APPLICATION OF RESPONSE SURFACE METHODOLOGY IN THE OPTIMIZATION AND PREDICTION OF PERCENTAGE (%) WELD DILUTION OF TIG MILD STEEL WELDMENTS

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Abstract

Many deaths resulting from catastrophic weld failures in Nigeria can greatly be prevented, avoided or reduced to a great extent if standard practice such as the use of quality product, experience in welding and use of effective process parameter are observed. This research is focused on how to obtain the best percentage weld dilution through optimizing the weld process parameter by using Response Surface Methodology (RSM), with the purpose of achieving optimum results.
In this study, several sets of experiments were carried out. The input parameters considered were the applied current, voltage, and gas flow rate. The TIG welding process was used to join two pieces of mild steel plates, after which the % weld dilution was measured respectively. The experimental result was analyzed using the RSM.
The results obtained showed that current of 140.01 Amp, voltage of 20.00 volt, welding speed of 150.00mm/min, and gas flow rate of 12.01 L/min will produce a weld with a percentage dilution of 59.3962% with a desirability value of 97.30%.

Keywords: Response, RSM, Dilution, Mild Steel, Voltage.

1. Introduction

Ganesh et al, (2017) liken the welding operation as a metallurgical sculptural process for the fusion of metals and also that this process increases the surface properties in the case of cladding. Welding Technology and Science is a dominant phenomenon in the area of Manufacturing Engineering (Kah and Martikainen, 2012). This has made it a field of global interest for Engineers and Scientist who have continually developed new methods for investigating the scope and quality of weld metal deposits. Weld metal deposits is made up of the welded joint of structural materials where failure may result from weld decay which mostly occurs due to the distortion of metal grains and absorption of moisture within the heat affected zones during welding (Juan et al, 2016). Most of the times, research on process parameter's effect on responses goes a long way to alter the overall output of the weld either positively or negatively. Therefore, Low weld quality can be influenced by a poor combination of the welding input parameters (Gautam, 2013). Therefore it is important, as suggested by Achebo and Etin-osa (2017) to optimize input parameters in order to obtain the best quality weld deposit. In Nigeria, the study of welding technology is gradually attracting the interest of Manufacturing and Industrial Engineers, as the importance of a good quality welded joint cannot be over emphasized (Imhansoloeva et al, 2018). Deaths resulting from catastrophic weld failures have remained unreported in Nigeria and therefore there is a need to educate local welders on the relevance to improve on weld quality. The mechanical strength of a weld can be used to determine the quality of the weld bead geometry, which can be described by the Bead Width, Height, Reinforcement, Weld Reinforcement Form Factor (WRFF) and Weld Penetration Size Factor (WPSF). WRFF and WPSF fall under the umbrella of the weld bead shape. Mistry (2016) opined that the weld bead shape of a welded joint determines the mechanical properties of the joint. Kumar, (2011) said that weld bead shape is an indication of bead geometry. The quality of weld deposit also known as weld bead depends on the metallurgical formulation of its bead geometry. Narayana and Srihari (2012) said that the study of weld bead geometry deals with the estimation of depth of penetration, area of bead, and dilution. Mistry (2016) defined Weld Penetration Shape Factor, as the ratio of the weld width to the penetration and, also defined Weld Reinforcement Form Factor as the ratio of weld width to reinforcement height. According to Dhas and Satheesh, (2013), the welded joint is considered to be sound and economical if it has a maximum penetration, minimum bead width, reinforcement and dilution. These qualities can be achieved if the input parameters are optimally selected. Omajene et al (2014) were of the opinion that the strength of a welded joint can be influenced by the composition of the metal, distortion of the heat affected zone and also the weld bead shape. Optimizing these strength enhancing properties of weld results in good quality weld with great reliability. Parikshit and Dilip, (2007) developed a relationship between welding parameters and weld bead profile parameters of GTAW welded experimental data by using conventional regression analysis and the neural network based approach.

In this study, the Response Surface Methodology is used to optimize and predict the input parameters and also assess the effect of the input parameters on the bead shape factors. This investigation is geared towards improving the quality and strength properties of weld bead shape factors and geometry.

2. Materials and Methods

2.1 Materials

The Tungsten Inert Gas (TIG) machine was used to weld 10 mm mild steel plates measuring 60mm in length, 40mm in width. One hundred and Fifty (150) pieces of plate were cut with the edges bevelled, machined and etched with a 2% NaCl. This experiment was repeated 30 times with each experiment having five specimens, thereby producing a total of one hundred and fifty welded joints. The input parameters used for this study were welding speed, current, arc voltage, and gas flow rate as shown in table 1. The TIG machine was connected to a welding gun and shielding gas consisting of 100% argon. The weld planimeter and weld bead profiler were used to determine the dimensions of the bead geometry.

Table 1: *welding process parameters limits*

Parameters	*Unit*	*Symbol*	*Coded value*	*Coded value*
			Low(-1)	*High(+1)*
Current	*Amp*	*A*	*140*	*160*
Gas flow rate	*Lit/min*	*F*	*12*	*14*
Voltage	*Volt*	*V*	*20*	*24*
Welding speed	*cm/min*	*S*	*150*	*170*

2.2

2.2. Methods

2.2.1: Response Surface Methodology (RSM)

Response surface methodology (RSM) is used to study the relationships that exist between process parameters (Inputs) and responses variables (outputs). RSM design can either be carried out using the Box-Behnken Design or the Central Composite Design. The Central Composite Design's advantages over Box-Behnken is that it allows the experimental researcher to see what effect the factors has on response if the experimental researcher goes beyond or below the chosen levels of factors Imhansoloeva et al, (2018).

In Central Composite Design the minimum numbers of factors it can accommodate is two. The number of experiments obtained for each number of factors is given by the formula

$N=2^n + 2n+n_c$

Where N is the number of runs, n is the number of factors n_c is the number of center points the researcher desire.

2.2.2. Recording the Responses

The percentage weld dilution were measured after the welding process have been completed by using equation (1).

% dilution = AR/AR+AP x 100 (1)

Where, AR = reinforcement area (mm2), %D= percentage dilution of weldment and AP= weld penetration area of weld (mm2)

2.2.3. Second-Order polynomial model

To account for a curvature in the response surface gotten from the experimental result, the first-order polynomial model would be 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 $\beta_{13} x_{1i}$. Is expressed in equation (2)

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

$$= \beta_0 + x_i' \beta + x_i' \beta x_i + \varepsilon_{ij}$$

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

"The second-order model is flexible, because it can take a variety of functional forms and approximates the response surface locally. Therefore, this model is usually a good estimation of the true response surface.

3. Results and Discussion

Table 2*: Process parameters and values for Percentage Weld Dilution for thirty (30) experimental runs or trials.*

Std	*Run*	*Voltage (Volt)*	*Current (Amp)*	*Welding Speed (mm/min)*	*Gas Flow Rate (L/min)*	*Dilution %*
26	*1*	*22.00*	*150.00*	*160.00*	*13.00*	*65.45*
29	*2*	*22.00*	*150.00*	*160.00*	*13.00*	*65.44*
30	*3*	*22.00*	*150.00*	*160.00*	*13.00*	*65.46*
25	*4*	*22.00*	*150.00*	*160.00*	*13.00*	*65.44*
27	*5*	*22.00*	*150.00*	*160.00*	*13.00*	*65.45*
28	*6*	*22.00*	*150.00*	*160.00*	*13.00*	*65.46*
18	*7*	*26.00*	*150.00*	*160.00*	*13.00*	*98.22*
23	*8*	*22.00*	*150.00*	*160.00*	*11.00*	*67.88*
21	*9*	*22.00*	*150.00*	*140.00*	*13.00*	*60.26*
20	*10*	*22.00*	*170.00*	*160.00*	*13.00*	*62.25*
19	*11*	*22.00*	*130.00*	*160.00*	*13.00*	*62.98*
24	*12*	*22.00*	*150.00*	*160.00*	*13.00*	*57.66*
17	*13*	*18.00*	*150.00*	*160.00*	*13.00*	*63.28*
22	*14*	*22.00*	*150.00*	*160.00*	*13.00*	*57.88*
5	*15*	*20.00*	*140.00*	*170.00*	*12.00*	*65.08*
4	*16*	*24.00*	*160.00*	*150.00*	*12.00*	*70.61*
7	*17*	*20.00*	*160.00*	*170.00*	*12.00*	*69.86*
14	*18*	*24.00*	*140.00*	*170.00*	*14.00*	*84.31*

10	*19*	*24.00*	*140.00*	*150.00*	*14.00*	*83.29*
6	*20*	*24.00*	*140.00*	*170.00*	*12.00*	*76.40*
16	*21*	*24.00*	*160.00*	*170.00*	*14.00*	*78.52*
2	*22*	*24.00*	*140.00*	*150.00*	*12.00*	*67.14*
8	*23*	*24.00*	*160.00*	*170.00*	*12.00*	*65.42*
3	*24*	*20.00*	*160.00*	*150.00*	*12.00*	*67.79*
9	*25*	*20.00*	*140.00*	*150.00*	*14.00*	*66.42*
13	*26*	*20.00*	*140.00*	*170.00*	*14.00*	*58,17*
1	*27*	*20.00*	*140.00*	*150.00*	*12.00*	*54.52*
11	*28*	*20.00*	*160.00*	*150.00*	*14.00*	*59.92*
12	*29*	*24.00*	*160.00*	*150.00*	*14.00*	*75.34*
15	*30*	*20.00*	*160.00*	*170.00*	*14.00*	*43.12*

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; Result of Table 4 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 % dilution was observed to be 43.120%; the maximum value was observed to be 98.220%, with a mean value of 67.067 and standard deviation of 9.968.

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

Study type	***Response surface***	***Run***	***30***							
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	***Voltage***	***Volt***	***Numeric***	*20.00*	*24.00*	*-1.00*	*1.00*	*22.000*	*1.789*	
B	***Current***	***Amp***	***Numeric***	*140.00*	*160.00*	*-1.00*	*1.00*	*150.000*	*8.944*	
C	***W.S***	***M/min***	***Numeric***	*150.00*	*170.00*	*-1.00*	*1.00*	*160.000*	*8.944*	

D	***GFR***	***L/min***	***Numeric***	*12.00*	*14.00*	*-1.00*	*1.00*	*13.000*	*0.894*		
Response	***Name***	***Units***	***Obs***	***Analysis***	***Minimum***	***Maximum***	***Mean***	***Std. Dev.***	***Ratio***	***Trans***	***Model***
Y1	***Dilution***	*%*	*30*	***Polynomial***	*43.120*	*98.220*	*67.067*	*9.968*	*2.278*	***None***	***Quadratic***

In assessing the strength of the quadratic model towards maximizing the % weld dilution, one way analysis of variance (ANOVA) was done for each response variable and result is presented in Table 4. Analysis of variance was needed to check whether or not the model is significant and also to evaluate the significant contributions of each individual variable and the combined and quadratic effects towards each response.

Figure 4: *ANOVA table for validating the model significance towards minimizing the % Dilution*

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	***2705.61***	***14***	***193.26***	***10.52***	***<0.0001***	***Significant***
A-Voltage	***1441.97***	***1***	***144197***	***78.51***	***0.0001***	
B-Current	***43.23***	***1***	***43.23***	***2.35***	***0.1458***	
C-WS	***3.31***	***1***	***3.31***	***0.18***	***0.6773***	
D-GFR	***2.78***	***1***	***2.78***	***0.15***	***0.7027***	
AB	***19.69***	***1***	***19.69***	***1.07***	***0.3169***	
AC	***26.75***	***1***	***26.75***	***1.46***	***0.2462***	
AD	***319.61***	***1***	***319.61***	***17.40***	***0.0008***	
BC	***53.77***	***1***	***53.77***	***2.93***	***0.1077***	
BD	***131.27***	***1***	***131.27***	***7.15***	***0.0174***	
CD	***88.13***	***1***	***88.13***	***4.80***	***0.0447***	
A^2	***444.11***	***1***	***444.11***	***24.18***	***0.0002***	
B^2	***0.50***	***1***	***0.50***	***0.027***	***0.8713***	
C^2	***53.46***	***1***	***53.46***	***2.91***	***0.1086***	
D^2	***6.09***	***1***	***6.09***	***0.33***	***0.5733***	

From the result of Table 4, the model F-value of 10.52 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, AD, BD, CD, A^2 are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model.

To validate the adequacy of the model based on its ability to minimizing % dilution, the goodness of fit statistics presented in Table 5 was employed;

Table 5: *GOF statistics for validating model significance in minimizing %dilution*

Std. Dev	***4.29***	***R-Squared***	***0.9076***
Mean	***67.07***	***Adj R-Squared***	***0.8213***
C.V%	***6.39***	***Pred R-Squared***	***0.4677***
PRESS	***1586.97***	***Adeq Precision***	***16.855***

Coefficient of determination (R-Squared) value of 0.9076 as observed in Table 5 shows the strength of response surface methodology and its ability to minimize the % dilution. Adjusted (R-Squared) value of 0.8213 as observed in Table 5 indicates a model with 82.13% reliability. Adeq Precision measures the signal to noise ratio. A ratio greater than 4 is desirable. Adequate precision values of 16.855 as observed in Table 5 indicate an adequate signal. This model can be used to navigate the design space and maximize the % weld dilution.

The optimal equation which shows the individual effects and combine interactions of the selected variables against the mesured responses (% Dilution) is presented based on the coded and actual variables in equation (3) and (4)

The coded equation for:

$$\%Dilution = +65.45 +7.75*A -1.34*B -0.37*C -0.34*D -1.11*A*B +1.29*A*C +4.47*A*D -1.83*B*C -2.86*B*D -2.35*C*D +4.02*A^2 -0.13B^2 -1.40C^2 -047D^2 \quad (3)$$

Final equation in terms of actual factors:

$$\%Dilution = -772.80865 -71.46240*A +8.14748*B +8.80873*C +43.26187*D -0.055469*A*B +0.064656*A*C +2.23469*A*D\ 0.018331*B*C -0.028644*B*D -0.23469*C*D +1.00596*A^2 -1.34896E-003B^2 -0.013961C^2 -0.47115D^2 \quad (4)$$

Where, A=voltage, B=current, C=welding speed, D=gas flow rate, A*B =voltage*current, A*C= voltage*welding speed, A*D= voltage*gas flow rate, B*C= current*welding speed, B*D= current*gas flow rate, C*D= welding speed*gas flow rate, A^2= voltage^2, B^2= current, C^2= welding speed^2 and D^2= gas flow rate^2

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 the % weld dilution response were obtained as presented in Figures 1

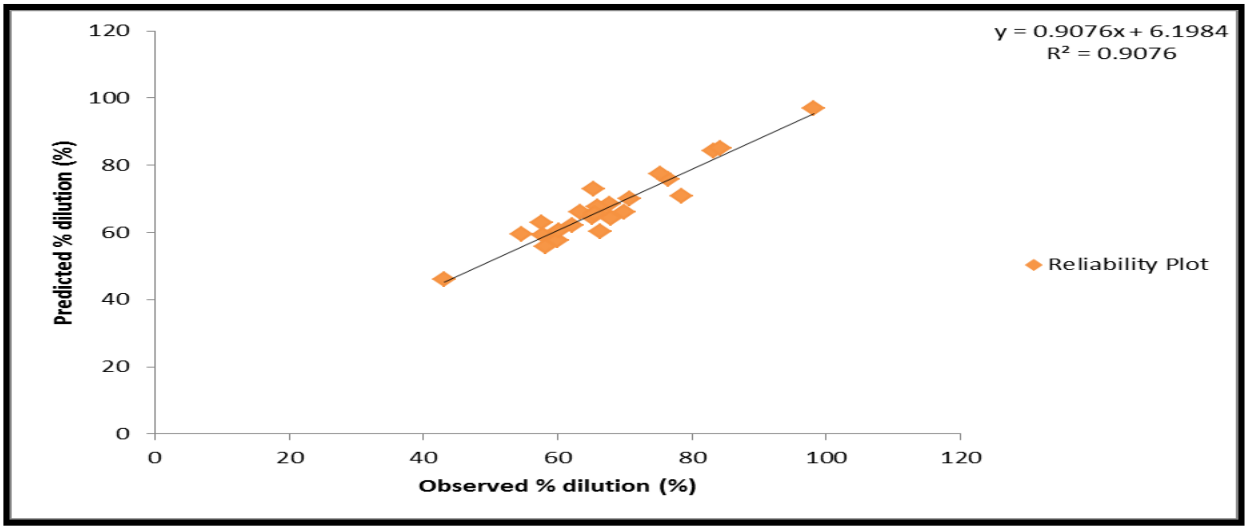


Figure 1: *Reliability plot of observed versus predicted % dilution*

The high coefficient of determination (r^2 = 0.9076) as observed in Figures 1 were used to established the suitability of response surface methodology in minimizing the % weld dilution.
To accept any model, its satisfactoriness must first be checked by an appropriate statistical analysis and to diagnose the statistical properties of the model, the normal probability plot of the % weld dilution residual presented in Figure 2 and was employed.

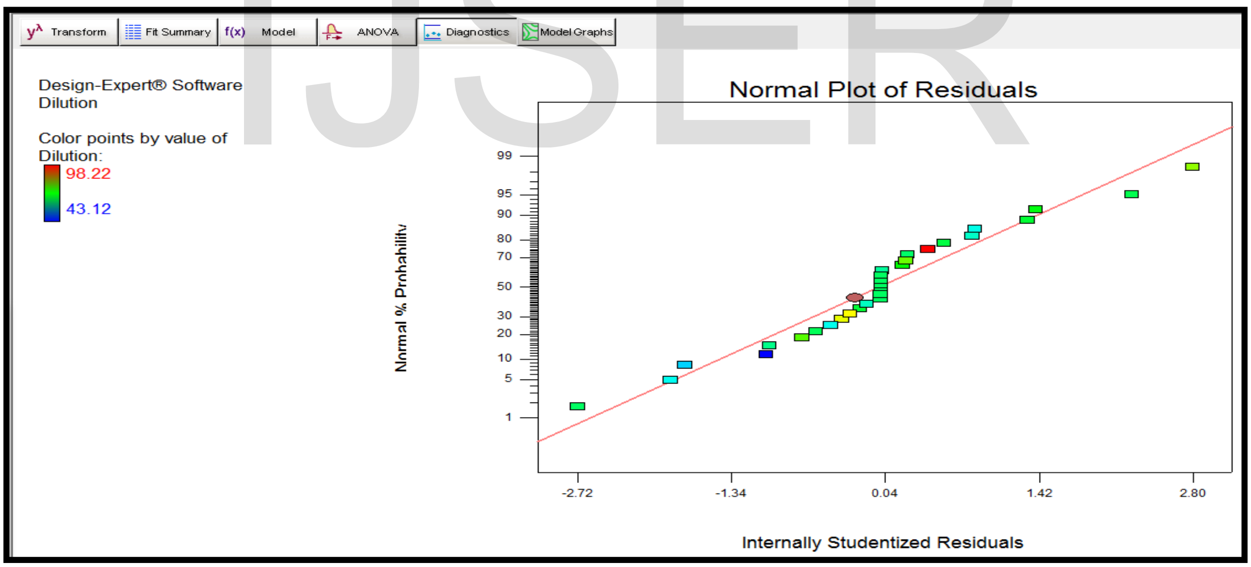


Figure 2: *Normal probability plot of studentized residuals for % dilution*

The 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 Figure 2 revealed that the computed residuals is 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 (% weld dilution), 3D surface plots is presented in Figure 3 was employed.

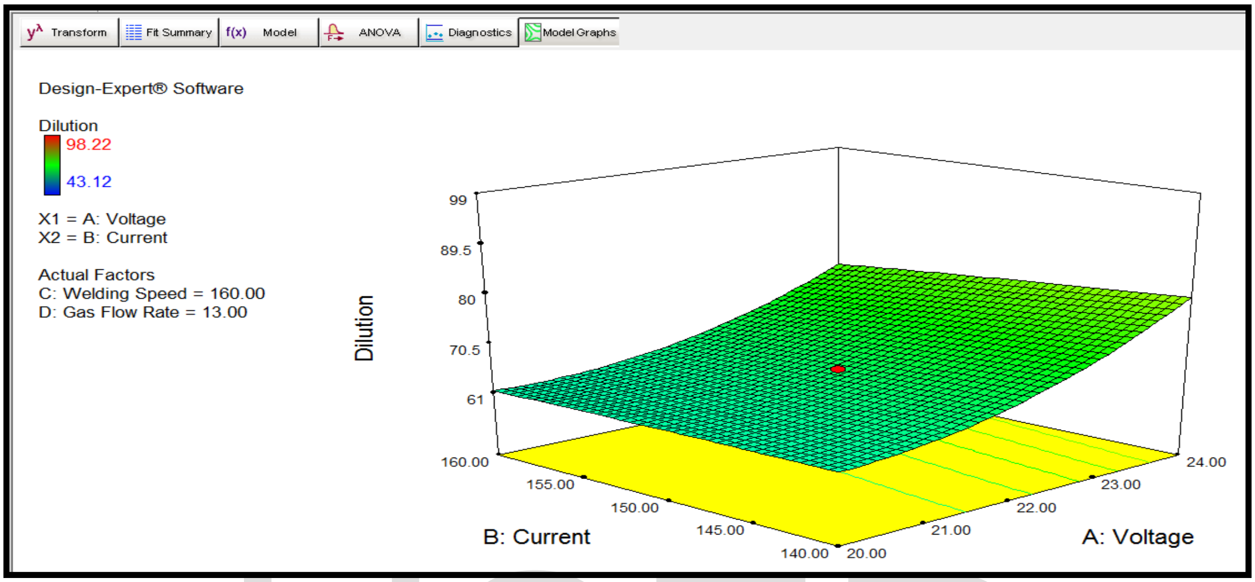


Figure 3: *Effect of current and voltage on % dilution*

The 3D surface plot as observed in Figure 3 shows the relationship between the input variables (voltage, current, welding speed and gas flow rate) and the response variable (% weld dilution). It is a 3 dimensional surface plot which was employed to give a clearer concept of the response surface. As the color of the curved surface gets darker, % weld dilution decreases proportionately. The presence of a colored 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 % weld dilution while also determining the optimum value of voltage, current, welding speed and gas flow rate. The interphase of the numerical optimization showing the goal of the objective function is presented in Figures 4

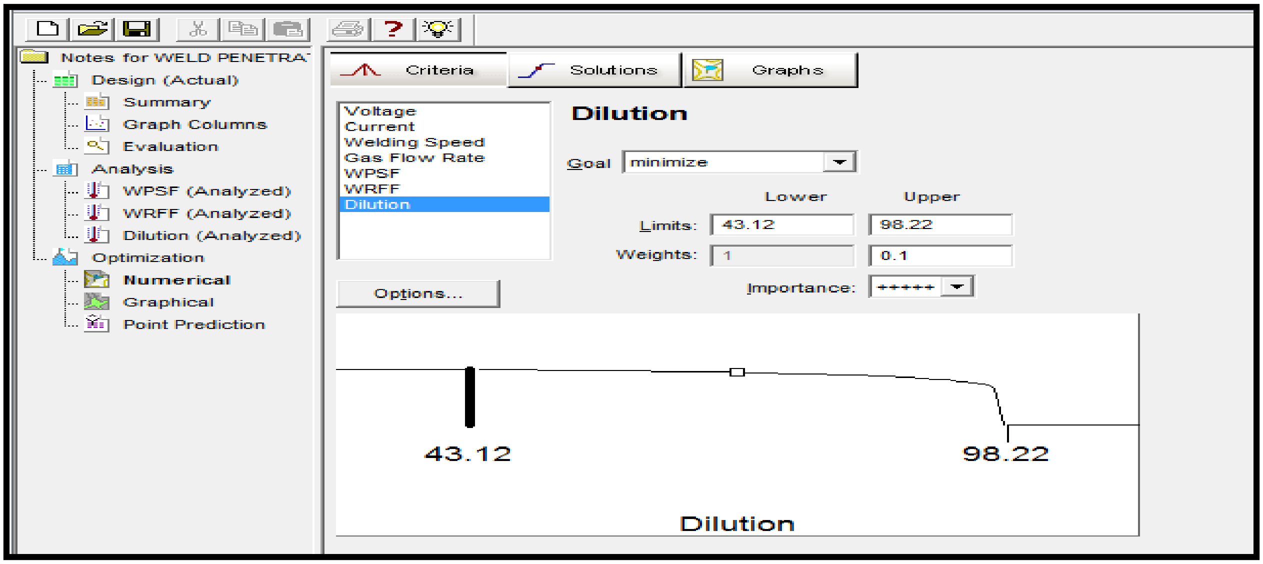
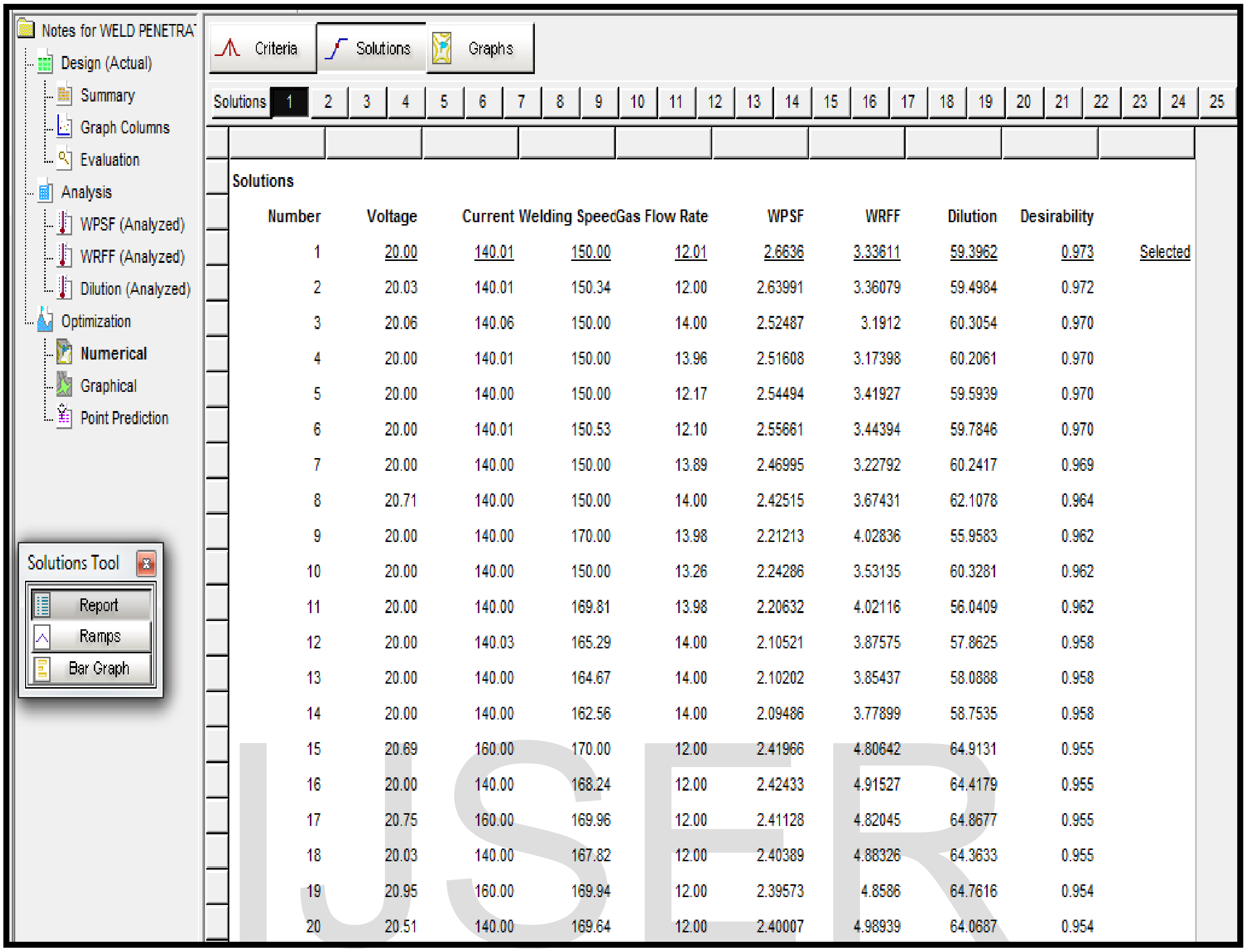


***Figure 4:** Interphase of numerical optimization model for minimizing % dilution*

The interface of numerical optimization defines the objective function (minimize or maximize) as the case maybe, defines the lower and upper limit of the response with the level of importance indicated. For a minimization case, the weight leans towards the lower limit as seen above for % weld dilution.

The numerical optimization produces about twenty (20) optimal solutions which are presented in Figure 5



Solutions

Number	Voltage	Current	Welding Speed	Gas Flow Rate	WPSF	WRFF	Dilution	Desirability	
1	20.00	140.01	150.00	12.01	2.6636	3.33611	59.3962	0.973	Selected
2	20.03	140.01	150.34	12.00	2.63991	3.36079	59.4984	0.972	
3	20.06	140.06	150.00	14.00	2.52487	3.1912	60.3054	0.970	
4	20.00	140.01	150.00	13.96	2.51608	3.17398	60.2061	0.970	
5	20.00	140.00	150.00	12.17	2.54494	3.41927	59.5939	0.970	
6	20.00	140.01	150.53	12.10	2.55661	3.44394	59.7846	0.970	
7	20.00	140.00	150.00	13.89	2.46995	3.22792	60.2417	0.969	
8	20.71	140.00	150.00	14.00	2.42515	3.67431	62.1078	0.964	
9	20.00	140.00	170.00	13.98	2.21213	4.02836	55.9583	0.962	
10	20.00	140.00	150.00	13.26	2.24286	3.53135	60.3281	0.962	
11	20.00	140.00	169.81	13.98	2.20632	4.02116	56.0409	0.962	
12	20.00	140.03	165.29	14.00	2.10521	3.87575	57.8625	0.958	
13	20.00	140.00	164.67	14.00	2.10202	3.85437	58.0888	0.958	
14	20.00	140.00	162.56	14.00	2.09486	3.77899	58.7535	0.958	
15	20.69	160.00	170.00	12.00	2.41966	4.80642	64.9131	0.955	
16	20.00	140.00	168.24	12.00	2.42433	4.91527	64.4179	0.955	
17	20.75	160.00	169.96	12.00	2.41128	4.82045	64.8677	0.955	
18	20.03	140.00	167.82	12.00	2.40389	4.88326	64.3633	0.955	
19	20.95	160.00	169.94	12.00	2.39573	4.8586	64.7616	0.954	
20	20.51	140.00	169.64	12.00	2.40007	4.98939	64.0687	0.954	

***Figure 5:** Optimal solutions of numerical optimization model*

From the results of figure 5, it was observed that current of 140.01 Amp, voltage of 20.00 volt, welding speed of 150.00mm/min and gas flow rate of 12.01 L/min will produce a weld material with % weld Dilution of 59.3962% which was selected by design expert as the optimal solution at a desirability value of 97.30%.

From the optimal solution, the contour plots showing the % weld dilution response variable against the optimized value of the input variable is presented in Figure 6

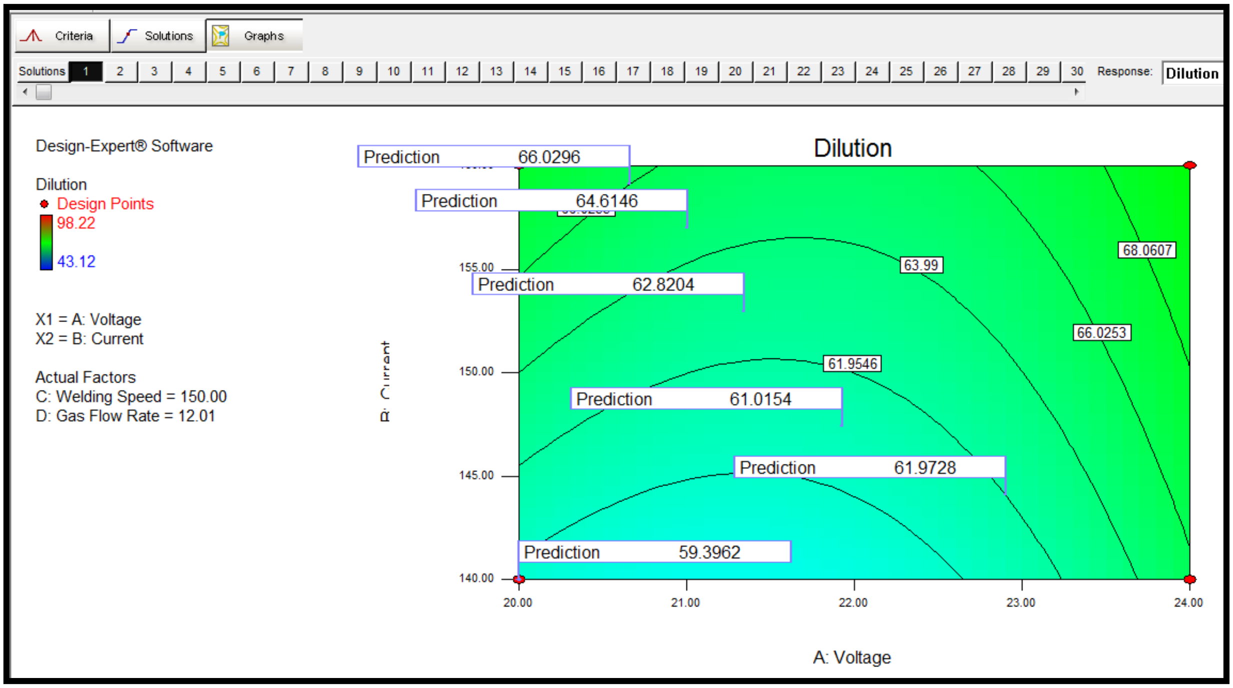


Figure 6: Predicting percentage dilution(% dilution) using contour plot

The contour plots in fig. 4.7c showed different predictions; when voltages =20.00, 21.00, 22.00, and 23.00, % dilution = 59.3962, 64.6146, 61.0154 and 61.9728 respectively.

4. Conclusion

In this study Mathematical model for percentage dilution for TIG four input process parameters (voltage, current, welding speed and gas flow rate) has been developed. The results obtained showed that current of 140.01 Amp, voltage of 20.00 volt, welding speed of 150.00mm/min, and gas flow rate of 12.01 L/min will produce a weld with % Dilution 59.3962%. This solution was selected at a desirability value of 97.30%.

By increasing the gas flow rate with welding speed and voltage at moderate level, the values of percentage dilution is at maximum. The results of this study will help reduce the cost of expensive and time wasting analytical methods employed during welding operation, and it will help fabrication industries to maximize the quality of their products. It is recommended that for effective weld dilution of fusion zone, welders should make use of current of 140.01 Amp, voltage of 20.00 volt, welding speed of 150.00mm/min, and gas flow rate of 12.01 L/min.

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