NUMERICAL PREDICTION AND OPTIMIZATION OF CALCULATED COOLING RATE OF LOW CARBONSTEEL WELDMENTS

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Abstract

Fast cooling rate is disadvantageous to a weldment because it can lead to problems such as serious micro structural changes, embrittlement at the heat affected zone and more. Therefore, optimizations of the weld process parameters are one sure way to reduce the adverse effect of fast cooling rates.

This study was carried out with the aim of optimizing and predicting thermal properties of low carbon (mild) steel weldments. The purpose of this study is to develop a model that maximize cooling rate using Response Surface Methodology (RSM). 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 welded together. The k-type thermocouple was used to determine the ambient, solidus and liquid us temperatures.

At the end, 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 calculated cooling rate of 17.1786 0C/sec.

Keywords: weld, DOE, CCD, GOF and TIG

Introduction

Arc welding is a process which usually involves the melting of two adjacent surfaces by the introduction of heat using the filler metal. Melting and solidification steps of welding are induced by the flow of heat, which is controlled by the rate of heat transfer in and around the weld metal. It should be noted that metallurgical structure of weld metal at the weld zone and heat affected zone (HAZ) is mainly determined by the extent of temperature rise and metal solidification after weld. The most widely accepted analytical solutions to predict thermal history of weld and rate of cooling are those of Rosenthal (1946). While Shahet al, (1995) took into account surface heat transfer, and extended Gaussian heat source. These two authors worked on the numerical analytical approach of cooling rate. According to Sarizam (2012) that also worked on cooling rate around the fusion and heat affected zone, He defined weld area, as the area that includes weld metal and HAZ. HAZ in metal can be divided into four main areas such as coarse grain HAZ (CGHAZ), fine grained supercritical HAZ (FGHAZ), intercritical HAZ (ICHAZ) and subcritical HAZ (SCHAZ). These four main areas reacts differently to cooling rate.

Kasuya and Yurioka(1993) discovered from their research, applying the Rosenthal’s solution moving heat source, that cooling rate in the HAZ did not depend on the location of the point heat source, but the quantity of heat introduced. Eagar et.al (1983), Easter ling (1992), Zhang et.al (2002) and Collins et.al (1983) all worked further to simplify the two limiting solutions derived by Rosenthal to obtain temperature and time profiles in the HAZ using the Numeric methods, where FEM was applied using 3- D heat flow and 2-D heat flow assumption. From their works, it could be deduced that the reason why heat input is very important is because it has a huge bearing on the cooling rate. Faster cooling rate is detrimental to the weld metal because they alters the microstructure thereby causing embrittlement in the heat affected zone.

Babuet.al (2012) in their work titled “Experimental Study on the Microstructure and Hardness of Laser Transformation Hardening of Low-alloy Steel” shows how heat transfer in base metal alters its grains structure of the weldment. Thus it will be evident that the range of temperature change is varied from at least the melting point of the material to the room temperature which causes metallurgical problems in welds. Morris (2001) has reported that many of the important mechanical properties of steel, including yield strength and hardness, the ductile-brittle transition temperature and susceptibility to environmental embrittlement can be improved by refining the grain size while Geels, (1998) and Gharibshahiyan et.al (2011) found that the metal grain microstructure defines a high number of properties in a material and that the quality of a welded joint can be judged from the grain size. These researchers all examined how the cooling rate alters the grain structures present around the fusion zone and the heat affected zone. Our research aim is to optimize the cooling rate using response surface methodology (RSM) to get the optimum process parameter required to prevent fast cooling rate that could alter the grain structure.

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 TIG welding setup. 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

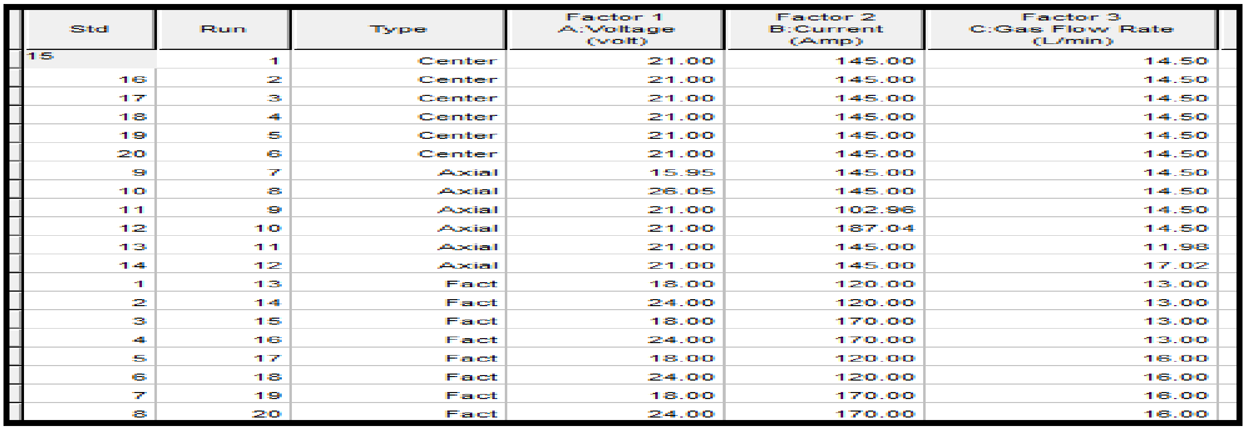
Figure 1: *shielding gas cylinder and regulator*

Figure 2: *TIG equipment*

To generate the experimental data for the optimization process;

i. 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.

ii. 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.



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)*

Results and Discussions

Each experimental run comprising the current, voltage and gas flow rate, used to join two pieces of mild steel plates measuring 60 x40 x10 mm, which eventually made up the specimen. For each experiment the cooling rates were measured respectively. Response surface method (RSM) was used to analyze the result.

The experimental design, numerical and graphical optimization was done with the aid of the design expert 7.1 software. Figure 2 shows the experimental results for the 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.

Table 2: *The Experimental results for cooling rate.*

Std	*Run*	*Voltage (Volt)*	*Current (Amp)*	*Gas Flow Rate (L/min)*	*Cooling Rate* (^{0}C/sec)
15	*1*	*21.00*	*145.00*	*14.50*	*16.67*
16	*2*	*21.00*	*145.00*	*14.50*	*16.67*
17	*3*	*21.00*	*145.00*	*14.50*	*16.79*
18	*4*	*21.00*	*145.00*	*14.50*	*16.69*
19	*5*	*21.00*	*145.00*	*14.50*	*16.71*
20	*6*	*21.00*	*145.00*	*14.50*	*17.73*

9	*7*	*15.95*	*145.00*	*14.50*	*15.00*
10	*8*	*26.05*	*145.00*	*14.50*	*11.54*
11	*9*	*21.00*	*102.96*	*14.50*	*18.75*
12	*10*	*21.00*	*187.04*	*14.50*	*14.29*
13	*11*	*21.00*	*145.00*	*11.96*	*14.35*
14	*12*	*21.00*	*145.00*	*17.02*	*11.54*
1	*13*	*18.00*	*120.00*	*13.00*	*20.00*
2	*14*	*24.00*	*120.00*	*13.00*	*13.04*
3	*15*	*18.00*	*170.00*	*13.00*	*17.64*
4	*16*	*24.00*	*170.00*	*13.00*	*10.00*
5	*17*	*18.00*	*120.00*	*16.00*	*13.64*
6	*18*	*24.00*	*120.00*	*16.00*	*17.64*
7	*19*	*18.00*	*170.00*	*16.00*	*12.00*
8	*20*	*24.00*	*170.00*	*16.00*	*13.00*

The model summary, which shows the factors and their lowest and highest values including the mean and standard deviation, is presented as shown in figure 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. The minimum cooling rate was observed to be 10.00 0C/sec, maximum value of 20.000 0C/sec, and mean value of 15.185 with a standard deviation of 2.673.

Table 3: *RSM design summary for optimizing weld parameters*

<table>
<tr><td colspan="11"><i>Study type   Response surface   Run   20</i></td></tr>
<tr><td colspan="11"><i>Initial Design Central composite   Blocks   No Blocks</i></td></tr>
<tr><td colspan="11"><i>Design Model Quadratic</i></td></tr>
<tr><td><i>Factor</i></td><td><i>Name</i></td><td><i>Units</i></td><td><i>Type</i></td><td><i>Low Actual</i></td><td><i>High Actual</i></td><td><i>Low Coded</i></td><td><i>High Cod</i></td><td><i>Mean</i></td><td><i>Std. Dev.</i></td><td></td></tr>
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							ed				
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	***Cooling rate***	^{0}C/sec	*20*	***Polynomial***	*10.000*	*20.000*	*15.185*	*2.673*	*2.000*	***None***	***Quadratic***

In assessing the strength of the quadratic model towards minimizing the heat input, one way analysis of variance (ANOVA) was done for each response variable and result is presented in Table 4. Analysis of variance was needed to check whether or not the model is significant and also to evaluate the significant contributions of each individual variable and their combined and quadratic effects towards each response From the result of table 4, the model F-value of 9.07 with computed p-value of 0.0009 implies the model is significant. There is only a 0.09% chance that a "Model F-Value" this large could occur due to noise. Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case A, B, AC, A2, C2 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.

In assessing the strength of the quadratic model towards maximizing the cooling rate one way analysis of variance (ANOVA) was done for each response variable and result is presented in table 4.

Table 4: *ANOVA table for validating the model significance towards maximizing the cooling rate*

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	***140.00***	***9***	***15.56***	***53.71***	***<0.0001***	***Significant***
A-Voltage	***17.41***	***1***	***17.41***	***60.11***	***<0.0001***	
B-Current	***26.94***	***1***	***26.94***	***93..02***	***<0.0001***	
C-GFR	***6.10***	***1***	***6.10***	***21.06***	***0.0010***	
AB	***1.69***	***1***	***1.69***	***5.84***	***0.0362***	
AC	***48.02***	***1***	***48.02***	***165.80***	***<0.0001***	
BC	***0.097***	***1***	***0.097***	***0.33***	***0.5760***	
A^2	***19.47***	***1***	***19.47***	***67.23***	***<0.0001***	
B^2	***2.541E-003***	***1***	***2.541E-003***	***8.775E-003***	***0.9272***	
C^2	***23.51***	***1***	***23.51***	***81.17***	***<0.0001***	
Residual	***2.90***	***10***	***2.90***			

From the result of Table 4, the Model F-value of 53.71 with computed p-value of < 0.0001 implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise. Values of "Prob > F" less than 0.0500 indicate model terms are significant.

In this case A, B, C, AB, AC, A2, C2 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.

To validate the adequacy of the model based on its ability to maximize the cooling rate, the goodness of fit statistics presented in table 5 were employed.

Table 5: *GOF statistics for validating model significance in maximizing cooling rate*

Std. Dev	***0.54***	***R-Squared***	***0.9797***
Mean	***15.18***	***Adj R-Squared***	***0.9615***

C.V%	*3.54*	*Pred R-Squared*	*0.8770*
PRESS	*17.57*	*Adeq Precision*	*25.614*

Coefficient of determination (R-Squared) value of 0.9797 as observed in table 5 shows the strength of response surface methodology and its ability to maximize the cooling rate to a desired value. Adjusted (R-Squared) value of 0.9615 as observed in table 5 indicates a model with 96.15% reliability. Adeq Precision measures the signal to noise ratio. A ratio greater than 4 is desirable. Adequate precision value of 25.614 as observed in table 5indicate an adequate signal. This model can be used to navigate the design space and maximize the cooling rate to the desired value.

The optimal equation which shows the individual effects and combines interactions of the selected variables against the mesured responses (cooling rate) is presented based on the coded variables in equation (1)

$$\begin{aligned} CCR = 3.55702 - 1.95726V + 0.12132A + 5.00863G - 6.13333\times 10^{-3}VA + 0.54444VG \\ - 2.12470\times 10^{-3}AG - 0.12915V^2 - 2.12470\times 10^{-5}A^2 \\ - 0.56766G^2 \qquad (1) \end{aligned}$$

Where

CCR = Calcualted Cooling Rate

V = voltage

A = current

G = Gas flow rate

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 Figures 4

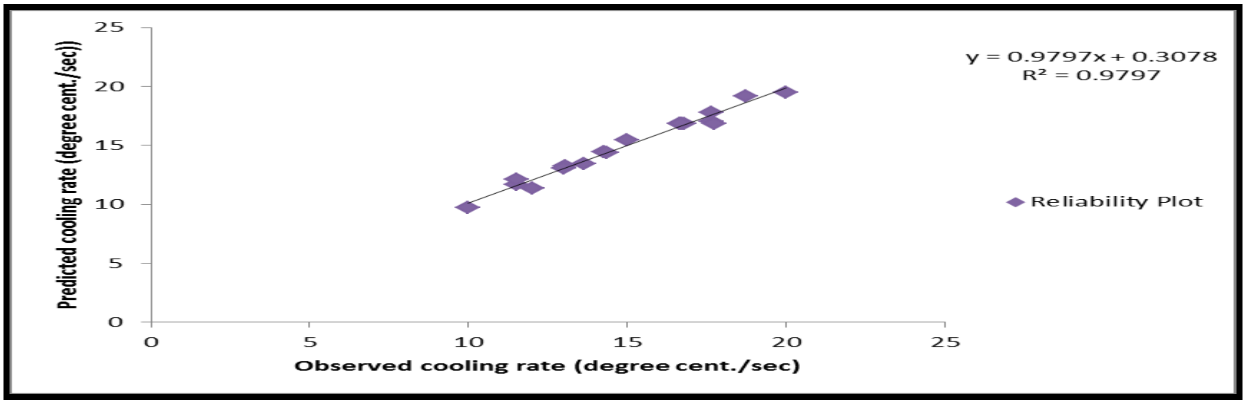


Figure 4: *Reliability plot of observed versus predicted cooling rate*

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 4.

The high coefficient of determination (r2 = 0.9797) as observed in Figure 4 was used to established the suitability of response surface methodology in maximizing the cooling rate 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 cooling rate, the normal probability plot of residual presented in Figure 5 were employed.

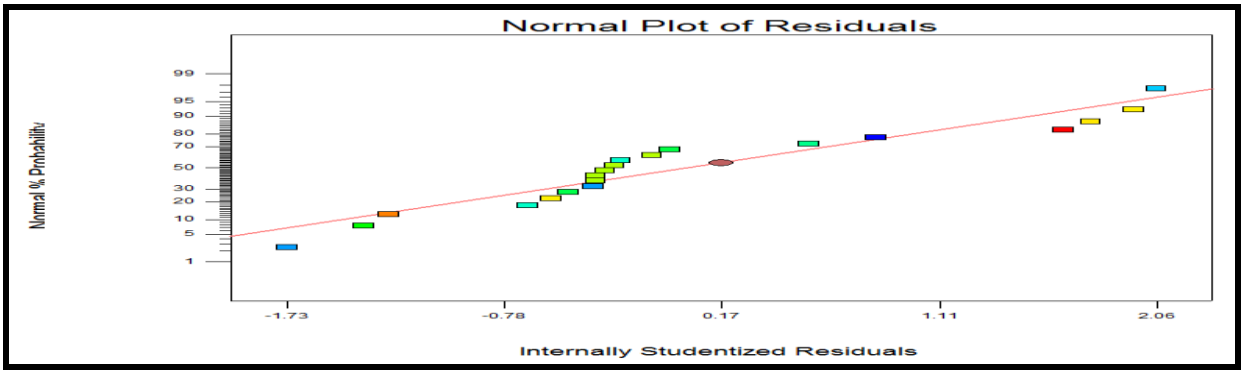


Figure 5: *Normal probability plot of student zed residuals for cooling rate*

The normal probability plot of student zed 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. Result of Figure 5 revealed that the computed residual 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 (cooling rate current and voltage), 3D surface plots presented in Figure 6 were employed.

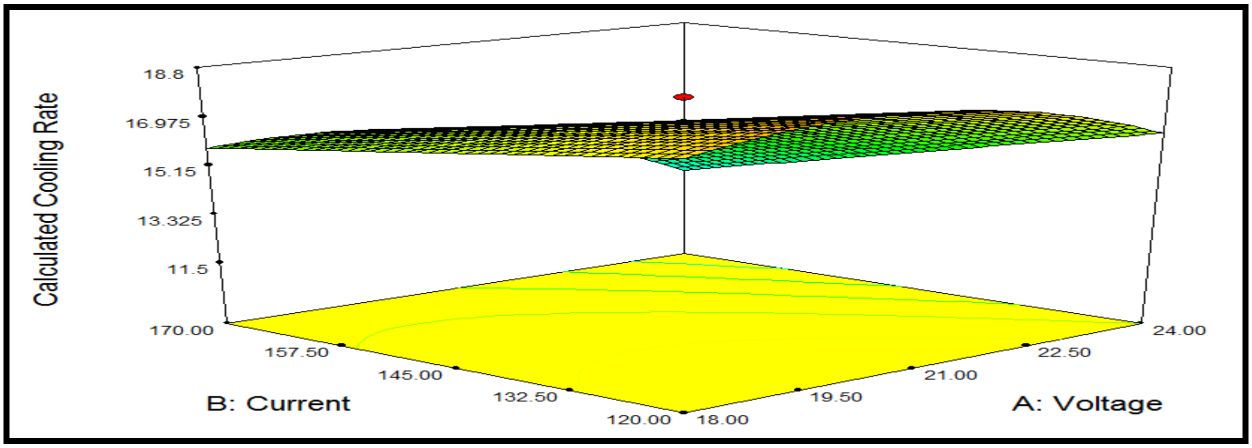
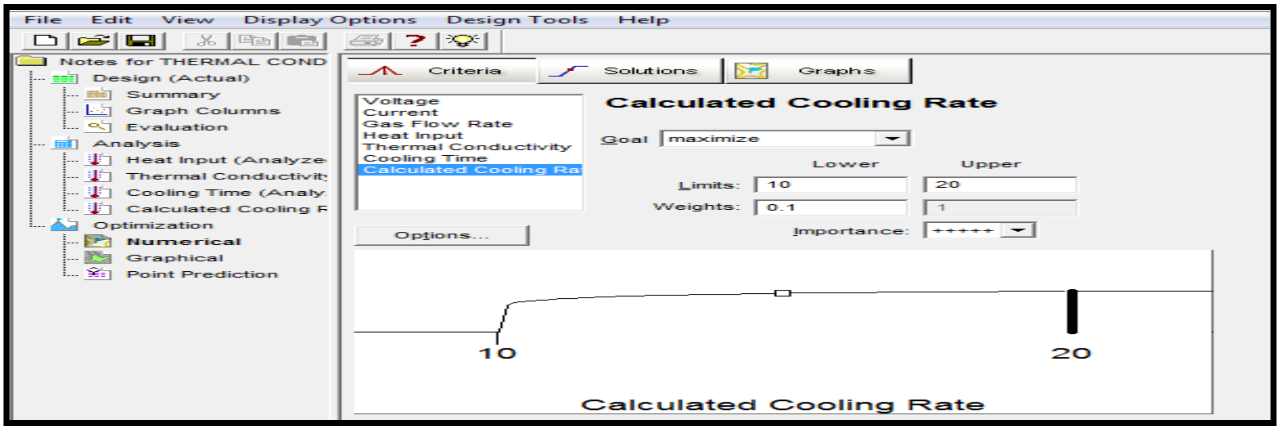


Figure 6: *Effect of current and voltage on calculated cooling rate*

The 3D surface plot as observed in Figure6 shows the relationship between the input variables (voltage, current and gas flow rate) and the response variable (cooling rate). 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 maximize the cooling rate 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 7.



Calculated Cooling Rate

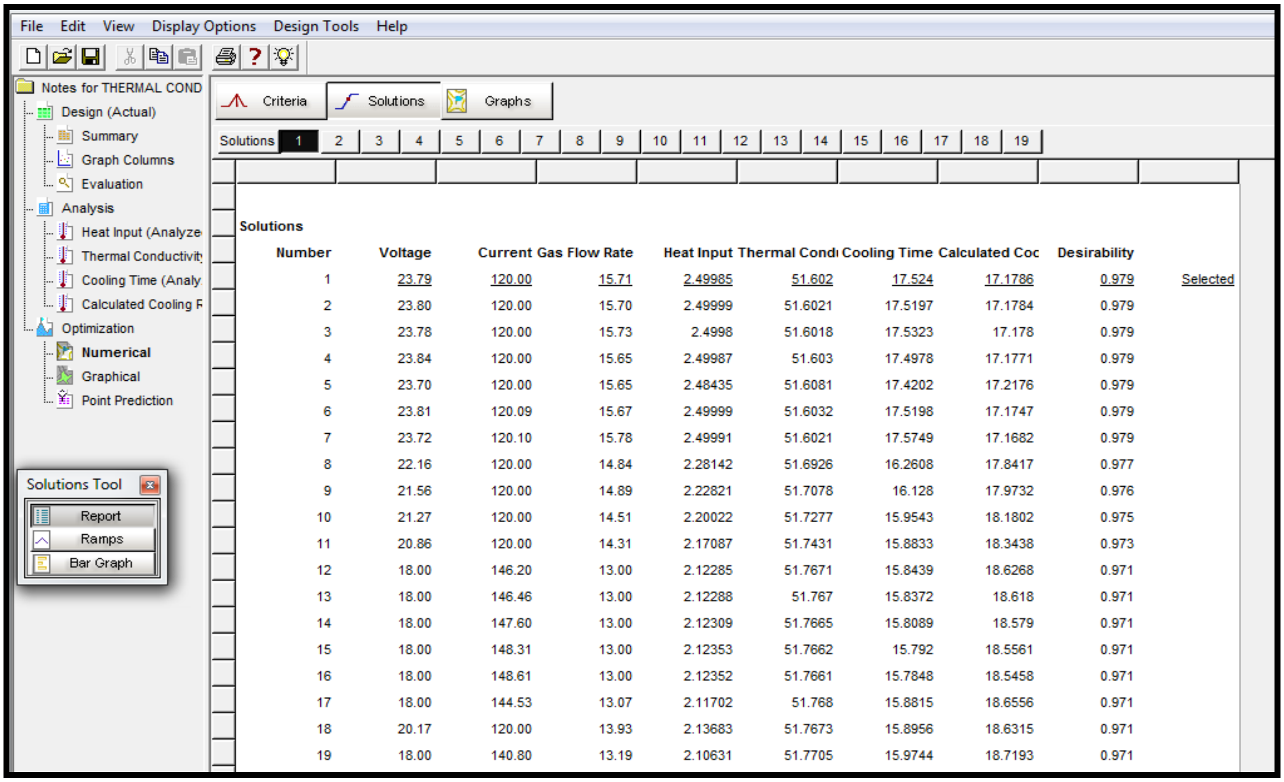
Goal: maximize

	Lower	Upper
Limits:	10	20
Weights:	0.1	1

Importance: +++++

Figure 7: *Interphase of numerical optimization model for maximizing cooling rate*

The numerical optimization produces about nineteen (19) optimal solutions which are presented as shown in figure 8



Solutions

Number	Voltage	Current	Gas Flow Rate	Heat Input	Thermal Condı	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	120.10	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	14.89	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	146.46	13.00	2.12288	51.767	15.8372	18.618	0.971	
14	18.00	147.60	13.00	2.12309	51.7665	15.8089	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 8: *Optimal solutions of numerical optimization model*

From the results of Figure 8, 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 a calculated cooling rate of 17.1786 0C/sec. 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 cooling rate variable is presented in Figure 9.

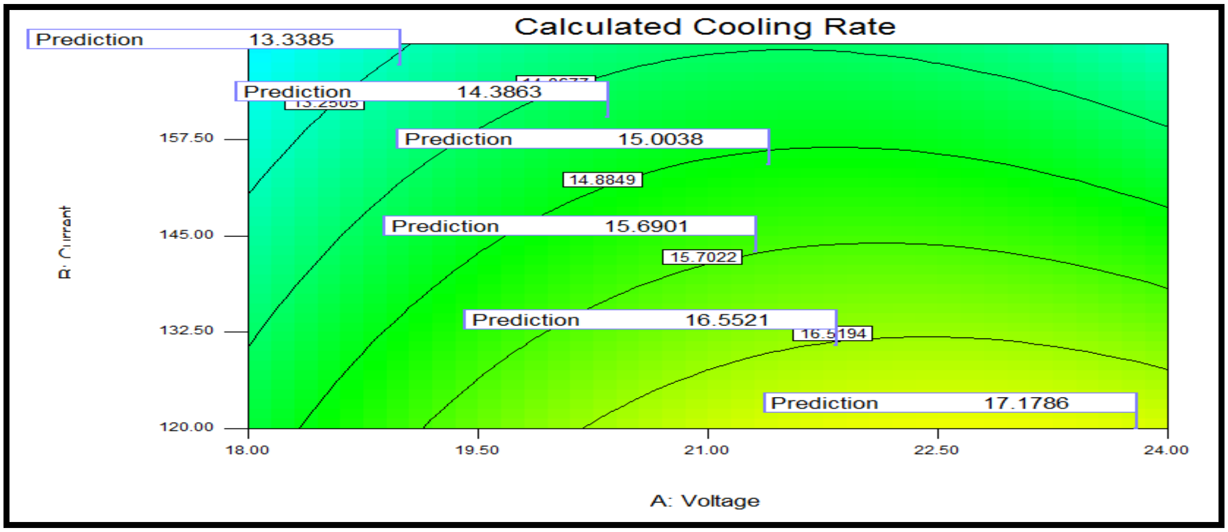


Figure 9: *Prediction of cooling rate using contour plot*

Discussion

In this study, the response surface methodology was used to optimize the cooling rate of gas tungsten arc mild steel welds, note that our aim was to maximize the cooling rate to discourage fast cooling rate that can alter the microstructure abruptly where may be detrimental to the weld zone. Due to the complexity of weld behavior, linear models are insufficient to account for variation in the behavior pattern of welds, therefore, a model was developed using the RSM, and 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.

Analysis of the model standard error was employed to assess the suitability of response surface methodology using the quadratic model to maximizing the cooling rate. In assessing the strength of the quadratic model towards maximizing the cooling rate, 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 maximize the cooling rate to a desired range, the goodness of fit statistics presented in table 5 were employed. Coefficient of determination (R-Squared) value of 0.9797 as observed in Figure 4 which shows the strength of response surface methodology and its ability to maximize the cooling rate to a desired value. Adeq Precision measures the signal to noise ratio. A ratio greater than 4 is desirable. Adequate precision values of 25.614 as observed in Table 5 indicate 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 assess 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 Figures 4.

The high coefficient of determination (r2 = 0.9797) were used to established the suitability of response surface methodology in maximizing the cooling rate to the desired range. To study the effects of combine variables on each response (cooling rate), 3D surface plots presented in Figure 6 were employed.

The 3D surface plot as observed in Figures 6 shows the relationship between the input variables (voltage, current and gas flow rate) and the response variables (cooling rate). 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. Finally, numerical optimization was performed to ascertain the desirability of the overall model. In the numerical optimization phase, we ask design expert to maximize the cooling rate to a desired range while also determining the optimum value of voltage, current and gas flow rate. From the results of Figure 8, 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 a calculated cooling rate of 17.1786 0C/sec. This solution was selected by design expert as the optimal solution with a desirability value of 97.90%. Response surface methodology using numerical optimization was effective in predicting the cooling rate of the welded material. It was also relevant in determining the exact mathematical relationship between the input parameters (voltage, current and gas flow rate) and the response variable (cooling rate). One of the fundamental challenges with RSM is the inability to accurately predict the response variables without design of experiment. It means therefore that the performance of RSM is dependent on the beauty of the design.

Conclusion

The cooling rate of a weldment is a very important factors considered in assessing the quality of welds. The higher the cooling rate of the welding process, the better the integrity of the weld. 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 97% for cooling rate. Adequacy precision measures the signal to noise ratio. A ratio greater than 4 is desirable. Adequate precision values of 25.614 were observed. The model produced numerical optimal solution of current 120.00Amp, voltage of 23.79 volt and a gas flow rate of 15.71 L/min, which will produce a welded material having a calculated cooling rate of 17.1786 ^{0}C/sec. This solution was selected by the design expert as the optimal solution with a desirability value of 97.90%.

It has been shown that the optimization and prediction of cooling rate have a significant effect on the quality and integrity of welded joints. It is, 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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