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PROCESS PARAMETER OPTIMIZATION OF PULSED TIG WELDING USING RSM

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Response surface methodology (RSM) is a statistical technique used to optimize the process parameter used in tungsten inert gas welding (TIG) for width of penetration (WOP). In this study influence of various input parameter were determined by using RSM. In this research design expert software 11 has been used to developed surface plot which represent the influence of various input parameter. The Surface plot obtained from Design Expert Software 11 represent that the actual value of response i.e. width of penetration (WOP) versus the predicted value of response are close to each other. The higher value of WOP represents higher strength; result obtained through analysis of variance (ANOVA) gives the highest value of F-ratio of welding current, and this result obtained from RSM showed that welding current is the most influencing parameter which affects performance characteristics.

Keywords: Tungsten Inert Gas Welding, Res ponse Surface Methodology, Central Composite Design, Design Expert Software, Analysis of Variance.

1. Introduction

TIG welding process is used to produce high-quality welds in a wide assortment of materials [1-2]. To enhance the penetration of TIG welding, a minute adjustment of the TIG procedure, i.e. active flux TIG (A-TIG), was first proposed by the E.O. Paton welding institute in the 1960s [1]. Many studies on the mechanism and application technology of the Activating flux TIG (A-TIG) process have been made [3-10]. A-TIG welding has been triumphantly used to weld many metal materials, including stainless steel [11-12] titanium alloys, [13-14] carbon steels, [15] etc. During Arc welding, 4 states of phases developed including solid, liquid, gas and plasma, all the while exist and commonly connect inside a volume of just 1000 mm^3. The temperature broadly goes roughly between 2000^0C in the arc plasma, 3000^0C in the tungsten cathode, 2000^0C in the liquid steel and the room temperature in the surroundings [16]. If plate thickness is increasing difficulties is arising to get proper penetration due insufficient penetration of the arc, this make necessity of edge preparation and use of filler rod of proper combination as shown in table 3 [17], by using argon as a shielding gas weld penetration is achievable in a single welding pass around 3 mm plate

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thickness, while this can be improved to 4 mm to 5 mm by using helium as shielding gas. Many researches are working to improve WOP or productivity of TIG welding [18]. The selection of one parameter at a time is a time consuming process therefore not considered nowadays in manufacturing industry, hence an optimization technique with respect to design of experiment (DOE) such as CCD of RSM to establish optimum condition for tensile strength [25]. In this study the surface plot is used to explain the main and interaction effect of the process parameter to identify the optimum parameter with their values. RSM is widely used statistical technique in process optimization [25].

2. Experimental Methodology

The research work is carried out with following steps given below;

- Identification of process parameter.
- Finding upper and lower limit of the process parameter.
- Selecting orthogonal array.
- Performing experiment as per design matrix
- Recording the responses.
- Using Design expert software to develop mathematical model
- Calculating polynomial coefficients.
- Checking adequacy of the developed model.
- Plotting surface plot to determine the interactive effect of process parameter.
- Analyze the result.

2.1.Selecting the base material & their mechanical properties

Austenitic stainless steel 321 sheets of dimension 75 × 100 × 12 mm are welded autogenously with a butt joint as shown in fig.1 and fig.2 [20]. The chemical composition of base metal, filler metal and mechanical properties of base material used is given in table1, table2 & table3 [27].

Table 1

Chemical Composition by weight %

Grade	C	Mn	Si	P	S	Cr	Ni	N
321	0.08	2.0	0.750	0.045	0.030	19	12	0.10

Table 2

Filler metal Composition

	C	Mn	Si	P	Cr	Ni	Mo	Cu	Al	S
316L	0.02	1.68	0.53	0.012	19.45	9.22	0.116	0.082	0.01	0.03

Table 3

Mechanical Properties of stainless steel 321

Grade	Tensile strength (MPa)	Yield strength (MPa)	Elongation (%)	Hardness	
				Rockwell	Brinell
321	515	205	40	95	217

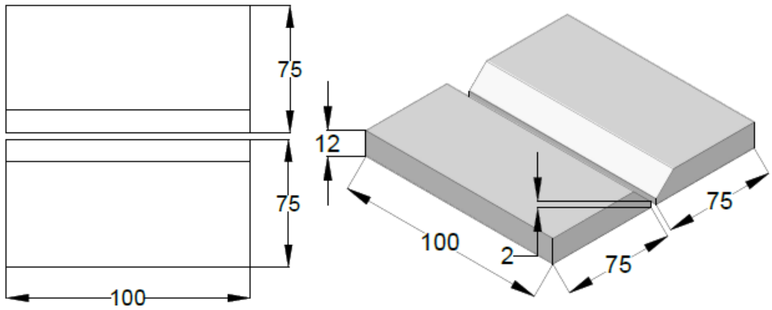

Fig. 1. Sample prepare for butt joint (top & isometric projection view).

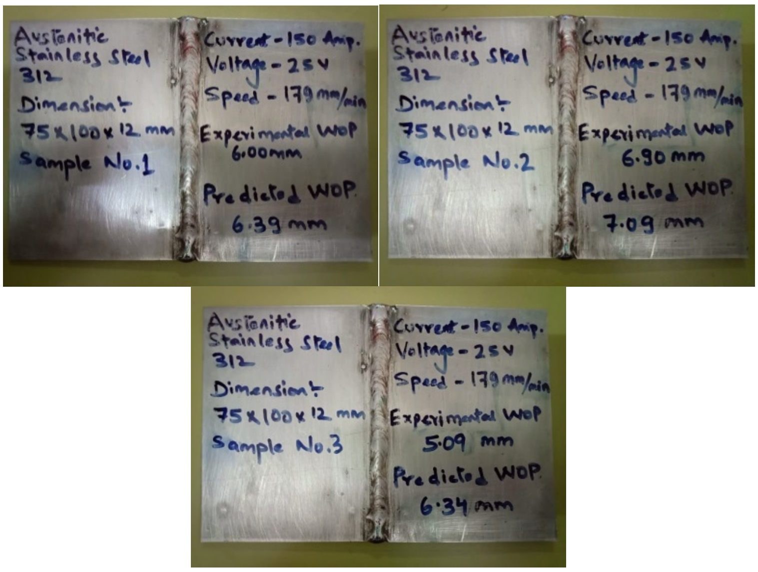

Fig. 2. Austenitic stainless steel sample after welding.

2.2.Process parameters with their working range

From the literature survey [21-22] and researcher work done in past the most important process parameters which are having greater influence on the tensile strength. Austenitic stainless steel 321 sheets of 75mm x 100mm x 12mm dimension was used for butt joint by A-TIG Miller Dnasty©400 208-575 V. Welding current (I), voltage (V), speed (S) and pulse on time are input parameters used for this experiment [23]. Input parameters with their levels are given in table3. The experiment was carried out at optimum in the laboratory. The range of input parameters selected is chosen is given in table 4.

Table 4

Experimental Factor for RSM

Input parameter	**Factor symbol**	**Level 1**	**Level 2**	**Level 3**	**Level 4**	**Level 2**
		-2	**-1**	**0**	**1**	**2**
Welding current (I)	A	140	150	160	170	180
Welding voltage (V)	B	24	25	26	27	28

Welding speed (S)	C	165	179	193	206	218
Pulse on time (%)	D	35	40	45	50	55

Table 5

Design of Experiment or central composite design arrangement

Run	Std	Factor symbol				Actual factor			
		A	B	C	D	Welding current	Welding voltage	Welding speed	Pulse on time
9	1	-1	-1	-1	-1	150	25	179	40
17	2	1	-1	-1	-1	170	25	179	40
12	3	-1	1	-1	-1	150	27	179	40
28	4	1	1	-1	-1	170	27	179	40
16	5	-1	-1	1	-1	150	25	206	40
1	6	1	-1	1	-1	170	25	206	40
20	7	-1	1	1	-1	150	27	206	40
11	8	1	1	1	-1	170	27	206	40
8	9	-1	-1	-1	1	150	25	179	50
24	10	1	-1	-1	1	170	25	179	50
5	11	-1	1	-1	1	150	27	179	50
18	12	1	1	-1	1	170	27	179	50
14	13	-1	-1	1	1	150	25	206	50
6	14	1	-1	1	1	170	25	206	50
27	15	-1	1	1	1	150	27	206	50
23	16	1	1	1	1	170	27	206	50
3	17	-2	0	0	0	140	26	193	45
15	18	2	0	0	0	180	26	193	45
7	19	0	-2	0	0	160	24	193	45
26	20	0	2	0	0	160	28	193	45
19	21	0	0	-2	0	160	26	218	45
4	22	0	0	2	0	160	26	193	45
29	23	0	0	0	-2	160	26	193	35
22	24	0	0	0	2	160	26	193	55
10	25	0	0	0	0	160	26	193	45
2	26	0	0	0	0	160	26	193	45
13	27	0	0	0	0	160	26	193	45
25	28	0	0	0	0	160	26	193	45
21	29	0	0	0	0	160	26	193	45
30	30	0	0	0	0	160	26	193	45

2.3.Central Composite Design (CCD)

The experimental design for this investigation is CCD and the response measured by RSM is the WOP [24-25]. Since the response WOP (y) is the function of input parameter as shown in Eq. 1. To optimize the process parameter for determining WOP, analyze the joined impact of the four diverse autonomous control parameter; welding current, voltage, speed and pulse on time, on WOP. The experimental design used in this study was CCD a two level four factor (2^4 + 2*4 + 6), with a total of 30 experiments was made in this investigation as shown in table 4. The framework for the four factors was ranged between five levels (- α, -1, 0, +1, and +α) [24].

2.4.Response surface methodology

The CCD conditions and responses obtained by performing experiment and RSM are given in tables 5. The WOP produced at different possible combination of process parameters were calculated by measuring the width of welded bead as shown in Fig. 3 and their predicted value is given in table 5.
The statistical steps used are

- RSM include ANOVA,
- Regression analysis, and
- Response surface plots of the interaction effects of the parameter to determine optimum parameter [24]. ANOVA is used to calculate interactive effects of the process parameters.

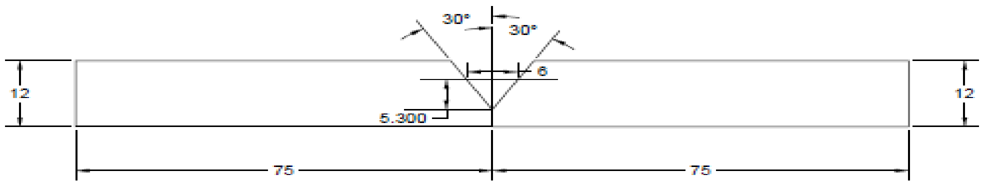

Fig. 3. Butt joint with 6 mm width of penetration (WOP)

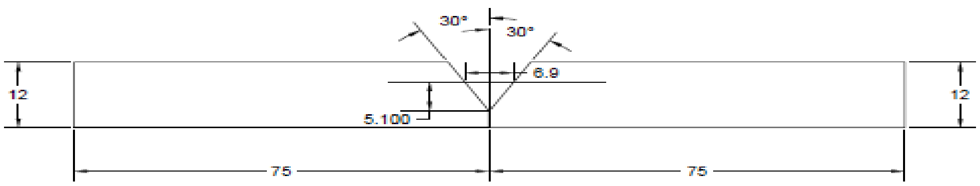

Fig. 4. Butt joint with 6.9 mm width of penetration (WOP)

Table 5

Central composite design

Run	Std	Actual factor				Experimental Value of WOP	Predicted value of WOP	Residual Error
		Welding current	Welding voltage	Welding speed	Pulse on time			
9	1	150	25	179	40	6.00	6.39	-0.39
17	2	170	25	179	40	6.90	7.09	-0.19
12	3	150	27	179	40	5.90	6.34	-0.44
28	4	170	27	179	40	6.20	6.43	-0.23
16	5	150	25	206	40	5.90	5.97	-0.07
1	6	170	25	206	40	5.96	6.06	-0.16

20	7	150	27	206	40	5.98	6.69	-0.71
11	8	170	27	206	40	6.03	6.17	-0.14
8	9	150	25	179	50	5.20	5.67	-0.47
24	10	170	25	179	50	7.60	7.68	-0.08
5	11	150	27	179	50	5.30	5.64	-0.34
18	12	170	27	179	50	6.50	7.04	-0.54
14	13	150	25	206	50	5.12	5.38	-0.26
6	14	170	25	206	50	6.60	6.78	-0.18
27	15	150	27	206	50	5.70	6.12	-0.42
23	16	170	27	206	50	6.80	6.91	-0.11
3	17	140	26	193	45	5.70	4.70	0.99
15	18	180	26	193	45	6.30	6.19	0.11
7	19	160	24	193	45	6.10	5.91	0.19
26	20	160	28	193	45	6.90	5.99	0.91
19	21	160	26	218	45	7.80	7.17	0.63
4	22	160	26	193	45	7.10	6.62	0.47
29	23	160	26	193	35	7.90	7.29	0.61
22	24	160	26	193	55	7.80	7.31	0.49
10	25	160	26	193	45	7.79	7.67	0.12
2	26	160	26	193	45	7.79	7.67	0.12
13	27	160	26	193	45	7.79	7.67	0.12
25	28	160	26	193	45	7.79	7.67	0.12
21	29	160	26	193	45	7.79	7.67	0.12
30	30	160	26	193	45	7.79	7.67	0.12

2.5.Model fitting

WOP is a response which is a function of current, voltage, speed and pulse on time as given in eq. (1). Every parameter of the exploratory arranging in table 4 was fitted to a second order polynomial equation of the second order developed by Design expert software 11 trial version software and presented in eq. (2), aiming to correlate the response parameters with the input parameters [25].

$$y = f(I, V, S, T) \quad (1)$$

Where y = response factor

$$y = B_0 + \sum_{i=1}^{n=4} B_i x_i + \sum_{i=1}^{n=4} B_{ii} x_i^2 + \sum_{i=1}^{n=3} . \sum_{j=i+1}^{n=4} B_{ij}\, x_i x_j + \varepsilon \quad (2)$$

Where y is the estimated response (here tensile strength)

n = no. of control parameters; B_0 = Constant;

B_i = Coefficient of linear (I, V, S & T)

B_{ii} = Coefficient of quadratic (I^2, V^2, S^2 & T^2)

B_{ij} = Coefficient of cross-product (I*V, V*S, S*T & I*T)

ε = Random error.; x = is the regression.

2.6.Regression model

Experiment was performed by varying input parameter using experimental design CCD. By applying regression analysis, the experiment results of the full factorial

CCD were fitted to polynomial eq. (3). The significance of the regression coefficient was measured by p-value, if p-value is less than 0.05 the regression coefficient is significant otherwise insignificant [24]. The response of the process parameter was used to develop a mathematical model shown in eq. (4). CCD is used to developed possible combination of process parameter to determine experimental value. The second order polynomial regression equation fitted between the response WOP (y) and the process parameters: welding current (A), voltage (B), speed (C) and pulse on time (D). From table 6, the ANOVA results showed that the developed model is significant. The mathematical model for WOP content (y) in terms of the coded factors of the process variables is given by eq. (4).

$$WOP(y) = 7.67 + 0.3721*A + 0.0204*B - 0.1363*C + 0.004*D - 0.1519*AB -0.1544*AC + 0.3269*AD + 0.1931*BC + 0.0044*BD + 0.0319*CD - 0.5549*A^2 - 0.42499*B^2 - 0.1924*C^2 - 0.0924*D^2 \quad (3)$$

The eq. (4) in terms of coded factors can be used to make predictions about the response for given levels of each factor. By default, the high levels of the factors are coded as +2 and low levels are coded as -2.

Table 7

ANOVA for the regression model equation

Source	**Coefficient**	**Sum of squares**	**df**	**Mean square**	**F-values**	**p-value**	
Model	7.67	18.92	14	1.35	3.97	0.0060	significant
A-welding current	0.3721	3.32	1	3.32	**9.77**	0.0069	
B-welding voltage	0.0204	0.0100	1	0.0100	0.0294	0.8661	
C-welding speed	-0.1363	0.4455	1	0.4455	**1.31**	0.2704	
D-pulse on time	0.0046	0.0005	1	0.0005	0.0015	0.9698	
AB	-0.1519	0.3691	1	0.3691	1.08	0.3141	
AC	-0.1544	0.3813	1	0.3813	1.12	0.3065	
AD	0.3269	1.71	1	1.71	5.03	0.0405	
BC	0.1931	0.5968	1	0.5968	1.75	0.2052	
BD	0.0044	0.0003	1	0.0003	0.0009	0.9765	
CD	0.0319	0.0163	1	0.0163	0.0478	0.8299	
A^2	-0.5549	8.45	1	8.45	24.83	0.0002	
B^2	-0.4299	5.07	1	5.07	14.90	0.0015	
C^2	-0.1924	1.02	1	1.02	2.98	0.1046	
D^2	-0.0924	0.2342	1	0.2342	0.6883	0.4197	
Residual		5.10	15	0.3402			
Lack of Fit		5.07	10	0.5070	76.04	< 0.0001	significant
Pure Error		0.0333	5	0.0067			
Cor Total		24.02	29				

R^2 = 0.7876 Adj.R^2 = 0.5893

After eliminating the insignificant coefficients from table 7. The mathematical model reduces to eq.5.

$$WOP(y) = 7.67+ 0.3721*A+0.3269*AD-0.5549*A^2-0.42499*B^2 \quad (4)$$

2.7.Adequacy check of mathematical model

The lack of fit test is not significant (p value > 0.05 is not significant) it showed that the model satisfactorily fitted to the experimental data. The coefficient of determination R^2 value is compared to adjusted R^2 to check the adequacy of the developed model [25]. The AVOVA result shown in table 6 indicated that the quadratic polynomial model was significant and adequate to represent the actual relationship between WOP and significant model input parameter as depicted by a very small p value 0.0001. The significance and adequacy of the established model were further elaborated by a high value of coefficient of determination R^2 value of 0.7876 and adjusted R^2 value of 0.5893. This means that the model shows 78.76% of the variation in the experimental data. The predicted value and the experimental value were in reasonable agreement since there values are very close to other which means that the data fit well with the model and give a convincingly good estimate of the response [26]. The significance and adequacy of the developed model were given by the higher value of the R^2 and adjusted R^2 for the developed correlation [25]. A line of perfect fit shows the relationship between the predicted and actual values, all the points of predicted and actual value are closer to the line of perfect fit as shown in figure 1 and hence it satisfy the adequacy of the developed model, the various point on the line of perfect fit represent that experimental value and predicted are close to each other [25].

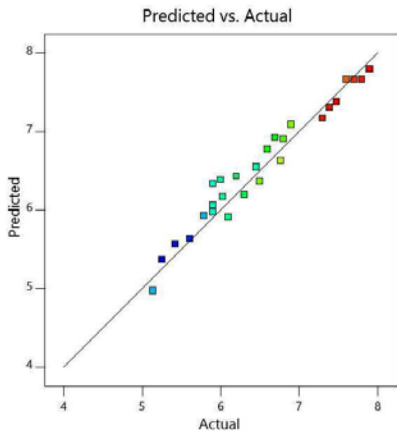

Fig. 5. Surface plot for actual value versus predicted values.

2.8.Response surface plot

The three dimensional surface plot developed by design expert software represent the interaction effect between process parameters with respect WOP [25] as shown in figs. 2–7. The linear interactive effect of current and voltage is negative as given in table 6 i.e. increasing the value of both the parameter result in a decrease in WOP as shown in fig. 2 of three dimensional surface plots [25]. The WOP declined beyond the current 150 ampere and 25 volt voltage respectively. The linear interactive effect of current and speed is negative as given in table 6 i.e. increasing the value of both the parameter result in a decrease in WOP as shown in fig. 3 of three dimensional surface plots [25]. The WOP declined beyond the current 150 ampere and 179 mm/min respectively. The linear interactive effect of current and pulse on time is positive as given in table 6 i.e. increasing the value of both the parameter increases WOP as shown fig. 4 of the three dimensional surface plot [25]. The WOP increase with simultaneously increasing in current and pulse on time to about 170 ampere and 50% respectively, beyond which the value of WOP declined. The linear interactive effect of voltage and speed is positive as given in table 6 i.e. increasing the value of both the parameter increases WOP as shown Fig. 5 of the three dimensional surface plot [25]. The WOP increase with simultaneously increasing in voltage and speed to about 27 volt and 206 mm/min respectively, beyond which the value of WOP declined. The linear interactive effect of voltage and pulse on time is positive as given in table 6 i.e. increasing the value of both the parameter increases WOP as shown Fig. 6 of the three dimensional surface plot [25]. The WOP increase with simultaneously increasing in voltage and pulse on time to about 27 volt and 50% respectively, beyond which the value of WOP declined. The linear interactive effect of speed and pulse on time is positive as given in table 6 i.e. increasing the value of both the parameter increases WOP as shown Fig. 7 of the three dimensional surface plot [25]. The WOP increase with simultaneously increasing in speed and pulse on time to about 206 mm/min and 50% respectively, beyond which the value of WOP declined. Welding speed and welding current are the most significant process parameter that effects the depth of penetration (WOP) as indicated by their highest F–values given in the ANOVA table 5.

The predicted value of WOP obtained from Design of expert software is 7.68 mm. The optimum combination of input parameter at this level is welding current 170 amps, voltage 25 volts, speed 179 mm/min and pulse on time 50%. To validate predicted value experiment is performed under this optimum combination of input parameter. The experimental value obtained is 7.60 mm which is closer to predicted value. Therefore regression model developed is satisfied.

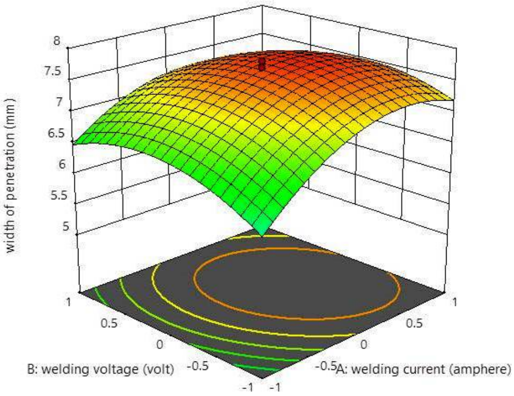

Fig 6. Interactive surface plot of AB .

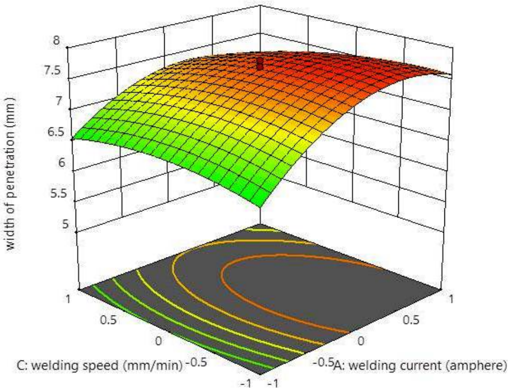

Fig 6. Interactive surface plot of AC.

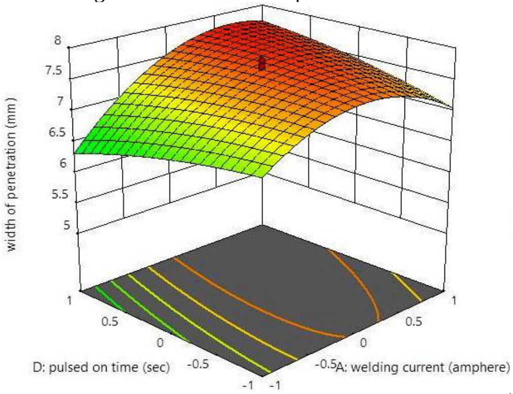

Fig. 7. Interactive surface plot of AD.

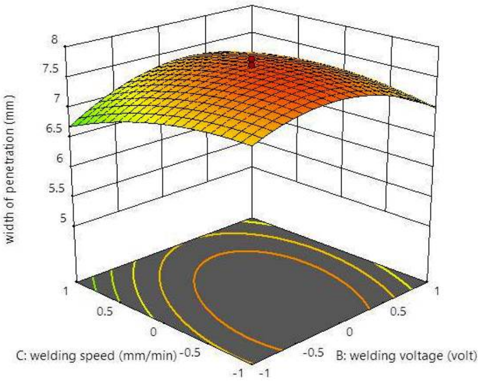

Fig. 8. Interactive surface plot of BC.

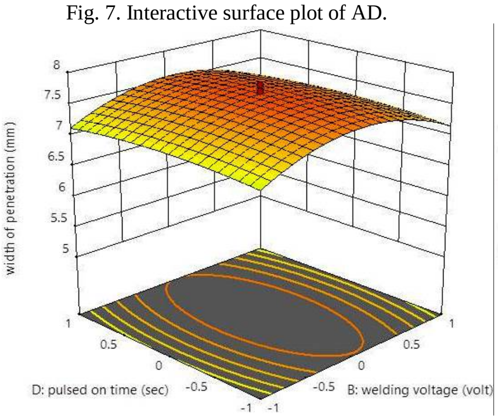

Fig. 9. Interactive surface plot of BD.

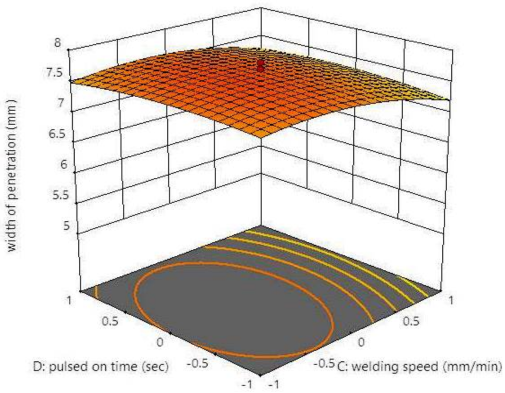

Fig. 10. Interactive surface plot of CD.

2.9.Result & Discussion

The parameter used in this study to determine the WOP and evaluate desired combination of input parameters, in this work under optimum conditions satisfies the standard. The result of ANOVA test demonstrates that the model developed was significant. It is found that welding speed has highest F-value which represent that it is the most crucial process parameter which affects the performance characteristics. RSM is the methodologies which give the possible interaction between process parameter by three dimensional surface plots and also helps in recognition of possible combination of optimum parameter. In this study optimum combination of process parameter are welding current 170, welding voltage 25 volt, welding speed 179 mm/min and pulse on time 50%. At this predicted optimum condition, the predicted WOP was 7.68 mm. The experimental value of WOP is 7.60 mm which validate the developed regression mathematical model. This demonstrates that RSM with appropriate CCD can be effectively applied to process parameter optimization.

Nomenclature

TIG Tungsten Inert Gas Welding. A-TIG Active Tungsten Inert Gas Welding.
GTAW Gas Tungsten Arc Welding.
RSM Response Surface Methodology. CCD - Center Composite Design.
ANOVA Analysis of Variance. R^2 Coefficient of determination.
WOP Width of Penetration.; MPa Mega Pascal.

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