Kovove Mater. 50 2012 153–159
DOI: 10.4149/km_2012_3_153

Effect of process parameters of pulsed current micro plasma arc welding on weld pool geometry of Inconel 625 welds

Kondapalli Siva Prasad[1]*, Chalamalasetti Srinivasa Rao[2], Damera Nageswara Rao[3]

[1] *Department of Mechanical Engineering, Anil Neerukonda Institute of Technology & Sciences, Visakhapatnam, Andhra Pradesh, India*
[2] *Department of Mechanical Engineering, Andhra University, Visakhapatnam, Andhra Pradesh, India*
[3] *Centurion University of Technology & Management, Odisha, India*

Received 1 July 2011, received in revised form 29 September 2011, accepted 7 October 2011

Abstract

Nickel alloys had gathered wide acceptance in the fabrication of light weight structures which require high temperature resistance and corrosion resistance, such as metallic bellows used in expansion joints used in aircraft, aerospace and petroleum industry, in which they are subjected to high temperature and corrosive environment. The effects of pulsing current parameters on weld pool geometry, namely front width, back width, front height and back height of pulsed current micro plasma arc welded Nickel alloy (Inconel 625) were analysed. Four factors, five levels, central composite design was used to develop mathematical models, incorporating pulsed current parameters and weld pool geometry. The mathematical models have been developed by Response Surface Method. The adequacy of the models was checked by ANOVA technique. By using the developed mathematical models, weld pool geometry parameters can be predicted.

Key words: pulsed current, micro plasma arc welding, Inconel 625, ANOVA

1. Introduction

Nickel alloys had gathered wide acceptance in the fabrication of light weight structures which require high temperature resistance and corrosion resistance, such as metallic bellows used in expansion joints used in aircraft, aerospace and petroleum industry, in which they are subjected to high temperature and corrosive environment. The present paper focuses on bellow manufacturing in which a thin sheet is to fold round in shape and the edges have to be welded longitudinally.

Welding thin sheets is quite different from welding thick sections, because during welding of thin sheets many problems are experienced. These problems are usually linked with heat input. Fusion welding generally involves joining of metals by application of heat for melting of metals to be joined. Almost all the conventional arc welding processes offer high heat input, which in turn leads to various problems such as burn through or melt through, distortion, porosity, buckling warping and twisting of welded sheets, grain coarsening, evaporation of useful elements present in coating of the sheets, joint gap variation during welding, fume generation from coated sheets, etc. Use of proper welding process, procedure and technique is one tool to address this issue [1]. MPAW is a good process for joining thin sheet, but it suffers from high equipment cost compared to GTAW. However, it is more economical when compared with Laser Beam Welding and Electron Beam Welding processes.

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. Today, plasma retains the original advantages it brought to the industry by providing an advanced level of control and accuracy to produce high quality welds in both miniature and 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

*Corresponding author: tel.: +91-9849212391; fax: +91-08933-226395; e-mail address: kspanits@gmail.com

Table 1. Chemical composition of Inconel 625 (wt.%)

C	Mn	P	S	Si	Cr	Ni	Al	Mo	Cb
0.03000	0.08000	0.00500	0.00044	0.12000	20.8900	61.6000	0.1700	8.4900	3.4400

Table 2. Important factors and their levels

			Levels				
SI No	Input factor	Units	–2	–1	0	+1	+2
1	Peak current	A	6	6.5	7	7.5	8
2	Back current	A	3	3.5	4	4.5	5
3	Pulse	s^{-1}	20	30	40	50	60
4	Pulse width	%	30	40	50	60	70

Table 3. Welding conditions

Power source	Secheron Micro Plasma Arc Machine (Model: PLASMAFIX 50E)
Polarity	DCEN
Mode of operation	Pulse mode
Electrode	2 % thoriated tungsten electrode
Electrode diameter	1 mm
Plasma gas	Argon and hydrogen
Plasma gas flow rate	6 $l\,m^{-1}$
Shielding gas	Argon
Shielding gas flow rate	0.4 $l\,m^{-1}$
Purging gas	Argon
Purging gas flow rate	0.4 $l\,m^{-1}$
Copper nozzle diameter	1 mm
Nozzle to plate distance	1 mm
Welding speed	260 mm min^{-1}
Torch position	Vertical
Operation type	Automatic

welding to high volume production welding and many others.

Pulsed current MPAW involves cycling the welding current at selected regular frequency. The maximum current is selected to give adequate penetration and bead contour, while the minimum is set at a level sufficient to maintain a stable arc [2, 3]. This permits arc energy to be used effectively to fuse a spot of controlled dimensions in a short time producing the weld as a series of overlapping nuggets. By contrast, in constant current welding, the heat required to melt the base material is supplied only during the peak current pulses allowing the heat to dissipate into the base material leading to narrower heat affected zone (HAZ) [4]. Advantages include improved bead contours, greater tolerance to heat sink variations, lower heat input requirements, reduced residual stresses and distortion, refinement of fusion zone microstructure and reduced width of HAZ. There are four independent parameters that influence the process: peak current, back current, pulse and pulse width.

From the literature review [5–10] it was understood that in most of the works reported in Plasma Arc Welding process, the effect of welding current, arc voltage, welding speed, wire feed rate, magnitude of ion gas flow, torch stand-off, plasma gas flow rate on weld quality characteristics like front melting width, back melting width, weld reinforcement, welding groove root penetration, welding groove width, front-side undercut are considered. However, much effort was not made to develop the mathematical models to predict the same especially when welding thin stainless steel sheets and also nickel alloys were in a flat position. Hence an attempt is made to correlate important pulsed current MPAW process parameters to weld pool geometry of Inconel 625 sheets by developing mathematical models.

Table 4. Design matrix and experimental results

SI No	Peak current (A)	Back current (A)	Pulse (s^{-1})	Pulse width (%)	Front width (mm)	Back width (mm)	Front height (mm)	Back height (mm)
1	–1	–1	–1	–1	1.218	1.144	0.0489	0.0488
2	1	–1	–1	–1	1.363	1.292	0.0468	0.0368
3	–1	1	–1	–1	1.153	1.093	0.0510	0.0400
4	1	1	–1	–1	1.273	1.214	0.0449	0.0349
5	–1	–1	1	–1	1.223	1.170	0.0461	0.0363
6	1	–1	1	–1	1.253	1.188	0.0475	0.0376
7	–1	1	1	–1	1.238	1.147	0.0479	0.0378
8	1	1	1	–1	1.231	1.171	0.0458	0.0358
9	–1	–1	–1	1	1.298	1.220	0.0479	0.0380
10	1	–1	–1	1	1.360	1.277	0.0451	0.0351
11	–1	1	–1	1	1.291	1.216	0.0452	0.0351
12	1	1	–1	1	1.331	1.275	0.0432	0.0333
13	–1	–1	1	1	1.214	1.141	0.0485	0.0374
14	1	–1	1	1	1.153	1.075	0.0470	0.0366
15	–1	1	1	1	1.275	1.202	0.0480	0.0380
16	1	1	1	1	1.192	1.125	0.0464	0.0374
17	–2	0	0	0	1.290	1.220	0.0478	0.0378
18	2	0	0	0	1.351	1.283	0.0449	0.0349
19	0	–2	0	0	1.221	1.151	0.0455	0.0355
20	0	2	0	0	1.196	1.127	0.0444	0.0344
21	0	0	–2	0	1.365	1.296	0.0462	0.0363
22	0	0	2	0	1.235	1.166	0.0444	0.0344
23	0	0	0	–2	1.169	1.106	0.0516	0.0426
24	0	0	0	2	1.230	1.153	0.0482	0.0382
25	0	0	0	0	1.300	1.231	0.0486	0.0386
26	0	0	0	0	1.350	1.281	0.0477	0.0377
27	0	0	0	0	1.292	1.221	0.0487	0.0387
28	0	0	0	0	1.288	1.219	0.0486	0.0386
29	0	0	0	0	1.273	1.201	0.0487	0.0387
30	0	0	0	0	1.270	1.202	0.0456	0.0356
31	0	0	0	0	1.170	1.101	0.0476	0.0375

2. Experimental set-up

2.1. Materials and methodology

Inconel 625 sheets of $100 \times 150 \times 0.25\,\mathrm{mm}^3$ are welded autogenously with square butt joint without edge preparation. The chemical composition of Inconel 625 stainless steel sheet is given in Table 1. High purity argon gas (99.99 %) is used as a shielding gas and a trailing gas right after welding to prevent absorption of oxygen and nitrogen from the atmosphere. From the literature four important factors of pulsed current MPAW as presented in Table 2 are chosen. The welding had been carried out under the welding conditions presented in Table 3. A large number of trial experiments were carried out using 0.25 mm thick Inconel 625 sheets to find out the feasible working limits of pulsed current MPAW process parameters. Due to wide range of factors, it was decided to use four factors, five levels, rotatable central composite design matrix to perform the number of experiments for investigation. Table 4 indicates the 31 sets of coded conditions used to form the design matrix. The first sixteen experimental conditions (rows) have been formed for main effects. The next eight experimental conditions are called as corner points and the last seven experimental conditions are known as centre points. The method of designing such matrix is dealt elsewhere [11, 12]. For the convenience of recording and processing the experimental data, the upper and lower levels of the factors are coded as +2 and –2, respectively, and the coded values of any intermediate levels can be calculated by using the expression [13]:

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

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.

2.2. Measurement of weld pool geometry

Three metallurgical samples were cut from each joint, with the first sample being located at 25 mm behind the trailing edge of the crater at the end of

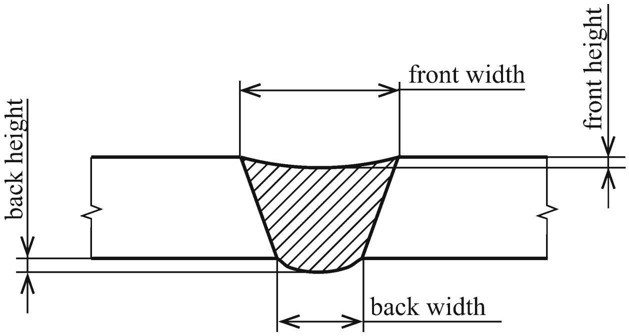

Fig. 1. Typical weld pool geometry [14].

the weld and mounted using Bakelite. Sample preparation and mounting were done as per 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, 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 using aluminium oxide initially and by utilizing diamond paste and velvet cloth in a polishing machine. The polished specimens were macro-etched by using Aqua regia solution to reveal the geometry of the weld pool (Fig. 1). Several critical parameters, such as front width, back width, front height and back height of the weld pool geometry (Fig. 2) were measured. The weld pool geometry was measured using Metallurgical Microscope (Make: Dewinter Technologie, Model No. DMI-CROWN-II) at 100× magnification.

3. Developing mathematical models

The weld pool geometry (W) is a function of peak current (A), back current (B), pulse (C) and pulse width (D). It can be expressed as [15–17]:

$$W = f(A, B, C, D). \quad (2)$$

The second order polynomial equation used to represent the response surface Y is given by [11]:

$$Y = b_o + \sum b_i x_i + \sum \beta_{ii} x_i^2 + \sum\sum b_{ij} x_i x_j + \varepsilon. \quad (3)$$

Using MINITAB 14 statistical software package, the significant coefficients were determined and final models were developed using only these coefficients to estimate front width, back width, front height and back height of the weld pool geometry.

Front width (FW):

$$\mathrm{FW} = 1.27757 + 0.01533X_1 - 0.00617X_2 - 0.03260X_3 + 0.01183X_4 - 0.01777X_2^2 - 0.02002X_4^2 - 0.03050X_1X_3 - 0.02400X_3X_4, \quad (4)$$

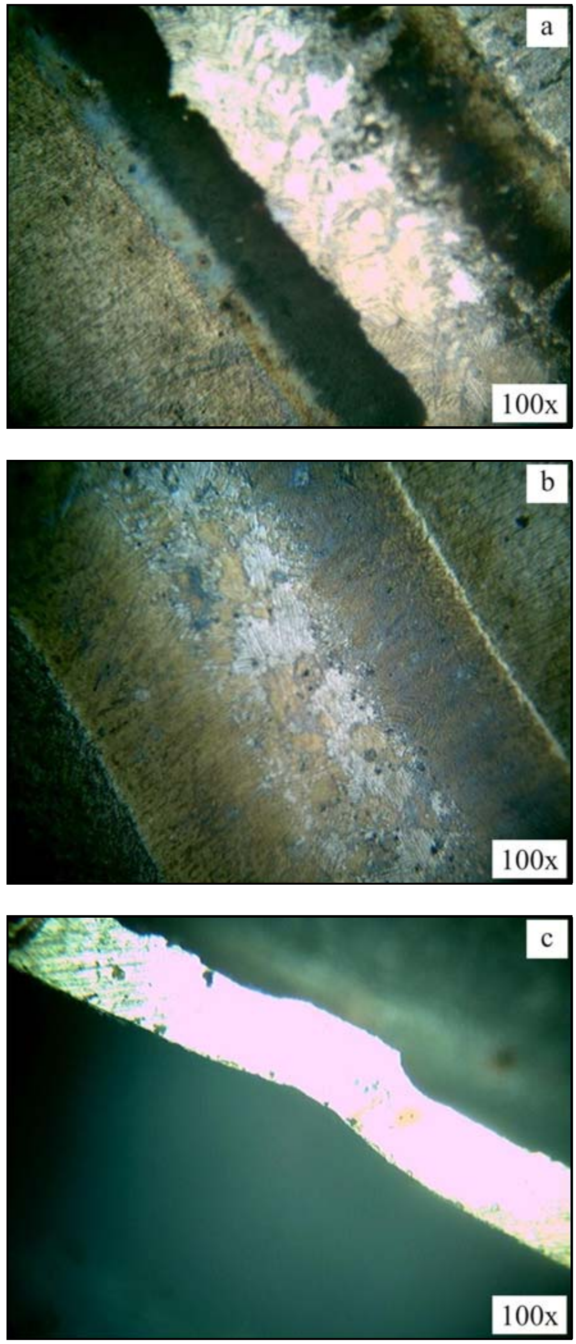

Fig. 2a,b,c. Macrographs of weld pool.

Back width (BW):

$$\mathrm{BW} = 1.20800 + 0.01708X_1 - 0.00467X_2 - 0.03217X_3 + 0.00858X_4 - 0.01781X_2^2 - 0.02019X_4^2 - 0.03037X_1X_3 - 0.02363X_3X_4, \quad (5)$$

Front height (FH):

$$FH = 0.047929 - 0.000942X_1 - 0.000317X_2 + 0.000025X_3 - 0.000600X_4 - 0.000701X_2^2 - 0.000613X_3^2 + 0.000537X_4^2 + 0.000800X_3X_4, \quad (6)$$

Table 5. ANOVA table

Source	Degrees of freedom	Fisher's ratio			
		Front width	Back width	Front height	Back height
Regression	14	6.37	6.19	5.41	5.65
Linear	4	7.68	7.51	6.69	7.78
Square	4	5.75	5.75	7.79	3.93
Interaction	6	5.92	5.61	2.96	5.38
Lack-of-fit	10	0.01	0.02	0.91	2.56
Remarks		Adequate	Adequate	Adequate	Adequate

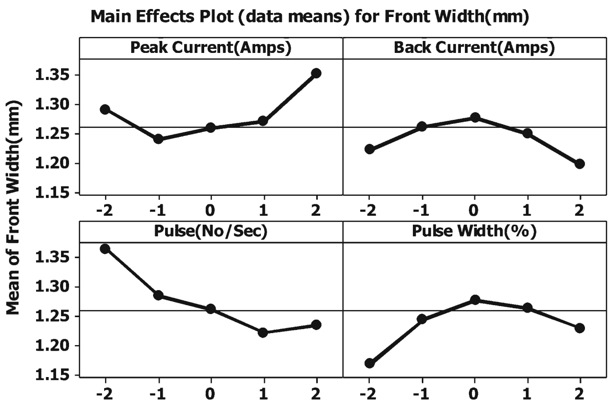

Fig. 3. Main effects for front width.

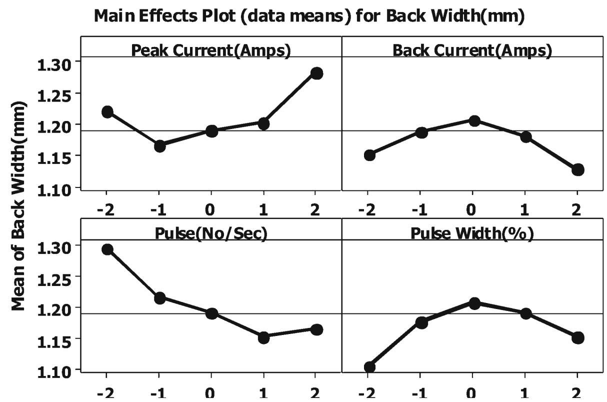

Fig. 4. Main effects for back width.

Back height (BH):

$$BH = 0.037914 - 0.001237X_1 - 0.000687X_2 - 0.000371X_3 - 0.001079X_4 + 0.001231X_1X_3 + 0.001306X_3X_4, \quad (7)$$

where X_1, X_2, X_3 and X_4 are the coded values of front width, back width, front height and back height.

4. Checking the adequacy of the developed models

The adequacy of the developed models was tested using the analysis of variance technique (ANOVA). As per this technique, if the calculated value of the 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.

The standard F_{ratio} (from F-table) is 7.87.

ANOVA test results for front width, back width, front height and back height are presented in Table 5. From ANOVA test results it was understood that the developed mathematical models were found to be adequate at 99 % confidence level and all the F_{ratio} values are less than standard F_{ratio} (from F-table). The value of coefficient of determination r^2 for the above developed models is found to be about 0.85.

5. Results and discussion

The mathematical models developed above can be employed to predict the geometry of weld pool geometry dimensions and their relationships for the range of parameters used in the investigation by substituting their respective values in coded form. Based on these models, the effects of the process parameters on the weld pool geometry dimensions are computed and plotted as depicted in Figs. 3 to 6.

5.1. Effect of peak current on weld pool geometry parameters

Front width and back width decrease with peak current up to 6.5 A and thereafter increase, whereas front height and back height increase up to 6.5 A and thereafter decrease. At lower peak currents up to 6.5 A, the heat input is less and hence low melting rate of the parent metal leading to lower front width and back width. When peak current increases beyond 6.5 A the heat input also increases and hence high melting rate of parent metal leads to higher front width and back width.

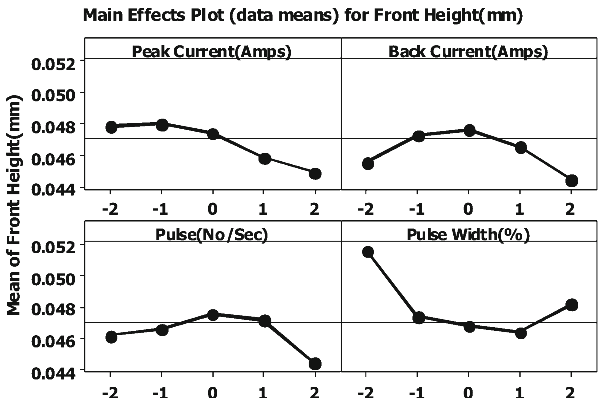

Fig. 5. Main effects for front height.

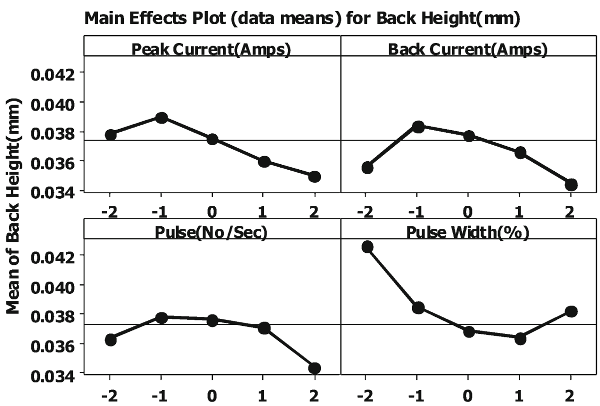

Fig. 6. Main effects for back height.

5.2. Effect of back current on weld pool geometry parameters

Front width, back width, front height increase up to 4 A and thereafter decrease, whereas back height increases up to 3.5 A and thereafter decreases. As the back current is helpful in maintaining continuous arc during welding, when the back current is low, i.e. up to 4 A, front width, back width and front height increase due to higher and dominating peak current, which generates large amount of heat. When the back current is increased beyond 4 A, it balances the heat input leading to lower heat input and hence front width, back width and front height decrease.

5.3. Effect of pulse on weld pool geometry parameters

Front width and back width decrease up to 50 pulses/s and thereafter increase, whereas front height increases up to 40 pulses/s and thereafter decreases and back height increases up to 30 pulses/s and thereafter decreases. This may be due to difference in heat input caused by variation of pulse. From 20 to 50 pulses/s, the interval between pulses is low and hence the heat input which enters the system at a moment decreases thereby decreasing the front width and back width. When the pulse is increased beyond 50 pulses/s, heat input which enters the system at a moment increases, thereby increasing the front width and back width.

5.4. Effect of pulse width on weld pool geometry parameters

Front width and back width increase up to 50 % and thereafter decrease, whereas front height and back height decrease up to 60 % and thereafter increase. The reason for effect of pulse width on weld pool geometry parameters is the same as that of pulse rate. From 30 to 50 % pulse width, the interval between pulse widths is high and hence the heat input which enters the system at a moment increases, thereby increasing the front width and back width. When the pulse width increases beyond 50 %, heat input which enters the system at a moment decreases, thereby decreasing the front width and back width.

From Figs. 3 to 6, it was understood that a peak current of 6.5 A, back current of 3.5 A, pulse of 40 pulses/s and pulse width of about 40 % were found to produce optimum results.

6. Conclusion

1. Mathematical models are developed for predicting the weld pool geometry dimensions of pulsed current micro plasma arc welding of Inconel 625 sheets.

2. The mathematical models developed can be employed easily in automated or robotic welding in the form of program, for obtaining the desired weld pool geometry dimensions.

3. Out of the four process variables considered peak current and pulse had a significant positive effect on most of the important weld pool geometry dimensions.

4. The mathematical models are developed considering only four factors and five levels (peak current, back current, pulse and pulse width). However, one may consider higher number of factors and their levels to improve the mathematical model.

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