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RESEARCH ARTICLE

OPTIMIZATION ANDPREDICTION OF THERMAL CONDUCTIVITY OF TIG MILD STEEL WELDMENTS

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ABSTRACT

Mild steel is in the classes of materials with high thermal conductive property, increasing the temperature unduly during welding would be detrimental to the microstructure of the weldment. In this research, we aim to minimize the thermal conductivity of mild steel during welding operation to get a quality weld. To achieve that, Response Surface Methodology (RSM) was employed, where twenty sets of experiments were carried out, adopting the central composite experimental design. Tungsten inert gas welding equipment was used to produce the welded joints; Argon gas was supplied to the weld to shield it from atmospheric interference. Mild steel plates of 60x40x10mm were cut and used as specimen for the work. The k-type thermocouple was used to determine the ambient, solidus and liquidus temperatures. The Response Surface Methodology was employed to analyze the data collected from the experiments. The RSM was employed to optimize and predict the thermal properties of mild steel weldments. The model produced a numerical optimal solution of: current 120.00 Amp, voltage of 23.79 volt and a gas flow rate of 15.71 L/min resulting in a welded material having a thermal conductivity of 51.602 W/m 0C

INTRODUCTION

Thermal conductivity is defined asthe amount of heat transmitted through a material.Totmeier and Gale, (2004) stressed the need for materials thermal conductivity to be known especially for steel alloys being used in welding and how it changes as a function of temperature. However, in the absence of a quantitative model it is difficult to assess the validity of this procedure. It is known that thermal conductivity controls the magnitude of the temperature gradients which occur in components during manufacture and usePeet *et al*, (2011). Hence, Heat transfer occurs at a higher rate across materials of high thermal conductivity than those of low thermal conductivity.Yadaiah and Bag (2012) used the constant value of 0.9 as the emissivity of the stainless steel in a thermal welding model and also analyzed the cooling influence of the weld pool during the welding process. The average heat transfer coefficient and the average Nusselt number are also presented. Staley and Evancho (2010) calculated cooling curves and transformation kinetics were used to calculate the resultant distribution of hardness using a quench factor for a high thermal material. Hasan et.al (2010) stated that a suitable model of thermal conductivity should help to improve the design of steels and in understanding of heat treatment, solidification and welding processes, design of steel structures and components, and also prediction of thermo–mechanical fatigue.

Materials of high thermal conductivity are widely used in heat sink applications and materials of low thermal conductivity are used as thermal insulation.Nechtelberger (1980) related the change in thermal conductivity λ of ferrite in cast iron by alloying to the thermal conductivity of pure iron λ0 by an equation of the form $\lambda = \lambda0 - \ln x$ where x is the solute concentrations in %. Since there is a large effect on thermal conductivity by any disturbance in the periodicity of the lattice, the temperature and thermal history of steels can be expected to greatly influence conductivity. Thermal conductivity of materials is temperature dependent. The reciprocal of thermal conductivity is called thermal resistivity. Metals with high thermal conductivity, exhibit high electrical conductivity. Sourmail et.al (2002) reported physical properties as a function of temperature for a number of different steels. The thermal conductivity of steel alloys diverge as temperature is decreased, pure iron having the highest thermal conductivity, followed by carbon steels, alloy steels and then by high–alloy steels. High-alloy steels having lower thermal conductivity at normal ambient temperatures than at high temperatures. At higher temperatures where austenite forms all the alloys have similar thermal conductivities. Thermal conductivity of an alloy will depend upon temperature and microstructure. The heat generated in high thermal conductivity materials is rapidly conducted away from the region of the weld. For metallic materials, the electrical and thermal conductivity correlate positively, i.e. materials with high electrical conductivity (low electrical resistance) exhibit high thermal conductivity. According to Zareie *et al*, (2003) and Aissan *et al* (2015)

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thermal conductive heat input is increased with increasing wire feeding speed but increasing welding speed decreases the welding heat input. When heat input increases, the cooling rate decreases for weld metal and increases the volume fraction of tempered martensite and coarsening of the microstructure of weld zone. Since mild steel is in the classes of material with high thermal conductive property, increasing the temperature unduly during welding would further affect the microstructure of the material. Therefore, in this research, we aim to minimize the thermal conductivity of mild steel during weld operation to get a quality weld.

MATERIALS AND METHODS

Materials

This study is centered on the experimental study of TIG mild steel welds, employing scientific design of experiments, expert systems, statistical and mathematical models and tests for thermal properties. The research data is made up of the gas tungsten arc welding input process parameters and the output process. The tungsten inert gas welding equipment was used to weld the plates after the edges have been bevelled and machined. Figure 1 shows the shielding gas cylinder and regulator, the welding process uses a shielding gas to protect the weld specimen from atmospheric interaction, 100% pure Argon gas was used in this research study. Figure 2 shows the thermocouple connection cable, figure 3 shows the TIG equipment setup while figure 4 shows the digital thermometer. The key parameters considered in this work are welding current, gas flow rate, welding voltage as shown in table 1 with a low and high range values, the Central Composite Design (CCD) tool in design expert 7.01 was employed. One hundred (100) pieces of mild steel coupons measuring 60 x 40 x10mm were used for the experiments; it was performed 20 times, using 5 specimens for each run.

Table 1. Process parameters and their levels

Parameters	Unit	Symbol	Coded value	Coded value
			Low(-1)	High(+1)
Current	Amp	A	120	170
Gas flow rate	Lit/min	F	13	16
Voltage	Volt	V	18	24

Figure 1. Shielding gas cylinder and regulator

Figure 2. Thermocouple Connection cable

Figure 3. TIG equipment

Figure 4. Digital Thermometer

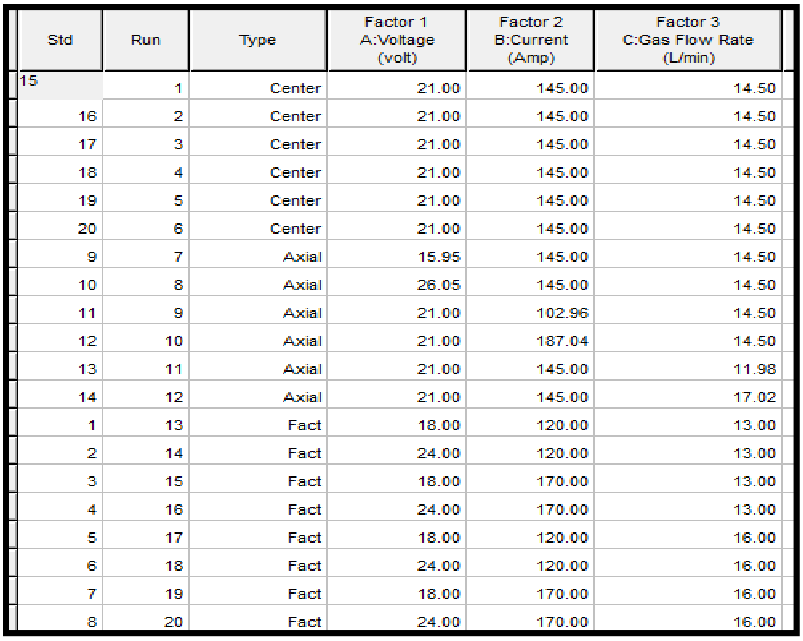
To generate the experimental data for the optimization process;

- First, statistical design of experiment (DOE) using the central composite design method (CCD) was done. Central composite design (CCD) is unarguably one of the most acceptable design for response surface methodology (RSM). The design and optimization was done using statistical software and for this particular problem, Design Expert 7.01 was employed.
- Secondly, an experimental design matrix having six (6) centre points, six (6) axial points and eight (8) factorial points resulting to 20 experimental runs was generated. Figure 3 shows the design matrix for the research work.

RESULTS AND DISCUSSIONS

Results

The experimental design, numerical and graphical optimization was done with the aid of the design expert 7.1 software. Table 2 shows the experimental results for the thermal conductivity, heat input, cooling time and cooling rate, the experiments were performed using the central composite design matrix. The design expert software was used to generate the experimental runs obeying the principles of experimental design. The model summary, which shows the factors and their lowest and highest values including the mean and standard deviation, is presented as shown in table 3. The result revealed that the model is of the quadratic type which requires the polynomial analysis order as depicted by a typical response surface design. For thermal conductivity, the minimum value was observed to be 51.546 W/m ^{0}C, maximum value of 51.999 W/m ^{0}C, mean value of 51.772 and standard deviation of 0.081. In assessing the strength of the quadratic model towards minimizing thermal conductivity one way analysis of variance (ANOVA) was done for each response variable and result is presented in table 4. In this case A, B, C, AB, AC, A^2, C^2 are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model.



Std	Run	Type	Factor 1 A:Voltage (volt)	Factor 2 B:Current (Amp)	Factor 3 C:Gas Flow Rate (L/min)
15	1	Center	21.00	145.00	14.50
16	2	Center	21.00	145.00	14.50
17	3	Center	21.00	145.00	14.50
18	4	Center	21.00	145.00	14.50
19	5	Center	21.00	145.00	14.50
20	6	Center	21.00	145.00	14.50
9	7	Axial	15.95	145.00	14.50
10	8	Axial	26.05	145.00	14.50
11	9	Axial	21.00	102.96	14.50
12	10	Axial	21.00	187.04	14.50
13	11	Axial	21.00	145.00	11.98
14	12	Axial	21.00	145.00	17.02
1	13	Fact	18.00	120.00	13.00
2	14	Fact	24.00	120.00	13.00
3	15	Fact	18.00	170.00	13.00
4	16	Fact	24.00	170.00	13.00
5	17	Fact	18.00	120.00	16.00
6	18	Fact	24.00	120.00	16.00
7	19	Fact	18.00	170.00	16.00
8	20	Fact	24.00	170.00	16.00

Figure 3. Central Composite Design Matrix (CCD)

Table 2. The Experimental results for Thermal conductivity

Std	Run	Voltage (Volt)	Current (Amp)	Gas Flow Rate (L/min)	Thermal Conductivity
15	1	21.00	145.00	14.50	51.7461
16	2	21.00	145.00	14.50	51.7461
17	3	21.00	145.00	14.50	51.7743
18	4	21.00	145.00	14.50	51.7643
19	5	21.00	145.00	14.50	51.7746
20	6	21.00	145.00	14.50	51.7773
9	7	15.95	145.00	14.50	51.7279
10	8	26.05	145.00	14.50	51.7399
11	9	21.00	102.96	14.50	51.7520
12	10	21.00	187.04	14.50	51.9985
13	11	21.00	145.00	11.96	51.8377
14	12	21.00	145.00	17.02	51.7399
1	13	18.00	120.00	13.00	51.7885
2	14	24.00	120.00	13.00	51.6831
3	15	18.00	170.00	13.00	51.7763
4	16	24.00	170.00	13.00	51.8253
5	17	18.00	120.00	16.00	51.7641
6	18	24.00	120.00	16.00	51.5456
7	19	18.00	170.00	16.00	51.7885
8	20	24.00	170.00	16.00	51.8552

Table 3. RSM design summary for optimizing weld parameters

Study type	Response surface	Run	20								
Initial Design	Central composite	Blocks	No Blocks								
Design Model	Quadratic										
Factor	Name	Units	Type	Low Actual	High Actual	Low Coded	High Coded	Mean	Std. Dev.		
A	Voltage	Volt	Numeric	18.00	24.00	-1.00	1.00	21.000	2.479		
B	Current	Amp	Numeric	120.00	170.00	-1.00	1.00	145.00	20.659		
D	GFR	L/min	Numeric	13.00	16.00	-1.00	1.00	14.500	1.240		
Response	Name	Units	Obs	Analysis	Minimum	Maximum	Mean	Std. Dev.	Ratio	Trans	Model
Y1	Thermal Conductivity	W/m 0C	20	Polynomial	51.546	51.999	51.772	0.081	1.009	None	Quadratic

To validate the adequacy of the model based on its ability to thermal conductivity the goodness of fit statistics presented in table 5 were employed; Coefficient of determination (R-Squared) values of 0.8924 as observed in table 5 shows the strength of response surface methodology and its ability to minimize the thermal conductivity to a desired value. Adjusted (R-Squared) value of 0.7956 as observed in table 5 indicate a model with 79.56% reliability. Adeq Precision measures the signal to noise ratio. A ratio greater than 4 is desirable. Adequate precision values of 14.207 as observed in table 5indicate an adequate signal. This model can be used to navigate the design space and minimize the thermal conductivity to the desired value. The optimal equation which shows the individual effects and combine interactions of the selected variables against the mesured responses (thermal conductivity) is presented in actual factors as shown in Figure 5.

Figure 4. ANOVA table for validating the model significance towards minimizing the thermal conductivity

Response 1 WPSF

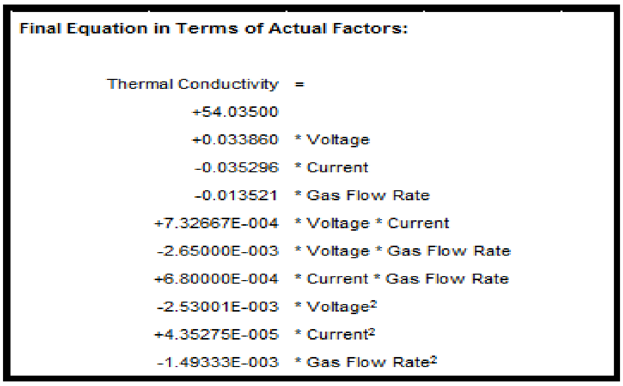
ANOVA for Response Surface Quadratic Model

Analysis of Variance table [Partial Sum of Squares-Types III]

Source	Sum of Square	df	Mean Square	F Value	P-Value Prob>F	
Model	0.12	9	0.013	9.22	0.0009	Significant
A-Voltage	2.589E-003	1	2.589E-003	1.85	0.2032	
B-Current	0.057	1	0.057	40.49	<0.0001	
C-GFR	5.918E-003	1	5.918E-003	4.24	0.0665	
AB	0.024	1	0.024	17.30	0.0019	
AC	1.138E-003	1	1.138E-003	0.81	0.3879	
BC	5.202E-003	1	5.202E-003	3.73	0.0824	
A^2	7.472E-003	1	7.472E-003	5.35	0.0432	
B^2	0.011	1	0.011	7.64	0.0200	
C^2	1.627E-004	1	1.627E-004	0.12	0.7399	
Residual	0.014	10	1.3967E-003			

Table 5. GOF statistics for validating model significance in minimizing thermal conductivity

Std. Dev	0.037	R-Squared	0.8924
Mean	51.77	Adj R-Squared	0.7956
C.V%	0.072	Pred R-Squared	0.1691
PRESS	0.11	Adeq Precision	14.207



Final Equation in Terms of Actual Factors:

Thermal Conductivity =
+54.03500
+0.033860 * Voltage
-0.035296 * Current
-0.013521 * Gas Flow Rate
+7.32667E-004 * Voltage * Current
-2.65000E-003 * Voltage * Gas Flow Rate
+6.80000E-004 * Current * Gas Flow Rate
-2.53001E-003 * Voltage²
+4.35275E-005 * Current²
-1.49333E-003 * Gas Flow Rate²

Figure 5. Optimal equation in terms of actual factors for minimizing thermal conductivity

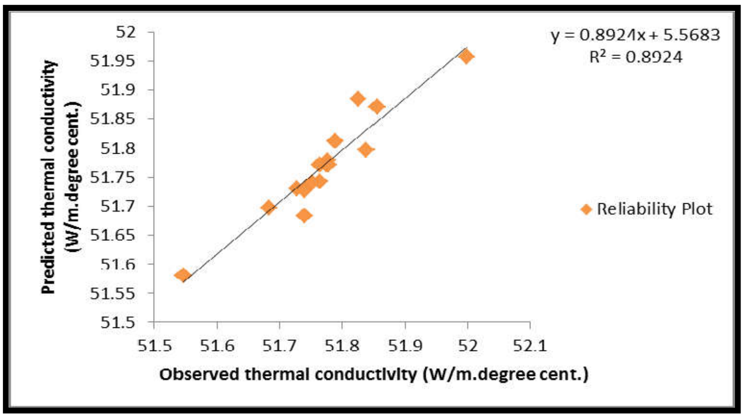


Figure 6. Reliability plot of observed versus predicted thermal conductivity

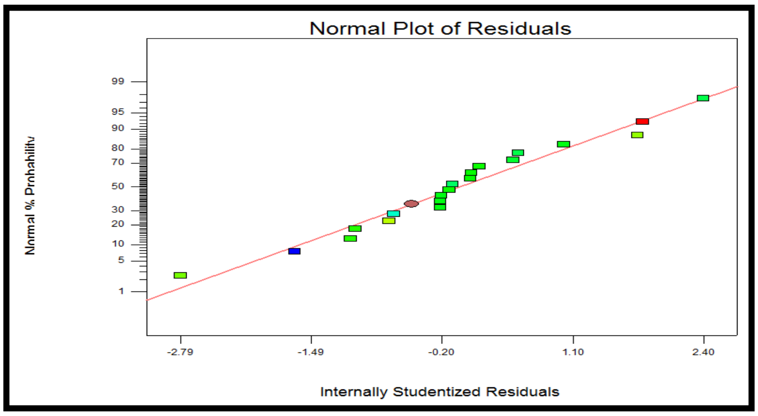


Figure 7. Normal probability plot of studentized residuals for thermal conductivity

The suitability of response surface methodology using the quadratic model, a reliability plot of the observed and predicted values of each response were obtained as presented in Figures 5. To asses the accuracy of prediction and established the suitability of response surface methodology using the quadratic model, a reliability plot of the observed and predicted values of each response were obtained as presented in Figure 6. The high coefficient of determination ($r^2 = 0.8924$) as observed in Figure 6 was used to establish the suitability of response surface methodology in minimizing the heat input to the desired range. To accept any model, its satisfactoriness must be checked by an appropriate statistical analysis. To diagnose the statistical properties of the model for thermal conductivity, the normal probability plot of residual presented in Figure 7 were employed.

The normal probability plot of studentized residuals was employed to assess the normality of the calculated residuals. The normal probability plot of residuals which is the number of standard deviation of actual values based on the predicted values was employed to ascertain if the residuals (observed – predicted) follows a normal distribution. It is the most significant assumption for checking the sufficiency of a statistical model. Results of Figure 6 revealed that the computed residuals are approximately normally distributed an indication that the model developed is satisfactory. In addition, result of the normal probability plot of residual also indicates that the data used are devoid of possible outliers. To study the effects of combine variables on each response (thermal conductivity current and voltage), 3D surface plots presented in Figure8 was employed.

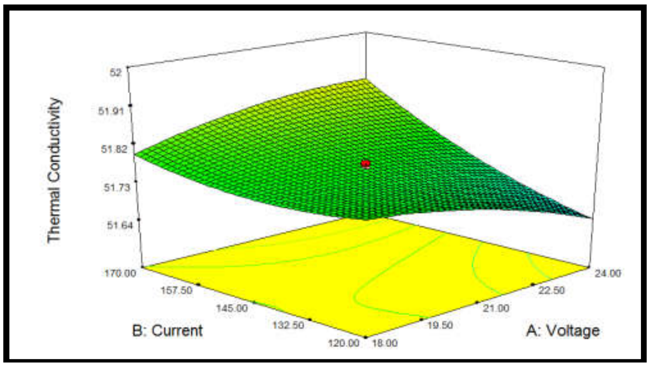
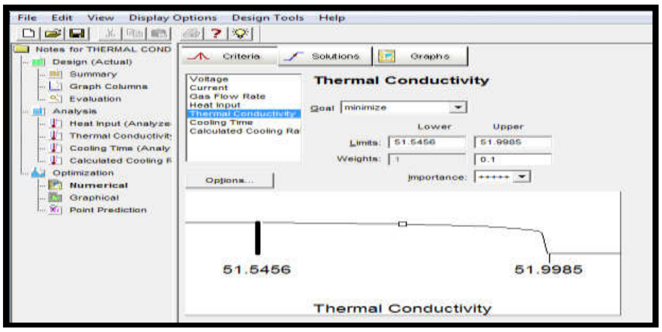


Figure 8. Effect of current and voltage on thermal conductivity

The 3D surface plot as observed in Figure 8 shows the relationship between the input variables (voltage, current and gas flow rate) and the response variable (thermal conductivity). It is a 3 dimensional surface plot which was employed to give a clearer concept of the response surface. As the colour of the curved surface gets darker, the cooling rate gets higher while the cooling time and thermal conductivity decreases proportionately.

Finally, numerical optimization was performed to ascertain the desirability of the overall model. In the numerical optimization phase, we ask design expert to minimize the thermal conductivity to a desired range while also determining the optimum value of voltage, current and gas flow rate. The interphase of the numerical optimization is presented as shown in Figure 9. The numerical optimization produces about nineteen (19) optimal solutions which are presented as shown in Figure 10.



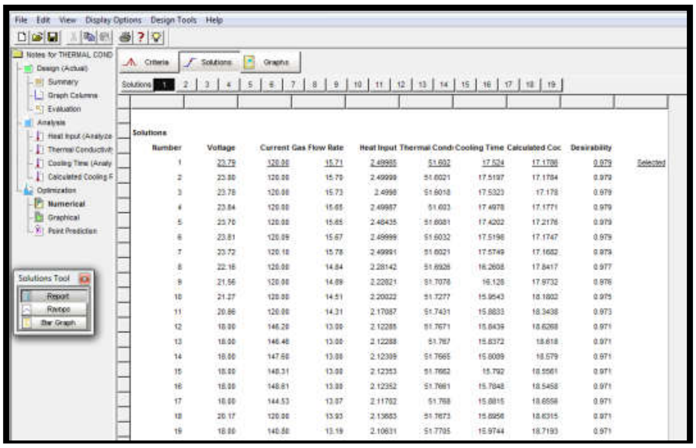
Thermal Conductivity

Goal: minimize

	Lower	Upper
Limits:	51.5456	51.9985
Weights:	1	0.1

Importance: +++++

Figure 9. Interphase of numerical optimization model for minimizing thermal conductivity



Solutions

Number	Voltage	Current	Gas Flow Rate	Heat Input	Thermal Cond	Cooling Time	Calculated Coc	Desirability	
1	23.79	120.00	15.71	2.49985	51.602	17.524	17.1786	0.979	Selected
2	23.80	120.00	15.70	2.49999	51.6021	17.5197	17.1784	0.979	
3	23.78	120.00	15.73	2.4998	51.6018	17.5323	17.178	0.979	
4	23.84	120.00	15.65	2.49987	51.603	17.4978	17.1771	0.979	
5	23.70	120.00	15.65	2.48435	51.6081	17.4202	17.2176	0.979	
6	23.81	120.09	15.67	2.49999	51.6032	17.5198	17.1747	0.979	
7	23.72	120.18	15.78	2.49991	51.6021	17.5749	17.1682	0.979	
8	22.16	120.00	14.84	2.28142	51.6926	16.2608	17.8417	0.977	
9	21.56	120.00	14.69	2.22821	51.7078	16.128	17.9732	0.976	
10	21.27	120.00	14.51	2.20022	51.7277	15.9543	18.1802	0.975	
11	20.86	120.00	14.31	2.17087	51.7431	15.8833	18.3438	0.973	
12	18.00	146.20	13.00	2.12285	51.7671	15.8439	18.6268	0.971	
13	18.00	146.48	13.00	2.12288	51.767	15.8372	18.618	0.971	
14	18.00	147.60	13.00	2.12309	51.7665	15.8009	18.579	0.971	
15	18.00	148.31	13.00	2.12353	51.7662	15.792	18.5561	0.971	
16	18.00	148.61	13.00	2.12352	51.7661	15.7848	18.5458	0.971	
17	18.00	144.53	13.07	2.11702	51.768	15.8815	18.6556	0.971	
18	20.17	120.00	13.93	2.13683	51.7673	15.8956	18.6315	0.971	
19	18.00	140.80	13.19	2.10631	51.7705	15.9744	18.7193	0.971	

Figure 10. Optimal solutions of numerical optimization model

From the results of *Figure 9*, it was observed that a current of 120.00 Amp, voltage of 23.79 volt and a gas flow rate of 15.71 L/min will produce a welded material having thermal conductivity of 51.602 W/m ^{0}C. This solution was selected by design expert as the optimal solution with a desirability value of 97.90%. Finally, based on the optimal solution, the contour plots showing each response variable against the optimized value of the thermal conductivity variable is presented in Figure 11.

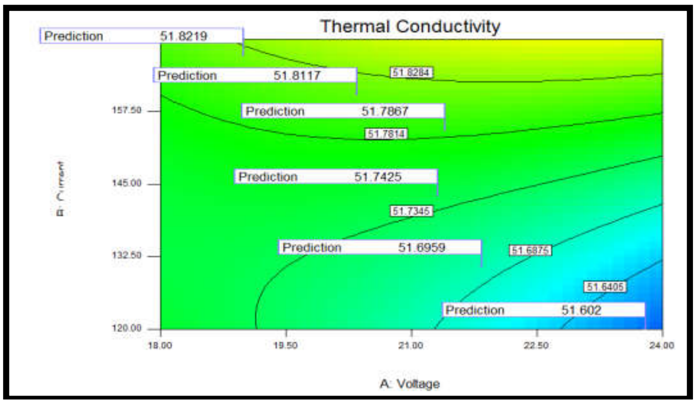


Figure 11. Prediction of thermal conductivity using contour plot

The optimal solution of numerical optimization revealed that a current of 120.00 Amp, voltage of 23.79 volt and a gas flow rate of 15.71 L/min will produce a welded material thermal conductivity of 51.602 W/m ^{0}C. This solution was selected by design expert as the optimal solution with a desirability value of 97.90%.

DISCUSSION

In this study, the response surface methodology was used to optimize the thermal conductivity of mild steel welds. Thermal conductivity is dependent upon the input process parameters current voltage and gas flow rate. A model was developed using the RSM Result of Table 3 revealed that the model is of the quadratic type which requires the polynomial analysis order as depicted by a typical response surface design. The interaction of current and voltage has a great effect on thermal conductivity. Analysis of the model standard error was employed to assess the suitability of response surface methodology using the quadratic model to optimize the heat input to a desired range, minimized the cooling time and thermal conductivity while also maximizing the cooling rate. In assessing the strength of the quadratic model towards minimizing the thermal conductivity, one way analysis of variance (ANOVA) was done for each response variable and result is presented in Table 4. To validate the adequacy of the model based on its ability to minimize the thermal conductivity to a desired range, the goodness of fit statistics presented in Table 5 was employed. Coefficient of determination (R-Squared) value of 0.8924 as observed in table 5 shows the strength of response surface methodology and its ability to minimize thermal conductivity to a desired value. Adeq Precision measures the signal to noise ratio. A ratio greater than 4 is desirable.

Adequate precision values of 14.207as observed in Table 5indicate an adequate signal. The diagnostic case statistics actually give insight into the model strength and the adequacy of the optimal second order polynomial equation. To asses the accuracy of prediction and established the suitability of response surface methodology using the quadratic model, a reliability plot of the observed and predicted values of each response were obtained as presented in Figure 6.The high coefficient of determination ($r^2 = 0.8924$) were used to established the suitability of response surface methodology in minimizing thermal conductivity, to the desired range. To study the effects of combine variables on each response (thermal conductivity), 3D surface plots presented in Figure 8 wasemployed. The 3D surface plot as observed in Figure8 shows the relationship between the input variables (voltage, current and gas flow rate) and the response variables (thermal conductivity). It is a 3 dimensional surface plot which was employed to give a clearer concept of the response surface. As the colour of the curved surface gets darker, thermal conductivity decreases proportionately. Finally, numerical optimization was performed to ascertain the desirability of the overall model. In the numerical optimization phase, we ask design expert to minimize thermal conductivity to a desired range while also determining the optimum value of voltage, current and gas flow rate. From the results of Figure 10, it was observed thata current of 120.00 Amp, voltage of 23.79 volt and a gas flow rate of 15.71 L/min will produce a welded material having thermal conductivity of 51.602 W/m ^{0}C. Response surface methodology using numerical optimization was effective in predicting the thermal conductivity of the welded material.

Conclusion

The integrity of a weld is determined by the quality of the weld bead geometry and thermal properties as demonstrated in this work. Also thermal conductivity, is a very important factor to be considered in assessing the quality of welds .The lower the thermal conductivity, the better the quality of the weld. It has been shown that the optimization and prediction of thermal conductivity have a significant effect on the quality and integrity of welded joints. Itis, therefore, recommended that welding and fabrication industries should endeavor to use the optimum welding process parameters obtained in this study to produce high quality welds in the Tungsten inert gas welding process for the class of materials considered in this study.

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