Nigerian Journal of Technology (NIJOTECH)
Vol. 41, No. 1, January, 2022, pp.45 –49
www.nijotech.com

Print ISSN: 0331-8443
Electronic ISSN: 2467-8821
http://dx.doi.org/10.4314/njt.v41i1.7

Selection of Optimum Process Parameters for Penetration Depth Improvement of Welded Mild Steel Joints

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Abstract

High and low heat input degrade weld and weaken bond of fabrications respectively resulting in poor mechanical properties and high failure rate. However, good penetration depth is important factor for quality weld of materials. The research examined various welds by central composite design and then analyzed by response surface methodology. The experiments were achieved using prepared 100 samples of mild steel welded plates measuring 6mm x 40mm x 80mm. The investigation was performed 20 times using 5 samples for each run and then the hardness was measured and analyzed. The results obtained show that the penetration depth terminating at the weld root favoured a high quality weld. The model produced numerical optimal solution of current 120amps, voltage 20volts and gas flow rate 12l/min will produce a welded structure having a penetration depth 5.510mm at a desirability value 95.7%.

Keywords: Penetration, Weldment, Mild Steel, Specimen

1.0 INTRODUCTION

Most Fabrication Industry has at least one welding machine for fusion of parent metal [1]. The quality of the welding process determines the reliability of the welded joint, this reliability could be seen in terms of the ruggedness of operation [2]. One major quality factor to consider during welding, is the degree of weld penetration. Poor depth of penetration during welding operation would most likely end in quick failure of the welded part, while weld with good depth of penetration has a better tendency to perform its designed task [3]. Inspections of weldment in terms of its depth of penetration is an important process as it plays a direct role in guaranteeing the reliability of the weld [4]. Basically, penetration depth could be examined visually or through the application of Non-destructive testing (NDT) technologies. Most a times, for accurate analysis of penetration depth using visual examination, it is recommended that the fusion zone of the weld, be cut open then examined. This process mostly results in the destruction of the samples, but is a common method used owing to the fact that it is the cheapest form of inspection. In most cases employing this technique, some samples are prepared specifically for this inspection process to ascertain the exact process parameters to produce a deeper penetration up to the root [5] and [6]. The NDT process of examining the depth of penetration is best suitable for tubes and pipes due to their complicated geometry. During welding, it is important keep weld speed fairly constant through the entire weld process to prevent inconsistences in quality of weld zone produced. [7] highlighted the importance of considering the effect of weld speed on depth of penetration during welding for better productivity, improvement and cost reduction. A simple experiment conducted at varying weld speed, proved that at constant arc voltage and welding current the depth of penetration will increase with increasing welding speed and is found to be maximum at optimum value after which depth of penetration starts decreasing with increase in welding speed. The heat input is regarded as the major factor responsible for weld penetration. Lower heat input produce weak bond and poor weld penetration depth, while excessive heat input create a wider heat affected zone and also degrade the mechanical properties of the weld, giving rise to internal stress know as residual stresses in and around the vicinity of the welded zone. Research has clearly established that residual stresses are always present in heat affected zone areas of welded material. Therefore, it is imperative that just the right amount of heat input be administered during welding for good weld penetration

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depth [8]. This could be achieved by experience acquired over time or experimentation.

The aim of this research is to establish the best process parameter to produce a quality weld with good penetration depth through experimental research [9] and [10].

2.0 MATERIALS AND METHODS

2.1. Materials

This research work was conducted at the university of Benin, though the Tungsten Inert Gas (TIG) welding method was conducted at the Department of Welding and fabrication technology, Petroleum Training Institute (PTI), Warri, Delta State, Nigeria. Measurement of responses and analysis were conducted in Engineering Laboratory of Faculty of Engineering, University of Benin. Table 1 present the process parameters employed for the research. The selected input parameters have the upper (+) and lower limits (-). All the materials used in this research were purchased from a local vendor. Weld samples used had dimension of 6mm x 40mm by 40mm.

2.2. Weld Penetration Form Factor Measurement

After welding, weld sample's dimension became 6mm by 40mm by 80mm. To measure the depth of penetration, five (5) samples were produced per run using the central composite design (CCD) of experiment. These samples were cut opened at their welded zone and sent to five different weld experts in Edo state for visual inspections. The average results obtained were taken as the response for the corresponding factors.

Response surface methodology (RSM) was employed to analyze the data, using design expert 13 software. CCD tool chosen for the RSM analysis, produced twenty (20) experimental runs of various mixing ratio of current, voltage and gas flow rate as seen in Table 2.

Table 1: Welding process parameters limits

Process parameters	Unit	Symbol	Low (-)	High (+)
Welding Current	Amp	I	120	170
Welding Voltage	Volts	V	20	25
Gas Flow Rate	Lit/mill	F	12	14

3.0 RESULTS AND DISCUSSION

3.1 Results

The study produced twenty experimental runs, each experimental run comprising the current, voltage and gas flow rate, used to join two pieces of mild steel plates measuring 6mm x 40mm x80mm. The penetration depth was measured through visual inspection by weld experts. The responses are shown in Table 2.

Table 2: Experimental result for the Penetration depth

Run	A: Welding Current	B: Welding Voltage	C: Gas Flow Rate	Penetration depth
	Amp	Volts	Lit/mill	mm
1	145	22.5	13	4.70288
2	145	22.5	13	4.54272
3	187.045	22.5	13	5.18336
4	145	22.5	11.3182	5.15424
5	170	20	12	4.68832
6	145	18.2955	13	4.60096
7	170	25	14	5.31004
8	120	20	14	4.71744
9	170	25	12	4.86304
10	120	25	12	5.40176
11	120	20	12	5.44544
12	102.955	22.5	13	5.56192
13	170	20	14	4.38256
14	145	22.5	14.6818	4.64464
15	145	22.5	13	4.61552

Run	A: Welding Current	B: Welding Voltage	C: Gas Flow Rate	Penetration depth
16	145	22.5	13	4.68144
17	145	26.7045	13	4.99408
18	145	22.5	13	4.77568
19	120	25	14	5.22704
20	145	22.5	13	4.38256

The fit statistics for the depth of penetrating is presented in Table 3. According to literature, for a model to be statistically significant, the difference between the predicted and adjusted R^2 must be less than 0.2. In this research, a difference of 0.131 which is less than 0.2 was obtained in Table 3.

The adequate Precision of 12.8046 which is used to measures the signal to noise ratio was obtained in our study. Literature states that the ratio should be greater than 4 to be desirable. Since the required condition for the fit statistics has been met, the model can now be employed to navigate the design space.

Table 3: Fit Statistics for the penetration depth

Std. Dev.	0.1269	R^2	0.9354
Mean	4.89	Adjusted R^2	0.8773
C.V. %	2.59	Predicted R^2	0.7463
		Adeq Precision	12.8046

Presented in Table 4 is the sum of squares which is a Type III – Partial, 16.10 was obtained for the Model F-value which describe a significant model. This means that there is only a 0.01% chance that an F-value this large manifest due to noise. The P-values less than 0.0500 shows that the model terms are significant. In this case A, B, C, AC, AB, BC, A^2 and C^2 obtained a P-val less than 0.05. This would increase the accuracy of our mathematical model in predicting the responses.

Based on the P-value obtained in Table 4, Eq. (1) was mathematically modelled in terms of coded factors for predicting the penetration depth (Pd). For minimal prediction error, more factors with P-value less than 5% should be included in the equation.

Table 4: ANOVA table for penetration depth

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	2.33	9	0.2594	16.10	< 0.0001	significant
A-Welding Current	0.3494	1	0.3494	21.68	0.0009	
B-Welding Voltage	0.3639	1	0.3639	22.58	0.0008	
C-Gas Flow Rate	0.1918	1	0.1918	11.90	0.0062	
AB	0.0506	1	0.0506	3.14	0.1068	
AC	0.1362	1	0.1362	8.45	0.0156	
BC	0.2132	1	0.2132	13.23	0.0046	
A^2	0.9598	1	0.9598	59.56	< 0.0001	
B^2	0.0432	1	0.0432	2.68	0.1327	
C^2	0.1187	1	0.1187	7.37	0.0218	
Residual	0.1611	10	0.0161			
Lack of Fit	0.0640	5	0.0128	0.6580	0.6714	not significant
Pure Error	0.0972	5	0.0194			
Cor Total	2.50	19				

$$Pd = 4.62 - 0.1599A - 0.1632B + 0.1185C + 0.0795AB + 0.1305AC + 0.1633BC + 0.2581A^2 + 0.0547B^2 + 0.0908C^2 \quad (1)$$

Where, A=voltage, B=current, C=gas flow rate

The reliability plot in Figure 1 was emplyed to examine the reliability of future prediction based on the response obtained from the actual vs predicted penetration depth. The blue square dots indicates the lowest limits of 4.4 mm penetration depth while the red square dots, shows the maximum penetration depth of 5.6mm on the welded specimen.

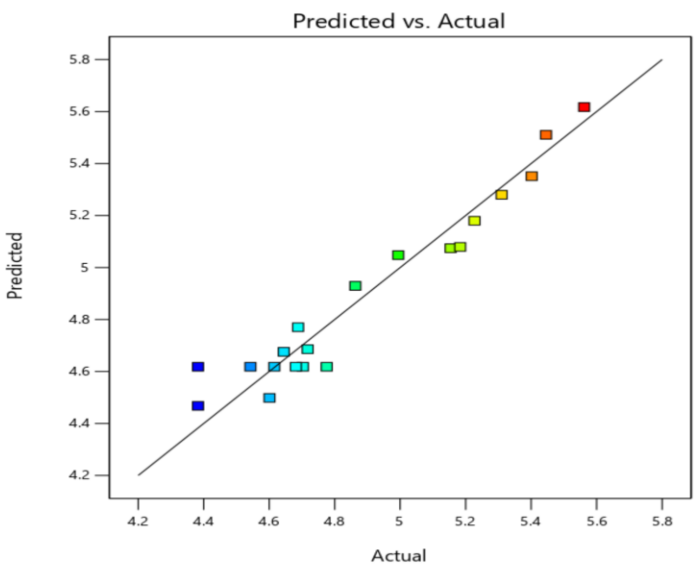

Figure 1: Reliability plot of observed versus predicted penetration responses

The 3D surface plot was employed to examine the effect of the welding voltage and current on the penetration depth of mild steel welded specimen. To simulate the effect of the weld process parameters on the response, at a gas flow rate of 13 L/min, the current and voltage could be varied to obtain the 3D surface plot architect presented in figure 2 using the available features in design expert 13 software. With these features on the software, better understanding of the effect of the factors on the responses could be established.

The interphase in Figure 3 with the maximization target for the penetration depth, was employed to optimize the response. In the numerical optimization phase, design expert 13 was instructed to maximize the penetration depth, while also determining the optimum value of voltage, current and gas flow rate.

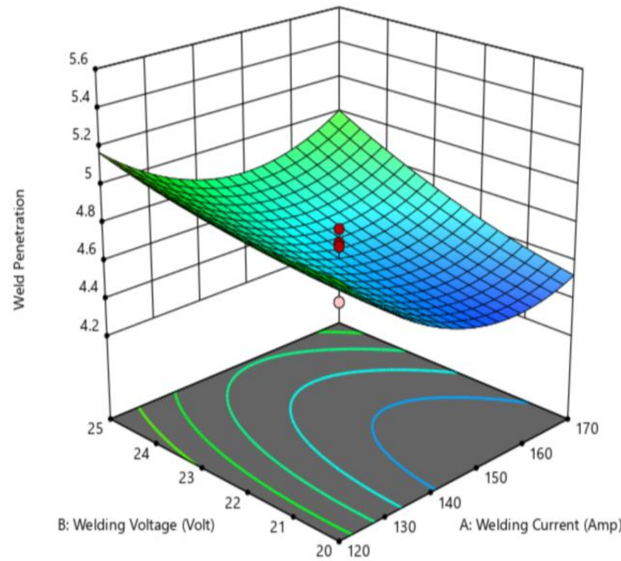

Figure 2: 3D surface plot for Penetration depth

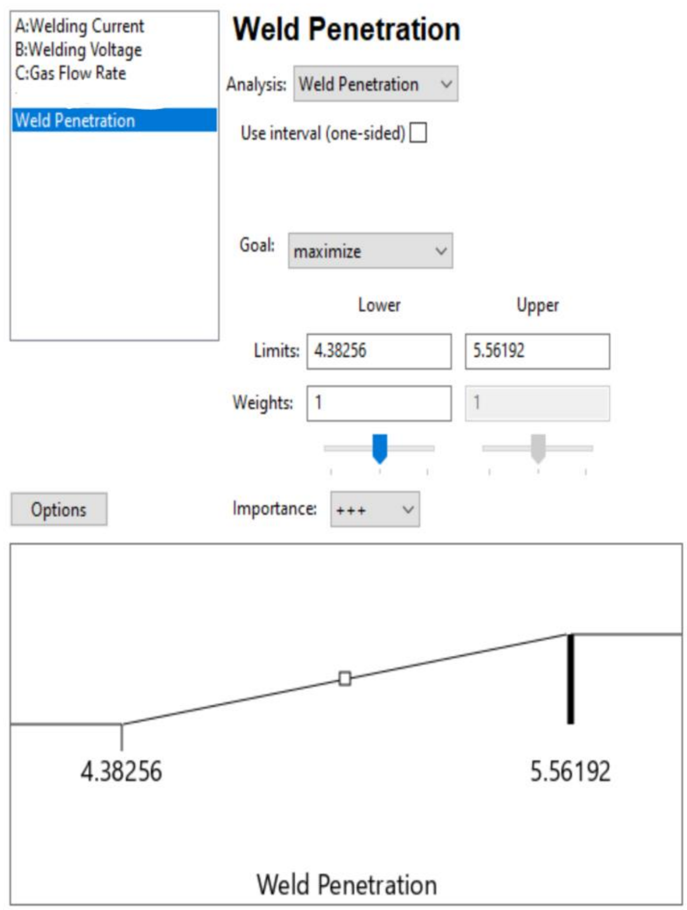

Figure 3: Interphase of numerical optimization of Penetration depth.

Table 5 shows five (5) out of the eighteen (18) optimal solutions obtained from the settings made in Figure 3.

Table 5: Optimal solutions of numerical optimization model

Number	Welding Current	Welding Voltage	Gas Flow Rate	Weld Penetration	Desirability	
1	120.000	20.000	12.000	5.510	0.957	Selected
2	120.000	20.036	12.000	5.507	0.954	
3	120.010	20.000	12.007	5.506	0.953	
4	120.177	20.000	12.000	5.505	0.952	
5	120.000	20.119	12.000	5.497	0.946	

Finally, from the optimal solution, the contour plots showing the depth of penetration response variable of voltage and current at a gas flow rate of 12 L/min, against the optimized value of the input variable is presented in Figure 4.

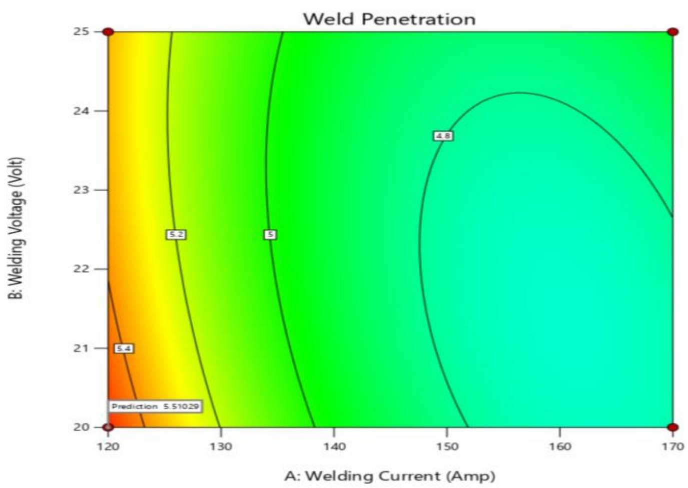

Figure 4: Predicting weld penetration depth using contour plot

3.2 Discussion

The Fit Statistics for the Penetration depth in Table 3, shows that The R^2 value of 0.9354, Predicted R^2 of 0.7463 and an Adjusted R^2 of 0.8773 were obtained. The difference between the predicted and adjusted R^2 of less than 0.2 was recorded, indicating a significant model. With an adequate Precision of 12.805, demonstrating a significant model. It meant that the mathematical model in Eq. (1), can be employed to navigate the design space. In Figure 1, the reliability plot developed was emplyed to compare the predicted response values obtained from using Eq(1) to that of the actual response. Based on the plot, it was observed that A positve linear relationship existed between the predicted and the actual response, with majority of the points clustering along the stright line. This indicates a good prediction model which can be employed for unknown prediction of the penetration depth. Figure 2 shows the 3D surface plot for the penetration depth with the lower penetration depth area denoted by the blue region and the green region representing the area with the highest depth of penetration. The 3D surface plot was used to determine the effect of current and voltage at a gas flow rate of 13 L/min on the penetration depth responses. From Figure 2, it was noticed that only current had a very strong effect on the response. Optimization was initiated using the interphase presented in Figure 3 with the lowest and highest depth of penetration of 4.4mm and 5.6mm being the optimization boundary space. Five (5) optimal results were selected as shown in Table 5 with the best having a current of 120.00 Amp, voltage of 20.00 volt and gas flow rate of 12.00 L/min, to produce a weld material with penetration depth of 5.510mm at a desirability value of 95.7%. To further understand better, the effect of the process parameters on the response, Figure 4 was employed. This plot also known as the contour plot, shows that at a constant gas flow rate of 12 L/mm, quality weld can be achieved with voltage ranging between 20-21 volts, and a current range of about 120-125 amp, represented the red area on the plot in Figure 4. It shows that current has a significant effect on either increasing or reducing the material toughness. From the contour plot, it was noticed that lower current 120 amp produced better penetration depth as compared with current input above 125amps.

4.0 CONCLUSION

In this study a mathematical model for predicting penetration depth presented in Eq. (1) has been developed with and optimum penetration depth of 5.510mm at a desirability value of 95.7%. This optimum penetration depth was achieved through the use of current of 120.00 Amp, voltage of 20.00 volt and gas flow rate of 12.00 L/min. The weld current was found to have a great influence on the depth of penetration of the weldment as compared to voltage and gas flow rate at a moderate level.

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