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Optimization of the Weld Bead Volume of Tungsten Inert Gas Mild Steel Using Response Surface Methodology

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Abstract

Welding defects unfavorably influence the desired properties of welded joints. The bead volume is key determining factor affecting the quality of welded joints. This study was carried out with the aim of optimizing and predicting the bead volume of low carbon steel using Response Surface Methodology (RSM). Thirty (30) sets of experiments were done, adopting the central composite experimental design. The tungsten inert gas welding equipment was used to produce the welded joints. Argon gas was supplied to the welding process to shield the weld from atmospheric interference. 10 mm thickness of mild steel plates was cut to size, measuring 60mm in length and 40mm in width. This study has shown that the current has very strong influence on the bead volume. The models developed possess a variance inflation factor of 1 and P- values < 0.05, indicating that the models are significant. The models also possessed a high goodness of fit with R^2 (Coefficient of determination) values of 91%. Adequate precision measures the signal to noise ratio. A ratio greater than 4 is regarded as desirable and the value obtained in this research was 15.5331. The model produced numerically obtained optimal solution of current of 143.095 Amp, voltage of 15.538 volts, weld speed of 2.19688 mm/min and showed that a gas flow rate of 12.2133 L/min produces a bead volume of 432.39 mm^3. This solution was selected by design expert as the optimal solution with a desirability value of 98.8%.

1. Introduction

The strength of a welded joint, depends on the reliability of the weld bond formation. The bead of a welded material is regarded as the bond formed along the groove of the mating welded surfaces. In other to improve the weld bead integrity, it is imperative to increase its thickness in an optimized manner. Optimization using expert software, a cutting-edge technique is a cost-effective method, employed to improve welded material. Optimization had been applied to several aspect of welded material producing high quality weld, resulting in improved weld responses [1]. Mathematical models have been developed using the fractional factorial technique to predict the weld bead geometry and shape relations, penetration, width, reinforcement height, width to penetration ratio and percentage dilution [2]. Also developed was a mathematical model based on weld bead geometry using the fractional factorial technique to optimize weld bead profile [3]. The factorial design is an effective tool for optimizing weld responses [4] employed the factorial design to

improve robotic GMAW process parameters of welding voltage, welding speed and arc current to produce three responses (bead width, bead height and weld penetration). The quadratic model is best suitable for modelling the responses of weld metal, although researcher used a linear regression equations for computing the weld features of melting rates, total fusion area, penetration, deposit area, bead height and bead width from submerged arc welding (SAW) process variables, the result produced a suitable welded joint[5].So many optimizations tool such as response surface methodology (RSM), genetic algorithm, Taguchi, linear programming are available for use[6]. Response surface methodology (RSM) models was developed to study the direct and interaction effects of SAW parameters (open circuit voltage wire feed rate, welding speed and nozzle-to-workpiece distance) on the cladding geometry (depth of penetration, height of reinforcement, weld width and dilution %) [7]. The importance of RSM to develop mathematical models and showed the robustness of contour plots in interpreting the relationship between the factors and the responses and the region of maximum and minimum effect had been highlighted [7]. Furthered work on the optimization of weld bead volume using the optimization module available in the MATLAB version 4.2b software package has been done. This optimization processes using expert systems, create logical ways of establishing cause-effect relation between input and output parameters [8-9]. Selection of optimized weld input parameters such as welding current, voltage, speed and time, against response of ultimate tensile strength of steel, creates an improved welded bond with good tensile strength which was achieved by the help of Taguchi Method has been presented [10].
The bead of a welded material is responsible for holding the materials together and therefore need to possess good quality strength to withstand internal and external stresses. In this research, the response surface methodology was employed to improve the bead quality of mild steel plate.

2.0. Methodology

This research study was conducted in two parts, the TIG welding operation was conducted at the Department of Welding and Fabrication Technology, Petroleum Training Institute (PTI), Warri, Delta State, Nigeria. 150 pieces of mild steel coupons measuring 60mm x 40mm x10mm was used for the experiments, with 30 runs for the designs of experiment (DOE), repeated five times. The responses were measured at the Departmental Workshop of Production Engineering, University of Benin. All Materials were sourced locally.

2.1.Identification of range of input parameters

Table 1, present the range of the process parameters obtained from literature. The four important factors considered for this analysis are the current, gas flow rate, voltage and weld speed.

Table 1: Process parameters and their levels

Parameters	*Unit*	*Symbol*	*Coded value*	*Coded value*
			Low (-1)	*High (+1)*
Current	*Amp*	*A*	*140*	*160*
Gas flow rate	*Lit/min*	*F*	*12*	*14*
Voltage	*Volt*	*V*	*20*	*24*
Welding speed	*m/min*	*S*	*0.5*	*6.5*

The process parameters in Table 1 were applied to generate the matrix presented in Table 2, using the central composite design. The CCD design of experiment was selected based on literature.

Table 2: Central composite design matrix (Actual factors)

		Factor 1	Factor 2	Factor 3	Factor 4
Std	**Run**	**A: Gas flow rate**	**B: Arc voltage**	**C: Welding current**	**D: Welding speed**
		Lit/min	**Volt**	**Amp**	**m/min**
27	1	13	22	150	3.5
26	2	13	22	150	3.5
1	3	13	22	150	2
15	4	13	22	150	5
18	5	13	22	150	3.5
20	6	13	22	150	3.5
11	7	13	26	150	5
22	8	11	22	150	3.5
6	9	13	22	150	2
23	10	13	22	170	0.5
19	11	13	22	130	3.5
29	12	13	22	150	3.5
7	13	13	18	150	2
30	14	13	22	150	3.5
8	15	12	20	140	2
4	16	12	24	160	2
21	17	12	20	160	3.5
5	18	14	24	140	2
17	19	14	24	140	3.5
28	20	12	24	140	3.5
13	21	14	24	160	5
2	22	12	24	140	2
24	23	12	24	160	6.5
3	24	12	20	160	2
12	25	14	20	140	5
10	26	14	20	140	5
9	27	12	20	140	5
14	28	14	20	160	5
25	29	14	24	160	3.5
16	30	14	20	160	5

2.2.Method of Data Collection

Equation (1) was employed to estimate the measured weld bead volume. 30 bead volume responses were obtained. V- butt weld operation was selected for this research process

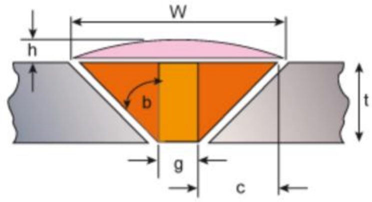

Figure 1: V- butt weld [14]

$$v = \left(\frac{2\tan b\left(ht+t^2\right)+g(h+2t)}{2}\right)l \quad \textbf{(1)}$$

v = Weld bead volume
t = Plate thickness
b = Bevel angle
g = Root gap
h = Height of weld cap from top of plate
l = Length of plate
The data obtained were analyzed using the response surface methodology

2.3.Testing the Adequacy of the Models Developed

To test the robustness of the model developed, analysis of variance (ANOVA) was employed.

3.0.Results and Discussion

One hundred and fifty welded samples were produced, with average weld bead volume obtained per five samples for each run, Table 3 shows the summary of the factors and the bead volume response. Gas flow rate, arc voltage, welding current and welding speed with their boundary conditions presented in Table 1 were applied to generate the factors and responses.

Table 3: Experimental results of bead volume

		Factor 1	Factor 2	Factor 3	Factor 4	Response 1
Std	Run	A: Gas flow rate	B: Arc voltage	C: Welding current	D: Welding speed	Weld Bead Volume
		Lit/min	Volt	Amp	m/min	mm^3
27	1	13	22	150	3.5	261.054
26	2	13	22	150	3.5	261.014
1	3	13	22	150	2	261.094
15	4	13	22	150	5	261.014
18	5	13	22	150	3.5	261.054
20	6	13	22	150	3.5	261.094
11	7	13	26	150	5	391.76
22	8	11	22	150	3.5	270.746
6	9	13	22	150	2	240.353
23	10	13	22	170	0.5	231.27
19	11	13	22	130	3.5	251.202

29	12	13	22	150	3.5	229.983
7	13	13	18	150	2	252.399
30	14	13	22	150	3.5	230.86
8	15	12	20	140	2	259.578
4	16	12	24	160	2	281.635
21	17	12	20	160	3.5	278.644
5	18	14	24	140	2	336.279
17	19	14	24	140	3.5	332.211
28	20	12	24	140	3.5	304.729
13	21	14	24	160	5	313.185
2	22	12	24	140	2	267.795
24	23	12	24	160	6.5	260.934
3	24	12	20	160	2	270.388
12	25	14	20	140	5	264.923
10	26	14	20	140	5	232.017
9	27	12	20	140	5	305.963
14	28	14	20	160	5	238.997
25	29	14	24	160	3.5	300.501
16	30	14	20	160	5	195.816

3.1.Modelling using RSM

A second order mathematical model presented in Equ.(2) was developed to describe the volume formation of the weld bead during the welding operation of mild steel plate, using TIG welding process. The input variables of the model include the gas flow rate (A), voltage (B), weld current (C) and welding speed (D).

$$\boldsymbol{Weld\ Bead}\ \textbf{Volume} = 25.695 - 269.163\text{A} + 100.409\text{B} - 48.102 + 34.093\text{D} + 271.368\text{AB} - 45.423\text{AC} + 10.884\text{AD} - 17.247\text{BC} - 14.321\text{BD} - 18.209\text{CD} + 74.078\text{A}^2 + 65.470\text{B}^2 - 27.749\text{C}^2 + 1.910\text{D}^2 \quad (2)$$

The model obtained in Equation.(2) describes a polynomial response behavior having a highest order of two for the model and also preventing model alias. Based on this, the quadratic vs 2FI source in design expert was selected with a p-value less than 0.05.

In assessing the strength of the quadratic model towards maximizing the WBV, one way ANOVA was applied and result obtained is presented in Table 4. For F-value of 11.11, it implies the model is statistically significant, with an error margin of 0.01% resulting from system noise. the gas flow rate (A), voltage (B), weld current (C) and welding speed (D) contributed in making the model significant. Although, individual factors might have p-value > 0.05, but cumulatively sums up to produce a model with p-value, less than 0.05.

Table 4: ANOVA for validating the model significance towards maximizing the WBV

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	39561.31	14	2825.81	11.11	< 0.0001	significant
A-Gas flow rate	218.69	1	218.69	0.8599	0.3684	
B-Arc voltage	1005.49	1	1005.49	3.95	0.0653	
C-Welding current	186.97	1	186.97	0.7352	0.4047	
D-Welding speed	299.16	1	299.16	1.18	0.2952	
AB	6916.34	1	6916.34	27.20	0.0001	
AC	143.68	1	143.68	0.5650	0.4639	
AD	28.76	1	28.76	0.1131	0.7413	
BC	174.00	1	174.00	0.6842	0.4211	
BD	578.60	1	578.60	2.28	0.1522	
CD	797.86	1	797.86	3.14	0.0968	
A^2	63.91	1	63.91	0.2513	0.6234	
B^2	7912.44	1	7912.44	31.11	< 0.0001	
C^2	305.05	1	305.05	1.20	0.2907	
D^2	38.42	1	38.42	0.1511	0.7030	
Residual	3814.61	15	254.31			
Lack of Fit	874.29	7	124.90	0.3398	0.9136	not significant
Pure Error	2940.32	8	367.54			
Cor Total	43375.92	29				

Based on the ANOVA presented in Table 4, the coefficient of determination (R^2) of the model was analyzed to give 0.9121 with an adjusted R^2 of 0.8300 and predicted R^2 of 0.6830. The difference between the adjusted and the predicted R^2 must not be more than 0.2 for the model to be statistically significant. The model, had a difference of 0.147 for the adjusted/predicted R^2 with an adequate precision ratio of 15.5331. The critical value assumed for this analysis was 5.90% with a standard deviation of 15.95 and a mean value of 270.28.

The 3D surfaces plots presented in Figure. 7, is used to establish the effects of gas flow rate, voltage and current on bead volume, the colour coding is used to signify area of effect depending on the desired response. For minimization of maximization, the surface plot helps us understand the targeted response region based on the colour code of the response surface plot and factors that can be manipulated to produce a desired result.

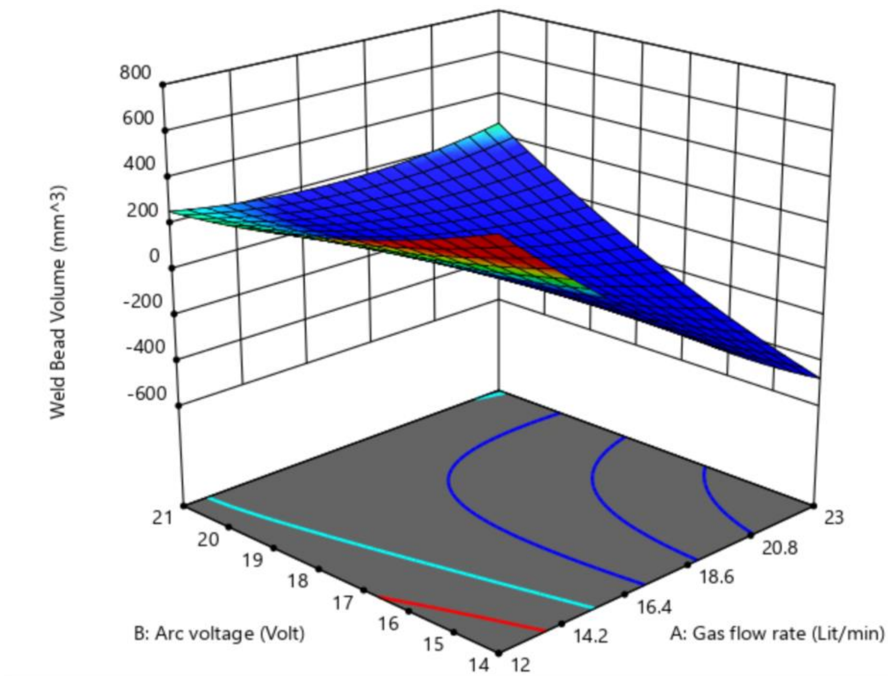

Figure 7:Effect of current, voltage on WBV

Table 5 present 9 optimized results with s/n 1 selected by design expert 13 as the most suitable as its factors produced the highest bead volume.

Table 5: Optimal solutions of numerical optimization model

Number	Gas flow rate	Arc voltage	Welding current	Welding speed	Weld Bead Volume	Desirability	
1	**12.213**	**15.354**	**143.095**	**2.197**	**432.397**	**1.000**	**Selected**
2	12.151	15.028	134.408	2.164	438.293	1.000	
3	12.259	16.404	133.143	4.922	427.263	1.000	
4	12.312	16.063	148.491	4.987	454.127	1.000	
5	12.297	15.957	172.219	4.845	434.067	1.000	
6	12.109	16.489	172.432	3.175	398.393	1.000	
7	12.144	16.174	171.902	2.266	406.269	1.000	
8	12.074	16.927	164.076	4.466	401.737	1.000	
9	13.351	14.140	135.228	4.203	437.561	1.000	

The Ramps diagram presented in Figure 9 is employed to select the best optimum weld process parameters. Design expert 13 was employed to analyze and produce the optimized factors and weld bead volume shown in the ramps diagram of Figure 9. The contour plot presented in Figure 10, is a 2D diagram employed to better understand the optimization region. Design expert indicate minimum and maximum regions with blue and red colour. To maximize the bead volume, design expert analyzed within the upper and lower boundary conditions of all factors employed to develop the model presented in Equation (1) to produce a suitable response in Table 5 with 432.397mm^3 as the selected optimum response.

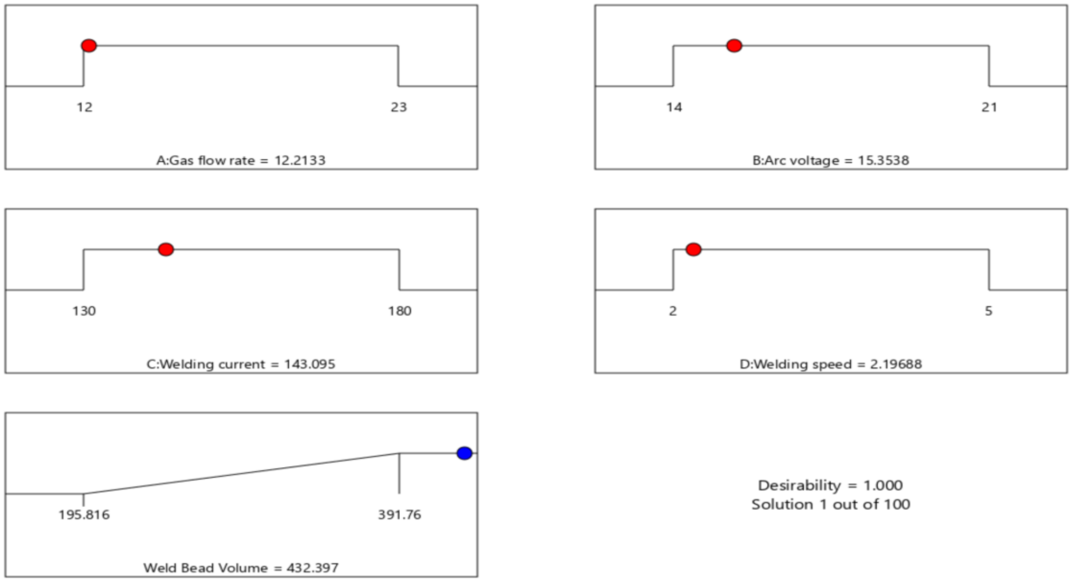

Figure 9: Ramps diagram of optimized factors and response

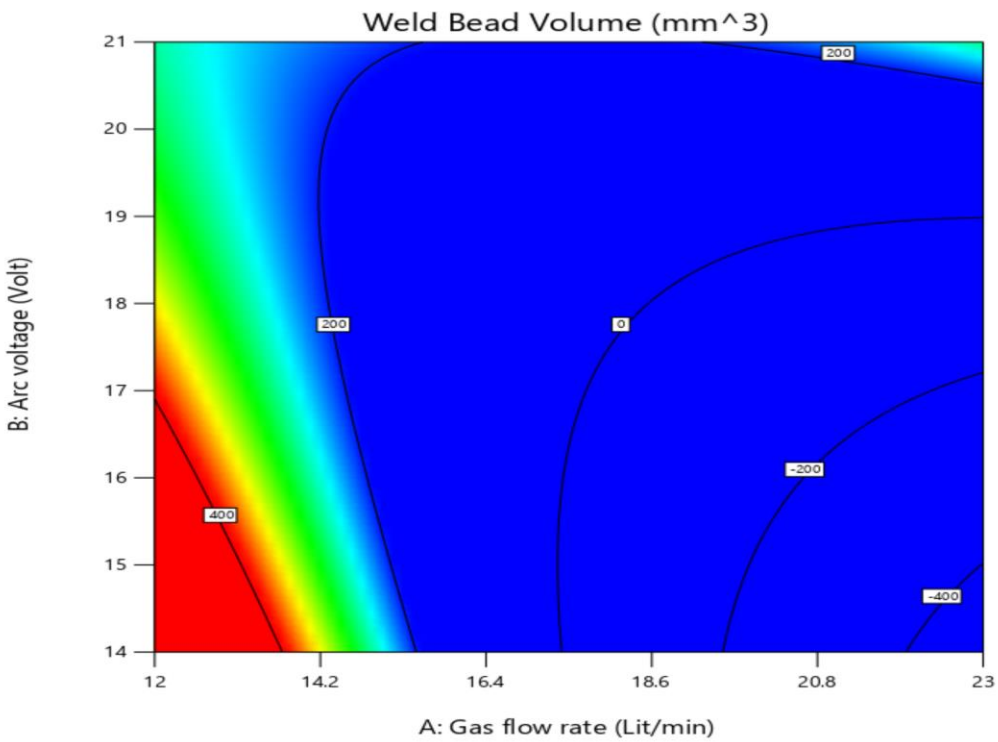

Figure 10: Contour plot for the bead volume

4.0. Conclusion

Weld bead volume is a very important factor that influences the integrity and quality of welded joint. In this study, response surface methodology was employed to optimize the bead volume of TIG welded joints and result shows that the model developed was adequate and suitable to describe the approximate formation of bead volume during weld. The study reveals produced a quadratic model. From the result of Figure. 6, the Model F-value of 11.11 implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large occured due to noise. For the model to be significant, the values of "Prob > F" less than 0.0500 should be targetted. In this case AB and B^2 in the model are significant. Values greater than 0.1000 indicate the model terms are not significant. The "Lack of Fit F-value" of 0.9136 implies the Lack of Fit is not significant relative to the pure error. Non-significant lack of fit is good as it indicates a model that is significant. From the result of Figure. 7, it was observed that the "Predicted R-Squared" value of 0.6830 is in reasonable agreement with the "Adj R-Squared" value of 0.8300 since the difference between them is not greater than 0.2. Adequate precision is employed to measure signal to noise ratio and any ratio greater than 4 is desirable for the signal to be adequate. The computed ratio of 15.5330 as observed in Figure 7 indicates a desirable signal. This model can be used to adequately maximize the weld bead volume.Equation(1) present the model equation which shows the individual effects and combine interactions of the selected input variables (gas flow rate, voltage, current and welding speed) against weld bead volume the high coefficient of determination ($r^2 = 0.9121$) as observed in Figure 7 was used to established the suitability of response surface methodology in maximizing the WBV.

Finally, numerical optimization was performed to ascertain the desirability of the overall model. In the numerical optimization phase, optimization tool was selected in Design expert 13 to maximize the weld bead volume (WBV), which produced an optimum gas flow rate, voltage, current and welding speed simultaneously.

From the results of Figure 9, it was observed that a gas flow rate of 12.2133 L/min, voltage of 15.3538 volt, current of 143.095 amp and a welding speed of 2.19688 mm/min will result in a welding process with the weld bead volume of 432.397 mm^3.

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