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Prediction of Weld Bead Geometry of Mild Steel Using Taguchi Technique and Multiple Regression Analysis

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Authors' contributions

This work was carried out in collaboration among all authors. Author WEO designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors JEU and DA managed the analyses of the study. All authors read and approved the final manuscript.

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ABSTRACT

The weld bead geometry is very important in predicting the quality of weld as cooling rate of the weld depends on it. For this purpose, the Taguchi technique was applied to determine optimum process parameters of weld bead geometry in submerged arc welding. The study involves using Taguchi's L_9 orthogonal arrays to conduct nine experiments on a 6 mm plate of IS2062 grade mild steel by using SKU MIL-SubArc AC/DC submerged arc welding machine with constant voltage. Three-levels of the four process parameters- arc voltage, welding current, welding speed and electrode stick out were considered and their effect on weld bead geometry−bead width, depth of penetration and weld reinforcement was observed. The signal to noise ratios was computed to determine the optimum parameters. From the results obtained, optimum process parameters of $A_3B_3C_1D_1$, $A_3B_2C_2D_2$ and $A_1B_1C_2D_3$ was suggested for weld bead width, weld penetration and weld reinforcement respectively. Regression analysis is done to establish the relationship between the input parameters and geometrical parameters of weld bead. The proposed mathematical model can be used to predict bead width, weld penetration and weld reinforcement values for any given SAW welding conditions.

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Keywords: Submerged arc welding; taguchi technique; multiple regression analysis; weld bead geometry.

1. INTRODUCTION

Submerged arc welding (SAW) method is one of the oldest automatic welding methods introduced in the nineties to provide high quality of weld in industries and research organizations. The Submerged arc welding method is often preferable because of its high production rate, high melting efficiency, ease of automation and low operator skill requirement. Submerged arc welding can be applied for a broad range of work pieces. The method is appropriate for fillet and butt welding of applications such as structural members in ships, manufacture of pressure vessels, massive water pipes, bridge beams, and thin sheet shells and so on. It is usually performed indoors in fabrication shops as working outdoors always carries the risk of undesirable levels of moisture finding their way into the joint or flux and resulting in porosity of the weld. For submerged arc welding operation to be done outdoors, special precautions such as the construction of a roof over the work area should be considered. The quality of weld in submerged arc welding is mainly influenced by independent variables such as arc voltage, welding current, electrode stick out and welding speed. These process parameters behave in a complex manner and their interactions affect the bead geometry, bead quality, metallurgical characteristics and mechanical properties of the weld metal [1,2]. It is very difficult to predict the process parameters involved in submerged arc welding. Many researchers have carried out several studies to predict the process parameters of submerged arc welding in order to obtain good quality of weld. Murugan et al. [3] studied the prediction and control of weld bead geometry and shape relationships in submerged arc welding of pipes. McPherson et al. [4] studied the structure of dissimilar welds by submerged arc welding process. Gunaraj et al. [5,6] developed analytical models to establish a relationship between process parameters and weld bead volume in submerged arc welding (SAW) of pipes. They also carried out the optimization of weld bead volume using the optimization module available in the MATLAB (Version 4.2b) software. Chandel et al. [7] studied the effect of current, polarity, electrode diameter and its extension on the melting rate, bead height, bead width and weld penetration in submerged arc welding. They concluded that for a given current the melting rate can be increased by using electrode negative polarity, longer electrode extension, and smaller diameter electrodes. They also showed that there are two other ways to increase the deposition rate without increasing the heat input. Kumanan et al. [8] worked on the application of Taguchi Technique and Regression Analysis to determine the optimal process parameters for SAW. They carried out an experiment on a semi automatic submerged arc welding machine and the signals to noise ratios have been computed to determine the optimum parameters. The percentage contribution of each factor was then validated by ANOVA technique. Multiple regression analysis was also carried out using SPSS software to develop mathematical models to predict the bead geometry for the given welding conditions. They also predicted the bead geometry from the developed model from the corresponding input data. Yang et al. [9] studied the effects of submerged arc welding process variables on the weld deposit area. Kaaoglu and Secgin [10] carried out the sensitivity analysis of submerged arc welding (SAW) parameters; welding current, welding voltage and welding speed for optimum weld bead geometry. The weld bead width, height and penetration were selected as design variables. A mathematical model was developed using multiple curvilinear regression analysis. The study revealed that the penetration is almost non-sensitive to the variations in voltage and speed. Pandey S. [11] proposed a relationship between welding current and direct SAW process parameters using two level half factorial designs. Interactive effects of direct parameters were also studied.

The quality engineering methods of Taguchi, employing design of experiments provide an efficient and systematic way to optimize designs for performance, quality and cost. It is one of the most important statistical tools for designing high quality systems at reduced cost [12-14]. The use of Taguchi method simplifies the optimization procedure for determining the optimal welding parameters in the SAW process. The use of Taguchi method simplifies the optimization procedure for determining the optimal welding parameters in the SAW process. Unal and Dean [15] applied the Taguchi technique to obtain design optimization in the manufacturing process. Abdul Ghani Khan et al. [16] explores the friction welding parameters that influence the output, namely tensile strength such as friction pressure, forging pressure, friction time and forging time using Taguchi method. Tarng et al. [17,18] used grey-based Taguchi methods to determine submerged arc welding process parameters in hard facing. In another study, they used fuzzy logic in the Taguchi method for the optimization of the submerged arc welding process. Datta et al. [19] applied Taguchi philosophy for parametric optimization of bead geometry and heat affected zone (HAZ) width in submerged arc welding using a mixture of fresh and fused flux. The experiment was carried out on mild steel plate of 100 mm by 40 mm by 12 mm using L9 orthogonal array. From the study, they concluded that 10% of slag mix can be used to obtain optimum bead width and depth of HAZ and 15 to 20% of slag mix for reinforcement and depth of penetration.

The aim of this study is to determine suitable levels of submerged arc welding process parameters for weld bead geometry of mild steel. For this purpose, Taguchi technique of design of experiments and multiple regression analysis have been applied to predict optimum process parameters of bead width, weld penetration and weld reinforcement and a proposed model for the prediction of optimal process parameters of weld bead geometry of mild steel plates for any SAW welding condition was developed.

2. EXPERIMENTAL DESIGN AND SET-UP

This experiment was performed using SKU MIL-SubArc AC/DC submerged arc welding machine with constant voltage and rectifier type power source with a 1000 A at 44 VDC to join IS2062 Grade B mild steel plates of dimensions 400 mm by 45 mm by 5 mm. Copper coated electrodes AWS ER70S-6, 3.2 mm diameter of coil form and basic-fluoride-type granular flux were used. A square butt joint with a 1 mm root opening was selected to join the plates in the flat position, keeping the electrode positive and perpendicular to the plate. Samples of 6 mm width were cut from the test piece, polished, etched and the bead geometries measured. The Rockwell hardness-testing machine with C scale was used to test for hardness of test piece. The chemical composition of the work material is shown in Table 1.

The operating variables of submerged arc welding are welding current, arc voltage, welding speed, electrode diameter, electrode extension (length of stick out), type of flux, width and depth of flux layer and polarity and current type (AC or DC). In order to select the welding process parameters to obtain a desirable weld quality, careful attention is needed. Though many direct and indirect parameters affect the quality of weld in submerged arc welding, after thorough literature survey, the key process parameters considered in this study are arc voltage, welding current, welding speed and electrode stick out. Welding current directly influences the depth of penetration. The welding arc voltage has a direct influence on the shape of weld bead and external bead appearance. The welding speed has a pronounced effect on the weld size and penetration for a given combination of welding current and welding voltage. At a given current the weld bead shape and the depth of penetration are affected by electrode diameter. The electrode stick out affects the deposition rate and the depth of penetration. Initial trial experiments were conducted on the test piece under consideration to decide the variables range and their levels. Finally, three-levels of the four process parameters, arc voltage, welding current, welding speed and electrode stick out were considered. The values of the welding process parameter at different levels are listed in Table 2. Conducting experiments by considering each variable at all the three levels is very costly and time consuming. Hence, in order to limit the total number of experiments in the present work, the Taguchi's L_9 orthogonal array is used for four variables with three levels. Similar orthogonal array was also reported by many researchers in their experimental work of submerged arc welding process on certain types of steels as well as for other manufacturing processes [7-9]. There are 8 degrees of freedom owing to the four sets of three level welding process parameters. In this study, an $L_9\,(3^4)$ orthogonal array, which has 8 degrees of freedom, was used. The experimental layout for the welding process parameters using the L_9 orthogonal array is shown in Table 3. By using Taguchi's L_9 orthogonal array in Table 3, detailed design of experiments is given in Table 4.

Edge preparation of the specimens is done by providing a 30° bevel on one side of the plate so that when two plates with bevel edge brought in contact with each other, then a butt joint of 'V' shape can be formed. The edges to be welded are cleaned properly in order to ensure dirt free surface. Two plates with butt joint are then clamped together with the help of 'C' clamp and the assembly is then preheated for approximately 30 min and the flux is also preheated. With this the atmospheric effect is minimized and chances of weld defects are also reduced. The specimen assembly is preheated along with the flux before the start of welding. The input variables are adjusted on the SAW machine as per the design of experiment for respective experiments. A very careful adjustment is required for the direction of trolley travel so that the wire feeding should be exactly at the center of V joint. This is because, as the welding proceeds, the steel plates may distort due to large amount of heat. Hence for this purpose proper clamping arrangement is provided for the weld joint. In the present work, all the 9 experiments are conducted very carefully in order to achieve good quality and defect-free weld joint for all the experiments. After completion of welding, each specimen is subjected to post weld heat treatment in the furnace in order to improve the mechanical properties. All the weld joints were prepared for analysis by measuring various outputs obtained from each experiment. In this study, the outputs considered for analysis purpose are weld bead width, weld reinforcement and weld penetration.

To prepare the test sample, some welded portion is removed by cutting it form the portion marked. For measuring the weld bead geometry and hardness, a specimen of 20 mm width is removed from the centre of weld joint of each plate and it is directly used for the measurement purpose. For tensile strength measurement, separate portion of 50 mm width is removed from which a tensile test specimen is prepared as per the ASTM E8 standard. Fig. 1 shows various test samples prepared from each experiment for conducting different tests.

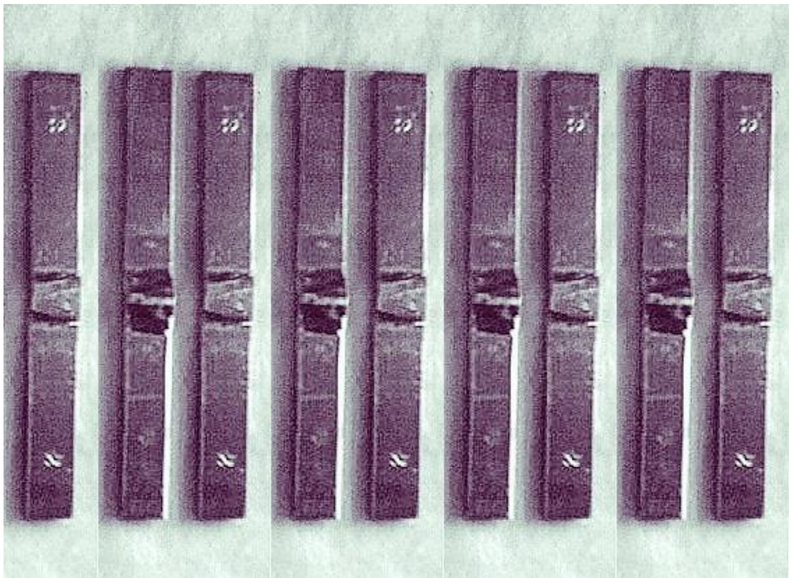

Fig. 1. Samples of welded plates

Table 1. Chemical composition of the base metal IS:2062 Grade B

Element	Carbon	Manganese	Silicon	Sulphur	Phosphorous
Percentage	0.22	1.50	0.4	0.045	0.045

Table 2. Welding parameters at different levels

Symbol	Welding parameter	Unit	Level 1	Level 2	Level 3
A	Arc voltage	V	22	25	28
B	Welding current	A	300	330	360
C	Welding speed	mm/min	800	900	1000
D	Electrode stick out	mm	20	22	24

Table 3. Experimental layout using $L_9\,(3^4)$ orthogonal array

Experiment no.	A Arc voltage	B Welding current	C Welding speed	D Electrode stick out
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

Table 4. Design of experiment

Experiment no.	Arc Voltage, V	Welding current, A	Welding speed, mm/min	Electrode stick out, mm
1	22	300	800	20
2	22	330	900	22
3	22	360	1000	24
4	25	300	900	24
5	25	330	1000	20
6	25	360	800	22
7	28	300	1000	22
8	28	330	800	24
9	28	360	900	21

2.1 Methods

2.1.1 Taguchi method

The quality engineering method of Taguchi, employing design of experiment (DOE) is one of the most important statistical tools for designing the high quality systems at reduced cost. The Taguchi method provides an efficient and systematic way to optimized designs for performance, quality and cost. Optimization of process parameters is the key step in the Taguchi's method to achieve high quality without increasing cost. Classical process parameter design is complex and not an easy task. To solve this task, the Taguchi method uses a special design of orthogonal arrays to study the entire process parameter space with a small number of experiments only. Taguchi has created a transformation of repetition data to another value, which is a measure of the variation present. The transformation is known as signal to noise (S/N) ratio. The S/N ratio consolidates several repetitions (at two data points are required) into one value, which reflects the amount of variation present. There are several S/N ratio depending on the characteristic; (i) Lower is better (LB), (ii) Nominal is better (NB), (iii) Higher is better (HB). The control factors that may contribute to reduce variation (improved quality) can be quickly identified by looking at the amount of variation present as a response. The bead width, depth of penetration and weld reinforcement of the weld bead geometries belong to higher-the-better quality characteristic. The loss function of the higher the better quality characteristic can be expressed as:

Higher the better,

$$L_f(MSD) = \left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \tag{1}$$

Where L_f is the overall loss function and y_i are the observed data (or quality characteristics) at the ith trial and n is the number of trials at the same level.

The overall loss function is further transformed into the signal to noise ratio. In the Taguchi method, the S/N ratio is used to determine the deviation of the quality characteristic from the desired value. The S/N ratio (η) can be expressed as:

$$\eta = -10logL_f \quad (2)$$

2.2 Multiple Regression Analysis

Multiple regression analysis technique is used to ascertain the relationships among variables. The most frequently used method among social scientists is that of linear equations. The multiple linear regression takes the following form:

$$Y = a + b_1X_1 + b_2X_2 + b_3X_3 + b_kX_k \quad (3)$$

Where Y is the dependent variable, which is to be determined; $X_1, X_2, X_3, \dots X_k$ are the known variables on which the predictions are to be made and $a, b_1, b_2, b_3, \dots, b_k$ are the coefficients and the values are determined by the method of least squares. Multiple regression analysis is used to determine the relationship between the dependent variables of bead width with welding current, arc voltage, welding speed, and wire diameter. The regression analysis was done using Minitab 15 version.

3. RESULTS AND DISCUSSION

After conducting all the experiments, the various responses were accurately measured and the effect of all input variables on each response was then analyzed to identify the critical variables affecting the various responses. The output variables considered in this work are: weld bead width, weld reinforcement, weld penetration, weld tensile strength and weld hardness. For measuring each of these responses, sophisticated equipments are used having high degree of accuracy. The various equipments used to carry out different tests are: Toolmakers microscope for measuring weld bead width and reinforcement, digital vernier caliper for measuring weld penetration, universal testing machine of capacity 1000 kN for measuring weld tensile strength and Rockwell hardness tester for measuring weld hardness. Before conducting all the tests and measurements, trials have been conducted to ensure the smooth functioning of respective equipment. The results obtained for each response are explained below with their analysis.

3.1 Effect of Process Parameters on Bead Width

The result obtained for weld bead width measurement at three different levels of arc voltage, welding current, welding speed and wire diameter is presented in Table 5. The bead width obtained for each experiment was analyzed to check the effect of each input variable on the bead width. MINITAB 15 software package was used to carry out the analysis of each response. Table 6 shows the experimental layout using L_9 orthogonal array and the result for the mean square deviation (MSD) and signal to noise ratio presented. The values of the mean square deviation and S/N ratios were obtained using equations (1) and (2). From the L_9 experimental layout in Table 6, the average S/N ratios for arc voltage, welding current, welding speed and wire diameter in various levels is computed. The largest S/N ratio average is indicated by (opt) as shown in Table 7. From Table 7, the optimal bead width was obtained by applying arc voltage 28 V, welding current 360 A, welding speed 800 mm/min and electrode stick out 20 mm for a plate of 6 mm thickness. It can therefore be predicted that if the path $A_3 - B_3 - C_1 - D_1$ is followed, optimal weld bead width will be achieved.

Table 5. Average measured bead width

Experiment no.	Arc Voltage, V	Welding current, A	Welding speed, mm/min	Electrode stick out, mm	Bead width, mm
1	22	300	800	20	14.0
2	22	330	900	22	12.0
3	22	360	1000	24	13.5
4	25	300	900	24	14.5
5	25	330	1000	20	15.5
6	25	360	800	22	15.0
7	28	300	1000	22	14.0
8	28	330	800	24	15.5
9	28	360	900	21	16.0

Table 6. Experimental layout using L_9 orthogonal array and S/N ratio for weld bead width

Experiment no.	Arc voltage, V	Welding current, A	Welding speed, mm/min	Electrode stick out, mm	Measured bead width, mm	Mean square deviation (MSD)	S/N ratio (dB)
1	22	300	800	20	14.0	196	22.92
2	22	330	900	22	12.0	144	21.58
3	22	360	1000	24	13.5	182.25	22.61
4	25	300	900	24	14.5	210.25	23.23
5	25	330	1000	20	15.5	240.25	23.81
6	25	360	800	22	15.0	225	23.52
7	28	300	1000	22	14.0	196	22.92
8	28	330	800	24	15.5	240.25	23.81
9	28	360	900	20	16.0	256	24.08

Table 7. Mean S/N ratio for weld bead width

Weld parameters	Levels	Mean bead width
Arc voltage, A	1 (22)	22.37
	2 (25)	23.52
	3 (28)	23.60(opt)
Welding current, B	1 (300)	23.02
	2 (330)	23.07
	3 (360)	23.50(opt)
Welding speed, C	1 (800)	23.42(opt)
	2 (900)	22.96
	3 (1000)	23.11
Electrode stick out, D	1 (20)	23.40(opt)
	2 (22)	22.67
	3 (24)	23.22

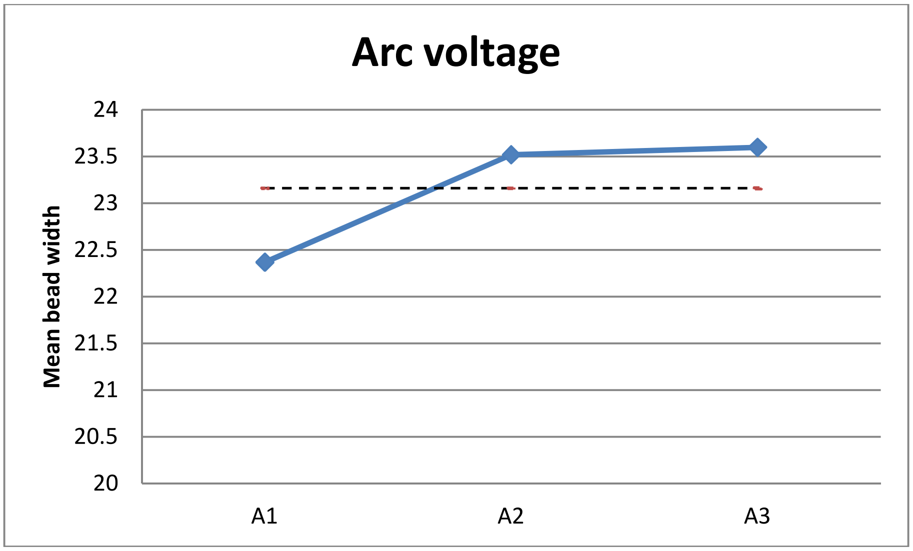

Fig. 2. Effect of arc voltage on bead width

Figs. 2-5 show the effects of process parameters on the weld bead width. Fig. 2 shows the effect of arc voltage on the weld bead width. From Fig. 2, it can be observed that as the values of the arc voltage increases from 22 V to 25 V, there was corresponding increase in bead width.

But as the arc voltage further increased from 25 V to 28 V, only small amount of increase in bead width was observed. In Fig. 3, the effect of welding current on the bead width is shown. It can be seen that as the welding current increases from 300 A to 330 A, the bead width increases slightly but as the welding current increases from 330 A to 360 A, the bead width showed much increase. Fig. 4 shows the effect of welding speed on the weld bead width. From Fig. 4, it is observed that as the welding speed is increased from 800 mm/min to 900 mm/min, a sharp decrease in bead width was observed. But as the welding speed increases from 900 mm/min to 1000 mm/min, the bead width is seen to be on the increase. Fig. 5 shows the effect of electrode stick out on weld bead width. From Fig. 5, it is observed that as the electrode stick out increases up to a certain level, a sharp drop in bead width was observed. But as the electrode stick out increases from 22 mm to 24 mm, there is sudden increase in bead width. From Figs. 2 to 5, it is observed that the arc voltage and welding current have the most significant effects on the weld bead width. As a result, a little variation in the welding current and the arc voltage is expected to have a significant effect on the bead width.

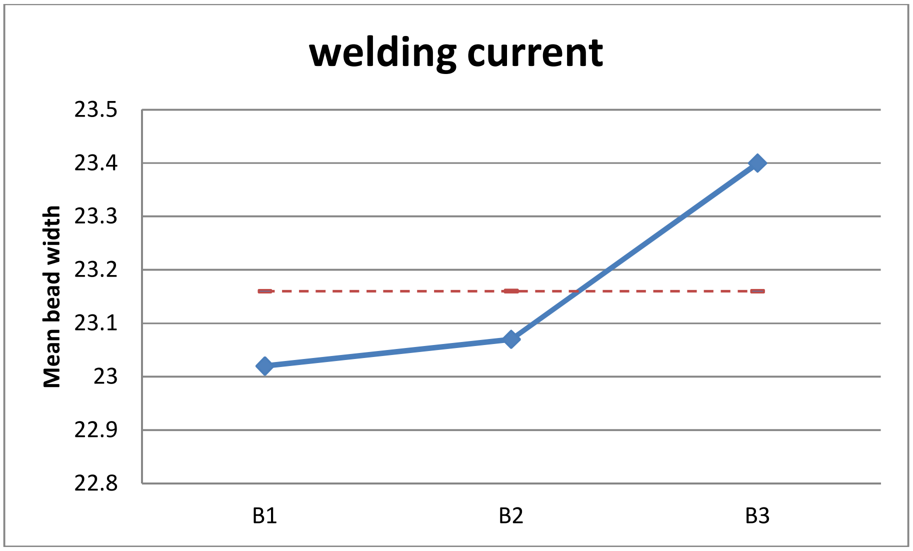

Fig. 3. Effect of welding current on bead width

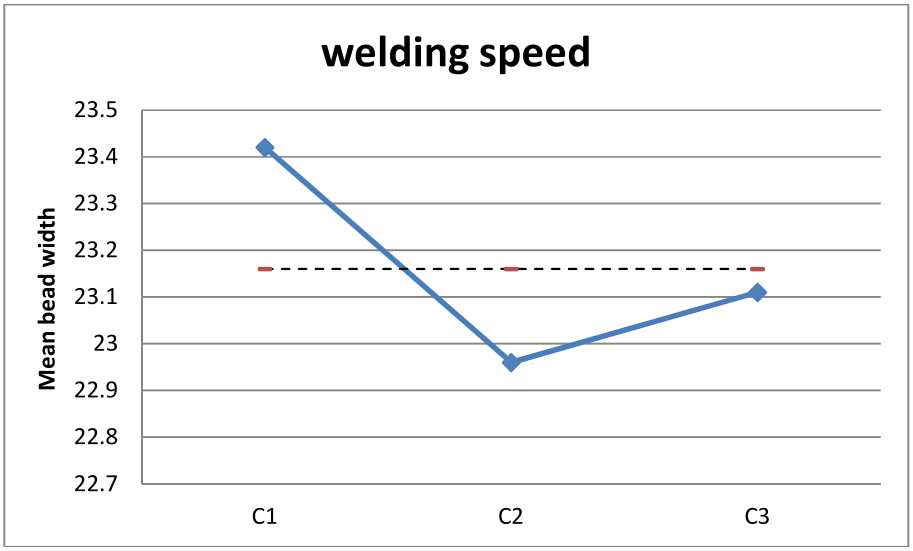

Fig. 4. Effect of welding speed on bead width

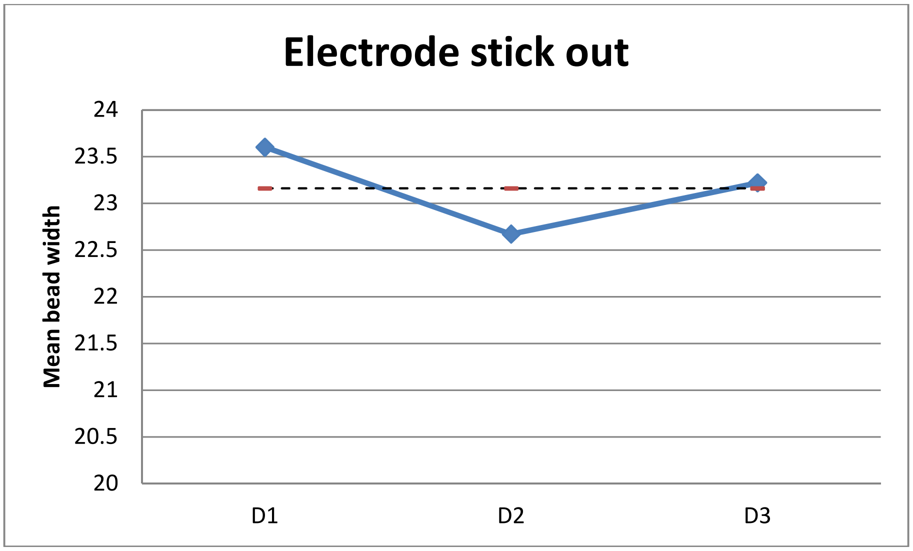

Fig. 5. Effect of electrode stick out on bead width

Multiple regression analysis technique (MRA) was applied to determine the relationship between the bead width and arc voltage, welding current, welding speed and electrode stick out. The regression analysis was done using Minitab 15 software package. The result of the regression analysis is shown in linear equations as follows:

$$Predicted\ bead\ width = -31.2 + 0.74 \times Arc\ voltage + 0.0657 \times Welding\ current + 0.0124 \times Welding\ speed - 0.0412 \times \text{Electrode stick out} \quad (4)$$

The coefficient of determination (R2) obtained is 87.72% which is very significant. The model can be used to obtain the weld bead width using different combinations of input variables.

3.2 Effect of Process Parameters on Bead Penetration

In order to produce a good weld joint, the filler material should fuse with the base material and the penetration should be towards the root gap of weld joint. The parameter setting was done through the design of experiment and different amount of penetration was obtained in each experiment. Measurement of the weld penetration was done through the cross section of weld joint. A high level of surface finish was obtained on the cross sectional area of weld joint by machining and polishing. The penetration obtained on each sample was measured by using digital vernier caliper having a least count of 0.01 mm. Table 8 shows the results for the weld penetration obtained for different sets of experiments. The penetration obtained for each experiment was analyzed to check the effect of each variable on the weld penetration.

Table 9 shows the experimental layout using L_9 orthogonal array and the result for the mean square deviation (MSD) and signal to noise ratio presented. The values of the mean square deviation and S/N ratios were obtained using equations (1) and (2). From the L_9 experimental layout in Table 9, the mean S/N ratios for bead penetration of is shown in Table 10. The highest S/N ratio average is indicated by (opt) and the effect is shown in Figs. 6-9. From Table 10, the optimal level of bead penetration is $A_3 - B_2 - C_2 - D_2$ i.e. arc voltage 28 V, welding current 330 A, welding speed 900 mm/min and electrode stick out 22 mm.

Figs. 6-9 show the effects of process parameters on the weld bead penetration. Fig. 6 shows the effect of arc voltage on the weld bead penetration. From Fig. 6, it can be observed that arc voltage has significant effect on weld bead penetration because of sudden changes in the penetration from low to high is observed as the voltage goes on increasing. In Fig. 7, the effect of welding current on the bead width is shown. It can be seen that the bead penetration increases as the welding current increases up to a certain level. But as the welding current is further increased from 330 A to 350 A, a sharp drop in bead penetration is observed. Fig. 8 shows the effect of welding speed on the weld bead penetration. From Fig. 8, it is observed that as the welding speed is increased from 800 mm/min to 900 mm/min, a sharp increase in bead penetration was observed. But as the welding speed increases from 900 mm/min to 1000 mm/min, a slight drop in bead penetration is observed. Fig. 9 shows the effect of electrode stick out on weld bead penetration. From Fig. 9, it is observed that as the electrode stick out increases up to a certain level; the bead penetration is seen increasing. But as the electrode stick out increases from 22 mm to 24 mm, there is sudden drop in bead penetration.

Table 8. Average weld penetration

Exp No.	Arc Voltage, V	Welding current, A	Welding speed, mm/min	Electrode stick out, mm	Weld penetration, mm
1	22	300	800	20	5.32
2	22	330	900	22	10.47
3	22	360	1000	24	6.15
4	25	300	900	24	7.86
5	25	330	1000	20	10.46
6	25	360	800	22	7.58
7	28	300	1000	22	8.69
8	28	330	800	24	10.47
9	28	360	900	21	8.76

Table 9. Experimental layout using L_9 orthogonal array and S/N ratio for weld penetration

Experiment no.	Arc voltage, V	Welding current, A	Welding speed, mm/min	Electrode stick out, mm	Weld penetration, mm	Mean square deviation (MSD)	S/N ratio (dB)
1	22	300	800	20	5.32	28.30	14.52
2	22	330	900	22	10.47	109.62	20.40
3	22	360	1000	24	6.15	37.82	15.78
4	25	300	900	24	7.86	61.78	17.91
5	25	330	1000	20	10.46	109.41	20.39
6	25	360	800	22	7.58	57.46	17.59
7	28	300	1000	22	8.69	75.52	18.78
8	28	330	800	24	10.47	109.62	20.40
9	28	360	900	20	8.76	76.74	18.85

Table 10. Mean S/N ratio for weld bead penetration

Weld parameters	Levels	Mean bead penetration
Arc voltage, A	1 (22)	16.9
	2 (25)	18.63
	3 (28)	19.34 (opt)
Welding current, B	1 (300)	17.07
	2 (330)	20.40 (opt)
	3 (360)	17.41
Welding speed, C	1 (800)	17.50
	2 (900)	19.05(opt)
	3 (1000)	18.32
Electrode stick out, D	1 (20)	17.92
	2 (22)	18.92(opt)
	3 (24)	18.03

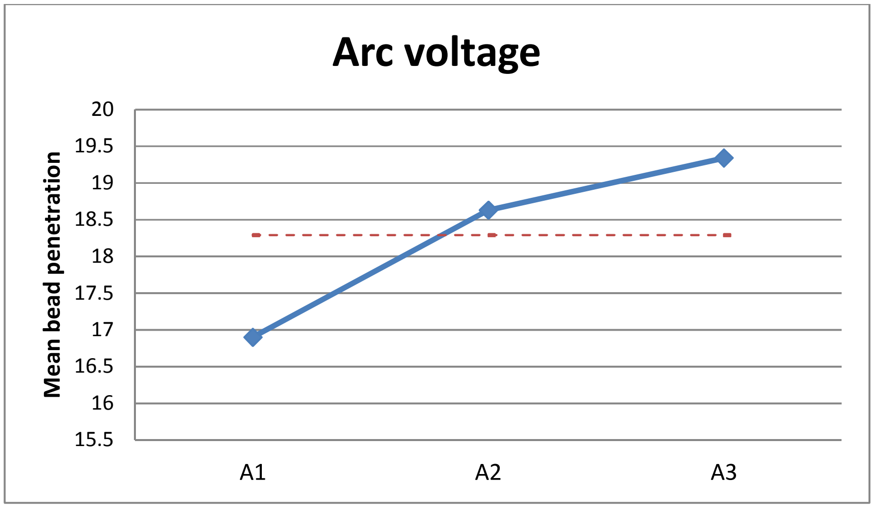

Fig. 6. Effect of arc voltage on bead penetration

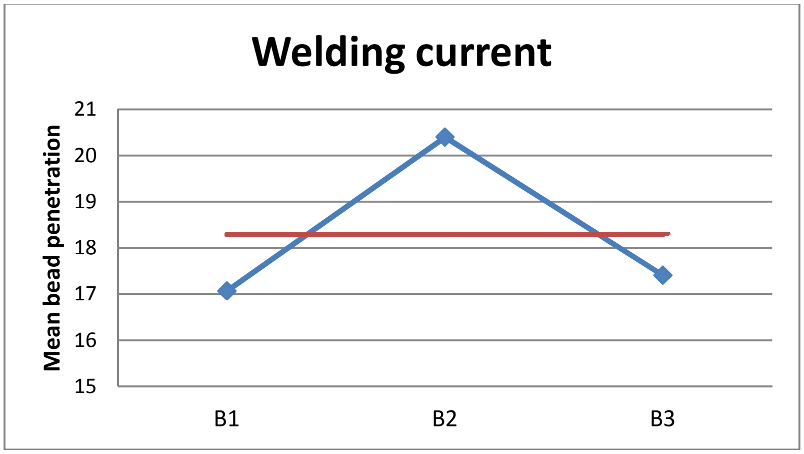

Fig. 7. Effect of welding current on bead penetration

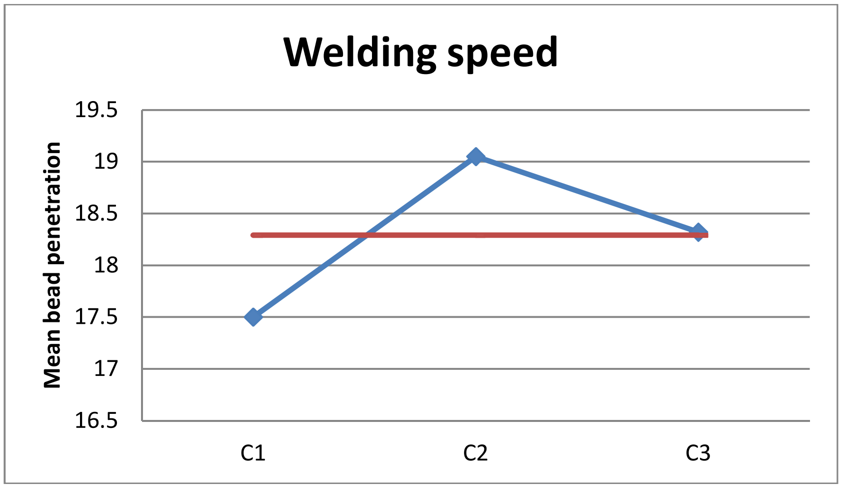

Fig. 8. Effect of welding speed on bead penetration

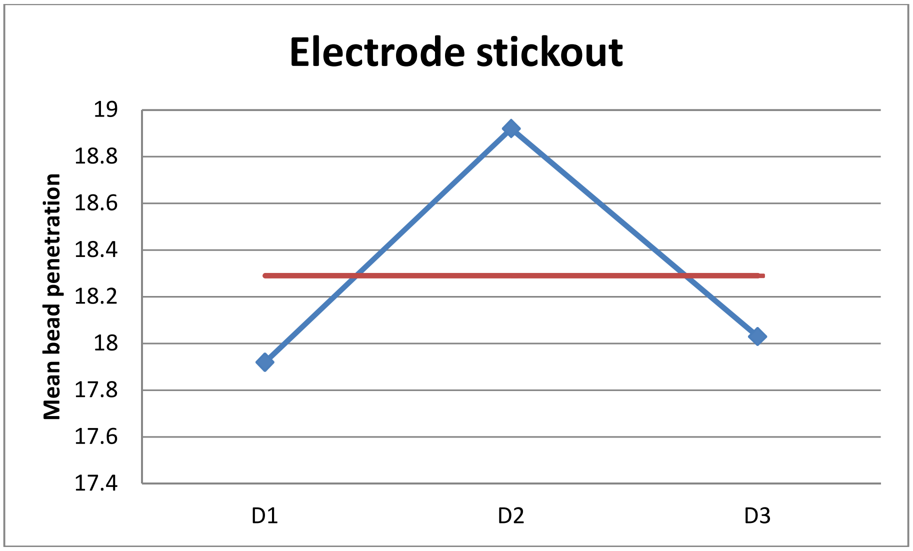

Fig. 9. Effect of electrode stick out on bead penetration

Multiple regression analysis technique (MRA) was applied to determine the relationship between the bead penetration and process parameters. The regression analysis was done using Minitab 15 software package. The result of the regression analysis is shown in linear equations as follows:

$$Predicted\ bead\ penetration = 27.5 - 0.87 \times Arc\ voltage + 0.0823 \times Welding\ current + 0.0324 \times Welding\ speed - 0.0532 \times \text{Electrode stick out} \quad (5)$$

Various tests were carried out on the weld penetration model and the coefficient of determination (R^2) obtained for the model is 84.4% which is very significant. The equation can be used to obtain the weld penetration using different combinations of process variables.

3.3 Effect of Process Parameters on Weld Bead Reinforcement

Similar to weld bead width, the weld reinforcement obtained for each set of experiment was measured using the Toolmakers microscope. Four readings were taken for each experiment and the average reinforcement was chosen. The result obtained for each experiment is shown in Table 11. Table 12 shows the result for signal to noise ratio of weld reinforcement using equations (1) and (2). The reinforcement obtained for each experiment was analyzed to check the effect of each variable on the weld reinforcement. Figs. 10-13 show the effect of process parameters on weld reinforcement while Table 13 shows the response table for mean weld reinforcement. The highest S/N ratio average is indicated by (opt) and the effect is shown in Figs. 10-13. From Table 13, the optimal level of weld reinforcement is A_1−B_1 − C_2−D_3 i.e. arc voltage 22 V, welding current 300 A, welding speed 900 mm/min and electrode stick out 24 mm. This means that optimal weld reinforcement can be achieved if the process parameters are set at these levels.

Figs. 10-13 show the effects of process parameters on the weld reinforcement. Fig. 10 shows the effect of arc voltage on the weld reinforcement. It is observed that arc voltage has inverse effect on weld bead reinforcement because of sudden changes in the weld reinforcement from high to low as the arc voltage is increases from 22 V to 25 V. But as the arc voltage is further increased from 25 V to 28 V, a steady increase in weld reinforcement is observed. Fig. 11 shows the effect of welding current on the bead reinforcement. Initial increase in welding current to a certain limit, 330 A, caused a rapid drop in weld reinforcement. But with further increase in current, small amount of increase in bead reinforcement is observed. Fig. 12 shows the effect of welding speed on the weld bead reinforcement. From Fig. 12, it is observed that as the welding speed is increased from 800 mm/min to 900 mm/min, a sharp increase in bead reinforcement is observed. But as the welding speed increases further from 900 mm/min to 1000 mm/min, gradual drop in weld reinforcement is observed. Fig. 13 shows the effect of electrode stick out on weld bead reinforcement. From Fig. 13, it is observed that as the electrode stick out increases up to a certain level; there was gradual drop in weld reinforcement. But as the electrode stick out increases from 22 mm to 24 mm, sudden jump in weld reinforcement is observed.

Multiple regression analysis technique (MRA) was applied to determine the relationship between the bead penetration and process parameters. The regression analysis was done using Minitab 15 software package. The result of the regression analysis is shown in linear equations as follows:

Table 11. Average weld reinforcement

Exp no.	Arc Voltage, V	Welding current, A	Welding speed, mm/min	Electrode stick out, mm	Weld reinforcement, mm
1	22	300	800	20	4.34
2	22	330	900	22	4.42
3	22	360	1000	24	3.85
4	25	300	900	24	8.94
5	25	330	1000	20	0.37
6	25	360	800	22	1.64
7	28	300	1000	22	3.37
8	28	330	800	24	2.78
9	28	360	900	21	4.56

Table 12. Experimental layout using L_9 orthogonal array and S/N ratio for weld reinforcement

Experiment no.	Arc voltage, V	Welding current, A	Welding speed, mm/min	Electrode stick out, mm	Weld reinforcement, mm	Mean square deviation (MSD)	S/N ratio (dB)
1	22	300	800	20	4.34	18.84	12.75
2	22	330	900	22	4.42	19.54	12.91
3	22	360	1000	24	3.85	14.82	11.71
4	25	300	900	24	4.94	24.40	13.87
5	25	330	1000	20	1.37	1.88	2.74
6	25	360	800	22	1.64	2.69	4.30
7	28	300	1000	22	3.37	11.36	10.55
8	28	330	800	24	2.78	7.73	8.88
9	28	360	900	20	4.56	20.79	13.18

Table 13. Mean S/N ratio for weld bead reinforcement

Weld parameters	Levels	Mean S/N ratio
Arc voltage, A	1 (22)	12.46 (opt)
	2 (25)	6.97
	3 (28)	10.87
Welding current, B	1 (300)	12.39 (opt)
	2 (330)	8.17
	3 (360)	9.73
Welding speed, C	1 (800)	8.64
	2 (900)	13.32 (opt)
	3 (1000)	8.33
Electrode stick out, D	1 (20)	9.56
	2 (22)	9.25
	3 (24)	11.49 (opt)

$$Predicted\ weld\ reinforcement = 34.5 - 0.53 \times Arc\ voltage + 0.0474 \times Welding\ current + 0.0523 \times Welding\ speed - 0.0465 \times Electrode\ stick\ out \quad (6)$$

The multiple regression model developed in equation (6) can be used to obtain the weld penetration using different combinations of process parameters.

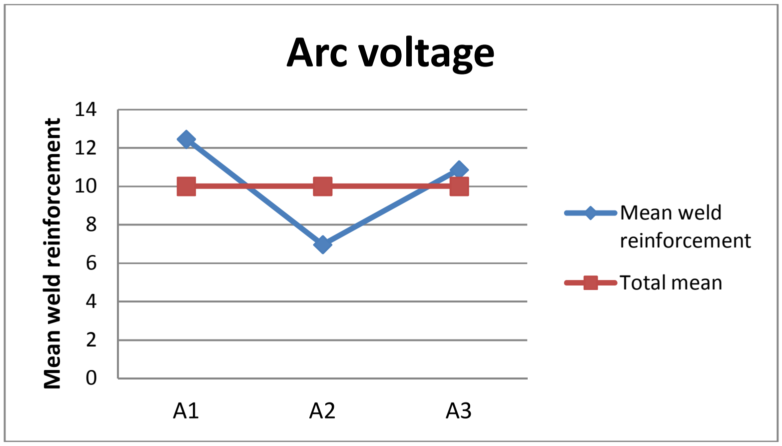

Fig. 10. Effect of arc voltage on weld reinforcement

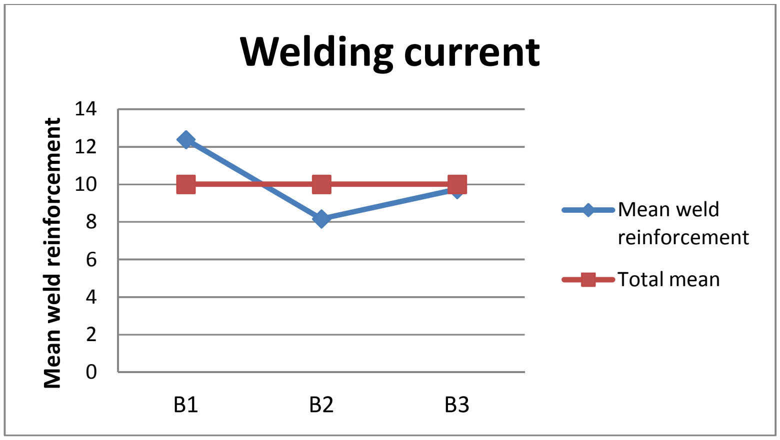

Fig. 11. Effect of welding current on weld reinforcement

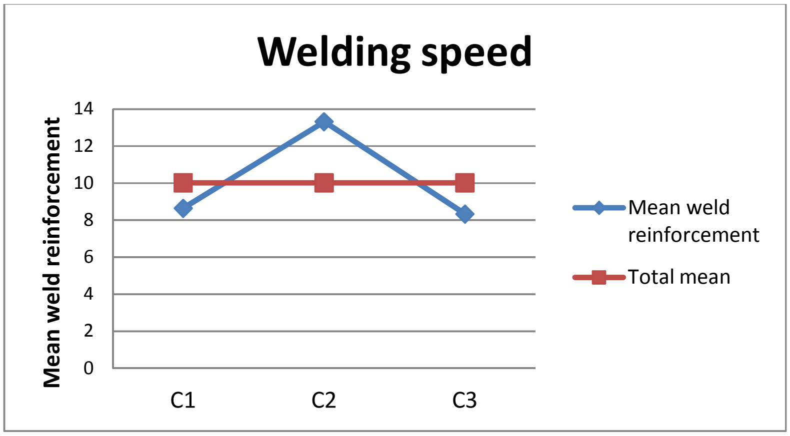

Fig. 12. Effect of welding speed on weld reinforcement

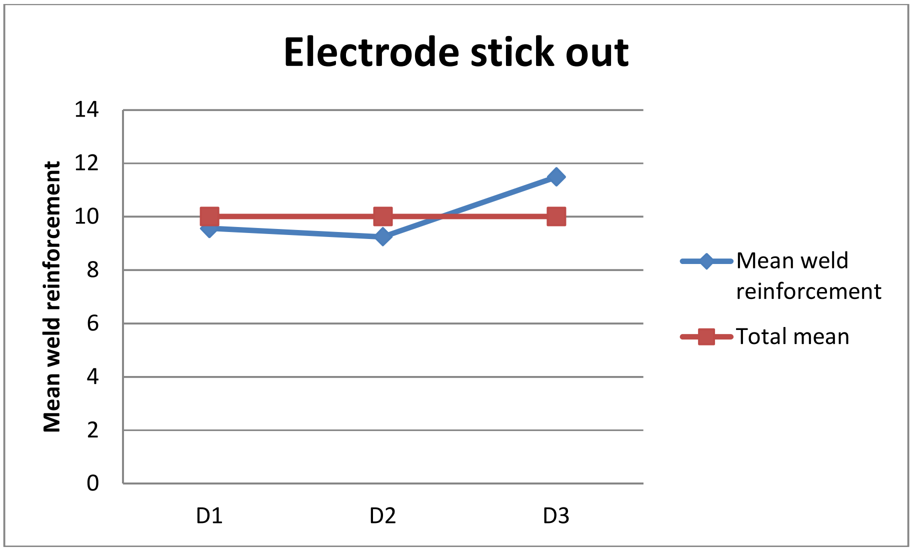

Fig. 13. Effect of electrode stick out on weld reinforcement

4. CONCLUSION

In this research study, the application of Taguchi technique and multiple regression analysis to predict optimal process parameters for bead width, weld penetration and weld reinforcement of 6 mm plate of IS2062 mild steel in submerged arc welding process is presented. The experiment involves using Taguchi's L_9 orthogonal array to carry out nine different experiments with three levels of process parameters and the average signal to noise ratios of the output parameters using the larger-the-better quality characteristic were computed. From the analysis conducted by applying the Taguchi technique, optimum process parameters of bead width, weld penetration and weld reinforcement can be achieved by following the path $A_3{-}B_3-C_1{-}D_1$, $A_3{-}B_2-C_2{-}D_2$ and $A_1{-}B_1-C_2{-}D_3$ respectively. Observations of the effects of the process parameters on weld bead geometry show that the weld bead width and weld penetration increase linearly with increase in welding current and arc voltage while weld reinforcement showed no significant increase. Multiple regression analysis was used to develop a proposed mathematical model which can be used to predict bead width, weld penetration and weld reinforcement values for any given welding conditions.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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