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Statistical Modelling and Optimization of Thermal Conductivity of Low Carbon Steel Weldment using Response Surface Methodology

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ABSTRACT

Thermal conductivity of a material is important because of its impact on the quality of weldments. Thus, there is a motivation to optimize the process variables that influence the thermal conductivity of the material. This study was carried out to model and optimize thermal conductivity of low carbon steel weldments using response surface methodology (RSM). A three variable central composite design (CCD) was used to design and plan the welding experiment and resulted in a total of 20 experimental runs as obtain from the Design Expert software. The independent variables studies were current, voltage and gas flow rate while the chosen response was thermal conductivity. A statistical model was developed for the optimization of the process variables using RSM and the model was experimentally validated by carrying out analysis of variance (ANOVA). The model was statistically significant ($p<0.05$) with a high coefficient of determination ($R^2=0.9976$) and low standard deviation (0.0042) with respect to the mean (51.7394). Thermal conductivity was significantly influenced by all three factors ($p<0.05$); although current and gas flowrate had overall antagonistic effect while voltage had a positive effect. Numerical optimization of the statistical model revealed the optimum welding condition and this was a current of 150.27 A, a voltage of 23 V, and a gas flow rate of 10 L/min, and this yielded low carbon steel weldment having thermal conductivity of 51.85 W/m^{o}C.

1. INTRODUCTION

A quality weld is a weld that meets specified requirements and performs excellently at any given time considering the designed life (Urena et al., 2000). Thus, there is motivation to produce weldments that will last the duration of the life of the installation it is used in without fear of failure.

Welding processes causes non-uniform heat flow which is distributed within the steel material from the hot zone to the cold zone. This heat flow has to be controlled till optimal flow is achieved to form quality weld (Suresh et al., 2012). The weld morphology, weld bead geometry, cooling rate and its performance depends on the desired heat flow to form quality welds (Sun et al., 2008). Thus, it becomes important to have good knowledge of thermal conductivity of materials undergoing welding. According to the American Welding Society (2014), thermal conductivity is a measure of how easy heat can flow in a material. Thus, a material with a high thermal conductivity, such as aluminum, can dissipate heat very quickly and the materials with low thermal conductivity, like stainless steels, do not dissipate heat as rapidly. Low thermal conductivity will cause distortion due to the increased shrinkage effect brought on by the steep temperature gradient. Therefore, higher thermal conductivity is preferred for steel materials, to stop distortion of welded joints.

Peet et al. (2011) opined that thermal conductivity controls the degree of the temperature rise which occurs in components during manufacture and use. According to their report, structural components exposed to thermal cycling, caused steep temperature gradients which lead to thermal stresses and they were also of the opinion that during welding, thermal conductivity limits the size of components that can be produced with the desired microstructure, since transformation depends on cooling rate and temperature. Weman (2003) reported that the higher the thermal conductivity of base material the lower the cooling rate of the base material and the smaller the heat affected zone and vice versa.

The thermal conductivity of a weldment during gas tungsten arc welding (GTAW) is typically influenced by factors such as current, voltage, gas flowrate, welding speed, heat input etc (Trivedi and Bhabhor, 2012). It is necessary to optimize these factors in order to achieve optimum process conditions during welding. Experimental design methods coupled with response surface methodology (RSM) have been reported to be very effective in achieving this and it has been successfully applied to the optimization of many welding processes (Tang et al., 1999; Pujari and Patil, 2014; Achebor and Salisu, 2015; Ozigagun and Achebor, 2017).

Hence, the aim of this study is to optimize the thermal conductivity of low carbon steel weldments using response surface methodology by investigating the effect of current, voltage and gas flow rate during gas tungsten arc welding.

2. MATERIALS AND METHODS

2.1. Materials

Low carbon steel pipe (ASTM A106 GR SMLS) of thickness 6.35 mm was used as specimen for this study. Other materials and equipment used include non-consumed tungsten electrode, shielding gas, welding machine, infra-red thermometer, thermocouple etc.

2.2. Welding Procedure

The experiment was conducted in Aveon Offshore Fabrication Yard, Rumuolumeni-Port Harcourt in Rivers State, Nigeria. The welding operations were carried out using samples of 400 mm length of 8" diameter pipe of low carbon steel with 6.35 mm thickness which were cut to size by hacksaw. The edge preparation was carried out by chamfering to a bevel angle of 30^o on each edge of the pipe in order to get a 60^o groove angle to form a single V groove type with a root face of 2.5 mm. The welding process used was gas tungsten arc welding due to its high quality, flexibility and excellent visual appearance with a minimal cleaning. Pure argon was selected as shielding gas because it is common, cheap and enhances arc stability. To ensure sound weld, a very strong weld, the joints were properly cleaned with a grinding machine to soundness. During fit-up of the pipe, 3.2 mm core wire of electrode was used to prepare the weld joint root gap before the tack-welding of the pipe. The filler material was selected with caution to prevent excessive porosity.

The K type thermocouples were used for measuring welding heat flow temperature. Each thermocouple was connected from the weld specimen to the digital meter for recording of temperature at same time interval. Three blind holes (each hole was 5 mm deep) were produced to the opposite of weld surface in each pipe, for the positioning of thermocouples during welding. First hole was made at 25 mm from the groove face of the prepared weld joint before weld and next holes were 1 mm apart from its previous hole in perpendicular direction to the weld joint groove axis. A total of three different layers of bead were achieved per run; root pass, hot pass and finish passes. For each run, root, hot and cap passes were used and the thermal conductivity was measured and the average value recorded. The chosen welding process variables in this study were welding voltage, arc current and gas flow rate and their levels were set according to the experimental design.

2.3. Experimental Design

A three variable central composite design for response surface methodology was used to study the combined effect of voltage, current and gas flow rate over five levels as shown in Table 1. The experimental runs were randomized to minimize the effects of unexplained variability in the observed responses due to extraneous factors.

Table 1: Coded and actual values of independent variables for predicting thermal conductivity

Variables	Symbols	Coded and actual levels				
		-1.682	-1	0	+1	+1.682
Current (A)	X_1	139.77	150	165.00	180	190.23
Voltage (V)	X_2	18.98	20	21.50	23	24.02
Gas flow rate (L/min)	X_3	8.98	10	11.50	13	14.02

The relation between the coded values and actual values is described as follows:

$$x_i = \frac{X_i - X_o}{\Delta X_i} \tag{1}$$

Where x_i and X_i are the coded and actual values of the independent variable respectively. X_o is the actual value of the independent variable at the centre point, and ΔX_i is the step change of actual value of the independent variable. A general second degree polynomial (Equation (2)) was fitted to the experimental data using the statistical package Design Expert 11.0.0 (Stat-ease Inc., Minneapolis, USA) to estimate the response of the dependent variable and predict the optimal point.

$$Y = b_o + \sum_{i=1}^{N} b_i X_i + \sum_{i,j=1}^{N} b_{ij} X_i X_j + \sum_{i=1}^{N} b_{ii} X_i^2 + \sum_{i=1}^{N} e_i \tag{2}$$

Y is predicted response, X_1, X_2 and X_3 are independent variables, b_o and b_i are offset and linear effects terms respectively while b_{ij} and b_{ii} are interaction terms and e_i is the error term.

Analysis of variance (ANOVA) was used to estimate the model parameters as well as determining the fit of the model. The effect of voltage, current and gas flow rate on thermal conductivity was quantitatively evaluated using response surface plots. The plots were generated by keeping one variable constant at the centre point and varying the other two within the experimental range.

3. RESULTS AND DISCUSSION

3.1. Statistical Results

The experiments carried out according to the three factor CCD resulted in 20 experimental runs with results shown in Table 2. The proposed second order multiple regression model (Equation 2) was fitted to the experimental data presented in Table 4.5 using multiple regressions. The following second order multiple regression models were found to represent the relationship between the independent variables (current, gas flow rate and voltage) and the chosen response (thermal conductivity). The equations represent thermal conductivity as a function of current (X_1), voltage (X_2) and gas flow rate (X_3).

$$\begin{aligned} \textit{Thermal conductivity} &= 54.41 - 0.031X_1 - 0.011X_2 - 0.34X_3 - 0.0013X_1X_2 \\ &+ 0.00078X_1X_3 + 0.011X_2X_3 + 0.00014X_1^2 + 0.0026X_2^2 - 0.0015X_3^2 \end{aligned} \tag{3}$$

The predicted response levels of thermal conductivity using Equations (3) are also presented in Table 2 for comparison.

Table 2: Experimental and predicted results for three factor CCD

Run	Factors						Response	
	Coded values			Actual values			Thermal conductivity (W/m°C)	
	X_1	X_2	X_3	X_1	X_2	X_3	Experiment	Predicted
1	1	1	-1	180.0	23.00	10.00	51.67	51.67
2	1	-1	1	180.0	20.00	13.00	51.69	51.69
3	-1	-1	1	150.0	20.00	13.00	51.69	51.69
4	-1	1	1	150.0	23.00	13.00	51.85	51.86
5	1	-1	-1	180.0	20.00	10.00	51.72	51.72
6	0	0	0	165.0	21.50	11.50	51.72	51.72
7	0	0	-1.68	165.0	21.50	8.98	51.72	51.72
8	1	1	1	180.0	23.00	13.00	51.74	51.74
9	0	0	0	165.0	21.50	11.50	51.71	51.72
10	0	0	0	165.0	21.50	11.50	51.72	51.72
11	0	0	0	165.0	21.50	11.50	51.72	51.72
12	1.68	0	0	190.2	21.50	11.50	51.72	51.73
13	-1.68	0	0	139.7	21.50	11.50	51.89	51.88
14	0	0	0	165.0	21.50	11.50	51.72	51.72
15	0	-1.68	0	165.0	18.98	11.50	51.68	51.68
16	0	0	0	165.0	21.50	11.50	51.72	51.72
17	0	1.68	0	165.0	24.02	11.50	51.79	51.78
18	-1	-1	-1	150.0	20.00	10.00	51.79	51.79
19	-1	1	-1	150.0	23.00	10.00	51.85	51.86
20	0	0	1.68	165.0	21.50	14.02	51.69	51.69

The fit of the statistical model for thermal conductivity was assessed by performing analysis of variance (ANOVA) and the results are presented in Table 3. As shown in Table 3, values of ‘‘Prob. > F’’ less than 0.05 indicate the model terms were significant. Values greater than 0.10 indicate the model terms were not significant. All the terms in the model representing thermal conductivity were significant as seen from their very low p value. This suggests that changes in the values of these variables could significantly affect the welding process. A model F-value of 466.90 and a very low probability value of $p<0.0001$ imply that the response model was significant and can be used for predictive purposes. The "Lack of Fit" F-value of 11.62 implies that there was insignificant lack of fit. The "Lack of Fit" p value of 0.088 implies that there is only 8.8% chance that the “Lack of Fit" F-value could occur due to noise.

Table 3: ANOVA results for model representing thermal conductivity

Sources	Sum of squares	Degree of freedom	Mean squares	F value	p value
Model	0.0726	9	0.0081	466.90	< 0.0001
X_1	0.0298	1	0.0298	1724.58	< 0.0001
X_2	0.0129	1	0.0129	748.46	< 0.0001
X_3	0.0010	1	0.0010	55.54	< 0.0001
X_1X_2	0.0064	1	0.0064	371.86	< 0.0001
X_1X_3	0.0024	1	0.0024	141.21	< 0.0001
X_2X_3	0.0050	1	0.0050	287.98	< 0.0001
X_1^2	0.0143	1	0.0143	826.94	< 0.0001
X_2^2	0.0005	1	0.0005	28.57	0.0003
X_3^2	0.0002	1	0.0002	9.81	0.0107
Residual	0.0002	10	0.0000		
Lack of Fit	0.0002	5	0.0000	11.62	0.088
Pure Error	0.0000	5	0.0000		
Cor Total	0.0728	19			

The coefficient of determination (R^2) of the model representing thermal conductivity was 0.9976 as shown in Table 4. The closeness of this value to unity indicates that the model was able to adequately represent the actual relationship between the variables considered in this study. The adjusted R^2 value is actually a better measure of model fit compared to the R^2 value. The adjusted R^2 value obtained was 0.9955 which means that the model explains 99.55% of the variability in the response for the region studied while the remaining 0.45% was as a result of chance. The standard deviation (0.0042) was observed to be relatively small compared to the mean values of thermal conductivity (51.7394) showing that there was very little dispersion about the mean. This further corroborates the significant fit of the models. The coefficient of variation (C.V) obtained was 0.0080%. The coefficient of variation indicates the degree of precision with which the runs were carried out. A low value of C.V suggests a high reliability and reproducibility of the results (Montgomery, 2005). An Adequate precision value of 72.129 was obtained. Cao et al. (2009) reported that this parameter measures the signal to noise ratio and a value greater than 4 is generally desirable and the model can be used to navigate the design space.

The adequacy of the quadratic model representing was further verified by running diagnostics on the model. The normal probability plot for the model representing thermal conductivity is presented in Figure 1. The normal probability plot indicates whether the residuals follow a normal distribution, i.e. follow the straight line. The clustering of the points around the straight line as shown in Figure 1 shows that the residuals indeed follow a normal distribution.

Table 4: Statistical information for ANOVA for thermal conductivity model

Parameter	Value
R-Squared	0.9976
Adjusted R-Squared	0.9955
Predicted R-Squared	0.9830
Mean	51.7394
Standard Deviation	0.0042
C.V %	0.0080
Adeq. Precision	72.1290

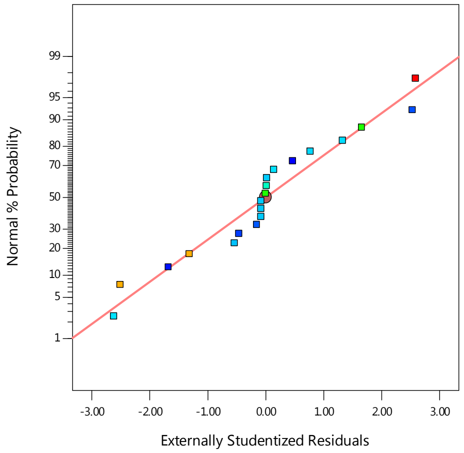

Figure 1: Normal probability plot for thermal conductivity model

Figure 2 shows the parity plot of the responses for thermal conductivity. It is a plot of the predicted response values versus the experimental response values. The purpose is to detect a value, or group of values, that are not easily predicted by the model. Comparison of the experimental values of the response and those predicted by the statistical model showed that there was an acceptable level of fit between the experimental and model predicted results. This is evident from the fact that the data points all clustered around the 45° diagonal line showing that there was minimal deviation between experimental and predicted values thus indicating optimal fit of the model.

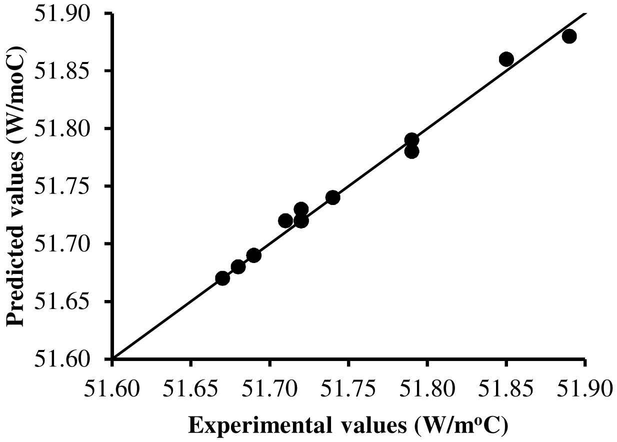

Figure 2: Parity plot for thermal conductivity model

3.2. Optimization of Thermal Conductivity

To determine the effect of the input variables on the responses, response surface plots were generated according to Equation 3. The three-dimensional (3D) plots were generated by varying two variables within the experimental range and maintaining the other one at its center point value. The resulting response surfaces showed the effect of current, gas flow rate and voltage on thermal conductivity.

The effect of current and gas flow rate on thermal conductivity is shown in Figure 3. The trend observed showed that an increase in current resulted in a decrease in thermal conductivity. On the other hand, gas flow rate positively influenced thermal conductivity as seen in the fact that when gas flow rate was increase, the thermal conductivity also increased.

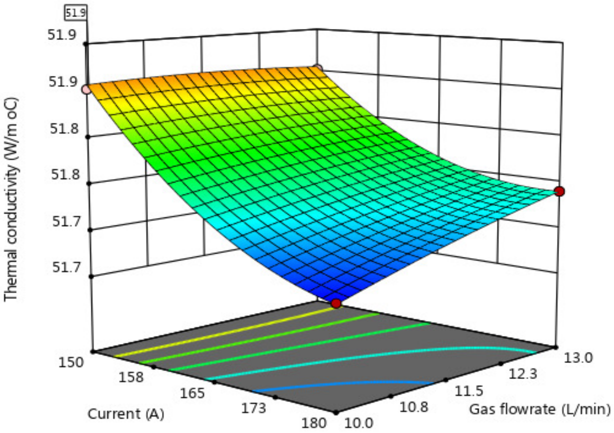

Figure 3: Effects of current and gas flow rate on thermal conductivity

The effect of voltage and gas flow rate on thermal conductivity is shown in Figure 4. The trend observed showed that increase in voltage generated an increase in thermal conductivity while increase in gas flow rate resulted in a decrease the thermal conductivity and vice versa.

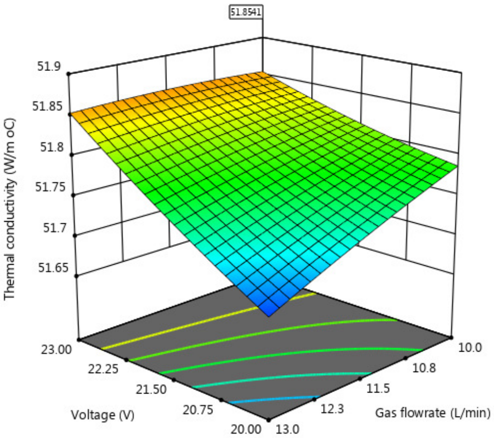

Figure 4: Effect of voltage and gas flow rate on thermal conductivity

Numerical optimization of the response was carried out to optimize the thermal conductivity. The values of the independent variables during numerical optimization were fixed within the experimental range. After evaluating the model graphs and the solutions suggested by the numerical optimization package, the optimum conditions were chosen as the one with the highest desirability value. The optimization results revealed that the optimum thermal conductivity was obtained as 51.85 W/m°C. This value was obtained at optimum conditions of current (150.27 A), voltage (23 V) and gas flow rate (10 L/min).

4. CONCLUSION

In this work, the effect of current, voltage and gas flowrate on thermal conductivity of low carbon steel weldments was studied quantitatively over five levels using a three variable central composite design for response surface methodology. The following conclusions can be drawn from the study.

- Thermal conductivity is significantly influenced by the process variables such as current, voltage and gas flowrate.
- Thermal conductivity is related to current, voltage and gas flowrate by a validated quadratic regression model.
- The quadratic regression model developed was able to predict to a high level of confidence, the thermal conductivity of low carbon steel weldments with high R^2 value.
- The combination of optimum process conditions was a current of 150.27 A, a voltage of 23 V, and a gas flow rate of 10 L/min, and this yielded low carbon steel weldment having thermal conductivity of 51.85 W/m^{o}C.

5. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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