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Modeling and optimization of friction stir welding parameters in joining 5086 H32 aluminium alloy

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Abstract. The present manuscript focuses on developing a mathematical model to predict the intergranular corrosion rate of friction stir welded AA5086 H32 aluminium alloy joints. Six factors-five levels central composite design matrix, having 52 experiments, was used in the design of experiments. The developed model was used to examine the impact of studied process parameters, i.e., rotational speed, welding speed, tool shoulder diameter, tool hardness, tilt angle, and pin profile, on intergranular corrosion rate of the welded joints. Response surface methodology was used to optimize the process parameters in minimizing the susceptibility to intergranular corrosion attack. The optimum combination of studied parameters to have minimum corrosion rate, i.e., 3.2 mg/cm^2, was 1296 rpm rotational speed, 79.4 mm/min welding speed, 14.9 mm tool shoulder diameter, 47.4 HRC tool hardness, 2.38° tilt angle, and square pin profile.

1. Introduction

Friction Stir Welding (FSW) is a non-conventional technique used to weld similar or dissimilar materials with the application of frictional heat produced due to relative motion between the workpieces and rotating tool [1]. The rotating pin of the welding tool is inserted into the material until the top stratum of the workpieces starts rubbing against the tool shoulder followed by feeding the tool transversely [2], as illustrated in Figure 1. The material gets softened due to frictional heat and starts flowing with the pin, which acts as a stirrer for the softened material; consequently, extrusion of the material starts from leading to trailing edges of the tool. The extruded material gets pressed by the forging action of the tool shoulder, which ultimately produces a solid bond between the workpieces to be joined. The pattern of material flow depends upon the FSW process parameters, which in turn determine the quality of the joint produced. The parameters showing dominance in affecting the performance characteristics of aluminium alloy joints fabricated using FSW are rotational and transverse speeds of the welding tool; however, other parameters like tool shoulder diameter, tilt angle, pin profile, and hardness of tool material also have considerable impact [3-5]. FSW is different from conventional joining methods in terms of temperature rise during the process, which is lower than the melting point of the workpiece materials in it, resulting in avoidance of many solidification defects that otherwise occur during the conventional welding techniques [6]. FSW is considered to be one of the most epochal inventions in the past decades as it has all the potential to join light structural materials like aluminium and its alloys, which are difficult to join using fusion welding methods [7,8].

The demand for aluminium and its alloys, in sheet and plate forms, is increasing in fabrication

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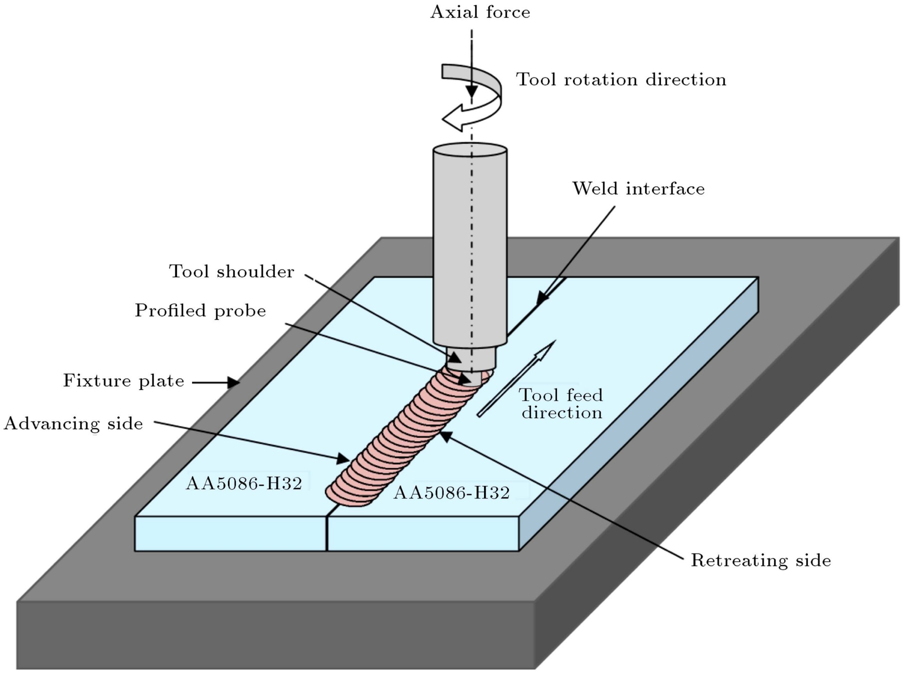

Figure 1. Schematic view of friction stir welding.

industries for various applications like bridge decks, ship panels, aerospace, and transportation components due to their light weight and low distortion [9]. AA5086 is representative of non-heat-treatable 5xxx series of aluminium alloys having high formability and moderate strength. It has applications in marine, automotive, and aerospace industries in fabrication of light structural components, where strength to weight ratio is a major concern and has to be as much as possible [10].

Colligan investigated the relevance of FSW to offshore and marine industries and suggested it as a cost-diminishing and defect-free joining method as compared to conventional joining methods [11]. Taban and Kaluc showed the superiority of FSW to the conventional joining methods in fabrication of AA5086 aluminium alloy joints [12]. Influence of rotational and welding speeds on microstructural and mechanical properties of AA5086 joints was studied by Aval and Loureiro and a sensible correlation between the studied parameters was found [13]. Jamalian et al. suggested the appropriate combination of welding parameters to get sound and defect-free AA 5086 aluminium alloy joints produced using FSW [14]. Amini and Gharavi experimentally set up the proportional relation between corrosion current density in heat affected zone and welding speed of tool in FSW of AA5086 aluminium alloy [15]. The microstructural and mechanical properties of AA5086 joints are different from those of the base material as explained by the numerous studies reported in the literature; on the other hand, corrosion behavior of the joints has received rare attention.

RSM is a promising technique with the average experimental error in predicting the response lower than those of the other optimization techniques. The significance of square and interaction terms can more easily be understood through RSM, whereas other optimization techniques, e.g., Taguchi, can be used only for linear interactions due to the aliasing in the interaction with the main effects [16]. The variation of response, as a function of control factors, can clearly be visualized through 3D response surfaces in RSM, whereas Taguchi technique provides only the average value of a response for particular levels of control factors.

Hence, an attempt is made to explore the influence of FSW parameters on intergranular corrosion behavior of AA5086 H32 joints. A mathematical model is developed to predict intergranular corrosion rate as a function of rotational and welding speeds, shoulder diameter, hardness of tool material, tilt angle, and pin profile. Response Surface Methodology (RSM) is utilized for optimization of the studied FSW parameters to minimize intergranular corrosion rate of AA5086 H32 joints.

2. Materials and methodology

Aluminium alloy AA5086 H32 sheet of 5 mm thickness was cut into small rectangular pieces having dimensions 200 mm×75 mm each, followed by edge preparation to secure precise butt configuration of two such pieces in welding. Tables 1 and 2 present the mechanical properties and chemical composition, respectively, of the base metal used in the study. The potential FSW process parameters affecting the quality of aluminium

Table 1. Mechanical properties of AA5086-H32.

UTS (MPa)	Yield strength (MPa)	Elongation (%)	Hardness (HV)	CR (mg/cm^2)
288	248	12	88	9.2

Table 2. Chemical composition of AA5086-H32.

Elements	Mg	Mn	Si	Fe	Cu	Zn	Cr	Ti	Ni	Al
Wt (%)	4.2	0.59	0.07	0.16	0.05	0.15	0.08	0.06	0.01	Balance

alloy joints, namely tool rotational speed (N), tilt angle (A), pin profile (P), welding speed (S), tool hardness (H), and diameter of tool shoulder (D), were identified based on their dominance and availability in experimental setup. The working range of the parameters was selected through review of the literature and trial experiments [17]. Six factor-five levels half fraction Central Composite Design (CCD) was chosen for Design Of Experiments (DOE). Table 3 shows the process parameters and their respective levels. The lower and upper levels of each parameter were coded as -2.37 and $+2.37$, while other three equidistant levels were coded as $+1$, 0, and -1. The selected DOE, consisting of 12 star points, 8 center points, and 32 fractional factorial design points ($2^6/2 = 32$), was considered to be an efficient tool for prediction and optimization of performance characteristics of friction stir welded joints [18,19]. The matrix, having 52 combinations of different levels for the selected process parameters, is shown in coded form in Table 4. Fifteen tools of H13 steel, having dissimilarity in pin profile, hardness, and shoulder diameter, were fabricated to meet the requirements of the design matrix. Figure 2 presents the tool pin profiles, i.e., Straight Cylindrical (SC), pentagonal (PT), square (SQ), hexagonal (HX), and Threaded Cylindrical (TC), used in the present study. A tailor made fixture was fabricated to fasten the pieces so as to withstand the welding forces. Single pass welding, parallel to the rolling direction of parent alloy, was carried out to join the workpieces. A Computerized Numerically Controlled (CNC) vertical milling center was used to carry out the experiments.

Figure 2. Tool pin profiles (SC, TC, SQ, PT, and HX).

Fifty-two experiments were performed by varying the parameters at a predefined level, as suggested by the design matrix. The machine parameters, i.e., rotational and welding speeds of the tool, were controlled through CNC program. The tool parameters, i.e., shoulder diameter, pin profile, and tool hardness, were controlled by changing the welding tool for each experiment. Tool tilt angle was controlled by tilting the fixture on which the workpieces rested during welding.

Intergranular corrosion rate of the welded specimens was studied as per the ASTM G67 standard [20]. Nitric Acid Mass Loss Test (NAMLT) was considered

Table 3. Identified parameters and levels.

Parameter	Notation	Unit	Levels				
			−2.37	**−1**	**0**	**1**	**+2.37**
Rotational speed	N	rpm	724	1000	1200	1400	1675
Welding speed	S	mm/min	37	65	85	105	132
Shoulder diameter	D	mm	7.8	12	15	18	22.1
Tool hardness	H	HRC	33	40	45	50	56
Tilt angle	A	Degree	0.8	1.5	2	2.5	3.2
Pin profile	P	—	SC	PT	SQ	HX	TC

Table 4. DOE matrix and experimental results.

Experiment number	Factors						CR (mg/cm^2)
	N	***S***	***D***	***H***	***A***	***P***	
1	-1	-1	-1	-1	-1	-1	8.8
2	1	-1	-1	-1	-1	1	6.6
3	-1	1	-1	-1	-1	1	7.2
4	1	1	-1	-1	-1	-1	6.4
5	-1	-1	1	-1	-1	1	8.4
6	1	-1	1	-1	-1	-1	7.6
7	-1	1	1	-1	-1	-1	7.7
8	1	1	1	-1	-1	1	6.2
9	-1	-1	-1	1	-1	1	8
10	1	-1	-1	1	-1	-1	5.8
11	-1	1	-1	1	-1	-1	6.9
12	1	1	-1	1	-1	1	5.7
13	-1	-1	1	1	-1	-1	7.9
14	1	-1	1	1	-1	1	6.7
15	-1	1	1	1	-1	1	7.6
16	1	1	1	1	-1	-1	6.5
17	-1	-1	-1	-1	1	1	8.3
18	1	-1	-1	-1	1	-1	7.3
19	-1	1	-1	-1	1	-1	8.8
20	1	1	-1	-1	1	1	6.4
21	-1	-1	1	-1	1	-1	8.7
22	1	-1	1	-1	1	1	6.5
23	-1	1	1	-1	1	1	7.7
24	1	1	1	-1	1	-1	6.7
25	-1	-1	-1	1	1	-1	6.5
26	1	-1	-1	1	1	1	4.5
27	-1	1	-1	1	1	1	6.8
28	1	1	-1	1	1	-1	5.5
29	-1	-1	1	1	1	1	6.7
30	1	-1	1	1	1	-1	5.3
31	-1	1	1	1	1	-1	7.1
32	1	1	1	1	1	1	5.7
33	-2.38	0	0	0	0	0	8.8
34	2.38	0	0	0	0	0	6.8
35	0	-2.38	0	0	0	0	5.3
36	0	2.38	0	0	0	0	7.3
37	0	0	-2.38	0	0	0	7.6
38	0	0	2.38	0	0	0	6.4
39	0	0	0	-2.38	0	0	8.2
40	0	0	0	2.38	0	0	6.8
41	0	0	0	0	-2.38	0	6.3
42	0	0	0	0	2.38	0	4.2
43	0	0	0	0	0	-2.38	7.1

Table 4. DOE matrix and experimental results (continued).

Experiment number	Factors						CR (mg/cm^2)
	N	***S***	***D***	***H***	***A***	***P***	
44	0	0	0	0	0	2.38	5.3
45	0	0	0	0	0	0	6.2
46	0	0	0	0	0	0	3.1
47	0	0	0	0	0	0	3.9
48	0	0	0	0	0	0	3.5
49	0	0	0	0	0	0	3.1
50	0	0	0	0	0	0	2.7
51	0	0	0	0	0	0	3
52	0	0	0	0	0	0	3.4

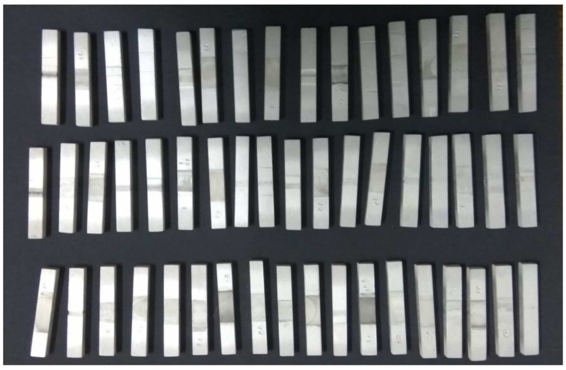

Figure 3. Corrosion test specimens (after test).

to examine the susceptibility of AA5086 H32 FSWed joints to intergranular corrosion. The weldments were sliced to prepare the corrosion test samples, as shown in Figure 3. The prepared samples were immersed in 5% NaOH solution and kept in hot air oven maintained at a temperature of 80°C for 1 minute followed by water rinse. Desmutting of the samples was done by immersion in nitric acid for 30 seconds followed by water rinse. An electronic weighing balance, having least count of 0.1 mg, was used to measure the weight of individual sample. The samples were immersed in test solution for 24 hours followed by water rinsing and gentle brushing to remove all corroded particles. The samples were weighted again with the same weighing balance and the loss of mass was calculated.

The testing was performed on a total of 104 samples taking two samples from each welded joint in order to reduce experimental errors. To get better accuracy, arithmetic mean was taken to determine the corrosion rate, i.e., mass loss per unit area, for each experiment/joint, which is given in Table 4.

3. Results and Discussion

The response variable, namely intergranular Corrosion Rate (CR), may be expressed as a function of input process parameters, i.e., tool rotational speed (N), tilt angle (A), pin profile (P), welding speed (S), tool material hardness (H), and tool shoulder diameter (D), as shown in Eq. (1):

$$CR = f(N, S, D, H, A, P). \quad (1)$$

The response surface 'Y' can be represented as a second-order polynomial expression as given in Eq. (2):

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

The above expression can be expanded to a six factors-five levels design as shown in Eq. (3):

$$\begin{aligned} CR = {} & b_0 + b_1(N) + b_2(S) + b_3(D) + b_4(H) + b_5(A) \\ & + b_6(P) + b_{11}(N^2) + b_{22}(S^2) + b_{33}(D^2) \\ & + b_{44}(H^2) + b_{55}(A^2) + b_{66}(P^2) + b_{12}(NS) \\ & + b_{13}(ND) + b_{14}(NH) + b_{15}(NA) + b_{16}(NP) \\ & + b_{23}(SD) + b_{24}(SH) + b_{25}(SA) + b_{26}(SP) \\ & + b_{34}(DH) + b_{35}(DA) + b_{36}(DP) + b_{45}(HA) \\ & + b_{46}(HP) + b_{56}(AP). \quad (3) \end{aligned}$$

The coefficients of intercept (b_o), single (b_i), quadratic (b_{ii}), and interaction (b_{ij}) terms in the above expression were calculated using the matrix method as explained by Eq. (4) and put into Eq. (3) to determine the final model for predicting the intergranular corrosion rate of FSWed AA5086 H32 joints. The developed model, in terms of coded factors, is presented in Eq. (5):

$$b = (X'X)^{-1} X'Y, \quad (4)$$

$$\begin{aligned} CR = {} & 3.61 - 0.66(N) + 0.0031(S) \\ & + 0.015(D) - 0.45(H) - 0.24(A) - 0.20(P) \\ & + 0.75(N^2) + 0.49(S^2) + 0.61(D^2) + 0.70(H^2) \\ & + 0.30(A^2) + 0.47(P^2) + 0.072(NS) \\ & + 0.078(ND) + 0.0031(NH) - 0.053(NA) \\ & - 0.034(NP) - 0.016(SD) + 0.17(SH) \\ & + 0.20(SA) - 0.0031(SP) + 0.13(DH) \\ & - 0.091(DA) + 0.016(DP) - 0.27(HA) \\ & + 0.15(HP) - 0.066(AP). \quad (5) \end{aligned}$$

The adequacy of the developed mathematical model was checked by analysis of variance (ANOVA) at 95% confidence level and the results are presented in Table 5. The results showed the significant performance of the model, and intergranular corrosion rate of FSWed AA5086 H32 joints might be predicted without actual experimentation using the developed mathematical model. The 'lack of fit' in the model was determined to be insignificant relative to pure error, which was desirable for any model to fit the predicted data. Figure 4 shows the deviation of observed valves of corrosion rate from the values predicted by the model. The coefficient of determination, i.e., R^2, is a statistical term, ranging from 0 to 1, which measures the amount of variation that can be explained by the developed model and should approach unity for a model to be perfect. The value of R^2, for the model developed in the present research work, came out to be 0.8882, indicating that approximately 89% of the variation in the response was explained by the input variables. The difference in predicted R^2 and adjusted R^2 should be less than 0.2 to have reasonable agreement between the two and for the developed model, it came out to be 0.1339, which was within the desired limit. Figure 5 presents the normal plot of residuals showing the normal distribution of the externally studentized residuals about the mean. The signal to noise ratio can be quantified by the term 'adequate precision', which must be greater than 4 for a model to be capable of navigating design space. The adequate precision for the developed model was 9.996, indicating the adequacy of the signal. The Coefficient of Variation (C.V.) was used as the standardized measure of dispersion and should be as low as possible, ranging from 0 to 1. The C.V. for the developed model was 0.1245, indicating the satisfactory dispersion of the data. Three test

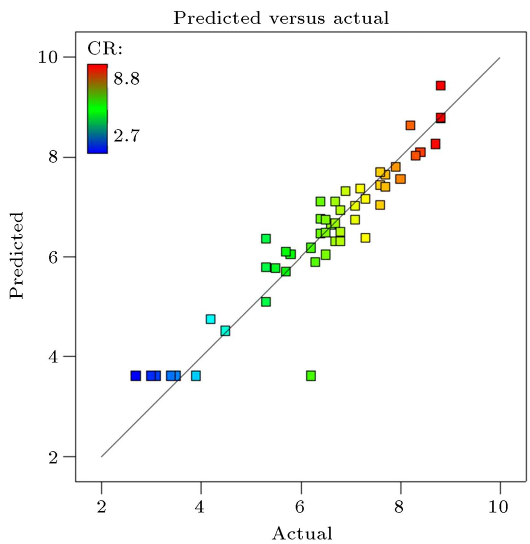

Figure 4. Actual versus predicted corrosion rates.

Table 5. ANOVA test results.

Source	**Sum of squares**	**df**	**Mean square**	***F*−value**	***p*−value prob>*F***	
Model	120.11	27	4.45	7.06	< 0.0001	significant
N, rotational speed	18.70	1	18.70	29.69	< 0.0001	
S, welding speed	7.456E-005	1	7.456E-005	1.184E-004	0.9914	
D, shoulder diameter	9.632E-003	1	9.632E-003	0.015	0.9026	
H, tool hardness	8.72	1	8.72	13.84	0.0011	
A, tilt angle	2.54	1	2.54	4.04	0.0559	
P, pin profile	1.78	1	1.78	2.83	0.1056	
NS	0.17	1	0.17	0.26	0.6131	
ND	0.20	1	0.20	0.31	0.5827	
NH	3.125E-004	1	3.125E-004	4.963E-004	0.9824	
NA	0.090	1	0.090	0.14	0.7082	
NP	0.038	1	0.038	0.060	0.8085	
SD	7.813E-003	1	7.813E-003	0.012	0.9122	
SH	0.95	1	0.95	1.50	0.2324	
SA	1.32	1	1.32	2.10	0.1605	
SP	3.125E-004	1	3.125E-004	4.963E-004	0.9824	
DH	0.53	1	0.53	0.83	0.3701	
DA	0.26	1	0.26	0.42	0.5244	
DP	7.813E-003	1	7.813E-003	0.012	0.9122	
HA	2.26	1	2.26	3.59	0.0704	
HP	0.75	1	0.75	1.19	0.2858	
AP	0.14	1	0.14	0.22	0.6441	
N^2	32.87	1	32.87	52.20	< 0.0001	
S^2	13.79	1	13.79	21.90	< 0.0001	
D^2	21.68	1	21.68	34.43	< 0.0001	
H^2	28.40	1	28.40	45.11	< 0.0001	
A^2	5.29	1	5.29	8.40	0.0079	
P^2	12.81	1	12.81	20.34	0.0001	
Residual	15.11	24	0.63			
Lack of fit	6.54	17	0.38	0.31	0.9758	Not significant
Pure error	8.57	7	1.22			
Cor total	135.22	51				

runs were conducted to confirm the predictions of the developed model, taking the combinations of input variables other than those in design matrix, and the results are shown in Table 6. The maximum error, out of three confirmatory test runs, came out to be 2.95%, confirming the adequacy of the developed mathematical model.

The influence of process parameters on intergranular corrosion rate of FSWed AA5086 H32 joints was analyzed using the developed model. MATLAB software package was used to generate a code for the developed mathematical relation between the corrosion rate and input variables and furthermore, to examine the effect of individual factors on corrosion rate by varying one factor at a time and keeping other factors at their intermediate levels. Figure 6 presents the effect of rotational speed on corrosion rate for all five pin profiles used in the present study. All the joints showed better corrosion resistance than the parent alloy irrespective of the speed at which welding tool was rotated during welding process. An improvement in corrosion resistance was observed as rotational speed was raised up to 1300 rpm, beyond which an increase in corrosion rate was observed, and this trend was common for all pin profiles. Figure 7 presents the impact of welding speed on the corrosion behavior of FSWed joints. It

Table 6. Confirmation test results.

Experiment no.	Input process parameters						Response (CR) mg/cm^2		Error (%)
	N (RPM)	S (mm/min)	D (mm)	H (HRC)	A (degree)	P	Predicted	Experimental	
1	1300	75	15	45	2.5°	SQ	3.50	3.58	2.23
2	1300	95	15	45	2°	SQ	3.61	3.72	2.95
3	1100	85	15	45	2.5°	SQ	4.41	4.51	2.22

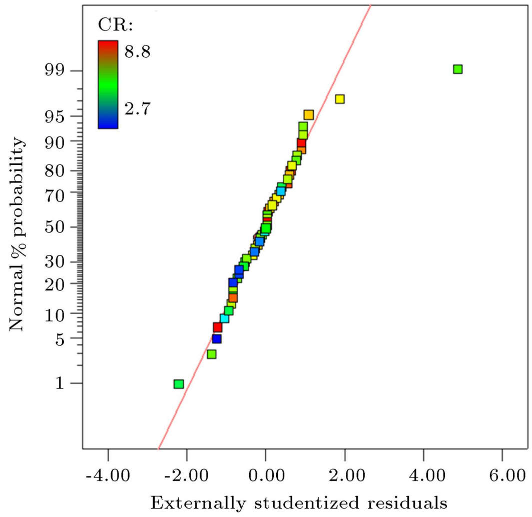

Figure 5. Normal probability plot of residuals.

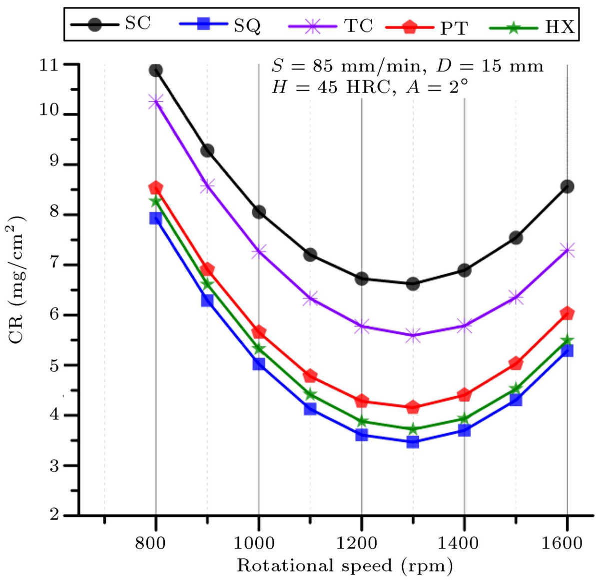

Figure 6. Effect of rotational speed on corrosion rate.

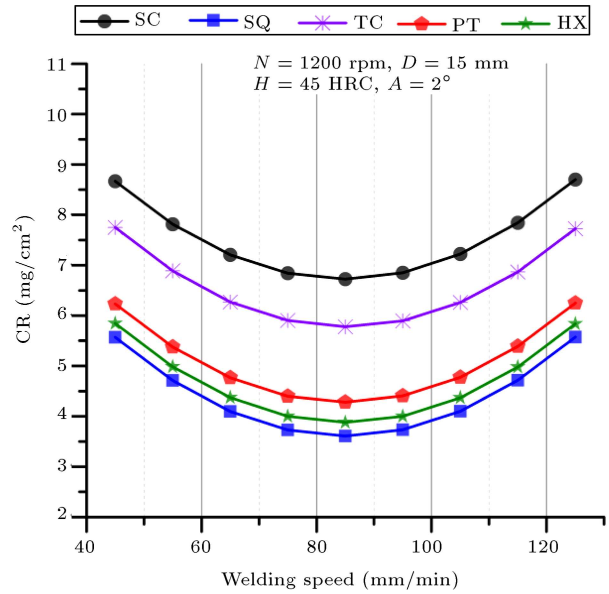

Figure 7. Effect of welding speed on corrosion rate.

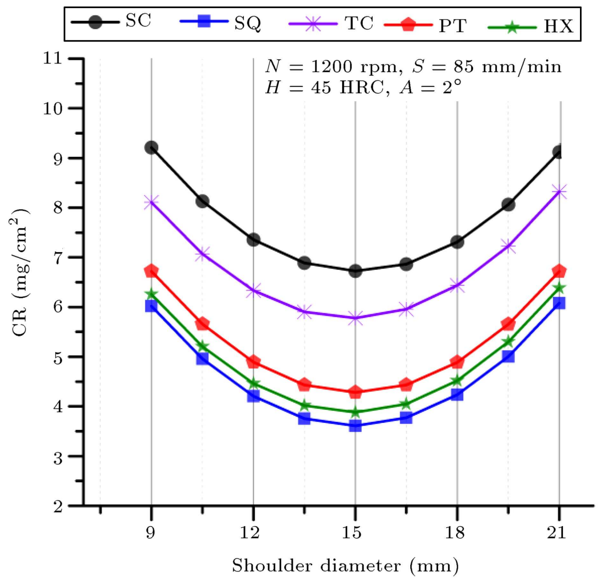

Figure 8. Effect of shoulder diameter on corrosion rate.

is clear from the figure that the joints produced by 80 mm/min to 100 mm/min welding speed had less susceptibility to intergranular corrosion irrespective of the type of pin profile used. Figures 8, 9, and 10 show the variation in corrosion rate as a function of shoulder diameter, tool hardness, and tilt angle, respectively, and confirm that these parameters have significant influence on the joint performance. The profiles of the tool pin also had considerable effect on corrosion rate as they were responsible for material movement during the welding process. The ratio of static to dynamic volume

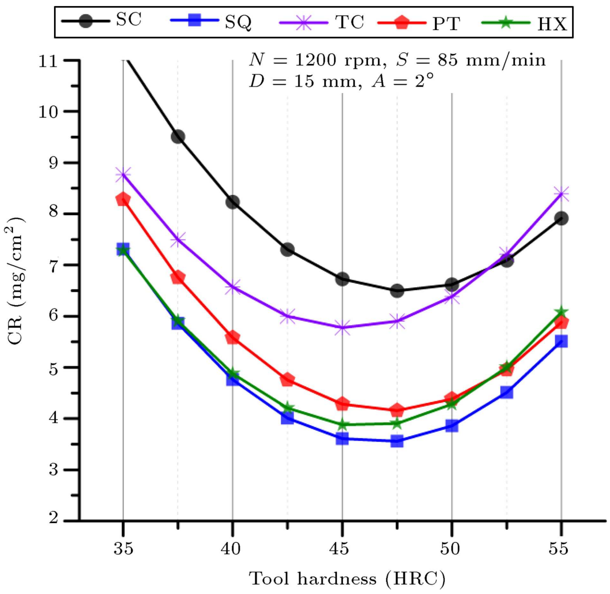

Figure 9. Effect of tool hardness on corrosion rate.

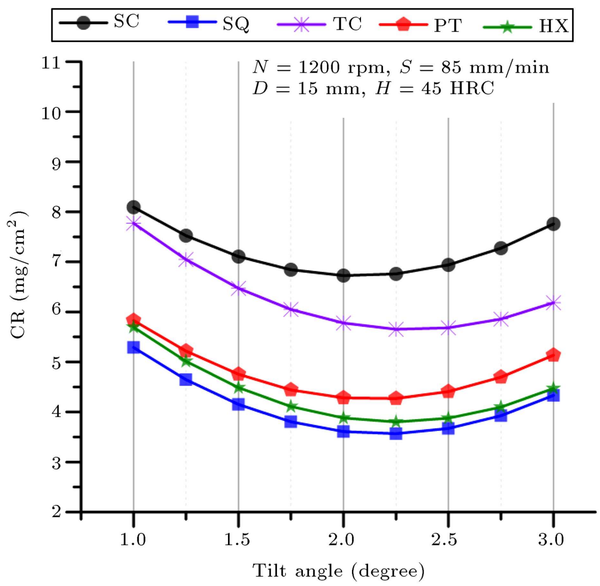

Figure 10. Effect of tilt angle on corrosion rate.

along with pulsating action of the tool pin controls the material flow pattern and ultimately affects the weld quality. The square pin profile shows better results irrespective of the combination of other process parameters, followed by hexagonal and pentagonal pin profiles. The square, pentagonal, and hexagonal pins produce 80 pulses/sec, 100 pulses/sec, and 120 pulses/sec, respectively, at 1200 rpm rotational speed during stirring of the materials. Although the pulse frequencies of pentagonal and hexagonal pin profiles are more than that of the square pin profile, the latter one provides better quality joints due to its better static to dynamic volume ratio, namely 1.57, than the pentagonal and hexagonal having the ratios of 1.32 and 1.209, respectively. In NAMLT test, intergranular corrosion in AA5086 H32 aluminum alloy was made by dissolution of β-phase (βAl-Mg) in aluminum matrix. The preferential attack of the precipitates of the dissolved compound around the grain boundaries caused the grains to corrode away from the specimen. Hence, the arrangement of β-phase compound, and average size and pattern of grains of the test specimen have key role in identifying the susceptibility to intergranular corrosion attack. The microstructural examination presented in Figures 11 and 12 shows refinement in grain size of nugget zone of the welded specimens as compared to the parent alloy and this justifies the improvement in corrosion resistance.

RSM was utilized for FSW parameters optimization to minimize the intergranular corrosion rate of AA5086 H32 joints. RSM is an efficient tool to establish mathematical relation between response and input variables affecting the response and hence, optimizing the process parameters as per the desired criteria [21]. The response surface and contour plots can be drawn as a function of interaction between any two input variables to explore the variation in response parameter. The apex and nadir of the surface give the optimum value if their desired criteria are to maximize and to minimize the response, respectively. In the present study, the desired criterion was to minimize the response; that is, it was intergranular corrosion rate, which should be as low as possible for any structure to be durable. The response surfaces and contour plots, showing the variation in corrosion rate, are presented in Figure 13. The input parameters corresponding to optimum value of corrosion rate, i.e., 3.2 mg/cm^2, were observed to be 1296 rpm rotational speed, 79.4 mm/min welding speed, 14.9 mm tool shoulder diameter, 47.4 HRC tool hardness, 2.38°tilt angle, and square pin profile.

4. Conclusion

FSW was successfully employed to join 5 mm thick AA5086 H32 aluminum alloy sheets. An adequate mathematical model was developed to predict intergranular corrosion rate of the FSWed AA5086 H32 joints. The impact of various input variables on the corrosion rate of welded specimens was studied with the help of the developed model and it was concluded that the studied parameters significantly affected the joint quality. The corrosion resistance of the FSWed specimens was found to be improved as compared to that of the base material. RSM was successfully utilized to optimize the process parameters and the optimum level of studied parameters were determined as 1296 rpm rotational speed, 79.4 mm/min welding speed, 14.9 mm tool shoulder diameter, 47.4 HRC tool hardness, 2.38° tilt angle, and square pin profile.

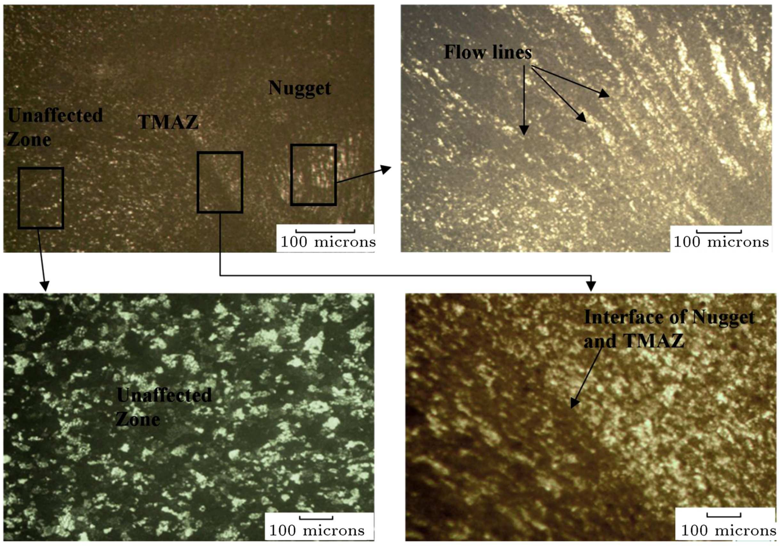

Figure 11. Microstructure of friction stir welded specimen.

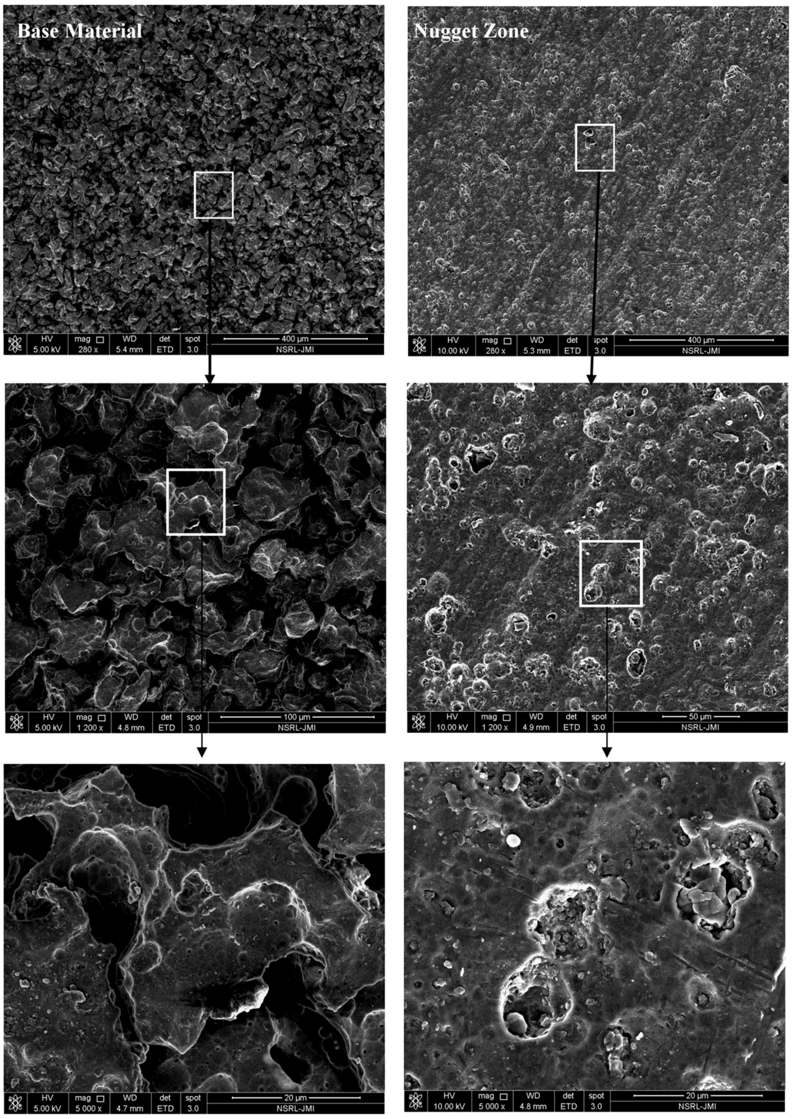

Figure 12. SEM micrographs of base material and nugget zone of welded specimen (after corrosion).

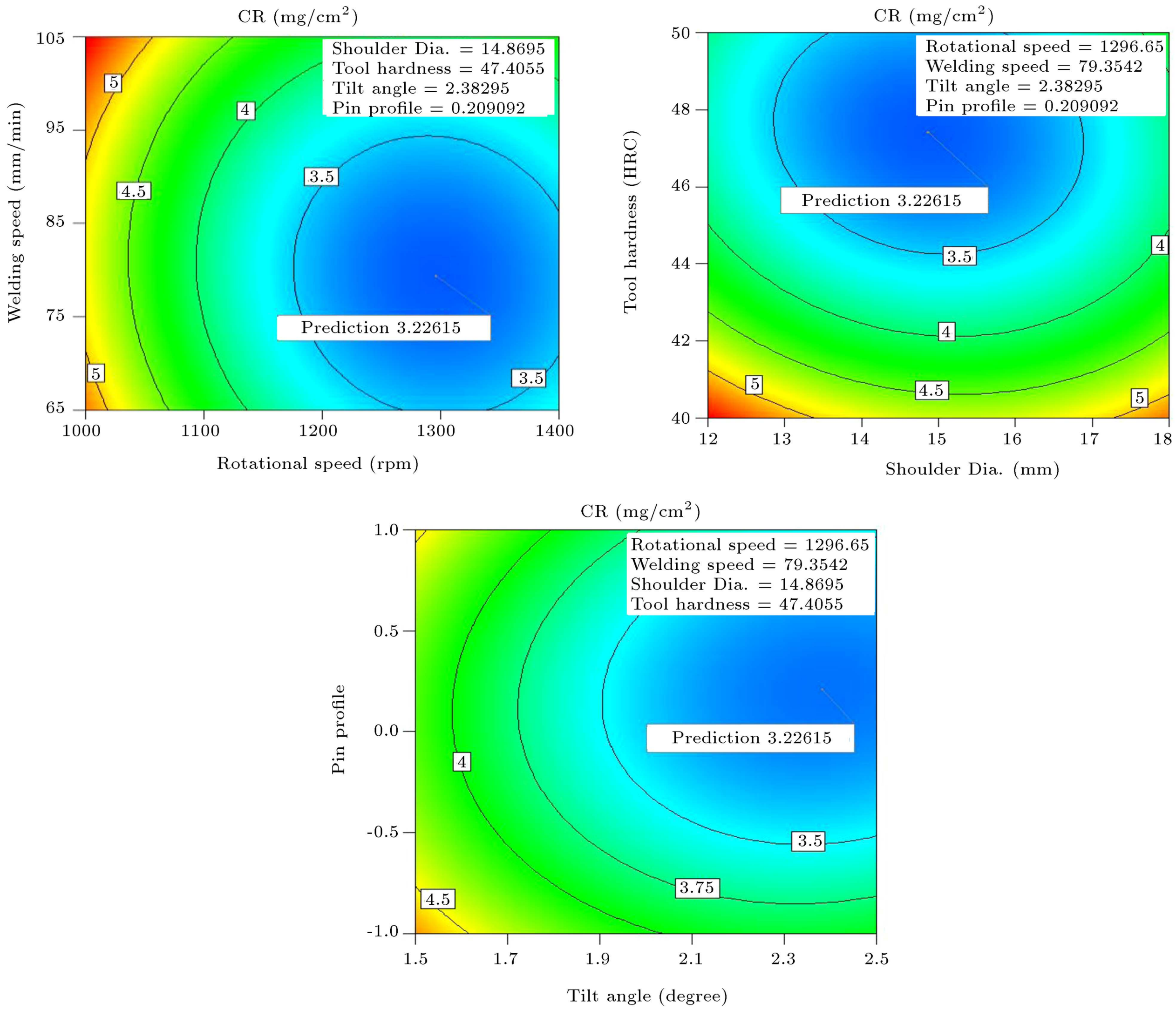

Figure 13. Contour plots of interaction effect of input parameters on corrosion rate.

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