Prediction of Bead Geometry Parameters of MIG Welded Aluminium 1200 Plates by Mathematical Modelling

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Abstract

Metal Inert Gas (MIG) welding is a procedure in which a wire electrode is heated and fed into the weld pool continuously from a welding gun. In this present work, bead geometry like bead width (BW), depth of penetration (DOP) and height of reinforcement (HOR) has been a using a mathematical model. The parameters of a weld bead of a fusion weld are important from a design point of view, as they affect the joint's mechanical strength and reliability during its serviceability. The present work is focused on analysing the effect of various welding input parameters like wire feed rate (WFR), voltage (V) and welding speed (WS) on the bead geometry parameters. The material is that has been selected is Al 1200 for the present work due to its widespread utility in manufacturing pipelines, shipbuilding industry and general fabrication work. A mathematical correlation between the bead and the input parameters is attempted. To execute the tests in a structured manner and construct a mathematical model, the design of experiment (DOE) technique was utilised. Optimization of the parameters was done to have the desired levels of the parameters of bead within the selected working range. Response surface methodology is used to analyse the graphical results. The final` model has been found to be adequate through the use of the Analysis of Variance approach.

Keywords: Bead geometry, input parameters, ANOVA, mathematical modeling, Response surface methodology, MIG welding.

1.   Introduction

MIG welding is a joining and fabrication process that has been widely used for many decades due to its benefits such as all-position welding ability, portability, versatility, ability to join all the materials whose filler wire is available and its ability to get fully automated [1]. An arc is formed between the specimen and a consumable electrode is used as the source of heat in this method. An externally supplied inert gaseous shield of argon, helium or their combination protects the arc and the molten pool from atmospheric contamination [2]. The consumable electrode is a wire spool that is fed through the feed rollers at a consistent rate [3]. The MIG welding is used for the fabrication purposes because of its deeper penetration and higher deposition rate [4].

Bead geometry parameters such as DOP, BW, and HOR are widely used to adjudge the weld joint quality as they are found to have a direct bearing on the mechanical properties and performance of the weld during its service life [5]. Literature survey and past experience have shown that these bead parameters are affected by input parameters like WFR, WS and V. It is therefore important to set the right welding parameters in advance to achieve desired quality weld [6]. The geometrical forms of the bead and its properties have a direct effect on the mechanical properties of the weld joints [7].

The material which is selected for this experimentation is Al plates (1200) which are widely used in a variety of applications such as spacecraft components, automobiles, ships, trains, airplane parts, household appliances, cans, foils etc. The dimensions of the specimen are 120 mm x 75 mm x 4 mm and they were butt-welded by using the MIG welding equipment as illustrated in Fig. 1. The experiments for this work were conducted in a structured manner by using statistical techniques of design of experiments. A 3 - level and 3 - factor face centered design was used and a total of 20 experimental runs were carried out as suggested by the design matrix developed by the design expert software. A mathematical model was developed to set up a relation between the input parameters and the response parameters and ANOVA is used to check adequacy. The parameters are then optimised to have the desired levels of bead parameters within the selected working range.

Fig. 1.The Experimental Setup

Researchers have attempted to forecast and explain the impact of the welding parameters on bead geometry through a variety of methods. The following is a list of some of the published research of several researchers in this field.

Study on the effect of the welding parameters on the properties of Al alloy 5052 was conducted, and it was discovered that all MIG process factors (V, wire-speed, gas flow) have a substantial effect on the tensile and micro hardness of the welded [8]. When the welding parameters were optimised and P-values for the various factors were obtained, it can be concluded that current and voltage are the main parameters among the three controllable factors that influence tensile strength during MIG welding (welding current, V, WFR) [9]. MIG welding contributes 36.8 per cent of welding current, 32.9 per cent of gas flow, and 30.3 per cent of feed rate. TIG welding contributes 93.2 per cent of the welding current and 6.8 per cent of the gas flow. Current is regarded as the most important characteristic in both MIG and TIG welding [10]. MIG welding was used to join AA6061-T6 metal in various shielding gas compositions. The porosity ratio in the joint reduced as the Helium content is increased due to the strong heat conductivity and ionisation energy of the Helium gas. In macro analyses of welded joints employing shielding gas with helium contents of 75% and 100%, no pores were observed [11]. On high strength Al alloy joints generated by MIG welding and TIG welding, the impacts of continuous and pulsed current techniques were investigated [12].

The above survey shows that very limited work has been reported on Al alloy 1200. This has been the motivation behind carrying out the present investigative work.

2.   Materials and Methodology

The welding set up has a 400 amps capacity with the characteristics of flat V- I. For the alignment of the Al plates welding fixtures were used. For making the weld joints, a mechanised welding manipulator was used to ensure a consistent pre-set WS. The range of WS obtainable from this system are 0-50 cm per minute.

40 pieces were cut with the help of band saw machine for the 20 joints as shown in Fig. 2. Table 1 shows input parameters and their respective ranges. A wire of Al 4043 is used as a filler material of diameter 1.2mm. Argon is also used as the shielding gas. The flow rate of the gas was 15lpm.

Fig. 2. Welded specimens.

Table 1. Input parameters with their respective values.

S. No.	Input Parameter	Unit	Symbols	Levels		
				-1	0	-1
1	WFR	m/min	A	3	4	5
2	WS	cm/min	B	40	45	50
3	V	V	C	20	22	24

All the 20 welds were then prepared for bead geometry investigations by using standard polishing techniques involving coarse, fine and ultra-fine polishing on rotary disc apparatus. These pieces were etched with Keller's. The etched specimen is shown in Fig. 3. This etched sample is further used to calculate the bead parameters.

Fig. 3. Weld test piece (Etched specimen).

3. Developing the design matrix observation table

DOE method was used to generate a three-factor, three-level matrix with a total of 20 runs using the face centered technique. The prepared specimens after etching were subjected to measurement of BW, HOR and DOP. The input parameters are selected on the basis of the past literature survey and some test runs conducted on the material. The input parameters with the measured values of these three response parameters are shown in observation table 2.

Table 2. Observation Table.

Std	Run	WFR m/min	WS cm/min	Voltage V	Response 1 BW mm	Response 2 HOR mm	Response 3 DOP mm
17	1	0	0	0	7.92	1.88	1.66
6	2	1	-1	1	8.77	2.01	2.30
20	3	0	0	0	8.12	1.89	3.27
14	4	0	0	1	7.73	2.17	1.81
4	5	1	1	-1	7.31	2.22	2.24
12	6	0	1	0	8.80	2.23	2.07
11	7	0	-1	0	8.58	1.95	1.94
5	8	-1	-1	1	5.81	1.95	0.95
7	9	-1	1	1	7.52	2.04	1.19

18	10	0	0	0	6.82	1.96	1.95
3	11	-1	1	-1	2.90	1.63	0.61
19	12	0	0	0	8.01	1.94	2.83
10	13	1	0	0	7.32	2.46	2.16
1	14	-1	-1	-1	2.90	1.64	0.53
2	15	1	-1	-1	7.23	2.04	3.84
9	16	-1	0	0	2.65	1.54	0.33
15	17	0	0	0	6.32	1.46	1.75
13	18	0	0	-1	5.43	1.94	1.82
16	19	0	0	0	8.04	2.09	1.69
8	20	1	1	1	10.65	2.67	3.86

4. Results

4.1 Developing Mathematical model

Following are the mathematical equations created with the help DOE software to express the quadratic relationships of the input and output parameters. These equations also express direct and interaction effects :

$$HOR = 1.93 + 0.2606A + 0.1182B + 0.1375C \qquad (1)$$

$$DOP = 2.01 + 1.08A + 0.1071C - 0.1147AC + 0.4155BC - 0.4897A^2 + 0.2718B^2 \qquad (2)$$

$$BW = 79.63 + 38.04A + 1.52B + 21.62C + 0.8732AC + 1.54BC + 11.27A^2 + 7.81B^2 + 0.5076C^2 (3)$$

4.2 Testing the significance of the developed models

The developed models were then tested for their adequacy by ANOVA technique and the findings are represented in table 3. In all three models, the calculated value of F-ratio is found to be greater than its tabulated value, as a result, all of the models are suitable.

Table 3. ANOVA Results

S. No.	Response	Sum of Square	df	Mean Square	F-Value	p-Value	R^2	Adequate
1	BW	79.63	9	8.85	18.75	<0.0001	0.9441	Yes
2	HOR	1.19	9	0.1327	3.22	0.0414	0.7434	Yes
3	DOP	13.99	9	1.55	3.65	0.0280	0.7665	Yes

4.3 Direct effects of the input parameters on bead geometry

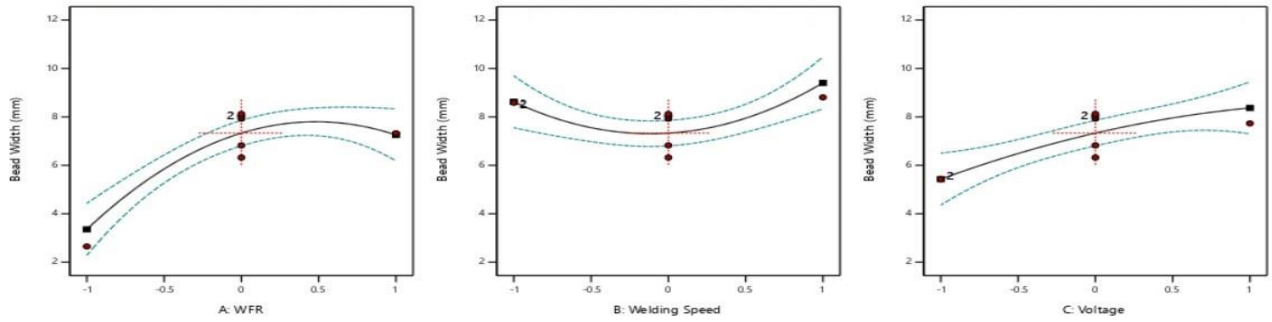### 4.3.1 Direct effects of WFR, WS and V on BW

Fig. 4. Direct effect of input parameters on BW.

WFR has a positive effect on BW. WS has initially negative, then positive effect on BW. V has a positive effect on BW, as shown in Fig. 4. The probable reason for these trends is that as WFR increases, the amount of weld current increases as well, resulting in more filler metal melting and spreading over a larger area, resulting in an increase in width. With the increase in WS, the heat input per unit weld decreases and less time is available for the filler wire to mix with base metal resulting in the lesser spread of filler on the base metal surface. V has a strong positive effect on bead geometry, which could be related to the fact that as V increases, the overall arc energy also increases, and the weld bead redistributes itself as the arc spreads wider, resulting in a wider bead.

4.3.2 Direct effects of WFR, WS and V on HOR
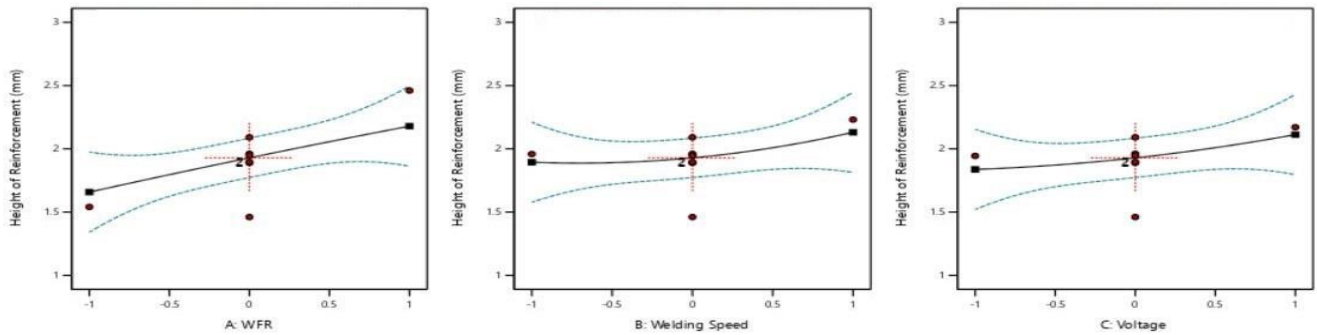
Fig. 5. Direct impacts on HOR.

According to Fig. 5., WFR has a positive, WS has a nominal positive effect and V has a slight positive effect on HOR. The most probable explanation for these trends is that when WFR increases, the amount of weld current also increases, resulting in increased melting of filler metal, which produces an increase in HOR. The HOR increases as the WS increases. This is most likely because as the speed increases, metal does not have the opportunity to enter the weld and instead sits on the base plate, resulting in an increase in the HOR.

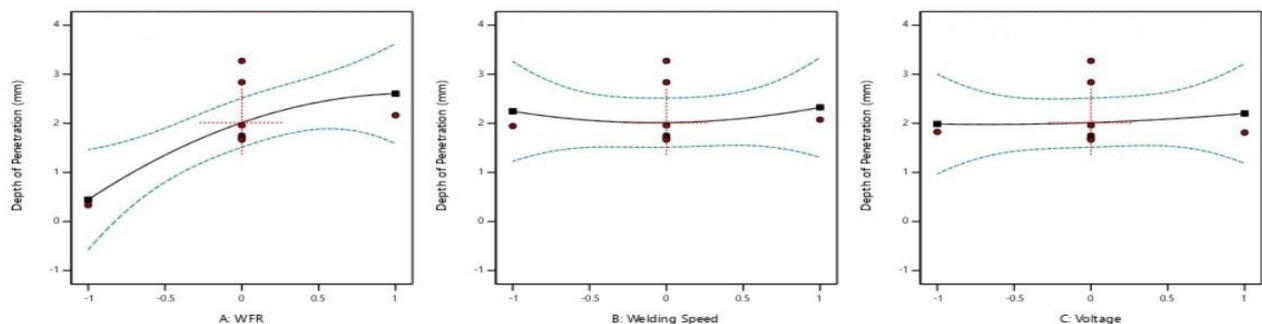### 4.3.3 Direct impacts of WFR, WS and V on DOP

Fig. 6. Direct effects on DOP.

From Fig. 6., it can be clearly seen that WFR has a positive effect on DOP as with the increase in WFR, the amount of heat input into the weld increases and the arc digging force also increases giving rise to a deeper weld. WS is found to have a slight decreasing effect as with the increase in WS, the heat input into the weld decreases resulting in less molten base metal and hence less DOP. V is found to have a slight positive effect on DOP as with the increase in V, the total heat input into the weld also increases thereby increasing the DOP.

4.4 Interactive effects of the input parameters on bead geometry

4.4.1 Interactive impacts of WS, WFR and V on BW

Interaction effects of WS, WFR and V on BW are shown as surface plots in Fig. 7-9.

It is evident that WS has initially negative and then positive effect on BW. The initial negative effect can be attributed to the fact that with the increase in WS the deposited metal does not get an opportunity to spread. However, the positive effect can be explained as the dominating interaction and positive effects of V and WS. WFR has found to have a positive effect on BW in all the cases which is quite logical because with the increase in WFR heat input increases resulting in more filler metal melting which thus gets an opportunity to spread over a wider area, increasing the BW. V has also been found to have a positive effect on BW as at increased V the arc line also increases as a result, the arc spreads wider, redistributing the molten metal across a larger width.
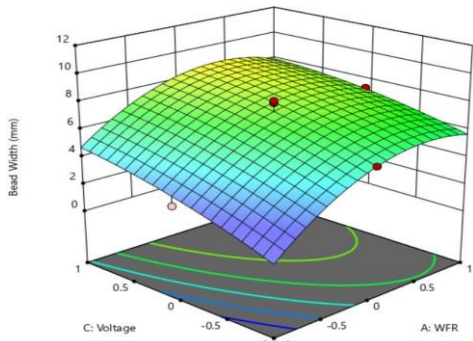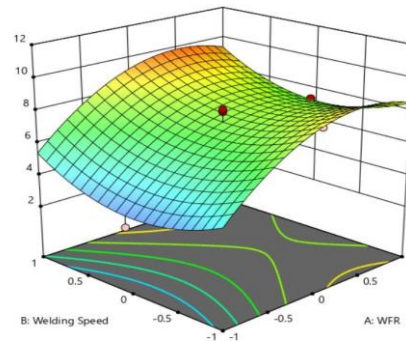

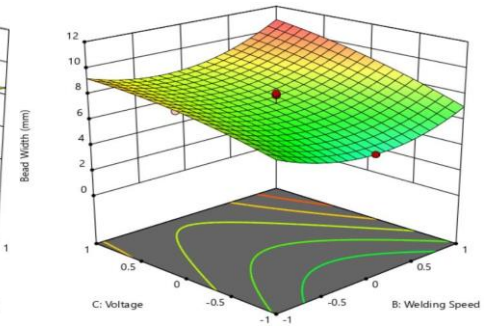**Fig. 7.** Impacts of V and WFR on BW   **Fig. 8.** Impacts of WS and WFR on BW**.**   **Fig. 9** Impacts of V and WS on BW.

4.4.2 Interactive effects of WS, WFR and V on HOR

Interactive impacts of WS, WFR and V on HOR are shown as surface plots in figure 10-12.

It is clear from the graph that the WS has a positive effect on HOR. The possible reason could be that with the increase in WS the deposition of the metal on the base metal is superficial and it does not plunge into the pool thereby slightly increasing the HOR. The WFR has a positive effect on HOR because of a larger amount of filler metal deposition due to more melting of the same. V however is found to have a slight positive effect on HOR which is in contradiction to normal trend which is positive. The probable reason for this anomaly could be the presence of dominating positive effects of other interacting factors.
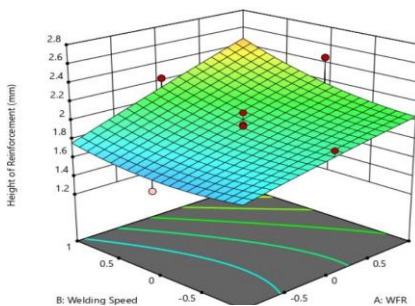

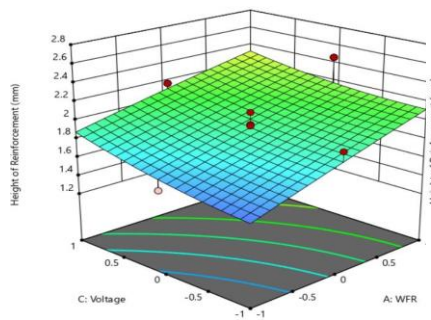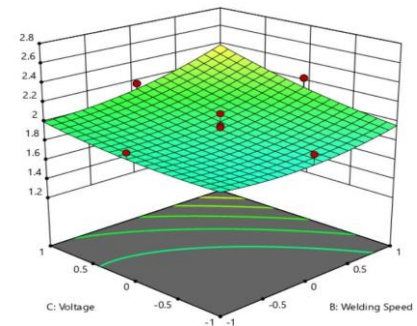**Fig. 10**. Impacts of WS and WFR on HOR.   **Fig.11.** Impacts of WFR and V on H.   **Fig.12.** Impacts of WS and V on HOR

5.4.3 Interactive effects of WS, WFR and V on DOP

Interactive impacts of WS, WFR and V on DOP are shown as surface plots in figure 13-15.

It can be clearly seen that WS has a slight negative effect on DOP. The possible reason could be the reduced heat input into the weld at higher weld speeds. WFR has a significant positive effect on DOP because of more heat input and more digging effect of the arc at higher WFR's. The V has a slight positive effect on DOP as with the increase in V, the total heat input into the weld also increases thereby increasing the DOP.
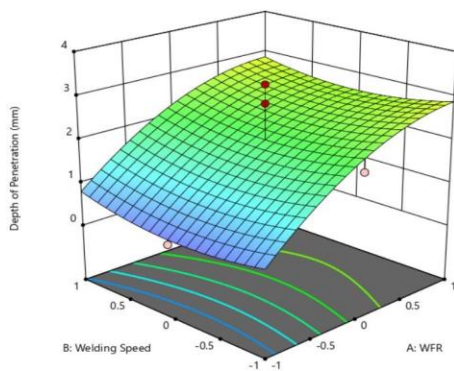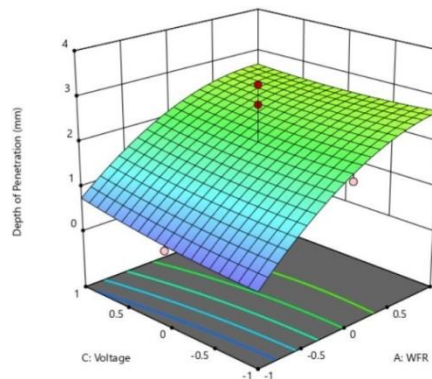

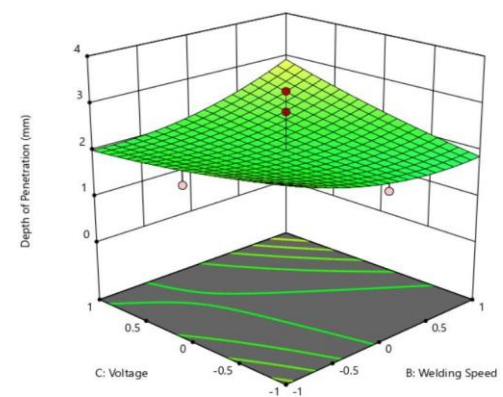**Fig. 13.** Impacts of WS and WFR on DOP   **Fig. 14.** Impacts of WFR and V on DOP   **Fig. 15**. Impacts of WS and V on DOP.

5. Conclusion

The following conclusion can be drawn from the experimentation:

- WFR and V are found to have a positive effect on BW. WS however has a negative first and then positive effect on BW.
- All three parameters are found to have a positive effect on HOR. WFR has the most dominating effect followed by WS and then V.
- WFR has a significantly positive effect on DOP, followed by V. WS however has a slightly negative effect on DOP.
- The optimum parameters for achieving maximum penetration of 3.39 mm are; WS=40 cm/min, V=20 V and WFR=5 m/min.
- The optimum parameters for achieving a maximum BW of 10.50 mm are; WS=50 cm/min, voltage=24 V and WFR=7.0 m/min.
- The optimum parameters for achieving a minimum HOR of 2.06 mm are; WS=40 cm/min, V=20V and WFR =3 m/min.

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