Modeling of Plasma Arc Welding of Inconel 617 Super Alloy Plates using RSM

Kadivendi Srinivas[1], Pandu R Vundavalli[2] and M Manzoor Hussain[3]
[1]Department of Mechanical Engineering, DVR & Dr. HS MIC College of Technology, Kanchikacherla, AP, India.
[2] School of Mechanical Sciences, IIT Bhubaneswar, Odisha, India
[3] Department of Mech. Engineering, JNTUH College of Engineering, Hyderabad, Telangana, India.
[1]kadivendi@gmail.com, [2]pandu@iitbbs.ac.in, [3]manzoorjntu@gmail.com
.

Abstract:

In the present work, an attempt is given to study the outcomes of input process parameters, namely weld current, weld speed and plasma gas flow rate on the bead geometry, that is bead width (BW) and bead height (BH) of Plasma Arc Welded Inconel 617 plates. In the present study, Bead on Plate (BoP) welding was done on 2 mm thick plates with the help of experiments designed using central composite design of experiments (CCD). The non-linear regression equations developed during this study were validated through experimental test cases. Further, it was depicted that the developed regression models were found to forecast the bead geometry with a reasonably good accuracy.

Key words: Inconel 617 super alloy, plasma arc welding, bead geometry, RSM, regression models.

1. Introduction

Plasma arc welding is an advancement of Gas Tungsten Arc Welding Process (GTAW) with a better control due to its constricted Nozzle and gas stream. It is seen that the constriction increased the heat per unit volume of the plasma arc [1]. Due to this, high temperatures in the order of 11000^{o}c will be developed, and is suitable for welding high temperature resistant alloys like Ni based super alloys. In addition to the above fact, it is important to note that the weld distortion will also be very less, which makes the Inconel 617 to be used for elevated temperature applications, like gas turbines, nuclear reactors and boilers. Central composite design (CCD) of experiments is a methodology by which one can conduct experiments to establish the non-linear regression models, which are extensively used to model various manufacturing processes. This technique was also applied for welding processes to determine the relation between input and output parameters of arc welding process. Gunaraj et al. [2] used CCRD with five-level four-factor to develop the mathematical models that were utilized to forecast the weld-bead geometry in the SAW. Further, they analyzed the outcome of OC voltage, plate-nozzle distance, weld feed rate and welding speed on output parameters, like bead width, penetration, reinforcement and dilution using RSM technique. Elangovan et al. [3] developed a mathematical model using CCD. In their research, they considered welding parameters, namely rotational speed of tool, axial force, welding speed and tool pin profile as inputs and tensile strength of AA6061 alloy as output parameter. Further, Sivaprasad et al. [4] used response surface method (RSM) based on CCD of experimental procedure to carryout experiments on Inconel 625 material with Pulsed current Micro plasma arc welding. Nanda et al. [5] developed second-order response surface model to predict the depth of penetration of duplex steel alloy 2205 weld bead due to variation of current, torch speed and arc gap. Moreover, Babu et al. [6] reported the effect of axial force, welding speed and rotational speed to predict the maximum tensile strength of the joint on aluminum alloy 5059 using central composite design. The results were analyzed with the help of

IOP Conf. Series: Materials Science and Engineering **390** (2018) 012048 doi:10.1088/1757-899X/390/1/012048

response surface graphs. Xu et al. [7] developed statistical models to forecast and enhance the geometry of weld bead after utilizing CCD based on RSM of experimentation in an automated all-position GMA welding. Rahimzadeh et al. [8] established a mathematical model to identify the hardness and grain size of joints of AA 7020 aluminum alloy which were friction stir-welded using RSM in conjunction with CCRD. Further, Ragavendran et al. [9] used CCD matrix to conduct the welding experiments. The multiple regression equations associating the process factors with the responses were established for the hybrid laser – TIG welding of 316LN steel. Benyounis et al.[10] designed experiments based on 3-level Box–Behnken method, to study the interactions between focal point position, welding speed and laser power on HAZ, penetration and width of the weld in laser welding on medium carbon steels. Tarang et al [11] have done the experimentation in GTAW by incorporating taguchi method to forecast the geometry of weld bead behavior with change in process parameters. Ren et al. [12] made a comparative study of fusion area associated with the fiber laser welding and CO_2 welding of Inconel 617.

From the literature, it has been observed that many researchers had used RSM technique to found the associations among the process factors and responses in different types of welding methods. They extensively used central composite design for experiments to perform welding on variety of advanced metals. The present work demonstrate the attempts made for modeling the plasma arc welded Inconel 617 plates using RSM technique by conducting bead on plate experiments using central composite design. Welding parameters, such as gas flow rate, weld current and welding speed are considered as inputs, and bead width and bead height treated as outputs. The non-linear models developed are validated with the assistance of real test scenarios.

2. Experimental Details

The investigational particulars related to the welding of Inconel 617 plates using transferred Plasma Arc Welding in melt-in mode is given below.

2.1. Specimen preparation

In the present Research, Inconel 617 plates of size 150 mm x 100 mm x 2 mm are utilized as work piece. Before welding, the surface of the specimen is cleaned with the help of wire brush, and acetone is used for degreasing and to remove the effects of oxidation. Autogenously plasma arc welding machine is used to conduct the experimentation. Special care has been taken to prevent the distortion of the weld plates by providing suitable clamping.

2.2. Design of Experiments

Central component design of experiments is used to conduct the experiments. Process factors, such as plasma gas flow rate (G), welding speed (N) and welding current (I) are considered to vary within the limits provided in Table 1. Once the experiments are conducted, the responses, namely bead width (BW) and bead height (BH) are measured for the BoP welds after taking their macro graphs with the help of optical microscope.

Table 1. Process factors and their varieties

Process factor	Units	Minimum value	Maximum value
Current(I)	amp	80	105
Speed(N)	mm/min	250	300
Gas flow rate(G)	LPM	2	2.5

IOP Conf. Series: Materials Science and Engineering **390** (2018) 012048 doi:10.1088/1757-899X/390/1/012048

2.3 Experimental Results of Bead on plate Trials:

The bead on plate weld is sectioned in transverse direction by using wire cut electric discharge machine. The samples are mounted on the base for proper support for the weld bead. The sample are etched and polished with the suitable etchant. Computer connected metallurgical microscope is used to check the height and width of bead profile for the specimens.

3. Results and Discussion

The MINITAB 17 software is used to analyze the experimental data. Response surface methodology (RSM) is used to obtain non-linear regression equations. Obtained non-linear equations are analyzed with the help of Analysis of variance (ANOVA) for both the responses, namely bead width (BW) and bead height (BH).

3.1 Responses- Bead width& Bead height

The non-linear regression equations obtained for bead width and bead height of BoP trials are given in Eqns. (1) and (2), respectively and are given below.

$$BW = 45.76 + 0.1263\, I - 0.3217\, N - 1.82\, G + 0.00186\, I*I + 0.000626\, N*N + 1.294\, G*G - 0.00072\, I*N - 0.10044\, I*G + 0.01635\, N*G \quad (1)$$

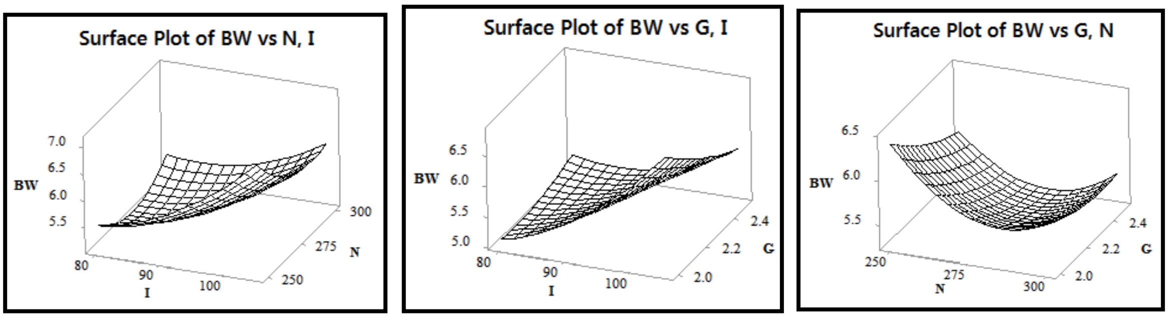
$$BH = -22.76 - 0.6486\, I + 0.5473\, N - 17.70\, G + 0.001970\, I*I - 0.000953\, N*N + 4.767\, G*G + 0.000507\, I*N + 0.06872\, I*G - 0.03507\, N*G \quad (2)$$

Once the non-linear regression equations that represent the relationship between the input process parameters and bead geometry of PAW of Inconel 617 plates is obtained, its statistical validity has been tested with the help of ANOVA and surface plots. The ANOVA table for the response bead width of BoP trail is given in Table 2.

Table 2. ANOVA table for the response – bead width of BoP

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model		7.59038	0.84338	230.82	0.000
Linear	9	4.06965	1.35655	371.27	0.000
I	3	3.26167	3.26167	892.67	0.000
N	1	0.41209	0.41209	112.78	0.000
G	1	0.39589	0.39589	108.35	0.000
Square	1	2.23675	0.74558	204.05	0.000
I*I	3	0.23367	0.23367	63.95	0.000
N*N	1	0.42031	0.42031	115.03	0.000
G*G	1	0.01800	0.01800	4.93	0.051
2-Way	1	1.28398	0.42799	117.14	0.000
Interaction	3	0.41228	0.41228	112.83	0.000
I*N	1	0.78820	0.78820	215.72	0.000
I*G	1	0.08350	0.08350	22.85	0.001
N*G	1	0.03654	0.00365		
Error	10	0.03190	0.00638	6.88	0.027
Lack-of-Fit	5	0.00464	0.00093		
Pure Error	5	7.62691			
Total	19				

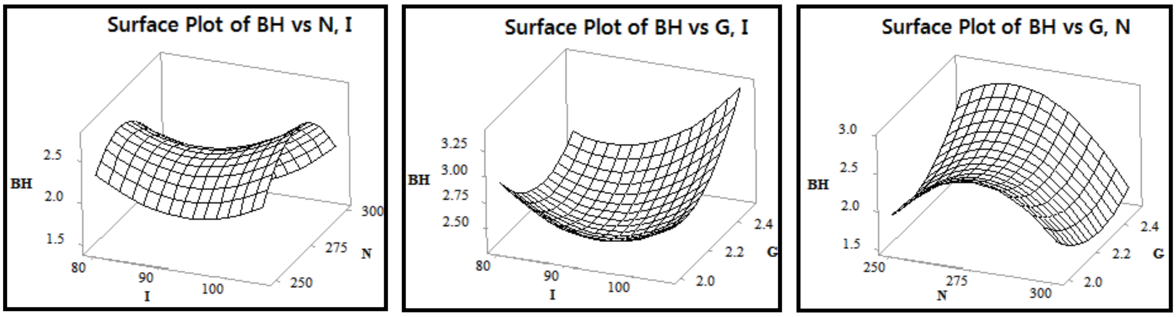
From Table 2, it was depicted that apart from the square term of plasma gas flow rate, all other terms such as interaction, linear and square terms have played significant role on the response, bead width. Similar study has also been conducted on the bead height of the BoP trails. It has been observed that the effect of linear and square terms of flow rate of plasma gas was insignificant when compared with other terms, because their p terms obtained are more than 0.05. Further, figure 1 and 2 shows the variation of responses such as bead width and bead height.



(a) (b) (c)

Fig. 1: Response plots showing the relationship between bead width with (a) welding speed and current, (b) gas flow rate and welding current, (c) gas flow rate and welding speed.

From the surface plots it has been found that the bead width is seen to increase with an increase in the combination of welding speed and current. Further bead width is found to be more at lower and high speed values and minimum at medium speed values. From Fig. (3), it has been observed that the bead height is found to be more for low and high values of current and at medium speed bead height is high compared to low at low and high speed values. The effect of gas flow rate on width and height of bead was observed to be very less compared to other input parameters, namely welding current and speed.



(a) (b) (c)

Fig. 2: Response plots showing the relationship between bead height with (a) welding speed and current, (b) gas flow rate and welding current, (c) gas flow rate and welding speed.

Further, the coefficient correlation values obtained for BW and BH were 0.98 and 0.99, respectively. From the results of ANOVA, surface plots and coefficients of correlation values, it can be concluded that, the non-linear regression equations established are statistically tolerable and can be utilized for performing predictions. The table showing the experimental and predicted values of bead width and bead height of PAW of Inconel 617 plates are given in Table 3. It has been observed that the predicted values obtained from the non-linear regression equations for BW and BH of the bead geometry are very close to the experimental values.

Table 3. The experimental and predicted data obtained for BW and BH of PAW welding

S. No	Weld current (I)	Weld speed (N)	Gas flow rate (G)	Expt. BW	Expt. BH	Predicted BW	Predicted BH
1	85	260	2.4	5.2510	2.4291	5.4064	2.5352
2	82	270	2.3	5.4040	2.5506	5.2359	2.5129
3	90	250	2.5	5.9365	2.6754	5.7638	2.5801
4	95	290	2.1	5.8976	2.2435	5.7553	2.1442
5	100	280	2.2	6.1234	2.3685	5.9581	2.4523
6	105	260	2.3	6.6956	2.6750	6.6302	2.7040
7	90	285	2.2	5.3456	2.0987	5.4053	2.1505
8	98	265	2.1	6.0234	2.4327	6.2273	2.3525

Further, the percentage error obtained for bead width and bead height of PAW was shown in Figure 3. It has been observed that the range of error percentage prediction of the responses such as BW and BH were {-3.38 to +3.11} and {-4.37 to +4.43} %, respectively.

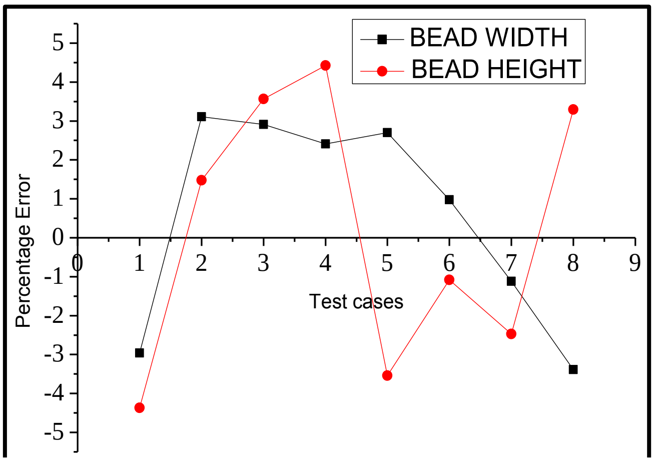


Fig. 3: Graph showing the percentage error for bead width and bead height of the PAW.

This shows that the non-linear regression equations have performed the predictions with a reasonably good accuracy.

4. Conclusion

The current research has made an attempt to establish the non-linear regression models for the bead width and bead height of BoP plasma arc welding of 2 mm thick Inconel 617 plates. The results of ANOVA and response surface plots show that the models are statistical adequate. Further, it has also been observed that the welding speed and welding current are having significant impact on the bead

IOP Conf. Series: Materials Science and Engineering **390** (2018) 012048 doi:10.1088/1757-899X/390/1/012048

geometry that is bead height and bead width, when compared with the other process parameter – plasma gas flow rate. Moreover, the prediction accuracy of the models show that the non-linear models are capable of predicting the responses without conducting the real experiments, which are expensive and time consuming.

References

[1] C.S. Wu, L. Wang, W.J. Ren, X.Y. Zhang. Plasma arc welding: Process, sensing, control and modeling. *Journal of Manufacturing Processes*. 2013, **16**(1):74-85.

[2] V. Gunaraj, N. Murugan. Application of response surface methodology for predicting weld bead quality in submerged arc welding of pipes. *Journal of Materials Processing Technology*, 1999, **88**:266-275.

[3] K. Elangovan, V. Balasubramanian, S. Babu. Predicting tensile strength of friction stir welded AA6061 aluminium alloy joints. *Materials and Design*, 2009, **30**:188-193.

[4] K S Prasad & S Rao Ch & N Rao D Application of grey relational analysis for optimizing weldbead geometry parameters of pulsed current micro plasma arcwelded inconel 625 sheets. *The International Journal of Advanced Manufacturing Technology*, 2015, **78**(1-4):625-632.

[5] N N Korra, M Vasudevan KR Balasubramanian.Optimization of A-TIG welding of duplex stainless steel alloy 2205 based on response surfacemethodology and experimental validation .*Journal of material design and applications*.2015, **230**(4): 837-846

[6] N. Babu, N. Karunakaran V. Balasubramanian. A study to estimate the tensile strength of friction stir welded AA5059 aluminium alloy joints, *The International Journal of Advanced Manufacturing Technology*,2017, **93**(1-4): 1–9.

[7] W. H. Xu & S. B. Lin & C. L. Fan & C. L. Yang, Prediction and optimization of weld bead geometry in oscillating arc narrow gap all-position GMA welding, *The International Journal of Advanced Manufacturing Technology*,2015,**79**(1-4): 183–196.

[8] A. Rahimzadeh I, R. Soufi, G. Hussain, R. V Barenji, A. Heidarzadeh, Establishing Mathematical Models to Predict Grain Size and Hardness of the Friction Stir-Welded AA 7020 Aluminum Alloy Joints, *Metallurgical and Materials Transactions B*,2014,**46**(1) :357-365.

[9] M. Ragavendran, N.Chandrasekhar, R.R kumar, Rajesh S, M.Vasudevan,A.K. Bhaduri, Optimization of hybrid laser – TIG welding of 316LN steel using response surface methodology (RSM), *Optics and Lasers in Engineering*, 2017,**94**:27-36.

[10] K.Y. Benyounis, A.G. Olabi, M.S.J. Hashmi.Effect of laser welding parameters on the heat input and weld-bead profile. *Journal of Materials Processing Technology*, 2005. **164–165**: 978–985.

[11] Y S Tarng, W H Yang.Optimization of the weld bad geometry in gas tungsten arc welding by Taguchi method.*Journal of Advanced Manufacturing Technology*.,1998,**14** :549-554.

[12] Wenjie Ren, Fenggui Lu, Renjie Yang, Xia Liu, Zhuguo Li, Seyed Reza ElmiHosseini. A comparative study on fiber laser and CO_2 laser welding of Inconel 617. *Marerials & Design*, 2015, **76**:207-214.