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Optimization Process Parameters of Submerged Arc Welding Using Factorial Design Approach

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Abstract:

This research study is investigating the weldability of the low carbon steel through studying the effects of the welding process parameters [welding current (I), arc voltage (U), welding speed (S)] on the weld joints' quality on the weld bead geometry [bead width (W), bead height (H), bead penetration (P)]. The crosses were welded using submerged arc welding. This study is based on the assumption that the optimum parameters of the welding process that lead to the optimum geometry of weld bead, must achieve high-quality welds, which can result in better weld bead geometry, mechanical, and metallurgical properties. Where an experimental part is based on the level factorial design of three process parameters. Then, the weld bead characteristics were measured for each sample. A series of experimental data was used to construct the mathematical models to predict the weld bead geometry characteristics for any given welding conditions. The mathematical modelling was developed using the multiple regression method by applying the multiple linear regression equation. The values of coefficients of the linear equation for the weld bead characteristics were calculated by regression method using package for social science SPSS software

Keywords: SAM, Weld Bead Geometry, Regression Analysis, Factorial Design, SPSS.

1. Introduction.

Submerged Arc Welding (SAW) is a high-quality welding process with a very high deposition rate. It is commonly used to join thick sections in the flat position. SAW is usually operated either as fully mechanized or automatically processed. However, it can be used semi automatically as well. During SAW process, the operator cannot observe the weld pool and not directly interfere with the welding process. As the automation in the SAW process increases, the direct effect of the operator decreases and the precise setting of parameters becomes much more important than manual welding processes. Figure (1) shows a schematic of the sample, wire, and flux during submerged arc welding.

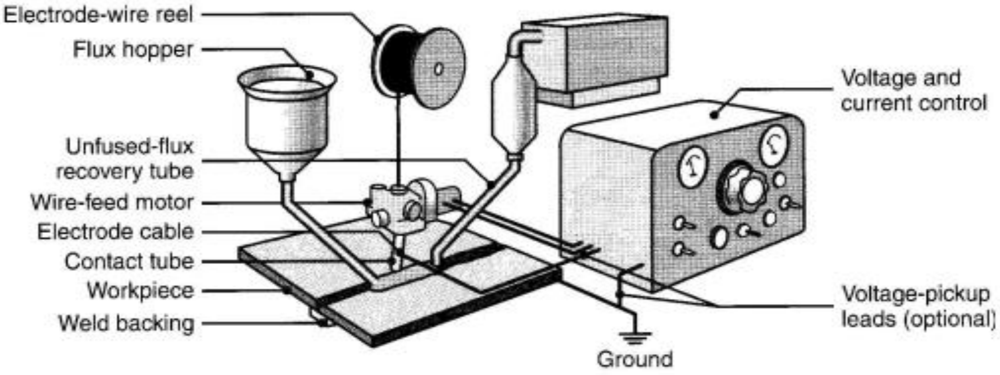

Figure 1. a schematic of the sample, wire, and flux during submerged arc welding

The experimental part is based on three-level factorial design process parameters and analysis of various process control variables and important weld bead parameters in SAW. In order to investigate the effect of input parameters on output parameters that determine the weld bead geometry, a series of experimental data was used to construct the mathematical models to predict the weld bead geometry characteristics for any given welding conditions. The mathematical modeling was developed using the multiple regression method by applying the multiple linear regression equation. The value of coefficients of the linear equations for the weld characteristics were calculated by a regression method using the package for social science SPSS software. Murugan et al. [1] studied the relationships between the submerged arc welding process parameters and the weld bead geometry of pipes. They reported that wire feed rate has a significant positive effect, but welding speed has an appreciable negative effect on penetration, whereas arc voltage has a less significant negative effect on penetration and reinforcement, which indicate that weld bead geometry is influenced by these process parameters. Serdar et al. [2] carried out a study on the sensitivity analysis of submerged arc welding process parameters; they reported that the current is the most important parameter in determining the penetration. Gunaragj et al. [3] in their study on heat-affected zone characteristics in submerged arc welding of structural steel pipes, they developed mathematical models to predict the heat-affected zone characteristics in submerged arc welding and concluded that heat input and wire feed rate have a considerable positive effect on almost all heat affected zone dimensions. Welding speed has a negative on all heat affected zone dimensions, whereas different HAZ layers increase with the increase in arc voltage. In addition to all these studies and investigations, there is still more work needed for the optimization of process variables for various alloys**.** S. kumanan et al. [4] experiments are conducted in the semi-automatic arc welding machine and S/N ratio are computed to determine the optimum parameters, the percentage contribution of each factorial is validated by multi regression analysis and ANOVA is conducted by using the SPSS software and the mathematical model is built to predict the weld bead geometry for given input parameters over output. Yang et al. [5] applied the curvilinear regression equation for modeling the submerged arc welding process, they found that curvilinear equations are very helpful in providing useful information. It is estimated that metal loss through vaporization was 4% for electrode positive polarity and 8% for electrode negative polarity.

2. Experimental Work:

The experimental part of this work is concerned with study the effect of input parameters on output parameters. The input parameters selected are welding current, arc voltage, and welding speed. The bead geometry characteristics (bead width, bead height, and bead penetration) were measured and used as output parameters as shown in figure (2).

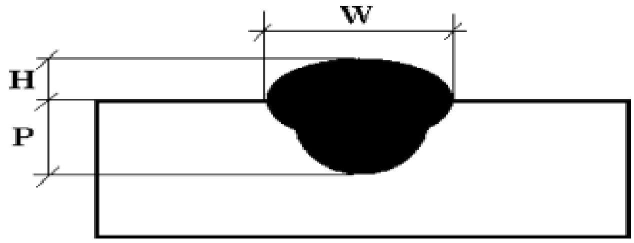

Figure 2. The weld bead geometry characteristic.

The as-received material used is a plate of low carbon steel (mild) steel, bead-on-plate type welds were deposited on samples that were cut from the as-received material in a rectangular with dimensions of 200*200*10 mm. The work piece used for the experiment is shown in Figure (3). Where three levels factorial design of three process parameters including interactions effects of the three parameters was used. This work involved performing a number of 27 welds to obtain the necessary data to construct the mathematical models. Table (1) shows three levels factorial design of three process parameters, while welding conditions according to factorial design were presented in table (2). The measured values of the weld bead characteristics were presented in table (3a and table 3 b and 3 c).

Figure 3. A workpieces used for the experiments

After performance of welding process, cross sections of the welds were cut and metallographic samples were prepared using standard methods such as grinding, polishing, and etching is shown in Figure (2), then the weld bead geometry characteristics were measured by measuring instrument for measuring the micro-dimensions up to micrometer of type Nikon V12 Tool Room Microscopy is shown in Figure (4).

Figure 4. Nikon V12 Tool Room Microscopy

Table 1. Three levels factorial design of three process parameters.

Exp No.	Process Parameters			Exp No.	Process Parameters			Exp No.	Process Parameters		
	A	B	C		A	B	C		A	B	C
1	1	1	1	10	2	1	1	19	3	1	1
2	1	1	2	11	2	1	2	20	3	1	2
3	1	1	3	12	2	1	3	21	3	1	3
4	1	2	1	13	2	2	1	22	3	2	1
5	1	2	2	14	2	2	2	23	3	2	2
6	1	2	3	15	2	2	3	24	3	2	3
7	1	3	1	16	2	3	1	25	3	3	1
8	1	3	2	17	2	3	2	26	3	3	2
9	1	3	3	18	2	3	3	27	3	3	3

Table 2. Welding conditions according to factorial design.

Exp No.	Current I(A)	Voltage U(V)	Speed S(mm/min)	Exp No.	Current I(A)	Voltage U(V)	Speed S (mm/min)
1	350	26	400	15	450	27	600
2	350	26	500	16	450	28	400
3	350	26	600	17	450	28	500
4	350	27	400	18	450	28	600
5	350	27	500	19	550	26	400
6	350	27	600	20	550	26	500
7	350	28	400	21	550	26	600
8	350	28	500	22	550	27	400
9	350	28	600	23	550	27	500
10	450	26	400	24	550	27	600
11	450	26	500	25	550	28	400
12	450	26	600	26	550	28	500
13	450	27	400	27	550	28	600
14	450	27	500				

Table 3a. bead width (W): welding conditions and measured values according to factorial design.

Exp No.	Current I(A)	Voltage U(V)	Speed S(mm/min)	Bead width (W_1) (mm)	Bead width (W_2) (mm)	Bead width (W^{-}) (mm)
1	350	26	400	15.430	15.570	15.500
2	350	26	500	14.125	14.095	14.110
3	350	26	600	11.175	11.125	11.150
4	350	27	400	16.650	16.658	16.654
5	350	27	500	15.340	15.280	15.310
6	350	27	600	12.355	12.375	12.365
7	350	28	400	17.835	17.815	17.825
8	350	28	500	15.745	15.775	15.760
9	350	28	600	13.250	13.180	13.215
10	450	26	400	21.340	21.320	21.330
11	450	26	500	18.935	18.975	18.955
12	450	26	600	15.380	15.360	15.370
13	450	27	400	22.845	22.855	22.850
14	450	27	500	19.350	19.650	19.500
15	450	27	600	15.580	15.620	15.600
16	450	28	400	22.870	22.910	22.890
17	450	28	500	18.835	18.855	18.845
18	450	28	600	16.525	16.565	16.545
19	550	26	400	23.460	23.480	23.470
20	550	26	500	20.625	20.655	20.640
21	550	26	600	18.080	18.040	18.060
22	550	27	400	25.040	24.960	25.000
23	550	27	500	21.250	21.350	21.300
24	550	27	600	18.725	18.715	18.700
25	550	28	400	27.240	27.280	27.260
26	550	28	500	23.700	23.740	23.720
27	550	28	600	19.450	19.550	19.500

[Bead width (W); W_1, W_2 the measured values, and W^{-} the mean of the measured value = $(W_1+W_2)/2$]

Table 3b. bead height (H); welding conditions and measured values according to factorial design.

Exp No.	Current I(A)	Voltage U(V)	Speed S(mm/min)	Bead height (H_1) (mm)	height width (H_2) (mm)	height width (H^{-}) (mm)
1	350	26	400	3.805	3.795	3.800
2	350	26	500	3.745	3.775	3.760
3	350	26	600	3.335	3.365	3.350
4	350	27	400	3.640	3.660	3.650
5	350	27	500	3.140	3.360	3.250
6	350	27	600	2.735	2.665	2.700
7	350	28	400	3.085	3.115	3.100
8	350	28	500	2.595	2.655	2.625
9	350	28	600	2.100	2.220	2.160
10	450	26	400	3.730	3.770	3.750
11	450	26	500	3.250	3.300	3.275
12	450	26	600	2.795	2.825	2.810
13	450	27	400	3.230	3.300	3.265
14	450	27	500	2.715	2.795	2.755
15	450	27	600	2.350	2.280	2.315
16	450	28	400	2.620	2.560	2.590
17	450	28	500	2.295	2.275	2.285
18	450	28	600	1.740	1.790	1.765
19	550	26	400	3.300	3.240	3.270

20	550	26	500	2.900	2.820	2.860
21	550	26	600	2.400	2.560	2.480
22	550	27	400	2.700	2.780	2.740
23	550	27	500	2.425	2.375	2.400
24	550	27	600	1.950	1.750	1.850
25	550	28	400	2.625	2.595	2.610
26	550	28	500	1.845	1.755	1.800
27	550	28	600	1.420	1.380	1.400

[Bead height (H); H_1, H_2 the measured values, and H^- the mean of the measured value = $(H_1+H_2)/2$]

Table 3c. bead penetration (P): welding conditions and measured values according to factorial design.

Exp No.	Current I(A)	Voltage U(V)	Speed S(mm/min)	Bead penetration(P_1) (mm)	Bead penetration (P_2) (mm)	Bead penetration (P^-) (mm)
1	350	26	400	4.820	4.860	4.840
2	350	26	500	5.050	5.150	5.100
3	350	26	600	5.275	5.325	5.300
4	350	27	400	4.690	4.730	4.710
5	350	27	500	5.130	5.170	5.150
6	350	27	600	5.175	5.055	5.115
7	350	28	400	4.400	4.360	4.380
8	350	28	500	4.800	4.850	4.825
9	350	28	600	5.000	5.030	5.015
10	450	26	400	5.295	5.315	5.305
11	450	26	500	5.220	5.210	5.215
12	450	26	600	5.550	5.510	5.530
13	450	27	400	5.160	5.200	5.180
14	450	27	500	5.405	5.385	5.395
15	450	27	600	5.625	5.675	5.650
16	450	28	400	4.940	5.060	5.000
17	450	28	500	5.285	5.305	5.295
18	450	28	600	5.405	5.445	5.425
19	550	26	400	6.000	5.920	5.960
20	550	26	500	6.435	6.465	6.450
21	550	26	600	6.200	6.160	6.180
22	550	27	400	5.820	5.900	5.860
23	550	27	500	6.015	5.985	6.000
24	550	27	600	6.225	6.275	6.250
25	550	28	400	5.800	5.740	5.770
26	550	28	500	5.640	5.800	5.720
27	550	28	600	6.100	6.000	6.050

[Bead penetration (P); P_1, P_2 the measured values, and P^- the mean of the measured value = $(P_1+P_2)/2$]

3. MATHEMATICAL MODELING:

3.1 Analysis of multiple linear regression:

Mathematical modeling of the SAW process may be constructed using multiple curvilinear regression analysis. In this regard, first, a mathematical form simulating the relation between weld bead characteristics (bead width, bead height, and penetration) and process parameters (welding current, welding voltage, welding speed) should be selected. The regression coefficients are calculated based on this selected form by correlating the experimental data series. The general equation of the multiple linear regressions takes the following form:

$$Y=a+b_1X_1+b_2X_2+b_3X_3+\ldots+b_kX_k+e \qquad (1)$$

Where:

Y is the dependent variable, which is to be predicted. X_1, X2, X3…X_K are 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.

e is the error.

The equation (1) can be written in the following form:

$$Y=a+b_1I+b_2U+b_3S+e \qquad (2)$$

Y= (W=bead width, H=bead height, P=bead penetration, all in mm) I= welding current (A), U=arc voltage (V), S=welding speed (mm/min) (a, b_1, b_2, b_3) are the regression coefficients.

e is the error.

3.1.1 The regression coefficients:

The coefficients values of the linear equations were calculated by the regression method using the commercial statistical program SPSS software (statistical package for social science). After the calculation of the regression coefficients, these coefficients were evaluated for their significance at 95% confidence level by T-test.

Table 4 a. calculated regression coefficients for bead width (W)

Weld bead characteristic	Regression coefficients	a	b_1	b_2	b_3
		-8.811	0.037	0.943	-0.029
Bead width	T-test	-1.644	18.971	4.897	-15.080
	Significant	0.114	0.000	0.000	0.000

Table 4 b. calculated regression coefficients for bead height (H)

Weld bead characteristic	Regression coefficients	a	b_1	b_2	b_3
		20.247	-0.004	-0.501	-0.004
Bead height	T-test	28.623	-15.272	-19.721	-17.370
	Significant	0.000	0.000	0.000	0.000

Table 4 c. calculated regression coefficients for bead penetration (P)

Weld bead characteristic	Regression coefficients	a	b_1	b_2	b_3
		5.606	0.005	-0.133	0.002
Bead penetration	T-test	5.781	16.638	-3.828	5.598
	Significant	0.000	0.000	0.001	0.000

Substituting these regression coefficients into equation (2), three mathematical models for submerged arc welding can be obtained for weld bead characteristics. These models were expressed by equations (3), (4), and (5).

$$W=-8.811+(0.037*I)+(0.943*U)-(0.029*S) \qquad (3)$$

$$H=20.247-(0.004*I)-(0.501*U)-(0.004*S) \qquad (4)$$

$$P=5.606+(0.005*I)-(0.133*U)+(0.002*S) \qquad (5)$$

The correlation coefficients, which were used in this study to evaluate the total significant of the mathematical models, are R, R^2, and adjusted-R^2.

R is the simple correlation coeficient.it measures the relation power between two variables or more. R^2 is the determination coefficient. It is used to measure the explanatory power of the developed models for the simple linear regression case (one independent variable with one dependent variable). It is defined as the ratio of the sum of squares of the regression and the total sum of squares. It can take on any value between 0 and 1 with a value closer to 1 Adjusted-R^2 is the correlation coefficient. It is to report the total explanatory power of the multiple linear regression models (because it considers the number of the independent variables). In general, it is best indicator of the fit quality. It also can take on any value less than or equal to 1, with a value closer to 1 indicating a better fit. The values of the coefficients R, R^2, and adjusted-R^2 for the bead characteristics are calculated by regression method using SPSS software. The results were presented in tables (5a), (5b), and (5 c). indicates a better fit.

Table 5 a. correlation coefficients for bead width (W) model.

Model	R	R²	Adjusted- R²	Std. Error of the Estimate
Bead width	0.982	0.964	0.959	0.817052

Table 5 b. correlation coefficients for bead height (H) model.

Model	R	R²	Adjusted- R²	Std. Error of the Estimate
Bead height	0.988	0.976	0.973	0.107807

Table 5 c. correlation coefficients for bead penetration (P) model.

Model	R	R²	Adjusted- R²	Std. Error of the Estimate
Bead penetration	0.982	0.964	0.959	0.817052

3.2 accuracy of the models:

To determine the residual value in each experiment, the developed mathematical models were used to predict the weld bead characteristics values [bead width (W), bead high (H), bead penetration (P)] for 27 experiments according to factorial design of experiments, then these values were compared with the measured and the residual values were calculated to determine the error percentage in each experiment. The error percentage can be calculated by the following equation:

% Error = [(measured value-predicted value)/predicted value]*100
Or % Error = [(residual/predicted value)*100] (6)
Tables (6 a), (6 b), and (6 c) present the measured, predicted, residual values, and the error percentage in each experiment.

Table 6 a. bead width (W); measured, predicted values, residual, and error percentage according to factorial design.

Exp No.	Bead width W⁻(mm)	Bead width W^ (mm)	Re	Error (%)	Exp No.	Bead width W⁻(mm)	Bead width W^ (mm)	Re	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				

(W^= the predicted, Residual Re=W⁻-W^)

Table 6 b. bead height (H); measured, predicted values, residual, and error percentage according to factorial design.

Exp No.	Bead height H⁻(mm)	Bead height H^ (mm)	Re	Error (%)	Exp No.	Bead height H⁻(mm)	Bead height H^ (mm)	Re	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	-5.37
7	3.100	3.219	-0.119	-3.69	21	2.480	2.621	-0.141	-6.16
8	2.625	2.819	-0.194	-6.88	22	2.740	2.920	-0.180	-4.76
9	2.160	2.419	-0.259	-10.70	23	2.400	2.520	-0.120	-12.73
10	3.750	3.821	-0.071	-1.85	24	1.850	2.120	-0.270	7.89
11	3.275	3.421	-0.146	-4.26	25	2.610	2.419	0.191	-10.84
12	2.810	3.021	-0.211	-6.98	26	1.800	2.019	-0.219	-13.52
13	3.265	3.320	-0.055	-1.65	27	1.400	1.619	-0.219	-5.78
14	2.755	2.920	-0.165	-5.65	Average of error percentage = -5.78				

(H^= the predicted value, Residual Re=H⁻-H^)

Table 6 c. bead penetration (H); measured, predicted values, residual, and error percentage according to factorial design.

Exp No.	Bead penetration P⁻ (mm)	Bead penetration P^ (mm)	Re	Error (%)	Exp No.	Bead penetration P⁻ (mm)	Bead penetration P^ (mm)	Re	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				

(P^= the predicted value, Residual Re=P⁻- P^)

4. Results and Discussion

In the first stage of this study (weld-on-plate), the application of the factorial design of experiments was used performing 27 welds. Tables (3a), (3b) and (3c) present the welding conditions and the measured values of the weld bead characteristics for 27 welds. Tables (4a), (4b) and (4c) present the values of the regression coefficients and their statistical significance for independent variables and that all the independent variables have significant effects on the multiple regression models according to T-test at a significant level of sig (pe)0.05; namely, welding current (I), arc voltage, and welding speed on the dependent variables; namely, bead width, bead height, and bead penetration using SPSS software. It is observed from table (5a) that the value of adjusted-R^2=0.959 for the bead width, this means that the independent variables, welding current, arc voltage, and welding speed could explain≈96% from the occurred changes in the bead width, and the rest ≈4% is referred to other factors, while the value of adjusted-R^2=0.973 for the bead height model as shown in table (5b), it indicates that the independent variables could explain ≈97% from the occurred changes in the bead height, and the rest =3% is referred to other factors. For the bead penetration model, the value of adjusted-R^2=0.917 as shown in table (5c), indicates that the independent variables could explain ≈92% from the occurred changes in the bead penetration, and the rest≈8% is referred to other factors. The presented results in table (6a) indicate that the average =1.19%. This means that the accuracy of the developed mathematical model =98.81% for the bead width. For the bead height, table (6b), the absolute value of the error percentage average=5.78%, this means that the accuracy of the developed mathematical model=94.22%. For the bead penetration, table (6c), the average of the error percentage=3.14, which means that the accuracy of the developed mathematical model=96.86%. It is clear from figures (5a), (5b) and (5c) that there is good accordance between the measured and the predicted values for the three characteristics of the weld bead, which supports the validity of the developed mathematical models.

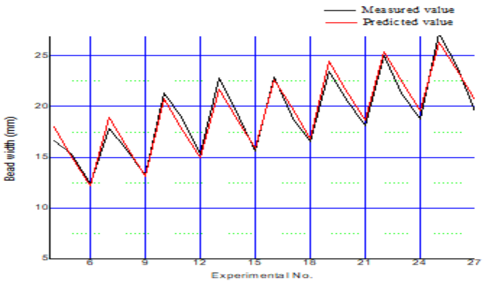

Figure 5a. the diagram representative of the measured and predicted values for bead width (W)

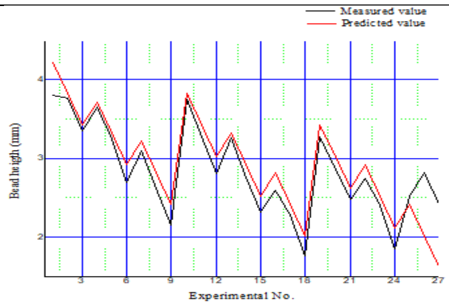

Figure 5b. the diagram representative of the measured and predicted values for bead height (H)

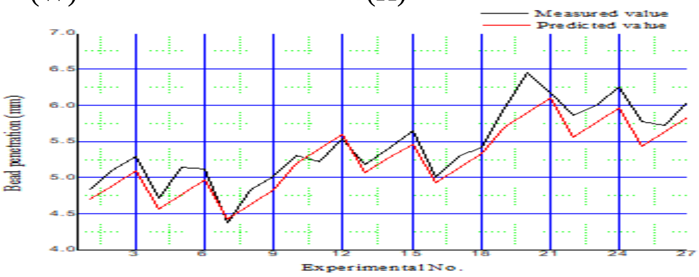

Figure 5 c. The diagram representative of the measured and predicted values for bead penetration **(P)**

It is clear from figures (6a), (6b) and (6c) that most points are located near the straight line. It is an indication that the normal distribution of errors. In other words, the assumption of the normal distribution is not violated.

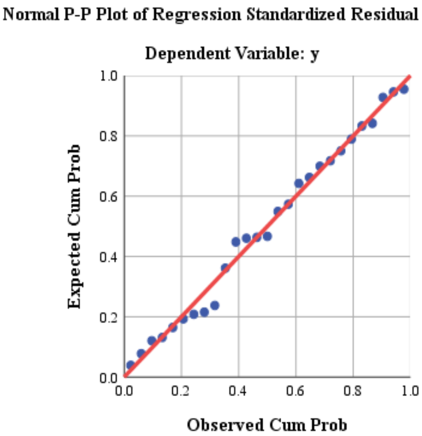

Figure 6a. Normality distributed errors for bead width (W)

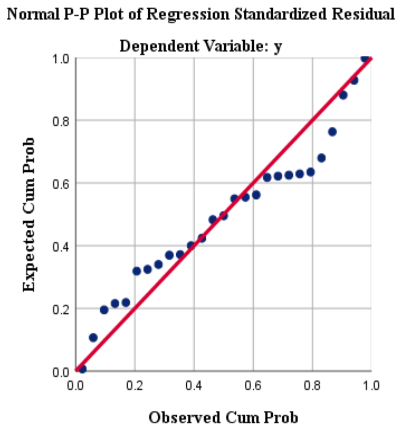

Figure 6b. Normality distributed errors for bead height (H)

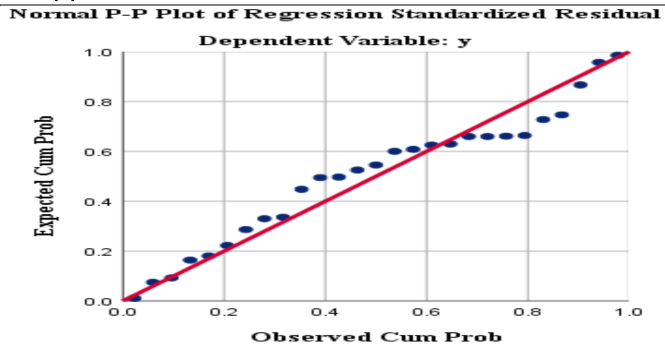

Figure 6a. Normality distributed errors for bead penetration (P).

5. Conclusions:

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

1. The three levels factorial design was found to be an effective tool for quantifying the main and interaction effect of variables on the weld bead geometry dimensions.
2. The mathematical modeling was developed from the experimental data using the regression method applying the multiple linear regression equation using SPSS software.
3. The developed mathematical models in this study can be effectively used to predict the desired dimensions of weld bead geometry [bead width (W), bead height (H), bead penetration (P)] for any given welding conditions. These mathematical models can be used to optimize the processes and to develop an automatic control system for welding power sources.
4. The F-test indicated that the mathematical model as a whole is significant.
5. Validation of the models and comparison of the measured and predicted values for the weld bead geometry characteristics revealed that the average of the models accuracy is about 97%.
6. The output result from the effect of the process parameters on the weld bead geometry characteristics revealed that the bead width increases with the increase in the welding current and the arc voltage; and decreases with an increase in the welding speed. The bead height decreases with the increase in the welding current, arc voltage, and welding speed. The bead penetration increases with the increase in the welding current and speed; and decreases with an increase in the arc voltage.

6. References:

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