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REVIEW ARTICLE

APPLICATION OF EXPERT METHODS FOR PREDICTING HEAT AFFECTED ZONE OF TIG WELDMENTS

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ABSTRACT

The heat-affected zone (HAZ) of a weld, is the area of base metal, which is not melted during welding but has had its microstructural properties altered by welding. In this study, the application of expert systems such as response surface method to optimize the heat affected zone using tungsten inert gas was pursued. The central composite design matrix was employed to collect data from the sets of experiments. The specimen was made from mild steel plates and welded with the tungsten inert gas process. Thereafter, the response surface methodology was employed to optimize and predict the responses from the process parameters. The result of the response surface method shows that the current has a very strong influence on the heat affected zone. The model for minimizing heat affected zone has a goodness of fit value of 94%. Finally, the numerical solution obtained shows that a current of 130Amp, a voltage of 20.94volts, and a speed of 0.48m/min produced a result with heat affected zone of 3.42mm, with a desirability of 0.76 which is acceptably very good.

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INTRODUCTION

The ever increasing demand for better efficiency and durability of products in the manufacturing industry, has given rise to optimization of process parameters which is highly essential for a manufacturing unit to respond promptly and efficiently to the rugged competitiveness and ever increasing demand for quality products in the market. When designing a welded component, it is imperative to consider not only the mechanical properties of the base material, but in particular the strength and properties of the weldments Lozano, (2018). Recent investigations indicate that a wider heat affected zone (HAZ) is more detrimental to creep properties than a thinner oneŚloderbach and Pająk, (2015). Altogether, the weld bead shape parameter like HAZ width play an important role in deciding the mechanical properties, creep properties and weld quality Singh et al, (2013). These shape parameters in turn are decided by welding process parameters like current, arc voltage and torch speed. Achebo and Odinikuku, (2015) show that to obtain optimal combinations of input process parameters, welders mostly use the trial-and-error-based approach, which is mostly expensive and time consuming, it is not also suitable for complex manufacturing processes. Research studies have shown that there is no known particular method that can be said is the best optimization model for welding processes.However, different researchers use different models to carry out their studies.

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Welding happens to be a non-linear manufacturing process, which requires an advanced model that can predict the interaction between the welding input parameters and their various outputs. Exploring certain aspects of the application of expert systems such as response surface method (RSM) to optimize the tungsten inert gas welding is the motive of this study. Although, previous investigators such Achebo and Ozigagun (2018) has applied expert systems to predict the weld bead reinforcement and undercut.As reported by Balasubramanian et al. (2008), current pulsing eliminates the micro segregation in the inter-dendritic region due to the reduced heat input. It is also reported that weld metal properties have been improved by usage of pulsing current. Vijay et al.(2016) as reported by many researchers, carbon migration is a prospective drawback and is extremely unenviable as it makes the material more brittle due to formation of carbides in unwanted locations. Also it results in carbon denuded soft zone thereby reducing the tensile strength. It is also reported that pulsed current has seized elemental migration, especially carbon than continuous welds. According to Kim et al. (2005), the quality of welded joints is largely affected by the welding process parameters. The quality of autogenous weld joint can be assessed by various bead geometric characteristics such as penetration, width and depth. Welding is influenced by many input parameters therefore it can be considered as multi-input, multi-output process. Kumar et al. (2009) has showed that optimized parameters increases the mechanical properties. For achieving the best weld quality, nowadays design of experiments (DoE) are widely applied to formulate mathematical models between welding input parameters and output variables to determine the optimal welding input parameters. The experimental optimization of any welding process is usually a highly expensive and arduous task, due to many kinds of associated non-linear events. Response Surface Methodology (RSM) serves as an alternative to this expensive experimental process. According to them, RSM is an assortment of statistical techniques used when the output (response) is affected by numerous input variables and the main aim is to optimize the response. A Survey done by Benyounis et al. (2008) and Buddu et al (2014) for modeling, controlling and optimizing of various welding process unveils high level of interest in incorporation of response surface methodology (RSM) to predict response and optimize welding process. According to Shanmugam et al. (2009), effect of parameters on response can be studied using RSM and optimal values can be obtained using contour plots. Ferreira and Bruns, (2007) mentioned that Box behnken design is adopted because it is an economical model compared to the central composite method, since it has less no of design points. Important input parameters identified are pulsing frequency, background current and peak current. Experimental optimization of the process parameters requires a number of trials and time consuming. Therefore, it becomes essential to devise a computational methodology to optimize the welding process parameters to achieve the target weld bead geometry and HAZ width. There exists a non-linear relation between the welding process parameters and the weld bead shape parameters. Soft computing techniques are the natural option for solving similar non-linear and complex problems in welding where a mathematical model is either too difficult to encode, does not exist and expensive to be evaluated.

MATERIALS AND METHODS

Materials: The key parameters considered in this work are welding current, welding speed, welding voltage. The range of the process parameters obtained from literature is shown in table 1. 100 pieces of mild steel coupons measuring 60mm x 40mm x10mm were used for thisexperiments. The experiment was performed 20 times, using 5 specimens for each run.Figure 1 shows the TIG welding setup.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 shielding gas cylinder and regulator.Plate 4 shows the thermocouple connection cable which is used to connect the thermocouple to the weld specimen, weld sample is shown in plate 3.The central composite design matrix was developed using the design expert software, producing 20 experimental runs. The input parameters and output parameters make up the experimental matrix and the responses recorded from the weld samples were used as the data. Figure 5 shows the central composite design matrix.

Second-Order polynomial model: When there is a curvature in the response surface the first-order model is insufficient. A second-order model is useful in approximating a portion of the true response surface with parabolic curvature. The second-order model includes all the terms in the first-order model, plus all quadratic terms like $\beta_{11} x_{1i}$ and all cross product terms like $\beta_{13} x_{1i}$. It is usually expressed as

$$y = \beta_0 + \sum_{j=1}^{q} \beta_{jj} x_j^2 + \sum\sum_{kj} \beta_{ij} x_i x_i + \varepsilon \quad (1)$$

Where $(x_{1i}, x_{2i},.., x_{iq})$, $\beta = (\beta_1, \beta_2,.., \beta_q)$

RESULTS AND DISCUSSION

The randomized design matrix comprising of three input variables namely; current (Amp), voltage (V), welding speed (m/min) and four response variables namely (arc length, liquidus temperature, heat input and heat affected zone) in real values is presented in Figure 6. For heat affected zone (HAZ), the minimum value was observed to be 4.920mm, with a maximum value of 14.660mm, mean value of 9.881 and standard deviation of 3.027. 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 7 To validate the suitability of the quadratic model in analyzing the experimental data, the sequential model sum of squares were calculated for heat affected zone **i**s presented in Figure 8. To test how well the quadratic model can explain the underlying variation associated with the experimental data, the lack of fit test was estimated for heat affected zone (HAZ). Results of the computed lack of fit is presented in Figure 9. The model statistics computed for heat affected zone (HAZ)based on the different model sources is presented in Figure10.

The model summary statistics of models fit shows the standard deviation, the r-squared and adjusted r-squared, predicted r-squared and the PRESS statistic for each complete model. Low standard deviation, R-Squarednear 1 and relatively low PRESS are the optimum criteria for defining the best model source. Based on the results of Figure 4.15, the quadratic polynomial model was suggested while the cubic polynomial model was aliased hence, the quadratic polynomial model was selected for this analysis. In assessing the strength of the quadratic model towards minimizing the heat affected zone (HAZ), one way analysis of variance (ANOVA) table was generated for minimizing the heat affected zone and result obtained is presented in Figure 11.

Analysis of variance (ANOVA) was needed to check whether or not the model is significant and also to evaluate the significant contributions of each individual variable, the combined and quadratic effects towards each response. To validate the adequacy of the quadratic model based on its ability to minimize the heat affected zone (HAZ), the goodness of fit statistics presented in Table 12 were employed. From the result of Figure 12, it was observed that the "Predicted R-Squared" value of 0.6278 is in reasonable agreement with the "Adj R-Squared" value of 0.8871. Adequate precisionmeasures the signal to noise ratio. A ratio greater than 4 is desirable. The computaed ratio of 15.074 observed in Figure 12indicates an adequate signal. This model can be used to navigate the design space and adequately minimize the heat affected zone (HAZ). The optimal equation which shows the individual effects and combine interactions of the selected input variables (current (Amp), voltage (V) and welding speed (m/min)) against the mesured response(heat affected zone) is presented in actual factors in Figure 13. To asses the accuracy of prediction and established the suitability of response surface methodology using the quadratic model, a reliability plot of the

Table 1. Process parameters and their levels

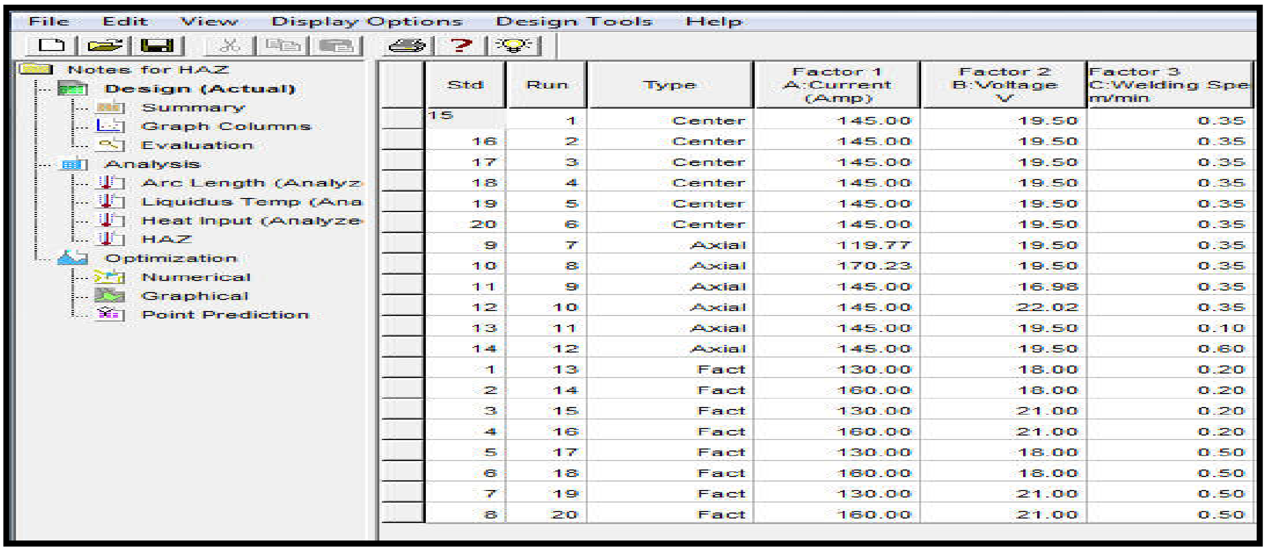
Parameters	Unit	Symbol	Coded value	Coded value
			Low(-1)	High(+1)
Current	Amp	A	100	180
welding speed,	M/min	F	0.10	0.6
Voltage	Volt	V	16	22

Plate 1. TIG equipment

Plate 2. Shielding gas cylinder and regulator

Plate 3. Weld samples

Plate 4. Thermocouple connection cable



Std	Run	Type	Factor 1 A:Current (Amp)	Factor 2 B:Voltage V	Factor 3 C:Welding Spe m/min
15	1	Center	145.00	19.50	0.35
16	2	Center	145.00	19.50	0.35
17	3	Center	145.00	19.50	0.35
18	4	Center	145.00	19.50	0.35
19	5	Center	145.00	19.50	0.35
20	6	Center	145.00	19.50	0.35
9	7	Axial	119.77	19.50	0.35
10	8	Axial	170.23	19.50	0.35
11	9	Axial	145.00	16.98	0.35
12	10	Axial	145.00	22.02	0.35
13	11	Axial	145.00	19.50	0.10
14	12	Axial	145.00	19.50	0.60
1	13	Fact	130.00	18.00	0.20
2	14	Fact	160.00	18.00	0.20
3	15	Fact	130.00	21.00	0.20
4	16	Fact	160.00	21.00	0.20
5	17	Fact	130.00	18.00	0.50
6	18	Fact	160.00	18.00	0.50
7	19	Fact	130.00	21.00	0.50
8	20	Fact	160.00	21.00	0.50

Figure 5. Central Composite Design Matrix (CCD)

Std	Run	Type	Factor 1 A:Current (Amp)	Factor 2 B:Voltage V	Factor 3 C:Welding Spe m/min	Response 1 Arc Length (mm)	Response 2 Liquidus Temp (degree C)	Response 3 Heat Input KJ/mm	Response 4 HAZ (mm)
15	1	Center	145.00	19.50	0.35	2	1187	0.3224	12.62
16	2	Center	145.00	19.50	0.35	3	1208	0.3321	12.41
17	3	Center	145.00	19.50	0.35	3	1208	0.3422	12.73
18	4	Center	145.00	19.50	0.35	3	1214	0.3215	12.56
19	5	Center	145.00	19.50	0.35	3	1236	0.3266	11.24
20	6	Center	145.00	19.50	0.35	3	1220	0.2857	11.27
9	7	Axial	119.77	19.50	0.35	2	1257	0.476	5.33
10	8	Axial	170.23	19.50	0.35	4	1523	0.559	5.39
11	9	Axial	145.00	16.98	0.35	4	1326	0.3786	7.52
12	10	Axial	145.00	22.02	0.35	3	1265	0.7873	4.92
13	11	Axial	145.00	19.50	0.10	2	1285	0.6724	14.66
14	12	Axial	145.00	19.50	0.60	2	1280	0.5993	14.28
1	13	Fact	130.00	18.00	0.20	2	1367	0.5967	10.25
2	14	Fact	160.00	18.00	0.20	4	1548	0.5894	8.63
3	15	Fact	130.00	21.00	0.20	2	1118	0.5699	11.12
4	16	Fact	160.00	21.00	0.20	4	1302	0.8577	11.78
5	17	Fact	130.00	18.00	0.50	4	1236	0.3313	8.14
6	18	Fact	160.00	18.00	0.50	4	1361	0.2939	9.82
7	19	Fact	130.00	21.00	0.50	2	1420	0.6786	5.08
8	20	Fact	160.00	21.00	0.50	2	1548	0.878	7.86

Figure 6. Design matrix showing the real values and the experimental values

Design Summary

Study Type	Response Surface	Runs	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	Current	(Amp)	Numeric	130.00	160.00	-1.000	1.000	145.000	12.395
B	Voltage	V	Numeric	18.00	21.00	-1.000	1.000	19.500	1.240
C	Welding Speed	m/min	Numeric	0.20	0.50	-1.000	1.000	0.350	0.124

Response	Name	Units	Obs	Analysis	Minimum	Maximum	Mean	Std. Dev.	Ratio	Trans	Model
Y1	Arc Length	(mm)	20	Polynomial	2.000	4.000	2.900	0.831	2.000	None	Quadratic
Y2	Liquidus Temp	(degree C)	20	Polynomial	1118.000	1548.000	1305.450	119.151	1.385	None	Quadratic
Y3	Heat Input	KJ/mm	20	Polynomial	0.286	0.878	0.510	0.191	3.073	None	Quadratic
Y4	HAZ	(mm)	20	Polynomial	4.920	14.660	9.881	3.027	2.980	None	Quadratic

Figure 7. RSM design summary

Response 4 HAZ Transform: None

*** WARNING: The Cubic Model is Aliased! ***

Sequential Model Sum of Squares [Type I]

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Mean vs Total	1952.49	1	1952.49			
Linear vs Mean	12.78	3	4.26	0.40	0.7550	
2FI vs Linear	15.32	3	5.11	0.43	0.7365	
Quadratic vs 2FI	144.25	3	48.08	44.15	< 0.0001	Suggested
Cubic vs Quadra	7.30	4	1.83	3.05	0.1077	Aliased
Residual	3.59	6	0.60			
Total	2135.72	20	106.79			

Figure 8: Sequential model sum of square heat affected zone (HAZ)

Lack of Fit Tests

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Linear	168.06	11	15.28	31.90	0.0006	
2FI	152.75	8	19.09	39.87	0.0004	
Quadratic	8.50	5	1.70	3.55	0.0954	Suggested
Cubic	1.19	1	1.19	2.49	0.1753	Aliased
Pure Error	2.39	5	0.48			

"Lack of Fit Tests": Want the selected model to have insignificant lack-of-fit.

Figure 9. Lack of fit test for heat affected zone (HAZ)

Model Summary Statistics

Source	Std. Dev.	R-Squared	Adjusted R-Squared	Predicted R-Squared	PRESS	
Linear	3.26	0.0697	-0.1047	-0.5669	287.12	
2FI	3.45	0.1533	-0.2375	-0.6804	307.91	
Quadratic	1.04	0.9406	0.8871	0.6278	68.20	Suggested
Cubic	0.77	0.9804	0.9380	-0.4543	266.48	Aliased

"Model Summary Statistics": Focus on the model maximizing the "Adjusted R-Squared" and the "Predicted R-Squared".

Figure 10. Model summary statistics for heat affected zone (HAZ)

Use your mouse to right click on individual cells for definitions.

Response 4 HAZ

ANOVA for Response Surface Quadratic Model

Analysis of variance table [Partial sum of squares - Type III]

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	172.35	9	19.15	17.58	< 0.0001	significant
A-Current	*0.95*	*1*	*0.95*	*0.87*	*0.3724*	
B-Voltage	*2.11*	*1*	*2.11*	*1.94*	*0.1938*	
C-Welding Speed	*9.72*	*1*	*9.72*	*8.92*	*0.0136*	
AB	*1.43*	*1*	*1.43*	*1.31*	*0.2788*	
AC	*3.67*	*1*	*3.67*	*3.37*	*0.0962*	
BC	*10.22*	*1*	*10.22*	*9.38*	*0.0120*	
A^2	*74.10*	*1*	*74.10*	*68.04*	*< 0.0001*	
B^2	*55.56*	*1*	*55.56*	*51.02*	*< 0.0001*	
C^2	*13.10*	*1*	*13.10*	*12.03*	*0.0060*	
Residual	10.89	10	1.09			
Lack of Fit	*8.50*	*5*	*1.70*	*3.55*	*0.0954*	*not significant*
Pure Error	*2.39*	*5*	*0.48*			
Cor Total	183.24	19				

Figure 11. ANOVA table for validating the model significance towards minimizing the heat affected zone

Std. Dev.	1.04	R-Squared	0.9406
Mean	9.88	Adj R-Squared	0.8871
C.V. %	10.56	Pred R-Squared	0.6278
PRESS	68.20	Adeq Precision	15.074

Figure 12. GOF statistics for validating model significance towards minimizing HAZ

Final Equation in Terms of Actual Factors:

HAZ	=
-487.76970	
+2.46860	* Current
+32.80602	* Voltage
+18.98914	* Welding Speed
+0.018778	* Current * Voltage
+0.30111	* Current * Welding Speed
-5.02222	* Voltage * Welding Speed
-0.010078	* Current^2
-0.87265	* Voltage^2
+42.37140	* Welding Speed^2

Figure 13. Optimal equation in terms of actual factors for minimizing the HAZ

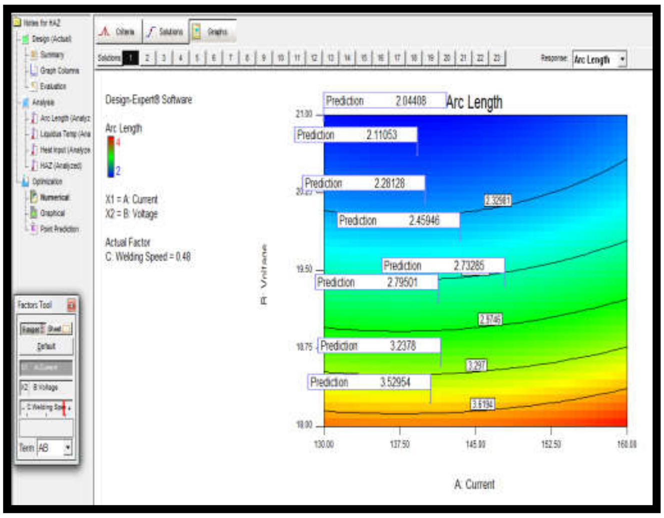


Fig.20. Predicting arc length using

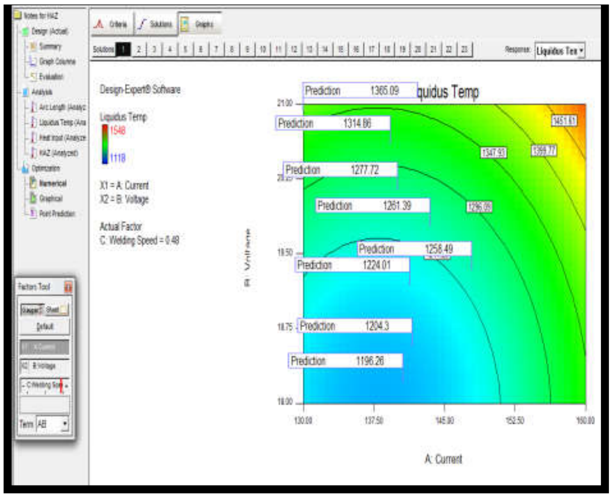


Fig 21: Predicting liquidus contour plot temperatureusing contour plot

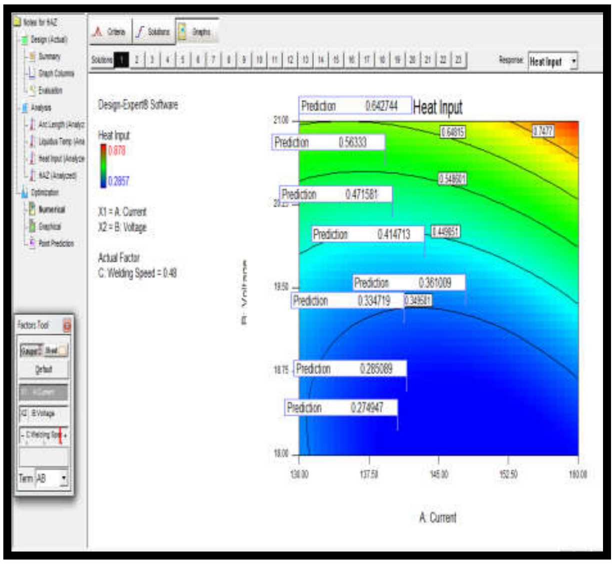


Figure 22. Predicting heat input using contour plot(HAZ) using contour plot

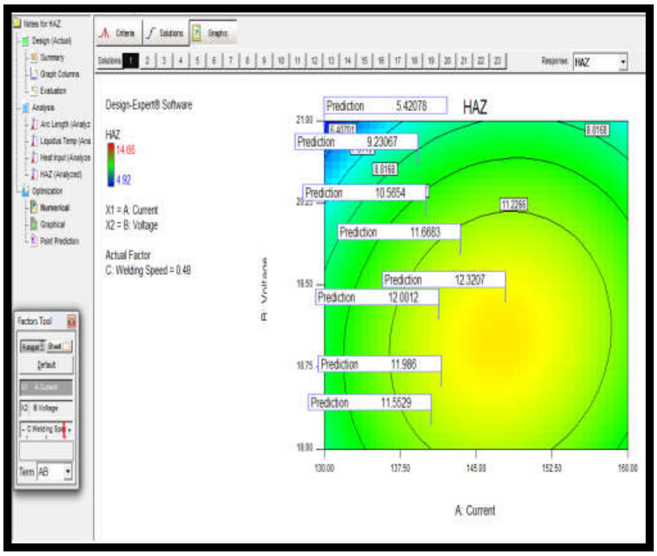


Figure 23. Predicting heat affected zone

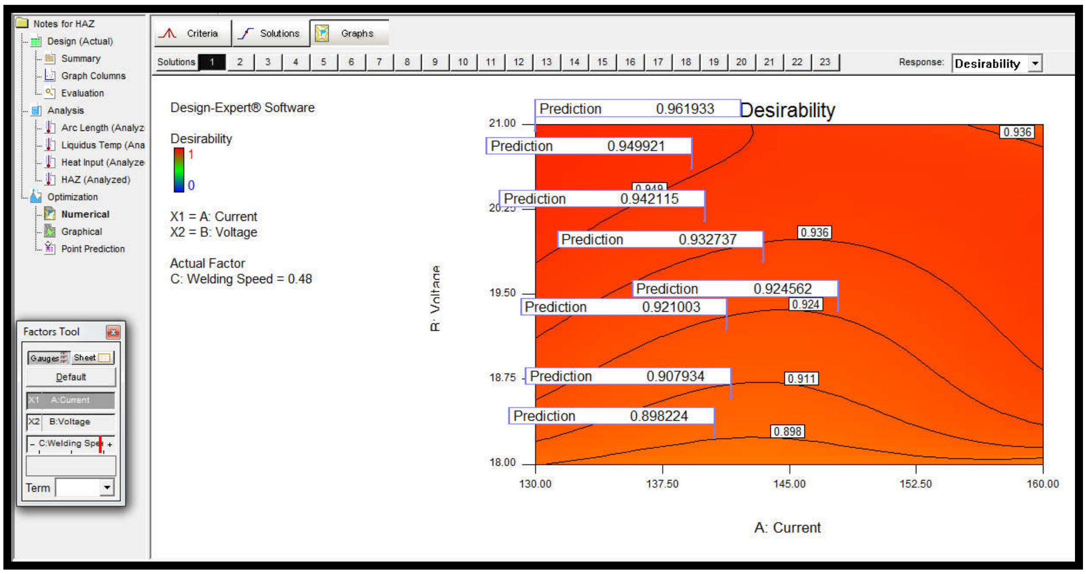


Figure 24. Predicting desirability using contour plot

observed and predicted values of heat affected zone obtained is presented in Figures 14The high coefficient of determination (r^2 = 0.9212, 0,9723, 0.9849 and 0.9406) as observed in Figure 12 was used to established the suitability of response surface methodology in minimizing the arc length, maximizing the liquidus temperature, minimizing the heat input and minimizing the heat affected zone (HAZ). To accept any model, its satisfactoriness must first be checked by an appropriate statistical analysis output. To diagnose the statistical properties of the response surface model, the normal probability plot of residual for minimizing heat affected zone(HAZ)ispresented in Figure 17The 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. Result of Figures 16 and 17 revealed that the computed residuals are approximately normally distributed which isan indication that the model developed is satisfactory.

To determine the presence of a possible outlier, the cook's distance plot was generated for the different responses. The cook's distance is a measure of how much the regression would change if the outlier is omitted from the analysis. A point that has a very high distance value relative to the other points may be an outlier and should be investigated. The generated cook's distance for minimizing the heat affected zone is presented in Figures 15The cook's distance plot had an upper bound of 1.00 and a lower bound of 0.00. Experimental values smaller than the lower bound or greater than the upper bounds are considered as outliers and must be properly investigated. Results of Figure 15 indicates that the data used for this analysis are devoid of possible outliers thus revealing the adequacy of the experimental. To study the effects of combine input variables on the response variable (heat affected zone), the 3D surface plot presented in Figure 16 was developed. The 3D surface plot as observed in Figure 16 shows the relationship between the input variables (current, voltage and welding speed) and the response variables (Arc length, liquidus temperature, heat input and heat affected zone). It is a 3 dimensional surface plot which was employed to give a clearer concept of the response surface. Although not as useful as the contour plot for establishing responses values and coordinates, this view may provide a clearer picture of the surface. As the colour of the curved surface gets darker, the arc length, heat input and heat affected zone decreases proportionately while the liquidus temperature increases. 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. In the numerical optimization phase, we ask design expert to minimize the arc length, maximize the liquidus temperature, minimize the heat input and minimize the heat affected zone (HAZ). In addition, the optimum current, voltage and welding speed was determined simultaneously. The interphase of the numerical optimization showing the objective function for heat affected zone is presented in Figure 18. The numerical optimization produced twenty (20) optimal solutions which are presented in Figure 19. From the results of Figure 19, it was observed that a current of 130.00amp, voltage of 20.94v and a welding speed of 0.48m/min will result in a welding process with the following properties Heat Affected Zone (HAZ) of 5.42078mm. This solution was selected by design expert as the optimal solution with a desirability value of 96.20%. Finally, based on the optimal solution, the contour plots showing each response variable (arc length) against the optimized value of the input variable is presented in Figure 20. Finally, based on the optimal solution, the contour plots showing each response variable (liquidus temperature) against the optimized value of the input variable is presented in Figure 21Finally, based on the optimal solution, the contour plots showing each response variable (heat input) against the optimized value of the input variable is presented in Figure 22Finally, based on the optimal solution, the contour plots showing each response variable (heat affected zone) against the optimized value of the input variable is presented in Figure 23. Finally, based on the optimal solution, the contour plots showing the desirability against the optimized value of the input variable is presented in Figure 24. As presented in Figure 24, the contour plot can be employed to predict the optimum values of the input variables based on the flagged response variables.

DISCUSSION

In this study, the response surface methodology and the artificial neural network was used to optimize and predict weld parameter. The solution of the optimization process was to determine the optimum value of each input variable namely: voltage(volt), current(Amp) and speed(m/min) that will minimise the heat affected zone. A statistical design of experiment (DoE) using the central composite design method (CCD) was done. The design and optimization was executed with the aid of statistical tool called Design Expert 7.01. An experimental design matrix having six(6) center points (k), six(6) axial points (2n) and eight(8) factorial points (2n)resulting to 20 experimental runs was generated. From the model design summary. For heat affected zone (HAZ), the minimum value was observed to be 4.920mm, with a maximum value of 14.660mm, mean value of 9.881 and standard deviation of 3.027. To test how well the quadratic model can explain the underlying variation associated with the experimental data, the lack of fit test was estimated for arc length. Model with significant lack of fit cannot be employed for prediction. Result of the computed lack of fit for heat affected zone is presented in Figure 9.In assessing the strength of the quadratic model towards optimizing a target response, one way analysis of variance(ANOVA) table was generated for each response variable and result obtained is presented in figures 11.To validate the adequacy of the quadratic model based on its ability to minimize the heat affected zone (HAZ), the goodness of fit statistics presented in Figure 12 was employed. To asses the accuracy of prediction and establish 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 14. The high coefficient of determination (r2 = 0.9406) as observed in figures 14 was used to established the suitability of response surface methodology in minimizing the heat affected zone (HAZ). To determine the presence of a possible outlier, the cook's distance plot was generated for the different responses. The cook's distance is a measure of how much the regression would change if the outlier is omitted from the analysis.

A point that has a very high distance value relative to the other points may be an outlier and should be investigated. The generated cook's distance for all the responses is presented in Figure 15. To study the effects of combine input variables on each response variable, namely; arc length, liquidus temperature, heat input and heat affected zone, 3D surface plots presented in figures 16 were developed. Finally, numerical optimization was performed to ascertain the desirability of the overall model. In the numerical optimization phase, the design expert was asked to minimize the heat affected zone (HAZ). In addition, the optimum current, voltage and welding speed was determined simultaneously. It can be deduced from the result of Figure 20 that the model developed based on response surface methodology and optimized using numerical optimization method, predicted the heat affected zone(HAZ) by an accuracy level of 99.47%. Finally, based on the optimal solution, the contour plots showing each response variable against the optimized value of the input variable is presented in Figure 20-24. Response surface methodology using numerical optimization was effective in predicting the optimal value of current, voltage and welding speed needed to minimize the heat affected zone (HAZ). It was also useful in determining the exact mathematical relationship between the input variables (current, voltage and welding speed) and each individual response variables (heat affected zone (HAZ)).

Conclusion

The quality and integrity of welded joints is highly influenced by the optimal combination of the welding input parameters. This study developed a model using expert systems, such as Response Surface Methodology to optimize and predict weld heat affected zone from input parameter such as current, voltage and welding speed. The result from the Response Surface Methodology analysis shows that a current of 130.00amp, voltage of 20.94V, speed of 0.48m/min will produce aheat affected zone of 5.42078mm with a desirability of 0.962.

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