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Prediction of Weld Pool Geometry in Pulsed Current Micro Plasma Arc Welding of SS304L Stainless Steel Sheets

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ABSTRACT

Pulsed Micro Plasma Arc Welding (MPAW) is a metal joining technique widely used in manufacturing of thin sheet components due to its inherent properties. The weld quality and productivity are controlled by the process parameters. The paper discuses about development of mathematical models for weld pool geometry of stainless steel 304L sheets. Design of experiments based on full factorial design is employed for the development of a mathematical model correlating the important controlled pulsed MPAW process parameters like peak current, background current, pulse and pulse width with front width, back width, front height and back height. The developed mode has been checked for adequacy based on ANOVA analysis. Weld bead parameters obtained by the models are found to confirm actual values with high accuracy. Using these models effect of pulsed MPAW process parameters on weld pool geometry are studied.

1. Introduction

The plasma welding process was introduced to the welding industry in 1964 as a method of bringing better control to the arc welding process in lower current ranges (*Modern Application News*, 1999). Today, plasma retains the original advantages it brought to the

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industry by providing an advanced level of control and accuracy to produce high quality welds in both miniature and pre precision applications and to provide long electrode life for high production requirements at all levels of amperage. Plasma welding is equally suited to manual and automatic applications. It is used in a variety of joining operations ranging from welding of miniature components to seam welding to high volume production welding and many others.

The welding optimization literature frequently reveals correlation among responses. (D.K.Zhang et.al,2010) studied the influence of welding current, arc voltage, welding speed, wire feed rate and magnitude of ion gas flow on front melting width, back melting width and weld reinforcement of Alternating Current Plasma Arc Welding process of LF6 Aluminum alloy of thickness 3mm using Artificial Neural Network- Back Propagation algorithm. (Sheng-Chai Chi et. al ,2001) developed an intelligent decision support system for Plasma Arc Welding of stainless steel plates of thickness range from 3 to 9 mm based on fuzzy Radial Basis Function (RBF) neural network by performing experiments using Taguchi method. (Y. F. Hsiao et. Al,2008) studied the optimal parameters process of plasma arc welding of SS316 of thickness 4mm by Taguchi method with Grey relational analysis is studied. Torch stand-off, welding current, welding speed and plasma gas flow rate (Argon) were chosen as input variables and welding groove root penetration, welding groove width, front-side undercut were measured as output parameters. (K.Siva et.al, 2008) used central composite rotatable full factorial design matrix and conducted experiments in optimization of weld bead geometry in Plasma arc hardfaced austenitic stainless steel plates using Genetic Algorithm. (A.K.Lakshminarayan et.al, 2008) predicted the Dilution of Plasma Transferred Arc Hardfacing of Stellite on Carbon Steel using Response Surface Methodology (RSM). (V Balasubramanian et.al, 2009) used Response Surface Methodology to predict and optimize the percentage of dilution of iron-based hardfaced surface produced by the Plasma transferred arc welding process.

From the earlier works, it has been observed that much work is not reported so far to investigate the effect of pulsed current MPAW process parameters on stainless steel weld characteristics; and developing the related mathematical models to predict the same especially for welding of thin stainless steel sheets. Hence an attempt was made to correlate important pulsed MPAW process parameters to bead geometry of thin AISI 304L stainless steel welds by developing mathematical models. The models developed will be very useful to predict the weld pool geometry parameters for desired bead geometry. A statistically designed experiment based on full factorial design has employed for the development of mathematical models (Montgomery DC ,2005).

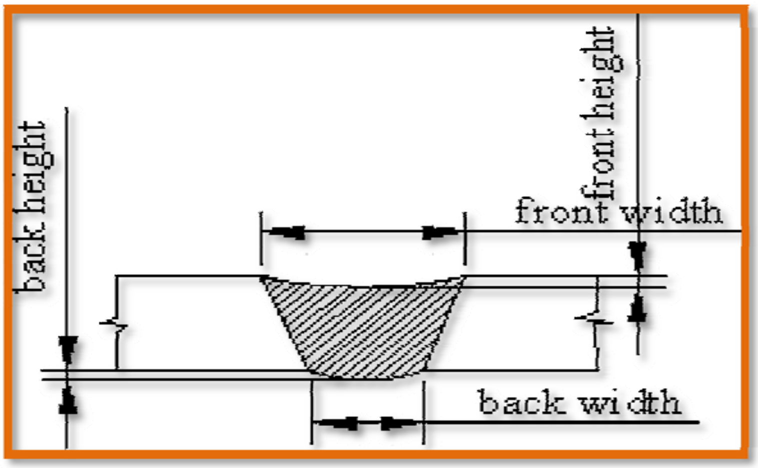

Figure 1: Typical weld pool geometry.

2. Experimental procedure

Austenitic stainless steel sheets of type AISI 304L 100×50×0.25 mm are welded autogenously with square butt joint without edge preparation. To evaluate the quality of MPAW welds, measurements of the front width, back width, front height and back height of the weld pool are considered. Figure 1 indicates the typical weld pool geometry. Table 1 indicates the chemical composition of AISI 304L stainless steel sheet. Experiments are conducted using the Pulsed Micro Plasma Arc Welding (MPAW) process with pulse DCEN. Industrial pure and commercial grade argon gases are used for shielding and back purging, respectively. Automatic voltage control available in the welding equipment is used. Fixture variation effects are not considered as the same setup has been used throughout the experiment. Some of the welding process parameters are fixed based on earlier work and also from the trial run so as to obtain full penetration weld. Trial runs are conducted to find the limits of each controllable process parameter so as to obtain full penetration weld, free from any visible defects. Because of computational ease and enhanced interpretability of the models, parameters are converted to coded form for developing mathematical models (Giridharan PK et.al, 2007). The upper limit of a factor is coded as +1 and the lower limit as

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−1. Table 2 represents the levels determined for process variables with their levels, units and notations for the pulsed MPAW process. Table 3 represents the fixed pulsed MPAW process parameters and their values.

Table 1: Chemical composition of austenitic stainless steel (AISI 304L) sheet.

Elements	Chromium	Silicon	Nickel	Carbon	Manganese	Iron
% by weight	18.2%	0.5%	8.5%	0.015%	1.6%	Balance

Table 2: Input variables and their levels

			Levels	
SI No	Input Factor	Units	-1	+1
1	Peak Current	Amps	6.5	7.5
2	Back Current	Amps	3.5	4.5
3	Pulse	No's /Sec	30	50
4	Pulse width	%	40	60

Table 3: Fixed pulsed MPAW process parameters and their values.

Power source	Secheron Micro Plasma Arc Machine (Model: PLASMAFIX 50E)
Polarity	DCEN
Mode of operation	Pulse mode
Electrode	2% thoriated tungsten electrode
Electrode Diameter	1mm
Plasma gas	Argon & Hydrogen
Plasma gas flow rate	6 Lpm
Shielding gas	Argon
Shielding gas flow rate	0.4 Lpm
Purging gas	Argon
Purging gas flow rate	0.4 Lpm
Copper Nozzle diameter	1mm
Nozzle to plate distance	1mm
Welding speed	260mm/min
Torch Position	Vertical
Operation type	Automatic

From the Design of Experiments and due to wide range of input process parameters, the present work is limited to use four factors, two levels, full factorial design matrix in order to simplify the present problem. Table 4 shows the measured values of output response by taking an average value of three samples of 16 sets of coded conditions used in the form of design matrix. The 16 experiments have been formulated as per 2^4 (two levels and four factors) factorial design.

3. Recording the Responses

Three samples are cut from the welded specimens at an interval of 25mm and mounted in Bakelite powder, polished and etched with Oxalic acid as per ASTM E3 and ASTM E340. Weld pool geometries are measured using Metallurgical Microscope make Dewinter Technologie, Model No. DMI-CROWN-II. Figure 2 represents the Photomacrographs of a typical weld specimen showing the bead profile at 100X magnification.

Figure 2: Photomacrographs of a typical weld specimen.

Table 4: Welding parameters and responses for the full factorial design.

Exp No	Peak Current (PC)	Back Current (BC)	Pulse (P)	Pulse Width (PW)	Front Width	Back Width	Front Height	Back Height
	Amperes	Amperes	No’s	%	Microns	Microns	Microns	Microns
1	7.5	3.5	30	60	1579.22	1499.50	63.209	57.775
2	6.5	4.5	30	60	1486.59	1361.64	59.137	49.443
3	7.5	4.5	50	60	1383.04	1301.22	53.953	48.422
4	6.5	3.5	50	40	1539.88	1480.60	54.191	49.422
5	7.5	4.5	30	60	1582.92	1506.41	76.886	71.209
6	7.5	3.5	50	40	1404.63	1283.25	71.247	65.947
7	6.5	3.5	30	60	1477.09	1393.14	60.583	54.737
8	6.5	3.5	50	60	1451.98	1372.69	61.896	54.251
9	6.5	3.5	30	40	1530.30	1453.96	57.514	52.538
10	6.5	4.5	50	60	1382.42	1305.11	63.619	58.265
11	7.5	3.5	50	60	1392.70	1337.14	59.083	54.855
12	6.5	4.5	30	40	1543.53	1466.85	42.855	36.559
13	7.5	3.5	30	40	1581.70	1537.70	48.824	42.514
14	7.5	4.5	50	40	1503.05	1436.88	64.101	59.595
15	7.5	4.5	30	40	1547.92	1474.37	52.275	46.553
16	6.5	4.5	50	40	1486.94	1408.72	65.613	58.092

4. Development of Mathematical Models

A low-order polynomial is employed for developing the mathematical model for predicting weld pool geometry. Equation (1) represents a typical mathematical model, in which the response is well modeled by a linear function of the independent variables.

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Table 5: ANOVA test results.

ANOVA for Front Width					
Source	DF	Seq SS	Adj SS	Adj MS	F
Main Effects	4	25659	25659	6415	1.40
2-Way Interactions	6	23462	23462	3910	0.85
3-Way Interactions	4	23142	23142	5785	1.26
Residual Error	1	4575	4575	4575	
Total	15	76837			
R^2 Value =94.05					
ANOVA for Back Width					
Source	DF	Seq SS	Adj SS	Adj MS	F
Main Effects	4	35868	35868	8967	2.47
2-Way Interactions	6	38078	38078	6346	1.75
3-Way Interactions	4	19057	9057	4764	1.31
Residual Error	1	3633	3633	3633	
Total	15	96636			
R^2 Value = 96.24					
ANOVA for Front Height					
Source	DF	Seq SS	Adj SS	Adj MS	F
Main Effects	4	499.22	499.22	124.80	2.48
2-Way Interactions	6	335.64	335.64	55.94	1.11
3-Way Interactions	4	157.23	157.23	39.31	0.78
Residual Error	1	50.23	50.23	50.23	
Total	15	1042.32			
R^2 Value = 95.18					
ANOVA for Back Height					
Source	DF	Seq SS	Adj SS	Adj MS	F
Main Effects	4	487.77	487.77	121.94	4.31
2-Way Interactions	6	336.44	336.44	56.07	1.98
3-Way Interactions	4	233.81	233.81	58.45	2.06
Residual Error	1	28.32	32	28.32	
Total	15	1086.34			
R^2 value = 97.39					

Where SS =Sum of Squares, MS=Mean Square, F=Fishers ratio

$$Y = \beta + \beta_1 x_1 + \beta_2 x_2 + \ldots\_ \beta_x x_x + \in \quad (1)$$

The regression coefficients were calculated using MINITAB14 software and Equations (2), (3), (4), and (5) represent the developed mathematical models with welding parameters in coded form.

$$\text{Front Width} = 1492.12+(38.45*X_1)-(6.42*X_2)+(7.07*X_3)+(5.85*X_4)+(26.12*X_1*X_2)+(9.6*X_1*X_3)+(24.67*X_1*X_4)+(2.1*X_2*X_3)+(4.17*X_2*X_4)-(7.86*X_3*X_4)+(16.27*X_1*X_2*X_3)+(28.66*X_1*X_2*X_4)-(10.35*X_1*X_3*X_4)-(15.91*X_2*X_3*X_4) \quad (2)$$

Back Width =1413.7+(46.21*X_1)-(5.53*X_2)-(1.79*X_3)+(8.53*X_4)-(34.34*X_1*X_2) +(15.69*X_2*X_3)+(27.73*X_1*X_4)+(9.46*X_2*X_3)-(1.52*X_2*X_4)-(9.7*X_3*X_4)+ (10.7*X_1*X_2*X_3)+(28.4*X_1*X_2*X_4)-(10.32*X_1*X_3*X_4)-(12.8*X_2*X_3*X_4) (3)

Front Height = 59.687-(1.253*X_1)-(0.756*X_2)+(3.032*X_3)-(4.457*X_4) +(1.146*X_1*X_2)+(3.509*X_1*X_3)-(1.707*X_1*X_4)-(1.891*X_2*X_3)+(0.676*X_2*X_4) -(0.639*X_3*X_4)+(0.937*X_1*X_2*X_3)-(0.304*X_1*X_2*X_4)+(0.529*X_1*X_3*X_4)+ (2.929*X_2*X_3*X_4) (4)

Back Height = 53.761-(1.212*X_1)-(0.513*X_2)+(2.845*X_3)-(4.545*X_4) +(0.637*X_1*X_2)+(3.731*X_1*X_3)-(1.436*X_1*X_4)-(1.886*X_2*X_3)+(0.671*X_2*X_4) -(0.795*X_3*X_4)+(0.571*X_1*X_2*X_3)-(0.195*X_1*X_2*X_4)+(1.25*X_1*X_3*X_4) +(3.562*X_2*X_3*X_4) (5)

Table 6: Comparison of actual and predicted values of responses.

	Front Width		Back Width		Front Height		Back Height	
Run Order	Actual	Predicted	Actual	Predicted	Actual	Predicted	Actual	Predicted
1	1579.22	1562.31	1499.5	1484.43	63.209	61.4371	57.775	56.4446
2	1486.59	1469.68	1361.64	1346.57	59.137	57.3651	49.443	48.1126
3	1383.04	1399.94	1301.22	1316.28	53.953	55.7249	48.422	49.7524
4	1539.88	1556.79	1480.6	1495.67	54.191	55.9629	49.422	50.7524
5	1582.92	1566.01	1506.41	1491.34	76.886	75.1141	71.209	69.8786
6	1404.63	1421.54	1283.25	1298.32	71.247	73.0189	65.947	67.2774
7	1477.09	1460.18	1393.14	1378.07	60.583	58.8111	54.737	53.4066
8	1451.98	1435.07	1372.69	1357.62	61.896	60.1241	54.251	52.9206
9	1530.3	1513.39	1453.96	1438.89	57.514	55.7421	52.538	51.2076
10	1382.42	1365.51	1305.11	1290.04	63.619	61.8471	58.265	56.9346
11	1392.7	1409.60	1337.14	1352.21	59.083	60.8549	54.855	56.1854
12	1543.53	1560.44	1466.85	1481.92	42.855	44.6269	36.559	37.8894
13	1581.7	1564.79	1537.7	1522.63	48.824	47.0521	42.514	41.1836
14	1503.05	1519.95	1436.88	1451.95	64.101	65.8729	59.595	60.9254
15	1547.92	1564.83	1474.37	1489.44	52.275	54.0469	46.553	47.8834
16	1486.94	1503.85	1408.72	1423.79	65.613	67.3849	58.092	59.4224

5. Checking the Adequacy of the Mathematical Models

The adequacy of the developed models is tested using Analysis of Variance (ANOVA) technique. As per this technique, if the calculated value of F_{ratio} of the developed model is less than the standard F_{ratio} (from F-table) value at a desired level of confidence (say 99%), then the model is said to be adequate within the confidence limit. ANOVA test results of all the responses are presented in Table 5.

The ANOVA table (Table 5) reveals that all the calculated F values are less than standard table F value; hence developed mathematical models are adequate.

6. Results & Discussion

Table 6 represents the predicted values of weld pool geometry. Figures 3, 4, 5, and 6 represents the scatter plots of weld bead parameters, indicating that the actual and predicted values of Weld pool geometry parameters are very close to each other.

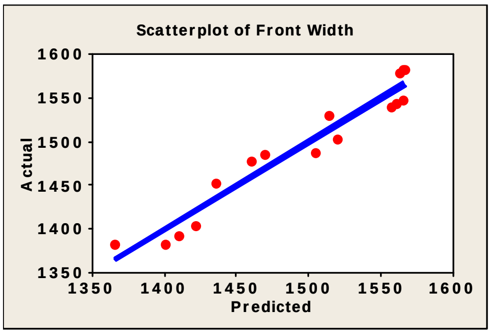


Figure 3: Scatter plot of Front Width

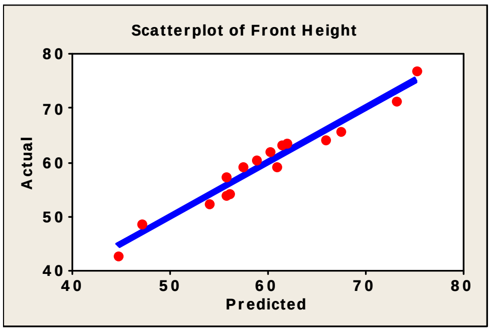


Figure 5: Scatter plot of Front Height

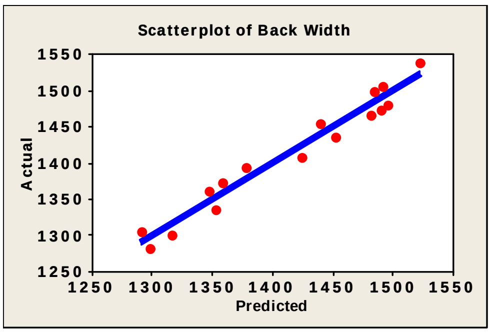


Figure 4: Scatter plot of Back Width

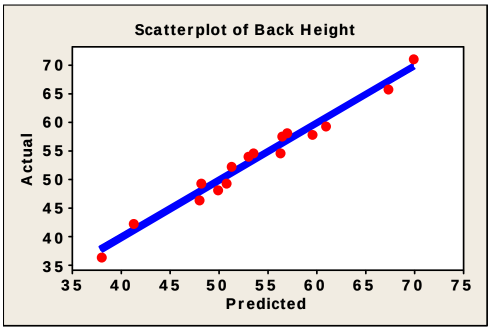
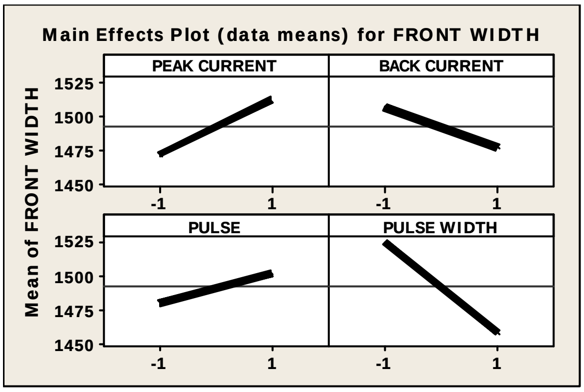


Figure 6: Scatter plot of Back Height

Figures 7, 8, 9, 10, 11, 12, 13, and 14 represent the main and interaction effects of different pulsed MPAW process parameters on the weld pool geometry. From Figures 7, 8, 9, and 10, it is understood from the results that peak current & pulse had more significant effect on weld pool geometry compared to back current and pulse width.



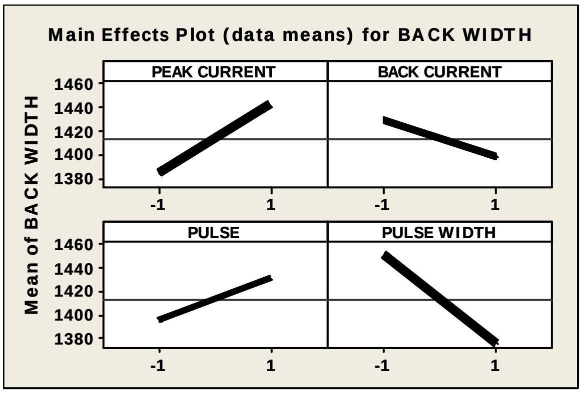
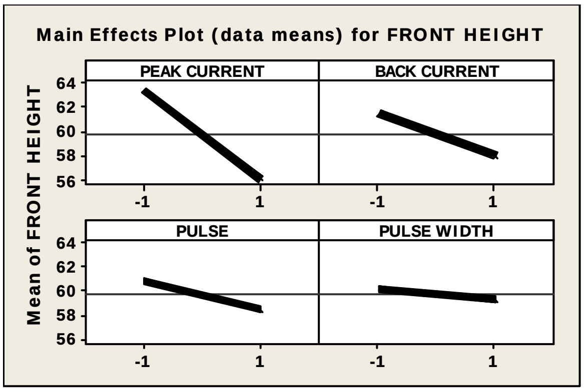


Figure 7: Main effects for Front Width. **Figure 8:** Main effects for Back Width.



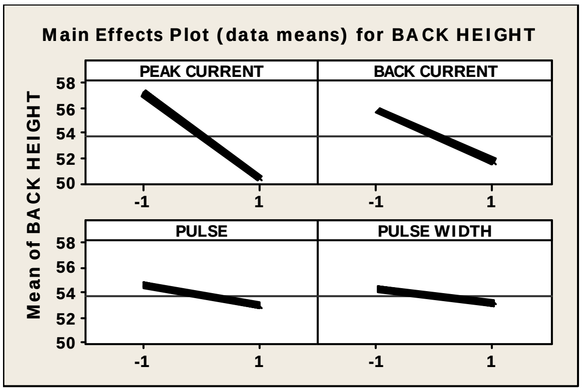


Figure 9: Main effects for Front Height. **Figure 10:** Main effects for Back Height.

As the peak current and number of pulses increases, heat input also increases, which leads to higher penetration and hence wider front and back widths. As the widths become wider the slopes become smaller, thereby decreasing the front and back heights. As the pulse with increases the weld pool geometry parameters decreases because of lower cooling rate of weld metal.

Back current is helpful in maintain the continuous arc, however increasing the back current decrease the weld pool geometry parameters because of large variation in pulse/sec.

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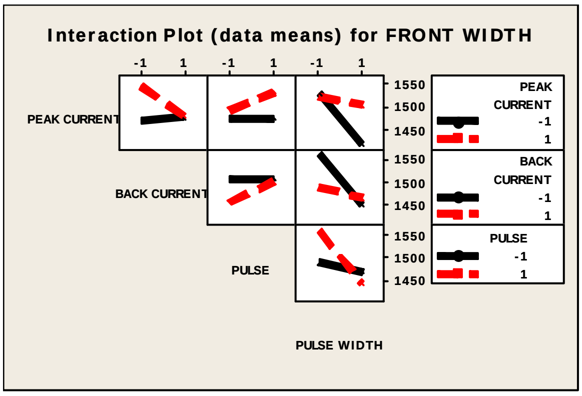

Figure 11: Main effects for Back Height.

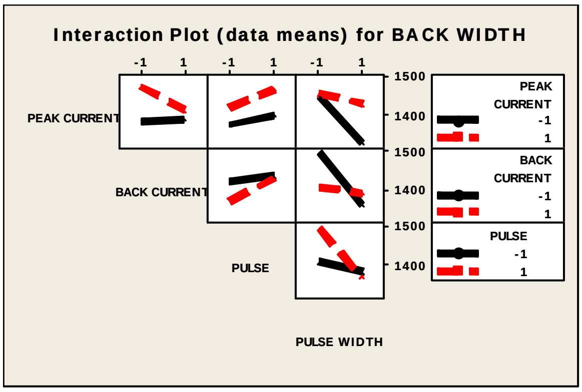

Figure 12: Interaction effect for Front Width.

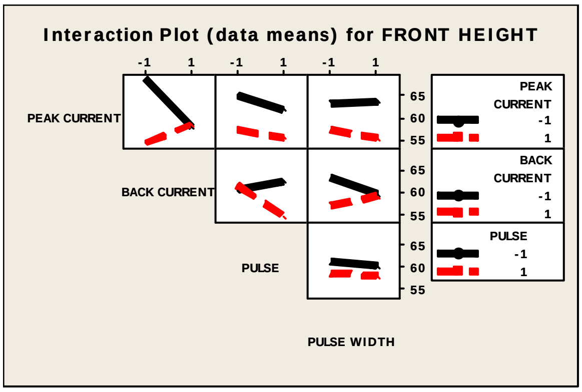

Figure 13: Interaction effect for Front Height.

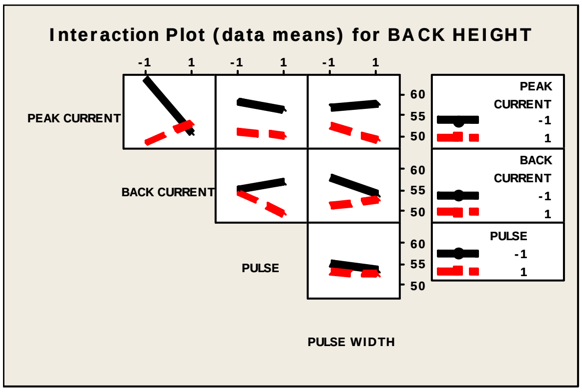

Figure 14: Interaction effect for Back Height.

From Figures 11 and 12, it is understood that the interaction effect on Front Width and Back Width are almost same i.e. the combined effect peak current and back current decrease in Front Width and Back Width, the combined effect of Peak Current and pulse increase the Front and Back Width and the combined effect of peak current and pulse width decrease in Front and Back Width.

From Figures 13 and 14 it is understood that the interaction effect on Front Width and Back Width are almost same i.e. the combined effect peak current and back current decrease in Front Width and Back Width, the combined effect of Peak Current and pulse decrease the Front and Back Width and the combined effect of peak current and pulse width increase in Front and Back Width.

Finally from Figures 11 to 14, it is understood that peak current and number of pulses has more significant effect on weld pool geometry parameters over other weld parameters.

7. Conclusion

From the developed mathematical models predicted values of weld pool geometry parameters were computed and found to be very close to actual values. Front Width & Back Width increases with Peak Current & Pulse, where as it decreases with Back Current and Pulse Width. Front Height and Back Height decreases with Peak Current, Back Current, Pulse and Pulse Width. The present study is limited to four process parameters namely peak current, back current, pulse and pulse width for predicting the weld pool geometry. One may consider other factors like welding speed, nozzle stand of distance, plasma and shielding gas flow rates and more levels for improving the statistical mathematical model.

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9. References

Lakshinarayana.A.K, Balasubramanian.V, Varahamoorthy.R and Babu.S. (2008). Predicted the Dilution of Plasma Transferred Arc Hardfacing of Stellite on Carbon Steel using Response Surface Methodology, *Metals and Materials International*, Vol.14, No.6, pp.779-789.

Balasubramanian.V, Lakshminarayanan.A.K, Varahamoorthy.R and Babu.S. (2009). Application of Response Surface Methodolody to Prediction of Dilution in Plasma Transferred Arc Hardfacing of Stainless Steel on Carbon Steel, *Science Direct*, Volume 16, Issue 1, pp.44-53.

Giridharan P.K, Murugan N. (2007). Effect of pulsed gas tungsten arc welding process parameters on pitting corrosion resistance of type 304L stainless steel welds, *Corros J*,63(5),pp.433–441.

Hsiao.Y.F, Tarng.Y.S and Huang.W.J. (2008). Optimization of Plasma Arc Welding Parameters by Using the Taguchi Method with the Grey Relational Analysis, *Journal of Materials and Manufacturing Processes*, 23, pp.51–58.

Montgomery DC, Design and analysis of experiments, 6th Ed. Wiley, New York, 2005.

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Plasma Welding: more accurate, better control at lower currents, *Modern Application News*, December 1999.

Siva.K, Muragan.N, Logesh.R. (2008). Optimization of weld bead geometry in Plasma transferred arc hardfacing austenitic stainless steel plates using genetic algorithm, *Int J Adv Manuf Technol*, Volume 41,Numbers 1-2, pp.24-30.

Sheng-Chai Chi, LI-Chang Hsu. (2001). A fuzzy Radial Basis Function Neural Network for Predicting Multiple Quality characteristics of Plasma Arc Welding, IEEE,0-7803-7078-3/01,pp.2807 -2812.

Zhang. D.K. and Niu.J.T. (2010). Application of Artificial Neural Network modeling to Plasma Arc Welding of Aluminum alloys, *Journal of Advanced Metallurgical Sciences*, Vol.13, No.1,pp.194-200.

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