Impact strength of Friction Stir Welded joints of dissimilar Aluminum alloy

Arun Gupta, Vipin

Abstract*: *Joining processes has been the heart of the manufacturing processes. Welding has played an important part in joining processes since its inception. Friction Stir Welding (FSW) has given promising results especially in the case of aluminum alloys. In the present paper, dissimilar aluminum alloy heat-treatable AA6082 T651and non-heat treatable AA 5083 O were friction stir welded as per design matrix generated according to the rotatable central composite design of response surface methodology. Impact toughness was measured from samples of welded joints. The impact toughness was mapped in terms of FSW parameters and the regression equation is generated. The response surfaces and contour plots are drawn and interpreted. The input parameters are optimized to achieve maximum impact strength. Confirmation runs were performed and found results were found close to the optimized values. The present research is useful for further augmentation of the FSW process of aluminum alloy.

Keywords*: *Friction Stir Welding, Impact Strength, Design of experiments, Aluminum alloy.

I. INTRODUCTION

Aluminum alloys have been the prime choice for marine, automotive and automobile industries due to its lightweight, high corrosion resistance and high strength and weight ratio [1]. AA 6082 is the age hardenable and AA 5083 is strain hardenable aluminum alloy and both posses above virtues and welding of above aluminum alloys may emerge the joint with properties of both the aluminum alloys [2]. Fusion welding of aluminum alloys generally results in oxide formation, reduced strength and other mechanical properties. Friction stir welding is a comparatively recent solid-state welding process that omits the shortcomings associated with other solid-state welding techniques. Friction stir welding technique results in equiaxed fine grain structure in stir zone of the joints [3]. Friction stir welded joints properties adamantly depend on various process parameters. FSW tool material, shoulder features, shoulder size are such important process parameters apart from welding tool rotational speed and transverse speed.[4],[5]. Mechanical Properties like impact strength is one such property influenced by various process parameters.

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* Correspondence Author

Arun Gupta*, Mechanical Engineering, Delhi Institute of Tool Engineering, Delhi, India. Email: arungupta04@gmail.com

Vipin, Department of Mechanical Engineering, Delhi Technological University, Delhi, India. Email: vipin@dce.ac.in

A sequential method may be followed to establish a model between mechanical properties FSW process parameters [6]. It has been investigated that square pin gives better ultimate tensile strength and finer grains than the cylindrical pin [7]. However, the size of the square pin may also affect the impact strength apart from other significant FSW parameters. In this paper, square pin size is elected in the combination of other process parameters for seeking its effect on the impact strength. Dissimilar AA 6082 T651 and AA 5083 O have been welded according to the design matrix generated from Central Composite Design (CCD) of Response Surface methodology. An empirical model has been established and its competence is judged by Analysis of Variance (ANOVA). Further, the interaction between the input variables has been evaluated. RSM has been also used to evaluate the maximum value of the impact strength at the optimum value of FSW input factors.

II. METHODOLOGY

A. Selection of Significant Parameters

On the basis of the literature review, four process parameters of the Friction Stir Welding have been identified and selected for the present analysis and are as follows: rotational speed of the tool, tool linear speed, tool tilt angle, and pin size. These parameters have been set as independent parameters whose effect is to be evaluated on the dependent parameter impact strength.

The rotational speed of the tool controls the heat generation during the FSW and its value should be selected in a suitable range to achieve a defect-free joint.

Tool linear speed also performs the function to control the heat generation during the FSW. To generate sufficient heat tool linear speed must lie in appropriate range as very high or low speed may consequence into the defective joint.

The tool tilt angle is the angle of the tool with the vertical axis. The tool tilt angle is always kept towards the trailing side of the tool movement to ensure appropriate consolidation of the joint. Square pin size has been selected fourth independent parameter. Pin size should be sufficiently large to withstand the various loads on the tool during FSW. Simultaneously pin size should not be too large to consolidate the joint. The ranges of independent parameters are based on the pilot runs and have been presented in Table 1.Impact strength is collectively influenced by the above-mentioned parameters and its analysis is performed based on experimental results.

B. Design Matrix Creation

The 6.35 mm thick aluminum alloys 6082 T651 and 5083 O plates were Friction Stir welded perpendicular to the rolling direction. Response surface methodology with rotatable Central Composite design was opted to conduct the experiments. In the design matrix, 16 factorial points, eight axial runs /star runs, and seven center runs are present. A total of 31 experiments were performed. The design matrix has been presented in Table 2. Sixteen factorial design points include all four variable are arranged in all possible combinations at +1 level and -1 level and give an estimation of the interaction terms. Eight stars/axial points include the one factor at +2 or -2 level and other parameters at the center point level and estimates the quadratic effect. At center points, all the factors are at zero level and estimate the error terms and quadratic effect.

C. Performing experiments and Results Generation

The aluminum alloy plates were sectioned to the size 200X40 X6.35 mm using a shaper machine. Acetone was used to clean the plates prior to FSW. The 5083 O plate being less hard was positioned on the retreating side[8].

Die steel H13 was used to manufacture the tool for FSW. The tool was turned and machined to the desired shape and subsequently hardened before the performing FSW. Five pins of square shape were manufactured using a very precise CNC milling machine. The size of each pin is as per Table I.

The specially designed FSW machine was used to join the plates to size 200X80X6.35 mm. The welding was performed as per the design matrix presented in table 2 in random order to minimize the error due to uncontrollable factors.

The Charpy impact test specimens of size 55X10X6.35mm were cut from the weld plates as per ASTM 23-18 using wire cut EDM. An Italy based Charpy impact testing machine was used to evaluate impact toughness. The values of impact toughness for the specimen were tabulated in Table-II.

III. ANALYZING THE RESULTS

A. The equation for Empirical Relationship

Response surface methodology is a statistical and mathematical technique used to fit a polynomial equation to the experimental data and evaluate the optimization of the output variable. In the present paper, the response impact toughness has been mapped in terms of independent parameters as mentioned in Table 1. The polynomial equation in terms of process parameters may be represented as below:

$$I = f(S, L, T, D) \quad (1)$$

The polynomial equation of second order representing general form is given below:

$$I = b_0 + \sum b_i x_i + \sum b_{ii} x_i^2 + \sum b_{ij} x_i x_j + e_r \quad (2)$$

The term b_0 represents mean of all the responses. Equation (2) is given in expanded form for the process parameters:

$$I = b_0 + b_1 S + b_2 L + b_3 T + b_4 D + b_{11} S^2 + b_{22} L^2 + b_{33} T^2 + b_{44} D^2 + b_{12} SL + b_{13} ST + b_{14} SD + b_{23} LT + b_{24} LD + b_{34} TD \quad (3)$$

'I' indicates the impact toughness, b_0 represents the mean of Responses, b_1, b_2, b_3, and b_4 represent the coefficient of linear parameters, b_{11}, b_{22}, b_{33} and b_{44} represent the coefficient of quadratic terms whereas b_{12}, b_{13}, b_{14}, b_{23}, b_{24} and b_{34} represent the interaction parameters coefficient.

The equation for impact toughness is given below:

$$I = 433.67 - 0.17 S - 0.64 L - 68.06 T - 107.93 D + 0.024 ST - 0.018 SD - 0.143 LD + 10.85 TD + 0.00015 S^2 + 0.009 L^2 + 11.56 D^2 \quad (4)$$

All the terms mentioned in the equation (3) are not significant. Only S, L, T, D, ST, SD, LD, TD, S^2, L^2 and D^2 were found to be significant as described in equation (4).

Table-I: Various independent parameters and their levels

Parameters	Units	Levels				
		-2	-1	0	1	2
Rotation Speed of tool (S)	(RPM)	600	700	800	900	1000
Linear speed (L)	(mm/min)	30	47.5	65	82.5	100
Tool tilt angle (T)	(Degree)	0.001	0.5	1	1.5	2
Side of square pin(D)	(mm)	4.2	4.6	5	5.4	5.8

Table- II: Design matrix with experimental response

Standard Order	S	L	T	D	I (Joules)	Predicted value	Error(%)
1	-1	-1	-1	-1	35.08	34.32	2.16
2	1	-1	-1	-1	34.00	34.12	-0.35
3	-1	1	-1	-1	32.00	32.02	-0.06
4	1	1	-1	-1	34.00	31.82	6.42
5	-1	-1	1	-1	36.00	33.46	7.06
6	1	-1	1	-1	38.00	38.19	-0.49
7	-1	1	1	-1	29.23	31.15	-6.58
8	1	1	1	-1	36.00	35.88	0.33
9	-1	-1	-1	1	28.50	29.25	-2.62
10	1	-1	-1	1	27.04	26.15	3.27
11	-1	1	-1	1	24.00	22.92	4.51
12	1	1	-1	1	18.59	19.83	-6.65
13	-1	-1	1	1	36.00	37.06	-2.95
14	1	-1	1	1	40.00	38.90	2.75
15	-1	1	1	1	30.00	30.73	-2.44
16	1	1	1	1	31.00	32.57	-5.07
17	-2	0	0	0	31.00	30.82	0.59
18	2	0	0	0	32.00	32.45	-1.42
19	0	-2	0	0	40.00	41.45	-3.63
20	0	2	0	0	34.00	32.82	3.48
21	0	0	-2	0	19.87	19.52	1.76
22	0	0	2	0	34.00	31.40	7.65
23	0	0	0	-2	35.51	37.05	-4.35
24	0	0	0	2	29.94	28.67	4.25
25	0	0	0	0	25.00	25.46	-1.84
26	0	0	0	0	24.00	25.46	-6.08
27	0	0	0	0	25.00	25.46	-1.84
28	0	0	0	0	26.00	25.46	2.08
29	0	0	0	0	23.00	25.46	-10.70
30	0	0	0	0	26.00	25.46	2.08
31	0	0	0	0	26.00	25.46	2.08

B. Competence of Empirical equation

The empirical equation framed has been checked using the Analysis of Variance (ANOVA) method. And its details have been presented in Table-III. ANOVA method indicates the quantification of change in response due to the change in levels of input parameters.

Goodness of fit of the polynomial equation fitted to the experimental data has been tested by calculating R-Square value and high value of R-Square value (0.9490) indicates that the equation is well fitted to the experimental data. Further 'Adjusted R Square', 'Predicted R Square' and 'Adequate precision' has been presented in Table-IV. Adequate precision signifies the signal to noise ratio and its value is large enough to explore the design realm with the generated regression model. The fisher Distribution (F-test) has been evaluated and the F ratio for the model is more than the tabular F-value indicating that the model is significant. In a similar analysis, the lack of fit was found to be insignificant since the F –value of the lack of fit is less than F- value from the table.

C. Results Interpretation

Regression coefficients have been presented in Table-V and being used for interpretation of the regression equation. For the quadratic regression equation, only significant terms have been considered. These terms indicate the change in response to a unit change in the independent factor while keeping other factors constant.

The main effect due to tool rotation speed is the least among other main effects. The interaction effect of independent factors tool tilt angle and tool pin size has evolved maximum whereas the quadratic effect of tool linear speed has been found maximum and afterward tool pin size has affected the impact strength in quadratic mode. The tool tilt angle quadratic effect is found insignificant.

The graph between external studentized residual against predicted value has been presented in Fig.-1 and the random trend of residual the graph ensures the assumption of constant variance.

The graph of predicted vs. actual value has been shown in Fig.-2 and the points follow a linear trend indicating good model formation.

D. Analysis of Model Graphs

The perturbation graph has been presented in Fig.3 which shows the deviation of impact toughness as each input factor is varied from the reference point by keeping other factors constant. The reference point has been kept at the center point (at zero levels in coded form) for each factor. The highest precipitous change in the plot of any factor indicates that the output is most susceptible to that factor. In the perturbation graph presented in Fig. 3, tool tilt angle appears to be the most prominent factor to affect impact toughness.

The response surfaces and contour plots for significant terms ST, SD, LD and TD of equation 4 with respect to impact toughness 'I' have been shown in Fig. 4, 5, 6, 7, 8, 9, 10 and 11. The interpretation of response surfaces and contour plots is as follows: the response surface for term ST has been drawn by drawing 'S' on X-axis, 'T' on Y-axis and the response 'I' on the Z-axis as shown in Fig 4. The red dots on the response surface indicate the design points. The change in response impact toughness (I) is more sensitive to change to Tilt angle (T) than a change in tool rotation speed (S) while keeping the other factors linear speed (L) and pin size (D) at 65 mm/min and 5 mm respectively.

The response surface for term SD has been drawn by drawing 'S' on X-axis, 'D' on Y-axis and the response 'I' on the Z-axis as in Fig.6. The red dots on the response surface indicate the design points. The change in response impact

TABLE –III: Details of ANOVA results

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	912.79	11	82.98	32.14	< 0.0001
A-S	4.02	1	4.02	1.56	0.2274
B-L	111.8	1	111.8	43.3	< 0.0001
C-T	211.7	1	211.7	81.99	< 0.0001
D-D	105.5	1	105.5	40.86	< 0.0001
AC	24.3	1	24.3	9.41	0.0063
AD	8.35	1	8.35	3.23	0.088
BD	16.2	1	16.2	6.27	0.0215
CD	75.34	1	75.34	29.18	< 0.0001
A^2	68.93	1	68.93	26.69	< 0.0001
B^2	246.4	1	246.4	95.43	< 0.0001
D^2	98.99	1	98.99	38.34	< 0.0001
Residual	49.06	19	2.58		
Lack of Fit	41.06	13	3.16	2.37	0.1486
Pure Error	8	6	1.33		
Cor Total	961.84	30			

TABLE –IV: Details of Fit Statistics

R^2	0.9490
Adjusted R^2	0.9195
Predicted R^2	0.8430
Adeq Precision	21.9370

TABLE –V: Values of regression coefficients

Factor	Coefficient Estimate
Intercept	25.46
A-S	0.4092
B-L	-2.16
C-T	2.97
D-D	-2.1
AC	1.23
AD	-0.7225
BD	-1.01
CD	2.17
A^2	1.54
B^2	2.92
D^2	1.85

toughness (I) is slightly more vulnerable to change to rotation speed (S) thanthe change in tool pin size(D) while keeping the other factorslinear speed (L) and tilt angle(T) at 65 mm/min and 0.001degree respectively

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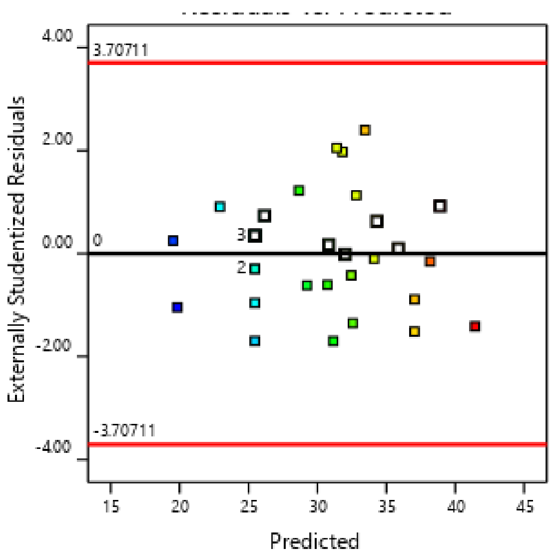

Fig.1: Graph of residual vs. predicted value

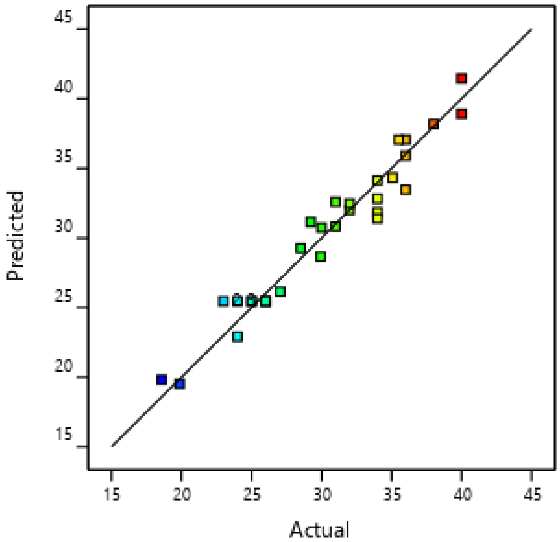

Fig. 2: Predicted vs. actual response

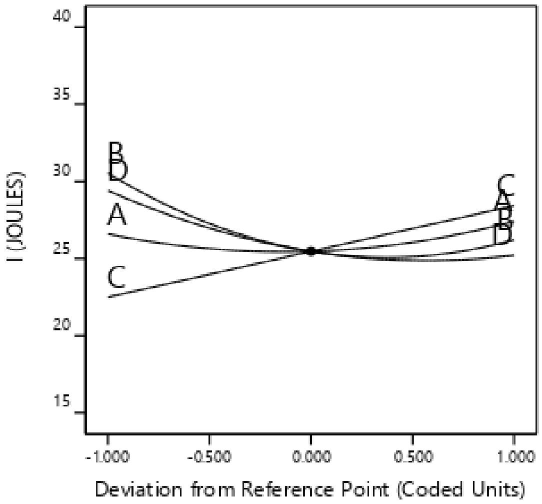

Fig.3: Perturbation curve

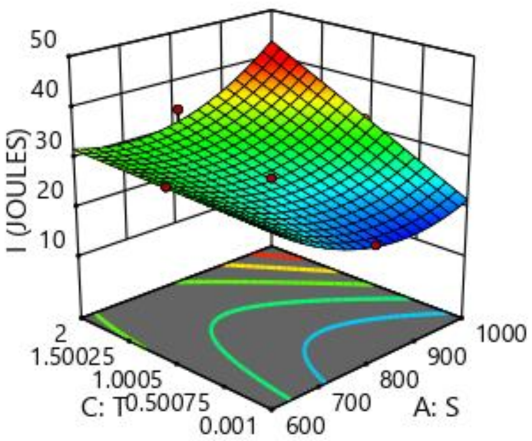

Fig.4: Response surface of ST

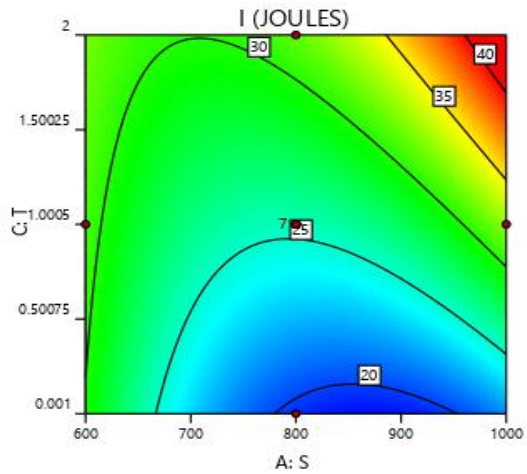

Fig.5: Contour plot of ST

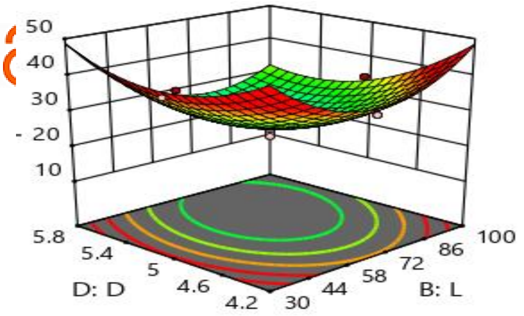

Fig.6: Response surface of SD

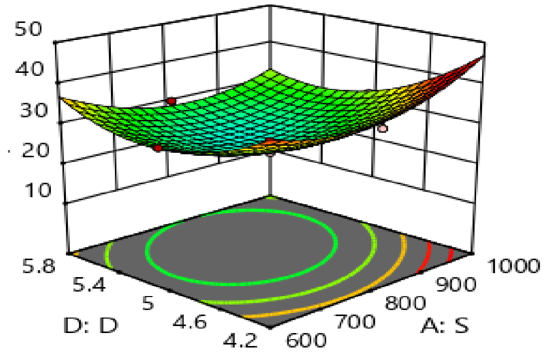

Fig.8: Response surface of LD

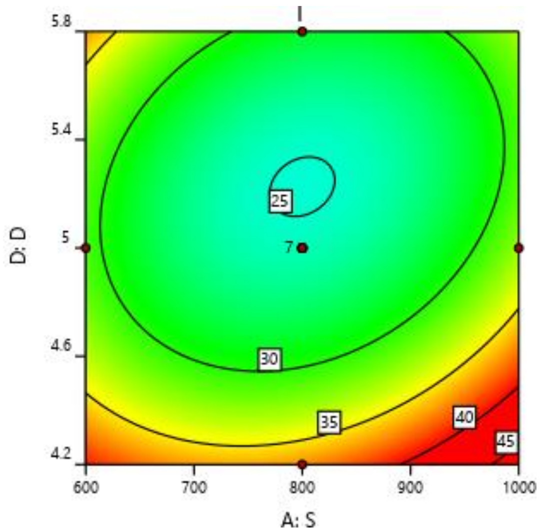

Fig.10: Response surface of TD

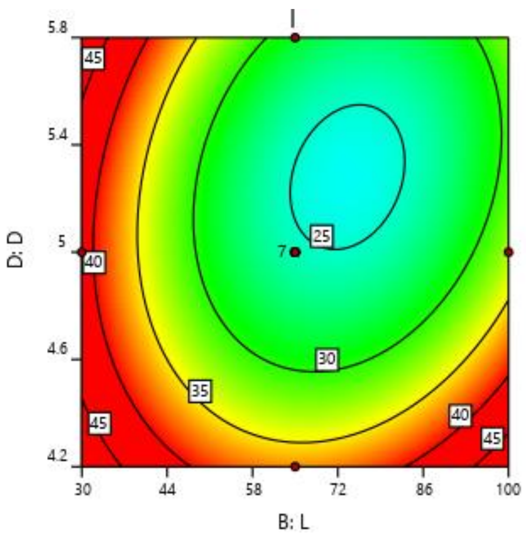

Fig.7: Contour plot of SD

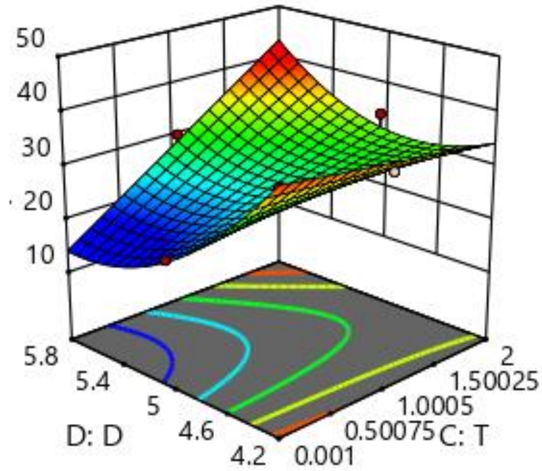

Fig.9: Contour plot of LD

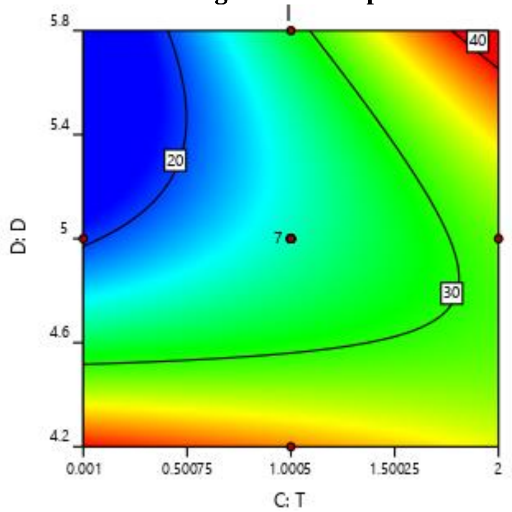

Fig.11:Contour plot of TD

The response surface for term BD has been drawn by drawing 'B' on X-axis, 'D' on Y-axis and the response 'I' on the Z-axis as shown in Fig 8. The red dots on the response surface indicate the design points. The change in response impact toughness (I) is more vulnerable to change to tool size (D) than change in tool linear speed (B) while keeping the other factors tool rotation speed (S) and tool tilt angle (T) at 800 rpm and 0.001 degrees respectively.

The response surface for term TD has been drawn by drawing on X-axis, 'D' on Y-axis and the response 'I' on the Z-axis as shown in Fig 10. The red dots on the response surface indicate the design points. The change in response impact toughness (I) is more vulnerable to change to the change in tool size (D) than the change in tool tilt angle (T) while keeping the other factors tool rotation speed (S) and tool linear speed (L) at 800 rpm and 65 mm/min respectively.

IV. OPTIMIZATION

Response surface methodology may be further used to find the optimum values of the input parameter to achieve the maximum value of impact strength. A numerical method has been used to optimize the impact strength (I) with the values as presented in Table-VI. The maximum values of the impact strength as per RSM are 72 joules with desirability value 0.872.

Confirmation runs were performed and the value of the output I was found in close tolerances of the maximum value.

Table VI: Optimization of the input factors

S	L	T	D	I	Desirability
999.9	30.0	2.0	5.7	72.1	0.872

V. RESULT AND DISCUSSION

1. The impact strength of friction stir welded joints of 6082T651 and 5083 O has been modeled in terms of the rotational speed of the tool, linear speed, tool tilt angle and side of the square pin.
2. The quadratic equation for predicting impact strength using response surface methodology has been generated with a 95% confidence level and competency of the equation has been verified using ANOVA.
3. Tool rotation speed has the least influence in case of main effects whereas interaction of tool tilt angle and square pin side has maximum influence on impact strength.
4. Response surface and contour plots have been drawn and analyzed for interactions analysis and seeking optimization in the least time.
5. The maximum value of impact strength has been found to be 72.1 Joules at a rotation speed, linear speed of the tool, tool tilt angle and square shape pin size of 999.9 rpm, 30 mm/min, 2.0 degree and 5.7 mm respectively.

VI. CONCLUSION

while seeking a combined effect of various input parameters on FSW joints impact strength, tool rotation speed variation has been evaluated to have the least influence on it. However, pin size is a relatively second most influential factor after tool tilt angle. The maximum value of impact strength has been achieved at 2-degree tool tilt angle and square pin side as 5.7 mm. A model establishing the relationship between the impact strength and input factors all varying simultaneously with high adequate precision has been generated and found to be sufficiently accurate. The relationship may be used for a forecast of the impact strength of FSW plates of thickness 6.35mm 5083 O and 6082 T651 with high accuracy.

REFERENCES

1. "P.A. Schweitzer, Aluminum and aluminum alloys, Met. Mater. Phys. Mech. Corros. Prop. (2003).
2. M. Ilangovan, S. R. Boopathy, and V. Balasubramanian, "Effect of tool pin profile on microstructure and tensile properties of friction stir welded dissimilar AA 6061–AA 5086 aluminum alloy joints," Def. Technol., vol. 11, no. 2, pp. 174–184, 2015.
3. R. I. Rodriguez, J. B. Jordon, P. G. Allison, T. Rushing, and L. Garcia, "Microstructure and mechanical properties of dissimilar friction stir welding of 6061-to-7050 aluminum alloys," Mater. Des., vol. 83, pp. 60–65, 2015.
4. D. Lohwasser and Z. Chen, Friction stir welding: From basics to applications. Elsevier, 2009.
5. N. Kulkarni, R. S. Mishra, and W. Yuan, Friction stir welding of dissimilar alloys and materials. Butterworth-Heinemann, 2015.
6. A. K. Lakshminarayanan and V. Balasubramanian, "Comparison of RSM with ANN in predicting tensile strength of friction stir welded AA7039 aluminum alloy joints," Trans. Nonferrous Met. Soc. China, vol. 19, no. 1, pp. 9–18, 2009.
7. J. Marzbanrad, M. Akbari, P. Asadi, and S. Safaee, "Characterization of the influence of tool pin profile on microstructural and mechanical properties of friction stir welding," Metall. Mater. Trans. B, vol. 45, no. 5, pp. 1887–1894, 2014.
8. J. F. Guo, H. C. Chen, C. N. Sun, G. Bi, Z. Sun, and J. Wei, "Friction stir welding of dissimilar materials between AA6061 and AA7075 Al alloys effects of process parameters," Mater. Des. 1980-2015, vol. 56, pp. 185–192, 2014.

AUTHORS PROFILE

Arun Gupta is presently working as an Assistant professor at Delhi Institute of Tool Engineering, Govt. of NCT of Delhi. He completed B.Tech. in Mechanical and Automation Engineering in 2003. He completed Masters in Engineering (M.E.) from Birla Institute of Technology and Science, Pilani (BITS Pilani) in Design Engineering. His research Area is Production Engineering and specifically Welding. He has more than three years of industrial experience and approximately 10 years of teaching experience and especially teaching Design engineering subjects like Strength of Materials, Theory of Machines, Machine Design, Engineering Mechanics, Finite Element Methods etc. He has published research papers in various National and International conferences and journals.

Vipin is presently working as Professor& HOD, Department of Mechanical Engineering, Delhi Technological University, Delhi. He is a graduate from Delhi College of Engineering in Mechanical Engineering and Post Graduate in Production Engineering from the Indian Institute of Technology, Delhi. He was awarded Ph.D. Degree from Delhi University. He has more than twenty-five years of teaching & research experience. He has published numerous research papers in various National and International journals & conferences. He has organized international conferences, FDP and STTP. He is the chief editor of the conference proceeding of ICAPIE 2016. His research areas are Production Engineering including optimization, composites, conventional/non-conventional Machining FSP/FSW, Welding, etc.