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Application of Response Surface Methodology (RSM) to Predict Penetration Area During TIG Welding at Steady State Condition

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Abstract

This study is centered on the application of response surface methodology to predict penetration area during TIG welding at steady state condition. This study developed a mathematical model using the second order quadratic polynomial model to select the best setting for the process parameters to produce the maximum penetration area in TIG welding. The parameters considered in this study are welding current, welding voltage and welding speed. The sampled steel plates were 100 pieces of mild steel coupons measuring 80 x 40 x10mm, the experiment was performed 20 times, using 5 specimens for each run. Argon was used as shielding gas. Tungsten inert gas machine was used in joining the weld materials. Obtained results showed that the second order quadratic polynomial equation is the best fit model which adequately explains the relationship between the processes parameters employed in the study. The results possessed good statistical sufficiency, having a very good strength for predicting the target response. The prediction strength and models reliability factor are in reasonable agreement with each other, the surface plots showed the combined interaction of input parameters on the response, and the ANOVA results revealed that the penetration area is very sensitive to the current parameter. The mathematical models developed have a high goodness of fit, adequate signal, strength which can predict the penetration area. The numerical optimal solution produced welded material having penetration area of 80.43mm^2 with a welding speed of 2.6mm/s, a current of 190Amp and voltage of 20.73 volt. RSM model selected the quadratic model as the suitable model for the heat input because it has a P value of < 0.05 as analyzed by analysis of variance table.

1. Introduction

TIG welding is believed to be the best in achieving quality welding process and fabrication of metals. It has the ability of allowing different shades or grades of steel products to be constructed using this process [1]. Ability to weld different materials could be determined by different factors which include bead geometry, thermal cracks, heat affected zone (HAZ) and bead penetration. These factors are influenced by various parameters like electrode's nature, length of arc, rate of deposition of metal, rate of arc travel and polarity [2]. Excessive heating and reduced cooling during welding processes has significant influence on the properties of weldment such as bead geometry [3]. Weld penetration is the largest distance between the surface of the base plate and depth to which the fusion has taken place in a welded material. It can be said to also be the rate at which the fusion line extends below the surface of the weldment [4]. There exists a direct relationship between Weld penetration and welding current, an increase or decrease in current can result in further increase or decrease in the weld penetration depth. Research have shown that weld penetration can be influenced by welding current, polarity, arc travel speed, electrode diameter etc. [5, 6]. Sushant [7] carried out a research on factors affecting penetration area and observed that higher welding current provides deep penetration and lower current provides lower penetration depth. Effects of welding speed and heat input rate parameters on depth of penetration was investigated by Abbasi et al. [8] and the result revealed that bead depth increases with increase in heat input [4]. Weld quality can be maximized by controlling the deposition rate of the molten metal deposit, maintaining a desired level is best to retain the strength and ability of the welded joint to bear adequate load. Experimental and statistical studies was carried out to produce an optimal deposition rate. The solution obtained shows that the input factors have very robust effect on the deposition rate [9]. Cost reduction is also as important as the quality of the products in the metal construction industry, so prediction and simulation of the desired properties is greatly important. Today, so many simulating tools are in existence, the ability to understand their strength, applicability, and compatibility with certain welding data must be of great importance. Fuzzy logic technique is one very reliable tool that can be used to effectively carryout predictive study. This expert method was employed to predict the weld penetration size factor of a weld considering welding speed current and voltage which gave a very good result [10].

2. Methodology

In this experiment, an optimal experimentation to maximize penetration area was conducted. Tungsten Inert gas welding process was used to join the weld specimen made of mild steel. The first step taken was to cut the mild steel coupons, sand paper and bevel the edges. Using the optimal experimental matrix as a guide, five set of welded samples was made for each experimental run which amounted to a total of one hundred weld samples.

2.1. Identification of Range of Input Parameters

The key parameters considered in this work are welding current (I), welding voltage (V), and welding speed (S). The range of the process parameters obtained for this study is shown in the Table 1:

Table 1: Process parameters and their levels

Process parameters	**Unit**	**Symbol**	**Low (-)**	**High (+)**
Welding Current	Amp	I	170	190
Welding Voltage	Volts	V	20	22
Welding Speed	Mm/Sec	M	2.6	3.0

2.2. Method of Data Collection

20 sets of experiment was conducted, considering the heat input as output parameter. The heat input was measured for each sample. The input parameters and output parameters make up the experimental matrix, and the responses recorded from the weld samples were used as the data. Table2 shows the central composite design matrix.

Table 2: Experimental results

Runs	Input Parameters			
	Current I, Amp	Speed mm/sec	Voltage, Volts	Penetration Area, mm^2
1	190	2.63	20.73	101.20
2	190	2.63	20.72	47.93
3	190	2.63	20.70	109.76
4	190	2.63	20.68	109.96

5	190	2.62	20.78	109.24
6	170	2.80	20.00	90.70
7	170	3.00	21.00	78.55
8	170	3.00	22.00	114.48
9	170	3.00	20.00	102.32
10	180	2.60	21.00	88.48
11	180	2.60	22.00	57.60
12	180	2.60	20.00	94.28
13	180	2.80	21.00	105.50
14	180	2.80	22.00	120.13
15	180	2.80	20.00	102.32
16	180	3.00	21.00	102.32
17	180	3.00	22.00	105.50
18	180	3.00	20.00	102.32
19	190	2.60	21.00	102.32
20	190	2.60	22.00	102.32

2.3 Experimental procedure

Mild steel plate was used as the base material for the single-pass surface welding with a direct current of reverse polarity. Grinding of the samples was carried out, sand cleaned and etched to get a fine edge because sample has to be free from grease and dirt. 100 pieces of mild steel coupons was produced for this experiment using 100% argon gas as the shielding gas. In this process the tungsten non consumable electrode having diameter 3 mm, the responses were measured and recorded respectively. A vernier caliper was used to measure the penetration area.

3. Results and Discussion

An attempt was made in this study to develop a response surface methodology model to predict penetration area. In this study, an attempt is made to develop a second order mathematical model to explain the relationship between; current (I), voltage (V) welding speed to reduce fume concentration and electrode melting rate, using response surface methodology (RSM).The first step taken in modeling of an RSM model is to validate the suitability of the quadratic model in analyzing the experimental data, and the sequential model sum of squares was calculated to check for the best model ,electrode melting rate sum of squares is in Table 3.

Table 3: Sequential Sum of Square for Bead Penetration

Source	Sum of Squares	Df	Mean Square	F Value	p-value Prob > F	
Mean vs Total	1.896E+005	1	1.896E+005			
Linear vs Mean	1579.05	3	526.35	1.87	0.1746	
2FI vs Linear	2828.18	3	942.73	7.37	0.0039	
Quadratic vs 2FI	1617.16	3	539.05	115.14	**< 0.0001**	**Suggested**

Cubic vs Quadratic	35.20	4	8.80	4.55	0.0497	Aliased
Residual	11.61	6	1.94			
Total	1.957E+005	20	9783.00			

In Table 3, the quadratic model was selected as the most suitable as having the lowest p-value < 0.0001. In assessing the strength of the quadratic model for the weld penetration area. To check for model suitability, the analysis of variance was generated. This is shown in Table 4.

Table 4: ANOVA Table for Bead Penetration Area

Source	Sum of Squares	Df	Mean Square	F Value	p-value Prob > F	
Model	6024.39	9	669.38	142.98	**< 0.0001**	**significant**
A-current	254.58	1	254.58	54.38	< 0.0001	
B-welding speed	1150.67	1	1150.67	245.79	< 0.0001	
C-voltage	173.80	1	173.80	37.12	0.0001	
AB	1456.67	1	1456.67	311.15	< 0.0001	
AC	620.62	1	620.62	132.57	< 0.0001	
BC	750.89	1	750.89	160.39	< 0.0001	
A^2	84.66	1	84.66	18.08	0.0017	
B^2	1247.40	1	1247.40	266.45	< 0.0001	
C^2	200.83	1	200.83	42.90	< 0.0001	
Residual	46.82	10	4.68			
Lack of Fit	38.40	5	7.68	4.57	0.0606	not significant

The ANOVA table shows us the process parameters having the most significant influence on the weld penetration area, the current and the welding speed is observed to have a very significant effect on the response with a p-value of < 0.0001. To validate the adequacy of the quadratic model based on its ability to reduce the electrode melting rate the goodness of fit statistics presented in Table 5.

Table 5: Goodness Of For Bead Penetration Area

Std. Dev.	2.16	R-Squared	0.9923
Mean	97.36	Adj R-Squared	0.9853
C.V. %	2.22	Pred R-Squared	0.9499
PRESS	303.88	Adeq Precision	48.110

The goodness of fit measures the strength and adequacy of the quadratic model. The results obtained shows that the model has 99% capacity to predict the weld penetration area when any change occurs in any of the input parameters. The optimal equation which shows the individual effects and combine interactions of the selected input variables (current, voltage and welding speed) against the weld penetration area is presented based on the actual values in equation 1.

$$\text{Bead penetration area} = +7911.80684 -46.70982X_1 +2120.03098X_3 -650.89482X_2 +6.74693X_1X_3+1.76156X_1X_2-96.88187X_3X_2-0.024237X_1^2-232.59014X_3^2+14.93216X_2^2 \quad 1.0$$

X_1 = Current

X_2 = Voltage

X_3 = Welding Speed

The response surface in figure 1 shows a 3D plot of the combined interaction between two input variables and the output to study the effects of welding speed and current on weld penetration area, 3D surface plots presented in Figure 1 was generated as follows:

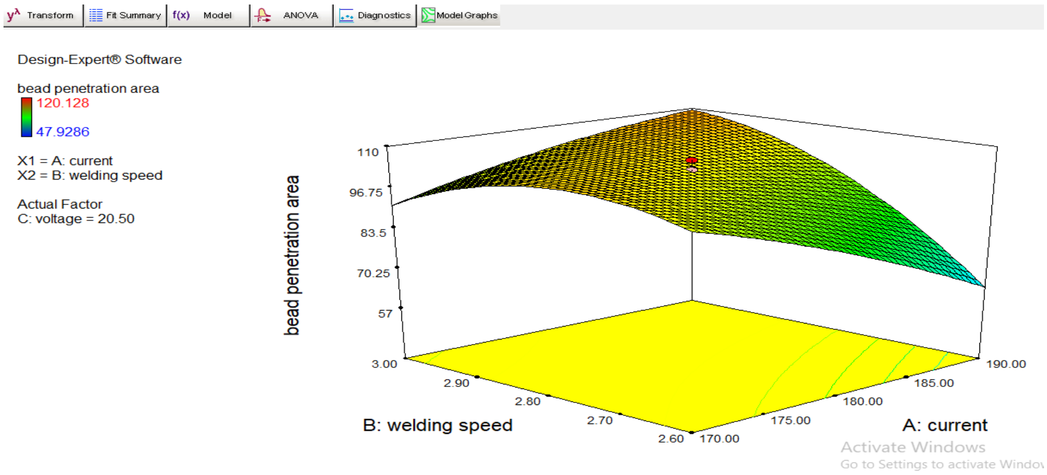

Figure 1: Effect of welding speed and Current on penetration area

The Figure above shows effects welding speed and current has on the weld penetration area. To study the effects of voltage and current on the penetration area, 3D surface plots presented in Figure 2 was generated as follows:

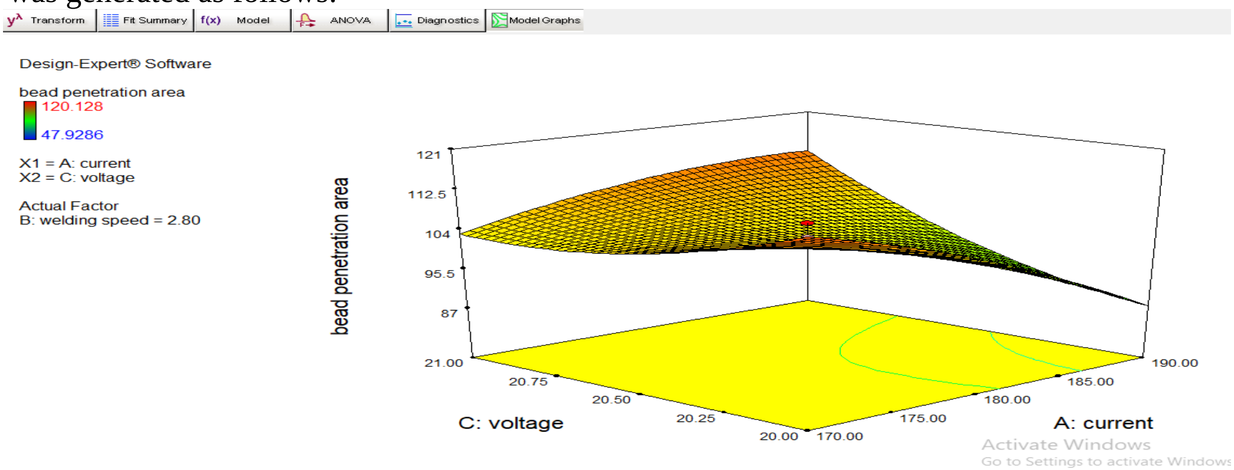

Figure 2: Effect of voltage and Current on penetration

Figure 2 above shows effects of voltage and current has on the weld penetration area. To study the effects of voltage and welding speed on the penetration area, 3D surface plots presented in Figure 3 was generated as follows:

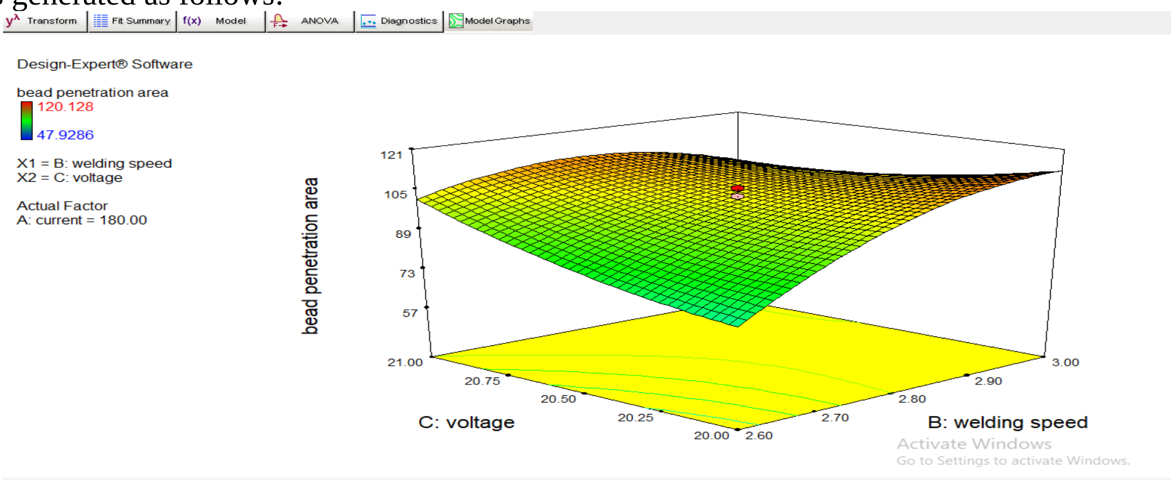

Figure 3: Effect of voltage and welding speed on penetration area

The surface plots in Figures 1 and 2 shows that the combined interaction between current has a significant effect on the weld penetration area, an increase in current will lead to corresponding increase in the weld penetration area. The final numerical optimal solution was obtained showing optimal results for current, welding speed and voltage that will produce maximum weld penetration area as shown in Table 6

Table 6: Table Showing Numerical Optimization Model

Number	Current (AMP)	welding speed (M/S)	voltage (Volts)	bead penetration area mm^2	Desirability	
1	**190.00**	**2.63**	**20.73**	**80.493**	**0.829**	Selected
2	190.00	2.63	20.72	80.2587	0.629	
3	190.00	2.63	20.70	79.9244	0.629	
4	190.00	2.63	20.68	78.8811	0.628	
5	190.00	2.62	20.78	81.9899	0.628	

4.0 Conclusion

In this study, an approach using Response Surface Methodology to develop a mathematical model to maximize the weld penetration area in TIG welding has been achieved. The influence of current, voltage and welding speed on the weld penetration area was investigated. The results obtained revealed that the second order quadratic polynomial equation is the best fit model that can accurately explain the effects of these input parameters on the penetration area. The results possessed good statistical sufficiency, having a very good coefficient of determination. The predicted R2 and the adjusted R2 are in reasonable agreement, surface plot showed the combined interaction of current and voltage on the response, and ANOVA results revealed that the penetration area is very sensitive to the current parameter. The mathematical models developed has a high goodness of fit, adequate signal and strength which can explain and predict the relationship between the penetration area and the input parameters. Table 6 shows that a welding current of 190amp, a welding speed of 2.63mm/s and welding voltage 20.73volt will produce penetration area of 80.43mm^2. This solution was selected by design expert as the optimal solution having a desirability value of 0.829.

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