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Evaluation of Ultimate Tensile Strength Parameters in Dissimilar Friction Stir Welded Joints Using Box-Behnken Experimental Design

S.Ravikumar[1, a*], V.SeshagiriRao[2, b], V.Pranesh[3, c]

[1]*Department of Mechanical and Production Engineering, Sathyabama University, Chennai, Tamilnadu, India*

[2]*Department of Mechanical Engineering, St. Joseph's College of Engineering, Chennai, Tamilnadu, India*

[3]*Under graduate student, Department of Mechanical and Production Engineering, Sathyabama University, Chennai, Tamilnadu, India*

[a]mahailakumar@gmail.com,[b]raosvaddi@hotmail.com,[c]pranesh.rv20@gmail.com

***Abstract**. This paper presents a mathematical model and optimization for dissimilar friction stir welded joints between AA6061-T651 and AA7075-T651 aluminium alloys which are widely used in aircraft and aerospace industries. Design of experiments has been used to study the effects of the welding parameters such as rotational speed, welding speed, and pin profiles (input data's) used on the prediction of ultimate tensile strength (output response) on welding of dissimilar aluminium alloys. The effect of these parameters on ultimate tensile strength has been investigated using Box-Behnken experimental design. Response contours were constructed for determining the optimum welding condition for the required tensile strength. The developed model establishes a correlation between rotational speeds, welding speeds and three pin profiles that influence the tensile strength of dissimilar FSW. Analysis of variance (ANOVA) is employed to study the tensile strength characteristics in welding operation of dissimilar alumimium alloys. The analysis of variance showed high coefficient of determination (R^2) value of 0.9995 for ultimate tensile strength, thus ensuring a satisfactory adjustment of the second order regression model with experimental data. The ultimate tensile strength of the predicted model during the confirmatory test has well within the tolerable limits.*

***Keywords**: Dissimilar friction stir welding, Aluminium alloys, Pin profiles, Analysis of variance (ANOVA), Box-Behnken design, Contour plots, Response surface methodology.*

Introduction

Friction stir welding process is a solid state joining technique considered to be the significant development over the past two decades which was invented and validated at the welding institute (TWI), United Kingdom in the year 1991[1]. In this process no melting occurs and the heat is generated internally by means of friction between the material-tool interface and the plastic deformation takes place without pre or post heating. FSW is immune to the defects and property deteriorations associated with the fusion welding such as melting and coarsening of strengthening phases [2].Materials with different aluminum alloys can be welded together with a least alteration in mechanical properties due to no melting [3]. Joints between dissimilar materials of 6061-T6 and 7075-T6 in aerospace structures mostly made by riveting which causes stress concentration and increase the weight of the final joints. Dissimilar welding of aluminium alloys is a core demand of the aircraft industries to substitute the traditional joining technologies with low costs and high efficiency ones such as friction stir welding in the future advanced design. Numerous papers can be found in the literature on various studies related to FSW of dissimilar aluminium alloys. The present research work focuses on the development of mathematical model to predict tensile strength for dissimilar friction stir welded joints of aluminium alloys AA6061-T651 and AA7075-T651. Generally, the Response Surface Methodology (RSM) has been used to analyze the effects of various process parameters ([5]-[13]). In this paper, RSM is used to obtain optimum values of the process parameters namely tool rotational speed, welding speed and pin profiles to predict tensile strength by developing a mathematical model to ascertain the significant coefficients at 95% confidence level. The ANOVA technique is used for testing the developed model for their adequacy and accuracy. Further, confirmatory experiments are conducted to validate the fitness of the developed model.

Experimental work

Aluminium alloys of AA6061-T651 and AA7075-T651 are selected to fabricate dissimilar joints using the FSW process. T651, for the above alloys, indicates that both the materials are solution heat treated, stretched and artificially aged. The length, width and thickness of both the aluminium alloy plates are chosen as 100, 50 and 6.35 mm respectively. Chemical compositions and the mechanical properties of AA6061-T651 and AA7075-T651 are given in Tables 1 and 2 respectively.

Table 1
Chemical composition of base aluminium alloys

Base alloys	Al	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti
6061-T651	97.16	0.8	0.4	0.27	0.09	0.96	0.21	0.01	0.06	0.02
7075-T651	89.76	0.05	0.1	1.3	0.03	2.69	0.2	0.01	5.78	0.06

The high strength aluminium alloy AA7075-T651 is placed at the RS and the aluminium alloy AA6061-T651, weaker alloy when compared with AA7075-T651, is positioned at the AS as the weaker alloy weakens the fabricated weld when kept at RS [4]. The process parameters that have greater influence on the tensile strength of dissimilar FSW joints are identified as rotational speed (*R*), welding speed (*W*) and tool pin profile (*P*). All the three tools made of H13 tool steel, with different profiles namely Simple Square (SS), Taper Cylindrical Threaded (TCT) and Taper Square Threaded (TST). Trail experiments are conducted to determine the working and feasible range of process parameters. The influenced process parameters and their working range for the dissimilar FSW of AA6061-T651 and AA7075-T651 are presented in Table 3. In the present study, the three-level and three-factorial Box-Behnken experimental design is chosen for finding out the relationship between the response (ultimate tensile strength) and the variables (welding parameters) ([12], [15] and [16]).

Table 2
Mechanical properties of base aluminium alloys

Aluminium alloys	Yield strength, (MPa)	Ultimate tensile strength, (MPa)	Tensile elongation, (%)	Micro hardness (VHN)
6061-T651	287.0	303.0	17.2	102.0
7075-T651	526.0	583.0	11.3	171.0

The high strength aluminium alloy AA7075-T651 is placed at the RS and the aluminium alloy AA6061-T651, weaker alloy when compared with AA7075-T651, is positioned at the AS as the weaker alloy weakens the fabricated weld when kept at RS [4]. The process parameters that have greater influence on the tensile strength of dissimilar FSW joints are identified as rotational speed (*R*), welding speed (*W*) and tool pin profile (*P*). All the three tools made of H13 tool steel, with different profiles namely Simple Square (SS), Taper Cylindrical Threaded (TCT) and Taper Square Threaded (TST). Trail experiments are conducted to determine the working and feasible range of process parameters.

The influenced process parameters and their working range for the dissimilar FSW of AA6061-T651 and AA7075-T651 are presented in Table 3. In the present study, the three-level and three-factorial Box-Behnken experimental design is chosen for finding out the relationship between the response (ultimate tensile strength) and the variables (welding parameters) ([12], [15] and [16]).

The actual design matrix is given in Table IV. Dissimilar FSW experiments are conducted according to this design. The ultimate tensile strength of each plate is obtained from the average values of the three tensile specimens. The development of a mathematical model and the statistical analysis are both performed by Design-Expert statistical software package.

Development of Mathematical model

Box-Behnken Design and the Response Equation

Response surface methodology is the collection of mathematical and statistical techniques that are useful for the modeling and analysis of problems in which a response of interest is influenced by several variables and the objective is to optimize this response. It also quantifies the relationship between the controllable input parameters and the obtained response surfaces [14].The Box-Behnken design is an independent quadratic design, that does not contain an embedded factorial or fractional factorial design [15]. For three factors, the Box-Behnken design offers some advantages in requiring a fewer number of runs [16]. The experiments were carried out as per RSM Box-Behnken experimental design [17]. The response function representing the Ultimate Tensile Strength (UTS) of the dissimilar friction stir welded joints is

functions of tool rotational speed (*R*), welding speed (*W*) and tool pin profile (*P*) which can be expressed as Eq. 1.

$$\mathrm{UTS} = f\,(R, W, P) \qquad (1)$$

The quadratic polynomial regression equation to represent the response surface 'y' for k factors is expressed [18] as Eq. 2

$$y = b_0 + \sum b_i\, x_i + \sum b_{ij}\, x_i x_j + \sum b_{ii}\, x_i^2 \qquad (2)$$

where b_0 is the intercept term, b_i is the linear term, b_{ii} is the quadratic term and b_{ij} is the interaction term. The response (UTS) equation can be expressed as

Table 3
Dissimilar friction stir welding parameters and the selected levels

S. No	Operating parameter	Symbol	Unit	Levels		
				Low (-1)	Middle (0)	High (1)
1	Tool rotational speed	*R*	(rpm)	800	900	1000
2	Welding speed	*W*	(mm/min)	90	100	110
3	Tool pin profile	*P*	-	SS	TCT	TST

Eq. 3

$$UTS = b_0 + b_1R + b_2W + b_3P + b_{12}RW + b_{13}RP + b_{23}WP + b_{11}R^2 + b_{22}W^2 + b_{33}P^2 \quad (3)$$

By applying multiple regression analysis on the design matrix and the response values, the following second-order polynomial equation in the actual form is established and is given as

Eq. 4

$$UTS = -2369.7 + 3.3495R + 19.8875W + 60.475P - 3.75 \times 10^{-3}RW + 0.0625RP - 0.3WP - 1.715 \times 10^{-3}R^2 - 0.079W^2 - 21.4P^2 \quad (4)$$

Checking the adequacy of the model developed

The mathematical model developed is used to predict the strength of the welded joint for various process parameters considered in this work. The predicted tensile strength from the model and the experimental values for the 17 runs are presented in Table IV. The variance was 9068analyzed (ANOVA) to test the significance of fit of the polynomial equation as given in Table V. A highly significant F-value for the model reveals the adequacy of the relation between the response and the process variables. Any term in the model with $p < 0.05$ is considered as significant. Therefore *R, W, P, RW, RP, WP,* R^2, W^2, P^2 are significant and the "lack of fit" is not significant.

Table 4
Box-Behnken Design Matrix and Experimental Results

Trial run	Process parameters			UTS (MPa)	
	R	*W*	*P*	Experimental	Predicted
1	1	0	-1	160	160.13
2	0	0	0	205	204.8
3	0	1	1	175	174.75
4	0	0	0	205	204.8
5	1	-1	0	184	183.63
6	0	0	0	205	204.8
7	0	0	0	204	204.8
8	-1	1	0	183	183.38
9	0	-1	-1	170	170.25
10	-1	-1	0	174	173.63
11	-1	0	-1	170	170.13
12	-1	0	1	160	159.88
13	0	-1	1	178	178.5
14	1	0	1	175	174.88
15	1	1	0	178	178.38
16	0	0	0	205	204.8
17	0	1	-1	179	178.5

The coefficient of determination (R^2) of the model is 0.9995 and the adjustable determination coefficient (adjusted.R^2) is 0.9988, which reveals the fitness of the developed model. The higher value of R^2 and lower values of the standard error of the model indicate that the regression model is quite adequate to predict the response. It is observed that the calculated F-ratio values are greater than the tabulated values at 95% confidence level which implies the model is adequate. Further, the validity of the model is tested by drawing scatter diagram which is given as Fig 1. The ultimate tensile strength values obtained through experiment and mathematical model show good agreement.

Validation of the Developed Model

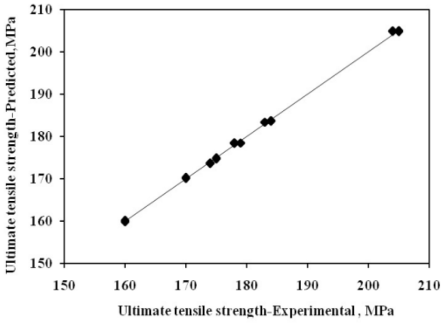

Fig.1. Scatter Diagram of the Developed Model for Ultimate Strength

Experiments are conducted to verify the developed regression model equation. Five experimental runs are made using different combination of parameters other than the design matrix combinations. Experimental values of the response are compared with the predicted values as given in Table 6 and the deviation is within ± 10% which shows the fitness of the developed empirical equation.

Table 5
Variance analysis of the second-order polynomial equation

Source	Sum of squares	Df	Mean square	F-value	p-value prob>F	Remark
Model	4046.89	9	449.65	1535.4	<0.0001	significant
R	12.5	1	12.5	42.68	0.0003	
W	10.12	1	10.12	34.57	0.0006	
P	10.13	1	10.13	34.57	0.0006	
RW	56.25	1	56.25	192.07	<0.0001	
RP	156.25	1	156.25	533.54	<0.0001	
WP	36	1	36	122.93	<0.0001	
R^2	1238.41	1	1238.41	4228.7	<0.0001	
W^2	262.78	1	262.78	897.29	<0.0001	
P^2	1928.25	1	1928.25	6584.3	<0.0001	
Residual	2.05	7	0.29			
Lack of fit	1.25	3	0.42	2.08	0.2451	not significant
Pure error	0.8	4	0.2			
Cor.total	4048.94	16				

Table 6
Results of Confirmatory Experiments

S.No	Parameters			Experimental values	Predicted values
	R	*W*	*P*	UTS (MPa)	UTS (MPa)
1	0.75	0.5	-1	166.23	167.56
2	-0.25	0.25	0	204.32	203.44
3	0.5	0.75	1	177.12	176.73
4	0.25	-0.25	0	172.85	173.55
5	-0.75	-0.5	-1	169.24	170.92

Results and discussions

From the regression model developed, the effects of welding process parameters namely tool rotational speed and welding speed on ultimate tensile strength of dissimilar friction stir welded joints are evaluated for various tool pin profiles. 3D response surface graphs and contour plots are formed by considering one parameter in the middle level and the other two parameters as variables (see Fig 2).

Rotational Speed (R)

The effect of rotational speed on tensile strength for various welding speed and pin profiles considered can be observed from Fig 2(a) to (d). For any particular welding speed, the tensile strength increases first, reaches a maximum value and then decreases with increasing the rotational speed as shown in Fig 2(a). Similar trend is observed for the tool pin profiles considered, as shown in Fig 2(c), ascending from SS, TCT and TST tools. Generally, the tensile strength is poor at lower rotational speeds due to inadequate tool stirring action. When the speed of the tool is increased to 900 rpm, the strain hardening effect induced by tool stirring action increases the tensile strength. The significant contribution of rotational speed of the tool in the development of the model is 30.58%.

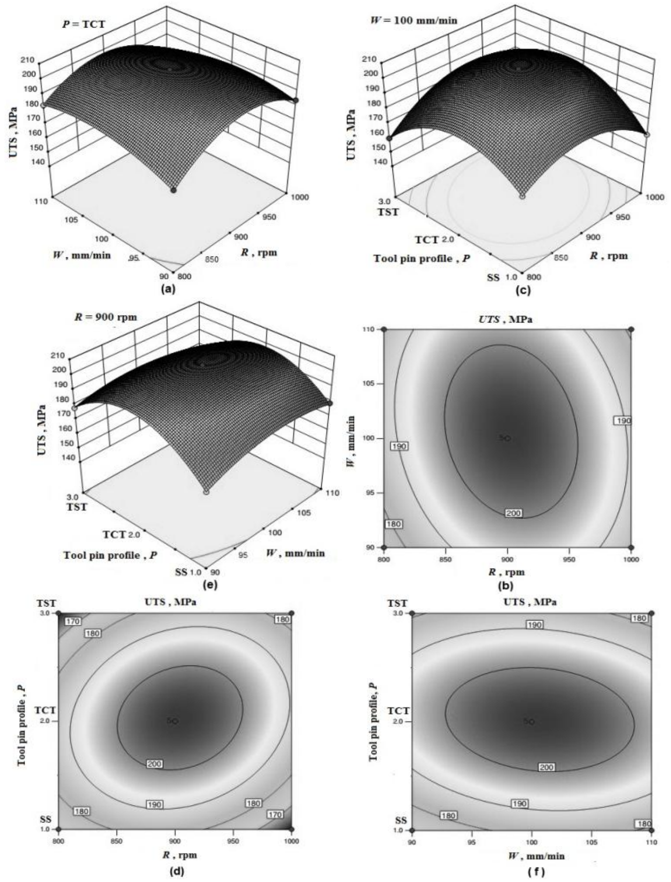

Fig.2. Response Surface Graphs (a,c,e) and its contour plots (b,d,f)

Welding Speed (W)

For a given rotational speed, the increase of welding speed increases the tensile strength to a certain value, as shown in Fig 2(a) and (b), and further increase of welding speed results in decrease of tensile strength. Similar behaviour can be observed from the Fig 2(e) and (f) for welding speed against three different pin profiles. For lowest (90 mm/min) and highest (110 mm/min) welding speeds, lower tensile strengths are observed. The lower welding speed significantly deteriorates the mechanical properties of joints due to larger heat input into the weld samples, however as the welding speed increases, the thermal cycles effect is minimized which leads to an increase in tensile strength. For all the welding speeds, the TCT tool exhibits higher tensile strength is observed. The significant contribution of welding speed of the tool in the development of the model is 6.49%.

Tool Pin Profile (P)

The effect of tool pin profiles on tensile strength for the range of welding speed and rotational speed considered for the present study can be observed from Fig 2(c) to (f). The dissimilar joints fabricated using the TCT tool has maximum tensile strength compared to the other tools. The significant contribution of tool pin profile in the development of the model is 47.63%.

Optimization of Welding Parameters

The optimum welding parameters by analysing the response surface graphs and contour plots are 885rpm; 102mm/min for the TCT pin profile and their predicted and experimental tensile strength were 204.24 and 203.32 MPa. A maximum point is observed from the response surface graphs (see Fig 2(a), 2(c) and 2(e)) indicating that there is a maximum tensile strength value inside the experimental region.

Conclusions

- **Three different tool pin profiles have been fabricated for dissimilar friction stir welds of the aluminium alloys AA6061-T651 and AA7075-T651. The feasible ranges of operating parameters are obtained after performing number of trial experiments and confirmed using Box-Behnken experimental design.**
- **A mathematical model is developed to predict the ultimate tensile strength of the dissimilar friction stir welds of aluminium alloys AA6061-T651 and AA7075-T651using response surface methodology. The difference between the experimental and mathematical equation is within ± 10% with 95% confidence level.**
- **To validate the fitness of the developed equation, confirmatory experiments were conducted and the tensile strength was compared. The comparison showed good agreement.**
- **The significant contribution of tool pin profile, rotational speed and welding speed in the development of mathematical equation are 47.63%, 30.58% and 6.49% respectively.**
- **The maximum tensile strength of 205 MPa is obtained for the rotational speed of 900 rpm and welding speed of 100 mm/min with Tapered Cylindrical Threaded (TCT) tool pin profile.**
- **The optimum welding parameters and the maximum tensile strength can also be directly obtained from response surface graphs and contour plots.**

References

[1] W.M. Thomas, E.D. Nicholas, J.C. Needham, M.G. Murch, S.P. Temple, and C.J. Dawes, "Friction stir butt welding", International Patent Application No PCT/GB92/ 02203, 1991.

[2] M.W. Mahoney, C.G. Rhodes, J.G. Flintoff, R.A Spurling and W.H. Bingel, "Properties of friction-stir-welded 7075-T651 aluminum, *Metall Mater Trans A*, 29A, pp.1955–1964, 1998.

[3] C.J. Dawes and W.M. Thomas, "Friction stir

process welds aluminum alloys" *Weld J* ,75,pp. 41-44,1996.

[4] P.Bahemmat, M.Haghpanahi, M.K.Besharati, S.Ahsanizadeh and H.Rezaei1, "Study on mechanical, micro and macrostructural characteristics of dissimilar friction stir welding of AA6061-T6 and AA7075-T6", Proc IMechE Part B: J. Eng Manuf , 224, pp.1854-1865,2010.

[5] V.Gunaraj and N.Murugan, "Application of response surface methodology for prediction weld bead quality in submerged arc welding of pipes", *J Mater Process Technol*, 88,266-75, 1999.

[6] P.K.Palani and N.Murugan, "Optimization of weld bead geometry for stainless steel claddings deposited by FCAW", *J Mater Process Technol,* 190, 291-299, 2007.

[7] M.Balasubramanian, V.Jayabalan and V.Balasubramanian, "Developing mathematical models to predict tensile properties of pulsed current gas tungsten arc welded Ti-6Al-4V alloy", *Mater Des*, 29, pp. 92-97, 2008.

[8] K.Elangovan , V.Balasubramanian and S.Babu, "Predicting tensile strength of friction stir welded 6061 aluminium alloy joints by mathematical model", *Mater Des*, 30, 188-193,2009.

[9] S.Rajakumar, C.Muralidharan and V.Balasubramanian, "Optimization of the friction-stir-welding process and tool parameters to attain a maximum tensile strength of AA7075–T6 aluminium alloy", *Proc IMechE Part B: J Eng Manuf*, 224, 1175-1191, 2009.

[10] A.K.Lakshminarayanan and V.Balasubramanian, "Comparison of RSM with ANN in predicting tensile strength of friction stir welded AA7039 aluminium alloy joints", *Trans Nonferrous Metals Soc of China*, 19,9-18,2009.

[11] S.J.Vijay and N.Murugan, "Influence of tool pin profile on the metallurgical and mechanical properties of friction stir welded Al– 10 wt. % TiB2 metal matrix composite", *Mater Des*, 31,3585-3589,2010.

[12] R.Palanivel , P.Koshy Mathews and N.Murugan, "Influences of tool pin profile on the mechanical and metallurgical properties of friction stir welding of dissimilar aluminum alloy", *Int J Eng Sci Technol*,2(6),2109-2115,2010.

[13] M.Ghaffarpour, B.M.Dariani , A.H.Kokabiand and N.A.Razani, "Friction stir welding parameters optimization of heterogeneous tailored welded blank sheets of aluminium alloys 6061 and 5083 using response surface methodology" *Proc IMechE Part B:J Eng Manuf* , 226(12),2013–2022.

[14] W.G. Cochran and G.M. Cox, *Experimental designs*, New York, Wiley, 1992.

[15] C. Montogomery, *Design and analysis of experiments*, 4 th ed. New York, Wiley, 1997.

[16] George Box and Donald Behnken, *Some new three level designs for the study of quantitative variables*, Technometrics, 2: pp,455–75,1960.

[17] G.E.P. Box and N.R. Draper. *Empirical model building and response surfaces*, New York, John Wiley and Sons, 1987.

[18] S.L.C.Ferreira , R.E.Bruns, H.S.Ferreira , G.D. Matos, J.M.David and G.C.Brandão , "Box–Behnken design, An alternative for the optimization of analytical methods", *Anal Chim Acta*,597,179–186,2007.