



INVESTIGATION ON WELDABILITY OF AA6063 ALUMINIUM ALLOY BY USING TUNGSTEN INERT GAS WELDING

1 Soumojit Dasgupta, 2 Thia Paul, 3 Munshi Rashidul Islam, 4 Ankit Das, 5 Arnab Chatterjee, 6 Biplab Sutradhar, 7 Kushal Mohanta, 8 Rohit Biswas

1, 2, 3 Assistant Professor, 4, 5, 6, 7, 8 UG Students
Department of Mechanical Engineering,
JIS College of Engineering, Kalyani, India

Abstract: Welding is a permanent joining process both by using gas torch or electricity to generate heat and also by using filler materials. Similar materials or dissimilar materials both can be joined by implementing welding process. Pressure can be used instead of filler materials to get the permanent joint. For fabricating various engineering components Welding has been considered as one of the best process in the recent years. Various applications include constructions, automotive industries, ship building, aerospace, etc. Gas Tungsten Arc Welding (GTAW) is one of the majorly applied welding processes. There are different welding factors which determine the soundness of weld and investigate the weldability of a metal. Weldability is defined as the easiness with which two or more similar or dissimilar metals can be joined without any problem. In GTAW, the Heat Input and the Gas Flow Rate are two major factors during the welding process. They have an influence on Weld Bead Geometry. One of the important characteristics of welding is considered as weld beads. Metals weldability has been determined by reinforcement height, width of the weld beads, and depth of penetration. In the present research work the Tungsten Gas Arc Welding (GTAW) was carried on AA6063 aluminium alloy. Response Surface Methodology (RSM) has been implemented to design the experiment that too CCD (Central Composite Design). Gas Flow Rate and Heat Input are the two factors and three level has been considered to create DOE. Bead geometry parameters were studied for different combinations of the mentioned factors. The influence of each factor on the bead geometry was analysed using ANOVA. It was observed that the maximum depth of penetration was obtained at heat input values of 0.36-0.4 kJ/mm and gas flow rate of 15.5 l/min. Minimum bead width is recommended and this was obtained at heat input of 0.45-0.48 kJ/mm and gas flow rate of 15-16 l/min. Nominal positive reinforcement height is acceptable and this is obtained through the entire range of heat input and gas flow rate of 10.5-13.5 l/min.

Index Terms - Weldability, GTAW, Bead Geometry, Response Surface Methodology, ANOVA

I. INTRODUCTION

Steel has been replaced by Aluminium in the wheels of automobile because of superior dissipation of heat during braking. Tire wear and road handling has been improved by implementing Aluminium in the wheel. High-strength and medium strength aluminium alloys are usually used in the marine applications and aerospace industries. Aluminium has excellent resistance to corrosion, extrudability, light weight, and also have excellent immunity related to stress corrosion.

Silicon and magnesium are the alloying elements of Aluminium 6063 alloy. Elements of aluminium alloy are controlled by aluminium association. Good weldability, heat treatment can be performed by the alloy. It has good mechanical properties too. 6063 aluminium alloy is preferred for extrusion process. Complex shapes with high quality surface can be achieved and it is very popular applications in architectural field. Heat treatment is the process for obtaining higher mechanical properties.

AA6063 precipitation hardening alloys are preferable for structural applications because of its wear resistance which is fundamental requirement for design. Si and Mg are the major elements for aluminium alloy 6063.

Si percentage varies between 0.35% to 1.3% and Mg varies between 0.6% to 1.2%. To obtain the best mechanical properties heat treatment has been performed. Alloying elements includes copper, zinc, and magnesium which have been added to Aluminium 6063 alloy to increase its mechanical properties. Some more alloys such as zirconium, titanium, and silver were also added to improve its properties. Chromium has been added to AA6063 to improve its intergranular corrosion resistance.

TIG welding or Gas Tungsten Arc Welding (GTAW) is one of the variants of arc welding. Preferably, AC is used during welding of aluminium alloys and composites. This article aims to investigate Weldability and Bead Geometry of the weld bead after TIG welding of grain refined AA6063 Aluminium Alloy Casting with added Ag and Fe.

II. EXPERIMENTAL PROCEDURE

2.1 Recognition of GTAW Process Parameters

The factors considered for GTAW of AA6063 are-

- i) Heat Input
- ii) Gas Flow Rate

2.2 Identifying the limits of the GTAW process parameters

Trial runs were conducted for determining the range of values for the above-mentioned factors. Finally, the following levels were considered.

Table 1: Welding Factors and their levels

Factors	Level 1 (-1)	Level 2 (0)	Level 3 (+1)
Heat Input (kJ/mm)	0.355	0.408	0.48
Gas flow rate (l/min)	8	12	16

Heat Input = $\eta \times V \times I / 1000 \times s$, where

η = Weld efficiency, generally considered as 0.75 or 75%

V = Weld voltage (Volt)

I = Weld current (Ampere)

S = weld speed (mm/s)

2.3 Design of Experiment

Design of Experiments (DOE) is a powerful statistical tool used to systematically design and analyse experiments to identify the significant factors that influence a response variable. In this experimental work Response Surface Methodology (RSM) is used as the DOE. It is a subset of DOE that is used to optimize a response variable by exploring the relationship between the response and the factors that affect it.

The RSM is used to find the optimal combination of factors that will produce the best response. It involves creating a mathematical model that relates the response to the factors, and then using this model to predict the response for different combinations of factor levels. The goal is to find the factor levels that give the maximum or minimum response.

The steps involved in the RSM include:

- 1.Design the experiment
- 2.Collect data
- 3.Fit the model
- 4.Check the model
- 5.Optimize the response

Overall, RSM is a powerful statistical tool that allows for the optimization of a response variable by exploring the relationship between the response and the factors that affect it. By following the steps outlined

above, researchers can use RSM to find the optimal combination of factor levels that will produce the best response.

2.4 Developing the experimental design matrix

Experimental runs were conducted using three factors and three levels. Response Surface Methodology (RSM) was used to design thirteen experiments. Various conditions are presented in Table 2.

Table 2: Experimental conditions for GTAW welding

Sl. No.	Run Order	Current (Coded Value)	Gas Flow rate (Coded Value)
1.	2	-1	-1
2.	7	+1	-1
3.	10	-1	+1
4.	4	+1	+1
5.	12	-1	0
6.	9	+1	0
7.	5	0	-1
8.	13	0	+1
9.	1	0	0
10.	3	0	0
11.	6	0	0
12.	8	0	0
13.	11	0	0



Figure 1: GTAW Welding Machine

2.5 Experimentation

GTAW was performed on AA6063 with a plate thickness of 10 mm using Arc welding machine, with the following specification as shown in Figure 2.

- i) Type- E 400
- ii) Maximum Continuous Hand Welding- 8 KVA
- iii) Welding Current Range at 55 OCV - 60 to 400 AMPS
- iv) Max. Continuous Hand welding Current- 55 OCV- 200 AMP
- v) Input (Primary) Current at Rated Output- 22 AMPS
- vi) Secondary OCV- 55 Volts

Filler Material used

Filler Material - ER4043 of diameter 2 mm.

Process

First, the material, i.e., AA6063, whose dimensions are 40 mm x 50 mm x15 mm, is cut into 26 pieces. After that, cleaning of base material is performed and finally edge preparation of AA6063 is performed. After that, GTAW is done resulting in 13 pairs of weldments. During welding, two factors were considered as input, i.e. Heat Input and Gas Flow Rate. After welding, we check the output parameters of the material in the form of weld bead geometry. The visual output after welding has been summarized in Table 3.

Table 3: Typical visual inspection of weld samples

Sl. No.	Weld Picture	Inspection Remarks
1.		Minute pin holes on bead surface.
2.		Minute pin holes on bead surface.
3.		Two pin holes on bead surface.
4.		Even weld profile throughout.

5.		Two pin holes on bead surface.
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III. Results and Discussion

The below results are summarized in the following Table 4.

Table 4: Measured values of Depth of Penetration

Sl. No	Current (A)		Voltage (V)	Weld Speed (mm/sec)	Heat Input (kJ/mm)	Gas Flow Rate (lit/min)	Depth Of Penetration (mm)	Bead Width (mm)	Height of reinforcement (mm)
	c.c.c	o.c.c							
1	100	100	15.4	3	0.355	8	8.5	15	6.5
2	140	140	14.0	3	0.48	8	6	12	6
3	100	100	14.2	3	0.355	16	8	15	7
4	139	140	13.4	3	0.48	16	5	9	4
5	100	100	13.6	3	0.355	12	10	15	5
6	140	140	15.9	3	0.48	12	3	15	12
7	120	120	16.0	3	0.48	8	10	15	5
8	120	120	13.7	3	0.408	16	5	11	6
9	120	120	14.9	3	0.48	12	2	12	10
10	120	120	13.6	3	0.408	12	4	14	10
11	120	120	13.6	3	0.408	12	4	12	8
12	120	120	13.8	3	0.408	12	3	12	9
13	120	120	12.5	3	0.408	12	4	11	7

3.1 Analysis of depth of penetration

Below mentioned Figure 2 represents the analysis of depth of penetration.

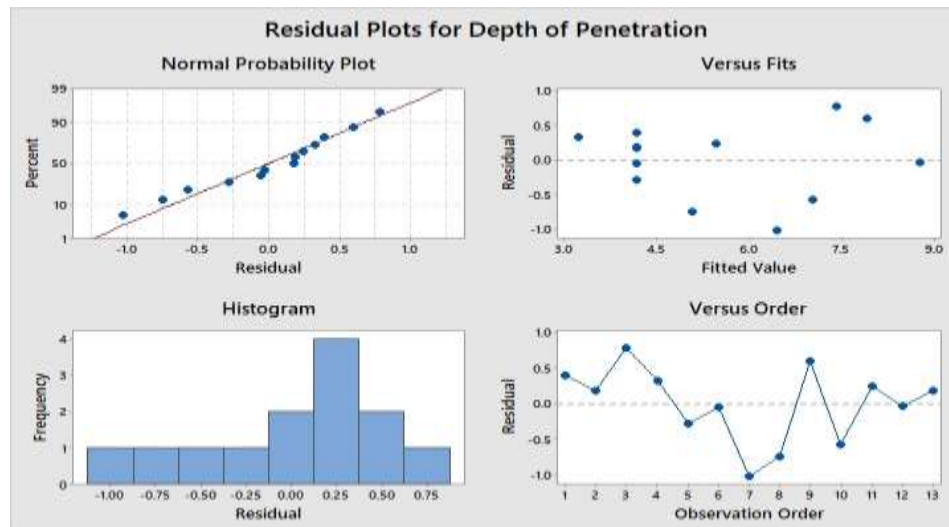


Figure 2: Residual Plots for Depth of Penetration

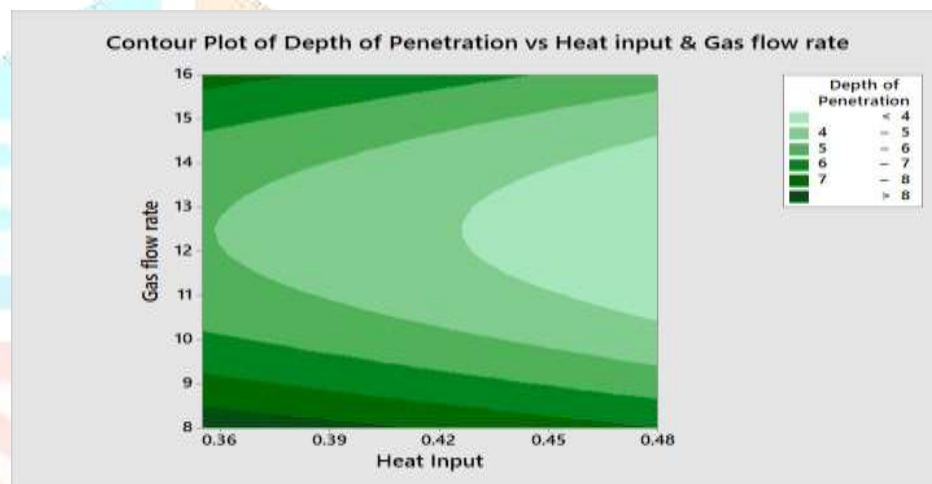


Figure 3: Contour Plot of Depth of Penetration with Heat Input & Gas Flow Rate

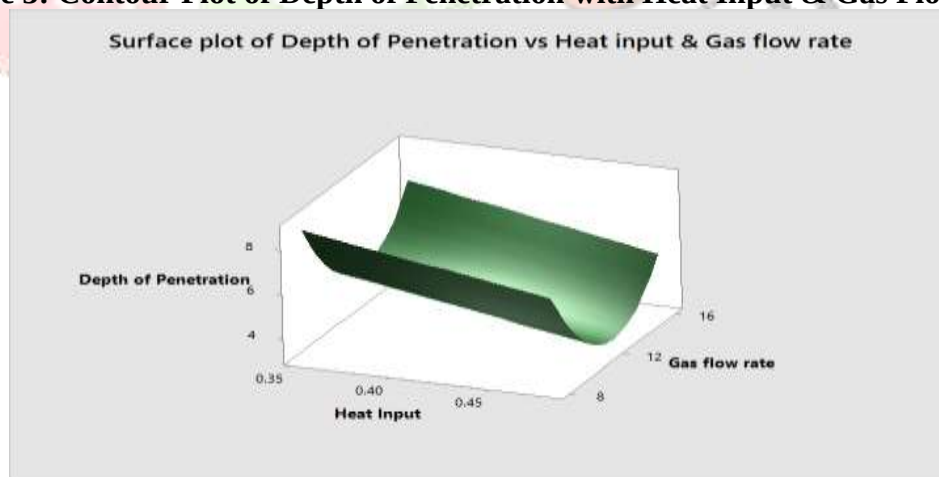


Figure 4: Surface Plot of Depth of Penetration with Heat Input & Gas Flow Rate

Figures 2 represent the Residual plots. Figure 3 represents the Contour plot of Depth of Penetration with Heat Input and Gas Flow Rate.

At approximately Heat Input of 0.34 KJ/mm, 0.408 KJ/mm, 0.48 KJ/mm and Gas Flow Rate of 8 litre/min, 12 litre/min, 16 litre/min, the depth of penetration is within the range of 2-10 mm. Likewise, different ranges of depth of penetration is obtained for variation between Heat Input and Gas Flow Rate.

Figure 4 represents the Contour Plot of Depth of Penetration with Heat Input and Gas Flow Rate. Here, the Heat Input is shown along the X-axis, Gas Flow Rate along the Y-axis and Depth of Penetration along the Z-axis.

The ANOVA is as follows-

Central Composite Design

Response Surface Regression: Depth of Penetration versus Heat Input, Gas flow rate

Analysis of Variance

Source	DF	Adj SS	AdjMS	F-Value	P-Value
Model	5	37.7919	7.5584	15.59	0.001
Linear	2	8.4122	4.2061	8.67	0.013
Heat Input	1	5.1708	5.1708	10.66	0.014
Gas flow rate	1	3.2413	3.2413	6.69	0.036
Square	2	29.3687	14.6844	30.29	0.000
Heat Input*Heat Input	1	0.0003	0.0003	0.00	0.980
Gas flow rate*Gas flow rate	1	25.1753	25.1753	51.92	0.000
2-Way Interaction	1	0.0110	0.0110	0.02	0.884
Heat Input*Gas flow rate	1	0.0110	0.0110	0.02	0.884
Error	7	3.3940	0.4849		
Lack-of-Fit	3	3.1234	1.0411	15.39	0.012
Pure Error	4	0.2707	0.0677		
Total	12	41.1860			

Model Summary

S R-sq
0.696320 91.76%

The ANOVA shows that Linear P-values for both Heat Input and Gas flow rate are less than 0.05. Thus, both the factors have significant contribution on the depth of penetration. Heat input has more influence compared to gas flow rate with P-values of 0.014 and 0.036 respectively. Also, the R-sq value of 91.76% is significantly higher, which denotes that the results are acceptable.

Analysis of bead width

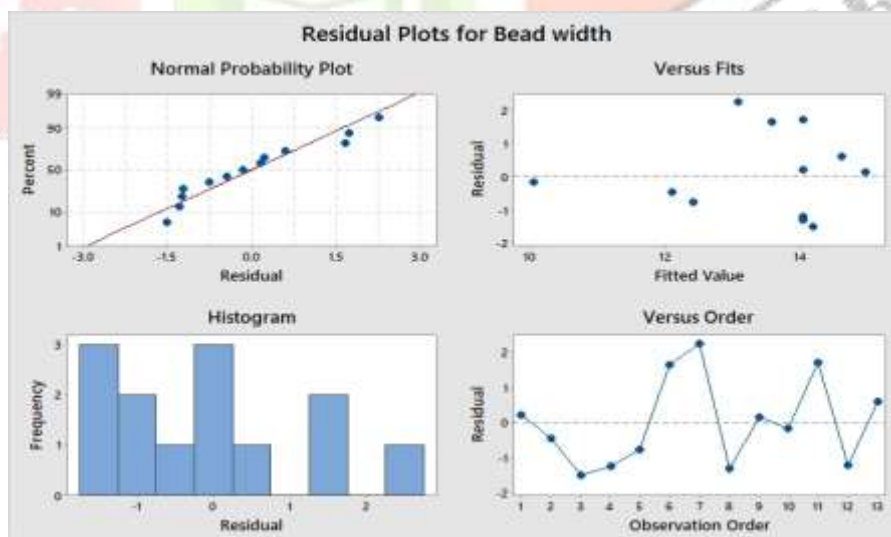


Figure 5: Residual Plots for Bead Width

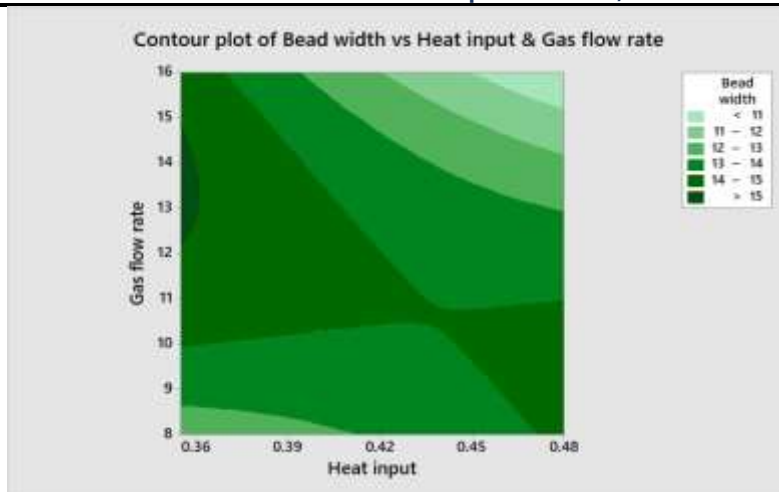


Figure 6: Contour Plot of Bead Width vs Heat Input & Gas Flow Rate

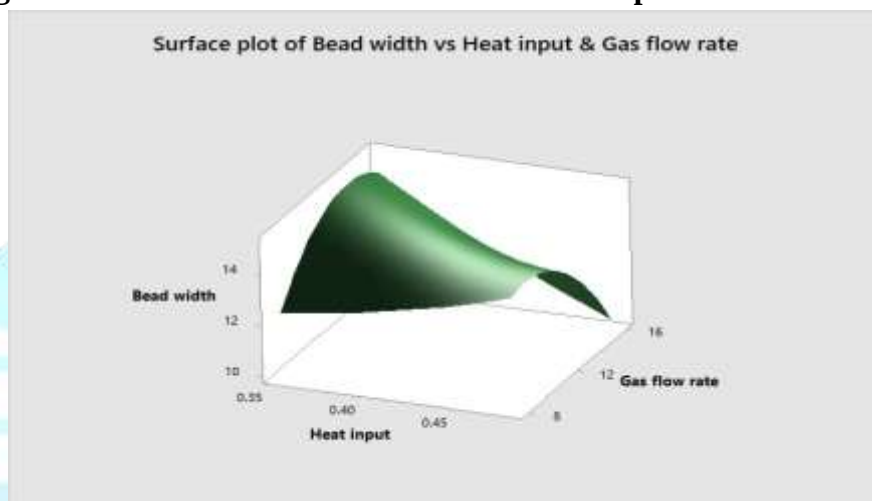


Figure 7: Surface Plot of Bead Width vs Heat Input & Gas Flow Rate

Figures 5 represent the Residual plots. Figure 6 represent the Contour plot of Bead Width vs Heat Input & Gas Flow Rate.

At approximately Heat Input of 0.355 KJ/mm, 0.408 KJ/mm, 0.48 KJ/mm and Gas Flow Rate of 8 litre/min, 12 litre/min, 16 litre/min, the Bead width is within the range of 9-15 mm. Likewise, different ranges of Bead Width is obtained for variation between Heat Input and Gas Flow Rate.

Figure 7 represents the Surface plot of Bead Width vs Heat Input and Gas Flow Rate. Here, the Heat Input is shown along the X-axis, Gas Flow Rate along the Y-axis and Bead Width along the Z-axis.

The ANOVA is as follows-

Central Composite Design

Response Surface Regression: Bead width versus Heat input, Gas flow rate

Analysis of Variance

Source	DF	Adj SS	AdjMS	F-Value	P-Value
Model	5	20.5311	4.1062	1.50	0.301
Linear	2	4.3234	2.1617	0.79	0.491
Heat input	1	2.9121	2.9121	1.06	0.037
Gas flow rate	1	1.4114	1.4114	0.52	0.006
Square	2	6.1588	3.0794	1.12	0.377
Heat input*Heat input	1	0.1392	0.1392	0.05	0.828
Gas flow rate*Gas flow rate	1	5.8110	5.8110	2.12	0.188
2-Way Interaction	1	10.0489	10.0489	3.67	0.097
Heat input*Gas flow rate	1	10.0489	10.0489	3.67	0.097
Error	7	19.1615	2.7374		
Lack-of-Fit	3	12.0658	4.0219	2.27	0.223
Pure Error	4	7.0957	1.7739		

Total

12 39.6926

Model Summary

S R-sq

1.65449 93.73%

The ANOVA shows that Linear P-values for both Heat Input and Gas flow rate are less than 0.05. Thus, both the factors have significant contribution on the bead width. Gas flow rate has more influence compared to Heat input with P-values of 0.006 and 0.037 respectively.

Also, the R-sq value of 93.73% is significantly higher, which denotes that the results are acceptable.

Analysis of Height of Reinforcement

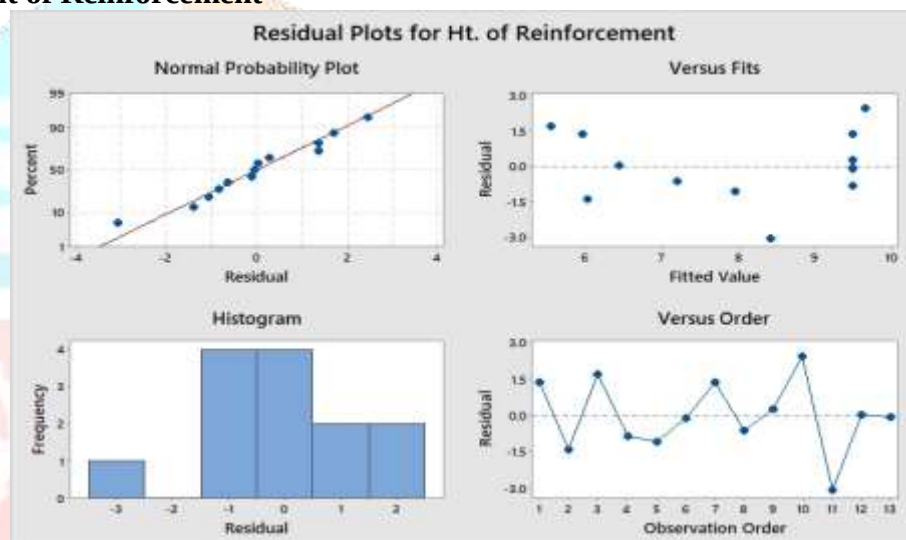


Figure 8: Residual Plots for Ht. of Reinforcement

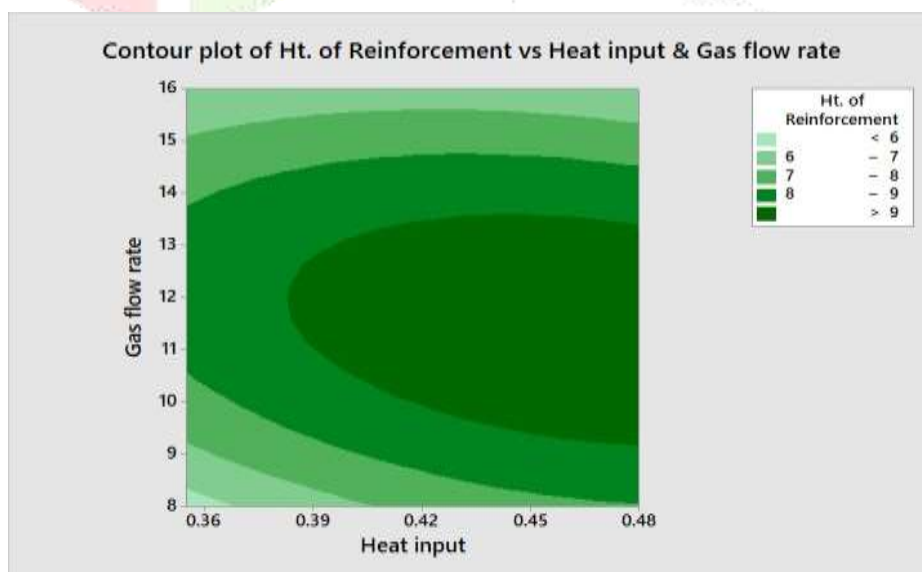


Figure 9: Contour Plot of Ht. of Reinforcement with Heat Input & Gas Flow Rate

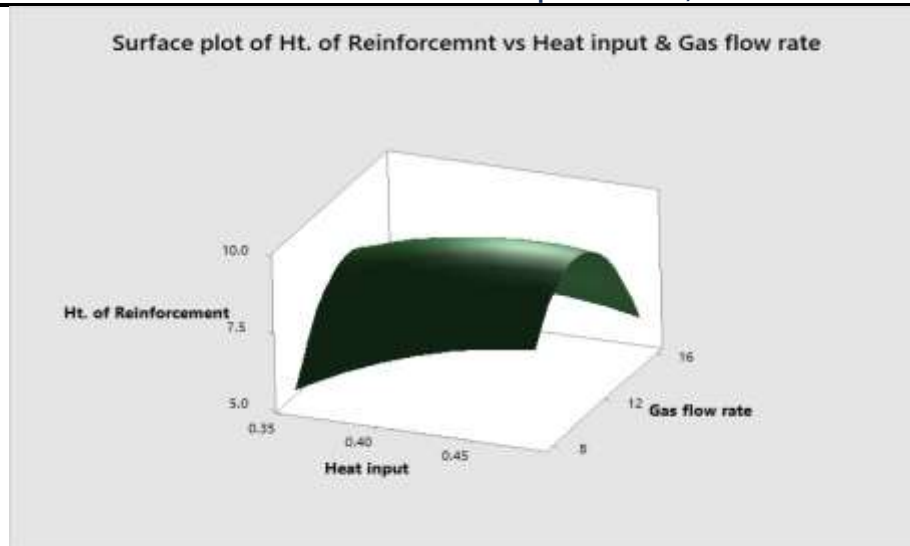


Figure 10: Surface Plot of Ht. of Reinforcement with Heat input & Gas Flow Rate

Figures 8 represent the Residual plots. Figure 9 represent the Contour plot of Ht. of Reinforcement with Heat Input & Gas Flow Rate.

At approximately Heat Input of 0.355 KJ/mm, 0.408 KJ/mm, 0.48 KJ/mm and Gas Flow Rate of 8 litre/min, 12 litre/min, 16 litre/min, the Ht. of Reinforcement is within the range of 5-12 mm. Likewise, different ranges of Ht. of Reinforcement is obtained for variation between Heat Input & Gas Flow Rate.

Figure 10 represents the Surface Plot of Ht. of Reinforcement with Heat Input & Gas Flow Rate. Here, the Heat Input is shown along the X-axis, Gas Flow Rate along the Y-axis and Ht. of Reinforcement along the Z-axis.

The ANOVA is as follows-

Central Composite Design

Response Surface Regression: Ht. of Reinforcement versus Heat input, Gas flow rate

Analysis of Variance

Source	DF	Adj SS	AdjMS	F-Value	P-Value
Model	5	30.9061	6.1812	1.63	0.268
Linear	2	3.1453	1.5726	0.42	0.676
Heat input	1	2.2940	2.2940	0.61	0.002
Gas flow rate	1	0.8513	0.8513	0.22	0.050
Square	2	26.4036	13.2018	3.48	0.089
Heat input*Heat input	1	0.5461	0.5461	0.14	0.715
Gas flow rate*Gas flow rate	1	19.5371	19.5371	5.16	0.057
2-Way Interaction	1	1.3572	1.3572	0.36	0.568
Heat input*Gas flow rate	1	1.3572	1.3572	0.36	0.568
Error	7	26.5187	3.7884		
Lack-of-Fit	3	23.9270	7.9757	12.31	0.017
Pure Error	4	2.5917	0.6479		
Total	12	57.4248			

Model Summary

S R-sq

1.94638 93.82%

The ANOVA shows that Linear P-values for Heat Input and Gas flow rate are less than and equal to 0.05 respectively. Thus, both the factors have significant contribution on the Height of reinforcement. Heat input has more influence compared to Gas flow rate with P-values of 0.002 and 0.050 respectively. Also, the R-sq value of 93.82% is significantly higher, which denotes that the results are acceptable.

IV. Conclusion

In this experimental investigation on the weldability of AA6063 aluminium alloy by using Tungsten Inert Gas welding process, Central Composite Design of the Response Surface Methodology was used as the design of experiment. Argon (99.9% pure) was used as the shielding gas. ER4043 rod was applied as the filler material of 2mm diameter. From the results, it is evident that both Heat Input and Gas Flow Rate have significant contribution on the Weld Bead Geometry parameters, i.e. depth of penetration, bead width and height of reinforcement.

The following inferences were concluded-

- i) It has been observed that the Weld Bead Geometry is improved maintaining a lower value of Heat Input. This is evident from the Contour plots of each analysis.
- ii) The maximum depth of penetration was obtained at heat input values of 0.36-0.4 kJ/mm and gas flow rate of 15.5 l/min.
- iii) Minimum bead width is recommended and this was obtained at heat input of 0.45-0.48 kJ/mm and gas flow rate of 15-16 l/min.
- iv) Nominal positive reinforced height is acceptable and this is obtained through the entire range of heat input and gas flow rate of 10.5-13.5 l/min.
- v) The ANOVA shows that Linear P-values for both Heat Input and Gas flow rate are less than 0.05. Thus, both the factors have significant contribution on the depth of penetration. Heat input has more influence compared to gas flow rate with P-values of 0.014 and 0.036 respectively.
- vi) The ANOVA shows that Linear P-values for both Heat Input and Gas flow rate are less than 0.05. Thus, both the factors have significant contribution on the bead width. Gas flow rate has more influence compared to Heat input with P-values of 0.006 and 0.037 respectively.
- vii) The ANOVA shows that Linear P-values for Heat Input and Gas flow rate are less than and equal to 0.05 respectively. Thus, both the factors have significant contribution on the Height of reinforcement. Heat input has more influence compared to Gas flow rate with P-values of 0.002 and 0.050 respectively.

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