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An Integrated Effect of Parameters on Mechanical Properties of Friction Stir Welded Dissimilar Aluminum Alloys

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Abstract: ***Welding has been the essence of the joining processes in various industrial and domestic applications. Friction Stir Welding has emerged as a potential solid-state welding process and has been used to weld two dissimilar Aluminum alloys AA 5083 O and AA 6082 T651. Generation of an empirical model for prior prediction of tensile properties from four prominent factors of Friction Stir Welding has been done. Four factors selected are tool rotation speed, tool transverse speed, tool tilt angle and square-shaped pin size. Tensile properties have been optimized using multivariable optimization. The relative impact of various factors on the tensile properties has been analyzed. Friction Stir Welding has been performed based on Response Surface Methodology and the design matrix was generated using Central composite rotatable design which includes five levels with 31 runs. The efficacy of the empirical models has been tested with Analysis of Variance and models generated were found accurate to predict the responses up to 95%. The response surfaces and contour plots of the input and response variables were generated and analyzed. The confirmatory run for the optimum values was performed with a percentage error of less than 3 percent. This paper may be useful in various industrial applications and an enhanced understanding of Friction Stir Welding.***

Keywords: ***Analysis of Variance, Design of experiments, dissimilar aluminum alloy, Friction Stir Welding.***

I. INTRODUCTION

Friction Stir Welding (FSW) has been one of the prominent solid-state welding technique used for welding aluminum and other materials since its invention in 1991[1]. Friction Stir Welding is found more suitable than fusion welding techniques due to formation of equiaxed, fine-grained structure in the stir/nugget zone of the weld metal [2]. Welding of aluminum was restricted before the inception of FSW due to problems related to other fusion welding processes, like oxide formation, requirement of skilled labor and reduced strength due to the melting of the faying surface.

Friction Stir welded joints performance is influenced by specific process parameters. The systematic procedure may be followed to establish a dependency on mechanical properties on the values of these process parameters for the FS welded joints. Further, the tensile

strength may be predicted for the given process parameters [3].

Tool majorly constitutes two parts called shoulder and pin and may have various features and sizes. The FSW tool plays a major role in FSW joints performance. Tool pin geometry and size predominantly influence the mechanical properties of the Friction Stir welded joint. The relative size of a particular pin affects the performance of the FSW joints. The forecast of mechanical properties of FS welded joints may be useful in various industrial applications and augment FSW Technology. In this investigation, an integrated effect of variation of square pin size and other key process parameters of FSW on Mechanical properties of dissimilar aluminum alloys is analyzed in a systematic manner using Response Surface Methodology (RSM). Friction Stir welding is performed on heat treatable AA 6082 T651 and non-heat-treatable AA5083O using Central Composite Design (CCD) and the mechanical properties of the welded joints are used to generate the empirical models. An endeavor to quantify the accuracy of the models has been performed using analysis of variance (ANOVA). Also, the interdependency among the input parameters has been evaluated. Multivariable Numerical Optimization of the mechanical properties in terms of input parameters has been performed using RSM.

II. METHODOLOGY

A. Identification of process parameters

From the literature review following parameters related to FSW have been identified and tabulated in Table I. Among the above parameters four parameters 1) Tool rotational Speed, 2) Transverse speed, 3) tilt angle and 4) square pin size were selected as independent variable for analyzing their effect on ultimate tensile strength, yield strength, and percentage elongation. Tool rotational speed is responsible for raising the temperature of base metal owing to frictional heat. The stirring of metal is dependent on the tool rotational speed. Further oxide layer breaking and mixing is also an effect of tool rotation speed.

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A high value of tool rotation speed may cause high frictional heat of the base metal. Welding speed governs the heat organization of the heat in friction stir welded joint. Too high of welding speed would render the weld joint cold and consequence into inappropriate joint. Too low welding speed would result in too hot FS welded joint again resulting Defective joint. Tilt angle, the inclination of the axis of the tool in trailing direction and vertical axis is accountable for thinning and appearance of weld.

The pin size i.e. the diameter of pin in case of cylindrical pin and side of the square in case of a square pin is also a significant process parameter. In case of, pin size is too small it may not withstand the load during the friction stir welding. If pin size is too large it may not be able to consolidate the joint satisfactorily. The main focus of this investigation has been the integrated effect of tool pin size and other process parameters on the above mentioned mechanical properties.

B. Development of Design Matrix

The percentage composition of AA 5083 O and AA 6082 T651 (6.35mm thick plate) has been presented in Table-II. The limits of the independent parameters were selected based on literature review and pilot runs conducted in the lab ensuring defect-free Friction Stir Welded joints. The size of square pin length is selected in a manner such that the ratio of shoulder diameter to the square pin diagonal remains between 2.4 and 3.4 and accordingly square pin side has been decided. Response surface methodology is an effective mathematics and statistics based methodology used for multivariate optimization. Rotatable Central Composite is an effectual tool of response surface methodology for creating an empirical model with quadratic effect. Table-III presents the levels of various factors and Table-IV manifests 31 combinations of experimental conditions in the form of a design matrix.

Table- I: Parameters affecting the performance of the FSW joints [4], [5]

Process parameters	Material based parameters	Tool based parameters	Clamp design
Tool Rotational speed	Melting point	Tool material	Clamp force
Transverse speed	Material properties	Pin geometry	Clamp Geometry
Tilt angle	Material thickness	Pin size	
Plunge force	Base material type(Similar / Dissimilar)	Shoulder features	
		Shoulder size	
		Thread pitch	

Table-II: Percentage chemical composition of base metal

Alloy	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
6082T651	1.0	0.25-.26	0.07-0.08	0.7	0.8	0.05	0.03	0.05	Remaining
5083O	0.1	0.16	0.03	0.66	4.5	0.06	0.03	0.07	Remaining

(a) (b)

Fig.1. Pictures of few FSW plates and FSW machine

In the present study, the design matrix has 2^{4}=16 factorial runs, 2x4=8 axial runs with $\alpha = \sqrt{4}=2$ and 7 center point runs. The factorial runs contribute to the assessment of interaction effects, axial points contribute towards estimation of quadratic terms in the model and center point runs give an estimate of error and also contribute towards assessment of quadratic terms [6].

C. Conduct of experiments and finding results

Dissimilar Aluminium alloy AA 5083 O and AA 6082 T651 were machined and sized to 200mm X 40mm using bandsaw and shaper machine. Aluminum plates were properly cleaned with Acetone to remove oil and dirt prior to the friction stir welding. The plates were positioned and clamped hydraulically in fixture of customized Friction stir welding machine presented in Fig. 1 (b) procured from R V Machine Tools. The plates of AA 6082 T651 being harder than the plates of AA5083 O were placed on the advancing side during the FSW [7]. The plates were friction stir welded perpendicular to the rolling direction in butt joint arrangement of size 200X80 mm to form the joint. H13 (Tool Steel) made tool with a square-shaped pin was used to consolidate the joint. Since the pin size is one of the process parameter, tools with 5 pins were machined from 30 mm diameter rod using lathe and CNC vertical milling machine. The tool shoulder was sized to 20mm diameter and subsequently hardened. Friction stir welding was performed (few welded specimens shown in Fig.1 (a) in random sequence to ensure balance in the effects of uncontrollable factors.

The tensile sub specimens of gauge length 25 mm presented in Fig. 2 were prepared from the welded joints as per ASTM B557 standards using wire EDM machine. The specimens were sliced perpendicular to the FS welding direction. The tensile test was performed on a servo based Universal testing machine available at Delhi Technological University at a strain rate of 2.5 mm/min at room temperature. The output parameters have been tabulated corresponding to the design matrix in Table-IV.

III. ANALYSIS OF RESULTS

A. Development of Empirical Relationship

Response surface methodology (RSM) is a technique used for mapping the desired responses and input parameters of our interest so that the responses may be predicted for a particular input. Despite, RSM is used to approximate the optimum value of response for a particular model [6]. In present investigation desired responses i.e. Ultimate tensile strength (UTS), Yield Strength (YS) & Percentage Elongation (PE) and independent parameters i.e. R, W, T & S may be functionally mapped as in equation (1), (2) and (3):

$$UTS= f\,(R, W, T, S) \quad (1)$$
$$YS= f\,(R, W, T, S) \quad (2)$$
$$PE= f\,(R, W, T, S) \quad (3)$$

The generalized second-order equation representing the response surface Y is given by equation (4).

$$Y=b_0 + \sum b_i x_i + \sum b_{ii} x^2_i + \sum b_{ij}\, x_i x_j + e_r \quad (4)$$

The term e_r the residual error is the measure of summation of pure error and lack of fit error. For present investigation, UTS or YS or EL regression equation has been given in equation (5).

$$UTS \text{ or } YS \text{ or } EL= b_0+ b_1 R + b_2 W + b_3T + b_4S + b_{11}R^2 + b_{22}W^2 + b_{33}T^2+ b_{44} S^2 + b_{12}RW + b_{13} RT + b_{14} RS + b_{23}WT + b_{24}WS + b_{34}TS \quad (5)$$

In the equation, b_0 indicates the intercept of the regression line. The coefficient terms b_1, b_2, b_3, and b_4 are linear terms while quadratic terms are represented by coefficients b_{11}, b_{22}, b_{33} and b_{44}.

Table-III: Values of Input parameters and their levels

Parameter	Units			Levels		
		-2	-1	0	+1	+2
Tool rotation speed(R)	(RPM)	600	700	800	900	1000
Welding speed (W)	(mm/min)	30	47.5	65	82.5	100
Tool tilt angle (T)	(Degree)	0	0.5	1	1.5	2
Side of square pin(S)	(mm)	4.2	4.6	5	5.4	5.8

Table-IV: Experimental design matrix and responses

Standard. order	R	W	T	S	UTS (MPa)	YS (MPa)	EL (%)
1	700	47.5	0.5	4.6	176	130	14.2
2	900	47.5	0.5	4.6	175	118	18.8
3	700	82.5	0.5	4.6	176	134	13.5
4	900	82.5	0.5	4.6	176	110	15.1
5	700	47.5	1.5	4.6	175	124	12.5
6	900	47.5	1.5	4.6	158	101	17.9
7	700	82.5	1.5	4.6	192	136	14.4
8	900	82.5	1.5	4.6	179	110	16
9	700	47.5	0.5	5.4	168	120	15.2
10	900	47.5	0.5	5.4	168	108	17.3
11	700	82.5	0.5	5.4	150	115	9.8
12	900	82.5	0.5	5.4	155	99	10.1
13	700	47.5	1.5	5.4	173	120	13.4
14	900	47.5	1.5	5.4	165	103	18.3
15	700	82.5	1.5	5.4	191	138	14.8
16	900	82.5	1.5	5.4	180	114	17.1
17	600	65	1	5	187	142	13.2
18	1000	65	1	5	185	107	19.2
19	800	30	1	5	161	108	16.8
20	800	100	1	5	175	115	10.6
21	800	65	0	5	144	106	6.95
22	800	65	2	5	164	112	11.1
23	800	65	1	4.2	189	135	18.6
24	800	65	1	5.8	181	127	19.7
25	800	65	1	5	171	109	14.2
26	800	65	1	5	174	110	11.2
27	800	65	1	5	176	111	13.6
28	800	65	1	5	172	114	15.0
29	800	65	1	5	174	108	11.7
30	800	65	1	5	173	110	12.1
31	800	65	1	5	170	108	13.7

Table-V: Gist of Analysis of Variance (ANOVA) results and Fit summary

Parameters	Source	Sum of squares	Degrees of freedom	Mean square	F-Ratio	P-value	Status
UTS	Model	3613.67	14	258.12	30.57	< 0.0001	Significant
	Residual	135.11	16	8.44			
	Lack of Fit	110.25	10	11.02	2.66	0.1216	Not significant
	Pure Error	24.86	6	4.14			
	R^2	0.9640					
	Adjusted R^2	0.9324					
	Predicted R^2	0.8216					
	Adequate Precision	24.3442					
YS	Model	3942.84	14	281.63	54.95	< 0.0001	Significant
	Residual	82.00	16	5.12			
	Lack of Fit	56.00	10	5.60	1.29	0.3919	not significant
	Pure Error	26.00	6	4.33			
	R^2	0.9796					
	Adjusted R^2	0.9618					
	Predicted R^2	0.9111					
	Adequate Precision	26.6180					
EL	Model	268.40	14	19.17	13.09	< 0.0001	Significant
	Residual	23.43	16	1.46			
	Lack of Fit	11.43	10	1.14	0.5718	0.7927	not significant
	Pure Error	11.99	6	2.00			
	R^2	0.9197					
	Adjusted R^2	0.8495					
	Predicted R^2	0.7184					
	Adequate Precision	14.2719					

Interaction terms are indicated by coefficient b_{12}, b_{13}, b_{14}, b_{23}, b_{24} and b_{34}. The empirical model has been developed with a 95% confidence level of significant coefficients. The final mathematical models developed to predict the Ultimate Tensile Stress (UTS), Yield Stress and Elongation in Actual form with the help of statistics-based software Design Expert 12.0.

$$UTS=929.726-0.603943R + 1.47642W-50.5327\,T-208.285S + 0.00025R\,W-0.06625\,R\,T + 0.0265625\,R\,S + 0.721429\,WT-0.330357WS+20.9375TS + 0.000312946R^2 -0.00447522W^2-19.4821\,T^2 + 17.9967S^2 \quad (6)$$

$$YS=1341-0.665\,R+0.403\,W-83.9T-354.7S -0.000929\,RW - 0.0325\,RT + 0.0250\,RS + 0.4857\,WT - 0.0179\,WS+ 16.88\,TS +0.000338R^2+0.00041\,W^2-2.00T^2+31.25\,S^2 \quad (7)$$

$$EL=272.207-0.0737669R+0.396368W-23.0589T-93.6706\,S-0.000400929RW+0.00682RT-0.00560312RS + +3.76688TS\ 0.121529W\,T-0.0721786\,WS +0.000085R^2+0.00072448W^2 -3.78701T^2+9.86326S^2 \quad (8)$$

B. Competency of the Empirical Relationship

The competence of the developed empirical model has been evaluated by Analysis of Variance (ANOVA) from details presented in Table-V. The adequacy of a model may be ensured by 1) significant model 2) non-significant of lack of fit and 3) high value of 'R square' and 4) 'R square adjusted'. The developed model is significant as its F- Value is less than the tabulated value at 95% confidence level. The lack of fit for the developed model is found to be non-significant as F value for lack of fit is more than that of tabulated value. The F value of lack of fit is 2.66 and corresponding P- value 0.1216 signifies that there is only 12.16 percent probability that lack of fit of F value 2.66 may happen due to noise. 'R square' value for the empirical model specified by equation 1 is 0.9640 indicating that the remaining 3.6% of the variation in predicted UTS value could not be explained by variation in independent variables.

'Adjusted R square' value for equation 1 is 0.9324 is obtained by making adjustments in 'R-square' value to accommodate the increase in the latter due to less valuable multiple independent variables. Predicted R square value is 0.86, 0.91 and 0.72 for UTS, YS and EL respectively and its difference from corresponding Adjusted R square value is less than 0.2. Adequate precision indicating signal to noise ratio is 24.34, 26.61and 14.27 for UTS, YS and EL and since all ratios are more than 4.0 they the respective empirical models are appropriate to navigate the design space.

C. Interpretation of results

The regression coefficient presented in Table-VI signifies the estimated change in response per unit variation in input factor maintaining all other factors constant. An analysis of regression coefficients has been performed and has been elucidated subsequently.
The relative effect of the tool tilt angle among all main effects has been the most prominent for response UTS. The relative effect of Tool rotation speed is among all main effects that have been more in response YS. The negative value of the respective regression coefficient indicates that increasing the tool rotation speed shall decrease the response YS. Tool rotation speed again emerges to be the most significant for the main effect in response EL.
Welding speed and tool tilt angle interaction effect is the most significant for UTS, YS, and EL. The interaction effect of tool tilt angle and pin size is the second most significant for UTS, YS, and EL. Tool rotation speed has been the most effective in the estimation of quadratic effects on UTS. Tool pin size S was found to be the second most prominent in the estimation of quadratic effects on UTS. Analyzing the quadratic effects of the tool pin size revealed its prominence on YS and EL.

Table-VI: List of regression coefficient

Regression coefficients	UTS	YS	EL
Intercept b_0	172.86	110	13.07
b_1	-2.04	-9.33	1.45
b_2	2.87	1.92	-1.22
b_3	4.54	1	0.7784
b_4	-3.04	-2.58	-0.1781
b_{12}	0.4375	-1.62	-0.7016
b_{13}	-3.31	-1.62	0.341
b_{14}	1.06	1	-0.2241
b_{23}	6.31	4.25	1.06
b_{24}	-2.31	-0.125	-0.5052
b_{34}	4.19	3.38	0.7534
b_{11}	3.13	3.37	0.8469
b_{22}	-1.37	0.125	0.2219
b_{33}	-4.87	-0.5	-0.9468
b_{44}	2.88	5	1.58

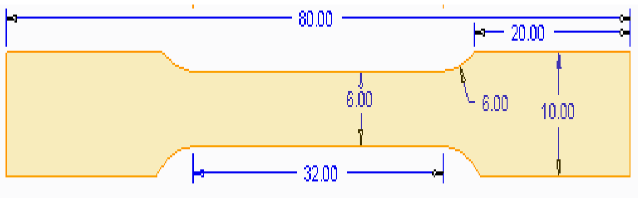
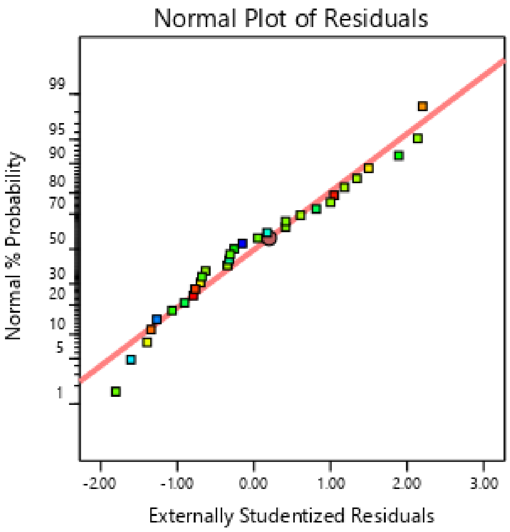


Fig.2. Tensile sub-specimen as per ASTM B557 [8]

Fig.3. Normal probability against the external



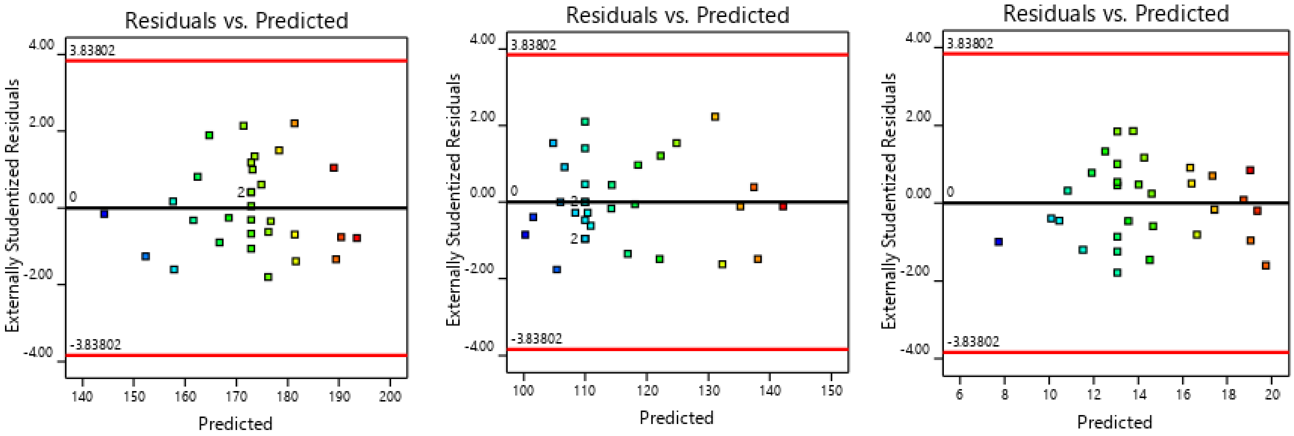
studentized residual of UTS

The normal probability plot of externally studentized residuals is beside the straight line signifying the errors are normally distributed as presented in Fig. 3.

Plots of Externally studentized residual vs. predicted values for response UTS, YS, and EL have been manifested in Fig 4. In the plot, values have been seen to be randomly scattered i.e. the range of the residuals should be constant to ensure a constant variance. The predicted values and Actual values of UTS, YS, and EL are lying along their respective straight lines with very slight deviations revealing the good accuracy of the calculated model as shown in Fig. 5.

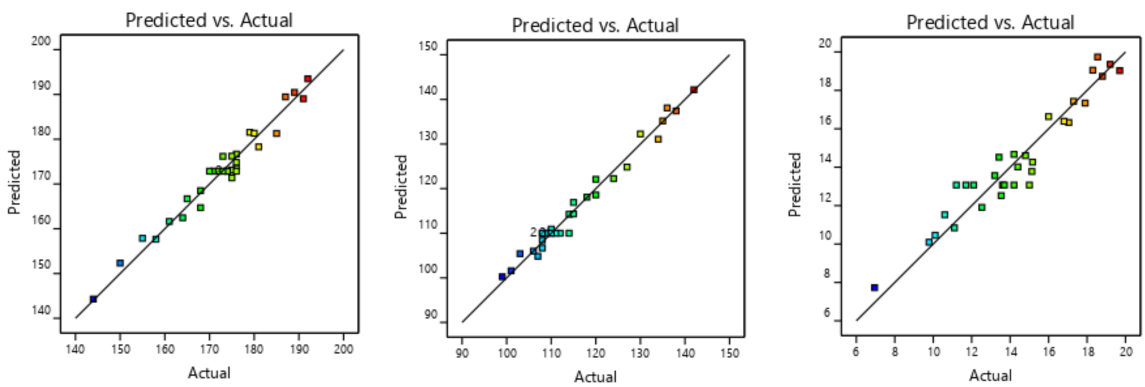
D. Analysis of Response Surface and Contour Plot

Response surface and contour plots serve the following purposes: 1) to signify the interaction/independence of the factors 2) to manifest the stationary point /saddle points and 3) to indicate an optimum value of desired response with sufficient accuracy. Response plots and contour plots have been presented in Fig. 6, Fig. 7 and Fig. 8
The response surface presented in Fig. 6 signifies the plots of independent factors S & R, S & W and S & T with UTS as response and other two independent factors kept at center point in each graph respectively. Red dotes indicate the design points in the plots. In a similar manner Fig. 7 and Fig. 8 represent the response surface plots for YS and EL as output respectively while other parameters are kept the same as mentioned above.



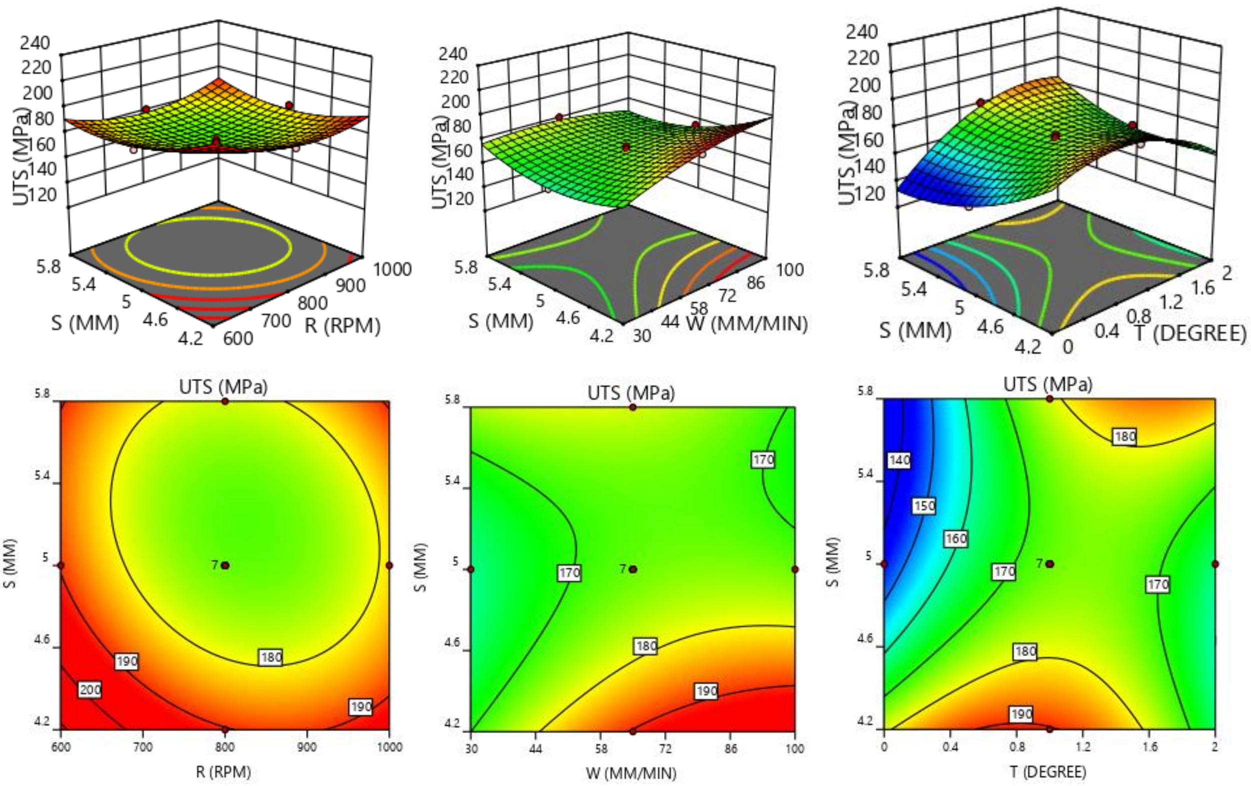
(a) UTS **(b) YS** **(c) EL**

Fig.4. Plot of Externally studentized residual vs. predicted values for response UTS, YS, and EL



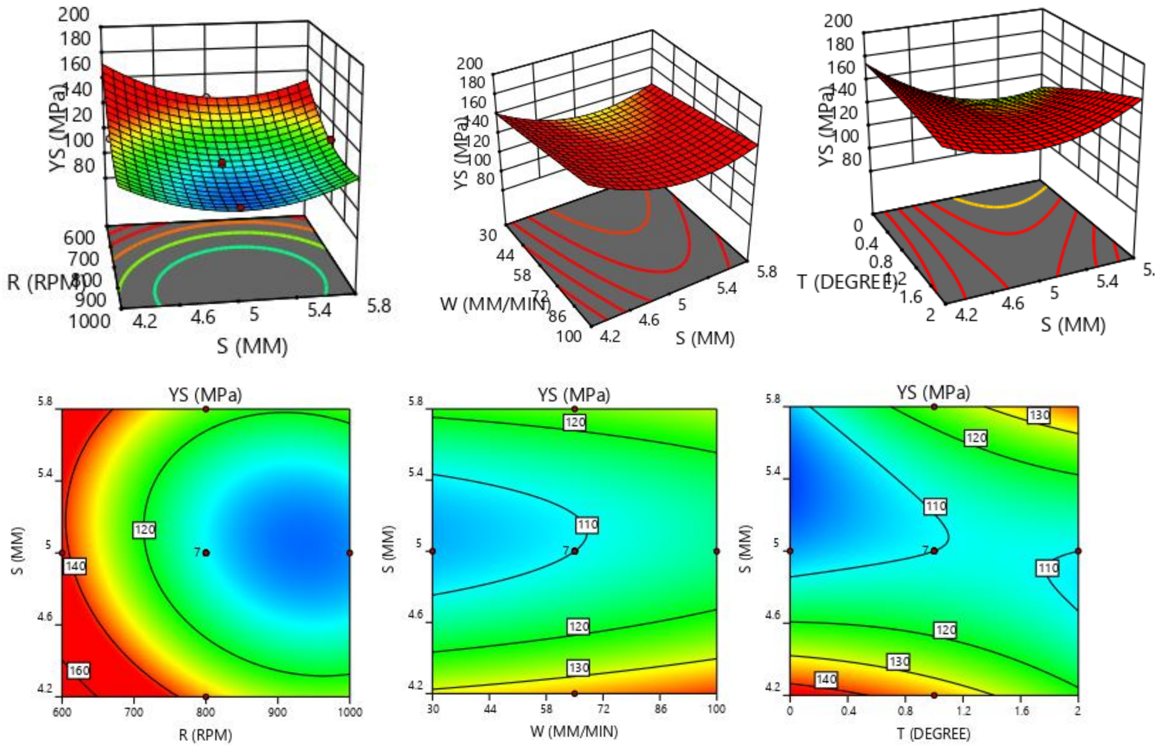
(a) UTS **(b) YS** **(c) EL**

Fig.5. Plots of predicted vs actual values of the response variables



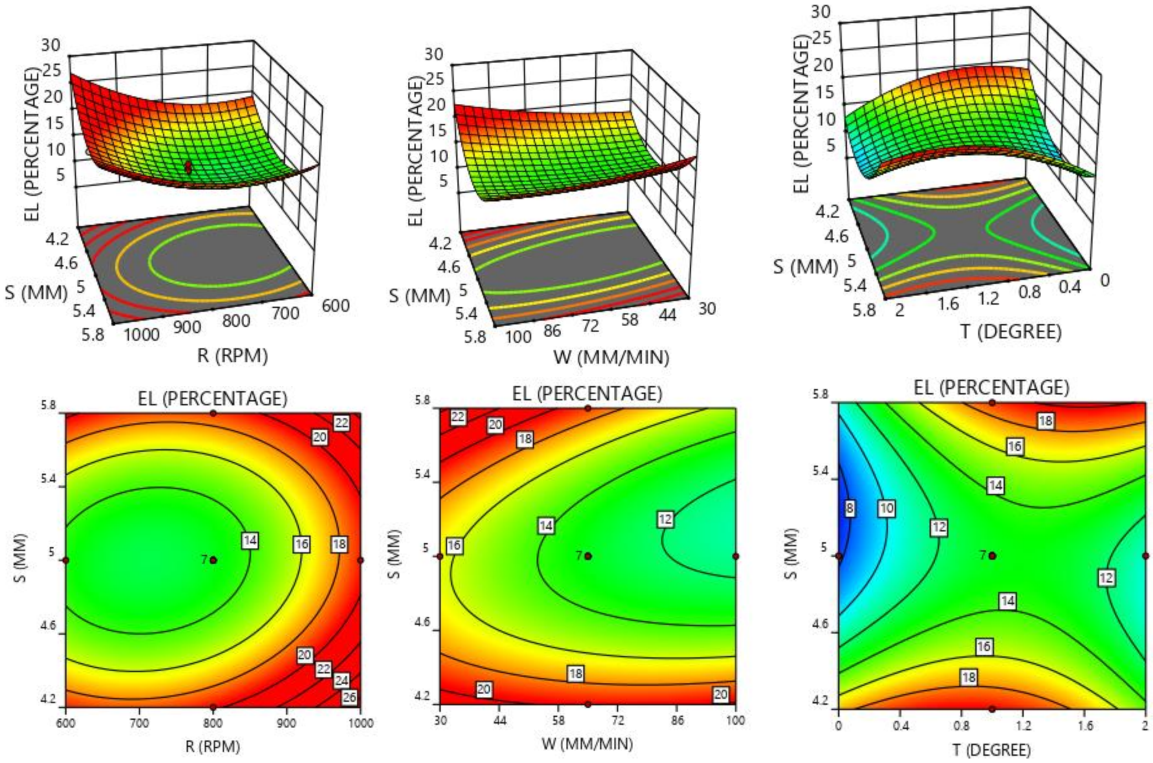
a) **b)** **c)**

Fig.6. Response surface and contour plots of UTS for the combination of pin size with other factors



a) b) c)

Fig.7. Response surface and contour plots of YS for the combination of pin size with other factors



(a) (b) (c)

Fig.8. Response surface and contour plots of EL for the combination of pin size with other factors

Table-VII: Optimized process parameters and responses

Tool rotation speed (RPM)	Welding speed(mm/min)	Tool tilt angle(degrees)	pin side length(mm)	UTS (MPa)	YS (MPa)	EL (%)	Desirability
600	99.8	2	5.8	224.7	200.2	23	0.877

The response surface presented in Fig. 6 signifies the plots of independent factors S & R, S & W and S & T with UTS as response and other two independent factors kept at center point in each graph respectively. Red dotes indicate the design points in the plots. In a similar manner Fig. 7 and Fig. 8 represent the response surface plots for YS and EL as output respectively while other parameters are kept the same as mentioned above. Response surface and contour plot in Fig. 6 (a) shows that UTS is more vulnerable to vary in case of a change in pin size S than a change in rotation speed (R), keeping Welding speed and Tilt angle at 65 mm/min and one degree respectively. Further contour plot in Fig. 6 (b) shows the high sensitivity of Change in UTS to change in pin size than change in welding speed while keeping rotation speed and tool tilt angle constant at 800 rpm and one-degree angle respectively in design space. It indicates the importance of pin size while seeking the effect of input parameters on ultimate tensile stress. Slight interaction effect of R & S, W & S, and S & T on response UTS may be concluded from Fig. 6 due to the elliptical profile of the said contours. The contour plot in Fig. 7 (a) shows that YS is more vulnerable to change in case of a change in pin size S than a change in rotation speed (R), keeping Welding speed and Tilt angle at 65 mm/min and one degree respectively. Further contour plot in Fig. 7(b) shows the high sensitivity of Change in YS to change in welding speed than change in pin size while keeping rotation speed and tool tilt angle constant at 800 rpm and one-degree angle respectively in design space. Contour plots manifested in Fig. 7 shows that there is an interaction effect between R & S, W & S and S & T on response yield stress. Within the design region, the interaction effect of R & S is less than that of W & S and S & T as concluded from 7 (a), 7 (b) and 7(c). Contour plot in Fig. 8 (a) exhibits that EL is more vulnerable to change in case of variation in rotation speed (R) than variation in pin size S, keeping Welding speed and Tilt angle at 65 mm/min and one degree respectively. Further contour plot in Fig. 8 (b) shows the high sensitivity of Change in EL to variation in welding speed than variation in pin size while keeping rotation speed and tool tilt angle constant at 800 rpm and one-degree angle respectively in design space. Contour plots manifested in Fig. 8 shows that there is an interaction effect of the between R & S, W & S and S & T on response elongation. Within the design region, the interaction effect of R & S is less than that of W & S and S & T as shown in 8 (a), 8 (b) and 8 (c).

IV. OPTIMIZATION

The most important purpose of Response surface Methodology is to find the values of the factors to maximize the response values. In this investigation, multivariate optimization has been performed using numerical methods. In multivariate optimization, the simultaneous maximization of all the responses has been performed and the following values have been evaluated and presented in Table-VII. At tool rotation speed= 600 rpm, welding speed=99.8 mm/min, tool tilt angle =2 degrees and square pin side length=5.8mm yield the maximum response of UTS 224.7 MPa, YS 200.2 MPa, and EL=23 percent. In the optimization process, the desirability=0.877 has been evaluated. The confirmatory run for the optimum values was performed with a percentage error of less than 3 percent.

V. RESULTS AND DISCUSSION

1. The prominent essence of this paper is to explore the collective contribution of tool rotation speed, tool transverse speed, tool tilt angle and square-shaped pin size of Friction Stir welding of 5083O and 6082 T651 on the estimate of ultimate tensile stress, yield stress, and percentage elongation.
2. Different parametric relationships of quadratic nature have been established for the prediction of various responses using Response surface methodology with sufficient accuracy of 95 % confidence level. The efficacy of the relationships generated has been analyzed by Analysis of Variance (ANOVA).
3. Tool tilt angle has Maximum main effect on the estimation of ultimate tensile stress, whereas tool rotation speed is a relatively most effective parameter in estimation of yield stress and elongation in selected design space. Welding speed and tool tilt angle interaction effect is the most significant for UTS, YS, and EL. Tool tilt angle and pin size interaction effect are the second most significant for UTS, YS, and EL. Square pin size has been the most prominent factor for quadratic effects in the estimation of UTS and YS.
4. Multivariable optimization reveals the maximum values of ultimate tensile stress, yield stress and elongation to 224.7 MPa, 200.2 MPa, and 23 percent respectively. Response surface and contour plots have been analyzed for seeking interactions and optimum response values.

VI. CONCLUSION

Pin size of square pin has an impact on the mechanical properties of Friction Stir Welded joints. It may be concluded that pin size of 5.8 mm side give maximum ultimate tensile stress, yield stress and percentage elongation with other input parameters at certain value. The interaction effect between square pin size with other parameters is also observed. However, a wider range of input factors may be explored with superior capacity machines and may reveal the results that may be utilized as standardized data for industrial applications.

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