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EXPERT OPTIMIZATION AND PREDICTION OF BEAD VOLUME OF MILD STEEL BUTT WELDED JOINT

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ABSTRACT

The volume of weld bead deposit on a welded joint, has a lot to say about the integrity of the weldment during its service life.Residual stresses, cracks etc can be greatly initiated with large weld bead. In this study, central composite design matrix was employed using Design Expert 7.01 software. A total of 20 sets of experiments were produced, the weld specimen was mild steel plate measuring 60mm x 40mm x 10mm. TIG welding machine with 100% Argon Shielding Gas was used for this experiment and at the end of the experiment, an optimum weld bead volume of1105.75mm^3/s was obtained with a coefficient of determination (R^2) value of 0.9744 usingresponse surface methodology (RSM) as the predictivemodeling tool. This quantity of bead volume is expected to contain the adequate molten metal that is required to make the desired bead penetration at a minimum cost with appropriate weld quality and productivity.

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INTRODUCTION

Tungsten Inert Gas (TIG) welding technique is a metal joining process that uses an arc with a non-consumable tungsten electrode on a work piece to create a permanent joint (Hussain *et al*, 2010, Achebo, 2012). An inert gas (argon, helium or a mixture of both) sustains the arc and protects the molten metal from atmospheric contamination. Filler materials might sometimes be used (Balasubramanian *et al*, 2010, Aghakhani *et al*, 2011). Huang *et al*, (2007) andFarhad and Heidari, (2010), described the TIG welding process as one of the most popular technologies for welding thin materials in manufacturing industries because it produces high quality welds. However, these authors compared TIG welding with the metal inert gas (MIG) welding process and stick weld and came to a conclusion that TIG welding has poor joint penetration when thick materials are welded in a single pass. In a research carried out by Vasudevan, (2007) and Marya and Edward, (2004), were of the opinion that activated TIG welding process was observed to typically increase the penetration capability by 200-300% and thereby reducing weld time and costs for manufacturers. Leconte *et al*, (2006) also applied activated TIG welding process and noted that it improves upon conventional GTAW, by increasing the single pass joining thickness from 6 to 10mm for stainless steel which was another breakthrough in time and cost reduction during weld operation, but ignoring the volume content of bead deposited might affect the quality of the welded joint. Venkatesan, (2014) andEsme *et al*, (2009) analyzed the sectional geometry of single-pass bead and the overlap of the adjacent beads to have critical effects on the dimensional accuracy and quality of metal parts. Therefore In order to find the parameter for optimization, weld bead profile study is needed

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MATERIALS AND METHODS

Materials: 100 pieces of mild steel coupons, measuring 60mm x 40mm x10mm 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 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 below.

Table 1. Welding Parameters and Their Levels

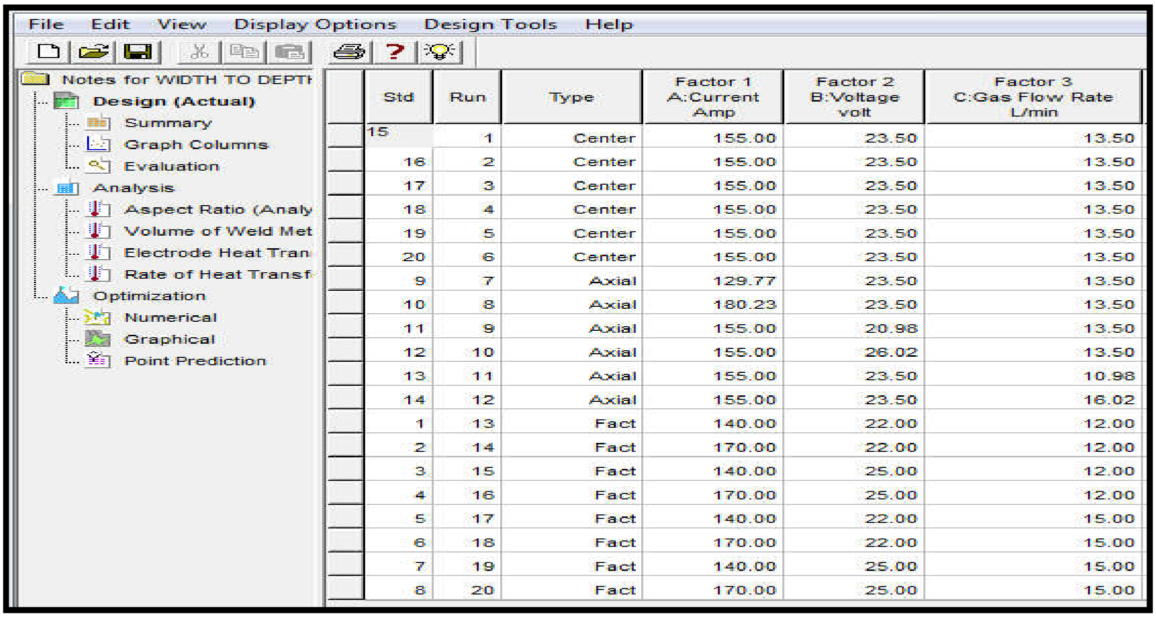
Parameters	Unit	Symbol	Coded value	
			Low (-1)	High (+1)
Current	Amp	A	120	190
Gas flow rate	Lit/min	G	10	17
Voltage	Volt	V	20	27

Figure 1. TIG Welding Torch

Figure 2. TIG Equipment

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)

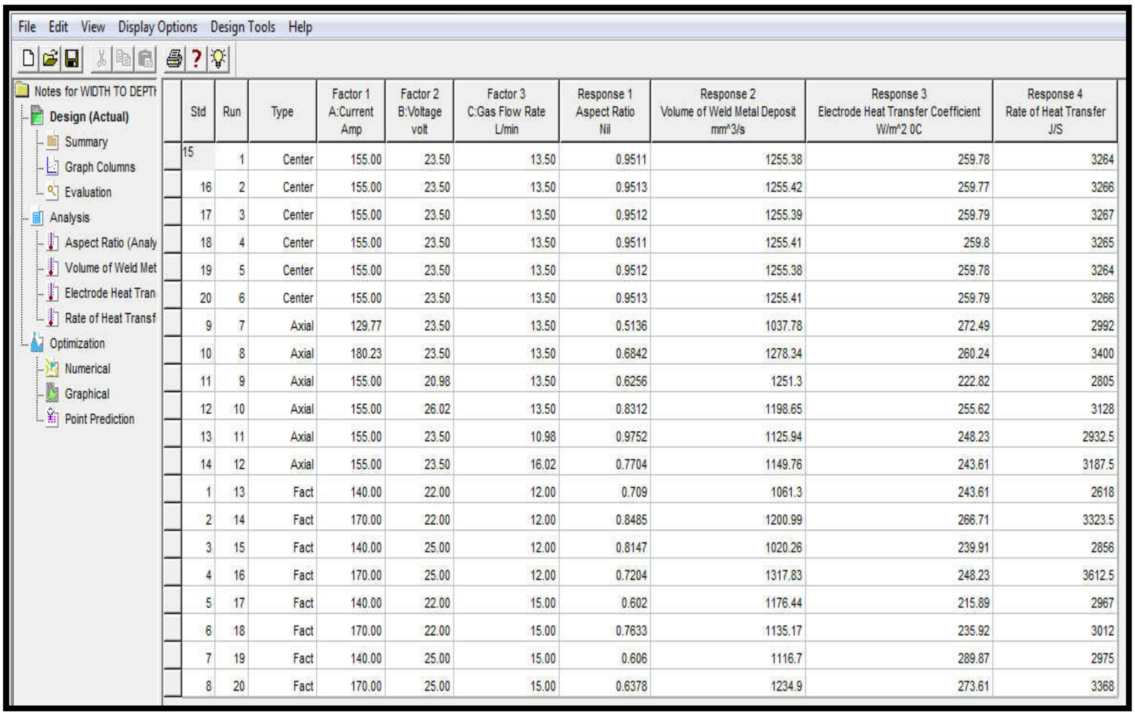
Methods: The Central Composite Design matrix with 6 central points, 6 axial points and 8 factorial points was developed using the Design Expert 7.01 software, which produced 20 experimental runs.

The input parameters and output parameters made-up the experimental matrix and the responses recorded from the weld samples were used as the data.Table 4 shows the Central Composite Design matrix.

RESULTS AND DISCUSSION

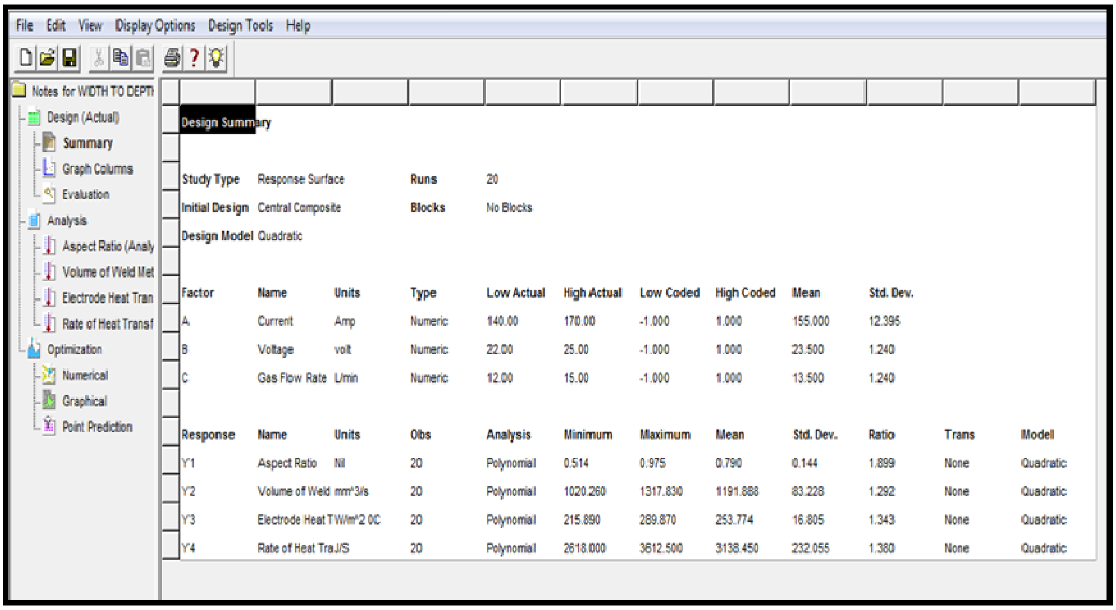
The optimization objective was to reduce the volume of weld metal deposit, the randomized design matrix comprising of three input variables (current, voltage and gas flow rate) and their ranges in real values is presented in Figure 5, the response variable of interest is circled in orange colour.

presented in Figure 9. Leverage of a point varies from 0 to 1 and indicates how much an individual design point influences the model's predicted values. 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 Table 9 shows that the predicted values are very close to the experimental values. Hence lower residual value which shows the adequacy of the model.



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		

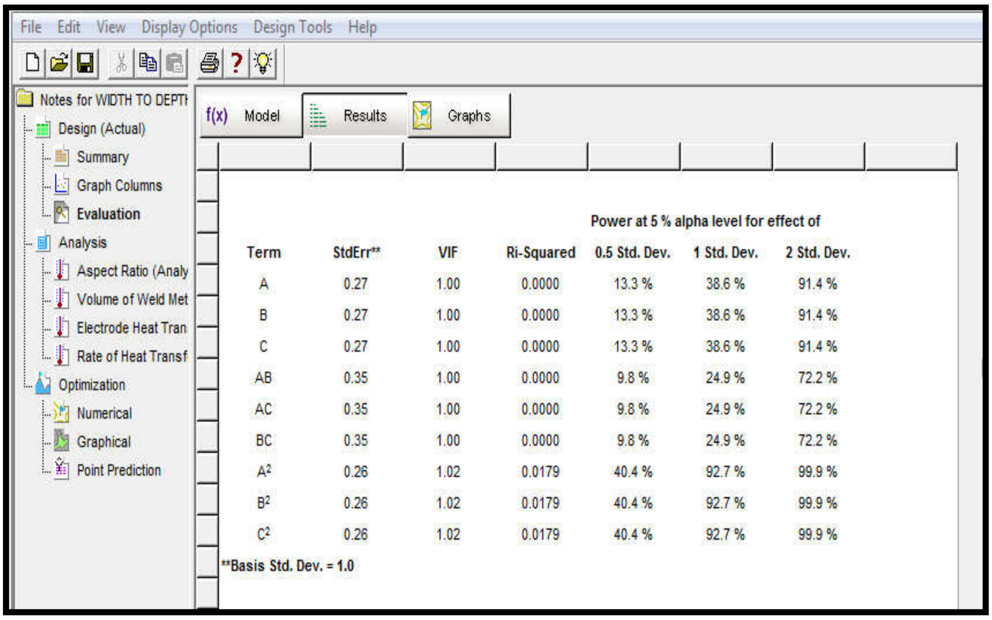
Factor	Name	Units	Type	Low Actual	High Actual	Low Coded	High Coded	Mean	Std. Dev.
A	Current	Amp	Numeric	140.00	170.00	-1.000	1.000	155.000	12.395
B	Voltage	volt	Numeric	22.00	25.00	-1.000	1.000	23.500	1.240
C	Gas Flow Rate	L/min	Numeric	12.00	15.00	-1.000	1.000	13.500	1.240

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

Analysis of the model standard error was employed to assess the suitability of response surface methodology using the quadratic model to maximize the electrode heat transfer coefficient, minimize the aspect ratio, minimize the volume of weld metal deposit and also minimize the rate of heat transfer from the heat source to the work piece. The computed standard errors for the selected responses are presented in Figure 7. To understand the influence of the individual design points on the model's predicted value, the model leveages were computed as

In assessing the strength of the quadratic model towards minimizing the volume of weld metal deposit one way analysis of variance (ANOVA) was done for each response variable and result is presented in Figure 10; From the result of Figure 10 the Model F-value of 42.24 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, AB, AC, A^2, B^2, C^2 are significant model terms.

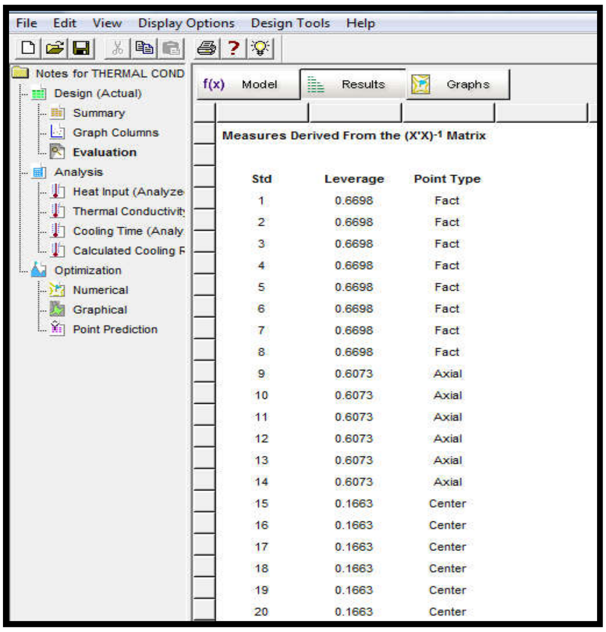


Power at 5 % alpha level for effect of

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

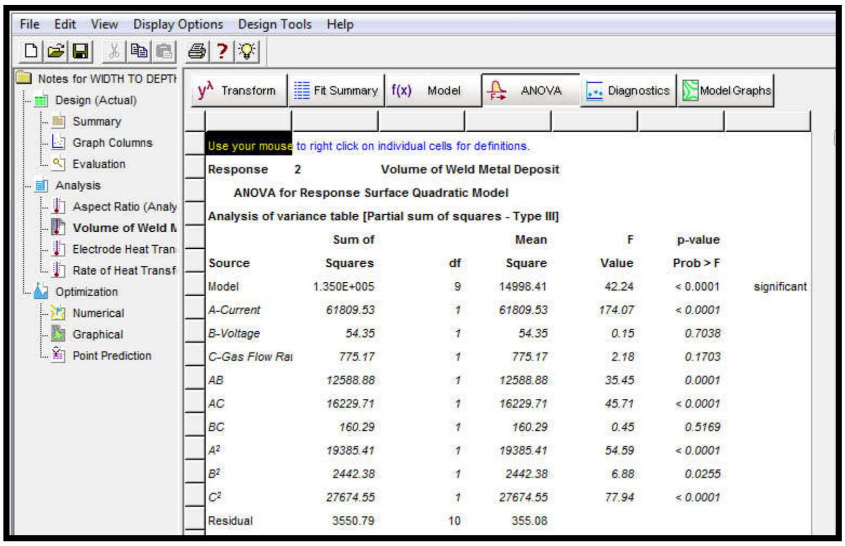
Figure 8. Result of Computed Standard Errors



Measures Derived From the $(X'X)^{-1}$ Matrix

Std	Leverage	Point Type
1	0.6698	Fact
2	0.6698	Fact
3	0.6698	Fact
4	0.6698	Fact
5	0.6698	Fact
6	0.6698	Fact
7	0.6698	Fact
8	0.6698	Fact
9	0.6073	Axial
10	0.6073	Axial
11	0.6073	Axial
12	0.6073	Axial
13	0.6073	Axial
14	0.6073	Axial
15	0.1663	Center
16	0.1663	Center
17	0.1663	Center
18	0.1663	Center
19	0.1663	Center
20	0.1663	Center

Figure 9. Computed model leverages



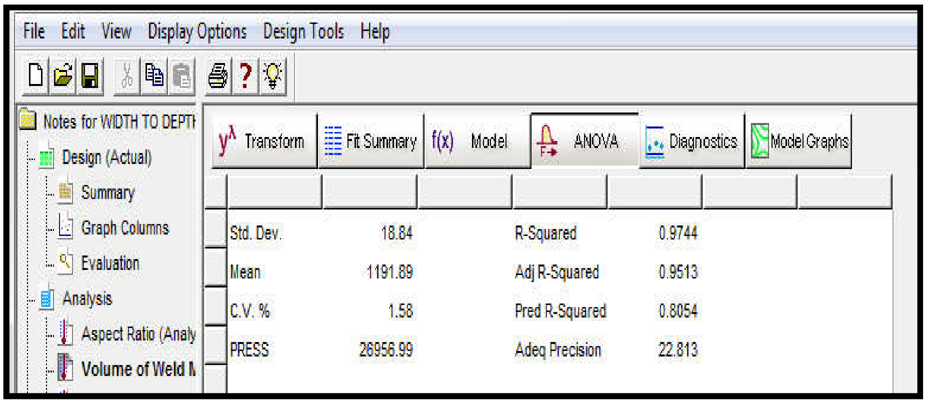
Response 2 Volume of Weld Metal Deposit

ANOVA for Response Surface Quadratic Model

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

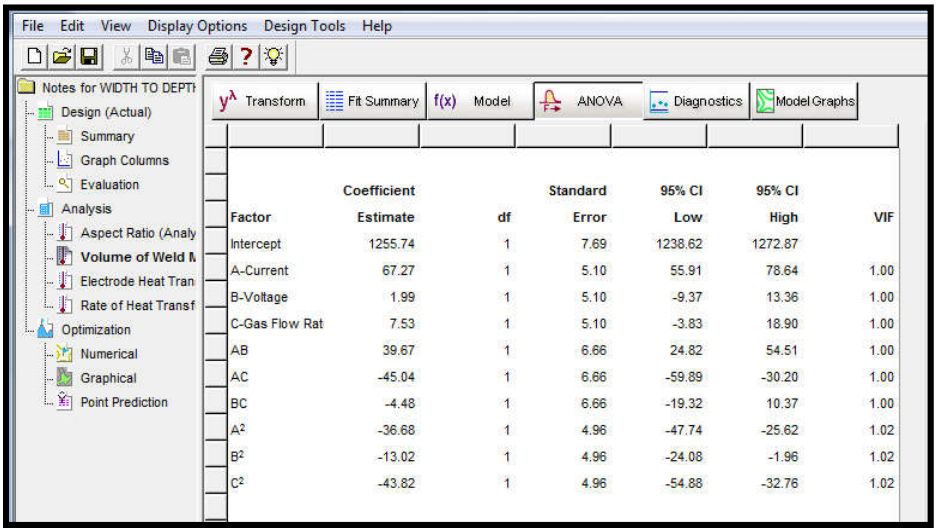
Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	1.350E+005	9	14998.41	42.24	< 0.0001	significant
A-Current	61809.53	1	61809.53	174.07	< 0.0001	
B-Voltage	54.35	1	54.35	0.15	0.7038	
C-Gas Flow Rat	775.17	1	775.17	2.18	0.1703	
AB	12588.88	1	12588.88	35.45	0.0001	
AC	16229.71	1	16229.71	45.71	< 0.0001	
BC	160.29	1	160.29	0.45	0.5169	
A^2	19385.41	1	19385.41	54.59	< 0.0001	
B^2	2442.38	1	2442.38	6.88	0.0255	
C^2	27674.55	1	27674.55	77.94	< 0.0001	
Residual	3550.79	10	355.08			

Figure 10. ANOVA table for validating the model significance towards minimizing the Volume of Weld Metal Deposit



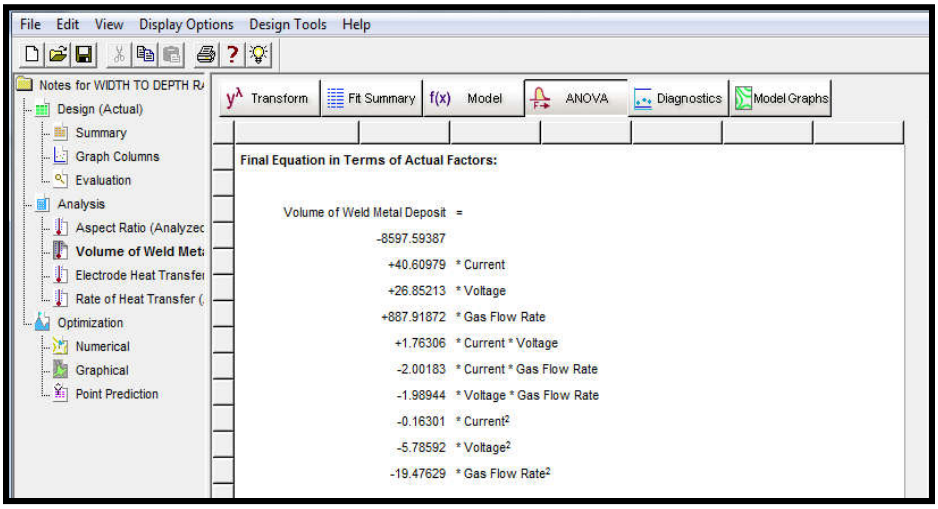
Std. Dev.	18.84	R-Squared	0.9744
Mean	1191.89	Adj R-Squared	0.9513
C.V. %	1.58	Pred R-Squared	0.8054
PRESS	26956.99	Adeq Precision	22.813

Figure 11. GOF Statistics for Validating Model Significance towards Minimizing the Volume of Weld Metal Deposit



Factor	Coefficient Estimate	df	Standard Error	95% CI Low	95% CI High	VIF
Intercept	1255.74	1	7.69	1238.62	1272.87	
A-Current	67.27	1	5.10	55.91	78.64	1.00
B-Voltage	1.99	1	5.10	-9.37	13.36	1.00
C-Gas Flow Rat	7.53	1	5.10	-3.83	18.90	1.00
AB	39.67	1	6.66	24.82	54.51	1.00
AC	-45.04	1	6.66	-59.89	-30.20	1.00
BC	-4.48	1	6.66	-19.32	10.37	1.00
A^2	-36.68	1	4.96	-47.74	-25.62	1.02
B^2	-13.02	1	4.96	-24.08	-1.96	1.02
C^2	-43.82	1	4.96	-54.88	-32.76	1.02

Figure 12. Coefficient Estimates Statistics for Minimizing the Weld Bead Volume



Final Equation in Terms of Actual Factors:

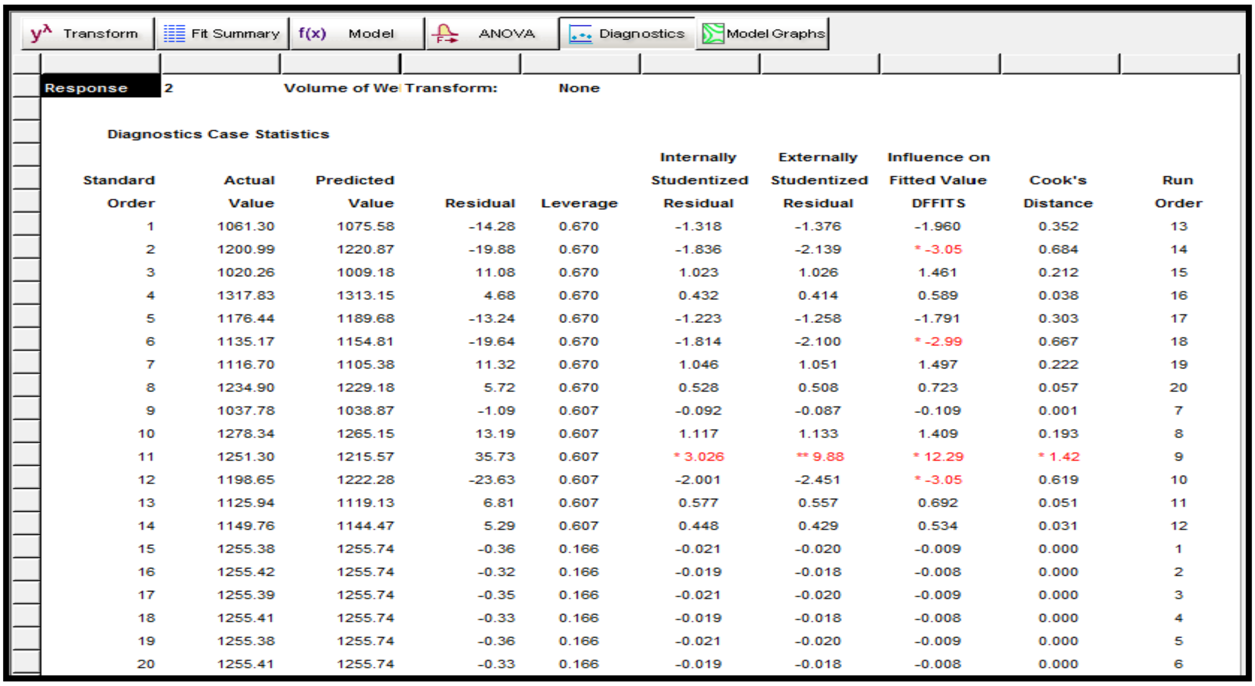
Volume of Weld Metal Deposit =
-8597.59387
+40.60979 * Current
+26.85213 * Voltage
+887.91872 * Gas Flow Rate
+1.76306 * Current * Voltage
-2.00183 * Current * Gas Flow Rate
-1.98944 * Voltage * Gas Flow Rate
-0.16301 * Current^2
-5.78592 * Voltage^2
-19.47629 * Gas Flow Rate^2

Figure 13. Optimal Equation in terms of Actual Factors for Minimizing the Weld Bead Volume

Values greater than 0.1000 indicate the model terms are not significant. To validate the adequacy of the model based on its ability optimize the volume of weld metal deposit. the goodness of fit statistics presented in Figure 11 were employed; Coefficient of determination (R-Squared) value of 0.9744 was obtained whichshows the strength of response surface methodology and its ability to minimize the volume of weld metal deposit. Adjusted (R-Squared) value of 0.9513 was also observed in figure 11 which indicates a model with 95.13% reliability.

Adeq Precision measures the signal to noise ratio. A ratio greater than 4 is desirable. 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 terms. Coefficient statistics for bead volume is presented in Figure 12. 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 (Volume of weld metal deposit), is presented based the actual factors as shown in Figure 13. The diagnostics case statistics which shows the observed values of each respones variable (Volume of weld metal deposit,) against their predicted values is presented in Figure 14.

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 bead volume is presented in Figures 15.



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	1061.30	1075.58	-14.28	0.670	-1.318	-1.376	-1.960	0.352	13
2	1200.99	1220.87	-19.88	0.670	-1.836	-2.139	* -3.05	0.684	14
3	1020.26	1009.18	11.08	0.670	1.023	1.026	1.461	0.212	15
4	1317.83	1313.15	4.68	0.670	0.432	0.414	0.589	0.038	16
5	1176.44	1189.68	-13.24	0.670	-1.223	-1.258	-1.791	0.303	17
6	1135.17	1154.81	-19.64	0.670	-1.814	-2.100	* -2.99	0.667	18
7	1116.70	1105.38	11.32	0.670	1.046	1.051	1.497	0.222	19
8	1234.90	1229.18	5.72	0.670	0.528	0.508	0.723	0.057	20
9	1037.78	1038.87	-1.09	0.607	-0.092	-0.087	-0.109	0.001	7
10	1278.34	1265.15	13.19	0.607	1.117	1.133	1.409	0.193	8
11	1251.30	1215.57	35.73	0.607	* 3.026	** 9.88	* 12.29	* 1.42	9
12	1198.65	1222.28	-23.63	0.607	-2.001	-2.451	* -3.05	0.619	10
13	1125.94	1119.13	6.81	0.607	0.577	0.557	0.692	0.051	11
14	1149.76	1144.47	5.29	0.607	0.448	0.429	0.534	0.031	12
15	1255.38	1255.74	-0.36	0.166	-0.021	-0.020	-0.009	0.000	1
16	1255.42	1255.74	-0.32	0.166	-0.019	-0.018	-0.008	0.000	2
17	1255.39	1255.74	-0.35	0.166	-0.021	-0.020	-0.009	0.000	3
18	1255.41	1255.74	-0.33	0.166	-0.019	-0.018	-0.008	0.000	4
19	1255.38	1255.74	-0.36	0.166	-0.021	-0.020	-0.009	0.000	5
20	1255.41	1255.74	-0.33	0.166	-0.019	-0.018	-0.008	0.000	6

Figure 14. Diagnostics Case Statistics Report of Observed and Predicted Volume of Weld Metal Deposit

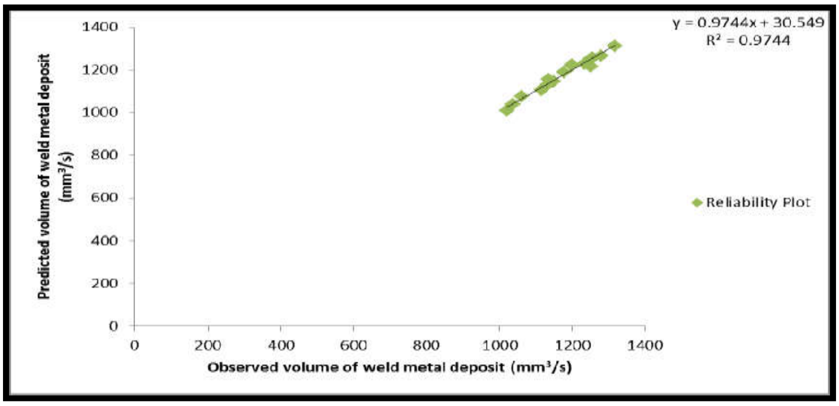


Figure 15. Reliability Plot of Observed versus Predicted Weld Bead Volume

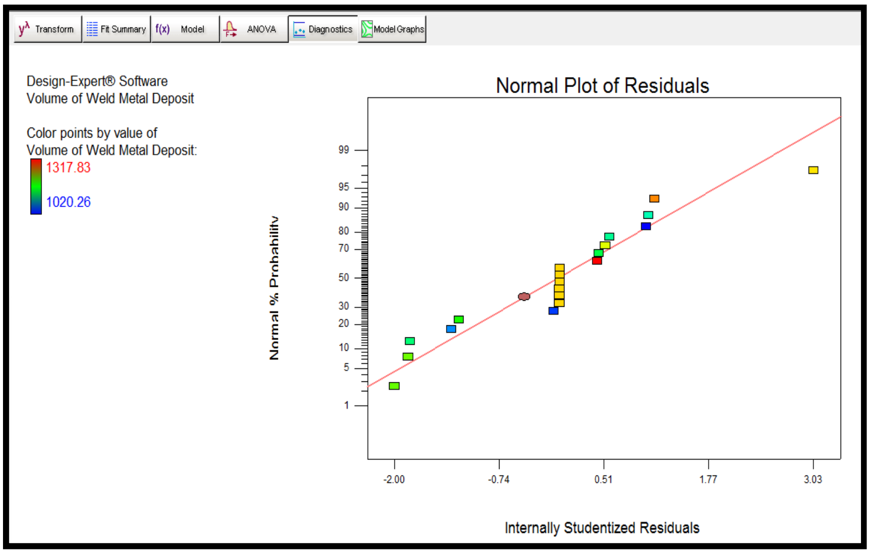


Figure 16. Normal Probability Plot of Studentized Residuals for minimizing Weld Bead Volume

To study the effects of combine variables on each response (Volume of weld metal deposit, 3D surface plots presented in Figure 17. 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 weld bead, also determining the optimum value of current, 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 19. From the results of figure 20 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 volume of weld metal deposit (1105.57mm^3/s. This solution was selected by Design Expert as the optimal solution with a desirability value of 96.70%.

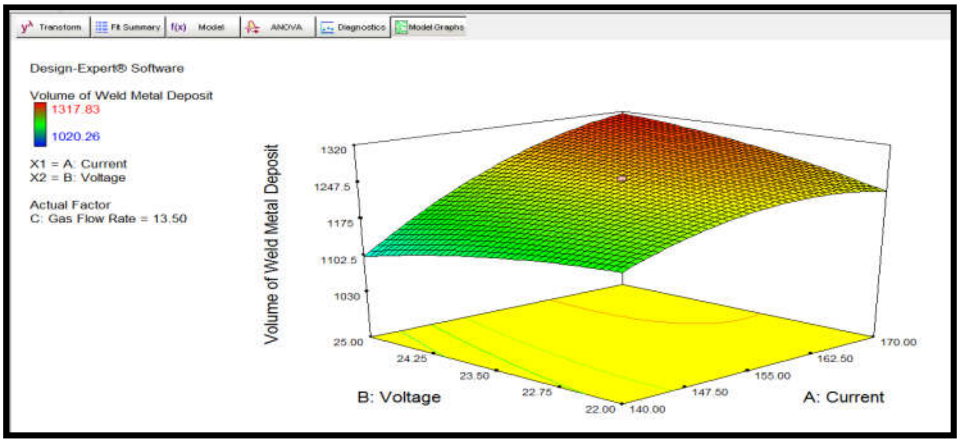


Figure 17. Effect of Current and Voltage on Volume of Weld Metal Deposit

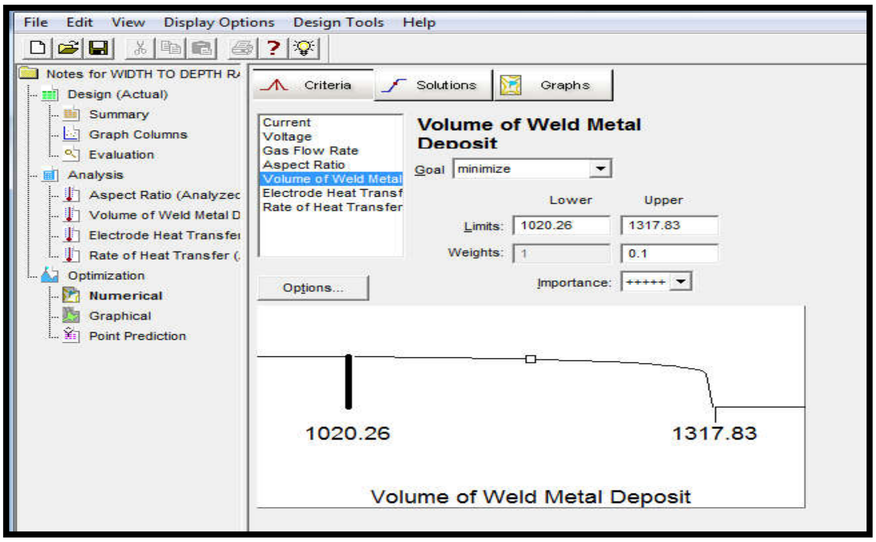
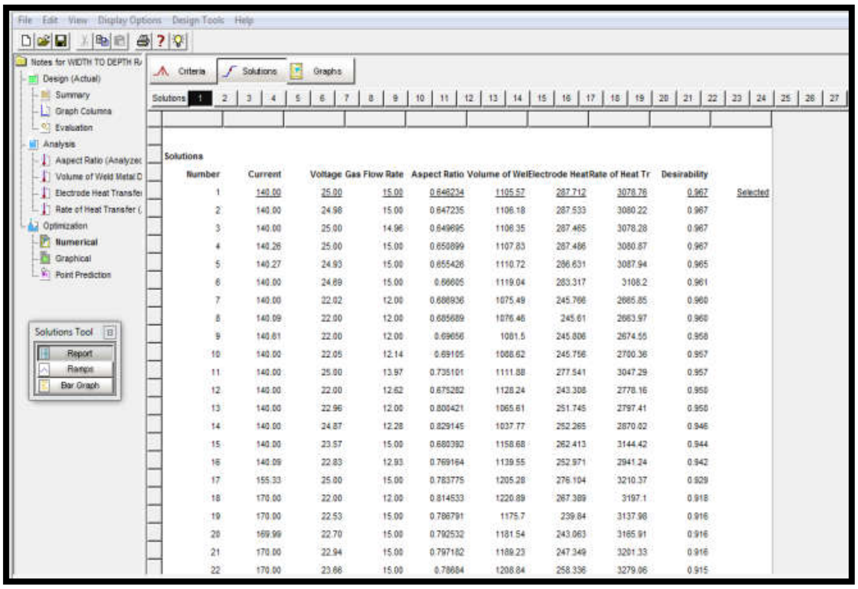


Figure 18. Interphase of Numerical Optimization Model for Optimizing the Weld Bead Volume



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	1068.62	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	0.958	
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

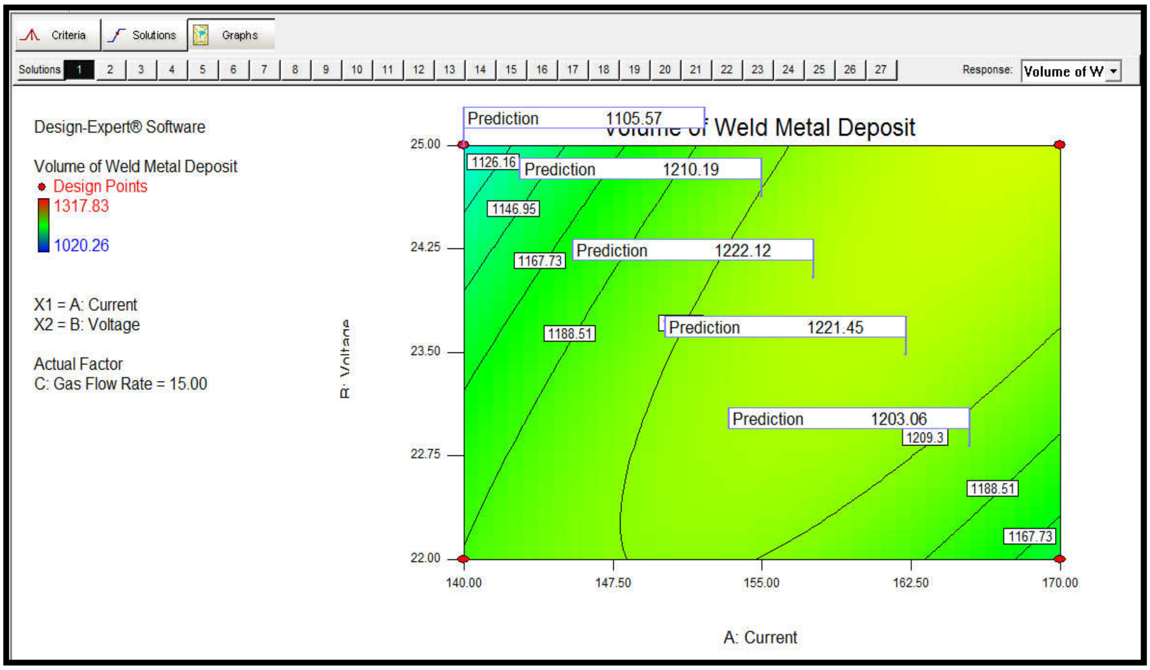


Figure 20. Predicting the Weld Bead Volume using Contour Plot

The contour plots showing weld bead volume response variable against the optimized value of the input variable is presented in Figure 20.

Conclusion

In this study, the response surface methodology was used to optimize the weld bead volume of tungsten inert gas mild steel welds. To validate the adequacy of the model based on its ability to optimize the weld bead volume, the goodness of fit statistics presented in Figure 11 was employed.Coefficient of determination (R^2) values of 0.9744 as observed in Figure 11 for weld bead volume indicated the adequacy of the models. To asses 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 Figures 16. The 3D surface plot as observed in Figures 18 shows the relationship between the input variables (voltage, current and gas flow rate) and the response variable (weld beadvolume).

Similarly, based on the optimal solution the expert system generated contour plots as observed in figures 21 showing several predicted responses and their respective input variables, all within the boundaries of experimental design. The quality of a weld is determined by the quality of the weld bead geometry and rate of heat transfer. The bead volume isa very important factor toconsider in assessing the quality of weldment. Weld bead geometry is described by the bead width, bead depth and bead volume. This study has shown that current has very strong influence on the on bead volume and rate of heat transfer. The models developed possess a variance inflation factor of 1.0 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 94% for aspect ratio, 97% for bead volume. Adequate precision value of 22.813 was observed for the Bead volume. The model produced numerical optimal solution of Current 140.0Amp, Voltage of 25Volt and a Gas flow rate of 15L/min will produce a welded material having a bead volume 1105.57mm^3 at a desirability value of 96.7%.

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