Prediction of Weld Quality in Plasma Arc Welding using Statistical Approach

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Abstract
The effect of various process parameters like welding current, torch height and welding speed on front melting width, back melting width and weld reinforcement of Plasma Arc Welding on Aluminum alloy is investigated by using standard statistical tool i.e., Response Surface Method . Variable Polarity Plasma Arc Welding is used for welding Aluminum alloy. Trail experiments are conducted and the limits of the input process parameters are decided. Two levels and three input process parameters are chosen and experiments are conducted as per design matrix. The coefficients are calculated by using regression analysis and the mathematical model is constructed. Analysis of Variance (ANOVA) is carried out to check the adequacy of the developed model. Fisher's test is conducted for standard tabulated values of F-ratio for a desired level of confidence (say 95%) and found that all the Fisher ratio values calculated for the input process parameters are within the table values and found to be adequate. By using the mathematical model the main and interaction effect of various process parameters on weld quality are studied.

Keywords*: Plasma Arc Welding, Process parameters, F-ratio, Welding current, Welding speed, Torch height, Front Melting Width, Back Melting Width, Weld Reinforcement.*

1 Introduction

The Plasma Arc Welding (PAW) process is essentially an extension of Gas Tungsten Arc Welding (GTAW). The energy density and gas velocity and momentum in the plasma arc are high [1]. As with Electron beam and laser beam welding, PAW exhibits a deep-weld effect. Variable Polarity Plasma Arc Welding (VPPAW) is developed for aluminum and its alloy [2]. With VPPAW, Al_2O_3 oxide film could be cleaned effectively. Gas in the molten pool could escape fully when vertical welding was applied. Therefore, welding quality of VVPAW is better than ordinary gas shielded welding. Comparing with other arc welding techniques, keyhole variable polarity plasma arc welding, which was developed on the base of industrial manufacturing and experimental research, not only can fulfill cathode cleaning of aluminum alternating current welding, but also decrease largely the burning loss of tungsten electrode. Hence, keyhole plasma arc welding may be the most ideal welding process for middle and thick aluminum alloy plates.

2 Description

Aluminum alloy AA5182 of 3mm thick as base material and AA5356 as a filler material are chosen and their chemical compositions are given in Table 1 and Table 2.
Alternating Current Plasma Arc Welding is used to weld the base metal [3][4]. Thoriated Tungsten electrode of diameter 3mm is used and the shielding gas used is Argon with flow rate of 800 Liters/Hour. The position of the welding gun is vertical to the work piece.
Trail experiments are conducted to establish the values of input variables and their ranges in which

experiments has to be conducted. As many factors have the effect on formation of welding seam of aluminum alloy, it is necessary to limit them. Wire feed rate is kept constant at 550mm/min

Table 1: Chemical composition of base metal AA5182 (weight percentage)

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	other	Al
0.06	0.19	0.02	0.24	4.46	0.03	0.03	0.01	0.02	Val.

Table 2: Chemical composition of filler wire AA5356 (weight percentage)

Mg	Mn	Cr	Ti	Al
5.00	0.35	0.10	0.15	Val.

3 Experimental Procedure

The step wise experimental procedure used for this study are briefly explained below.

3.1 *Identification of input process parameters and response variables*

Front melting width, Back Melting Width and Weld reinforcement are chosen as output parameters and welding current, Torch height and welding speed as input process variables. The weld bead parameters are shown in Figure 1.

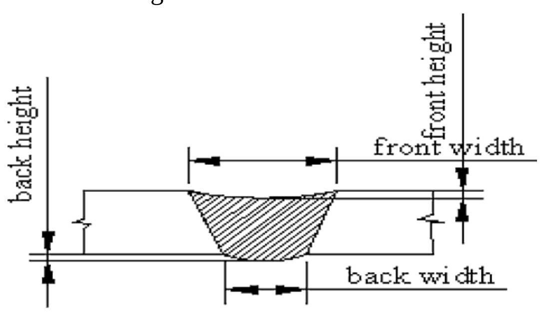

Figure 1: Weld bead parameters

3.2 *Working ranges of input process parameters*

The working ranges of all selected parameters are fixed by conducting trail runs [5]. The experiments are carried out by varying one of the parameters while keeping the rest of them at constant values. The working range of each parameter is decided upon by inspecting the weld bead for a smooth appearance and the absence of visible defects such as surface porosity, undercut etc. The upper limit of the parameter is coded as +1 and the lower limit was coded as -1. The coded values for intermediate values can be calculated using the following Equation-1:

$$X_i = 2[2X-(X_{max} + X_{min})] / (X_{max} – X_{min}) \qquad (1)$$

Where X_i is the required coded value of a parameter X. The X is any value of the parameter from X_{min} to X_{max}, where X_{min} is the lower limit of the parameter and X_{max} is the upper limit of the parameter. The selected levels of the selected process parameters with their units and notations are given in Table 3.

Table 3: Chosen welding process parameters and their levels.

		Welding Current(I) (Amperes)	Torch Height(H) (mm)	Welding Speed(N) (mm/sec)
Maximum value	+1	95	6	5.42
Minimum value	-1	85	4	3.75

3.3 *Development of Design matrix*

2^k factorial design matrix for conducting the experiments is selected, where k is number of input process variables [6]. Two levels and three input process parameters are selected. The number of experiments conducted is 2^3 =8. The typical Design matrix is shown in Table 4.

Table 4: showing typical design matrix

+	+	+	+	+	+	+
+	+	-	+	-	-	-
+	-	+	-	-	+	-
-	+	+	-	+	-	-
-	-	-	+	+	+	-
-	-	+	+	-	-	+
-	+	-	-	-	+	+
+	-	-	-	+	-	+

3.4 *Recording the Response Variables*

Transverse section of each weld overlay is observed by cutting using power hacksaw from mid length position of the welds and the end faces are machined. These specimens are prepared by the usual metallurgical polishing methods and etched with 2%

nital [7][8]. The weld bead profiles are traced using a reflective type optical projector of 10X. The profile images were imported to AutoCAD 2004 software as raster image and profiles are traced in 2D form. From the 2D diagram, the front melting width, back melting width and weld reinforcement are measured. The observed input and output values are shown in Table 5.

3.5 *Development of mathematical models*

The response function representing any of the weld bead parameters can be expressed using Equation 2.

$$Y = f(X_1, X_2, X_3) \quad (2)$$

Where Y is the response i.e. output parameters and X_1, X2, X3 are the input variables [9].

In most Response Surface Method (RSM) problems, the form of the relationship between the response and the independent variable is unknown. Thus the first step in RSM is to find suitable approximation for the true function of relationship between Y and the set of independent variables. Usually, a low-order polynomial in some region of the independent variables is employed. If the response is well modeled by a linear function of the independent variables then the approximating function is the first order model as shown in Equation 3.

$$Y = k + ax_1 + bx_2 + cx_3 + abx_1x_2 + bcx_2x_3 + cax_1x_3 + abcx_1x_2x_3 \quad (3)$$

Where a,b,c are regression coefficients and K represents error or noise observed.

The regression coefficients are calculated using the design matrix shown in Table 4.

The final mathematical models are developed after checking adequacy of each individual input parameter by conducting Fishers test.

Front Welding Width

$$FW = 6.61 - 0.11I + 0.42H - 0.11N - 0.13IH - 0.19HN + 0.09NI - 0.09IHN$$

Back Welding Width

$$BW = 0.35 + 0.02I - 0.11H + 0.06N - 0.05IH + 0.06HN - 0.09NI + 0.12IHN$$

Weld Reinforcement

$$FR = 3.61 - 0.23I + 0.50H - 0.38N - 0.22IH - 0.13HN + 0.25NI + 0.09IHN$$

3.6 *Checking the Adequacy of the developed model*

The adequacy of the developed models is tested using the analysis of variance (ANOVA) technique [9].

Table 5: Experimental input and output values

Welding Current (Amperes) (I)	Torch Height (mm) (H)	Welding Speed (mm/sec) (N)	Welding Current (Amperes) (I)	Torch Height (mm) (H)	Welding Speed (mm/sec) (N)	Front melting width (mm) (FW)	Back melting width (mm) (BW)	Weld Reinforcement (mm) (FR)
+	+	+	95	6	5.42	6.48	0.47	3.30
+	+	-	95	6	3.75	7.10	0.16	4.02
+	-	+	95	4	5.42	6.48	0.22	3.20
-	+	+	85	6	5.42	7.50	0.26	3.90
-	-	-	85	4	3.75	6.28	0.28	3.70
-	-	+	85	4	5.42	6.05	0.73	2.52
-	+	-	85	6	3.75	7.60	0.06	5.27
+	-	-	95	4	3.75	5.94	0.65	3.00

The relative contributions of the factors are determined from ANOVA. As per this technique, if the calculated value of F-ratio of the developed model do not exceed the standard tabulated value of F- ratio for a desired level of confidence (say 95%), then the model is said to be adequate within the confidence limits. The calculated F-ratio (variance ratio) for Front Melting width, Back Melting width and Weld Reinforcement are shown in Table 6, 7, 8 respectively.

3.6.1 ANOVA for Front Melting Width

ANOVA analysis for Front melting Width is given in Table 6. The values of sum of squares (SS) for various factors are given in third column of Table 6, are a measure of relative importance of the factors in changing the Front Melting Width. From column five of Table 6 it is observed that Torch Height contributes a major portion of the total variation followed by Welding speed and Welding current. The F-ratio values obtained are below the tabulated value and hence the developed mathematical model is adequate.

Table 6: Analysis of variance for Front Melting Width

K	6.61	SS	DOF	F -Ratio
I	- 0.11	0.09	1	0.6
H	0.42	1.41	1	9.4
N	- 0.11	0.09	1	0.6
IH	- 0.13	0.13	1	0.86
HN	- 0.19	0.28	1	1.86
NI	0.09	0.06	1	0.4
IHN	- 0.09	0.06	1	0.4
SSR		2.12	7	
SST		2.27	15	
SSE		0.15	8	

3.6.2 ANOVA for Back Melting Width

ANOVA analysis for Back Melting Width is given in Table 7. The values of sum of squares (SS) for various factors are given in third column of Table 7, are a measure of relative importance of the factors in changing the Back Melting Width. From column five of Table 7 it is observed that Torch Height contributes a major portion of the total variation followed by Welding speed and Welding current. The F-ratio values obtained are below the tabulated value and hence the developed mathematical model is adequate

Table 7: Analysis of variance for Back Welding Width

K	0.35	SS	DOF	F -Ratio
I	0.02	0.0032	1	0.077
H	-0.11	0.0968	1	2.349
N	0.06	0.0288	1	0.699
IH	0.05	0.02	1	0.485
HN	0.06	0.0288	1	0.699
NI	-0.09	0.0648	1	1.572
IHN	0.12	0.1152	1	2.796
SSR		0.3576	7	
SST		0.3988	15	
SSE		0.0412	8	

3.6.3 ANOVA for Weld Reinforcement

ANOVA analysis for Weld Reinforcement is given in Table 7. The values of sum of squares (SS) for various factors are given in third column of Table 7, are a measure of relative importance of the factors in changing the Back Melting Width. From column five of Table 8 it is observed that Torch Height contributes a major portion of the total variation followed by Welding speed and Welding current. The F-ratio values obtained are below the tabulated value and hence the developed mathematical model is adequate

Table 8: Analysis of variance for Weld Reinforcement

K	3.61	SS	DOF	F -Ratio
I	- 0.23	0.4232	1	2.4238
H	0.50	2	1	11.4547
N	- 0.38	1.1552	1	6.6162
IH	- 0.22	0.3872	1	2.2176
HN	- 0.13	0.1352	1	0.7743
NI	0.25	0.5	1	2.8636
IHN	- 0.09	0.0648	1	0.3711
SSR		4.6656	7	
SST		4.8402	15	
SSE		0.1746	8	

where

SS = Sum of Squares
DOF = Degree of Freedom
SSR = Sum of squares between rows
SSE = Sum of squares due to error
SST = Total sum of squares
SSE = SST - SSR (Should be positive)
$SST = \sum Y^2 - \{(\sum Y)^2/N\}$
Y = Optimisation parameter
N = Number of Trails
$SSR = \sum SS$
Fisher Ratio 'F' = SS /{(SSE/DOF)}

4 Results & Discussion

Figures 2, 3, 4 represent the variation of Front melting width, Back melting width and Weld reinforcement for experimental, linear model and Non-linear model. figures 5, 6, 7 represents the scatter diagram indicated how the experimental values and predicted values (Non-linear model values) vary. Variation of Front melting width, Back melting width and weld reinforcement with welding current, Torch height and welding speed are shown in figures 8, 9, 10.

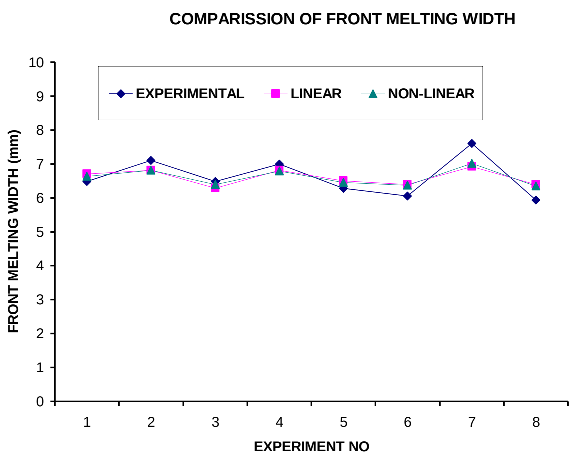

Figure 2: Comparison of Front melting width

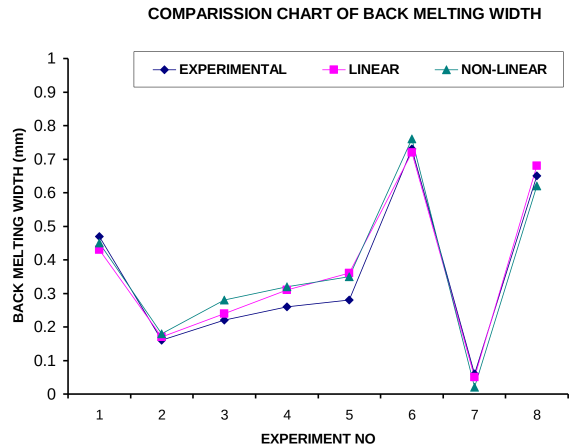

Figure 3: Comparison of Back melting width

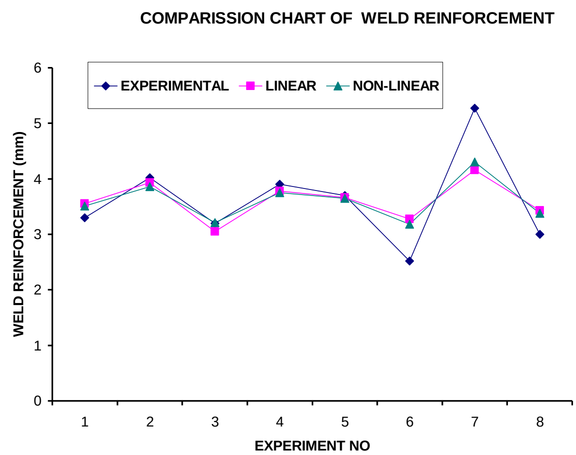

Figure 4: Comparison of Weld reinforcement

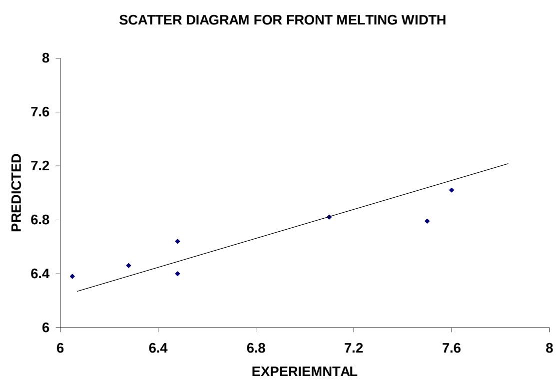

Figure 5: Scatter plot for Front melting width

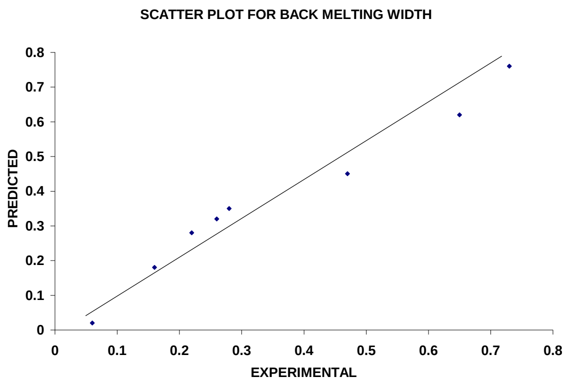

Figure 6: Scatter plot for Back melting width

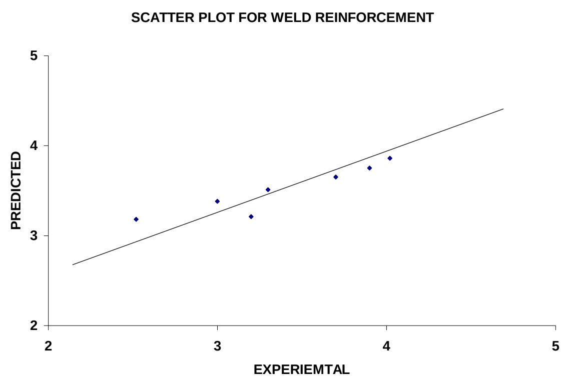

Figure 7: Scatter plot for Weld reinforcement

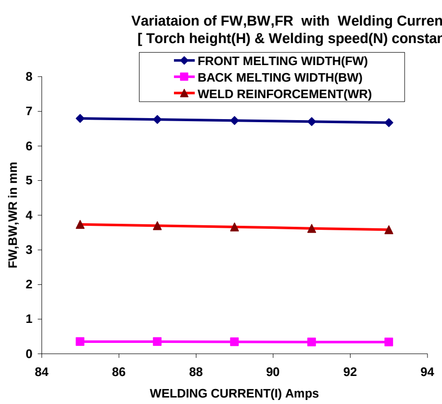

Figure 8: Variation of FW, BW, FR with Welding current (I)

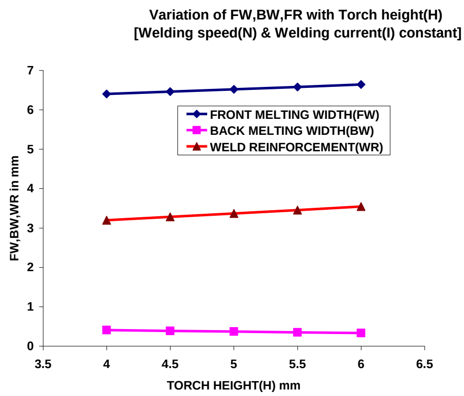

Figure 9: Variation of FW, BW, FR with Torch Height (H)

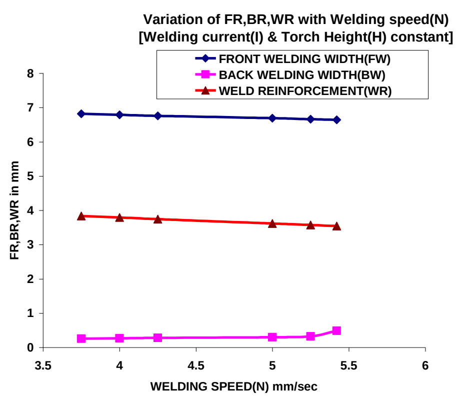

Figure 10: Variation of FW, BW, FR with Welding Speed (N)

The detailed analysis and observations are mentioned in the next section i.e. in conclusions.

5 Conclusions

From the experimentation, ANOVA, linear and nonlinear analysis the following observations are made.

1. Response Surface Method is convenient to predict the main effects and the interaction effects of different influential combination of Plasma Arc Welding parameters with in the range of investigations on front melting width, back melting width and weld reinforcement.
2. Response Surface Method is found to be easy and accurate for developing mathematical models for predicting the front melting width, back melting width and weld reinforcement with in the working region of the process variables.

3. The values obtained in Non-linear case are more accurate and closer to experimental values compared to linear values.
4. By keeping Torch height and welding speed constant and increasing welding current, Front melting width, Back melting width and weld reinforcement decreases.
5. By keeping welding current and welding speed constant and increasing Torch height, Front melting width and Back melting width increases where as weld reinforcement decreases.
6. By keeping welding current and keeping Torch height and increasing welding speed, Front melting width and Back melting width decreases where as weld reinforcement increases.
7. Because of the complexity in the input parameters the present work is limited to three parameters variation and its influence on Front melting width, Back melting width and Weld reinforcement. However there are other factors like wire feed rate, flow rate of shielding gas etc which also influence the weld quality are kept constant.

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