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Modeling and Optimization of Penetration Depth Using Genetic Algorithm, Focusing on Submerged Arc Welding

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[Modeling and Optimization of Penetration Depth Using Genetic Algorithm,Focusing on Submerged Arc Welding]

Modeling and Optimization of Penetration Depth Using Genetic Algorithm, Focusing on Submerged Arc Welding

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ABSTRACT

Submerged arc welding is a production process directly affected by various input parameters and interactions, and these effects will directly affect the output results. This research investigated the impact of arc voltage, electric current intensity, electrode stick-out, welding speed, and the thickness of the layer of nanoparticles on the penetration depth. In this study, Central Composite Rotatable Design and analysis of variance were used to examine the effect of input variables on output results and reduce time and costs. Ultimately, the Genetic Algorithm was used to find the optimal levels of selected parents. The results indicate that increasing the arc voltage and the electric current intensity due to more input heat transfer caused more melting of the base metal and thus increased the penetration depth. The difference in thermal conductivity between the base metal and the nanoparticles results in less heat transfer to the inner layers of the workpiece; therefore, the high thickness of the layer of nanoparticles reduces the penetration depth. On the other hand, increasing the thickness of the layer of nanoparticles increased the weld's height and width.

Keywords: Nanoparticles, Modeling and optimization, Central composite rotatable design (CCRD), Submerged arc welding (SAW).

1. Introduction

Submerged arc welding is a method of connecting different parts. The arc between the electrode wire and the workpiece is submerged under a layer of powdered flux delivered in front of the electrode from a hopper [1]. Due to features and benefits such as high sedimentation rate, high quality of welding components, and wide range of applications in various industries, including construction, welding of pipes, welding of different thicknesses of ferrous and non-ferrous steel, and pressure vessels that cover an extensive range of workpieces [2-5]. Welding quality is affected by welding parameters such as speed, current, and voltage. Therefore, it is essential to determine the proper level of the input parameters of this welding process to achieve a desired quality welded connection [6-8]. Vedrtnam et al. used the RSM method and genetic algorithm to determine the values of process input parameters and predict the welding geometry [9].

On the other hand, researchers always use different nanoparticles in welding processes and evaluate the obtained results considering the advantages of nanoparticles. So, in recent years, many publications have focused on nanoparticle use. For instance, the mechanical properties and microstructures of ASTM A36 steel plates have been used in submerged arc welding by adding TiO_2 to the flux [10]. In another study, the TiO_2 nano-powder parameter was employed as an input parameter on the steel sheet, and it concluded that the penetration depth significantly increased [11]. More interestingly, the fuzzy logic method was considered to predict the effect of submerged arc welding parameters on weld bead penetration [12]. Another study evaluated the thickness of the coating layer of nanomaterials. MgO was used as an input parameter for the submerged arc welding process to predict the penetration depth. The RSM was used to find the relationship between the inputs and outputs of the process. The author concluded that the model proposed the level of MgO nanoparticles at a low level [13]. Choudhary et al. studied the strength and toughness of the fluxes containing CaO, TiO_2, Al_2O_3, and MgO compounds on a low-carbon steel sheet using a two-level Taguchi design method to obtain a good level of flux composition [14]. Aghakhani et al. considered the thickness of the Cr_2O nanoparticles as an input parameter of SAW welding to optimize the dilution. They reported that increasing the thickness change from 0 to 0.25 percent changed dilution from 61.5 to 62.8 percent [15]. In similar studies, the nanoparticles' effect has also been investigated [16-17].

This paper investigated the impact of input parameters (arc voltage, electric current intensity, electrode stick-out, welding speed, and the nano-particle layer thickness) on the geometry of the created welds. The Central Composite Rotatable Design was used to determine the process input parameters. Then, the regression model derived from the input data and the test results were optimized by genetic algorithm, and the optimal values of the process input parameters were determined to achieve the highest penetration depth.

2. Genetic Algorithm

Genetic Algorithm is a collection of numerical optimization inspired by Darwinian natural evolution, introduced by John Holland in 1975 and used as a general way to solve a wide range of issues [18-21]. The genetic algorithm begins with answers under the primary population shown by chromosomes. The solutions are evaluated, and the best people are selected and used to create the population of subsequent generations according to the three actors of selection, intersection, and mutation operators. The answer to the problem solved by it is expected to be constantly improved [22-27]. With the help of genetic algorithms, one can obtain an optimal solution for a computational problem that can maximize or minimize a function [28].

This study uses a genetic algorithm to find an optimal level of the welding process (SAW) input parameters to achieve the maximum penetration depth. In this regard, the prediction of input quantities, including the percentage of nanoparticles added and their adaptation to the values obtained from the experiments, can be too critical. The flowchart regarding the genetic algorithm is shown in Figure 1.

3. Experimentation and data collection

The penetration depth is the maximum vertical distance between the sheet's surface, the upper horizontal surface of the welded section, to the part melted in the base metal (Figure 2). Indeed, the experiments were performed by submerged arc welding (SAW) process with DC reverse polarity on St37 steel with a size of 15×50×150 mm^3 by welding of PARS CAT P2310 semi-automatic robot with PARC ARC 1203T power supply with constant voltage curve. Arc voltage, electric current intensity, electrode stick-out, welding speed, and the thickness of the layer of nanoparticles have been considered input parameters. The chemical composition of the filler metal 11-50 within the diameter of 3.2 mm is also shown in Table 1. The consumed flux in this research is a rutile aluminate agglomerate and can be used up to 800 amps with AC and DC currents. This flux suits welding construction steels, pressurized tank steels, and pipe-making steels. The granulation of this flux is under DIN 32522: 2-16, and its chemical composition is shown in Table 2. The maximum and minimum ranges were set for each parameter according to the implementation of several experiments based on one variable at a time and checking the weld quality in welded samples. Then the parameters arc voltage (V), electric current intensity (I), electrode stick-out (N), welding speed (S), and the thickness of the layer of nanoparticles in five-level (-2, -1, 0, +1, and +2) were determined by Central Composite Rotatable Design (Table 3). The design matrix and the results are presented in Table 4.

Table 1- Chemical composition of the welding wire

Element	**C**	**Mn**	**Si**	**Fe**
%W	0.04-0.08	0.9-1.3	0.5-0.8	Balance

Table 2- Chemical composition of the consumed flux

$SiO_2 + TiO_2$	**$Al_2O_3 + MnO$**	**CaF_2**
% 5	% 55	% 30

Table 3- Input parameters and their ranges

Parameter	**Coded values**				
	-2	**-1**	**0**	**+1**	**+2**
Arc Voltage (volts)	24	26	28	30	32
Electric current (amp)	500	550	600	650	700
Electrode stick-out (mm)	30	32.5	35	37.5	40
Welding Speed (mm/min)	300	350	400	450	500
Nano-layer thickness (mm)	0	0.25	0.5	0.75	1

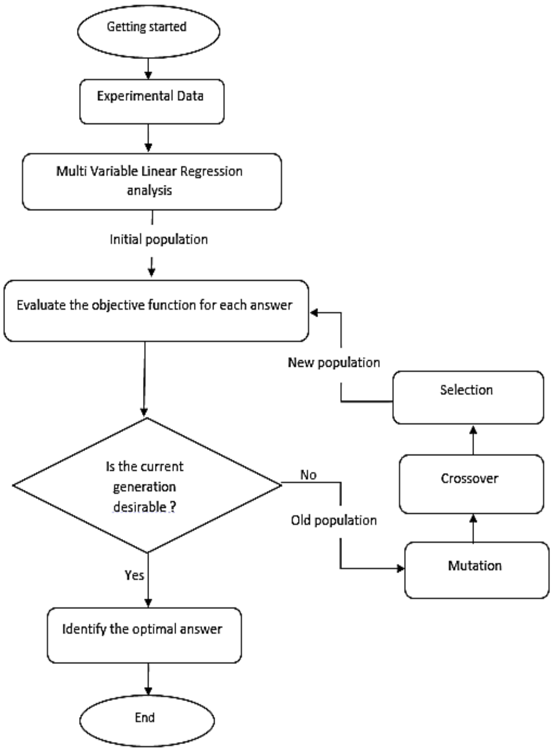

Figure 1-Flowchart of Genetic Algorithm

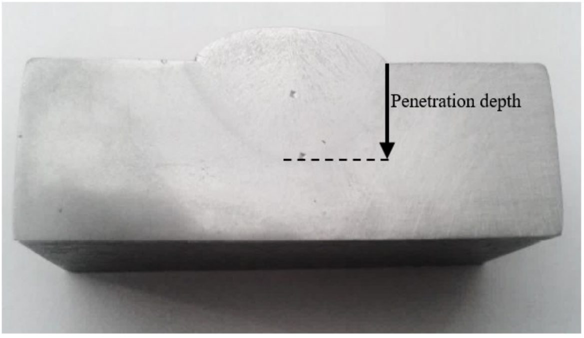

Figure 2-Weld-melted zone in the prepared workpiece

Table 4- Input parameters and their ranges

Std.	**V**	**I**	**N**	**S**	**F**	**Penetration depth**
1	0	0	0	0	0	7.01
2	0	0	0	-2	0	8.14
3	-1	1	-1	1	1	7.65
4	-1	-1	1	1	1	4.14
5	1	1	1	-1	-1	9.28
…	…	…	…	…	…	…
30	2	0	0	0	0	7.89
31	0	0	2	0	0	6.81
32	0	-2	0	0	0	4.64

4. Results and discussion

The effect of arc voltage, electric current intensity, electrode distance from the nozzle, welding speed, and nanoparticle layer thickness on penetration depth was investigated (Figure 3). The results show that increasing the electric current intensity increases the welding penetration depth by increasing the melting speed of base metal and welding wire.

As the current increases from 500 to 700 amps, the heat input to the workpiece increases, and more base metal is melted, thereby increasing the penetration depth. Although the heat input to the workpiece increased as the arc voltage increased from 24 to 32 V, the melting rate of the electrode did not change much. Higher welding voltage can cause a slight increase in the penetration depth of the weld [29,32].

The considerable distance of the nozzle from the workpiece causes insufficient protection of the welding pool and melt. Still, on the other hand, a concise space of the nozzle causes the tip of the nozzle to burn due to the high temperature of the welding pool [33,34]. Increasing the distance between the electrode and the nozzle decreases the amount of heat input to the workpiece.

As the welding speed increases, the heat input to the welding area decreases. Therefore, the penetration depth increases [31-35]. The results show that the heat input to the workpiece has been reduced by increasing the welding speed. The nanoparticles used in this study can introduce large amounts of manganese oxide and alumina into the weld pool. Since the thermal conductivity of the nanoparticle powder is lower than that of the base metal, increasing the thickness of the nanoparticles decreases the penetration depth. The cubic model was used to establish relationships between process input parameters. Analysis of Variance (ANOVA) was performed for statistical analysis and validity of the proposed model considering input parameters and interactions (Table 5). The p-value for the model is less than 0.000. In the remaining part, the disproportion value is equal to 0.1354.

The average value reported from the model based on response data is 7.11. Std. Dev represents the scatter value of the data relative to the Mean value, equal to 0.278. The importance of R^2, Adjusted R^2, and Predicted R^2, critical statements in confirming a regression model, are 0.9871, 0.9764, and 0.9401, respectively. The Adeq Precision, which shows the Signal to Noise ratio, equals 40.9043. Regression equation (1) shows the equation obtained regarding actual parameters for depth penetration.

$$\text{Penetration depth} = 7.12 + (0.493\,V) + (1.173\,I) - (0.178\,N) - (0.468\,S) - (0.362\,F) + (0.124\,V\,I) - (0.123\,VS) - (0.174\,VF) - (0.0943\,II) + (0.526\,IS) - (0.188\,NS) + (0.283\,NF) - (0.109\,SF) + (0.0755\,FF) \qquad (1)$$

Diagnostic plots were used to evaluate the results. The standard probability plot of the studentized residuals and plot of studentized residuals versus predicted values are shown in Figures 3 and 4. Moreover, the predicted versus actual properties and the histogram plot of the experimental data obtained are shown in Figures 5 and 6. Figure 7 illustrates the interaction between the main parameters affecting the weld penetration depth. As the results show, a simultaneous increase of arc voltage to 32 volts and current to 700 Amp increase the penetration depth. However, the effect of increasing the intensity of electric current on the penetration depth is greater than the amount of welding voltage (V-I, Figure 7). Due to reducing the input heat and the melting rate of the base metal, increasing the welding speed reduces the penetration depth (V-S, Figure 7). Increasing the welding voltage and electric current intensity with decreasing the welding speed and the distance of the electrode to the plate surface indicates that if the thickness of the layer of nanoparticles is at lower levels, the penetration depth will increase (V-F, Figure 7). Simultaneous increase of electric current and reducing the welding speed are critical parameters in increasing the penetration depth (I-S, Figure 7).

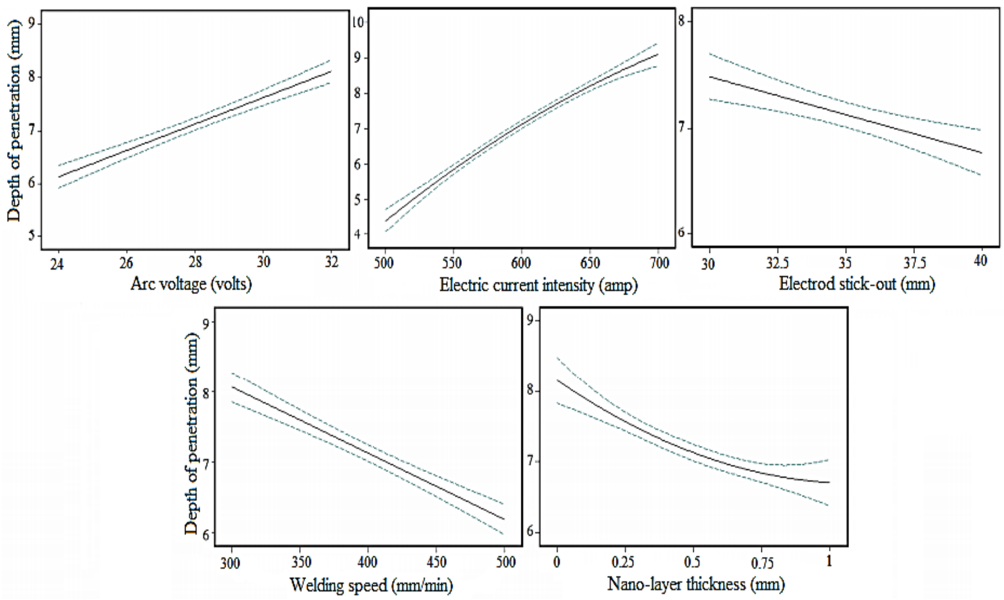

Figure 3-The effect of input parameters on the penetration depth

Table 5- Results of ANOVA for penetration depth

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	56.05	14	4.00	92.67	< 0.0001	significant
A-Arc voltage	5.85	1	5.85	135.44	< 0.0001	
B-Electric current intensity	33.06	1	33.06	765.37	< 0.0001	
C-Electrode stick-out	0.7668	1	0.7668	17.75	0.0006	
D-Welding Speed	5.27	1	5.27	122.07	< 0.0001	
E-Nano-layer thickness	3.16	1	3.16	73.17	< 0.0001	
AB	0.2475	1	0.2475	5.73	0.0285	
AD	0.2426	1	0.2426	5.61	0.0299	
AE	0.4865	1	0.4865	11.26	0.0037	
BD	4.44	1	4.44	102.81	< 0.0001	
CD	0.5663	1	0.5663	13.11	0.0021	
CE	1.28	1	1.28	29.69	< 0.0001	
DE	0.1914	1	0.1914	4.43	0.0505	
B^2	0.2670	1	0.2670	6.18	0.0236	
E^2	0.1757	1	0.1757	4.07	0.0598	
Residual	0.7344	17	0.0432			
Lack of Fit	0.6381	12	0.0532	2.76	0.1354	not significant
Pure Error	0.0963	5	0.0193			
Cor Total	56.78	31				
Std. Dev.	0.2078		R^2		0.9871	
Mean	7.11		Adjusted R^2		0.9764	
C.V. %	2.92		Predicted R^2		0.9401	
			Adeq Precision		40.9043	

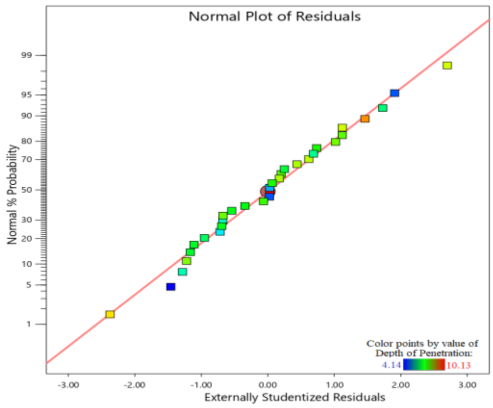

Figure 3-Normal probability plot of the studentized residuals

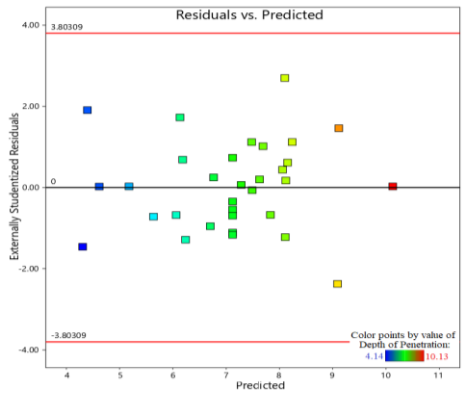

Figure 4-Plot of studentized residuals versus predicted values

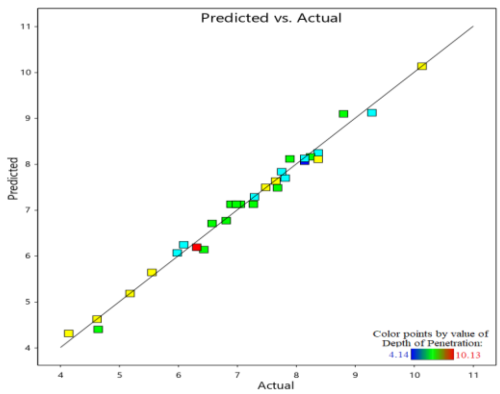

Figure 5-predicted versus actual plot

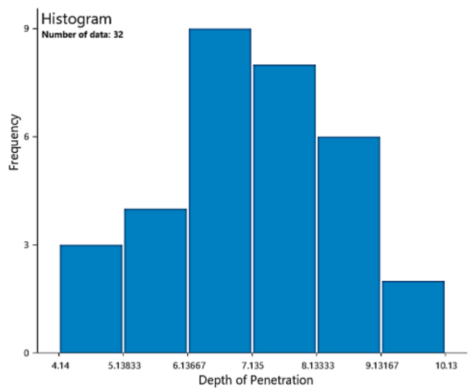

Figure 6-Histogram plot of experimental data

5. Genetic algorithm optimization

This study aimed to achieve the maximum penetration depth, so the nonlinear multiple regression equation obtained from the modeling part was considered a fitness function (-f). Considering the existing constraints, the genetic algorithm obtained optimal values for the input parameters. The population size and the number of generations were 100 and 151, respectively, with lower and upper boundary values of [-2, -2, -2, -2, -2] and [2, 2, 2, 2, 2]. The optimal value determined by the genetic algorithm for the penetration depth was 15.6448 mm.

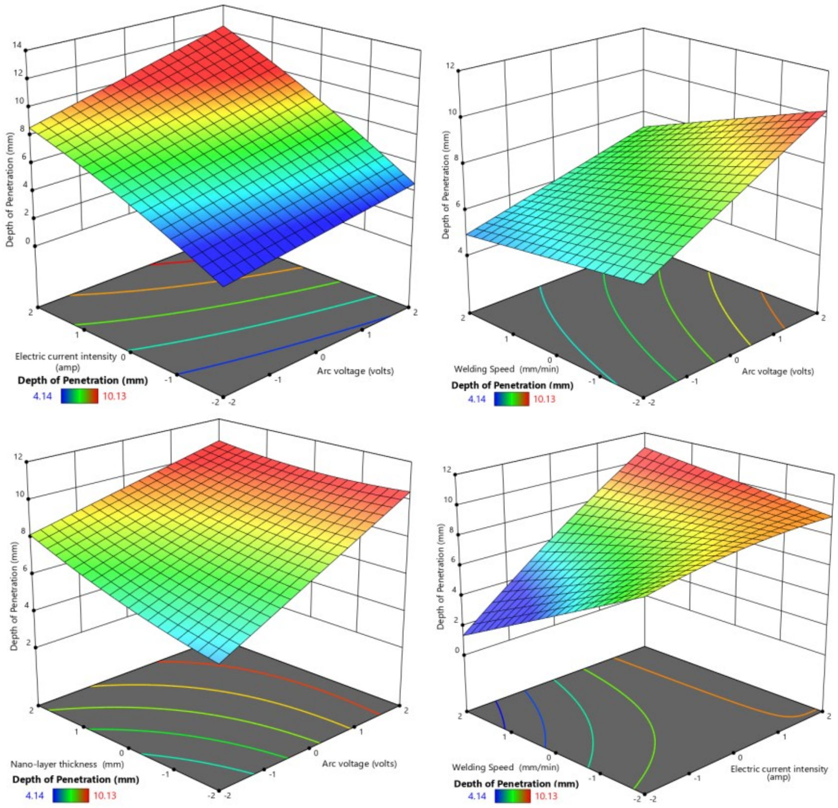

Figure 7-Interaction between input parameters affecting the penetration depth

Table 6- Optimal level obtained for input parameters by genetic algorithm

Parameter	Arc Voltage	Electric current intensity	Electrode stick-out	Welding Speed	Nano-layer thickness	penetration depth
Coded value	+2	+2	-2	+2	-2	15.6448 mm
Actual value	32 volts	700 amps	30 mm	500 mm/min	0 mm	

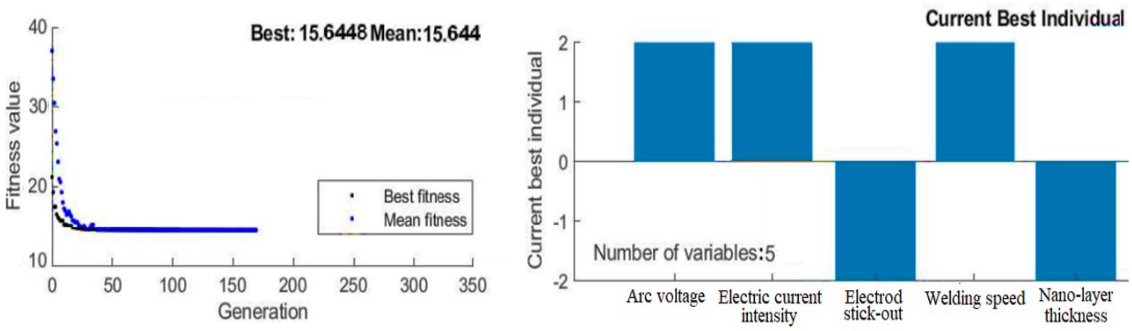

Figure 4-Best fitness of the penetration depth and optimal levels of input parameters determined by genetic algorithm

6. Conclusions

The penetration depth is the distance from the surface of the plate to the bottom of the pool or the lower boundary where melting has taken place. This study investigated the effect of arc voltage, electric current intensity, electrode stick-out, welding speed, and the thickness of the layer of nanoparticles as influential parameters. The values of the selected parameters were determined using the central composite rotatable design. Additionally, the effect of the parameters and the interaction between them was investigated. Finally, the modeled regression function was obtained between the values of the input parameters and the output variable. The results showed that:

• Increasing the electric current intensity to 700 amps increases the heat input to the welding pool, melting the base metal and increasing the penetration depth.

• By increasing the arc voltage from 24 to 32 volts, the heat entering the welding pool increases, but the melting rate of the electrode does not change much. As a result, the penetration depth increases slightly.

• Increasing the thickness of the layer of nanoparticles had significant effects on the geometry of the welding. The presence of nanoparticles, due to the barrier that prevents heat transfer caused by the difference in thermal conductivity coefficients, reduced the heat input to the inner layers of the workpiece and decreased the penetration depth. Conversely, in welded samples, the thickness of the layer of nanoparticles resulted in a slight increase in the width.

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