OPTIMIZING SUBMERGED ARC WELDING PROCESS VARIABLES USING TAGUCHI METHOD

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Abstract

This paper investigates submerged arc welding (SAW) process variables on the quality of the weld bead geometry parameters and identifying the optimum process variables (current (I), voltage (V), and speed (S)). The experimentation is conducted for (Fe-0.137C-0.483Mn-0.356Si) in wt.% steel using bead-on-plate (BOP) technique. To determine the significant effect of these variables on achieving the desired weld bead quality (W,R,P), the researchers employed the orthogonal array for Taguchi L9 to reduce the number of the necessary experimental results for signal-to-noise ratio (S/N) calculations. The signal-to-noise ratios and the mean of the (S/N) ratios of the output responses are calculated to determine the optimum process variables. Analysis of Variance (ANOVA) is used to assess the impact of welding process variables on the characteristics of the weld bead parameters and the percentage contribution (PeC) of each variable. Experimental results revealed that the optimum levels for each of the response parameters in this study are ($I_1V_1S_3$) for bead width (W), ($I_3V_3S_3$) for bead reinforcement (R), and ($I_3V_2S_3$) for bead penetration (P). The ANOVA analysis results indicated that the welding current contributed significantly out of the three process variables used, especially with regard to width and penetration, followed by the welding speed. However, for the reinforcement, the PeC of the arc voltage is the highest, followed by the welding current and welding speed.

Keywords: SAW, Taguchi L9 orthogonal array design, S/N ratio, ANOVA and F-Test

Introduction:

Submerged arc welding is preferred over other welding processes because it provides many advantages. Some of these advantages are deeper penetration, higher deposition rate, excellent surface appearance, high melting efficiency, availability in automatic or semi-automatic mode, improved safety, lower welder skill requirement, and high-quality welds. Due to these advantages, this process has found many applications, both for relatively thin sheets and thick plates, include the fabrication of pressure and marine vessels, tanks, bridges, shipbuilding, oil/gas pipelines, and surfacing. This welding process can weld ferrous and nonferrous metals and alloys such as low carbon, low alloy steels, stainless steels, Ni, and Ti (Houldcroft 1989; Singh 2020; Akbar and Kadhim 2015; Al-Dawood and Saadoon 2015).

Generally, the submerged arc welding process obtains a welded joint with the desired weld bead parameters and excellent mechanical properties with minimum distortion. Welding variables have a significant influence in determining the quality of a weld joint; therefore, it is essential to study the stability of these variables to achieve high-quality weld characteristics with optimum mechanical properties (Karaoglu and Secgin 2008). These variables include current, voltage, speed, nozzle-to-plate distance, wire feed rate, flux type, and plate thickness (Jain et al. 2018; Choudhary et al. 2018; Vedrtnam et al. 2018; Abohusina 2018).

Many studies have investigated the selection of welding process variables and the determination of their optimum effects on weld bead characteristics (bead width, bead reinforcement, bead penetration) and mechanical properties, such as (hardness, UTS, impact, yield strength, bending, toughness) by methods such as Taguchi (Al-Dawood and Saadoon 2017; Pu et al. 2017; Deshmukh and Teli 2014; Sharma and Khan 2013; Bhardwaj et al. 2015), Taguchi coupled with grey relational analysis (Datta et al. 2008), Taguchi coupled with utility theory (Barma et al. 2012), regression analysis (Frefer and Abohusina 2021), Taguchi and regression analysis (Akbar and Kadhim 2015, Abohusina 2018, Kumanan et al. 2007), response surface methodology (Jain et al. 2018), regression and sensitivity analysis (Karaoglu and Secgin 2008), regression analysis, response surface methodology and genetic algorithm (Vedrtnam et al. 2018), regression analysis, desirability approach, genetic and jay algorithms (Choudhary et al. 2018). The reported results of these studies are different from each other, and this is due to the various tested material and welding variables selected. Since welding variables greatly influence the quality of a weld joint, even small changes in these variables may cause unexpected output results and welding performance (Karaoglu and Secgin 2008).

The main objectives of this study are to determine the impact of submerged arc welding process variables; current (I), voltage (V), and speed (S) on the weld bead geometry bead penetration (P), bead reinforcement (R), and bead width (W) using bead-on-plate (BOP) technique of (Fe-0.137C-0.483Mn-0.356Si) in wt.% steel and to determine the optimal welding variables to yield the desired weld bead quality.

The orthogonal array (OR) for Taguchi L9 design of experiments (DOE) is employed to reduce the number of the necessary experimental runs with results comparable to a full factorial experiment (Ross 1988). Signal to noise (S/N) ratios and mean (S/N) ratios analyses are used to find the significant effects of the selected variables used on the output parameters (responses) and improving the SAW process performance within the experimental field. ANOVA is applied to estimate the most significant process variables contributing to optimum bead qualities (Abohusina 2018).

Experimental Work:

Equipment and Material:

In this study, a semi-automatic submerged arc welding machine is made by Sweden ESAB (Elektriska Svetsnings-Aktiebolaget), the English translation is (Electric Welding Limited) company. A constant-voltage and direct-current power source are employed with a 3.2mm diameter copper-coated wire electrode in a coil form equivalent to (DIN 8557-S1) specification produced by ESAB company. The chemical composition of this electrode is shown in Table 1. The overhanging length of the electrode beyond the nozzle is 25mm. The distance between the electrode tip and the workpiece is 3mm, submerged under a layer of basic fluoride type granular flux equivalent to N.F. (A81-319) FP/B 34/23 ARI specification keeping the electrode positive polarity.

The as-received material used in this study is a steel plate with a thickness of 10mm. It has a chemical composition, as shown in Table 2. The bead-on-plate technique is used. Welds are deposited on samples in a rectangular shape with dimensions of 500×100×10mm.

Table 1. Composition of the wire electrode.

Element wt. %	C	Mn	Si	S	P	Cu
Wire Electrode	0.09	0.5	0.01	0.05	0.03	0.20

Table 2. Composition of the as-received material.

Element	C	Mn	Si	P	S	Ni	Cr	Mo	Cu	Fe
Wt.%	0.137	0.483	0.356	0.024	0.038	0.088	0.119	0.008	0.097	98.650

Selection of Process Variables and Design of OA for Taguchi DOE

Table 3 presents the values of the selected welding process variables and their different levels, while Figure 1 shows weld bead geometry characteristics.

Table 3. Welding process variables and their levels.

Welding process variable	Unit	Levels of the variable		
		1	2	3
Welding current (I)	Ampere	350	450	550
Arc voltage (V)	Voltage	26	27	28
Welding speed (S)	mm/min	400	500	600

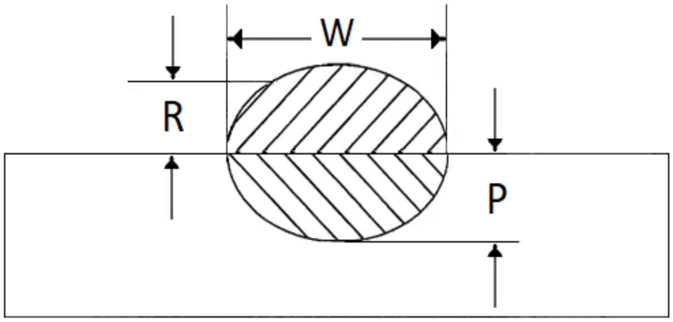

Figure 1. Weld bead geometry characteristics.

After the performance of the welding process, cross-sections of the welds were cut, and samples were prepared using the standard method; then, the weld bead geometry characteristics are measured by the micro-dimensions up to micrometer of type Nikon V12 microscope. Welding conditions according to Taguchi design are presented in Table 4.

Table 4. OA L9 (3^3) for Taguchi DOE and welding conditions.

Exp. No.	L9 (3^3)	Welding conditions		
		I	V	S
1	1 1 1	350	26	400
2	1 2 2	350	27	500
3	1 3 3	350	28	600
4	2 1 2	450	26	500

5	2 2 3	450	27	600
6	2 3 1	450	28	400
7	3 1 3	550	26	600
8	3 2 1	550	27	400
9	3 3 2	550	28	500

Analysis of (S/N) Ratios:

In the Taguchi method, (S/N) ratios determine the number of performance variations from the desired values (Ross 1988). The control variables that may contribute to improved quality can be quickly identified by the number of variations present as a response.

In this study, the analysis of the (S/N) ratios is applied for only nine experiments according to Taguchi L9 (3^3) DOE. All the interactions between the welding variables are neglected.

There are three categories of performance in the analysis of the (S/N) ratios:(a) lower-is-better (LB), (b) higher-is-better (HB), and nominal-is-best (NB). In this study, the output parameters (responses), namely, bead width (W) and bead reinforcement (R), belong to the quality characteristic of the lower-is-better type and bead penetration (P) belongs to the quality characteristic of the higher-is-better type. Equations 1 and 2 are used to compute the values of (LB) and (HB), respectively (Ross 1988; Hatab and Zaid 2008; Abohusina 2018).

For lower-the-better (LB) type, the following equation is used:

$$\text{signal-to-noise ratio (LB)} = -10 \log \left[\frac{1}{n} \sum_{i=1}^{n} Y_i^2\right] \text{……………………..(1)}$$

For higher-the-better (HB) type, the following equation is used:

$$\text{signal-to-noise ratio (HB)} = -10 \log \left[\frac{1}{n} \sum_{i=1}^{n} 1 / Y_i^2\right] \text{……………….. (2)}$$

Where n is the number of experiments and Y_i is the i^{th} experimental value for the performance characteristic. In this study, Y_i represents the bead geometry characteristics (W, R, P).

Mean of the Signal-to-Noise (S/N) Ratio:

After finding the values of the (S/N) ratios, the mean S/N ratios at each level for various variables are calculated, and graphs are drawn. The optimal levels are determined from the highest values of the mean S/N ratios among levels of the variables (Abohusina 2018).

Analysis of Variance (ANOVA) According to Orthogonal Array L9(3^3):

For analyzing the significant effect of the welding process variables on the response of the output bead parameters, ANOVA is used to investigate which process variables significantly affect the performance characteristic (bead geometry). This analysis is carried out for a level of significance of 0.05 for a level of confidence of 95%.

The analysis of variance can be accomplished based on the total sum of squares (SS)T from the total mean of the (S/N) ratio according to equation (3):

$$(\mathbf{SS})\mathrm{T} = \sum_{\mathbf{i}=1}^{\boldsymbol{n}} (\boldsymbol{S}/\boldsymbol{N})_i^2 - \frac{\mathbf{1}}{\boldsymbol{n}} \left[\sum_{\mathbf{i}=1}^{\boldsymbol{n}} (\boldsymbol{S}/\boldsymbol{N})_{\mathbf{i}} \right]^2 \text{…………...………………(3)}$$

Where n represents all the experiment runs and *(S/N)i* is the calculated signal-to-noise ratio value of the i^{th} quality characteristic.

(SS)T decomposed into the sum of squares due to each tested variable (SS)f and the sum of squares due to the error (SS)e, which can be expressed by equations (4) and (5):

$$(SS)\mathrm{f} = \sum_{j=1}^{h} \frac{((S/N)\mathrm{j})^2}{h} - \frac{1}{n}\left[\sum_{i=1}^{n}(S/N)i\right]^2 \quad \text{…………………………….}(4)$$

$$(SS)\mathrm{e} = (SS)\mathrm{T} - \sum (SS)\mathrm{f} \quad \text{……………..…………………………….}(5)$$

Where j is the level number of the specific variable and h is the repetition of each variable's levels. The degree of freedom (DF) due to error is calculated by using equation (6):

$$\mathbf{(DF)}\mathrm{e} = \mathbf{(DF)}\mathrm{T} - \sum \mathbf{(DF)}\mathrm{f} \quad \text{...…………………………………………}(6)$$

The variance for each factor is calculated by using equation (7):

$$\mathbf{(V)}\mathrm{f} = \mathbf{(SS)}\mathrm{f} / \mathbf{(DF)}\mathrm{f} \quad \text{……….……………………………………….…}(7)$$

The variance due to error is calculated using equation (8):

$$\mathbf{(V)}\mathrm{e} = \mathbf{(SS)}\mathrm{e} / \mathbf{(DF)}\mathrm{e} \quad \text{…..……………………………………….…}(8)$$

The expected sum of the squares for each variable $(\widetilde{SS})\mathrm{f}$ is given by equation (9):

$$(\widetilde{SS})\mathrm{f} = (SS)\mathrm{f} - ((DF)\mathrm{f} \,.\, (V)\mathrm{e} \quad \text{………………………………….…….}(9)$$

The Fisher test (F) determines which process variables statistically significantly affect the performance characteristic. The large value of the F-test means that the effect is great on the performance characteristic due to the change of the process variables. The F-test can be expressed by equation (10):

$$\textbf{F-value} = \mathbf{(V)}\mathrm{f} / \mathbf{(V)}\mathrm{e} \quad \text{………………………...…….……….….…..}(10)$$

The percentage contribution (**PeC**) for each variable can be used to evaluate the importance of each variable on the performance characteristic and can be expressed by equation (11):

$$\mathbf{PeC} = \frac{(\widetilde{SS})\mathrm{f}}{(SS)\mathrm{T}} \mathbf{\ x\ 100} \quad \text{…………………………………………………….}(11)$$

Equations (1 to11) used to calculate the S/N ratios and ANOVA analysis can be found in many reported literature references such as (Ross 1988; Hatab and Zaid 2008; Abohusina 2018). In this study, the experimental design and the calculations are conducted with EXCEL and SPSS software applications.

Results and Discussion

Results

Analysis of the Signal–to–Noise (S/N) Ratio:

The measured bead characteristics and the signal-to-noise (S/N) ratio values according to the loss function for the three bead characteristics are shown in Table 5.

Table 5. Bead (P, R, W) and S/N ratios according to OA L9 (3^3).

Exp No.	**I**	**V**	**S**	**W (mm)**	**(S/N) ratio**	R (mm)	**(S/N) ratio**	P (mm)	**(S/N) ratio**
1	350	26	400	15.500	-23.806	3.800	-11.596	4.840	13.697
2	350	27	500	15.310	-23.700	3.250	-10.223	5.150	14.236
3	350	28	600	13.215	-22.421	2.160	-6.679	5.015	14.005

4	450	26	500	18.955	-25.555	3.275	-10.304	5.215	14.345
5	450	27	600	15.600	-23.863	2.315	-7.288	5.650	15.041
6	450	28	400	22.890	-27.193	2.590	-8.264	5.000	13.978
7	550	26	600	18.060	-25.134	2.480	-7.876	6.180	15.820
8	550	27	400	25.000	-27.959	2.740	-8.752	5.860	15.357
9	550	28	500	23.720	-27.502	1.800	-5.097	5.720	15.145

Mean (S/N) Ratios:

The most significant value of the mean (S/N) ratios for the three levels for each of the process variables is the optimum because a high value of signal-to-noise ratio indicates that the signal is much higher than the random effects of the noise factors (Kumanan et al. 2007).

Tables (6a-6c) and Figures (2a-2c) show the calculations of the mean of the (S/N) ratios for the three process variables with their different levels for weld bead characteristics.

Table 6 (a). Mean of S/N ratios and rank for width according to OA L9 (3^3).

Variable	Variable levels	$(\overline{S/N})$ Ratio	Optimum level	Delta=Max-Min	Rank
Welding current (I)	$I_1 = 350$ $I_2 = 450$ $I_3 = 550$	-23.309 -25.537 -26.865	I_1	3.556	1
Arc voltage (V)	$V_1 = 26$ $V_2 = 27$ $V_3 = 28$	-24.832 -25.174 -25.706	V_1	0.874	3
Welding speed (S)	$S_1 = 400$ $S_2 = 500$ $S_3 = 600$	-26.319 -25.585 -23.806	S_3	2.513	2

Table 6 (b). Mean of S/N ratios and rank for reinforcement according to OA L9 (3^3).

Variable	Variable levels	$(\overline{S/N})$ Ratio	Optimum level	Delta=Max-Min	Rank
Welding current (I)	$I_1 = 350$ $I_2 = 450$ $I_3 = 550$	-9.508 -8.620 -7.250`	I_3	2.258	2
Arc voltage (V)	$V_1 = 26$ $V_2 = 27$ $V_3 = 28$	-9.930 -8.761 -6.687	V_3	3.243	1
Welding speed (S)	$S_1 = 400$ $S_2 = 500$ $S_3 = 600$	-9.539 -8.549 -7.290	S_3	2.249	3

Table 6 (c). Mean of S/N ratios and rank for penetration, according to OA L9 (3^3).

Variable	Variable levels	$(\overline{S/N})$ Ratio	Optimum level	Delta = Max-Min	Rank
Welding current (I)	$I_1 = 350$ $I_2 = 450$ $I_3 = 550$	13.980 14.455 15.442	I_3	1.462	1
Arc voltage (V)	$V_1 = 26$ $V_2 = 27$ $V_3 = 28$	14.621 14.878 14.378	V_2	0.500	3
Welding speed	$S_1 = 400$	14.345	S_3	0.610	2

(S)	S_2 = 500 S_3 = 600	14.576 14.955			

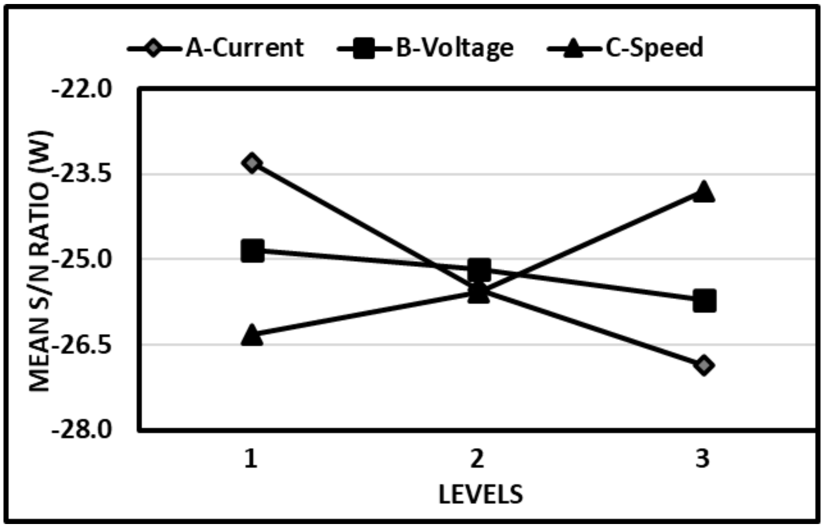

Figure 2 (a) Effects of SAW variables on mean S/N ratios of (W).

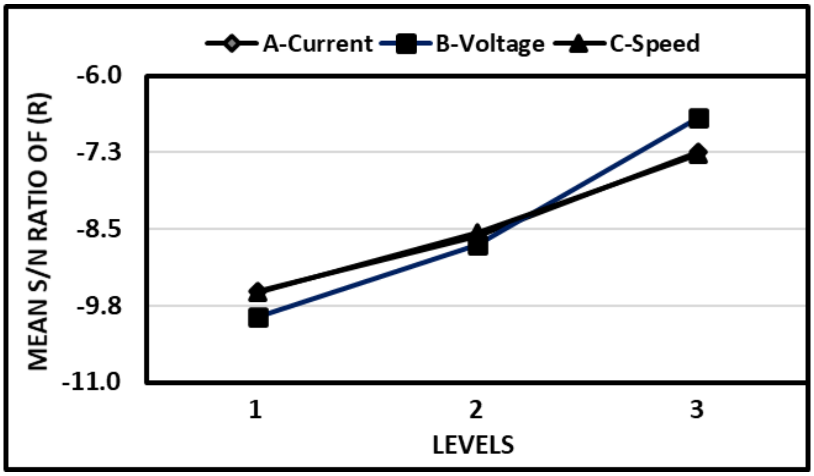

Figure 2 (b) Effects of SAW variables on mean S/N ratios of (R).

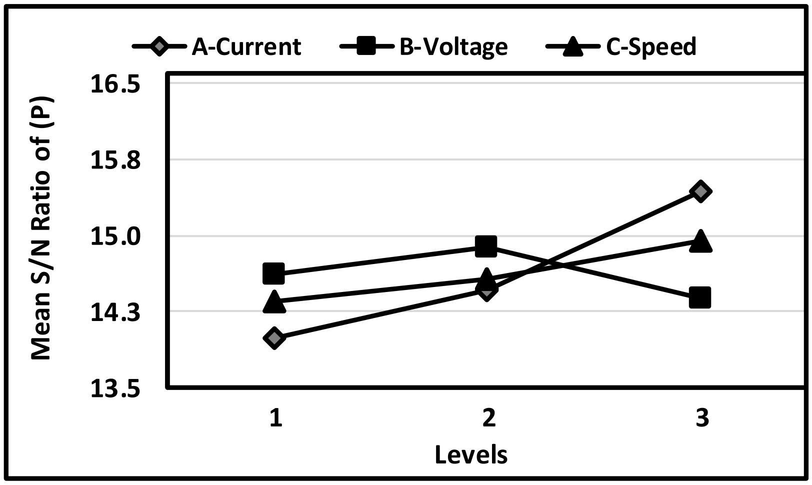

Figure 2 (c) Effects of variables on mean S/N ratios of (P).

Analysis of Variance (ANOVA) According to OA L9 (3^3):

Tables (7a-7c) present the analysis of variance results for the signal-to-noise (S/N) ratios for the three performance characteristics.

Table 7 (a). ANOVA results for (S/N) Ratio for width according to orthogonal array L9

Variable	DF	SS	Variance	F-Value	p-Value	PeC	Rank
Current-A	2	19.3726	9.6863	131.7721	0.0075	63.0934	1
Voltage-C	2	1.1633	0.5816	7.9125	0.1122	3.7885	3
Speed-B	2	10.0218	5.0109	68.1680	0.0145	32.6393	2
Error	2	0.1470	0.0735			0.4788	
Total	8	30.7046				100.000	

Table 7 (b). ANOVA results for reinforcement, according to orthogonal array L9 (3^3).

Variable	DOF	SS	Variance	F-Value	p-Value	PeC	Rank
Current-A	2	7.7672	3.8836	7.6471	0.1157	23.7850	2
Voltage-C	2	16.2003	8.1002	15.9498	0.0590	49.6093	1
Speed-B	2	7.6726	3.8363	7.5539	0.1169	23.4953	3
Error	2	1.0157	0.5079			3.1103	
Total	8	32.6558				100.000	

Table 7 (c). ANOVA results for penetration, according to orthogonal array L9 (3^3).

Variable	DOF	SS	Variance	F-Value	p-Value	PeC	Rank
Current-A	2	3.3386	1.6693	187.1160	0.0053	77.5892	1
Voltage-C	2	0.3763	0.1882	21.0905	0.0453	8.7453	3
Speed-B	2	0.5702	0.2851	31.9559	0.0303	13.2508	2
Error	2	0.0178	0.0089			0.4147	
Total	8	4.3030				100.000	

Discussion:

The results from the analysis of the (S/N) ratios shown in Table 5 indicate that the optimum levels of the welding process variables are as follows: for the width is determined to be ($I_1V_3S_3$) with the highest value of the (S/N) ratio is (-22.421) and the minimum (W) value achieved is (13.215mm) as in experiment No 3. However, for the reinforcement, the (S/N) ratio level is ($I_3V_3S_2$), and the value of the (S/N) ratio is (-5.097), and the minimum (R) value is (1.800mm) as in experiment No 9. For bead penetration, the (S/N) ratio level is ($I_3V_1S_3$) as in experiment no 7 with a value of (15.820) and the maximum (P) value is (6.180mm).

The outcome results from calculating the mean (S/N) ratio for each variable are presented in Table 6 and Figure 2. They revealed that the optimum levels of the welding process variables are as follows: for the weld bead width, the optimum level is ($I_1V_1S_3$), whereas for the weld bead reinforcement, the optimum level is ($I_3V_3S_3$), and for bead penetration is ($I_3V_2S_3$).

After predicting the optimum conditions (levels) obtained from the mean (S/N) ratio for each variable, new confirmation experiments are designed and conducted with the new optimum levels of the welding variables. The purpose of these confirmation experiments is to validate the conclusions drawn during the mean (S/N) ratios analysis. The achieved optimum values for width, reinforcement, and penetration are 11.150mm, 1.4mm, 6.250mm, respectively.
By comparing the results of all variables for all output parameters using both the (S/N) ratios and the mean (S/N) ratios, the experimental results indicate the following: (a) any changes in the values of the design welding process variables can alter the performance characteristic. These variables play an essential role in the quality of welding operation (Akbar and Kadhim 2015; Karaoglu and Secgin 2008). (b) the experimental results also accentuate that the procedure of the mean (S/N) ratios calculations are better than the procedure of (S/N) ratios analysis for determining the optimum level of the process variables (Akbar and Kadhim 2015; Karaoglu and Secgin 2008).
The improvements in the bead parameters are as follows: (a) for the bead width is 15.6%, (b) for the bead reinforcement is 22.2%, and (c) for bead penetration is 1.1%.

According to the resulted mean (S/N) ratios and ANOVA analysis, as can be seen in Tables 6 & 7 and Figure 2, the effects of these are as follows:

Bead Width:

The welding current has the most significant effect on bead width followed by welding speed and, to less extent, the arc voltage. As the current increases, the width decreases, but as the speed increases, the width increases.

Welding current and speed are the main variables influencing the bead width, as shown in ANOVA analysis. The PeC of current, speed, and voltage on the bead width are 63.0934, 32.6393, and 3.7885, respectively. The p-values for both current (0.0075) and speed (0.0145) are less than 0.05, which is an indication that both variables are significant (current more critical than speed), where the p-value for the voltage is 0.1122. It is higher than 0.05 and indicates that voltage is an insignificant variable. Also, the F-value for the current and speed is higher than that of the voltage.

Bead Reinforcement:

The arc voltage significantly affects bead reinforcement than both current and speed, as shown in the mean (S/N) ratios and ANOVA results. From ANOVA analysis, voltage almost having a p-value equals 0.05. Still, both current and speed having p-values higher than 0.05 (0.1157) for current and (0.1169) for speed, so they have an insignificant effect compared to arc voltage.

The PeC of voltage, current, and speed on the bead reinforcement are 49.6093, 23.7850, and 23.4953, respectively. The F-value for the voltage is higher than both F-values for current and speed, and the higher, the more significant.

Bead Penetration:

All three variables influence the bead penetration with different rates, as shown in ANOVA analysis. Welding current is the most critical variable in determining the bead penetration, followed by speed and then voltage, as shown in the mean (S/N) ratios and ANOVA analysis results.

The bead penetration increases with the increase in the welding current. As the speed increases, the bead penetration increases, but the effect is less critical. The PeC of current, speed, and voltage on the bead penetration are 77.5892, 13.2508, and 8.7453, respectively. The p-values for all variables; current (0.0053), speed (0.0303), and arc voltage (0.0453) are less than 0.05. These values indicate that all these variables are significant (current more significant, followed by speed, and then voltage), where the F-values, the higher, the more significant the variable.

Conclusions:

From the experimental results of this study, the following conclusions can be drawn:

(1) The welding current is the primary variable that significantly influences the bead width and penetration, followed by welding speed and then the arc voltage. The arc voltage is the most crucial parameter in determining the bead reinforcement, followed by current and then speed.

(2) The optimum levels of the process variables are as follows: (a) for the width are ($I_1V_1S_3$) (350A, 26V,600mm/min), (b) for the reinforcement are ($I_3V_3S_3$) (550A,28V,600mm/min), and (c) for the penetration are ($I_3V_2S_3$) (550A,27V,600mm/min).

(3) The improvements in the bead parameters are: (a) for the bead width is 15.6%, (b) for the bead reinforcement is 22.2%, and (c) for bead penetration is 1.1%.

(4) The PeC of welding current, welding speed, and arc voltage on the bead width are 63.0934, 32.6393, and 3.7885, respectively. The F-value for current is (131.7721), for speed is (68.1680), and for voltage is (7.9125); this is a strong proof that both the current and speed are the most important variables influencing the bead width and that the current is more significant than speed.

(5) The PeC of arc voltage, welding current, and welding speed on the reinforcement are 49.6093, 23.7850, and 23.4953, respectively. The F-value for voltage is (15.9498), for current is (7.6471), and for speed is (7.5539), which indicates that voltage influences bead reinforcement more than current and speed.

(6) The PeC of welding current, welding speed, and arc voltage on the penetration are 77.5892, 13.2508, and 8.7453, respectively. The F-value for current is (187.1160), for speed is (31.9559), and for voltage (21.0905); this is a strong proof that the current is the most critical variable influencing the bead penetration.

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