OPTIMIZATION ANDPREDICTION OF COOLING TIME IN LOW CARBON STEEL WELDMENTS

Enegide, Fergus Uche,;[1]Achebo J, [2] and Osaremwinda, J.O[3]
(Enegide, F) and (Achebo, J)
[1,2,3] Department of Production Engineering
University of Benin
Benin City, Edo State, Nigeria

Abstract

Controlling the temperature distribution in a weldment is critical; the thermal properties resulting from the temperature distribution have a great influence on the weld quality, especially during weld cooling and solidification process. Cooling time is a function of heat input, excessive heat input causes prolonged cooling time giving rooms to micro structural changes which can greatly affect HAZ, Mechanical properties etc. Therefore, minimizing the cooling time helps minimize the detrimental micro structural changes that may result from the process.

This study is aimed at optimizing and predicting cooling time of a welded structure. Response Surface Methodology (RSM) was the expert software used. 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

At the end of the research, 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 cooling time of 17.524 sec. This solution was selected by design expert as the optimal solution with a desirability value of 97.90%.

Keywords: Mild steel, TIG, Cooling Time, HAZ and CCD

Introduction

Achebo, (2011),Etin-osa and Achebo, (2017) and Imhansoloeva et al, (2018) define welding as the most reliable, efficient and practical metal joining process which is widely used in industries such as nuclear, aerospace, automobile, transportation, oil and gas, construction, etc. But in spite of the many advantages, there are some limitations affecting this welding process Kasuya, and Yurioka(1993), Babu et.al(2012). Welding defects alters the desired properties of welded joints. Temperature distribution significantly affects responses such as weld microstructure and HAZ hardness when cooling time is prolonged. As a result of local heating during welding process, controlling the temperature distribution is critical. Differential heating and cooling experienced during welding can result to metallurgical heterogeneity, residual stresses and distortions in welded jointsGeels, (1998), Gharibshahiyan, (2011) and Fonda, (2004). Poor combination of welding thermal properties such as heat input, thermal conductivity and cooling time will definitely amount to poor weld quality. The welding heat input has a great influence on the weldments properties. Mechanical properties and toughness of weldment depend on microstructure of weld metal. The cross sectional area of a weld is generally proportional to the amount of heat input. As more energy is supplied to the arc, more filler material and base metal will be melted per unit length, resulting in a larger weld bead. A change in microstructure directly affects the mechanical properties of weld, which develops into residual stresses and distortion of the weld joints. Therefore it is pertinent to study various aspects related to heat flow in welding such as weld thermal cycle, cooling rate and solidification time, peak temperature and heat affected zone. Cooling rate is a primary factor that determines the metallurgical and microstructure of the weld. The most important characteristic of heat input is that it governs the cooling rates in welds and thereby affects the mechanical properties of the weld. Therefore, the control of heat input is very important in arc welding for quality control. Lazic (2010) considered the cooling time between 800 and 500 ºC (t8/5) predicted the influence that the heat source has on a welded joint from the center of the bead towards the base metal. In summary, minimum cooling time is encouraged for quality weldment. It is important to be able to predict the thermal characteristics such as the cooling rate, heat input, cooling time and thermal conductivity of the heat affected zone. This research would be based on the optimisation and prediction of the cooling rate of a weldment

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. 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

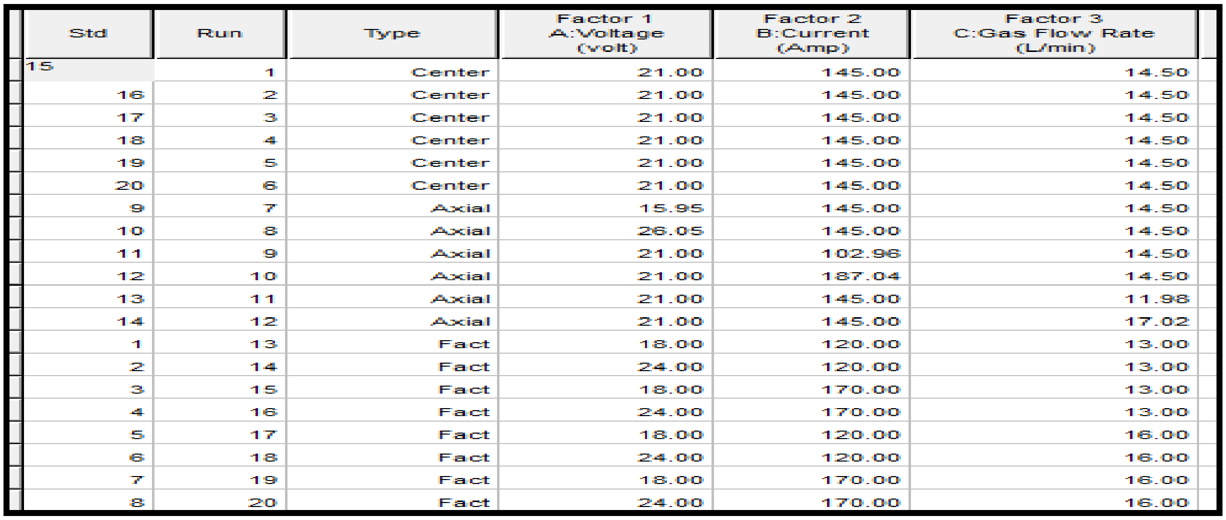
Figure 1: *shielding gas cylinder and regulator*

Figure 2 *Thermocouple Connection cable*

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)*

Response Surface Methodology

Response Surface Methodology (RSM) experts often search for the conditions that would optimize the process of interest. In other words, they want to determine the values of the process input parameters at which the responses reach their optimum. The optimum could be either a minimum or a maximum of a particular function in terms of the process input parameters. RSM is one of the optimization techniques currently in widespread usage to describe the performance of the welding process and find the optimum of the responses of interest. RSM is a set of mathematical and statistical techniques used for modeling and predicting the response of interest affected by several input variables with the aim of optimizing this response (Myers and Montgometry, 1995).

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.

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

Std	*Run*	*Voltage (Volt)*	*Current (Amp)*	*Gas Flow Rate (L/min)*	*Cooling time (Sec)*
15	*1*	*21.00*	*145.00*	*14.50*	*18*
16	*2*	*21.00*	*145.00*	*14.50*	*18.2*
17	*3*	*21.00*	*145.00*	*14.50*	*18.5*
18	*4*	*21.00*	*145.00*	*14.50*	*18.2*
19	*5*	*21.00*	*145.00*	*14.50*	*18.4*
20	*6*	*21.00*	*145.00*	*14.50*	*18.5*
9	*7*	*15.95*	*145.00*	*14.50*	*20*
10	*8*	*26.05*	*145.00*	*14.50*	*26*
11	*9*	*21.00*	*102.96*	*14.50*	*16*

12	*10*	*21.00*	*187.04*	*14.50*	*21*
13	*11*	*21.00*	*145.00*	*11.96*	*21*
14	*12*	*21.00*	*145.00*	*17.02*	*26*
1	*13*	*18.00*	*120.00*	*13.00*	*15*
2	*14*	*24.00*	*120.00*	*13.00*	*23*
3	*15*	*18.00*	*170.00*	*13.00*	*17*
4	*16*	*24.00*	*170.00*	*13.00*	*30*
5	*17*	*18.00*	*120.00*	*16.00*	*22*
6	*18*	*24.00*	*120.00*	*16.00*	*17*
7	*19*	*18.00*	*170.00*	*16.00*	*25*
8	*20*	*24.00*	*170.00*	*16.00*	*32*

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. The minimum value of cooling time was observed to be 15.000 Sec; the maximum value was 32.000 Sec with a mean value of 21.040 and standard deviation of 4.533.

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 Coded</i></td><td><i>Mean</i></td><td><i>Std. Dev.</i></td><td></td></tr>
<tr><td><i>A</i></td><td><i>Voltage</i></td><td><i>Volt</i></td><td><i>Numeric</i></td><td><i>18.00</i></td><td><i>24.00</i></td><td><i>-1.00</i></td><td><i>1.00</i></td><td><i>21.000</i></td><td><i>2.479</i></td><td></td></tr>
</table>

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 time***	Sec	*20*	***Polynomial***	*15.00*	*32.000*	*21.040*	*4.533*	*21.33*	***None***	***Quadratic***

In assessing the strength of the quadratic model towards minimizing the cooling time 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 minimizing the cooling time*

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	***386.96***	***9***	***43.00***	***17.96***	***<0.0001***	***Significant***
A-Voltage	***80.18***	***1***	***80.18***	***33.48***	***0.0002***	
B-Current	***91.81***	***1***	***91.81***	***38.34***	***0.0001***	
C-GFR	***27.58***	***1***	***27.58***	***11.52***	***0.0068***	
AB	***36.13***	***1***	***36.13***	***15.09***	***0.0030***	
AC	***45.12***	***1***	***45.12***	***18.84***	***0.0015***	
BC	***10.13***	***1***	***10.13***	***4.23***	***0.0666***	
A^2	***47.78***	***1***	***47.78***	***19.95***	***0.0012***	

B^2	***0.76***	***1***	***0.76***	***0.32***	***0.5853***	
C^2	***57.51***	***1***	***57.51***	***24.02***	***0.0006***	
Residual	***23.95***	***10***	***2.39***			

From the result of table 4 the Model F-value of 17.96 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.

To validate the adequacy of the model based on its ability to minimize the cooling time the goodness of fit statistics presented in table 5 were employed;

Table 5: *GOF statistics for validating model significance in minimizing cooling time*

Std. Dev	***1.55***	***R-Squared***	***0.9417***
Mean	***21.04***	***Adj R-Squared***	***0.8893***
C.V%	***7.35***	***Pred R-Squared***	***0.5371***
PRESS	***190.23***	***Adeq Precision***	***13.773***

Coefficient of determination (R-Squared) values of 0.9417as observed in table 5 shows the strength of response surface methodology and its ability to minimize the cooling time to a desired value. Adjusted (R-Squared) value of 0.8893 as observed in table 5 indicates a model with 88.93% reliability. Adeq Precision measures the signal to noise ratio. A ratio greater than 4 is desirable. Adequate precision value of 13.773 as observed in table 5indicate an adequate signal. This model can be used to navigate the design space and minimize the cooling time and thermal conductivity, maximize the cooling rate and optimize the heat input to the desired value.

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

$$CT = 244.79891 - 4.14512V - 1.03294A - 18.06622G + 0.028333VA - 0.52778VG - 0.03AG + 0.20232V^2 + 3.67754 \times 10^{-4}A^2 + 0.88783G^2 \quad (1)$$

Where

CT = Cooling time

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

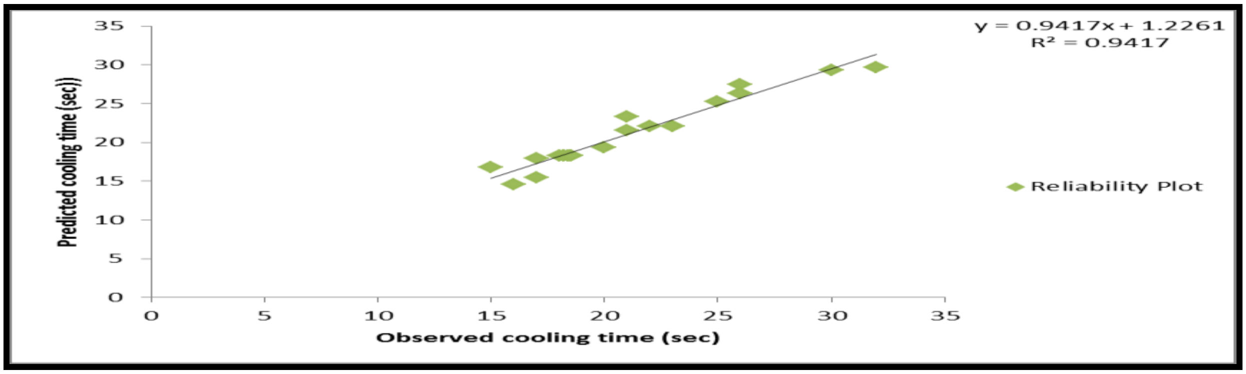


Figure 4: *Reliability plot of observed versus predicted cooling time*

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 was obtained as presented in Figures 4

The high coefficient of determination (r2 = 0.9417) as observed in Figure 4 was used to established the suitability of response surface methodology in minimizing the cooling time 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 cooling time, the normal probability plot of residual presented in Figure 5 were employed.

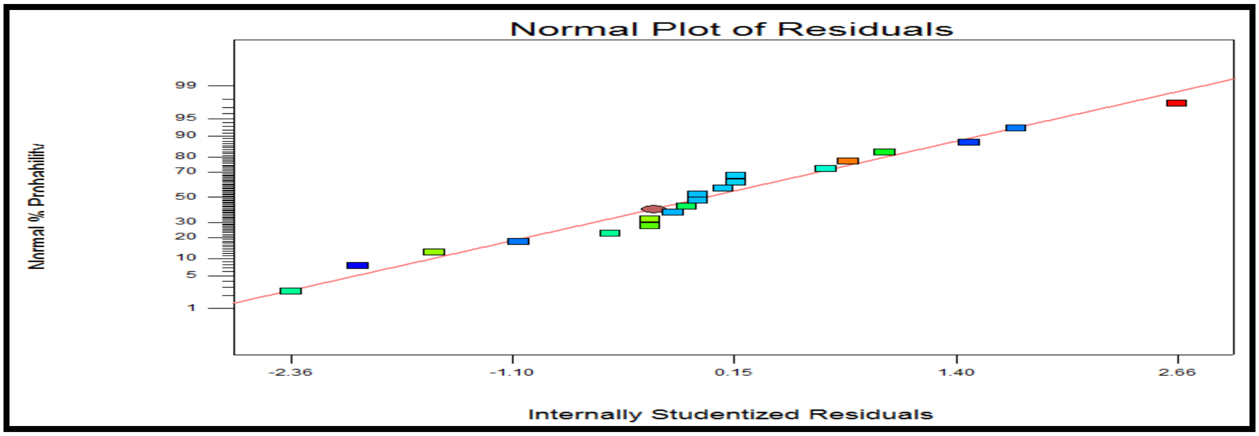


Figure 5: *Normal probability plot of student zed residuals for cooling time*

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. Results of Figure 5 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 (cooling time current and voltage), 3D surface plots presented in Figure 6 were employed.

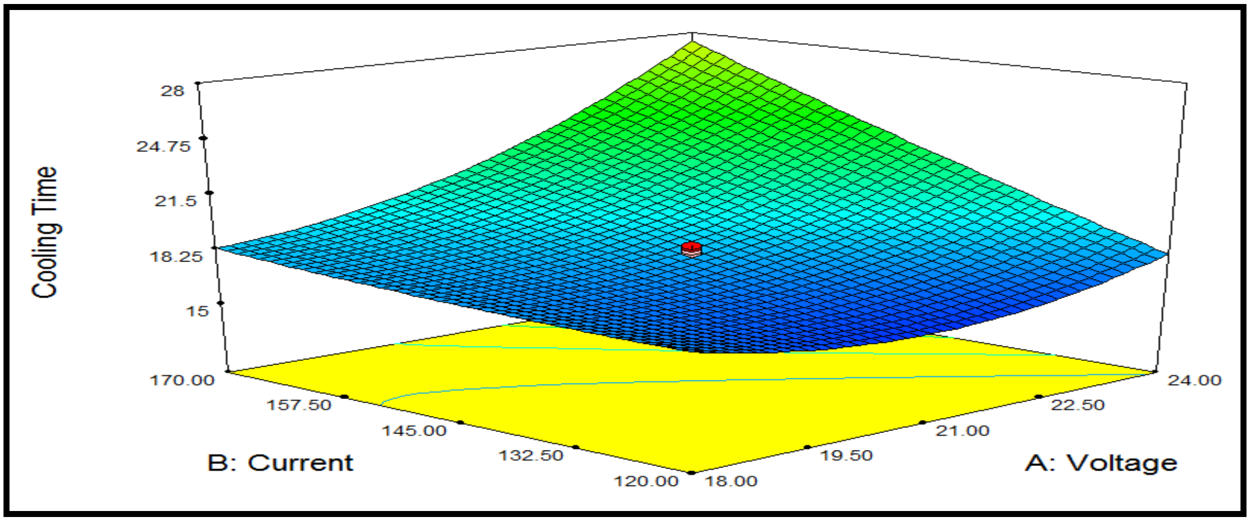
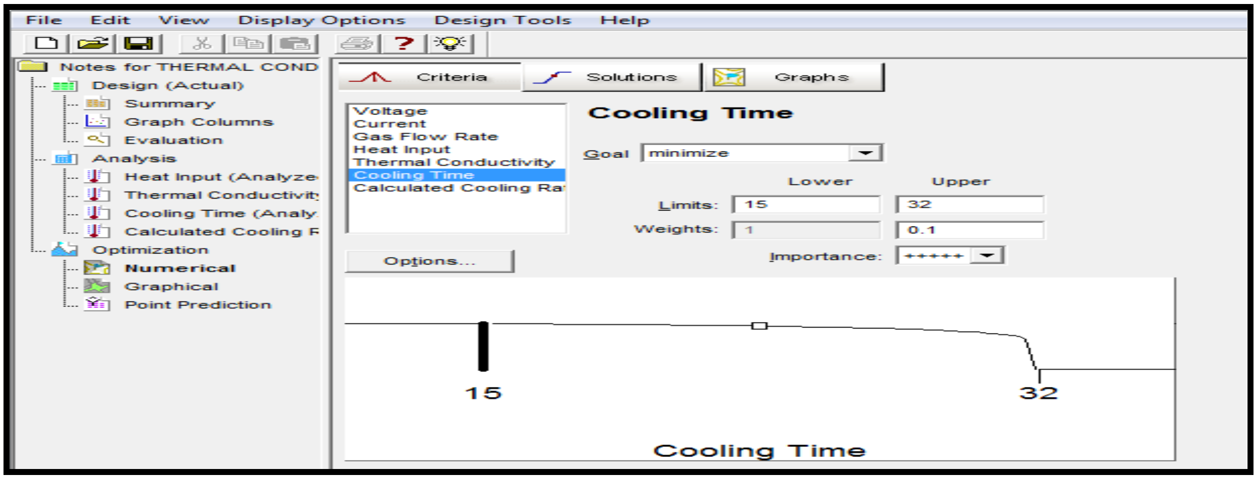


Figure 6: *Effect of current and voltage on cooling time*

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 (heat input, thermal conductivity, cooling time and 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. The presence of a coloured hole at the middle of the upper surface gave a clue that more points lightly shaded for easier identification fell below the surface.

Finally, numerical optimization was performed to ascertain the desirability of the overall model.

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 cooling time 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



Cooling Time

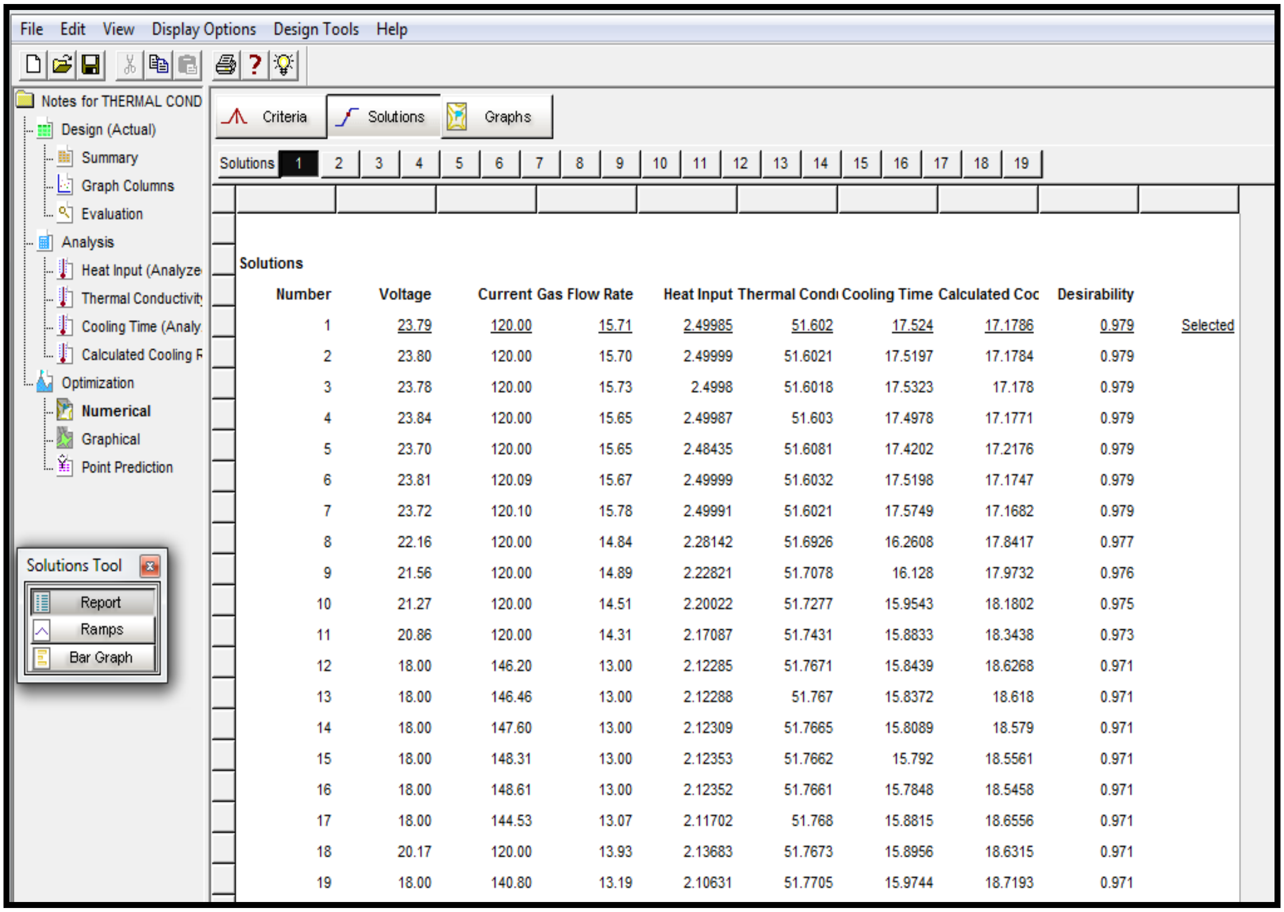
Goal: minimize

	Lower	Upper
Limits:	15	32
Weights:	1	0.1

Importance: +++++

Figure 7: *Interphase of numerical optimization model for minimizing cooling time*

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 cooling time of 17.524 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 time variable is presented in Figure 9.

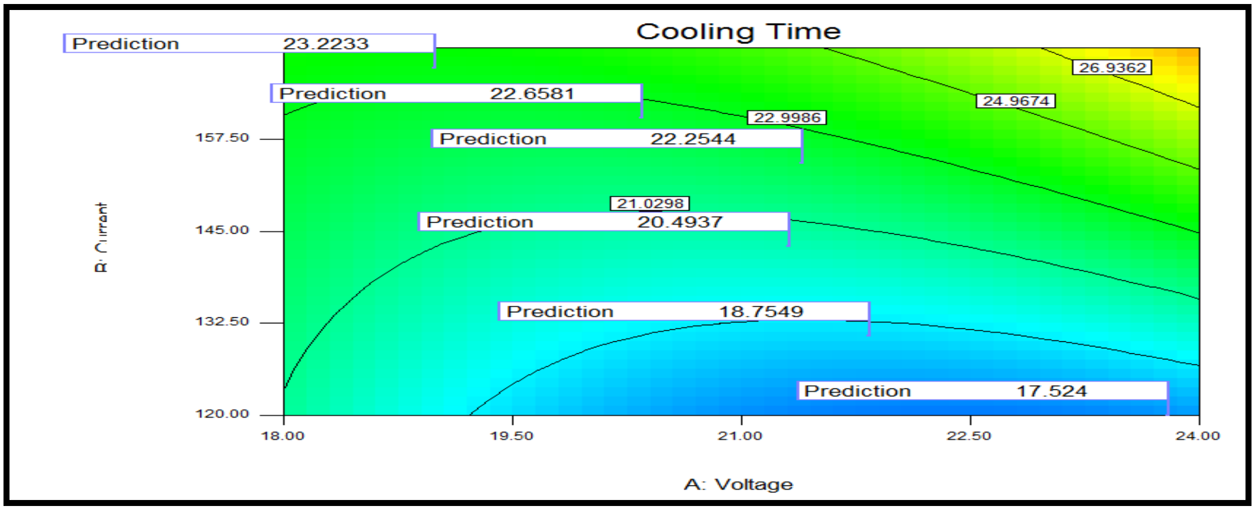


Figure 9: *Prediction of cooling time using contour plot*

Response surface methodology using numerical optimization was effective in predicting cooling time 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 variables (cooling time). One of the fundamental challenges with RSM is its 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.

Discussion

In this study, the response surface methodology was used to optimize the cooling time of gas tungsten arc mild steel welds. 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 welding voltage and gas flow rate has influence on the cooling time, a high voltage results in a high heat input and cooling time.

Analysis of the model standard error was employed to assess the suitability of response surface methodology using the quadratic model to minimize the cooling time. In assessing the strength of the quadratic model towards minimizing the cooling time 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 cooling time to a desired range, the goodness of fit statistics presented in table 5 was employed. Coefficient of determination (R-Squared) value of 0.9417 as observed in table 5 shows the strength of response surface methodology and its ability to minimize the cooling time to a desired value. Adeq Precision measures the signal to noise ratio. A ratio greater than 4 is desirable. Adequate precision values of 13.773 as 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 Figures 4.

The high coefficient of determination (r2 = 0.9417) was used to established the suitability of response surface methodology in minimizing the cooling time to the desired range. To study the effects of combine variables on each response (cooling time), 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 time). 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 time decreases. 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 cooling time 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 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 a cooling time of 17.524 sec. This solution was selected by design expert as the optimal solution with a desirability value of 97.90%.

Conclusion

The better the integrity of the weld and also the lower the cooling time the better the quality of the weld. In this study the Response Surface Methodology was employed to optimize and predict the thermal properties of low carbon steel weldments. 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 R2 (Coefficient of determination) values of 94% for cooling time. Adequacy precision measures the signal to noise ratio. A ratio greater than 4 is desirable. Adequate precision values of 13.773 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 that will produce a welded material having cooling time of 17.524 sec. This solution was selected by the design expert as the optimal solution with a desirability value of 97.90%.

It is recommended that welders should adopt this process parameter to achieve a minimal cooling time.

Reference

Achebo, J. I., (2011), Optimization of GMAW protocols and parameters for improving weld strength quality applying the Taguchi method, Proceeding of the World Congress on Engineering, Vol.1, WCE 2011,July 6-8, London U.K.

Collins Eruogun Etin-osa and Joseph Ifeanyi Achebo. (2017). Analysis of Optimum Butt Welded Joint for Mild Steel Components Using FEM (ANSYS). American Journal of Naval Architecture and Marine Engineering DOI: 10.11648/j.aas.20170206.12

Nicholas Afemhonkike Imhansoloeva, Joseph Ifeanyi Achebo, Kessington Obahiagbon, John Osadolor Osarenmwinda, Collins Eruogun Etin-Osa. (2018). "Optimization of the Deposition Rate of Tungsten Inert Gas Mild Steel Using Response Surface Methodology". Scientific Research Publishing. vol.10, pp784-804

Kasuya, T., and Yurioka, N. (1993). Prediction of welding thermal history by a comprehensive so- lution. Welding Journal 72(3): 107-s to 115-s.

Babu, P. D., Buvanashekaran, G., & Balasubramanian, K. R. (2012). Experimental Study on the Microstructure and Hardness of Laser Transformation Hardening of Low-alloy Steel. Transactions of the Canadian Society for Mechanical Engineering, 36(3), 241 – 245.

Geels, K. (1998): The true microstructure of materials, Micro structural Sci., 26 195-204.

Gharibshahiyan, E. Raouf, A. H. Parvin, N. and Rahimian, M. (2011): The effect of microstructure on hardness and toughness of low carbon welded steel using inert gas welding. Materials and Design. 32(4): 2042-2048.

Fonda, R. W., Bingert, J. F., Colligan, K. J., Development of grain structure during friction stir welding, Scripta Materialia 51 (2004), pp. 243-248.

Lazic, V. N. (2010): Theoretical-Experimental Determining of Cooling Time (T(8/5)) in Hard Facing of Steels for Forging Dies, Thermal Science, 1, pp. 235–246, DOI No. 10.2298/TSCI1001235L.

Lazic, V. N. (2010): Energetic Analysis of Hard Facing and Weld Cladding of An Air Powered Drop Hammer Damaged Ram, Thermal Science, suppl, pp. S269–S284, DOI No. 10.2298/TSCI100501021L.

Myers RH and Montgomery DC (1995). Response Surface Methodology (New York: John Wiley & Sons).