70	0.0019	significant
Residual	1.93	10	0.19			
Lack of Fit	1.30	5	0.26	2.05	0.2242	
Pure Error	0.63	5	0.13			
Cor Total	15.33	19				
Std. Dev.	0.44			R-Squared	0.8739	
Mean	6.22			Adj R-Squared	0.7603	
C.V. %	7.07			Pred R-Squared	0.2462	
PRESS	**11.56**			**Adeq Precision**	**10.580**	

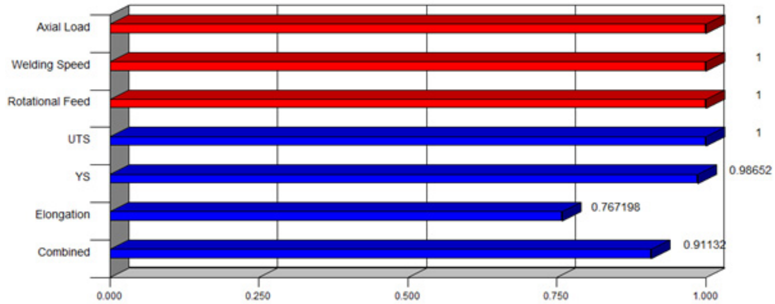

Fig. 7 Bar graph showing the maximum desirability of 0.91 for the combined objective

4. Conclusion

In this study, the UTS, YS and TE in FSW process were modelled and analyzed through response surface methodology (RSM). A central composite design (CCD) in RSM consisting of three variables. Rotational speed, traverse speed and axial force have been employed to carry out the experimental study. Analysis of variance (ANOVA) was applied to study; the following points can be concluded:

- Empirical relationship were developed to estimate the Ultimate tensile strength, Yield strength and tension Elongation of friction stir welded AA 6061-T6 aluminium alloy. The ANOVA analysis showed that the developed model can be effectively used to predict the UTS,YS and TE of the joints at 95% confidence level.
- UTS and YS of the FS welded joints increased with the increase of tool rotational speed, welding speed and tool axial force up to a maximum value, and then decreased.
- TE of joints increased with increase of rotational speed and axial force, but decreased by increasing of welding speed, continuously.
- A maximum tensile strength of 197.50 MPa, Yield strength of 175.25MPa and % of Elongation of 6.96 was exhibited by the FSW joints fabricated with the optimized parameters of 1199 r/min rotational speed, 30 mm/min welding speed and 9.0 kN axial force.

References

[1] Thomas, W. M., Nicholas, E. D., Needham, J . C., Murch, M. G.,Templesmith P., And Dawes, C. J. 1991. Friction Stir Butt Welding, U.S. Patent No. 5 460 317.
[2] Franchim, A.S., Fernandez F.F., Travessa, D.N., 2011.Microstructural aspects and mechanical properties of friction stir welded AA2024-T3 aluminium alloy sheet. Mater Des;32 pp.4684–4688.
[3]Rajakumar, S., Muralidharan, C., Balasubramanian, V. 2011.Predicting tensile strength, hardness and corrosion rate of friction stir welded AA6061-T6 aluminium alloy joints. Mater Des; 32:pp.2878–90.
[4] Mahoney, M.W., Rhodes, C.G., Flintoff, J.G., Spurling RA., Bingel WH. 1998. Properties of friction stir welded 7075 T651 aluminium. Metall Mater Trans A 1998;29:1955–64.
[5] Colligan, K., 1999.Material flow behaviour during friction stir welding of aluminium. Weld J;7pp.229–37.
[6] Arbegast, W.J., Mishra, R.S., Mahaney,M.W. 2007. Friction Stir Welding and Processing, ASM International, Materials Park, OH, , pp. 273–308.
[7] Won Bae Lee., Yun-Mo Yeon., Seung-Boo Jung., 2004. Mechanical properties related to micro structural variation of 6061 Al alloy joints by friction stir welding. Mater Trans; 45pp, 1700–1705.
[8] Chao, YJ., Qi X., 1998.Thermal and thermo-mechanical modeling of friction stir welding of aluminium alloy 6061–T6. J Mater Proc Manf Sci;7 pp.215–33
[9] Jayaraman, M., Sivasubramanian, R., Balasubramanian, V., Lakshminarayanan, AK., 2008. Prediction of tensile strength of friction stir

welded A356 cast aluminium alloy using response surface methodology and artificial neural network. J Manuf Sci Prod Res;9 pp.1–21.
[10] Rajakumar, S., Muralidharan, C., Balasubramanian ,V., 2010.Optimization of the frictionstir- welding process and the tool parameters to attain a maximum tensile strength of AA7075-T6 aluminium alloy. J Eng Manuf;224pp.1175–91.
[11] Lakshminarayanan, AK., Balasubramanian, V., 2008. Process parameters optimization for friction stir welding of RDE-40 aluminium alloy using Taguchi technique. Trans Nonferr Metal Soc China;18 pp.548–54.
[12] Sundaram, N.S., Murugan, N., 2010. Tensile behavior of dissimilar friction stir welded joints of aluminium alloys. Mater Des;31pp.4184–93.
[13] ASTM E8M-09. 2009, American society for testing and materials (ASTM). In: Standard test methods for tension testing of metallic materials, vol. 03.01.West Conshohocken (PA): Annual book of ASTM standards.
[14] Cochran, Cox, G M., 1962. Experimental design [M]. New Delhi: Asia Publishing House.
[15] Miller, J E., Freund, Johnson, R., 1996. Probability and statistics for dngineers [M]. New Delhi: Prentice Hall.