

Optimization of Weld Bead Profile Parameters in TIG Welding Process for Inconel 718 Alloy Using RSM and Regression Analysis

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ABSTRACT

Gas Tungsten Arc Welding (GTAW) is broadly used for fabricates the components of gas turbines, power plants, nuclear plants, and petrochemical industries and aircraft engines made of super alloy Inconel 718. In this study, the selection of welding parameters for obtaining most favorable weld bead profile in the gas tungsten arc welding of Inconel 718 alloy is presented. The effect of four welding process parameters (input) namely welding current (I), welding voltage (V), welding speed (S), and shielding gas (G) on weld depth (WD), weld width (WW) and depth to width ratio (DW) of Inconel 718 alloy which is welded by gas tungsten arc welding process was experimentally done and analyzed. Based on Response Surface Methodology (RSM) design, twenty seven numbers of welded test coupons were prepared by varying welding parameters (current, voltage, welding speed, and shielding gas). Applying Response Surface Methodology, concurrent effects of welding process parameters on weld depth, weld width and depth to width ratio were obtained in the course of three separate regression equations. Based on the investigational outcomes constructive recommendations have been specified in order to select the appropriate welding process parameters to obtain most favorable weld bead profile. In this paper the consequence of welding parameters (current, voltage, welding speed, and shielding gas) on weld bead profile characters (weld depth, weld width, and depth to width ratio) were explained and predictive model for weld bead profile characters (weld depth, weld width, and depth to width ratio) were developed for Inconel 718 alloy. It is found that current, voltage, welding speed, and shielding and along with their interactions have considerable effect on the weld depth, weld width and depth to width ratio.

KEYWORDS: GTAW, RSM, Inconel, Welding Process Parameters, Experimental Investigation

1. INTRODUCTION

GTAW process in which the source of heat is an arc formed in between non consumable tungsten electrode and the metal which is going to weld, and the arc and the molten weld pool are protect from atmospheric contamination with a gaseous shield of inert gases such as argon, helium, or argon helium mixture. It is accepted that GTAW is the one of the advanced high- quality metal joining process (Dongjie, 2012). Inconel 718 is a nickel-based super alloy generally used in elevated temperature applications including turbine engines and power generation because of its superior mechanical properties (Janaki Ram G, 2005). GTAW is one of the generally applied welding processes in manufacturing industry to nonferrous (Inconel718) and stainless steels for superior quality weld and low investment (Hsuan-Liang Lin, 2012). Fundamentally, GTAW weld quality is effectively organized by the weld bead profile, because the mechanical properties of welded joints are determined by the dimensions of weld bead profile. Hence, it is very essential to select the welding process parameters for obtaining most favorable weld bead profile.

Generally, the preferred welding parameters are selected based on knowledge or from a welding handbook. On the other hand, this does not make sure that the selected welding parameters can make the best or near best weld bead profile for that particular welding process and environment (Jung, 2002).

At the beginning (Lee, 2000) and (Revendra, 1987) have investigated the relation between welding parameters and weld bead profile by using regression analysis. (Wenchao Dong, 2011) have experimented on the effect of welding parameters (welding speed, welding current, and electrode gap) and dynamic constituent oxygen on the weld bead profile characters and power of the Marangoni convection of GTAW welded AISI 304 stainless steel. The results showed that variation of welding parameters and oxygen content will change the power of the marangoni convection and the shape of the weld bead profile. (Nagesh, 2010) were used the experimental data of pure 1100 aluminum plates welded by GTAW process. They optimized and predict the weld pool geometry by using genetic algorithm (GA) and back propagation neural network (BPNN). (Parikshit Dutta, 2007) have developed relationship between welding parameters and weld bead profile parameters of GTAW welded experimental data by using conventional regression analysis and neural network based approach. (Vidyut Dey, 2009) have experimented with electron beam welded AISI 304 stainless steel. They have optimized the welding parameters for minimize weld area by using genetic algorithm. They have applied Responds Surface Method (RSM) for predict the quality of weld bead profile of submerged arc welded pipes (Murugan, 2005). It has developed the models for optimum weld bead profile of pulsed GTAW welded titanium alloy using RSM (Balasubramanian, 2016)

Based on the previous research It is noted that there is no research work have published to understand the relation between welding process parameters and weld bead profile of Inconel 718 alloy welded by GTAW process. It is identified as a research gap that most of the researchers have consider current, voltage, and welding speed as the input welding parameter for weld bead profile study .However there is no researches have consider type of shielding gas is one of the input welding parameter for weld bead profile study. Hence this research is paying attention on the optimization of some important welding parameters namely current, voltage, welding speed and shielding gas to achieve most favorable weld bead profile characters like Bead Depth (BD), Bead Width (BW) and Depth to Width Ratio (DW) through the generation of mathematical models. The objective of this study is to obtain optimum weld bead profile, this is meant that the WD, DW should be maximum value and WW should be minimum value.

Hence the present work is proposed with TIG welded Inconel 718 alloy by using RSM. RSM is one of the key application of Design of Experimentation (DOE) be able used to predict unknown data's through the use of empirical model (Madadi, 2012) and (Kiaee, 2014).

Research plan and execution: In order to obtain optimum bead profile quality the experimentation was designed to conduct the following order

- i. Determine the Significant Input Parameters and Finding Their Range
- ii. Preparation of Design of Experimentation (DOE)
- iii. Execute the Experimentation as per DOE
- iv. Measure the Weld Bead Profile Characters (Responses)
- v. Developing the Regression Equations
- vi. Checking the Suitability of the Regression Model
- vii. Validation of Regression Model

Selection of Significant Input Parameters and Their Range: Based on previous research results, the research gap identified and the effect of welding process parameter on weld bead profile characters, the following GTAW process parameters are consider as an input parameters. They are Welding Current (I), Welding Voltage (V), Welding Speed(S), and Shielding Gas (G)

For finding the range of input process parameters, there are large number of welding trail have been carried out. According to the literature (Kumar A, and Sundarajan S, 2009), trail welding have been recognized as the standard procedure for find the range of the input parameters. During trail welding changing any one of the input parameter and maintain the remaining parameters as constant (Selthil Kumar T et al., 2007). The range of welding current, welding voltage, welding speed, and shielding gas has been decided based on the acceptance of visual inspection of weld bead. Acceptance of the visual inspection meant that the weld bead should be free from surface crack, porosity, incomplete penetration, and lack of fusion. The identified welding process parameters and their ranges are present in Table 1. The constant welding parameters are given in Table 2.

Table.1.Welding Parameters and Their Range

Welding Parameter	Notation	Level		
		-1	0	1
Welding Current (Amp)	I	40	50	60
Welding Voltage (Volts)	V	8	10	12
Welding speed (mm/sec)	S	0.6	0.8	1
Shielding Gas	G	Ar - 1	He - 2	Ar (70%)+He (30%) -3

Table.2.Constant Welding Parameters

Process Parameter	Constant Value
Argon (Ar) Flow Rate (l/min)	10
Helium (He) Flow Rate (l/min)	20
Ar (70%)+He (30%) Flow Rate (l/min)	15
Electrode Material	98% W + 2% Zr
Electrode Diameter, mm	2
Filler Wire	ER NiFeCr-2
Filler Wire Diameter, mm	1.6

2. MATERIALS AND METHODS

Preparing the Design of Experimentation (DOE): DOE is the group of technique that used to study the effect of different input parameters through the controlled experimentation. RSM is the statistical tool that can be used for preparation of DOE. In this research a four factor three level Box-Behnken design has been used for preparation of DOE. Assume 1, 2 and 3 are the numerical values assigned for type of shielding gas, i.e. helium, argon, and argon helium mixture respectively. The DOE consists of 27 experimentation that are given in table 3

Execute the Experimentation as per DOE: In this investigation nickel based alloy Inconel 718 (980°C solution annealed) were used as a base metal. The dimension of the base metal is 150x60x2 mm as shown in Fig. 1. The filler wire ERNiFeCr – 2 (AWS classification) 1.6 mm diameters was used as an electrode.

Table.3.Design of Experimentation (DOE)

Exp. No.	Welding Current (Amp)	Welding Voltage (Volts)	Welding Speed (mm/sec)	Shielding Gas
1	10	1	2	60
2	8	0.8	3	50
3	8	0.8	1	50
4	12	0.8	1	50
5	10	0.8	2	50
6	12	0.8	3	50
7	10	0.6	2	60
8	10	0.6	2	40
9	10	1	2	40
10	8	0.8	2	40
11	10	1	1	50
12	10	0.6	1	50
13	10	1	3	50
14	8	0.8	2	60
15	12	0.8	2	60
16	8	0.6	3	50
17	12	0.8	2	40
18	10	0.8	2	50
19	10	0.8	3	60
20	10	0.8	1	40
21	8	1	2	50
22	10	0.8	2	50
23	10	0.8	1	60
24	12	0.6	2	50
25	10	0.8	3	40
26	8	0.6	2	50
27	12	1	2	50



Fig.1.Inconel 718 Sheet (150x60x2mm)

The welding joints has been fabricated by using an automatic GTAW machine (make: polysoud). Before welding the Inconel 718 alloy plates were cleaned, wire brushed, edge prepared, and decreased by standard procedure. The fixtures and mechanical clamp has been used to form a tight square butt configuration of pair of base metal sheet as shown in Fig. 2. Twenty seven set of Inconel 718 sheets were welded according to the combination of GTAW process parameters present in DOE Table 3. Since the base metal is 2mm thick, a single pass welding procedure is performed to fabricate the test coupon. The photographs of fabricated test coupons are displayed in Fig. 3.

Measure the Bead Profile Characters (Responses): Two transverse weld bead profile specimens were machined on the middle of each welded test coupon. These bead profile specimens were polished using disc polisher with different grade (220 – 1200 grits) SiC papers and final finished polishing with diamond paste. To expose the bead profile characters the specimens were deeply etched with Glyceregia (ASTM E409 – 99). The bead profile characters, i.e. Bead Depth (BD) and bead width (BW) were measured using 3D profile projector (make: Sipcon) based on illustration of bead profile given in Fig. 4. The measured values of WD, WW and DW are presented in Table 4.

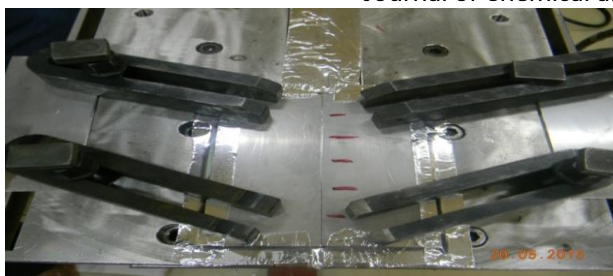


Fig.2. Photograph of Weld Joint Preparation

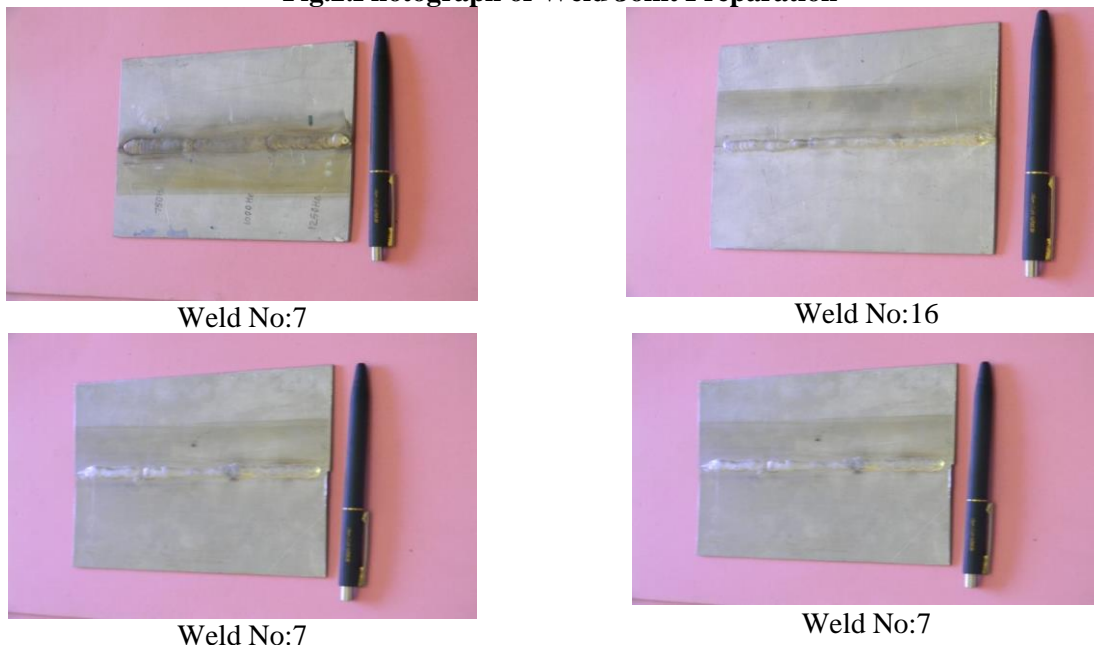


Fig.3. Welded Test Coupon

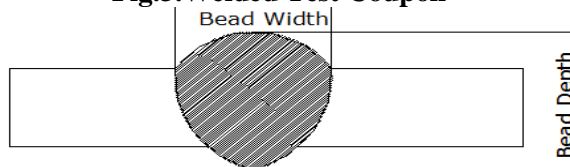


Fig.4. Illustration of Bead Profile

Developing the Regression Equations: The output (bead profile characters – responses) X such as weld depth, weld width and depth to width ratio are the function of current, voltage, welding speed and type of shielding gas. The weld bead characters can be express as;

$$X = f(I, V, S, G) \tag{1}$$

The second order polynomial (regression) equation that represents the response function ‘X’

$$X = a_0 + \sum a_i X_i + \sum a_{ii} X_i^2 + \sum a_{ij} X_i X_j \tag{2}$$

Where a_0 represent for standard response and a_i, a_{ij} is stand for for the coefficient that represent for major and interactive effect of process parameters. Consider four parameters; the selected regression equation could be expressed as;

$$X = a_0 + a_1 (I) + a_2 (V) + a_3 (S) + a_4 (G) + a_{11} (I^2) + a_{22} (V^2) + a_{33} (S^2) + a_{44} (G^2) + a_{12} (IV) + a_{13} (IS) + a_{14} (IG) + a_{23} (VS) + a_{24} (VG) + a_{34} (SG) \tag{3}$$

In this present study, Box- Behnken design which precisely fit the second order responds surface was used. All the coefficients were obtained by applying Box- Behnken design using the minitab-14 software package. The concluding regression model to predict the bead profile characters of GTAW welded Inconel 718 super alloy was obtained as;

$$\begin{aligned} \text{WD} = & 1.93624 + (I * 0.0198743) + (V * 0.127084) + (S * 0.00744447) + (G * -0.0849107) + (I * I * -0.000155111) \\ & + (V * V * -0.00199081) + (S * S * -0.786056) + (G * G * 0.00627274) + (I * V * -0.00110038) \\ & + (I * S * 0.0108337) + (I * G * 0.00187925) + (V * S * 0.0201893) + (V * G * -0.0142279) + (S * G * 0.125887) \end{aligned}$$

$$\begin{aligned} \text{W W} = & 9.77089 + (I * 0.120229) + (V * 0.094435) + (S * -8.0046) + (G * -4.0049) + (I * I * -0.000907087) + (V * V * - \\ & 0.00804944) + (S * S * 0.151892) + (G * G * 0.891834) + (I * V * 0.00265137) + (I * S * 0.0293525) + (I * G * - \\ & 0.009393) + (V * S * 0.311167) + (V * G * 0.0445728) + (S * G * -0.158944) \end{aligned}$$

$DW = 0.247284 + (I^* - 0.00587081) + (V^* - 0.00891941) + (S^* 0.561452) + (G^* 0.198104) + (I^* I^* 0.0000524088) + (V^* V^* 0.00137707) + (S^* S^* - 0.0409097) + (G^* G^* - 0.0421884) + (I^* V^* - 0.0000115375) + (I^* S^* - 0.00300537) + (I^* G^* 0.0003616) + (V^* S^* - 0.0297779) + (V^* G^* - 0.00652679) + (S^* G^* 0.0535739)$

Table.4.Experimental Results (Responses)

Exp. No.	Weld Depth (mm)	Weld Width (mm)	Depth to Width Ratio
1	3.102	7.526	0.412
2	3.111	6.911	0.450
3	3.052	8.300	0.368
4	3.186	9.810	0.325
5	3.111	7.594	0.410
6	3.130	8.787	0.356
7	3.151	8.799	0.358
8	3.090	7.609	0.406
9	2.954	6.101	0.484
10	2.968	6.119	0.485
11	3.026	8.377	0.361
12	3.180	9.786	0.325
13	3.060	7.106	0.431
14	3.138	7.184	0.437
15	3.182	8.899	0.358
16	3.102	7.837	0.396
17	3.100	7.622	0.407
18	3.135	7.594	0.413
19	3.175	8.335	0.381
20	3.089	8.287	0.373
21	2.983	6.010	0.496
22	3.118	7.594	0.411
23	3.168	9.641	0.329
24	3.166	8.899	0.356
25	3.021	7.357	0.411
26	3.109	7.592	0.410
27	3.074	7.806	0.394

Checking the Suitability of the Regression Model: The suitability of the generated regression model was tested using ANOVA testing. The test results of ANOVA for WD, WW and DW are present in the Table 5, 6 and 7. In this testing results shows that the P value of all the terms of three models are less than 0.05. The calculated F ratio of all the regression models are less than the standard F ratio (from table). Based on the ANOVA test results it is understood that all the three regression models are significant with required confidence level (95%).

Validation of Regression Model: Based on the results of percentage error calculation the regression models were validated. The percentage error was calculated using the below equation

$$\% \text{ Error} = \frac{\text{Experimental value} - \text{Calculated value}}{\text{Calculated value}} * 100$$

The Table 8 and 9 shows the output of the error calculation of WD, WW and DW respectively. It was confirmed that all the three regression equations are accepted to predict WD, WW and DW for the required accuracy of more than 95%.

Table.5.ANOVA Result of Weld Depth (WD)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	14	0.109651	0.109651	0.007832	71.01	0.000
Linear	4	0.091881	0.088291	0.022073	200.11	0.000
Square	4	0.007457	0.007564	0.001891	17.14	0.000
Interaction	6	0.010312	0.010312	0.001719	15.58	0.000
Residual Error	12	0.001324	0.001324	0.000110		
Lack-of-Fit	10	0.001021	0.001021	0.000102	0.67	0.727
Pure Error	2	0.000303	0.000303	0.000151		
Total	26	0.110975				

Table.6.ANOVA Result of Weld Width (WW)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	14	27.5994	27.5994	1.97138	593.95	0.000
Linear	4	21.8281	22.4538	5.61346	1691.26	0.000
Square	4	5.6107	5.4744	1.36860	412.34	0.000
Interaction	6	0.1606	0.1606	0.02676	8.06	0.001
Residual Error	12	0.0398	0.0398	0.00332		
Lack-of-Fit	10	0.0398	0.0398	0.00398		
Pure Error	2	0.0000	0.000	0.00000		
Total	26	27.6392				

Table.7.ANOVA Result of Depth to Width Ratio (DW)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	14	0.056143	0.056143	0.004010	104.83	0.000
Linear	4	0.041561	0.043425	0.010856	283.79	0.000
Square	4	0.012725	0.012658	0.003165	82.72	0.000
Interaction	6	0.001856	0.001856	0.000309	8.09	0.001
Residual Error	12	0.000459	0.000459	0.000038		
Lack-of-Fit	10	0.000454	0.000454	0.000045	17.29	0.056
Pure Error	2	0.000005	0.000005	0.000003		
Total	26	0.056602				

Table.8.Result of Error Calculation – Weld Depth and Weld Width

Exp. No.	WD (mm) Experimental Value	WD(mm) Predicted Value	%Error	Max. Error	WW (mm) Experimental Value	WD (mm) Predicted Value	%Error	Max. Error
1	3.102	3.103	0.036	0.431	7.526	7.473	0.701	1.294
2	3.111	3.100	0.324		6.911	6.966	0.786	
3	3.052	3.058	0.226		8.300	8.321	0.256	
4	3.186	3.195	0.301		9.810	9.759	0.519	
5	3.111	3.121	0.337		7.594	7.592	0.020	
6	3.130	3.123	0.214		8.787	8.760	0.298	
7	3.151	3.161	0.315		8.799	8.756	0.490	
8	3.090	3.089	0.034		7.609	7.659	0.651	
9	2.954	2.944	0.336		6.101	6.141	0.658	
10	2.968	2.978	0.346		6.119	6.107	0.204	
11	3.026	3.027	0.053		8.377	8.410	0.391	
12	3.180	3.179	0.001		9.786	9.747	0.402	
13	3.060	3.063	0.076		7.106	7.170	0.881	
14	3.138	3.138	0.000		7.184	7.215	0.438	
15	3.182	3.173	0.258		8.899	8.938	0.433	
16	3.102	3.103	0.021		7.837	7.828	0.114	
17	3.100	3.102	0.068		7.622	7.617	0.071	
18	3.135	3.121	0.431		7.594	7.592	0.020	
19	3.175	3.181	0.204		8.335	8.318	0.206	
20	3.089	3.080	0.282		8.287	8.281	0.081	
21	2.983	2.983	0.005		6.010	5.933	1.294	
22	3.118	3.121	0.104		7.594	7.592	0.020	
23	3.168	3.158	0.298		9.641	9.683	0.434	
24	3.166	3.164	0.058		8.899	8.950	0.566	
25	3.021	3.028	0.239		7.357	7.291	0.904	
26	3.109	3.101	0.248		7.592	7.582	0.128	
27	3.074	3.079	0.162		7.806	7.799	0.095	

Table.9.Result of Error Calculation - Depth to width Ratio

Exp. No.	DW Experimental Value	DW Predicted Value	%Error	Max. Error
1	0.412	0.415	0.726	2.374
2	0.450	0.450	0.057	
3	0.368	0.374	1.616	
4	0.325	0.325	0.072	
5	0.410	0.411	0.282	
6	0.356	0.348	2.243	
7	0.358	0.365	1.912	
8	0.406	0.402	1.113	
9	0.484	0.476	1.773	
10	0.485	0.483	0.361	
11	0.361	0.362	0.302	
12	0.325	0.322	1.012	
13	0.431	0.434	0.707	
14	0.437	0.435	0.368	
15	0.358	0.359	0.521	
16	0.396	0.395	0.326	
17	0.407	0.408	0.424	
18	0.413	0.411	0.487	
19	0.381	0.378	0.700	
20	0.373	0.377	1.054	
21	0.496	0.495	0.220	
22	0.411	0.411	0.048	
23	0.329	0.321	2.374	
24	0.356	0.358	0.585	
25	0.411	0.420	2.132	
26	0.410	0.409	0.015	
27	0.394	0.396	0.594	

3. RESULTS AND OBSERVATION

The effect of four welding process parameters i.e. welding current, welding voltage, welding speed and shielding gas and their effects on WD, WW and DW is analysed and studied using the experimental value. Experimental values are plotted as a counter plot and they are displayed in Fig. (4-6). The plotted counter plots are efficiently used to understand the effect of GTAW parameters on weld profile characters of GTAW welded Inconel 718 alloy joint

Effect of Welding Parameters on Weld Depth: Effect of welding parameters on WD is graphically shown in Fig. 5. From Fig. 5(a), it is evident that the optimum (maximum) WD is yielded when the current and the voltage is in higher level. It is clear that the WD increases as the voltage and current increases. It is observed from Fig. 5(b) that the maximum WD is shown as the welding speed is at low level. It is understood from Fig. 5(c) that the Helium shielding gas is the most influencing shielding gas on WD. The interactive effect of voltage and speed on WD is graphically explained in Fig. 5(d).

Effect of Welding Parameters on Weld Width: Effect of welding parameters on WW is graphically shown in Fig. 6. From Fig. 6(a), it is evident that the optimum (minimum) WW is yielded when the current and the voltage is in higher level. It is clear that the WW increases as the voltage and current increases. It is observed from Fig. 6(b) that the minimum WW is shown as the welding speed is at higher level. It is understood from Fig. 6(c) that the Helium shielding gas is the most influencing shielding gas on WW. The interactive effect of voltage and speed on WW is graphically explained in Fig. 6(d).

Effect of Welding Parameters on Depth to Width ratio: Effect of welding parameters on DW is graphically shown in Fig. 7. From Fig. 7(a), it is evident that the optimum (maximum) DW is yielded when the current and

the voltage is in low level. It is clear that the DW is increases as the voltage and current decreases. It is observed from Fig. 7(b) that the maximum DW is shows as the welding speed is at higher level. It is understand from Fig. 7(c) that the Argon shielding gas is the most influencing shielding gas on WD. The interactive effect of voltage and speed on DW is graphically explained in Fig. 7(d).

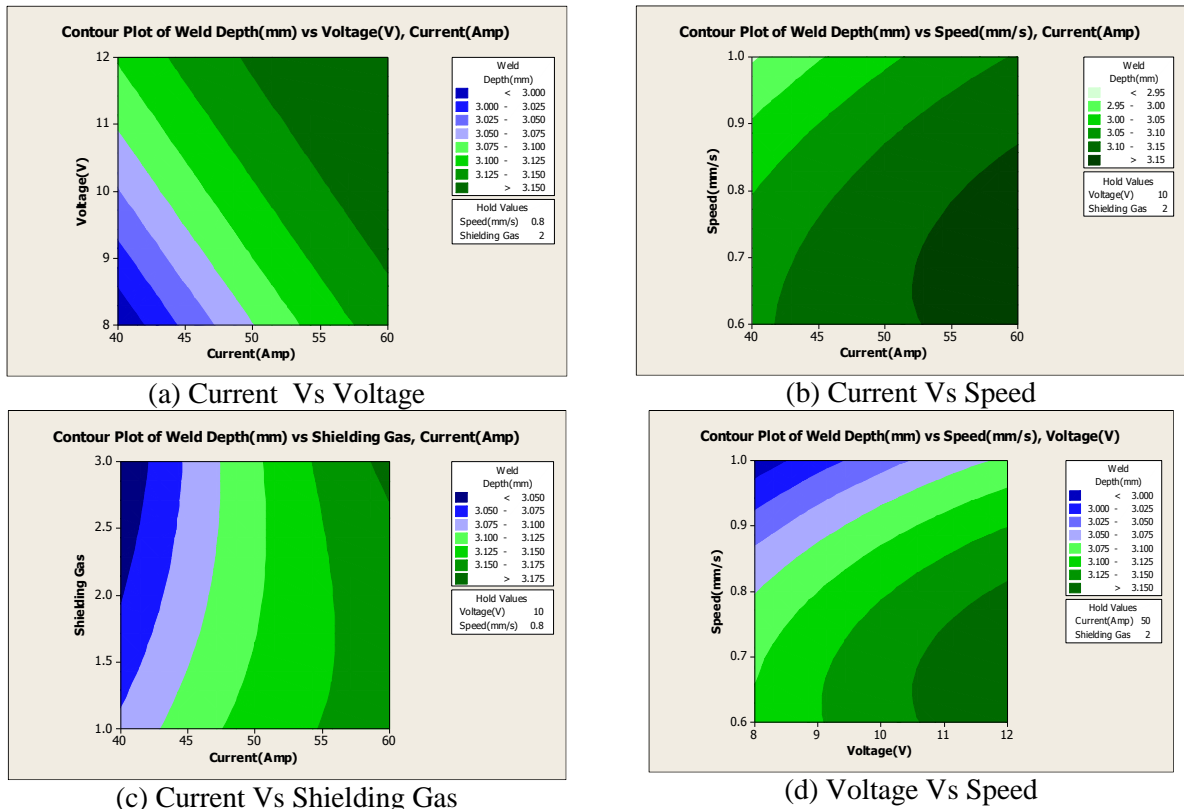


Fig.4.Effect of Welding Parameters on WD

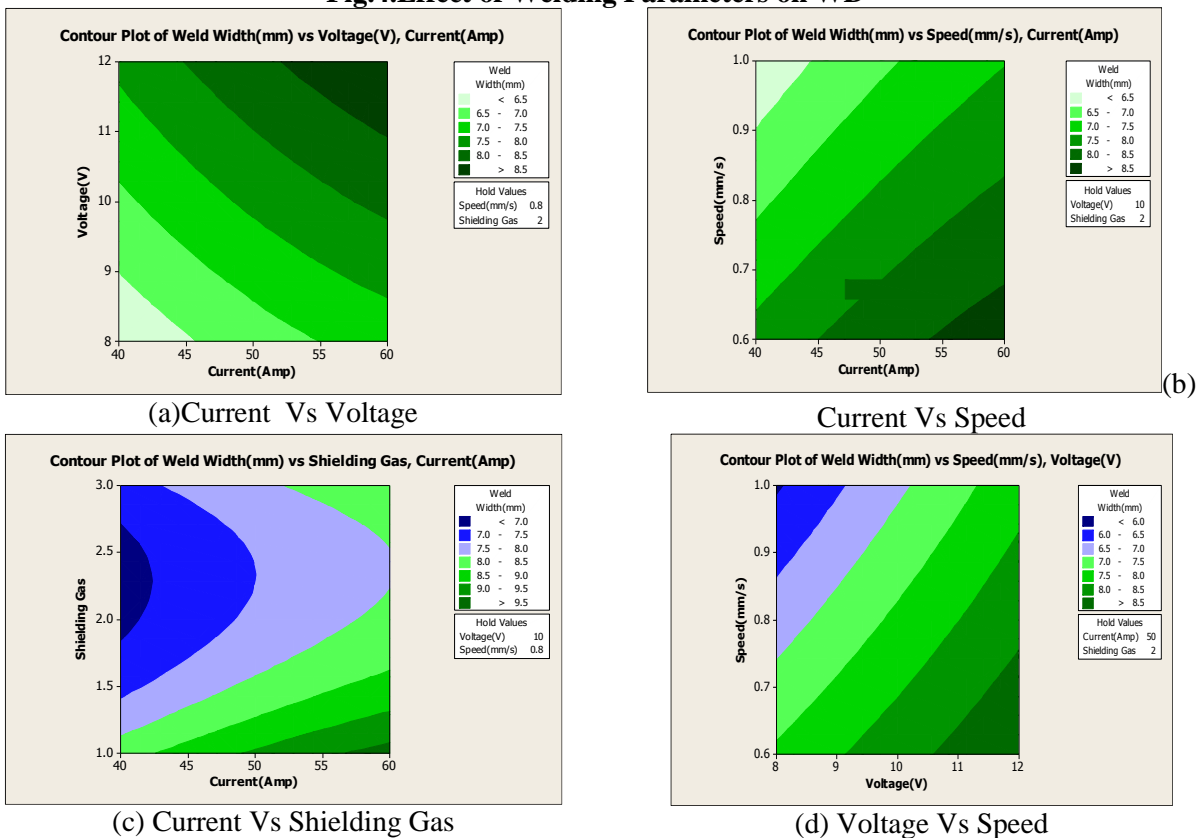


Fig. 5: Effect of Welding Parameters on WW

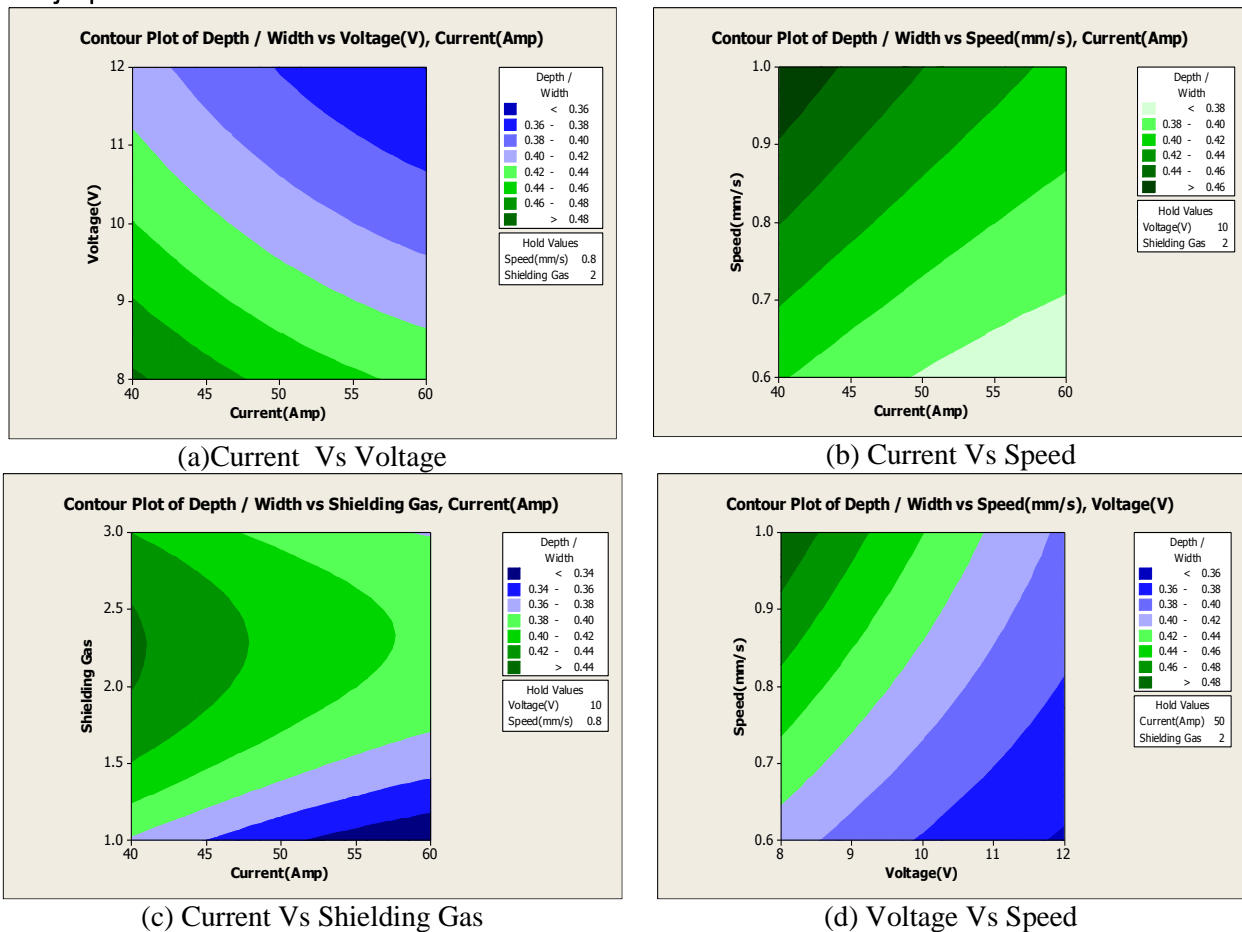


Fig.6.Effect of Welding Parameters on DW

4. CONCLUSION

In this investigation, the selection of welding process parameters for obtain favorable weld bead profile characters of GTAW welded Inconel 718 alloy has been discussed.

The two level four factors Box – behknen design has been adopted for experimentation. Based on the experimental results obtained the mathematical model was developed to predict the bead profile characters of GTAW welded Inconel 718 alloy using RSM. The developed prediction models can be efficiently used to calculate the bead width, bead depth and depth to width ratio of GTAW welded Inconel 718 alloy at 95% accuracy level

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