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Establishing Mathematical Relation to Predict Tensile Strength of Friction Stir Welded AA2024 Aluminium Alloy Joints

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Abstract

The present research article focuses on the development of mathematical model to envisage tensile strength of AA2024aluminium alloy joints fabricated by friction stir welding. Response surface methodology is used to establish the model and checked by ANOVA for its adequacy. The developed model is used, further, to optimize the friction stir welding parameters. The values of process parameters to achieve optimum tensile strength i.e. 294.6 MPa are observed to be 1436.31 rpm rotational speed, 61.68 mm/min transverse feed and 15.48 tool shoulder diameter.

Keywords: Tensile Strength, FSW, RSM, Aluminium Alloy.

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INTRODUCTION

Since its invention in 1991, Friction stir welding (FSW) is getting considerable recognition as a green solid state joining method having enough ability to weld the materials with low melting point, especially aluminium alloys due to its striking benefits as compare to the fusion welding. Aluminum alloys are among the most utilized structural materials in manufacturing, military and aerospace sectors and considered as a replacement of ferrous metal in some applications. The joining of aluminium alloys, using fusion welding methods, is never been easy as it encounter several undesirable defects like hot cracks, porosity, solidification defects. FSW techniques make use of the frictional heat generated by the stirring and rubbing of tailor made welding tool with the material to be weld. The schematic view of FSW method is illustrated in Figure 1.The heat produced is sufficient enough to soften the parent material but not to melt it. The softened metal starts flowing with the turning pin of the tool and get pressed due to axial load exerted through the shoulder. The simultaneous rotational flow and pressing of soften material results in a solid bond. In the past decades, FSW was considered to be one of the most significant inventions in joining of metals because of its environment friendliness, efficiency and versatility and has been employed to weld copper alloys [1-3], aluminum alloy [4-7] and titanium alloys [8-10]. There is a number of process parameters in any welding method, which affects the quality of joint produced. The selection of these parameters to get superior quality joints is always a challenging task for the fabricators. It is not possible to use each and every combination of different factors to check the desired quality characteristics as it involves wastage of the available resources like men, material and time. Various techniques have been used by the researcher for developing and analyzing the models and quality evaluation of different industrial applications [12-16]. To counter this situation, researchers have developed some methodology to predict the quality characteristics without actual experimentation.

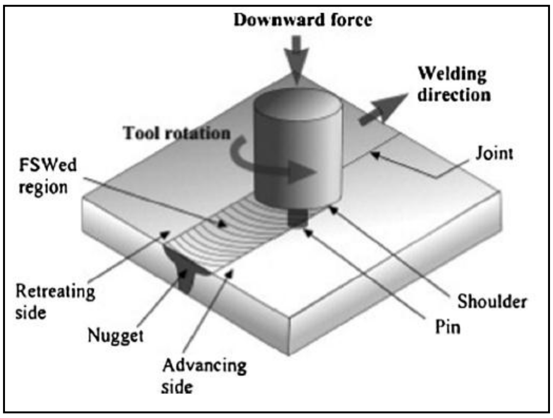

Figure 1: Schematic view of FSW [11]

Response Surface Methodology (RSM) is one of such methodology used to establish mathematical relation between the output and input parameters. Tensile strength and microhardness are among the vital output parameters to define the quality of the welding joints. RSM is successfully utilized by many researchers in the recent past to envisage the tensile strength of FS welded joints of different aluminium alloys.AA2024 belongs to the 2xxx family of aluminium alloys having copper as major alloying element which is getting widespread popularity in the field of aircrafts manufacturing. The present research aims at the establishmentof mathematical relationto determine the tensile strengthof FS welded AA2024 joints and then to optimize the selected parameters through the developed model using RSM.

MATERIALS AND METHODS

One factor at a time technique was used to determine the potential process parameters and their working range by conducting several trial runs. The physical appearance and defect free macrostructure were the criterion for selection of feasible range and levels of selected parameters as presented in Table 1.

Table1. Selected parameters

Parameters	Level				
	-1.682	-1	0	1	1.682
Rotational speed N(rpm)	1064	1200	1400	1600	1736
Welding speed S (mm/min)	34.7	45	60	75	85.2
Shoulder Diameter D (mm)	10	12	15	18	20

H13 hot die steel was used to fabricate the tailor made tool having square profiled probe, due to its better performance in joining aluminium alloys by FSW. The tool parameters used for the study are shown in Table 2.

Table 2: Tool Parameters

Tool Material	H 13 Die Steel
Pin Diameter	5 mm
Pin Profile	Square
Shoulder Type	Concave
Concavity	6°
Hardness	55 HRC
Pin Length	4.8 mm
Shoulder Length	80 mm

The welding tools were manufactured by CNC turner and Electric discharge machining. All the tools were heat treated to increase the hardness up to 55 HRC to limit the tool wear during welding process. Aluminium alloy AA2024 was utilized as base material to explore theinfluence of selected FSW parameters on the quality of welds. The rolled sheet of 5 mm thickness was processed on a shear cutting press to cut the specimens of 150 mm x 75 mm x 5 mm. Two such pieces were butted together on a specially designed and fabricated fixture. The fixture was designed to ensure the square butt configuration of the welding joint. Table 3 and Table 4 present the chemical composition and properties of AA2024 aluminium alloy respectively.

Table 3: Chemical Composition of AA2024

Elements	Cu	Mg	Mn	Fe	Si	Al
Wt %	4.19	1.62	0.61	0.5	0.48	Balance

Table 4: Mechanical Properties of AA2024

Material	UTS(MPa)	Yield Strength(MPa)	% Elongation	Hardness(HV)
AA2024	452	346	19	114

The design of experiment used for the current study was a 3 factor 5 level matrix comprising of 20 numbers of experiments to be carried out for developing the desired mathematical model. The coded and actual values of parameters for each experiment are shown in table 5.

Table 5: Design of experiments

Std. order	Process parameters (coded)			Process parameters (actual)			Response UTS (MPa)
	N	S	D	N (rpm)	S (mm/min)	D(mm)	
1	-1	-1	-1	1200	45	12	257
2	1	-1	-1	1600	45	12	265
3	-1	1	-1	1200	75	12	267
4	1	1	-1	1600	75	12	269
5	-1	-1	1	1200	45	18	267
6	1	-1	1	1600	45	18	277

7	-1	1	1	1200	75	18	270
8	1	1	1	1600	75	18	273
9	-1.682	0	0	1064	60	15	265
10	1.682	0	0	1736	60	15	278
11	0	-1.682	0	1400	34.7	15	269
12	0	1.682	0	1400	85.2	15	280
13	0	0	-1.682	1400	60	10	271
14	0	0	1.682	1400	60	20	276
15	0	0	0	1400	60	15	294
16	0	0	0	1400	60	15	292
17	0	0	0	1400	60	15	292
18	0	0	0	1400	60	15	294
19	0	0	0	1400	60	15	298
20	0	0	0	1400	60	15	293

A computer assisted vertical milling center was engaged to perform the experiments. ASTM E8 standard was followed for preparation oftensile test specimens. The average of three values for tensile strength was used for the analysis purpose, as presented in Table 5.

RESULTS AND DISCUSSION

The response i.e. tensile strength as a function of tool rotational speed (N), transverse speed (S) and tool shoulder diameter (D) may be shown as in below equation

$$Y(TS) = f(N, S, D)$$

The response surface can be represented by following polynomial equation for 3 factors

$$Y = b_0 + b_1N + b_2S + b_3D + b_{11}N^2 + b_{22}S^2 + b_{33}D^2 + b_{12}NS + b_{13}ND + b_{23}SD$$

In the above equation b_i ,b_{ii} and b_{ij} are the coefficients of single, interactions and squared terms and were calculated with the help of Design Expert Software. By using the calculated coefficients, following mathematical model was set up to envisage the tensile strength.

$$TS = 293.96+3.29N+2.31S+2.74D-8.70N^2-7.63S^2-7.99D^2-1.62NS+0.38ND-1.87SD$$

Table 6: ANOVA test results

Source	Sum of Squares	D.O.F	Mean Square	F Value	Prob>F	Results
Model	2752.39	9	305.82	31.16	< 0.0001	Significant
N	147.38	1	147.38	15.01	0.0031	
S	72.65	1	72.65	7.40	0.0215	
D	102.47	1	102.47	10.44	0.0090	
N-S	21.12	1	21.12	2.15	0.1731	
N-D	1.13	1	1.13	0.11	0.7420	
S-D	28.12	1	28.12	2.87	0.1214	
N^2	1089.63	1	1089.63	111.01	< 0.0001	
S^2	840.02	1	840.02	85.58	< 0.0001	
D^2	919.62	1	919.62	93.69	< 0.0001	
Residual	98.16	10	9.82			
Lack of Fit	73.32	5	14.66	2.95	0.1299	Not Significant
Pure Error	24.83	5	4.97			
Cor. Total	2850.55	19				

Table 6 illustrates the result of Analysis of Variance test, used to make sure the competence of the mathematical model. The result shows that developed model is adequate and significant as the F-value for the model is 31.16. The F-value for lack of fit, is 2.95, implies that the lack of fit is insignificant. The value of predicted determination coefficient R^2 must be approaching unity for goodness of fit for any mathematical model. In the present case it comes out to be 0.7928 showing that the goodness of fit of the model is approaching perfectness. The model is having value of adjusted R^2 as 0.9346 proving the significance of the model. The value of adequate precision for the model is 16.148 which is greater than 4 indicating adequacy of the signal.

RSM is among the most significant tools utilized to optimize the process parameters. Using RSM, values of process parameters to achieve optimum tensile strength are set up to be 1436.31rpm rotational speed, 61.68 mm/min transverse feed and15.48 tool shoulder diameter. Figure 2-3shows the influence of welding parameters on strength of FS welded AA2024 aluminium alloy joints. It is clear from Figure 2 (a) and (b) that value of strength of AA2024 joints raisesas tool rotational speed increases up to a certain level and then starts decline.Transverse feed and Shoulder diameter follows almost similar pattern in terms of effect on tensile strength. The peak of the response plot marks the optimum valve of tensile strength. In the currentinvestigation the optimum value of tensile strength is 294.6 MPa, determined through the analysis of response surface and contour plots.

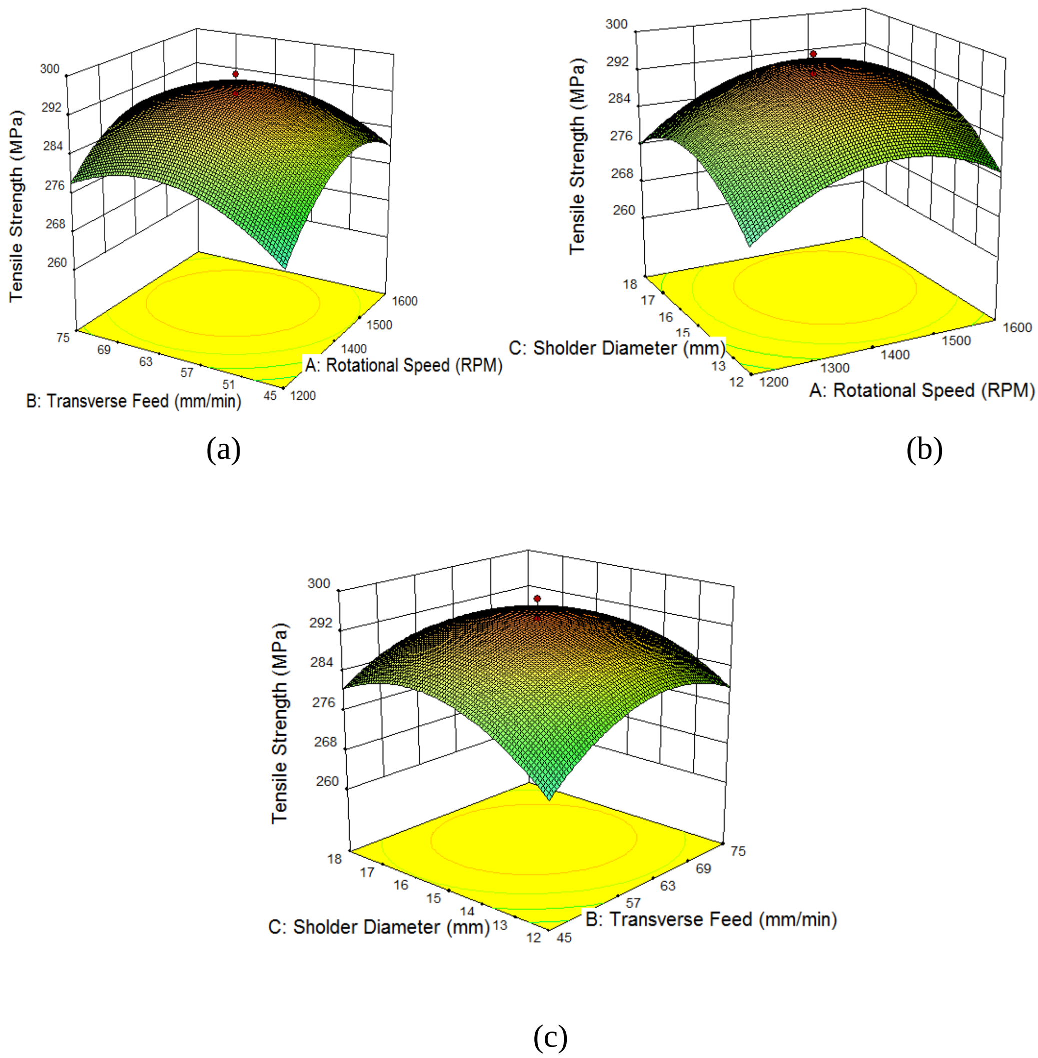

Figure 2. Response surface as a function of (a) rotational speed and transverse feed (b) rotational speed and shoulder diameter (c) shoulder diameter and transverse feed

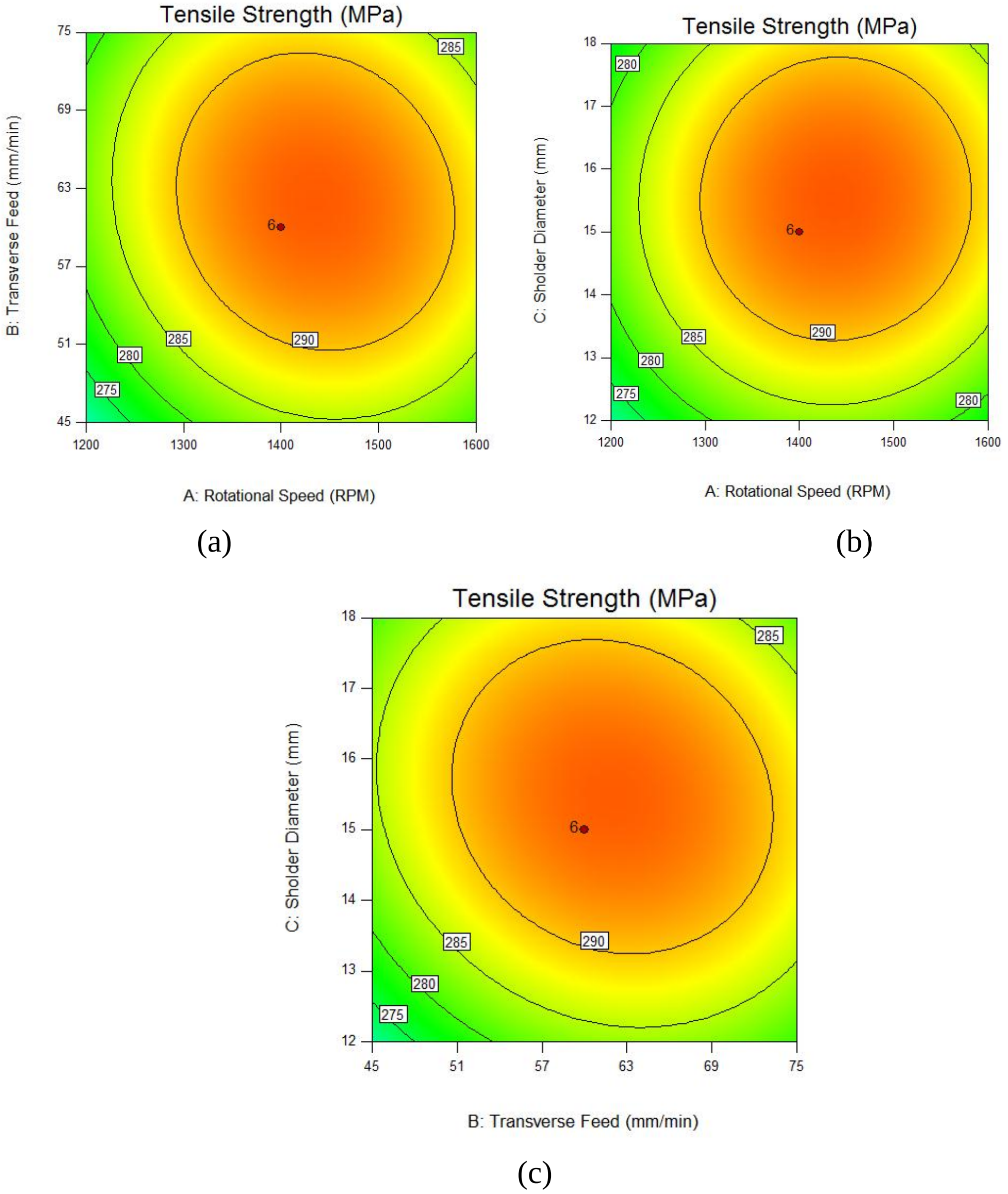

Figure 3 Contour Plots of Tensile Strength for (a) rotational speed and transverse feed (b) rotational speed and shoulder diameter (c) shoulder diameter and transverse feed

CONCLUSION

The present attempt was to develop a mathematical model to envisage tensile strength of FS welded AA2024 joints and is successfully completed. The model was found to be adequate and significant. Further the developed model was utilized to optimize the welding parameters. The optimum value of tensile strength and the combination of parameters at which this value is optimized, were determined.

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