

# Optimization of the Deposition Rate of Tungsten Inert Gas Mild Steel Using Response Surface Methodology

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#### Abstract

In welding, so many factors contribute to good quality welds. The deposition rate is the rate of weld metal deposit at fusion zone during welding, which also is a key factors affecting the quality of welded joints. Too high or low deposition rate compromises the integrity of weld. This study was carried out with the aim of providing an approach for producing better weldments by optimizing and predicting deposition rate of low carbon steel using Response Surface Methodology (RSM). 30 sets of experiments were done, adopting the central composite experimental design. The tungsten inert gas welding equipment was used to produce the welded joints. Argon gas was supplied to the welding process to shield the weld from atmospheric interference. Mild steel coupons measuring  $60 \times 40 \times 10$  mm was used for the experiments. The results obtained show that the voltage and current have very strong influence on the deposition rate. The models developed possess a variance inflation factor of 1. And P-value is less than 0.05, indicating that the model is significant. The models also possessed a high goodness of fit with R<sup>2</sup> (Coefficient of determination) values of 91%. The model produced numerically obtained optimal solution of current of 160.00 Amp, voltage of 20 volts and a gas flow rate of 17 L/min produces a welded material having deposition rate of 0.4637 kg/hr. This solution was selected by design expert as the optimal solution with a desirability value of 98.8%. A weld simulation using the optimum value obtained produced a weld with good quality.

# **Keywords**

Deposition Rate, Welded Joints, Welding Equipment

### **1. Introduction**

According to [1] in industries like ship building, pressure vessel, off shore, aviation, heavy construction, the need of higher metal deposition rate welding is always required to increase the productivity. Metal deposition in combination with fabrication offers a product with high structural integrity, produced with a minimum of scrap. [2] concluded that the Shape of Metal Deposit process (SMD) is a viable method for fabricating local, complex features in aerospace components.

Several techniques have been developed to improve the metal deposition rate beyond that of standard, single wire SAW to increase the productivity. An extensive research work on optimization of welding process was done by [3] [4] and [5]. [6] made early a kind of weld deposition analyses, weaved welds for cladding of a surface with welded material. According to [7], Tungsten Inert Gas Arc Welding is a commonly used welding technique due to its versatility and ease that can be maintained in almost all type of working conditions. Stainless Steel (SS316) possessing high strength and toughness is usually known to offer major challenges during its welding. In this work, Taguchi's DOE approach is used to plan and design the experiments to study the effect of welding process parameters on metal deposition rate and hardness of the weld bead. [8] claimed that different process parameters of Gas Tungsten Arc Welding (GTAW) affect the weldment quality. Increasing welding current increases the deposition rate and reduces the hardness.

[9] and [10] showed by their works that on selecting input parameters such as welding current, voltage, speed and time against response of ultimate tensile strength of steel, optimization was achieved with the help of Taguchi Method.

Having a detailed review of literature, it was discovered that the optimization of Tungsten Inert Gas deposition rate of mild steel weld have not been established to the best of our knowledge. The aim of the study is to provide an approach for producing better weld joints considering deposition rate of Tungsten Inert Gas mild steel weld.

### 2. Methodology

This research study is centered on the experimental study of TIG mild steel welds, employing scientific design of experiments, expert systems, statistical and mathematical models. The TIG sets of experiment were conducted at the Department of Welding and Fabrication Technology, Petroleum Training Institute (PTI), Warri, Delta State, Nigeria. 150 pieces of mild steel coupons measuring 60  $\times$  40  $\times$  10 was used for the experiments, the experiment was performed 30 times using 5 specimen for each run. The materials used in the experiment are TIG equipment (Miller machine), shielding gas cylinder and regulator and TIG Torch.

#### 2.1. Identification of Range of Input Parameters

The key parameters considered in this work are welding current, welding speed, gas flow rate, and welding voltage. The range of the process parameters obtained from literature is shown in Table 1.

Parameters	Units	symbol	lower	Higher
Gas flow rate	Lit/min	F	12	23
Arc voltage	Volt	V	14	21
Welding current	Amp	А	130	180
Welding speed	mm/min	S	2	5

#### Table 1. Process parameters and their levels.

#### 2.2. Method of Data Collection

The central composite design matrix was developed using the design expert software, producing 30 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 1 shows the central composite design matrix. Response surface methodology 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. In Box-Behnken Design the minimum number of factors it can accommodate is three and it has three level of factors which are the Upper level, Lower level and Centre point. In this article, the Central Composite Design was adopted. Central Composite design is also a response surface method (RSM) as stated earlier which apart from its three level factors has axial point (also known as star point), and this axial point increases the number of levels to five levels to give the experimental design flexibility and robustness. 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

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

where *N* is the number of runs, *n* is the number of factors  $n_c$  is the number of centre points the researcher desire

The data obtained were analysed using the Response Surface Methodology

### 2.3. Testing the Adequacy of the Models Developed

The analysis of variance (ANOVA) was used to test the adequacy of the models developed. The statistical significance of the models developed and each term in the regression equation were examined using the sequential F-test, lack-of-fit test and other adequacy measures (*i.e.*  $R^2$ , Adj- $R^2$  Pred.  $R^2$  and Adeq. Precision ratio) using the same software to obtain the best fit. The Prob. > F (sometimes called p-value) of the model and of each term in the model can be computed by means of ANOVA. If the Prob. > F of the model and of each term in the model does not exceed the level of significance (say a = 0.05) then the model may be considered adequate within the confidence interval of (1-a). For the lack-of-fit test, the lack of fit could be considered insignificant if the Prob. > F of the lack of fit exceeds the level of significance.

	🏐 <b>?</b>   3	<b>Q</b> :					
Notes for ENGR NICOLAS     Design (Actual)     Summany	Std	Run	Туре	Factor 1 A:Current Amp	Factor 2 B:Voltage Volt	Factor 3 C:Welding Speed Cm/min	Factor 4 D:GFR L/min
Graph Columns	27	1	Center	170.00	21.00	50.00	16.00
- Craluation	25	2	Center	170.00	21.00	50.00	16.00
- Analysis	30	з	Center	170.00	21.00	50.00	16.00
	29	4	Center	170.00	21.00	50.00	16.00
Weld Bead Volume (	28	5	Center	170.00	21.00	50.00	16.00
Optimization	26	6	Center	170.00	21.00	50.00	16.00
	1	7	Fact	160.00	20.00	45.00	15.00
Graphical	2	8	Fact	180.00	20.00	45.00	15.00
I Ai Point Prediction	3	9	Fact	160.00	22.00	45.00	15.00
	4	10	Fact	180.00	22.00	45.00	15.00
	5	11	Fact	160.00	20.00	55.00	15.00
	6	12	Fact	180.00	20.00	55.00	15.00
	7	13	Fact	160.00	22.00	55.00	15.00
	8	14	Fact	180.00	22.00	55.00	15.00
	9	15	Fact	160.00	20.00	45.00	17.00
	10	16	Fact	180.00	20.00	45.00	17.00
	11	17	Fact	160.00	22.00	45.00	17.00
	12	18	Fact	180.00	22.00	45.00	17.00
	13	19	Fact	160.00	20.00	55.00	17.00
	14	20	Fact	180.00	20.00	55.00	17.00
	15	21	Fact	160.00	22.00	55.00	17.00
1	16	22	Fact	180.00	22.00	55.00	17.00
1	17	23	Axial	150.00	21.00	50.00	16.00
	18	24	Axial	190.00	21.00	50.00	16.00
1	19	25	Axial	170.00	19.00	50.00	16.00
-	20	26	Avial	170.00	23.00	50.00	16.00

Figure 1. Central composite design matrix (CCD), method of data analysis.

#### 2.4. Test for Model Adequacy and Model Significance

The significance of the model will be determined using analysis of variance (ANOVA), Differential Functioning of Items and Texts (DFITS) a measure of the influence of each observation on the values fitted. The significance of the input process parameters for the two responses was determined using the P-value of the lack of fit and the input process parameters were compared using a significance level of significance of Alpha  $\alpha = 0.05$  (Table 2).

### 2.5. Model Validation for ANOVA

The coefficient of determination,  $R^2$ , was used to validate the obtained model for the weld deposition rate. While the adjusted coefficient of determination is obtained and used to validate the proposed model.

### 2.6. Methods of Model Validation for Response Surface Methodology (RSM)

Different validation techniques were used to validate the predictions from the response surface methodology (RSM) model developed. Validation techniques used were: Desirability plots, residuals, DFITS, mean square errors (MSE), least significant difference (LSD) bars, Ramp plots, overlay plots, perturbation plots, contour plots, steepest ascent optimization comprising 3-D plots and response surface plots.

# 3. Results and Discussion

In this study, thirty experimental runs were carried out, each experimental run comprising the current, voltage, welding speed and gas flow rate, used to join two pieces of mild steel plates measuring  $60 \times 40 \times 10$  mm. The weld deposition rate were measured, respectively. The results are shown in **Figure 2**.

# 3.1. Modelling and Optimization Using RSM

In this study, a second order mathematical model was developed between some selected input variables, namely; current (I), voltage (V), welding speed (WS),

Variation Source	Degree of FreedomDf	Sum of Squares SS	Mean Square MS	Fisher Ratio F-value
Error of residuals	<i>n</i> – 2	$SSE = \sum_{i=1}^{c} \sum_{j=1}^{ni} (y_{ij} - \hat{y}_{ij})^2$	$MSE = \frac{SSE}{n-2}$	
Regression	1	$SSR = \sum_{i=1}^{c} \sum_{j=1}^{ni} \left( \hat{y}_{ij} - \overline{y} \right)^2$	$MSR = \frac{SSR}{1}$	$F = \frac{MSR}{MSE}$
Lack of fit	C-2	$SSLF_i = \sum_{i=1}^{c} \sum_{j=1}^{m} \left( \overline{y}_{ij} - \hat{y}_{ij} \right)^2$	$MSLF = \frac{SSLF}{c-2}$	$F^* = \frac{MSLF}{MSPE}$
Total	<i>n</i> – 1	$SSTD = \sum_{i=1}^{c} \sum_{j=1}^{ni} \left( \mathcal{Y}_{ij} - \overline{\mathcal{Y}}_{ij} \right)^2$	-	-

Table 2. Analysis of variance components.

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Notes for ENGR NICOLAS		Std	Run	Туре	Factor 1 A:Current Amp	Factor 2 B:Voltage Volt	Factor 3 C:Welding Speed Cm/min	Factor 4 D:GFR L/min	Response 1 Weld Deposition Rate Kg/hr
- III Summary		27	1	Center	170.00	21.00	50.00	16.00	0.334
- ST Evaluation		25	2	Center	170.00	21.00	50.00	16.00	0.256
- Analysis		30	3	Center	170.00	21.00	50.00	16.00	0.258
- Uveld Deposition Rat		29	4	Center	170.00	21.00	50.00	16.00	0.26
- UVeld Bead Volume (		28	5	Center	170.00	21.00	50.00	16.00	0.255
- 🔄 Optimization		26	6	Center	170.00	21.00	50.00	16.00	0.253
		1	7	Fact	160.00	20.00	45.00	15.00	0.1887
- 🔛 Graphical		2	8	Fact	180.00	20.00	45.00	15.00	0.2631
- X: Point Prediction		3	9	Fact	160.00	22.00	45.00	15.00	0.15
		4	10	Fact	180.00	22.00	45.00	15.00	0.456
		5	11	Fact	160.00	20.00	55.00	15.00	0.2653
		6	12	Fact	180.00	20.00	55.00	15.00	0.21
ĺ		7	13	Fact	160.00	22.00	55.00	15.00	0.2215
		8	14	Fact	180.00	22.00	55.00	15.00	0.4024
		9	15	Fact	160.00	20.00	45.00	17.00	0.456
		10	16	Fact	180.00	20.00	45.00	17.00	0.2653
		11	17	Fact	160.00	22.00	45.00	17.00	0.2123
		12	18	Fact	180.00	22.00	45.00	17.00	0.253
		13	19	Fact	160.00	20.00	55.00	17.00	0.384
		14	20	Fact	180.00	20.00	55.00	17.00	0.1309
		15	21	Fact	160.00	22.00	55.00	17.00	0.2263
ľ		16	22	Fact	180.00	22.00	55.00	17.00	0.1558
		17	23	Axial	150.00	21.00	50.00	16.00	0.1458
		18	24	Axial	190.00	21.00	50.00	16.00	0.168
		19	25	Axial	170.00	19.00	50.00	16.00	0.32
		20	26	Axial	170.00	23.00	50.00	16.00	0.224

Figure 2. Experimental results of deposition rate.

gas flow rate (GFR) and weld deposition rate (WDR) using response surface methodology (RSM).

The target of the optimization model was to maximize the weld deposition rate.

The final solution of the optimization process was to determine the optimum value of each input variable namely: current (Amp), voltage (Volt), welding speed (cm/min) and gas flow rate (l/min) that will maximize the weld deposition rate (WDR).

To generate the experimental data for the optimization process:

1) First, 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. For this particular problem, Design Expert 7.01 was employed.

2) Secondly, an experimental design matrix having six (6) center points (k), eight (8) axial points (2n) and sixteen (16) factorial points (2<sup>n</sup>) resulting to 30 experimental runs was generated.

The randomized design matrix comprising of four input variables namely; current (Amp), voltage (Volt), welding speed (cm/min), gas flow rate (l/min) and weld deposition rate (kg/hr) in coded is shown in Figure 3.

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	6	6 <b>?</b>   3	2:1						
Design (Coded)		Std	Run	Туре	Factor 1 A:Current Amp	Factor 2 B:Voltage Volt	Factor 3 C:VVelding Speed Cm/min	Factor 4 D:GFR L/min	Response 1 Weld Deposition Rate Kg/hr
Graph Columns	-	27	1	Center	0.000	0.000	0.000	0.000	0.334
- Stabution	<u> </u>	25	2	Center	0.000	0.000	0.000	0.000	0.256
- M Analysis		30	з	Center	0.000	0.000	0.000	0.000	0.258
Weld Deposition Rat	_	29	4	Center	0.000	0.000	0.000	0.000	0.26
🚛 Weld Bead Volume (		28	6	Center	0.000	0.000	0.000	0.000	0.255
🔄 Optimization		26	8	Center	0.000	0.000	0.000	0.000	0.253
··· Mumerical		1	7	Fact	-1.000	-1.000	-1.000	-1.000	0.1887
Graphical		2	8	Fact	1.000	-1.000	-1.000	-1.000	0.2631
I N Point Prediction		3	9	Fact	-1.000	1.000	-1.000	-1.000	0.15
		- 4	10	Fact	1.000	1.000	-1.000	-1.000	0.456
		5	11	Fact	-1.000	-1.000	1.000	-1.000	0.2653
		6	12	Fact	1.000	-1.000	1.000	-1.000	0.21
		7	13	Fact	-1.000	1.000	1.000	-1.000	0.2215
		8	14	Fact	1.000	1,000	1.000	-1.000	0.4024
	<u> </u>	9	15	Fact	-1.000	-1.000	-1.000	1.000	0.456
		10	16	Fact	1.000	-1.000	-1.000	1.000	0.2653
		11	17	Fact	-1.000	1.000	-1.000	1.000	0.2123
		12	18	Fact	1.000	1.000	-1.000	1.000	0.253
		13	19	Fact	-1.000	-1.000	1.000	1.000	0.384
		14	20	Fact	1.000	-1.000	1.000	1.000	0.1309
		15	21	Fact	-1.000	1.000	1.000	1.000	0.2263
		16	22	Fact	1.000	1.000	1.000	1.000	0.1558
		17	23	Axial	-2.000	0.000	0.000	0.000	0.1458
		18	24	Axial	2.000	0.000	0.000	0.000	0.168
		19	25	Axial	0.000	-2.000	0.000	0.000	0.32
		20	26	Axial	0.000	2.000	0.000	0.000	0.224
		21	27	Axial	0.000	0.000	-2.000	0.000	0.336
		22	28	Axial	0.000	0.000	2.000	0.000	0.225
		23	29	Axial	0.000	0.000	0.000	-2.000	0.335
		24	30	Axial	0.000	0.000	0.000	2.000	0.336

Figure 3. Design matrix showing the coded values and the experimental values.

The design matrix comprising of four input variables namely; current (Amp), voltage (Volt), welding speed (cm/min), gas flow rate (l/min) and weld deposition rate (kg/hr) in actual values is shown in **Figure 4**.

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 5**; Result of **Figure 5** 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 weld deposition rate (WDR) was observed to be 0.131 kg/hr, with a maximum value of 0.456 kg/hr, mean value of 0.265 and standard deviation of 0.085.

To validate the suitability of the quadratic model in analyzing the experimental data, the sequential model sum of squares were calculated for weld deposition as presented in **Figure 6**.

The sequential model sum of squares figure shows the accumulating improvement in the model fit as terms are added. Based on the calculated sequential model sum of square, the highest order polynomial where the additional terms are significant and the model is not aliased was selected as the best fit. From the results of **Figure 6**, it was observed that the cubic polynomial was aliased hence cannot be employed to fit the final model. In addition, the quadratic and 2FI model were suggesed as the best fit thus justifying the use of quadratic polynomial in this analysis

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 each of the responses. Model with significant lack of fit cannot be employed for prediction. Results of the computed lack of fit for weld deposition rate as presented in **Figure 7**.

From the results of **Figure 7** it was again observed that the quadratic polynomial had a non-significant lack of fit and was suggest for model analysis while the cubic polynomial had a significand lack of fit hence aliased to model analysis.

Design (Actual)	Std	Run	Туре	Factor 1 A:Current Amp	Factor 2 B:Voltage Volt	Factor 3 C:Welding Speed Cm/min	Factor 4 D:GFR L/min	Response 1 Weld Deposition Rate Kg/hr
Graph Columns	27	1	Center	170.00	21.00	50.00	16.00	0.33
Evaluation	25	2	Center	170.00	21.00	50.00	16.00	0.25
alysis	30	3	Center	170.00	21.00	50.00	16.00	0.25
eld Deposition Rat	29	4	Center	170.00	21.00	50.00	16.00	0.26
eld Bead Volume I	28	5	Center	170.00	21.00	50.00	16.00	0.255
ization	26	6	Center	170.00	21.00	50.00	16.00	0.253
umerical	1	7	Fact	160.00	20.00	45.00	15.00	0.1887
aphical	2	8	Fact	180.00	20.00	45.00	15.00	0.2631
	3	9	Fact	160.00	22.00	45.00	15.00	0.15
_	4	10	Fact	180.00	22.00	45.00	15.00	0.456
_	5	11	Fact	160.00	20.00	55.00	15.00	0.2653
_	6	12	Fact	180.00	20.00	55.00	15.00	0.21
_	7	13	Fact	160.00	22.00	55.00	15.00	0.2215
	8	14	Fact	180.00	22.00	55.00	15.00	0.4024
_	9	15	Fact	160.00	20.00	45.00	17.00	0.456
_	10	16	Fact	180.00	20.00	45.00	17.00	0.2653
_	11	17	Fact	160.00	22.00	45.00	17.00	0.2123
_	12	18	Fact	180.00	22.00	45.00	17.00	0.253
	13	19	Fact	160.00	20.00	\$5.00	17.00	0.384
_	14	20	Fact	180.00	20.00	55.00	17.00	0.1309
_	15	21	Fact	160.00	22.00	55.00	17.00	0.2263
_	16	22	Fact	180.00	22.00	55.00	17.00	0.1558
_	17	23	Axial	150.00	21.00	50.00	16.00	0.1458
	18	24	Axial	190.00	21.00	50.00	16.00	0.168
_	19	25	Axial	170.00	19.00	50.00	16.00	0.32
	20	26	Axial	170.00	23.00	50.00	16.00	0.224
	-							
-	21	27	Axial	170.00	21.00	40.00	16.00	0.336
	22	28	Axial	170.00	21.00	60.00	16.00	0.225
	23	29	Axial	170.00	21.00	50.00	14.00	0.335
-	24	30	Avial	170.00	21.00	50.00	18.00	0.336



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Notes for ENGR NICOLAS												
- 📰 Design (Coded)	Design Su	nmary				<i>.</i>						
- Summary												
Craph Columns	Study Typ	Response Sur	ace	Runs	30							
L S Evaluation	Initial Desi	gn Central Compo	site	Blocks	No Blocks							
- Analysis	Design Mo	del Quadratic										
- Weld Deposition Rat	-											
Cotimization	Factor	Name	Units	Туре	Low Actual	High Actual	Low Coded	High Coded	Mean	Std. Dev.		
Numerical	A	Current	Amp	Numeric	160.00	180.00	-1.000	1.000	170.000	8.944		
- M Graphical	В	Voltage	Volt	Numeric	20.00	22.00	-1.000	1.000	21.000	0.894		
- Xi Point Prediction	C	Welding Speed	Cm/min	Numeric	45.00	55.00	-1.000	1.000	50.000	4.472		
	D	GFR	L/min	Numeric	15.00	17.00	-1.000	1.000	16.000	0.894		
	Response	Name	Units	Obs	Analysis	Minimum	Maximum	Mean	Std. Dev.	Ratio	Trans	Model
	Y1	Weld Depositio	n Kg/hr	30	Polynomial	0.131	0.456	0.265	0.085	3.484	None	Quadratic
	¥2	Weld Bead Vo	u mm^3	30	Polynomial	26.934	115.088	63.580	23.325	4.273	None	Quadratic

Figure 5. RSM design summary.

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Notes for ENGR NICOLAS		Et Summary	- f(x) Model				Granha
- E Design (Coded)	y nanonani	in Communitier y	-(4)	F-	- Dragn		rerapito
🖮 Summary							
- Graph Columns	Response	1	Weld Deposition	Transform:	None		
S Evaluation	*** WARNING: 1	The Cubic Mod	el is Aliased! *	*			
Malysis							
- 🕼 Weld Deposition F	Sequential Mo	del Sum of Sa	uares (Type II				
Weld Bead Volume (		Sum of		Mean	F	n value	
🚵 Optimization	-	Sumon		General		p-value	
- Mumerical	Source	squares	ar	square	value	Prop > r	
🎦 Graphical	Mean vs Total	2.10	1	2.10			
Point Prediction	Linear vs Mean	0.013	4	3.223E-003	0.40	0.8068	
	2FI vs Linear	0.16	6	0.026	11.39	< 0.0001	
	Quadratic vs 2FI	0.034	4	8.481E-003	12.86	<u>&lt; 0.0001</u>	Suggested
	Cubic vs Quadra	4.592E-003	8	5.740E-004	0.76	0.6495	Aliased
	Residual	5.303E-003	7	7.576E-004			
	Total	2.32	30	0.077			
	"Seguential Mor	del Sum of Sque	res ITune II*: Se	lact the highest o	rder polynomial	where the	
	additional terms	are circificent o	nd the medalia a	et alianed	roer polynomial	where ule	
	additional terms	are significant a	na the model is n	ot allased.			



The model statistics computed for weld deposition rate based on the different model sources as presented in **Figure 8**.

From the results of **Figure 7** it was again observed that the quadratic polynomial had a non-significant lack of fit and was suggest for model analysis while the cubic polynomial had a significand lack of fit hence aliased to model analysis.

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Notes for ENGR NICOLAS	<u>у</u> х	Transform	Fit Summary	f(x) Model		Diagnos	tics Model	Graphs	
Analysis     Weld Deposition F     Weld Bead Volume (     Optimization     Optimization     Sraphical     Ŷin Dest Destines	La	ack of Fit Tes Source Linear 2FI Quadratic	sts Sum of Squares 0.20 0.039 4.848E-003	df 20 14	Mean Square 9.821E-003 2.769E-003 4.848E-004	F Value 9.73 2.74 0.48	p-value Prob > F 0.0096 0.1356 0.8486	Suggested	
<u>s.</u> Point Prediction		Cubic Pure Error	2.557E-004 5.047E-003	2	1.279E-004 1.009E-003	0.13	0.8838	Aliased	
		Lack of Fit Te:	sts": Want the se	lected model to h	ave insignificant la	ick-of-fit.			



	Std.		Adjusted	Predicted		
Source	Dev.	R-Squared	R-Squared	R-Squared	PRESS	
Linear	0.090	0.0601	-0.0902	-0.4567	0.31	
2FI	0.048	0.7956	0.6880	0.6391	0.077	
Quadratic	0.026	0.9538	0.9108	0.8358	0.035	Suggested
Cubic	0.028	0.9753	0.8975	0.7943	0.044	Aliased
"Model Summary St	atistics": Foo	us on the model	maximizing the "	Adjusted R-Square	d"	

Figure 8. Model summary statistics for weld deposition rate (WDR).

The summary statistics of model 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 unity and relatively low PRESS are the optimum criteria for defining the best model source. Based on the results of **Figure 7** and **Figure 8** the quadratic polynomial model was suggested while the cubic polynomial model was aliased hence, the quadratic polynomial model was selected for this analysis.

Analysis of the model standard error was employed to assess the suitability of response surface methodology using the quadratic model to maximize the weld deposition rate (WDR. The computed standard errors for the selected responses is presented in **Figure 9**.

From the results of **Figure 9**, it was observed that the model possess a low standard error ranging from 0.20 for the individual terms, 0.25 for the combine effects and 0.19 for the quadratic terms. Standard errors should be similar within type of coefficient; smaller is better. 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. Variance inflation factor (VIF) of approximately 1.0 as observed in Figure 8 was good since ideal VIF is 1.0. VIF's above 10 are cause for alarm, indicating coefficients are poorly estimated due to multicollinearity. In addition, the Ri-squared value was observed to be between 0.0000 to 0.0476 which is good. High Ri-squared (above 1.0) means that design terms are correlated with each other, possibly leading to poor models.

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Notes for ENGR NICOLAS	f(:	x) Model	Results	 Graphs					
Design (Coded)			1	1		1 /		1 1	1
Summary	$\square$								
Graph Columns		1							
Evaluation	$\square$	1				Power at 5 % a	Ipha level for o	effect of	
- d Analysis		Term	StdErr**	VIF	<b>Ri-Squared</b>	0.5 Std. Dev.	1 Std. Dev.	2 Std. Dev.	
Veid Deposition Rat		A	0.20	1.00	0.0000	20.9 %	63.0 %	99.5 %	
Contimization		в	0.20	1.00	0.0000	20.9 %	63.0 %	99.5 %	
Numerical		с	0.20	1.00	0.0000	20.9 %	63.0 %	99.5 %	
Graphical		D	0.20	1.00	0.0000	20.9 %	63.0 %	99.5 %	
Point Prediction		AB	0.25	1.00	0.0000	15.5 %	46.5 %	96.2 %	
		AC	0.25	1.00	0.0000	15.5 %	46.5 %	96.2 %	
	$\square$	AD	0.25	1.00	0.0000	15.5 %	46.5 %	96.2 %	
		BC	0.25	1.00	0.0000	15.5 %	46.5 %	96.2 %	
		BD	0.25	1.00	0.0000	15.5 %	46.5 %	96.2 %	
		CD	0.25	1.00	0.0000	15.5 %	46.5 %	96.2 %	
	$\square$	A2	0.19	1.05	0.0476	68.7 %	99.8 %	99.9 %	
		B <sup>2</sup>	0.19	1.05	0.0476	68.7 %	99.8 %	99.9 %	
II /		C <sup>2</sup>	0.19	1.05	0.0476	68.7 %	99.8 %	99.9 %	
		D <sup>2</sup>	0.19	1.05	0.0476	68.7 %	99.8 %	99.9 %	
		**Basis Std. Dr	ev. = 1.0						

Figure 9. Result of computed standard errors.

The correlation matrix of regression coefficient is presented in Figure 10.

Lower values of the off diagonal matrix as observed in **Figure 10** indicates a well fitted model that is strong enough to navigate the design space and adequately optimize the selected response variables. From the results of **Figure 10** it was observed that the off diagonal matrix had coefficients that were approximately 0.00 which is an indication that the quadratic model was the ideal one for this analysis since off diagonal matrix greater than 0.00 is cause for alarm indicating a model having coefficients that are poorly correlated.

To understand the influence of the individual design points on the model's predicted value, the model leveages were computed as presented in Figure 11.

Leverage of a point varies from 0 to 1 and indicates how much an individual design point influences the model's predicted values. A leverage of 1 means the predicted value at that particular case will exactly equal the observed value of the experiment, *i.e.*, the residual will be 0. The sum of leverage values across all cases equals the number of coefficients (including the constant) fit by the model. The maximum leverage an experiment can have is 1/k, where k is the number of times the experiment was replicated. Leverages of 0.6698 and 0.6073 calculated for both the factorial and axial points coupled with 0.1663 for the center point as observed in **Figure 11** shows that the predicted values are 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 maximizing the weld deposition rate (WDR) one way analysis of variance (ANOVA) figure was generated for deposition rate and result obtained is presented in Figure 12.

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. From the result of **Figure 12**, the Model F-value of 22.14 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 B, C, AB, AC, AD, BD, CD, A2, D2 are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. The

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Notes for ENGR NICOLAS	f(	x) Model	Results	🔀 Graphs					
- Bummary									
Graph Columns	_								
Evaluation		Correlation	Matrix of Regres	sion Coefficie	nts				
Analysis			Intercept	A	в	С	D	AB	AC
······································		Intercept	1.000						
weld bead volume (		A	-0.000	1.000					
Numerical		в	-0.000	-0.000	1.000				
Graphical		с	-0.000	-0.000	-0.000	1.000			
2 Point Prediction		D	-0.000	-0.000	-0.000	-0.000	1.000		
		AB	-0.000	-0.000	-0.000	-0.000	-0.000	1.000	
		AC	-0.000	-0.000	-0.000	-0.000	-0.000	-0.000	1.000
		AD	-0.000	-0.000	-0.000	-0.000	-0.000	-0.000	-0.000
		BC	-0.000	-0.000	-0.000	-0.000	-0.000	-0.000	-0.000
		BD	-0.000	-0.000	-0.000	-0.000	-0.000	-0.000	-0.000
		CD	-0.000	-0.000	-0.000	-0.000	-0.000	-0.000	-0.000
		A <sup>2</sup>	-0.535	-0.000	-0.000	-0.000	-0.000	-0.000	-0.000
		B <sup>2</sup>	-0.535	-0.000	-0.000	-0.000	-0.000	-0.000	-0.000
		C <sup>2</sup>	-0.535	-0.000	-0.000	-0.000	-0.000	-0.000	-0.000
		D2	-0.535	-0.000	-0.000	-0.000	-0.000	-0.000	-0.000
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Figure 10. Correlation matrix of regression coefficients.

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Notes for CONEL RSM	fo	x) Model	Results	- Graphs	1				
Design (Actual)			1				1	1	1
Graph Columns									_
Evaluation									
Analysis		Std	Leverage	Point Type					
Bead Width (BW) (A		1	0.6698	Fact					
HAZ (Analyzed)		2	0.6698	Fact					
Optimization		3	0.6698	Fact					
		4	0.6698	Fact					
- Di Graphical		5	0.6698	Fact					
Xi Point Prediction		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					
		Average -	0.5000						

Figure 11. Computed model leverages.

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III Summary								<u>_</u>
Graph Columns	Use your mouse to r	ight click on individual c	ells for definition	ons.				
I S Evaluation	Response	1 Wel	Deposition	Rate				
- Matysis	ANOVA for Re	sponse Surface Qua	dratic Model					
Weld Deposition F	Analysis of varian	ce table [Partial sum	of squares -	Type III]				
Continuenting		Sum of		Mean	F	p-value		
Numerical	Source	Squares	df	Square	Value	Prob > F		
Graphical	Model	0.20	14	0.015	22.14	< 0.0001	significant	
Point Prediction	A-Current	2.458E-004	1	2.458E-004	0.37	0.5508		
_	B-Voltage	3.220E-003	1	3.220E-003	4.88	0.0431		
	C-Welding Speed	9.212E-003	7	9.212E-003	13.96	0.0020		
	D-GFR	2.124E-004	1	2.124E-004	0.32	0.5788		
	AB	0.049	7	0.049	73.67	< 0.0001		
	AC	0.011	7	0.011	17.39	0.0008		
	AD	0.060	1	0.060	90.92	< 0.0001		
	BC	8.644E-004	7	8.644E-004	1.31	0.2703		
	BD	0.030	7	0.030	45.32	× 0.0001		
	CD	6.848E-003	1	6.848E-003	10.38	0.0057		
	A2	0.021	7	0.021	31.38	< 0.0001		
	B <sup>2</sup>	4.650E-005	1	4.650E-005	0.070	0.7942		
	C2	3.221E-004	1	3.221E-004	0.49	0.4954		
	D2	8.093E-003	7	8.093E-003	12.27	0.0032		
	Residual	9.895E-003	15	6.597E-004				
	Lack of F	it 4.848E-003	10	4.848E-004	0.48	0.8486	not significant	
	Pure Erro	or 5.047E-003	5	1.009E-003				
	Cor Total	0.21	29					
	Cor Total	0.21	29					



"Lack of Fit F-value" of 0.48 implies the Lack of Fit is not significant relative to the pure error. There is an 84.86% chance that a "Lack of Fit F-value" this large could occur, due to noise. Non-significant lack of fit is good as it indicates a model that is significant. To validate the adequacy of the quadratic model based on its ability to maximize the weld deposition rate (WDR) the goodness of fit statistics presented in **Figure 13**.

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Notes for ENGR NICOLAS	$y^{\lambda}$ Transform	Fit Summary f(x) Mode	ei 🔒 anova 💽	Diagnostics	Model Graphs	
- 📑 Summary				1		
- 🔄 Graph Columns					,	
Cvaluation	Std. Dev.	0.026	R-Squared	0.9538		
Analysis	Mean	0.26	Adj R-Squared	0.9108		
Weld Deposition F	C.V. %	9.70	Pred R-Squared	0.8358		
Weld Bead Volume	PRESS	0.035	Adeq Precision	17.704		
···· M Optimization						
Graphical	The "Pred R-S	quared" of 0.8358 is in reasonabl	e agreement with the "Adj R-	Squared" of 0	.9108.	
Point Prediction						

**Figure 13.** GOF statistics for validating model significance towards maximizing the weld deposition rate (WDR).

From the result of Figure 13, it was observed that the "Predicted R-Squared" value of 0.8358 is in reasonable agreement with the "Adj R-Squared" value of 0.9108. Adequate precision measures the signal to noise ratio. A ratio greater than 4 is desirable. The computaed ratio of 17.704 as observed in Figure 13 indicates an adequate signal. This model can be used to navigate the design space and adequately maximize the weld deposition rate (WDR).

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 weld deposition rate is presented in **Figure 14**.

The optimal equation which shows the individual effects and combine interactions of the selected input variables (current, voltage, welding speed and gas flow rate) against weld deposition rate is presented based on the coded variables in **Figure 15**.

The optimal equation which shows the individual effects and combine interactions of the selected input variables (current, voltage, welding speed and gas flow rate) agains tweld deposition rate is presented based on actual factors in **Figure 16**.

The diagnostics case statistics which shows the observed values of (weld deposition rate (WDR) against their predicted values is presented in **Figure 17**. 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 higher leverages as observed in **Figure 17** is an indicator 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 weld deposition rate is presented in **Figure 18**.

The high coefficient of determination ( $r^2 = 0.9538$ ) as observed in Figures 4.26 was used to established the suitability of response surface methodology in maximizing the weld deposition rate (WDR).

To accept any model, its satisfactoriness must first be checked by an appropriate statistical analysis output. To diagnose the statistical properties of the

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Notes for ENGR NICOLAS	3	/ <sup>A</sup> Transform	Fit Summary f(x)	Model	<b>A</b>	ANOVA	Diagnostics	Model Graphs			
- III Summary	_									^	
Graph Columns	_										
Evaluation			Coefficient			Standard	95% CI	95% CI			
Analysis		Factor	Estimate		df	Error	Low	High	VIF		
Weld Deposition F		Intercept	0.27		1	0.010	0.25	0.29			
		A-Current	3.200E-003		1	5.243E-003	-7.975E-003	0.014	1.00		
Numerical		B-Voltage	-0.012		1	5.243E-003	-0.023	-4.088E-004	1.00		
Graphical		C-Welding Speed	-0.020		1	5.243E-003	-0.031	-8.417E-003	1.00		
Point Prediction		D-GFR	-2.975E-003		1	5.243E-003	-0.014	8.200E-003	1.00		
		AB	0.055		1	6.421E-003	0.041	0.069	1.00		
		AC	-0.027		1	6.421E-003	-0.040	-0.013	1.00		
		AD	-0.061		1	6.421E-003	-0.075	-0.048	1.00		
		BC	7.350E-003		1	6.421E-003	-6.336E-003	0.021	1.00		
		BD	-0.043		1	6.421E-003	-0.057	-0.030	1.00		
		CD	-0.021		1	6.421E-003	-0.034	-7.002E-003	1.00		
		A <sup>2</sup>	-0.027		1	4.904E-003	-0.038	-0.017	1.05		
		B <sup>2</sup>	1.302E-003		1	4.904E-003	-9.151E-003	0.012	1.05		
		C <sup>2</sup>	3.427E-003		1	4.904E-003	-7.026E-003	0.014	1.05		
		D <sup>2</sup>	0.017		1	4.904E-003	6.724E-003	0.028	1.05		
		]									

**Figure 14.** Coefficient estimates statistics generated for maximizing the weld deposition rate (WDR).

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Notes for ENGR NICOLAS	y <sup>A</sup> Transform									
- B Summary										
- Graph Columns	Final Equation in Terms of Coded Factors:									
- S Evaluation										
- Analysis	Weld Deposition Rate =									
- Weld Deposition F	+0.27									
Weld Bead Volume (	+3.200E-003 *A									
Continization	-0.012 *B									
Graphical	-0.020 ° C									
Point Prediction	-2.975E-003 * D									
	+0.055 *A*B									
	-0.027 * A * C									
	-0.061 * A * D									
	+7.350E-003 * B * C									
	-0.043 *B*D									
	-0.021 * C * D									
	-0.027 * A2									
	+1.302E-003 * B <sup>2</sup>									
	*3.427E-003 * C <sup>2</sup>									
	+0.017 * D2									



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Notes for ENGR NICOLAS	y <sup>A</sup> Transform	
- 🔡 Summary		1
- Graph Columns	Final Equation in Terms of Actual Factors:	1
<u>S</u> Evaluation		1
- Analysis	Weld Deposition Rate =	
Weld Bood Volume	-19.74360	1
Optimization	+0.10273 * Current	
Numerical	-0.38508 * Voltage	
- Sraphical	+0.10874 * Welding Speed	
Point Prediction	+1.60278 * GFR	
	+5.51125E-003 * Current * Voltage	
	-5.35500E-004 * Current * Welding Speed	
	-6.12250E-003 * Current * GFR	
	+1.47000E-003 * Voltage * Welding Speed	
	-0.043225 * Voltage * GFR	
	-4.13750E-003 * Welding Speed * GFR	
	-2.74729E-004 * Current <sup>2</sup>	
	+1.30208E-003 * Voltage2	
	+1.37083E-004 * Welding Speed <sup>2</sup>	
	+0.017177 * GFR <sup>2</sup>	

**Figure 16.** Optimal equation in terms of actual factors for maximizing weld deposition rate (WDR).

response surface model, the normal probability plot of residual presented in Figure 19.

The normal probability plot of studentized residuals was employed to assess the normality of the calculated residuals. The normal probability plot of

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Notes for ENGR NICOLAS	<b>_</b>	λ Transform	ER Commons	£(w)	Marter 1		Disenseting	-	<u>م</u>			
- 🏥 Design (Coded)	y	raistom	The Sommery	1(x)	mouer	ANOVA		Model Graph	•			
- M Summary												
Graph Columns		Response	1	Weld D	eposition Rate	Transform:	None					
- S Evaluation												
- Analysis		Diagno	stics Case Stat	istics								
Weld Deposition F								Internally	Externally	Influence on		
weid Bead Volume (		Standard	Actual		Predicted			Studentized	Studentized	Fitted Value	Cook's	Run
··· M Optimization		Order	Value		Value	Residual	Leverage	Residual	Residual	DFFIT S	Distance	Order
Numerical		1	0.19		0.21	-0.017	0.583	-0.999	-0.999	-1.182	0.093	7
Ŷil Point Prediction		2	0.26		0.28	-0.014	0.583	-0.865	-0.857	-1.014	0.070	8
		3	0.15		0.14	6.375E-003	0.583	0.385	0.373	0.442	0.014	9
		4	0.46		0.44	0.020	0.583	1.191	1,210	1.431	0.132	10
		5	0.77		0.75	0.010	0.583	1 146	1 159	1 371	0.122	11
		6	0.21		0.25	1 383E 003	0.583	0.083	0.081	0.095	0.001	12
Diagnostics Tool	$\square$	-	0.21		0.21	7 4225 002	0.503	-0.003	0.426	-0.555	0.019	12
	-	,	0.22		0.21	7.433E-003	0.565	0.440	0.430	0.516	0.019	13
Diagnostics Influence	-	•	0.40		0.40	2.000E-003	0.563	0.169	0.104	0.194	0.003	14
	$\square$	9	0.46		0.45	6.408E-003	0.583	0.387	0.375	0.444	0.014	15
Ext. Student e	-	10	0.27		0.28	-0.012	0.583	-0.698	-0.685	-0.811	0.045	16
Leverage	-	11	0.21		0.22	-2.750E-003	0.583	-0.166	-0.160	-0.190	0.003	17
DFFITS		12	0.25		0.26	-9.775E-003	0.583	-0.590	-0.576	-0.682	0.032	18
DFBETAS		13	0.38		0.41	-0.024	0.583	-1.441	-1.499	-1.774	0.194	19
Cook's D		14	0.13		0.13	2.842E-003	0.583	0.171	0.166	0.196	0.003	20
Report		15	0.23		0.20	0.024	0.583	1.421	1.476	1.746	0.188	21
		16	0.16		0.14	0.012	0.583	0.750	0.739	0.874	0.052	22
		17	0.15		0.15	-7.242E-003	0.583	-0.437	-0.425	-0.503	0.018	23
		18	0.17		0.17	2.158E-003	0.583	0.130	0.126	0.149	0.002	24
Clear Points		19	0.32		0.30	0.022	0.583	1.345	1.385	1.639	0.169	25
		20	0.22		0.25	-0.027	0.583	-1.651	-1.764	* -2.09	0.254	26
Diagnostics Influence		21	0.34		0.32	0.014	0.583	0.831	0.822	0.972	0.064	27
		22	0.23		0.24	-0.019	0.583	-1.137	-1.150	-1.360	0.121	28
	-	23	0.34		0.34	-8.992E-003	0.583	-0.542	-0.529	-0.626	0.027	29
Ext. Student ei	-	24	0.34		0.33	3 908E-003	0.583	0.236	0.228	0.270	0.005	30
Leverage	-	25	0.26		0.27	0.012	0.167	0.560	0.555	0.248	0.004	2
DFFITS	-	~ ~	0.20		0.27	-0.013	0.167	-0.903	0.000	0.206	0.004	-
DFBETAS	-	20	0.25		0.27	-0.016	0.107	-0.097	-0.004	-0.306	0.006	,
Cook's D	-	27	0.33		0.27	0.065	0.167	2.758	3.796	1.697	0.101	1
Report	_	28	0.26		0.27	-0.014	0.167	-0.611	-0.598	-0.267	0.005	5
	_	29	0.26		0.27	-9.333E-003	0.167	-0.398	-0.387	-0.173	0.002	4
	_	30	0.26		0.27	-0.011	0.167	-0.483	-0.471	-0.210	0.003	3
	_	* Exceeds limit	5									
Clear Points												

**Figure 17.** Diagnostics case statistics report of observed versus predicted weld deposition rate (WDR).







**Figure 19.** Normal probability plot of studentized residuals for maximizing weld deposition rate (WDR).

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 19** revealed that the computed residuals are approximately normally distributed an indication that the model developed is satisfactory.

To determine the presence of a possible outlier in the experimental data, 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 deposition rate is presented in **Figure 20**.

The cook's distance plot has 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 20** indicates that the data used for this analysis are devoid of possible outliers thus revealing the adequacy of the experimental data.

To study the effects of current and voltage on deposition rate, 3D surface plots presented in **Figure 21**. To study the effects of gas flow rate and welding speed on deposition rate, 3D surface plots presented in **Figure 22**. The 3D surface plot as observed in **Figure 22** and **Figure 23**, shows the relationship between the input variables (current and voltage), (welding speed and gas flow rate) against the response variables (weld deposition rate) 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 weld deposition rate increases proportionately. The presence of a coloured hole at the middle of the upper surface gave a clue that more points lightly shaded for easier identification fell below the surface.

Finally, numerical optimization was performed to ascertain the desirability of the overall model. In the numerical optimization phase, we ask design expert to maximize the weld deposition rate (WDR). In addition, the optimum current, voltage, welding speed and gas flow rate was determined simultaneously.



Figure 20. Generated cook's distance for weld deposition rate (WDR).









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		Weld Deposition Rate

**Figure 23.** Interphase of numerical optimization model for maximizing weld deposition rate (WDR).

The interphase of the numerical optimization of deposition rate showing the objective function is presented in **Figure 23**.

The constraint set for the numerical optimization algorithm is presented in **Figure 24**.

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Weld Deposition Rat			Lower	Upper	Lower	Upper							
Weld Bead Volume (	Name	Goal	Limit	Limit	Weight	Weight	Importance						
📙 🕍 Optimization	Current	is in range	-1	1	1	1	3						
- 🔀 Numerical	Voltage	is in range	-1	1	1	1	3						
- Maraphical	Welding Speed	is in range	-1	1	1	1	3						
Point Prediction	GFR	is in range	-1	1	1	1	3						
	Weld Deposition	maximize	0.1309	0.456	0.1	1	5						
	Weld Bead Volu	maximize	26.9339	115.088	0.1	1	5						

Figure 24. Constraints for numerical optimization of selected responses.

The numerical optimization produces about twenty two (22) optimal solutions which are presented in Figure 25.

From the results of **Figure 25**, it was observed that a current of 160.020 amp, voltage of 20.00 vol, a welding speed of 47.460 cm/min and gas flow rate of 17.000 L/min will result in a welding process with the following properties: Weld deposition rate (WDR) 0.436708 kg/hr. This solution was selected by design expert as the optimal solution with a desirability value of 98.80%.

The ramp solution which is the graphical presentation of the optimal solution is presented in **Figure 26**.

The desirability bar graph which shows the accuracy with which the model is able to predict the values of the selected input variables and the corresponding responses is shown in **Figure 27**.

It can be deduce from the result of **Figure 27** that the model developed based on response surface methodology and optimized using numerical optimization method, predicted the weld deposition rate by an accuracy level of 99.39%. 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 28** and **Figure 30**. To identify the region with the optimum current and voltage, predicting the optimum deposition rate response a contour plot is produced in **Figure 28**.

To identify the region with the optimum gas flow rate and welding speed, predicting the optimum deposition rate response using contour plot is produced in **Figure 29**. To predict the desirability of the model a contour plot is produced in **Figure 30**.

As presented in Figures the contour plot can be employed to predict the optimum values of the input variables based on the flagged response variables.

#### 3.2. Discussion

In this study, the optimization of weld deposition rate (WDR) was done using response surface methodology (RSM). The target of the optimization model was to Maximize the weld deposition rate, statistical design of experiment (DOE), using the central composite design method (CCD) was done. The design and optimization was executed with the aid of Design Expert 7.01.

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ID Wald Depending Dat		Number	Current	Voltage	Welding Speed	GFR	Weld Depositio	Weld Bead Volu	Desirability	
Weld Bead Volume		1	160.020	20.000	47,460	17.000	0.436708	101.269	0.988	Selected
- A Optimization	-	2	160.000	20.000	47.630	17.000	0.435974	101.428	0.988	
Numerical	-	3	160.000	20.000	47.060	17.000	0.438465	100.822	0.988	
Di Graphical	-	4	160.000	20.000	47 730	17 000	0.435464	101 515	0.988	
		5	160.060	20.000	46 450	17 000	0.441598	99.921	0.988	
		6	160.000	20.000	46 140	17 000	0 44343	99.4209	0.988	
	-	7	180.000	22.000	51 140	15 000	0.410485	107 842	0.988	
	-		180.000	22.000	50 500	15 000	0.412682	107 129	0.000	
	-	, i	180.000	22.000	51.670	15 000	0.40873	108 223	0.988	
Solutions Tool	-	10	180.000	22.000	E1 980	15 000	0.407009	108 304	0.088	
Report		11	180.000	21,000	51.000	15.000	0.409291	107.939	0.900	
Ramps	-		100.000	21.550	47.000	13.000	0.405201	107.020	0.000	
E Bar Graph	-	12	160.000	20.020	47.000	17.000	0.434163	101.095	0.966	
	-	13	160.000	20.000	40.020	17.000	0.430423	101.862	0.966	
	-	14	160.080	20.000	45.600	17.000	0.445823	98.2679	0.988	
	<u> </u>	15	160.000	20.020	46,960	17.000	0.436596	100.36	0.966	
	-	16	180.000	22.000	49.210	15.000	0.417456	104.86	0.988	
	<u> </u>	17	180.000	22.000	53.200	15.000	0.404148	108.269	0.987	
	<u> </u>	18	180.000	22.000	53.290	15.000	0.40344	108.167	0.987	
	-	19	180.000	22.000	48.270	15.000	0.421238	102.475	0.987	
	<u> </u>	20	179.920	22.000	48.190	15.000	0.420968	102.206	0.986	
	<u> </u>	21	180.000	22.000	54.260	15.000	0.401351	107.379	0.986	
		22	180.000	22.000	54.830	15,000	0.399967	106.581	0.986	





Figure 26. Ramp solution of numerical optimization.



Figure 27. Prediction accuracy of numerical optimization.

The model summary, which is presented as shown in **Figure 5**, revealed that the model is of the quadratic type, which requires the polynomial analysis order as depicted by a typical response surface design. To validate the suitability of the quadratic model the sequential model sum of squares were calculated for the response presented in **Figure 6**. To test how well the quadratic model can explain the underlying variation associated with the experimental data, the lack of fit test statistic was estimated for each of the responses.

The summary statistics of model 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-Squared near unity and relatively low PRESS are the optimum criteria for defining the best model









source. Variance inflation factor (VIF) of approximately 1.0 as observed in **Figure 7** was good since ideal VIF is 1.0. VIF's above 10 are cause for alarm.

To understand the influence of the individual design points on the model's predicted value, the model leverages were computed as presented in Figure 11. Leverage of a point varies from 0 to 1 and indicates how much an individual design point influences the model's predicted values. A leverage of 1 means the predicted value at that particular case will exactly equal the observed value of the



Figure 30. Predicting desirability using contour plot.

experiment, *i.e.*, the residual will be 0. Leverages of 0.6698 and 0.6073 calculated for both the factorial and axial points coupled with 0.1663 for the center point as observed in **Figure 11** shows that the predicted values are 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 maximizing the weld deposition rate (WDR), one way analysis of variance (ANOVA) figure was generated for deposition rate and result obtained is presented in **Figure 12**. To validate the adequacy of the quadratic model based on its ability to maximize the weld deposition rate (WDR) the goodness of fit statistics presented in **Figure 13**. From the result of **Figure 13**, it was observed that the "Predicted R-Squared" value of 0.8358 is in reasonable agreement with the "Adj R-Squared" value of 0.9108. Adequate precision measures the signal to noise ratio. A ratio greater than 4 is desirable. The computaed ratio of 17.704 as observed in **Figure 13** indicates an adequate signal. This model can be used to navigate the design space and adequately maximize the weld deposition rate (WDR).

The optimal equation which shows the individual effects and combine interactions of the selected input variables (current, voltage, welding speed and gas flow rate) against weld deposition rate is presented based on actual factors in **Figure 16** and **Figure 17**. The diagnostics case statistics which shows the observed values of (weld deposition rate (WDR) against their predicted values is presented in **Figure 17**. 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 higher leverages as observed in **Figure 17** is indicators of a well fitted model. To assess 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 weld deposition rate is presented in **Figure 18**.

To determine the presence of a possible outlier in the experimental data, 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 deposition rate is presented in **Figure 20**. To study the effects of current and voltage on deposition rate, 3D surface plots presented in **Figure 22**.

The 3D surface plot as observed in **Figure 22** and **Figure 23**, shows the relationship between the input variables (current and voltage), (welding speed and gas flow rate) against the response variable (weld deposition rate). 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 weld deposition rate and the weld bead volume increase proportionately. The presence of a coloured hole at the middle of the upper surface gave a clue that more points lightly shaded for easier identification fell below the surface.

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

From the result of **Figure 25**, it was observed that a current of 160.020 amp, voltage of 20.00 vol, a welding speed of 47.460 cm/min and gas flow rate of 17.000 L/min will result in a welding process with weld deposition rate (WDR) 0.436708 kg/hr. This solution was selected by design expert as the optimal solution with a desirability value of 98.80%.

The desirability bar graph, which shows the accuracy with which the model is able to predict the values of the selected input variables and the corresponding responses, is shown in **Figure 18**. It can be deduced from the result of **Figure 27** that the model developed, based on response surface methodology and optimized, using numerical optimization method, predicted the weld deposition rate by an accuracy level of 99.39%. Finally, based on the optimal solution, the contour plots showing each response variable against the optimized value of the input variable are presented in **Figure 28** and **Figure 29**, respectively. To identify the region with the optimum current and voltage, predicting the optimum deposition rate response a contour plot is produced in **Figure 28**. To identify the region with the optimum gas flow rate and welding speed, predicting the optimum deposition rate response, a contour plot is produced in **Figure 29**.

# 4. Conclusion

In this study, the response surface methodology to optimize the deposition rate of TIG welded joints and result shows that they are suitable models. Weld deposition rate is a very important factor that influences the integrity and quality of welded joint. The study reveals that respond surface methodology (RSM) produced a good model for predicting weld deposition rate. it was observed that a current of 160.020 amp, voltage of 20.00 vol, a welding speed of 47.460 cm/min and gas flow rate of 17.000 L/min will result in a welding process with weld deposition rate (WDR) 0.436708 kg/hr. It has been shown that the optimization and prediction of weld deposition rate has improved the quality of welded joints.

A weld simulation was carried out using the optimum value obtained from the response surface methodology to produce a welded sample with good quality. It is, therefore, recommended that welding and fabrication industries should endeavor to use the optimum welding process parameters obtained in this study to produce high quality welds in Tungsten inert gas welding process, as applicable.

#### **Conflicts of Interest**

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

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