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Contents **المحتويات**

Research Papers in English

الأوراق البحثية باللغة العربية

THE EFFECT OF THE SUBMERGED ARC WELDING VARIABLES ON BEAD GEOMETRY OF MILD STEEL USING REGRESSION ANALYSIS TECHNIQUE

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الملخص

في اللحام بالقوس المغمور، تتأثر جودة غرزة اللحام بشكل كبير بمتغيرات عملية اللحام. تهدف هذه الدراسة لتحديد تأثير تيار اللحام (I)، وجهد القوس (V)، وسرعة اللحام (S) على قيم عرض الغرزة (BW)، وارتفاع تقوية الغرزة (BR)، وعمق تغلغل الغرزة (BP) المقاسة من التجارب التي أجريت والقيم المتوقعة من النماذج الرياضية. أجريت العمليات التجريبية على أساس تصميم العوامل ثلاثية المستوى لثلاث متغيرات من متغيرات عملية اللحام. تم تطوير النماذج الرياضية باستخدام تقنية تحليل الانحدار الخطي المتعدد باستخدام تطبيقات برمجية (SPSS) و (Excel). لقد تم حساب القيم المتوقعة لابعاد الشكل الهندسي لغرزة اللحمة ومقارنتها مع القيم المقاسة للتحقق من دقة النماذج الرياضية المطورة. تشير النتائج إلى أن النماذج تتنبأ بابعاد الشكل الهندسي لغرزة اللحمة بشكل كافٍ ضمن حدود متغيرات اللحام المستخدمة. بعد التنبؤ بقيم غرزات اللحمة، تم دراسة تأثير هذه المتغيرات على ابعاد الشكل الهندسي للغرزة. أظهرت النتائج أن تيار اللحام هو المتغير الأكثر أهمية الذي يؤثر على عرض الغرزة وعمق تغلغل الغرزة، وأن دقة النماذج الرياضية المطورة لعرض الغرزة، وارتفاع تقوية الغرزة، وعمق تغلغل الغرزة هي 98.81٪، و94.23٪، و96.86٪ على التوالي.

ABSTRACT

In the submerged arc welding process, weld quality is greatly affected by welding variables. This study aims to determine the effects of welding current (I), arc voltage (V), welding speed (S) on the values of the bead width (BW), bead reinforcement (BR), and bead penetration (BP) measured values from the experiments and the predicted values from the models. The experimental runs are done on the three-level factorial design of three process variables. The mathematical models are developed by applying the multiple linear regression analysis technique (method) using SPSS and Excel software applications. The predicted values of the weld bead geometry dimensions (parameters) are calculated and compared with the measured ones to verify the developed mathematical models' accuracy. The results indicate that the models predict the weld bead geometry dimensions adequately within the limits of the welding variables being used. After predicting the weld bead values, the effects of these variables on bead geometry dimensions are studied. The results reveal that welding current is the most significant variable affecting BW and BP. The accuracy of the developed mathematical models for the BW, BR, and BP is 98.81%, 94.23%, and 96.86%, respectively.

KEYWORDS: SAW; Process Variables; Factorial Design; Regression Analysis; Weld Bead

INTRODUCTION

Steel by far is one of the world's most essential materials in the modern world. It is fundamental to every aspect of our lives due to its versatile durability, strength, affordability, and infinitely recyclable. Low carbon steel is the most widely used material in the industry for moderate and service requirements, including structural fabrication applications [1,2]. The submerged arc welding (SAW) process is an essential joining process widely used in metal fabrication industries. This process's quality ranks higher than other arc-welding processes due to the reliability, deep penetration, high strength joint, high surface appearance, high efficiency, low operator skill requirement, ease of automation, increased productivity, and deposition rate. This welding process was used for various materials include a wide range of carbon steels, low and high alloy steel, stainless steels, Ni-based alloys, Monel, and other non-ferrous alloys [3-5].

In the welding industry, weld quality mainly depends on the mechanical properties of the weld metal and heat-affected zone (HAZ), which, in turn, is influenced by the weld bead geometry (output parameters) that is affected by the process variables (input parameters). For the submerged arc welding process, these variables include welding current, arc voltage, welding speed, size of electrode, wire feed rate, electrode stick out, nozzle to plate distance, preheat, heat input rate [2,6-8].

In order to obtain high-quality welds, the selection of optimum variables should be performed according to engineering facts. Besides, in industrial welding automatic machines (robots), even minor alterations in the welding process variables may cause unexpected welding performance. So, it is essential to study the welding process variables' stability to achieve high-quality welds. Predicting the effects of minor changes in design parameters provides necessary information in engineering design. Therefore, using mathematical modeling methods to predict the relationship between the process variables and response (output) parameters will improve the submerged arc welds' quality and reduce experimental runs, time, and cost [6,7].

In the literature, significant studies reported various aspects of mathematical modeling and process optimization using statistical design experiments based on full factorial, fractional factorial, Regression analysis [6-17], central rotatable design, response surface methodology, genetic and java algorithms, desirability techniques [18-26], and Taguchi analysis [6,11,17,27] correlating welding process variables (input parameters) with bead geometry parameters (output responses) to predict the responses for any given welding conditions. The analysis of variance (ANOVA) is used to check the mathematical models' adequacy and significance for predicting the SAW variables for optimum output parameters. These studies focused on the various output responses such as bead width (BW), bead reinforcement (BR), bead penetration (BP), the width of HAZ, mechanical properties such as (hardness, UTS, impact, yield strength), and percentage of dilution, etc. The value and nature of the responses depend upon the range and selection of the process variables. The results of these studies suggest that these variables and their interaction effects influence the weld bead geometry, consequently on the HAZ, dilution, and mechanical properties. The mathematical models developed were found to be satisfactory and suitable to predict the output responses.

The objective (aim) of this study is to determine the effects of three input variables, welding current, arc voltage, and welding speed, on three out parameters, bead width, bead reinforcement, and bead penetration measured values from the experimental runs and the predicted values from the models. The experimental runs are done on the three-level factorial design of three process variables. The mathematical models are developed by applying the multiple linear regression analysis method using SPSS and Excel software applications.

MATERIAL AND EXPERIMENTAL PROCEDURE

Material

The material used in this study is mild steel with chemical composition of (Fe-0.137C, 0.483Mn, 0.356Si, 0.119Cr, 0.097Cu, 0.088Ni, 0.038S, 0.024P, 0.008Mo) wt. %. A 3.2 mm diameter copper-coated wire electrode in a coil form equivalent to (DIN 8557-S1) specification produced by ESAB company with a chemical composition (Fe-0.09C, 0.5Mn, 0.1Si) wt.%.

Welding Procedure

In this study, a semi-automatic submerged arc welding (SAW) machine made by Sweden ESAB Company with a constant-voltage and direct-current power source was employed. The overhanging length of the electrode beyond the nozzle is 25 mm. The distance between the electrode tip and the workpiece is 3 mm, submerged under a layer of basic fluoride type granular flux equivalent to NF (A81-319) FP/B 34/23 ARI specification keeping the electrode positive polarity. Bead-on-plate type welds were deposited on samples was cut in a rectangular shape with a dimension of (500×100×10) mm.

Welding Process Variables and Levels

In this study, three of the most significant design process variables, namely, welding current (A), arc voltage (V), welding speed (mm/min) with three levels for each one, were selected and used as input parameters. The weld bead geometry parameters, namely, bead width (BW), bead reinforcement (BR), bead penetration (BP), were measured and used as output responses. The input-output relationship was determined using the regression analysis technique, based on the data collected as per the experiments' full factorial design.

The mathematical modeling was developed using the multiple linear regression analysis technique. Table (1) presents the selected welding process variables' values and their different levels, while Figure (1) shows weld bead geometry parameters.

Table 1: Welding variables with different levels

Symbol	Welding Variables	Levels of parameter		
		1	2	3
I	current	350	450	550
V	voltage	26	27	28
S	speed	400	500	600

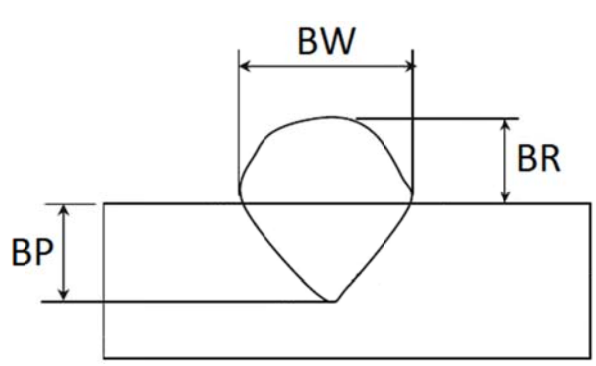

Figure 1: Weld bead parameters

Experimental Data

A three-level factorial design of three process variables was used. Individual and interaction effects of the welding process variables on weld bead parameters were investigated. This work involves performing a number of 27 welds to obtain the necessary data to construct the mathematical models.

After the welding process's performance, cross-sections of the welds were cut, and metallographic samples were prepared using standard methods. The weld bead geometry parameters were measured by Nikon V12 Tool Room Microscopy.

Construction of the Mathematical Models for SAW Process and Statistical Evaluation

Mathematical modeling in the arc welding process can be constructed using multiple linear regression analysis method [6,8,11]. It is suitable for analyzing the objective function representing the relationship between one dependent factor and two independent factors or more. The multiple regression analysis aims to predict variations in the dependent factors due to the changes in the independent factors. Thereby it is a standard for measured values accuracy, where the predicted values by the mathematical models are compared with the measured values. In case the difference between them is slight, then this indicates the accuracy of the measurements and the experiment's correct performance [6,8,11].

In this study, the multiple linear regression equations were reported as a mathematical form simulating the relationship between the process variables (independent factors); welding current, arc voltage, welding speed, and the weld bead dimensions (dependent factors); bead width, bead reinforcement, bead penetration.

The experimental data obtained according to factorial design was used to develop the mathematical models, and these models were used to predict the weld bead dimensions.

The general equation of the multiple linear regressions takes the following form [6, 28]:

$$\mathbf{Y = a + b_1X_1 + b_2X_2 + b_3X_3 + b_KX_K} \quad (1)$$

Where, Y is the dependent factor (output parameters) that is to be predicted X_1, X_2, X_3, X_K is the K known variables on which the predictions are to be made. a, b_1, b_2, b_3, b_K are the regression coefficients. The regression coefficients are determined by SPSS and Excel software applications. In this study, the equation (1) can be written in the following form [6]:

$$\mathbf{Y = a + b_1\, I + b_2\, V + b_3\, S} \quad (2)$$

Y = (BW = bead width, BR = bead reinforcement, BP = bead penetration, all in mm);
I = welding current (A), V = arc voltage (V), S = welding speed (mm/min).

The regression method was used to calculate the coefficient of the linear equations for weld bead geometry dimensions using SPSS and Excel software applications and evaluated for their significance at 95% confidence level by F-test.

Checking the Models Adequacy

An analysis of variance (ANOVA) technique is used to test the developed mathematical models' adequacies. F-statistic was utilized to confirm the total significance of the developed mathematical models at a significant level of 0.05 (95% confidence level) [6, 16, 29-30], where accuracy results of the mathematical models can be evaluated by the error percentage and the residual error [6,15]. The error percentage can be calculated by the following equation [6,15,31]:

$$\% \boldsymbol{Error} = \left[\frac{(\boldsymbol{measures\ value} - \boldsymbol{predicted\ value})}{\boldsymbol{predicted\ value}}\right] \boldsymbol{x100} \quad \boldsymbol{or}$$

$$\% \boldsymbol{Error} = \left[\left(\frac{\boldsymbol{residual}}{\boldsymbol{predicted\ value}}\right) \boldsymbol{x100}\right] \qquad \textbf{(3)}$$

The accuracy percentage of the developed models can be calculated by the following equation:

$$\% \boldsymbol{Model\ accuracy} = \boldsymbol{100}\% - |\boldsymbol{average\ of\ the\ error\ percentage}| \qquad \textbf{(4)}$$

Other measures that are commonly used to illustrate a fitted regression model's adequacy are coefficient of determination (R^2) and adjusted R^2 [6,15-16,29-30].

RESULTS AND DISCUSSION

Measurement of Weld Bead Geometry

Welding conditions according to factorial design and the measured values of bead parameters are presented in Table (2).

Table 2: The measured parameters according to factorial design

Exp. No.	I	V	S	$\overline{BW}$	$\overline{BR}$	$\overline{BP}$	Exp. No.	I	V	S	$\overline{BW}$	$\overline{BR}$	$\overline{BP}$
1	350	26	400	15.500	3.800	4.840	**15**	450	27	600	15.600	2.315	5.650
2	350	26	500	14.110	3.760	5.100	**16**	450	28	400	22.890	2.590	5.000
3	350	26	600	11.150	3.350	5.300	**17**	450	28	500	18.845	2.285	5.295
4	350	27	400	16.654	3.650	4.710	**18**	450	28	600	16.545	1.765	5.425
5	350	27	500	15.310	3.250	5.150	**19**	550	26	400	23.470	3.270	5.960
6	350	27	600	12.365	2.700	5.115	**20**	550	26	500	20.640	2.860	6.450
7	350	28	400	17.825	3.100	4.380	**21**	550	26	600	18.060	2.480	6.180
8	350	28	500	15.760	2.625	4.825	**22**	550	27	400	25.000	2.740	5.860
9	350	28	600	13.215	2.160	5.015	**23**	550	27	500	21.300	2.400	6.000
10	450	26	400	21.330	3.750	5.305	**24**	550	27	600	18.700	1.850	6.250
11	450	26	500	18.955	3.275	5.215	**25**	550	28	400	27.260	2.610	5.770
12	450	26	600	15.370	2.810	5.530	**26**	550	28	500	23.720	1.800	5.720
13	450	27	400	22.850	3.265	5.180	**27**	550	28	600	19.500	1.400	6.050
14	450	27	500	19.500	2.755	5.395							

(Note: $\overline{BW}$, $\overline{BR}$, $\overline{BP}$ indicate the mean value of the bead dimensions).

Regression Analysis

The coefficient values of the linear equations for weld bead dimensions were calculated by regression method, as shown in Table (3).

Table 3: Calculated regression coefficients for weld bead parameters

	Regression coefficients			
	a	b_1	b_1	b_1
BW	-8.811	0.037	0.943	-0.029
BR	20.247	-0.004	-0.501	-0.004
BP	5.606	0.005	-0.133	0.002

The mathematical models that can be used to predict the weld bead geometry, bead width, bead reinforcement, and bead penetration in the SAW process were constructed using the multiple linear regression method. These models can be expressed by the equations (5-7):

$$\mathrm{BW} = -8.811 + (0.037\ \mathrm{x\ I}) + (0.943\ \mathrm{x\ V}) - (0.029\ \mathrm{x\ S}) \qquad (5)$$

$$BR = 20.247 - (0.004 \text{ x I}) - (0.501 \text{ x V}) - (0.004 \text{ x S}) \quad (6)$$

$$BP = 5.606 + (0.005 \text{ x I}) - (0.133 \text{ x V}) + (0.002 \text{ x S}) \quad (7)$$

These mathematical models were evaluated statistically using statistical evaluation parameters (correlation coefficients) R, R^2, and adjusted R^2, which their values were calculated by regression method using SPSS and Excel software applications. Table (4) displays the values of the correlation coefficients of the weld bead geometry models.

Table 4: Correlation coefficients of the mathematical models

Correlation coefficients	Weld bead dimensions		
	BW	BR	BP
R	0.982	0.988	0.963
R^2	0.964	0.976	0.927
Adjusted - R^2	0.959	0.973	0.917
Std. Error of estimate	0.817	0.108	0.148

Models Adequacy and Accuracy

The ANOVA results for the weld bead geometry by SPSS and Excel software applications are showed in Tables (5a-5c).

Table 5a: ANOVA results of the mathematical model for BW.

	Model		
	Regression	Residual	Total
SS	408.068	15.354	423.423
DF	3	23	26
MS	136.023	0.668	
F	203.757		

Table 5b: ANOVA results of the mathematical model for BR.

	Model		
	Regression	Residual	Total
SS	10.737	0.267	11.005
DF	3	23	26
MS	3.579	0.012	
F	307.951		
P	0.000		

Table 5c: ANOVA results of the mathematical model for BP.

	Model		
	Regression	Residual	Total
SS	6.345	0.502	6.848
DF	3	23	26
MS	2.115	0.022	
F	96.848		
P	0.000		

It is observed from Tables (5a-5c) the high significance for the F-test (sig < 0.0001), which accentuates the high explanatory power of the multiple linear regression models statistically. Hence, it indicates the adequacy of the developed mathematical models in the prediction of weld bead geometry. Tables (6a-6c) present the measured and predicted values, the residual, and the error percentage for the weld bead geometry in each experiment. The excellent fit between the measured and the predicted values of the performance characteristics indicates the accuracy of the developed mathematical models, so it supports the using validity of the models to predict the performance characteristics. The complete fit between the measured and the predicted values indicates that the residual is zero, which means that the models' accuracy was 100%; practically, this case is challenging to achieve.

Table 6a: Measured and predicted values, residual, and error % for BW according to factorial design.

Exp No.	$\overline{BW}$	$\widehat{BW}$	Residual $Re = \overline{BW} - \widehat{BW}$	Error (%)	Exp No.	$\overline{BW}$	$\widehat{BW}$	Residual $Re = \overline{BW} - \widehat{BW}$	Error (%)
1	15.500	17.057	-1.557	-9.12	**15**	15.600	15.900	-0.300	-1.88
2	14.110	14.157	-0.047	-0.33	**16**	22.890	22.643	0.247	1.09
3	11.150	11.257	-0.107	-0.95	**17**	18.845	19.743	-0.898	-4.54
4	16.654	18.000	-1.346	-7.47	**18**	16.545	16.843	-0.298	-1.76
5	15.310	15.100	0.210	1.39	**19**	23.470	24.457	-0.987	-4.03
6	12.365	12.200	0.165	1.35	**20**	20.640	21.557	-0.917	-4.25
7	17.825	18.943	-1.118	-5.90	**21**	18.060	18.657	-0.597	-3.19
8	15.760	16.043	-0.283	-1.76	**22**	25.000	25.400	-0.400	-1.57
9	13.215	13.143	0.072	0.54	**23**	21.300	22.500	-1.200	-5.33
10	21.330	20.757	0.573	2.76	**24**	18.700	19.600	-0.900	-4.59
11	18.955	17.857	1.098	6.14	**25**	27.260	26.343	0.917	3.48
12	15.370	14.957	0.413	2.76	**26**	23.720	23.443	0.277	1.18
13	22.850	21.700	1.150	5.29	**27**	19.500	20.543	-1.043	-5.07
14	19.500	18.800	0.700	3.72					
Average of error percentage = -1.19									

(Note: $\overline{BW}$ = the mean of the measured values and $\widehat{BW}$ = the predicted values

Table 6b: Measured and predicted values, residual, and error % for BR according to factorial design.

Exp No.	$\overline{BR}$	$\widehat{BR}$	Residual $Re = \overline{BR} - \widehat{BR}$	Error (%)	Exp No	$\overline{BR}$	$\widehat{BR}$	Residual $Re = \overline{BR} - \widehat{BR}$	Error (%)
1	3.800	4.221	-0.421	-9.97	**15**	2.315	2.520	-0.205	-8.13
2	3.760	3.821	-0.061	-1.59	**16**	2.590	2.819	-0.229	-8.12
3	3.350	3.421	-0.071	-2.07	**17**	2.285	2.419	-0.134	-5.53
4	3.650	3.720	-0.070	-1.88	**18**	1.765	2.019	-0.254	-12.58
5	3.250	3.320	-0.070	-2.10	**19**	3.270	3.421	-0.151	-4.41
6	2.700	2.920	-0.220	-7.53	**20**	2.860	3.021	-0.161	-5.32
7	3.100	3.219	-0.119	-3.69	**21**	2.480	2.621	-0.141	-5.37
8	2.625	2.819	-0.194	-6.88	**22**	2.740	2.920	-0.180	-6.16
9	2.160	2.419	-0.259	-10.70	**23**	2.400	2.520	-0.120	-4.76
10	3.750	3.821	-0.071	-1.85	**24**	1.850	2.120	-0.270	-12.73
11	3.275	3.421	-0.146	-4.26	**25**	2.610	2.419	-0.191	-7.89
12	2.810	3.021	-0.211	-6.98	**26**	1.800	2.019	-0.219	-10.84
13	3.265	3.320	-0.055	-1.65	**27**	1.400	1.619	-0.219	-13.52
14	2.755	2.920	-0.165	-5.65					
Average of error percentage = -5.78									

(Note: $\overline{BR}$ = the mean of the measured values, $\widehat{BR}$ = the predicted values)

Table 6c: Measured and predicted values, residual, and error % for BP according to factorial design.

Exp No.	$\overline{BP}$	$\widehat{BP}$	Residual $Re = \overline{BP} - \widehat{BP}$	Error (%)	Exp No	$\overline{BP}$	$\widehat{BP}$	Residual $Re = \overline{BP} - \widehat{BP}$	Error (%)
1	4.840	4.698	0.142	3.02	**15**	5.650	5.465	0.185	3.38
2	5.100	4.898	0.202	4.12	**16**	5.000	4.932	0.068	1.37
3	5.300	5.098	0.202	3.96	**17**	5.295	5.132	0.163	3.17
4	4.710	4.565	0.145	3.17	**18**	5.425	5.332	0.093	1.74
5	5.150	4.765	0.385	8.07	**19**	5.960	5.698	0.262	4.59

6	5.115	4.965	0.150	3.02	**20**	6.450	5.898	0.552	9.35
7	4.380	4.432	-0.052	-1.17	**21**	6.180	6.098	0.082	1.34
8	4.825	4.632	0.193	4.16	**22**	5.860	5.565	0.295	5.30
9	5.015	4.832	0.183	3.78	**23**	6.000	5.765	0.235	4.07
10	5.305	5.198	0.107	2.05	**24**	6.250	5.965	0.285	4.77
11	5.215	5.398	-0.183	-3.39	**25**	5.770	5.432	0.338	6.22
12	5.530	5.598	0.068	-1.21	**26**	5.720	5.632	0.088	1.56
13	5.180	5.065	0.115	2.27	**27**	6.050	5.832	0.218	3.73
14	5.395	5.265	0.130	2.46					
Average of error percentage = 3.14									

(Note: $\overline{BP}$ = the mean of the measured values and $\widehat{BP}$ = the predicted values)

Table (7) shows the accuracy values resulting from the mathematical models for bead geometry, while Figures (2a-2c) illustrate the accuracy's representative diagrams. It is clear from the Table; the accuracy of the developed mathematical models is higher than 94%, which is very high and an excellent indicator.

Table 7: Accuracy of the developed mathematical models

	Bead dimensions		
	BW	BR	BP
Average of error percentage	-1.19	-5.78	3.14
The absolute value of error percentage average	1.19	5.78	3.14
Accuracy (%)	98.81	94.22	96.86

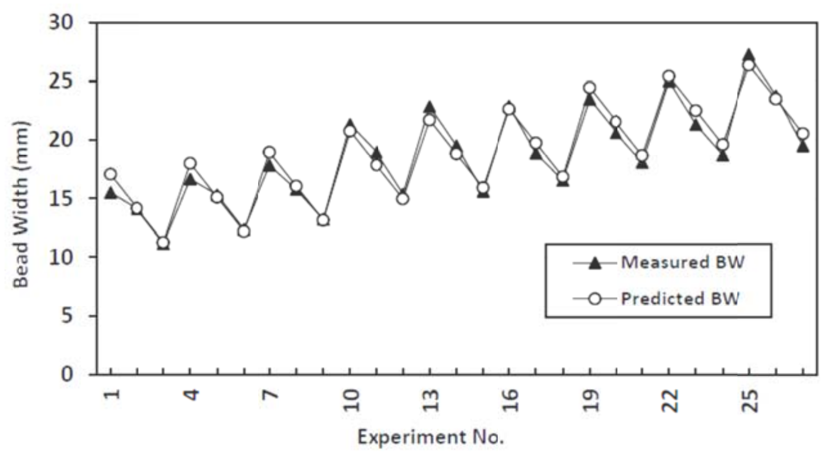

Figure 2a: The measured and predicted values for BW.

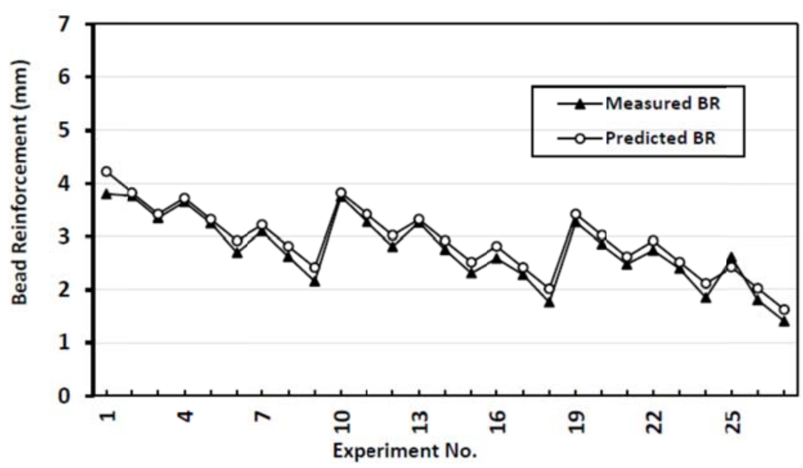

Figure 2b: The measured and predicted values for BR.

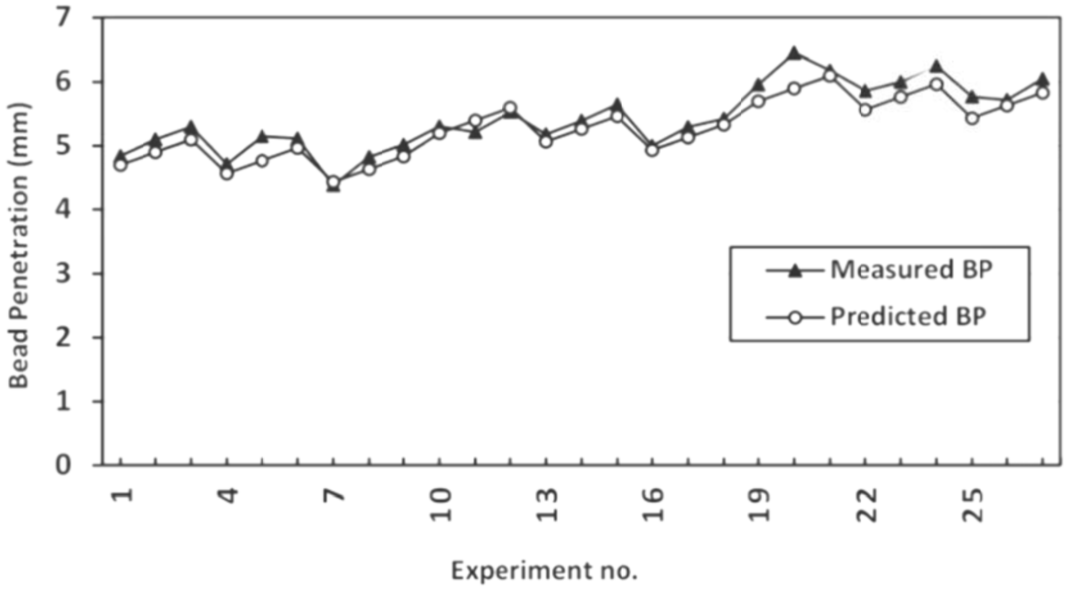

Figure 2c: The measured and predicted values for BP.

It is evident from Figures (2a-2c) that there is a good agreement between the measured and the predicted values for the weld bead geometry, which supports the developed mathematical models' validity and accuracy.

Normal Distribution of Errors

The assumption of the normal distribution of the error limits was tested by obtaining the residual's normal probability plots by SPSS software application, as shown in Figures (3a and 3c).

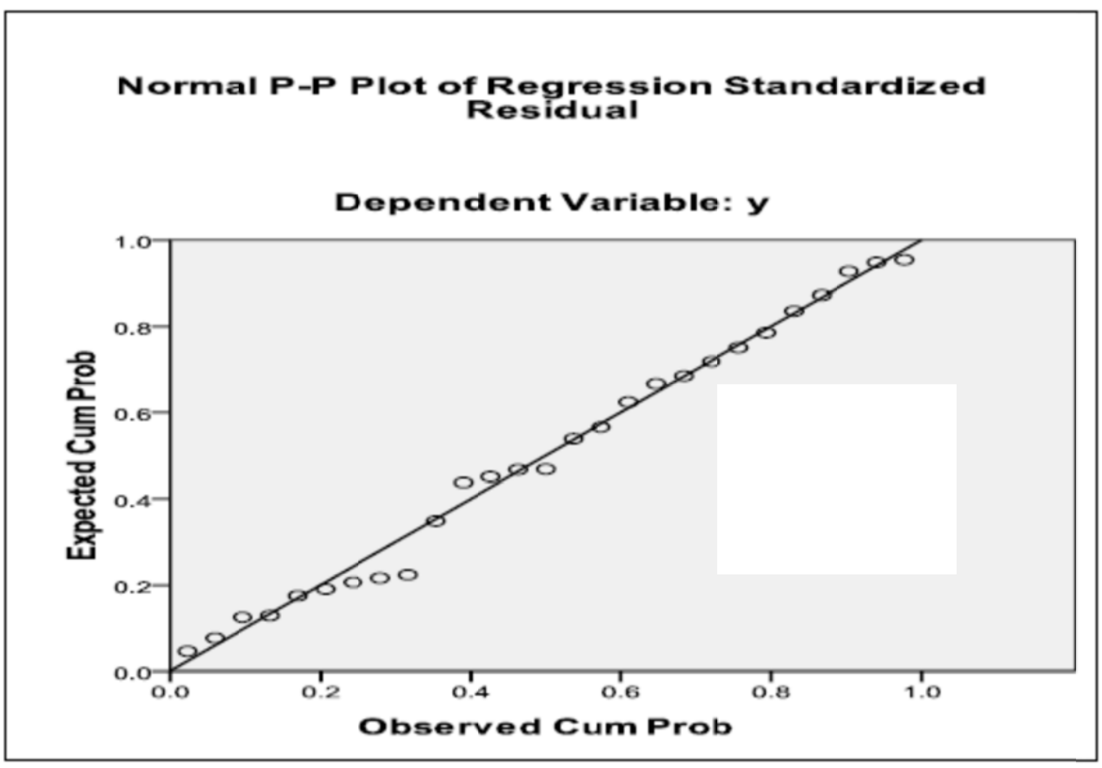

Figure 3a: Normality distributed errors for bead width.

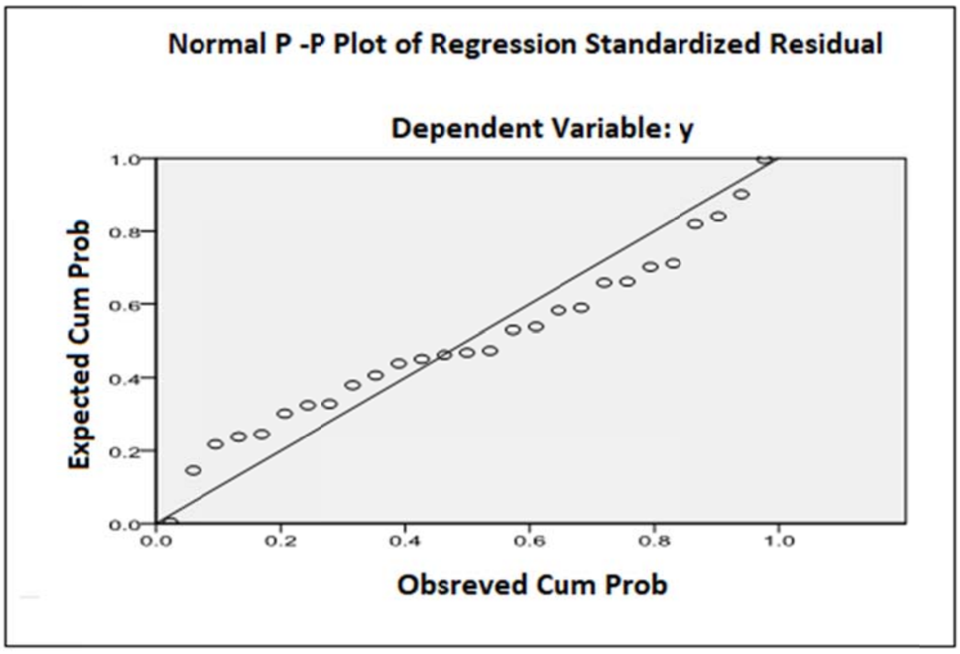

Figure 3b: Normality distributed errors for bead reinforcement.

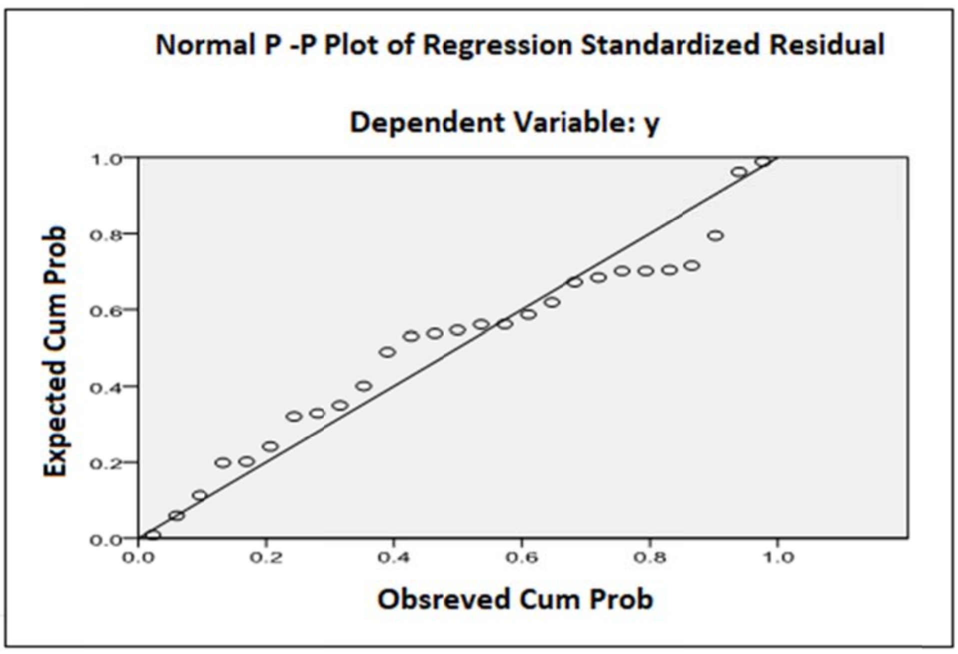

Figure 3c: Normality distributed errors for bead penetration.

It is clear from Figures (3a and 3c) that most points are located near the straight line. It is an indication of the normal distribution of errors. In other words, the assumption of the normal distribution is not violated.

Effect of Welding Variables on the Predicted Values for BW, BR, BP

This study aims to predict the impact of a slight change in the submerged arc welding process variables (welding current, arc voltage, and welding speed) on the weld bead geometry (bead width, bead reinforcement, and bead penetration). The welding conditions and the predicted values of the weld bead geometry by the mathematical models according to factorial design (FD) are presented in Table (8).

Table 8: Welding conditions and predicted values for BW, BR, and BP according to FD

Exp. No.	I	V	S	$\widehat{BW}$	$\widehat{BR}$	$\widehat{BP}$	Exp. No.	I	V	S	$\widehat{BW}$	$\widehat{BR}$	$\widehat{BP}$
1	350	26	400	17.057	4.221	4.698	**15**	450	27	600	15.900	2.520	5.465
2	350	26	500	14.157	3.821	4.898	**16**	450	28	400	22.643	2.819	4.932
3	350	26	600	11.257	3.421	5.098	**17**	450	28	500	19.743	2.419	5.132
4	350	27	400	18.000	3.720	4.565	**18**	450	28	600	16.843	2.019	5.332
5	350	27	500	15.100	3.320	4.765	**19**	550	26	400	24.457	3.421	5.698
6	350	27	600	12.200	2.920	4.965	**20**	550	26	500	21.557	3.021	5.898
7	350	28	400	18.943	3.219	4.432	**21**	550	26	600	18.657	2.621	6.098
8	350	28	500	16.043	2.819	4.632	**22**	550	27	400	25.400	2.920	5.565
9	350	28	600	13.143	2.419	4.832	**23**	550	27	500	22.500	2.520	5.765
10	450	26	400	20.757	3.821	5.198	**24**	550	27	600	19.600	2.120	5.965
11	450	26	500	17.857	3.421	5.398	**25**	550	28	400	26.343	2.419	5.432
12	450	26	600	14.957	3.021	5.598	**26**	550	28	500	23.443	2.019	5.632
13	450	27	400	21.700	3.320	5.065	**27**	550	28	600	20.543	1.619	5.832
14	450	27	500	18.800	2.920	5.265							

(Note: $\widehat{BW}, \widehat{BR}, \widehat{BP}$ = the predicted values)

Direct Effect of the Welding Variables on Bead Width (BW)

At constant values for arc voltage and welding speed, bead width increases by 3.7 mm with the increase in welding current by 100 A. The minimum value for the weld BW (11.257 mm) is observed at a lower current (350 A), lower voltage (26 V), and higher welding speed of 600 mm/min, as shown in experiment 3. At constant values for welding current and speed, bead width increases by 0.943 mm with the increase in arc voltage by 1 V. This means that bead width is more affected by voltage variation at high welding current values. At constant values for welding current and arc voltage, bead width decreases by 2.9 mm with the increase in welding speed by 100 mm/min, as shown in Table (8).

Interaction Effects of the Welding Variables on Bead Width (BW)

At a constant welding speed value, bead width increases by 4.643 mm with the increase in welding current and arc voltage by 100 A and 1 V, respectively. However, at constant welding speed value, bead width increases by 2.757 mm with the increase in welding current by 100 A and the decrease in arc voltage by 1 V, as shown in Table (8).

The previous results in Table 8 show that the increase or decrease of bead width directly relates to the increase or decrease in welding current more than the arc voltage. This indicates that the welding current is more potent than arc voltage for bead width, so the welding current is more significant than arc voltage in determining bead width [6].

At a constant welding current value, bead width increases by 3.843 mm with the decrease in welding speed by 100 mm/min and the increase in arc voltage by 1 V. However, at a constant welding current value, bead width decreases by 1.957 mm with the increase in welding speed by 100 mm/min, and arc voltage by 1 V, respectively, as shown in Table (8).

The obtained results in Table (8) indicate that the negative effect on the heat input due to the increase of welding speed is stronger than the positive effect due to the increase in arc voltage, so increasing or decreasing bead width is more related to the change in welding speed value. Therefore, welding speed is more significant than arc voltage in determining bead width [6].

At a constant arc voltage value, bead width increases by 6.6 mm with the increase in welding current by 100 A and the decrease in welding speed by 100 mm/min. However, at a constant arc voltage value, bead width increases by 0.8 mm as the welding current and welding speed increase by 100 A and 100 mm/min, respectively, as shown in Table (8). For the reasons mentioned earlier, welding current is more significant than welding speed in determining bead width.

In general, the output results from studying the interaction effects of the process variables on BW revealed that welding current is the most critical parameter in determining BW [6].

Direct Effect of the Welding Variables on Bead Reinforcement (BR)

At constant arc voltage and welding speed values, bead reinforcement decreases by 0.4 mm with the increase in the welding current by 100 A. However, at constant values of both welding current and welding speed, bead reinforcement decreases by 0.501 mm as the arc voltage increases by 1 V. But at constant values of arc voltage and welding current, bead reinforcement decreases by 0.4 mm with the increase in welding speed by 100 mm/min, as shown in Table (8).

Interaction Effects of the Welding Variables on Weld Bead Reinforcement (BR)

At a constant welding speed, bead reinforcement decreases by 0.901 mm with the increase in welding current and arc voltage by 100 A and 1 V, respectively. However, at a constant welding speed, bead reinforcement increases by 0.101 mm with the increase in welding current by 100 A and decrease in arc voltage by 1 V, as in the same Table.

The result implies that bead reinforcement is more affected by arc voltage than welding current. In other words, arc voltage is more significant than the welding current in determining the BR [6].

At a constant value of welding current, bead reinforcement decreases by 0.901 mm with the increase in welding speed and arc voltage by 100 mm/min and 1 V, respectively. However, at a constant value of welding current, bead reinforcement increases by 0.101 mm with the increase in welding speed by 100 mm/min and the decrease in arc voltage by 1V, as shown in Table (8).

This result implies that BR is more affected by arc voltage than welding speed. In other words, arc voltage is more significant than welding speed in determining the BR [6].

At a constant value of arc voltage, BR decreases by 0.8 mm with the increase in welding current and welding speed by 100 A and 100 mm/min, respectively. However, at a constant value of arc voltage, it is observed that there is no change in the value of bead reinforcement with the increase in welding current and decrease in welding speed, as shown in Table (8). This is because welding current and welding speed has the same effect on the BR, where the changing amount in bead reinforcement due to the variations in welding current and welding speed is 0.4 mm by each one. The decreasing amount in BR due to the increase in welding current is equal to the BR increasing amount due to decreasing welding speed.

In general, all three process variables affect the bead reinforcement at different rates. The output results from studying the direct effect of the process variables on BR revealed that BR values change due to variations in welding current, welding speed, arc voltage being 0.4 mm, 0.4 mm, and 0.501 mm by each variable, respectively. It is clear from these results that the value change of the BR by arc voltage variations is relatively more significant than the other two values of the changing amount by welding current and speed.

Direct Effect of the Welding Variables on Bead Penetration (BP)

At constant arc voltage and welding speed, bead penetration increases by 0.5 mm with the increase in welding current by 100 A. However, at constant welding current and welding speed values, bead penetration decreases by 0.133 mm with the arc voltage increase by 1 V, as shown in Table (8). The lower value of the changing amount in BP due to arc voltage variations indicates that BP is almost not sensitive to arc voltage variations. But at constant values of arc voltage and welding current, bead penetration increases by 0.2 mm with the increase in welding speed by 100 mm/min, as in the same Table. The last result revealed that bead penetration increases with the increase in welding speed in most experiments, but it is a slight increase, 0.2 mm. It indicates that welding speed has a marginally positive effect on bead penetration.

Interaction Effects of the Welding Variables on Weld Bead Penetration (BP)

At a constant value of welding speed, bead penetration increases by 0.367 mm with the increase in welding current and arc voltage by 100 A and 1 V, respectively. However, at a constant value of welding speed, bead penetration increases by 0.633 mm with the increase in welding current and the decrease in arc voltage by 100 A and 1 V, respectively, as shown in Table (8). It is observed from the results that bead penetration increases with the increase in current more than with the increase arc voltage. In other words, welding current is more significant than arc voltage in determining bead penetration.

At a constant value of welding current, bead penetration increases by 0.067 mm with the increase in welding speed and arc voltage by 100 mm/min and 1 V, respectively. However, at a constant value of welding current, bead penetration increases by 0.333 mm with the increase in welding speed by 100 mm/min and decrease in arc voltage by 1 V, as shown in Table (8). These results indicate that bead penetration is affected by welding speed more than arc voltage.

At constant arc voltage value, bead penetration increases by 0.7 mm with the increase in welding current and welding speed by 100 A and 100 mm/min, respectively. However, at a constant arc voltage value, bead penetration increases by 0.3 mm with the increase in welding current by 100 A and the decrease in welding speed by 100 mm/min, as shown in Table (8). The results indicate that BP is more affected by welding current than welding speed.

CONCLUDING REMARKS

Experiments conducted using three-level factorial design were conducted to develop mathematical models to predict the weld bead geometry for submerged arc welding (SAW) on 10 mm (Bead-On-Plate) mild steel.

Based on the experimental investigations and previous analysis, the following conclusions can be drawn:

1- The three-level factorial design was a useful tool for quantifying each variable's effect and their interactions on the weld bead geometry dimensions.
2- The mathematical models were developed from the experimental data by applying the multiple regression method using SPSS and Excel software applications.

3- The results indicate that the proposed models predict the responses adequately within the limits of welding variables being used.
   a- ANOVA is used to determine the adequacy of the mathematical models. The high F-test values and ($p < 0.0001$) indicate the developed models' adequacy in predicting the weld bead geometry dimensions.
   b- The sound fit between the measured and predicted bead geometry parameters also indicates the developed models' adequacy and accuracy.
   c- The great values of the coefficient of determination (R^2) and adjusted R^2 values also indicate that the proposed regression models are quite adequate.
4- The study's developed mathematical models can be effectively used to predict the desired weld bead geometry (BW, BR, BP) for any given welding conditions. These models can be used to optimize submerged arc welding process variables, especially for automatic welding machines.
5- The results show that the accuracy of the developed mathematical models for the bead width, bead reinforcement, and bead penetration was 98.81%, 94.225%, and 96.86%, respectively.
6- The results reveal that welding current is the most significant parameter in determining bead width and bead penetration.
7- The values of bead penetration and bead width increase with the increase in welding current, but the value of bead reinforcement decreases. However, with the increase in arc voltage, BP and BR's values decrease, and BW values increase. The BW and BR values decrease with the increase in welding speed, but the value of the BP increases.
8- The results show that the interaction effects have considerable influence over the weld bead geometry, and their effects cannot be neglected.

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