Studying Factors Affecting Fusion Pool Geometry of Micro Plasma Arc which Remelts Austenitic Stainless Steel Sheets (AISI 316L) by Using Response Surface Method

by

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Micro Plasma Arc welding is used to remelt thin sheets of austenitic stainless steel (AISI 316L) 1mm. In this article the effects of micro plasma factors (2.4 mm electrode diameter) on fusion pool geometry parameters namely width, height and HAZ's width of austenitic stainless steel sheets are analyzed. The mathematical models have been developed by response surface method, in which three factors, three levels and central composite design were used to develop mathematical models, incorporating micro plasma parameters and fusion pool geometry. The adequacy of the models was checked by ANOVA technique. Variations of output responses with input process variables were discussed in both effects: main and interaction. As a result, fusion pool geometry parameters can be estimated by using the developed mathematical models.

Key words:

Micro plasma arc welding, Fusion pool geometry, ANOVA, Response surface method

1 Introduction

Welding thin sheets plays an important role in reducing structure weight which has gained importance in several engineering fields¹⁾. Austenitic stainless steel has excellent strength and good ductility at high temperature. Such as that is used in aircraft, aerospace, and in medical industry, where it is subject to high temperature and corrosive environment²⁾.

Plasma arc welding (PAW) is a constricting arc welding process; it is brought to the industry by providing an advanced level of control and accuracy to produce high quality products. From the literature review³⁾⁻¹¹⁾, it was understood that many researchers studied the influence of PAW process parameters on bead geometry using statistical techniques like Taguchi method, response surface method (RSM), artificial neural network and genetic algorithm. However, in all the works reported so far researchers have concentrated on thick materials; but not much effort was made to develop mathematical models to predict the models especially when welding thin stainless steel sheets in a flat position. An attempt is made to correlate important micro PAW (MPAW) process parameters to remelt fusion pool geometry of AISI 316L stainless steel sheets by developing mathematical models using statistical tools.

2 Experimental Setup

2.1 Materials and Methodology

AISI 316L stainless steel sheets of 100 × 50 × 1 mm were used. A fusion pool autogenously was formed with MPAW process through central long line (100mm). The chemical composition of AISI 316L stainless steel sheet is given in

Table 1. High purity argon gas (99.99%) was used as both a shielding gas and a trailing gas to prevent absorbing oxygen and nitrogen from the atmosphere. The welding has been carried out under the welding conditions presented in Table 2. Three important factors of MPAW process chosen from literature are presented in Table 3. A large number of trail experiments are carried out using 1 mm thick AISI 316L stainless steel sheets to find out the feasible working limits of MPAW process parameters. Due to wide range of factors, it was decided to use three factors, namely plasma flow rate F_1 , plasma current I_c , and welding speed S_p , with three levels for each factor. Face Centered central composite design matrix to specify the number of experiments for investigation was chosen. Table 4 includes the 20 set of coded conditions used to form the design matrix. The standard order “ S_{td} ” was randomized in order to minimize the unexpected variability in the observed response. The experimental conditions (rows) have been formed to meet main effects, corner points and center points. The method of designing such matrix is dealt with somewhere else¹²⁾. For the convenience of recording and processing the experimental data, the upper and lower levels of the factors are coded as +1 and -1, respectively and the coded values of any intermediate levels can be calculated by using the following formula¹³⁾:

$$X_i = \frac{2X - (X_{\max} + X_{\min})}{X_{\max} - X_{\min}} \quad (1)$$

Where X_i is the required coded value of parameter X which is either I_c , S_p or F_1 . X belongs to the range $[X_{\max}-X_{\min}]$, where $X_{\min}$ is the lower limit the parameter and $X_{\max}$ is the upper limit of the parameter.

Table 1 Chemical composition of austenitic stainless steel sheets (wt%).

C	Si	Mn	P	S	Cr	Mo	Ni
0.024	0.46	1.29	<0.005	<0.005	16.50	2.03	10.06

Table 2 Welding conditions.

Power source	Fronius micro plasma arc machine
Model number	TransTIG 3000- Plasma Module 10
Polarity	Direct current electrode negative (DCEN)
Mode of operation	Continues current (CC)
Electrode	2% thoriated tungsten electrode
Electrode diameter	2.4 mm
Plasma gas	Argon
Shielding gas	Argon
Shielding gas flow rate	15 Lpm
Purging gas	Argon
Purging gas flow rate	0.4 Lpm
Copper nozzle diameter	2.4 mm
Nozzle to plate distance	1 mm
Torch position	Vertical
Operation type	Automatic

Table 3 Important factors and their levels.

	Input factor	Units	Symboll	-1	0	+1
1	Current	Amperes	I_c	13	14	15
2	Speed	cm/min	S_p	18	20	22
3	Plasma flow	L/min	F_1	0.8	0.9	1.0

Table 4 Design matrix and experimental results.

S_{td}	Run	S_p	I_c	F_1	Height H (mm)	Width W (mm)	HAZ (mm)
1	1	-1	-1	-1	0.384	1.655	0.041
15	2	0	0	0	0.334	1.879	0.087
5	3	-1	-1	1	0.436	1.871	0.067
11	4	0	-1	0	0.356	1.943	0.029
8	5	1	1	1	0.415	1.849	0.069
10	6	1	0	0	0.257	1.568	0.058
4	7	1	1	-1	0.292	1.685	0.052
16	8	0	0	0	0.324	1.881	0.077
9	9	-1	0	0	0.432	2.024	0.169
2	10	1	-1	-1	0.221	1.621	0.016
18	11	0	0	0	0.279	1.895	0.092
13	12	0	0	-1	0.251	1.843	0.081
3	13	-1	1	-1	0.497	2.206	0.178
14	14	0	0	1	0.268	1.939	0.082
7	15	-1	1	1	0.704	2.294	0.189
6	16	1	-1	1	0.235	1.662	0.027
17	17	0	0	0	0.302	1.802	0.075
12	18	0	1	0	0.402	2.059	0.118
20	19	0	0	0	0.282	1.875	0.079
19	20	0	0	0	0.293	1.905	0.069

2.2 Measurement of Fusion Pool Geometry

The metallurgical samples were cut at fusion pool, with the sample being located at 50 mm behind the trailing edge of the

crater at the end of the fusion pool and has been mounted by using Bakelite. Preparing the samples and mounting them were done as in ASTM E 3-1 standard. The transverse faces of

the samples were surface grounded using 120 grit size belt with the help of belt grinder. They were polished using grade 1/0 (245 mesh size), grade 2/0 (425 mesh size) and grade 3/0 (515 mesh size) sand paper. The specimens were further polished by initially using aluminum oxide and by utilizing diamond paste and velvet cloth in the polishing machine. The polished specimens were macro-etched by using 10% oxalic acid solution to reveal the fusion pool geometry to measure their parameters (Fig.1 and Fig. 2) by using metallurgical microscope (Make: Nikon Eclipse, Model No: E400 POL) at $\times 100$ magnification.

Fig. 1 Typical fusion pool geometry.

Fig. 2 Metallographic fusion pool.

3 Developing Mathematical Models

In most RSM problems⁽¹³⁾⁻⁽¹⁵⁾, the relationship between the

response (Y) and the independent variables is unknown. If the response is well modeled by a linear function then the approximating function is in the first order model.

$$Y = b_0 + \sum b_i x_i + \varepsilon \quad (2)$$

Where ε is the rest.

If interaction terms are added to main effects then the model is capable of representing some curvature.

$$Y = b_0 + \sum b_i x_i + \sum \sum b_{ij} x_i x_j + \varepsilon \quad (3)$$

The curvature results from twisting the plane which is induced by the interaction term $b_{ij} x_i x_j, i \neq j$.

If the curvature in the response function is not adequately modeled by Equation (3), then a logical model is considered.

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

Where b_{ii} represents pure second order or quadratic effects. Equation (4) is a second order response surface model.

Using MINITAB 16 and Design Expert 10 statistical software to develop the final models with significant coefficients which correspond to the value of $P < 0.05$, where P is the level of significance as shown in Table 5.

$$\text{Height}(H) = 0.3 - 0.103S_p + 0.068I_c \quad (5)$$

$$+ 0.041F_l + 0.049S_p^2 + 0.084I_c^2 + 0.033I_c F_l \quad (6)$$

$$\text{Width}(W) = 1.885 - 0.166S_p + 0.134I_c \quad (7)$$

$$+ 0.060F_l - 0.108S_p^2 + 0.096I_c^2 - 0.090S_p I_c$$

$$\text{HAZ} = 0.084 - 0.0422S_p + 0.0426I_c$$

$$+ 0.023S_p^2 - 0.0169I_c^2 - 0.226S_p I_c$$

4 Checking Adequacy of the Developed Models

The adequacy of the developed models was tested using the analysis of variance technique (ANOVA) which is presented in Table 5, where the developed mathematical models are found to be adequate at 90% confidence level.

Table 5 Short ANOVA tables.

Short ANOVA for height			Short ANOVA for width			Short ANOVA for HAZ		
P	Term	Coefficient	P	Term	Coefficient	P	Term	Coefficient
<0.002	Constant	0.299473	<0.002	Constant	1.885	<0.002	Constant	0.0840
<0.002	S_p	-0.103300	<0.002	S_p	-0.166	<0.002	S_p	-0.0422
<0.002	I_c	0.0678000	<0.002	I_c	0.1341	<0.002	I_c	0.0426
0.003	F_l	0.0413000	0.015	F_l	0.0605	0.099	F_l	0.0066
0.035	S_p^2	0.0493182	0.020	S_p^2	-0.108	0.007	S_p^2	0.0231
0.002	I_c^2	0.0838182	0.033	I_c^2	0.096	0.035	I_c^2	-0.01686
0.109	F_l^2	-0.0356818	0.738	F_l^2	-0.013	0.229	F_l^2	-0.00886
0.201	$S_p I_c$	-0.0162500	0.003	$S_p I_c$	-0.090	<0.002	$S_p I_c$	-0.0226
0.228	$S_p F_l$	-0.0152500	0.602	$S_p F_l$	-0.012	0.787	$S_p F_l$	-0.00113
0.019	$I_c F_l$	0.0330000	0.979	$I_c F_l$	-0.0006	0.787	$I_c F_l$	-0.00113

Confirmation tests are carried out at different conditions to check the accuracy of the developed models. The details of confirmation tests and predicted values of the fusion pool geometry parameters are presented in Table 6. However, the developed model is valid within the range of specified weld

input parameters. Figures 3-5 indicate the scatter plots for fusion pool geometry parameters and reveal that the experimental and predicted values are close to each other within the specified limits.

Table 6 Confirmation test results.

S_p	I_c	F_1	Experimental			Predicted			Relative error		
			Height H (mm)	Width W (mm)	HAZ (mm)	Height H (mm)	Width W (mm)	HAZ (mm)	H	W	HAZ
-1	-1	0	0.416	1.764	0.062	0.452	1.816	0.067	0.08	0.03	0.08
0	1	1	0.466	2.011	0.096	0.490	2.162	0.106	0.05	0.07	0.09
-1	1	0	0.564	2.062	0.19	0.620	2.264	0.198	0.09	0.09	0.04
1	0	1	0.227	1.546	0.056	0.236	1.645	0.062	0.04	0.06	0.10

Fig.3 Scatter plot of height.

Fig.4 Scatter plot of width.

Fig.5 Scatter plot of HAZ.

5 Results and Discussion

The developed mathematical models above can be employed to predict the fusion pool geometry dimensions and their relationships for the range of parameters used in the investigation by substituting their respective values in coded forms. Based on these models, the effects of the process parameters on the fusion pool geometry dimensions are computed and plotted as shown in Fig. 6-11.

Fig. 6 Main effects for height.

Fig.7 Main effects for width.

Fig.8 Main effects for HAZ's width.

5.1 Main effect

The variations of fusion pool geometry parameters namely width, height and HAZ's width of AISI 316L fusion pool with MPAW input process parameters are presented in Fig. 6, Fig. 7 and Fig. 8. Width, height and HAZ's width parameters decrease in relation based on welding speed as heat input decreases. Height decreases slowly, but only a little bit with current from -1 to 0 coded values, then beyond it, the height increases. For width and HAZ, both increase with current in different rates. At lower current, up to coded value -1, the heat input is less and hence low melting rate of the parent metal

leads to lower width and HAZ. When the current increases beyond coded value -1, the heat input also increases and hence high melting rate of base metal leads to higher width and HAZ. As the flow rate is helpful in maintaining continuous arc during welding, when the flow rate is high up to coded value 1, height, width and HAZ increase due to high and dominant current which generates large amount of heat.

5.2 Interaction effect

Contour plots play a very important role in the study of the response surface method. By generating contour plots using

Fig. 9 Contour plots of H ; (a) I_c and S_p , (b) F_l and S_p , (c) F_l and I_c .

Fig. 10 Contour plots of W ; (a) I_c and S_p , (b) F_l and S_p , (c) F_l and I_c .

Fig. 11 Contour plots of HAZ; (a) I_c and S_p , (b) F_l and S_p , (c) F_l and I_c .

Fig. 12 Graphical optimization.

Table 7 Optimal point characteristics.

Width	Height	HAZ	S_p	I_c	F_1
1.574	0.221	0.024	1.00	-0.786	-1.00

software (Design Expert 10) for response surface analysis, the optimum is specified by characterizing the shape of the surface. If circular contours occur, this suggests the independence of factor effects; while elliptical contours may indicate factor interaction. Figures 9(a), (b) and (c) represent the contour plots for height and Figs. 10(a), (b) and (c) represent the contour plots for width, whereas Figs. 11(a), (b) and (c) represent contour plot for HAZ's width. From the contour plot in Fig.9(a), it can be seen that height is more sensitive to speed than to current. From Fig.9(b), it is clear that speed affects height more than flow rate. From Fig.9(c), it can be seen that height is sensitive to both flow rate and current. The contour plot in Fig.10(a) shows that width is sensitive to both speed and current. From Fig.10(b), it can be seen that width is more sensitive to speed than to flow rate, whereas Fig.10(c) shows that width is more sensitive to current than to flow rate. From Fig.11(a), it can be seen that HAZ is sensitive to both speed and current. From Fig.11(b), it is clear that HAZ's width is more sensitive to speed than to flow rate, whereas Fig.11(c) shows that HAZ's width is more sensitive to current than to flow rate. All the contour plots prove that speed and current are the most important factors which affect the pool geometry parameters of stainless steel AISI 316L.

The optimum pool geometry is achieved when HAZ and width become narrower and height gets lower. The optimal response point can be calculated by the software (Design

Expert 10), as shown in Fig. 12 and explained in Table 7.

6 Conclusions

Three factors (speed, current, flow rate), three levels (-1, 0, +1), full factorial design matrix based on the central composite, face centered design technique were used for the development of mathematical models to predict the fusion pool geometry parameters for AISI316L stainless sheets by micro plasma arc welding process. By using mathematical models, the most predicted results are very close to the experimental ones. It is proved that pool parameters are sensitive to speed and current. Speed is the most dominant factor out of the selected factors, since when speed decreases, heat input decreases leading to narrow width, low height and small HAZ. The optimal fusion pool is achieved when the welding speed is coded value 1, current is coded value -0.786 and flow rate is coded value -1.

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