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Simulation-Based Optimization of Aspect Ratio in Tungsten Inert Gas Welding

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Abstract

The shape of the fusion zone after weld in terms of its width-to-depth ratio is known as the aspect ratio, large aspect ratios in welded joints usually results in cracks formation during solidification of the weld; it also results in tensile residual stresses at the fusion zone. In this study, central composite design matrix was employed using Design Expert 7.01 software to optimize the aspect ratio of mild steel welded joint. A total of 20 sets of experiments were produced; the weld specimen was mild steel plate measuring 60 mm × 40 mm × 10 mm. TIG welding machine with 100% Argon Shielding Gas was used for this experiment and at the end of the experiment, an optimum weld aspect ratio of 0.646 was achieved using current of 140 amp, voltage of 25 volt and gas flow rate of 15 L/min. This value of 0.646 is expected to contain the minimum adequate molten metal just enough to make the desired bead penetration to form good aspect ratio at a minimum cost with appropriate weld quality and productivity. This would help minimize the formation of cracks after weld.

Keywords

Welded Joints, Aspect Ratio, Mild Steel, TIG, Weld Crack

1. Introduction

Premature failure of welded structures had resulted in great loss of life and properties; it had also been a huge engineering problem, huge source of concern cutting across all strata of engineering [1] failures that often results from welded joint can sometimes be linked to poor combinations of process parameters which often manifest in the form of cracks [2]. Their work proved that some of these failures originate at welded joints; this area is very critical to the overall lifespan of the weld is determined by the welded joint.

Visual defects appearance in welds compromises the quality of weldment and can manifest in forms such as deformation, excessive undercut, porosity, and cracks. Crack defects are regarded as the worst since even a minute crack can grow and lead to failure [3] that is why a good weld aspect ratio is required for quality welded joints. [4] showed that metal structures at their welded joints, do not have the same strength characteristics as the parent material; this means to optimize the strength enhancing properties at the welded joint; optimum process parameters are required. And to further minimize the cost of try and error approach, a robust design of experiment would be imperative [5].

It was suggested by [6] that one of the proven ways of enhancing the strength and lifespan of structural material at welded joints is to optimize its aspect ratio where, the optimum weld parameter is geared towards ensuring quality weld all the time. Over the years, the desired process parameters of welded joints have been gleamed out by applying various multi criteria optimization tools and statistical models in an attempt to broaden the scope, and increase the options open to researchers and developers in arriving at optimum process parameters to meet specific needs [7] and [8]. According to [9] and [10], the preferred welding parameters are selected based on knowledge or from a welding handbook. It should be noted that, this does not ensure that the selected welding parameters can make the best or near best weld bead profile for that particular welding process and environment. It is therefore desirous to produce welded joints and metal products that are of high quality, but with more precision, less energy, and time constraints by careful selection of the various process control parameters through some established guidelines or models.

2. Materials and Methods

2.1. Materials

One hundred (100) pieces of mild steel coupons, measuring 60 mm × 40 mm × 10 mm were used for the experiments, the experiment was performed 20 times using, 5 specimen for each run. **Figure 1** shows the weld torch. **Figure 2** shows

Figure 1. TIG welding torch.

Figure 2. TIG equipment.

the TIG machine. Figure 3 shows the argon gas cylinder and regulator for varying the gas flow rate while. Figure 4 shows the mild steel weld sample. The range of values of the process parameters was obtained from the open literature accessed and each parameter has two levels which comprise the high and low as expressed in Table 1.

2.2. Methods

The Central Composite Design matrix with 6 central points, 6 axial points and 8 factorial points was developed using the Design Expert 7.01 software, which produced 20 experimental runs. The input parameters and output parameters made-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.

3. Results and Discussion

3.1. Results

The optimization objective was to reduce the aspect ratio of welded joint, the randomized design matrix comprising of three input variables (current, voltage and gas flow rate) and their ranges in real values is presented in Figure 6, the response variable of interest is circled in orange colour.

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.

Result of Figure 7 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 aspect ratio was observed to be 0.514 with a maximum value of 0.975, mean value of 0.790 and standard deviation of 0.144.

Analysis of the model standard error was employed to assess the suitability of response surface methodology using the quadratic model to minimize the aspect

Figure 3. Shielding gas cylinder and regulator.

Figure 4. Weld samples.

Std	Run	Type	Factor 1 A:Current Amp	Factor 2 B:Voltage volt	Factor 3 C:Gas Flow Rate L/min
15	1	Center	155.00	23.50	13.50
16	2	Center	155.00	23.50	13.50
17	3	Center	155.00	23.50	13.50
18	4	Center	155.00	23.50	13.50
19	5	Center	155.00	23.50	13.50
20	6	Center	155.00	23.50	13.50
9	7	Axial	129.77	23.50	13.50
10	8	Axial	180.23	23.50	13.50
11	9	Axial	155.00	20.98	13.50
12	10	Axial	155.00	26.02	13.50
13	11	Axial	155.00	23.50	10.98
14	12	Axial	155.00	23.50	16.02
1	13	Fact	140.00	22.00	12.00
2	14	Fact	170.00	22.00	12.00
3	15	Fact	140.00	25.00	12.00
4	16	Fact	170.00	25.00	12.00
5	17	Fact	140.00	22.00	15.00
6	18	Fact	170.00	22.00	15.00
7	19	Fact	140.00	25.00	15.00
8	20	Fact	170.00	25.00	15.00

Figure 5. Central Composite Design Matrix (CCD).

Std	Run	Type	Factor 1 A:Current Amp	Factor 2 B:Voltage volt	Factor 3 C:Gas Flow Rate L/min	Response 1 Aspect Ratio Nil	Response 2 Volume of Weld Metal Deposit mm^3/s	Response 3 Electrode Heat Transfer Coefficient W/m^2 0C	Response 4 Rate of Heat Transfer J/S
15	1	Center	155.00	23.50	13.50	0.9511	1255.38	259.78	3264
16	2	Center	155.00	23.50	13.50	0.9513	1255.42	259.77	3266
17	3	Center	155.00	23.50	13.50	0.9512	1255.39	259.79	3267
18	4	Center	155.00	23.50	13.50	0.9511	1255.41	259.8	3265
19	5	Center	155.00	23.50	13.50	0.9512	1255.38	259.78	3264
20	6	Center	155.00	23.50	13.50	0.9513	1255.41	259.79	3266
9	7	Axial	129.77	23.50	13.50	0.5136	1037.78	272.49	2992
10	8	Axial	180.23	23.50	13.50	0.6842	1278.34	260.24	3400
11	9	Axial	155.00	20.98	13.50	0.6256	1251.3	222.82	2805
12	10	Axial	155.00	26.02	13.50	0.8312	1198.65	255.62	3128
13	11	Axial	155.00	23.50	10.98	0.9752	1125.94	248.23	2932.5
14	12	Axial	155.00	23.50	16.02	0.7704	1149.76	243.61	3187.5
1	13	Fact	140.00	22.00	12.00	0.709	1061.3	243.61	2618
2	14	Fact	170.00	22.00	12.00	0.8485	1200.99	266.71	3323.5
3	15	Fact	140.00	25.00	12.00	0.8147	1020.26	239.91	2856
4	16	Fact	170.00	25.00	12.00	0.7204	1317.83	248.23	3612.5
5	17	Fact	140.00	22.00	15.00	0.602	1176.44	215.89	2967
6	18	Fact	170.00	22.00	15.00	0.7633	1135.17	235.92	3012
7	19	Fact	140.00	25.00	15.00	0.606	1116.7	289.87	2975
8	20	Fact	170.00	25.00	15.00	0.6378	1234.9	273.61	3368

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	140.00	170.00	-1.000	1.000	155.000	12.395
B	Voltage	volt	Numeric	22.00	25.00	-1.000	1.000	23.500	1.240
C	Gas Flow Rate	L/min	Numeric	12.00	15.00	-1.000	1.000	13.500	1.240

Response	**Name**	**Units**	**Obs**	**Analysis**	**Minimum**	**Maximum**	**Mean**	**Std. Dev.**	**Ratio**	**Trans**	**Model**
Y1	Aspect Ratio	Nil	20	Polynomial	0.514	0.975	0.790	0.144	1.899	None	Quadratic
Y2	Volume of Weld	mm^3/s	20	Polynomial	1020.260	1317.830	1191.888	83.228	1.292	None	Quadratic
Y3	Electrode Heat T	W/m^2 0C	20	Polynomial	215.890	289.870	253.774	16.805	1.343	None	Quadratic
Y4	Rate of Heat Tra	J/S	20	Polynomial	2618.000	3612.500	3138.450	232.055	1.380	None	Quadratic

Figure 7. RSM design summary for optimizing weld parameters.

Table 1. Welding parameters and their levels.

Parameters	Unit	Symbol	Coded value	
			Low (−1)	High (+1)
Current	Amp	A	120	190
Gas flow rate	Lit/min	G	10	17
Voltage	Volt	V	20	27

ratio. The computed standard errors for the selected responses are presented in Figure 8.

From the results of Figure 8, it was observed that the model have a low standard f(x) Model | Results | Graphs

				Power at 5 % alpha level for effect of		
Term	StdErr**	VIF	Ri-Squared	0.5 Std. Dev.	1 Std. Dev.	2 Std. Dev.
A	0.27	1.00	0.0000	13.3 %	38.6 %	91.4 %
B	0.27	1.00	0.0000	13.3 %	38.6 %	91.4 %
C	0.27	1.00	0.0000	13.3 %	38.6 %	91.4 %
AB	0.35	1.00	0.0000	9.8 %	24.9 %	72.2 %
AC	0.35	1.00	0.0000	9.8 %	24.9 %	72.2 %
BC	0.35	1.00	0.0000	9.8 %	24.9 %	72.2 %
A^2	0.26	1.02	0.0179	40.4 %	92.7 %	99.9 %
B^2	0.26	1.02	0.0179	40.4 %	92.7 %	99.9 %
C^2	0.26	1.02	0.0179	40.4 %	92.7 %	99.9 %

**Basis Std. Dev. = 1.0

Figure 8. Result of computed standard errors.

error ranging from 0.27 for the individual terms, 0.35 for the combine effects and 0.26 for the quadratic terms. Standard errors should be similar within type of coefficient; smaller is better. The Variance inflation factor (VIF) of approximately 1.0 as observed in Figure 8 was good since ideal VIF is 1.0. In addition, the Ri-squared value was observed to be between 0.0000 to 0.0179 which is good. The correlation matrix of regression coefficient is presented in Figure 9. Lower values of the off diagonal matrix as observed in Figure 9 indicates a well fitted model that is strong enough to navigate the design space and adequately optimize the selected response variables.

Leverages of 0.6698 and 0.6073 calculated for the factorial and axial points coupled with 0.1663 for the center point as observed in Figure 10 shows that the predicted values are very close to the experimental values. Hence lower residual value which shows the adequacy of the model.

In assessing the strength of the quadratic model towards minimizing the aspect ratio, one way analysis of variance (ANOVA) was done for each response variable and result is presented in Figure 10 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 Figure 10, the Model F-value of 18.34 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, C, AB, A2, B2, C2 are significant model terms. Values greater than 0.1000 indicate the model terms are not significant.

To validate the adequacy of the model based on its ability to minimize the aspect ratio, the goodness of fit statistics presented in Figure 11 were employed.

To obtain the optimal solution, we first consider the coefficient statistics and the corresponding standard errors. The computed standard error measures the difference between the experimental terms and the corresponding predicted

Correlation Matrix of Regression Coefficients

	Intercept	A	B	C	AB	AC	BC
Intercept	1.000						
A	-0.000	1.000					
B	-0.000	-0.000	1.000				
C	-0.000	-0.000	-0.000	1.000			
AB	-0.000	-0.000	-0.000	-0.000	1.000		
AC	-0.000	-0.000	-0.000	-0.000	-0.000	1.000	
BC	-0.000	-0.000	-0.000	-0.000	-0.000	-0.000	1.000
A^2	-0.529	-0.000	-0.000	-0.000	-0.000	-0.000	-0.000
B^2	-0.529	-0.000	-0.000	-0.000	-0.000	-0.000	-0.000
C^2	-0.529	-0.000	-0.000	-0.000	-0.000	-0.000	-0.000

Figure 9. Correlation matrix of regression coefficients.

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

Response 1 Aspect Ratio

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	0.39	9	0.044	18.34	< 0.0001	significant
A-Current	*0.020*	*1*	*0.020*	*8.51*	*0.0154*	
B-Voltage	*2.984E-003*	*1*	*2.984E-003*	*1.26*	*0.2883*	
C-Gas Flow Rat	*0.050*	*1*	*0.050*	*21.15*	*0.0010*	
AB	*0.016*	*1*	*0.016*	*6.95*	*0.0249*	
AC	*2.734E-003*	*1*	*2.734E-003*	*1.15*	*0.3083*	
BC	*1.228E-003*	*1*	*1.228E-003*	*0.52*	*0.4884*	
A^2	*0.23*	*1*	*0.23*	*96.61*	*< 0.0001*	
B^2	*0.093*	*1*	*0.093*	*39.20*	*< 0.0001*	
C^2	*0.012*	*1*	*0.012*	*5.21*	*0.0456*	
Residual	0.024	10	2.373E-003			

Figure 10. ANOVA table for validating the model significance towards minimizing the Aspect Ratio (AR).

Std. Dev.	0.049	R-Squared	0.9429
Mean	0.79	Adj R-Squared	0.8915
C.V. %	6.16	Pred R-Squared	0.5609
PRESS	0.18	Adeq Precision	12.790

Figure 11. GOF statistics for validating model significance towards minimizing the aspect ratio.

terms. Coefficient statistics for aspect ratio is presented in Figure 12.

Variance inflation factor (VIF) value of 1.00 for the individual and combine

Factor	Coefficient Estimate	df	Standard Error	95% CI Low	95% CI High	VIF
Intercept	0.95	1	0.020	0.91	1.00	
A-Current	0.038	1	0.013	9.088E-003	0.068	1.00
B-Voltage	0.015	1	0.013	-0.015	0.044	1.00
C-Gas Flow Rat	-0.061	1	0.013	-0.090	-0.031	1.00
AB	-0.045	1	0.017	-0.084	-7.038E-003	1.00
AC	0.018	1	0.017	-0.020	0.057	1.00
BC	-0.012	1	0.017	-0.051	0.026	1.00
A^2	-0.13	1	0.013	-0.15	-0.098	1.02
B^2	-0.080	1	0.013	-0.11	-0.052	1.02
C^2	-0.029	1	0.013	-0.058	-6.975E-004	1.02

Figure 12. Coefficient estimates statistics for minimizing the aspect ratio.

terms, 1.02 for the quadratic terms as observed in Figure 12 indicate a significant model in which the variables are highly correlated with the responses.

The optimal equation which shows the individual effects and combine interactions of the selected input variables (Current, Voltage and Gas flow rate) against the mesured responses (Aspect ratio), is presented the actual factors as shown in Figure 13.

The diagnostics case statistics which shows the observed values of each respones variable (Aspect ratio) against their predicted values is presented in Figure 14. The diagnostic case statistics actually give insight into the model strength and the adequacy of the optimal second order polynomial equation.

Lower residual values resulting to lower leverages as observed in Tables are indicators of a well fitted model. 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 aspect ratio is presented in Figure 15.

To accept any model, its satisfactoriness must be checked by an appropriate statistical analysis. To diagnose the statistical properties of the model, the normal probability plot of residual of aspect ratio is presented in Figure 16.

To study the effects of combine variables on each response (Aspect ratio, 3D surface plots presented in Figure 17.

The 3D surface plot as observed in Figure 17 shows the relationship between the input variables (current, voltage and gas flow rate) and the response variables (Aspect ratio) to the work piece. 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 aspect ratio 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 aspect ratio, also determining the optimum value of current,

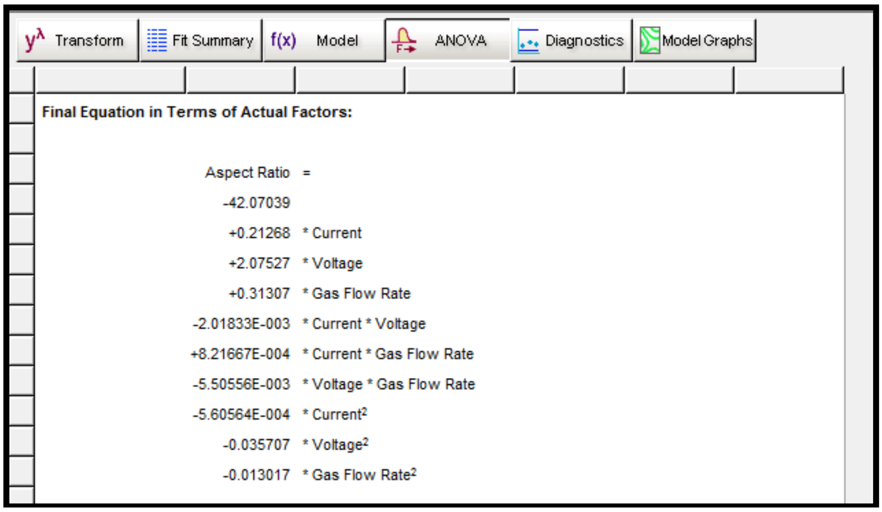
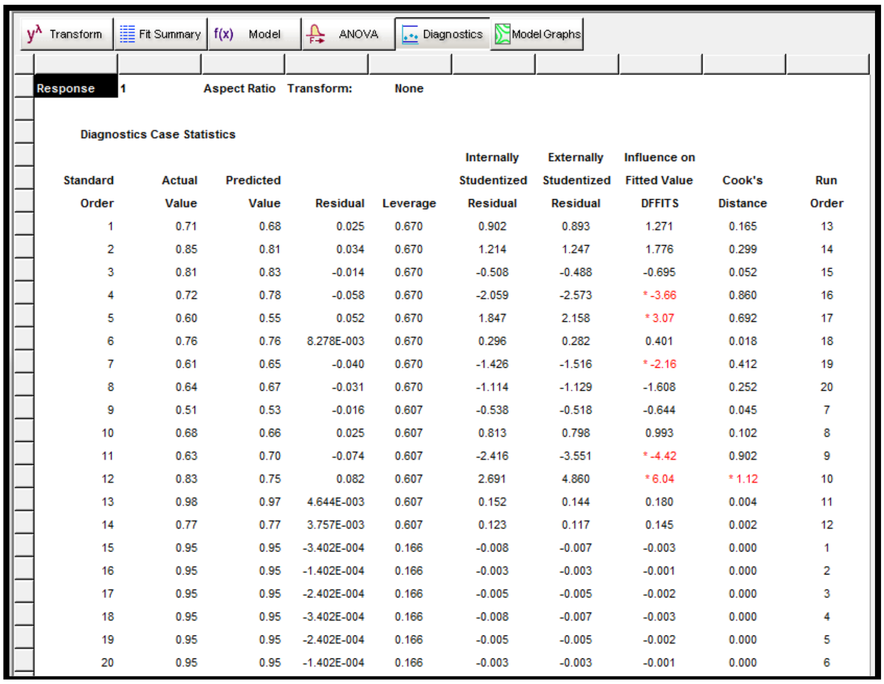


Figure 13. Optimal equation in terms of actual factors for minimizing the aspect ratio.



Response 1 Aspect Ratio Transform: None

Diagnostics Case Statistics

Standard Order	Actual Value	Predicted Value	Residual	Leverage	Internally Studentized Residual	Externally Studentized Residual	Influence on Fitted Value DFFITS	Cook's Distance	Run Order
1	0.71	0.68	0.025	0.670	0.902	0.893	1.271	0.165	13
2	0.85	0.81	0.034	0.670	1.214	1.247	1.776	0.299	14
3	0.81	0.83	-0.014	0.670	-0.508	-0.488	-0.695	0.052	15
4	0.72	0.78	-0.058	0.670	-2.059	-2.573	* -3.66	0.860	16
5	0.60	0.55	0.052	0.670	1.847	2.158	* 3.07	0.692	17
6	0.76	0.76	8.278E-003	0.670	0.296	0.282	0.401	0.018	18
7	0.61	0.65	-0.040	0.670	-1.426	-1.516	* -2.16	0.412	19
8	0.64	0.67	-0.031	0.670	-1.114	-1.129	-1.608	0.252	20
9	0.51	0.53	-0.016	0.607	-0.538	-0.518	-0.644	0.045	7
10	0.68	0.66	0.025	0.607	0.813	0.798	0.993	0.102	8
11	0.63	0.70	-0.074	0.607	-2.416	-3.551	* -4.42	0.902	9
12	0.83	0.75	0.082	0.607	2.691	4.860	* 6.04	* 1.12	10
13	0.98	0.97	4.644E-003	0.607	0.152	0.144	0.180	0.004	11
14	0.77	0.77	3.757E-003	0.607	0.123	0.117	0.145	0.002	12
15	0.95	0.95	-3.402E-004	0.166	-0.008	-0.007	-0.003	0.000	1
16	0.95	0.95	-1.402E-004	0.166	-0.003	-0.003	-0.001	0.000	2
17	0.95	0.95	-2.402E-004	0.166	-0.005	-0.005	-0.002	0.000	3
18	0.95	0.95	-3.402E-004	0.166	-0.008	-0.007	-0.003	0.000	4
19	0.95	0.95	-2.402E-004	0.166	-0.005	-0.005	-0.002	0.000	5
20	0.95	0.95	-1.402E-004	0.166	-0.003	-0.003	-0.001	0.000	6

Figure 14. Diagnostics case statistics report of observed and predicted aspect ratio.

voltage and gas flow rate. The interphase of the numerical optimization is presented as shown in Figure 18.

The numerical optimization produces about twenty two (22) optimal solutions which are presented as shown in Figure 18.

From the results of Figure 19 it was observed that a current of 140.00 Amp, voltage of 25.00 volt and a gas flow rate of 15.00 L/min will produce a weld material with aspect ratio of (0.646234). This solution was selected by Design Expert as the optimal solution with a desirability value of 96.70%.

It can be deduce from the result that the model developed based on response surface methodology and optimized using numerical optimization method,

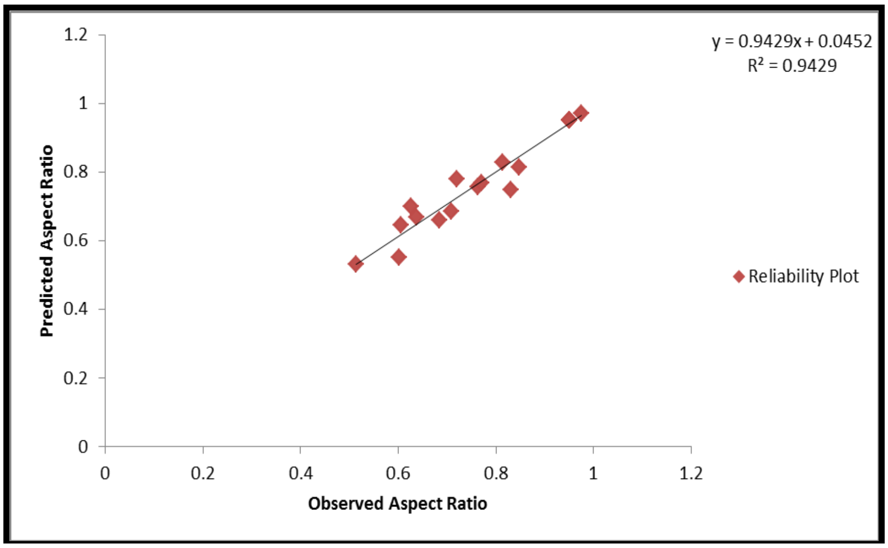


Figure 15. Reliability plot of observed versus predicted aspect ratio.

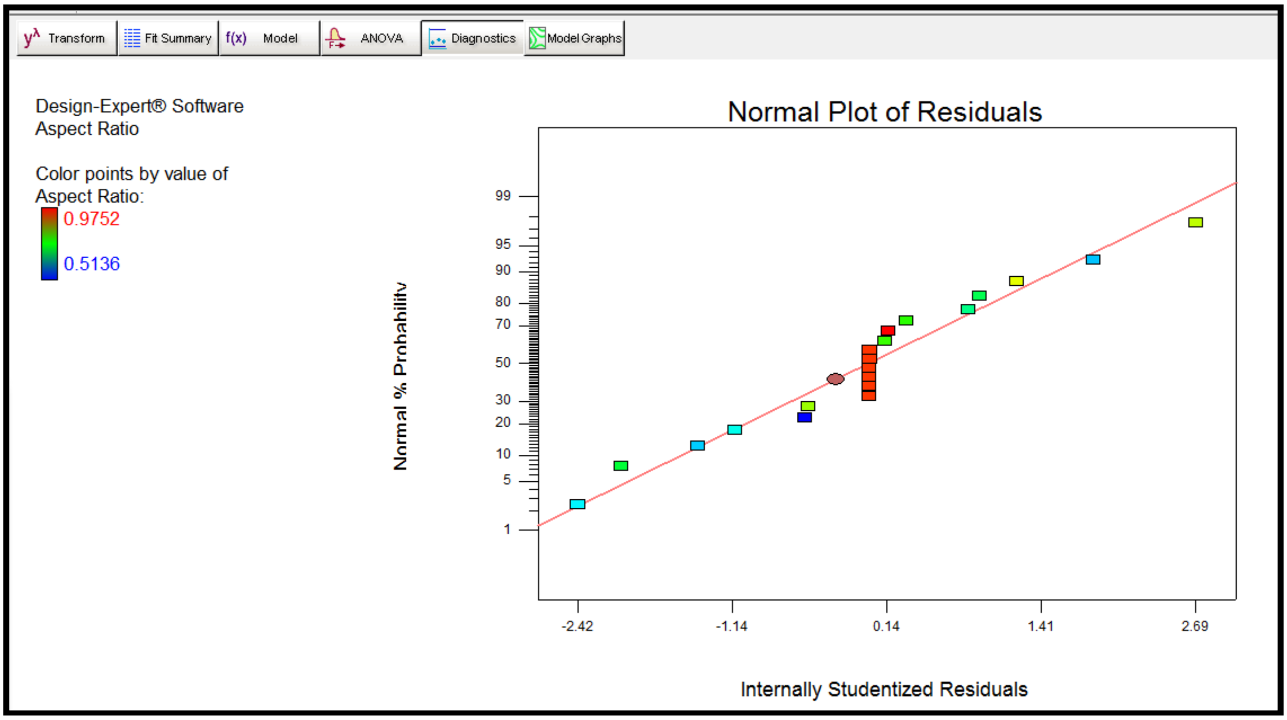


Figure 16. Normal probability plot of studentized residuals for minimizing aspect ratio.

Aspect ratio with an accuracy of 96.67%.

One of the uniqueness of Response Surface Methodology (RSM) is its ability to carry out predictions based on the numerical optimal solution or models it developed. RSM displays this strenght by generation of contur plots which shows the response varaible of interest and the coresponding input factors. Hence, based on the optimal solution, the contour plots showing aspect ratio response variable against the optimized value of the input variable is presented in Figure 20.

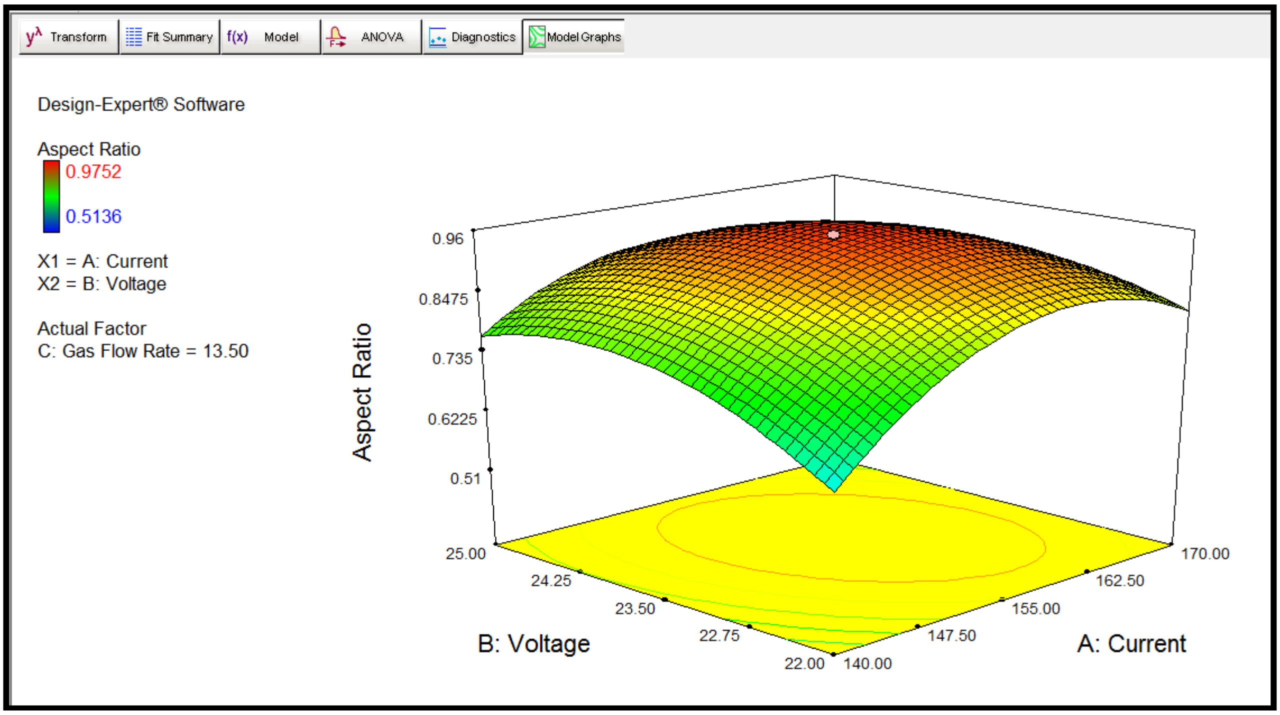


Figure 17. Effect of Current and Voltage on Aspect Ratio Ransfer.

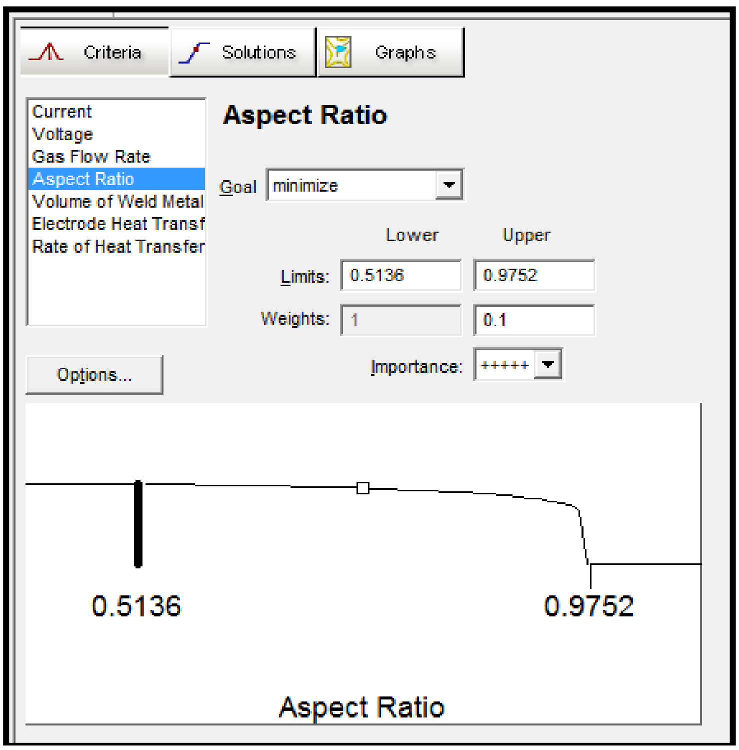
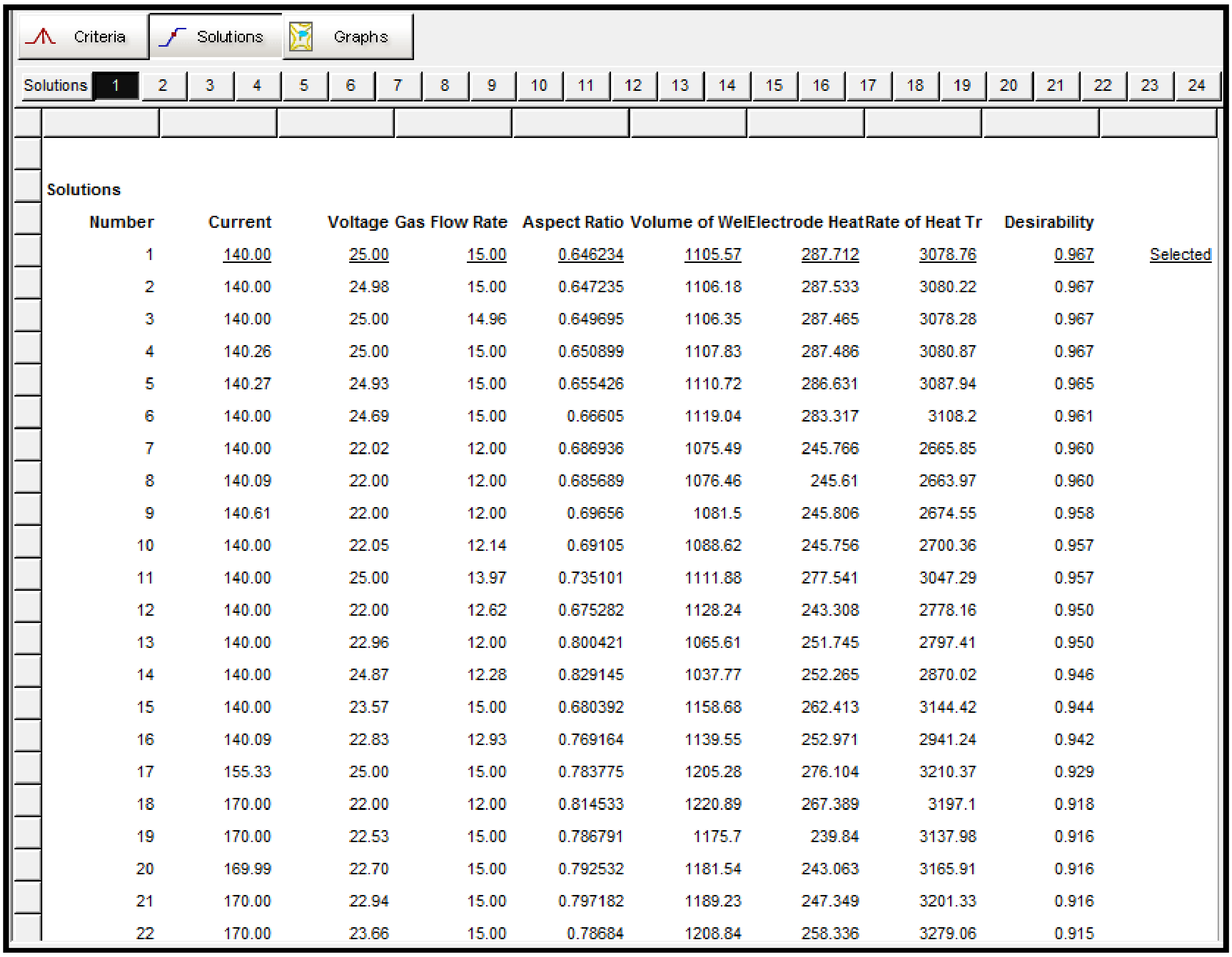


Figure 18. Interphase of numerical optimization model for minimizing the aspect ratio.

3.2. Discussion

In this study, the response surface methodology was used to optimize the aspect



Solutions

Number	Current	Voltage	Gas Flow Rate	Aspect Ratio	Volume of Wel	Electrode Heat	Rate of Heat Tr	Desirability	
1	140.00	25.00	15.00	0.646234	1105.57	287.712	3078.76	0.967	Selected
2	140.00	24.98	15.00	0.647235	1106.18	287.533	3080.22	0.967	
3	140.00	25.00	14.96	0.649695	1106.35	287.465	3078.28	0.967	
4	140.26	25.00	15.00	0.650899	1107.83	287.486	3080.87	0.967	
5	140.27	24.93	15.00	0.655426	1110.72	286.631	3087.94	0.965	
6	140.00	24.69	15.00	0.66605	1119.04	283.317	3108.2	0.961	
7	140.00	22.02	12.00	0.686936	1075.49	245.766	2665.85	0.960	
8	140.09	22.00	12.00	0.685689	1076.46	245.61	2663.97	0.960	
9	140.61	22.00	12.00	0.69656	1081.5	245.806	2674.55	0.958	
10	140.00	22.05	12.14	0.69105	1088.62	245.756	2700.36	0.957	
11	140.00	25.00	13.97	0.735101	1111.88	277.541	3047.29	0.957	
12	140.00	22.00	12.62	0.675282	1128.24	243.308	2778.16	0.950	
13	140.00	22.96	12.00	0.800421	1065.61	251.745	2797.41	0.950	
14	140.00	24.87	12.28	0.829145	1037.77	252.265	2870.02	0.946	
15	140.00	23.57	15.00	0.680392	1158.68	262.413	3144.42	0.944	
16	140.09	22.83	12.93	0.769164	1139.55	252.971	2941.24	0.942	
17	155.33	25.00	15.00	0.783775	1205.28	276.104	3210.37	0.929	
18	170.00	22.00	12.00	0.814533	1220.89	267.389	3197.1	0.918	
19	170.00	22.53	15.00	0.786791	1175.7	239.84	3137.98	0.916	
20	169.99	22.70	15.00	0.792532	1181.54	243.063	3165.91	0.916	
21	170.00	22.94	15.00	0.797182	1189.23	247.349	3201.33	0.916	
22	170.00	23.66	15.00	0.78684	1208.84	258.336	3279.06	0.915	

Figure 19. Optimal solutions of numerical optimization.

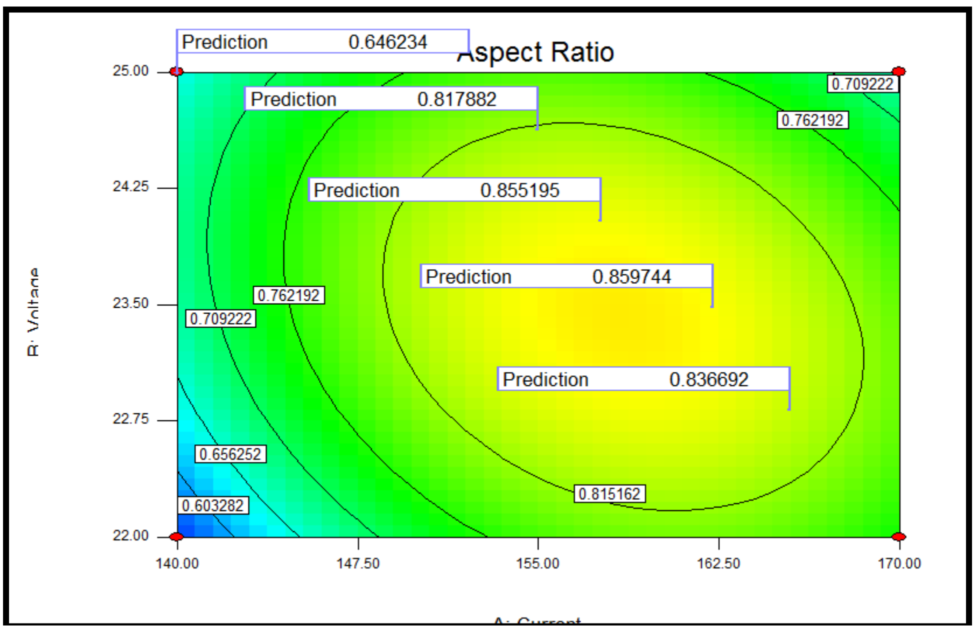


Figure 20. Predicting the Aspect ratio using contour plot.

ratio of tungsten inert gas mild steel welds. A model was developed using RSM. Result of **Figure 7** 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 optimize the selected responses to a desired range. From the results of **Figure 8**, it was observed that the model have a low standard error ranging from 0.27 for the individual terms, 0.35 for the combine effects and 0.26 for the quadratic terms. Standard errors should be similar within type of coefficient; the smaller the standard error the better the model. The error values were also observed to be less than the model basic standard deviation of 1.0 which suggests that response surface methodology was ideal for the optimization process. The correlation matrix of regression coefficient is presented in **Figure 9**. A lower value of the off diagonal indicates a well fitted model that is strong enough to navigate the design space and adequately optimize the selected response variables. In assessing the strength of the quadratic model, one way analysis of variance (ANOVA) was done for each response variable and result is presented in **Figure 10**. To validate the adequacy of the model based on its ability to optimize the weld aspectratio, the goodness of fit statistics presented in **Figure 11** was adopted. Coefficient of determination (R2) values of 0.9427 as observed in **Figure 11** for aspect ratio, which indicated the adequacy of the models. Adequate precision values of 12.79 as observed for aspect ratioin **Figure 11** indicated adequacy of the strength of the 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 the 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 **Figure 15**.

The 3D surface plot as observed in **Figure 17** shows the relationship between the input variables (voltage, current and gas flow rate) and the response variables (aspect ratio). It is a 3 dimensional surface plot which was employed to give a clearer concept of the response surface in terms of the strength of the interactions between the input variables and the respective selected responses. Similarly, based on the optimal solution the expert system generated contour plots as observed in **Figure 20** showing several predicted responses and their respective input variables, all within the boundaries of experimental design.

Finally, numerical optimization was performed to ascertain the desirability of the overall model. In the numerical optimization phase, Design Expert was asked to minimize the aspect ratio, while also determining the optimum value of voltage, current and gas flow rate.

4. Conclusion

The aspect ratio is a very important factor considered in assessing the quality of welds. The models developed possess a variance inflation factor of 1.0 and P-values < 0.05 indicating that the model is significant; the model also possessed a high goodness of fit with R^2 (Coefficient of determination) values of 94% for aspect ratio. Adeq Precision measures the signal to noise ratio; a ratio greater than 4.0 is desirable. Adequate precision values of 12.79 were observed for the Aspect ratio. The model produced numerical optimal solution of Current 140.0 Amp, Voltage of 25 Volt and a Gas flow rate of 15 L/min will produce a welded material having aspect ratio of 0.646234 at a desirability value of 96.7%. Therefore, the aspect ratio was minimized, optimized within a controlled range. In this research, the following has been established. An approach using the Response Surface Methodology to determine the optimum aspect ratio which translates into better weld quality has been successfully demonstrated. It has been shown that the optimization and prediction of aspect ratio 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 achieved in this study to produce high quality welds in Tungsten inert gas welding process.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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