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RESEARCH ARTICLE

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Development of Mathematical Models for Prediction of Weld Bead Geometry Parameters of Gas Metal Arc Welded Joints of AA7020

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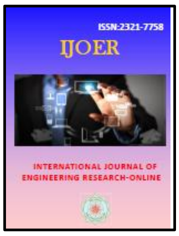

ABSTRACT

Gas Metal Arc welding process aims to produce welded joint with the excellent mechanical properties with minimum distortion and desired weld bead parameters. In welding, input process parameters decides the quality of weld joint. Manufacturer are facing problem of controlling the process input parameters to obtain a good welded joint with the bead geometry. Prediction of weld bead geometry play very important role in determining the quality of weld. This paper aims at developing the mathematical models to predict the weld bead geometry of gas metal arc welded joints of Aluminium Alloy 7020 using response surface method.

1. INTRODUCTION

In arc welding, the change in welding parameters changes the heat input which affects the quality and metallurgical properties of the weld. The high heat input causes welding defects like porosity, distortion; grains gap variations, buckling, etc. Also, the developments of thermal residual stress are based on thermal cycle. Therefore, it is very important to control the welding parameters for obtaining weld bead geometry [1]. Gas metal arc welding (GMAW) is used to join a wide range of materials and therefore plays a critically important role in many industry sectors. Welding is particularly important in heavy industry, which includes farming equipment and machinery, process equipment for manufacturing and mining, and infrastructure for petroleum refining and distribution. During the welding process, number of input process parameters involves which decides the quality of welded joints. To get the desired weld quality in GMAW process, it is essential to know interrelationships between input and output process parameters.

The prediction and optimization of process parameters is an important aspect in welding process. Therefore, the mathematical model that predict and control the bead geometry require to be developed which plays an important role in determining mechanical properties [2]. This paper aims at developing the mathematical models to predict the weld bead geometry of gas metal arc welded joints of Aluminium Alloy (AA) 7020 using response surface method.

2. LITERATURE REVIEW

The selection of appropriate set of welding parameters become one of the most important tasks in welding process for obtaining optimal weld bead geometry. The mathematical models that predict and thereby control the weld bead are required to be developed. Developing the mathematical models is not an easy task because there are some unknown nonlinear process parameters. Therefore, it is better to solve this problem by experimental models like multiple regression analysis (MRA) which is utilized to establish the empirical models for various welding processes [3]. It is essential to control shape of weld bead geometry which plays an important role in determining mechanical properties as it is affected by weld bead geometry shape. Therefore, proper selection of process parameter is necessary. It is not easy task to developed mathematical models which gives relationship between input and output process parameters of GMAW process because there were some unknown nonlinear process parameters [4]. Therefore, it is better to solve this problem by experimental models.

One of the experimental models was a multiple regression technique that was utilized to establish the empirical models for various welding processes [5]. Datta *et al* [6] proposed multiple regression models for predicting the bead geometry volume of Submerge Arc Welding (SAW) process. Gunaraj *et al* [7-8] developed mathematical models using the five-level factorial techniques for prediction and optimization of weld bead for the SAW process. An intelligent system for GMAW process based on multiple regressions and neural network were developed by Kim *et al* [9]. Li *et al* [10] studied the non-linear relationship between the geometry variables and process parameters of SAW process using Self-Adaptive Offset Network (SAON). Process parameters and bead geometry relationship for Tungsten Inert Gas (TIG) welding process using a back propagation neural network investigated by Tang et al [11].

Increasing use is made of aluminium and its alloys, which is mainly due to its low weight/strength ratio, and its high resistance to corrosion and precipitation hardening, discovered by accident at the beginning of the century by Alfred Wilm. Medium strength 7XXX aluminium alloys are widely used as welded structures and in transportation. The applications of these alloys are limited by the behaviour of the welded joints. Selection of this alloy is influenced by its applicability to land transport and being a high productivity sector, it is perhaps one of the most resistant to applying this light alloy to its designs, which is understandable due to the myth that 'aluminium cannot be welded'. Therefore, considering the quality required in this sector, it was decided to carry out a study of medium strength AA7020 [12].

Chemical compositions of the base metal AA7020 T6 plate and the Al-Mg alloy known as AA5356 as filler metal, in the form of 1.2 mm diameter wire is also shown in Table 1.

TABLE 1 CHEMICAL COMPOSITION OF AA7020 AND AA5356

Chemical composition (%)								
	Si	**Fe**	**Cu**	**Mn**	**Mg**	**Zn**	**Ti**	**Al**
AA 7020	0.298	0.35	0.10	0.25	1.30	4.70	0.08	The rest
AA 5356	Max. 0.25	0.40	0.10	0.15	5.0	Max 0.10	0.10	The rest

3. EXPERMENTATION

A proper planned procedure is required to develop the mathematical models which predict and control the bead geometry parameters for GMAW process includes the following steps [13]:

1. Identification of process parameters and their limits.
2. Development of design matrix and conducting the experiments as per design matrix.
3. Recording the responses.
4. Developing the mathematical models.
5. Calculating the coefficients of the polynomials and checking the adequacy of the models developed.
6. Arriving at the final mathematical models.

3.1 ***Identification of Process Parameters and their Limits:*** The independently controllable process parameters were identified: they are welding voltage, welding current, feed rate and gas flow rate and their working ranges are 16-36V, 40-300A, 3-5m/min and 5-25lit/min respectively. The upper limits of a factor are coded as +2 and the lower limit as -2. The coded values for intermediate values were calculated from the following relationship:

$X_i = 2[2X-(X_{max} + X_{min})] / [X_{max} - X_{min}]$

Where, X_i is the required coded values of the variable X;

X is any value of the variable from X_{min} to X_{max};

X_{min} is the lower level of the variable and

X_{max} is the upper level of the variable.

The process parameters levels with their units and notations are given in Table 2.

TABLE 2 WELDING PROCESS PARAMETERS AND THEIR LEVELS

Parameters	**Parameters levels**				
	-2	**-1**	**0**	**1**	**2**
Voltage V (Volt)	16	21	26	31	36
Current I (Amp.)	40	105	170	235	300
Feed Rate S (m/min.)	3	3.5	4	4.5	5
Gas Flow Rate G (lit/min)	5	10	15	20	25

3.2 Development of Design Matrix and Conducting the Experiments as Per Design Matrix: To evaluate the bead geometry, the test plates of Aluminium Alloy 7020 having dimension of 125 mm × 100 mm× 2.5 mm with a single V groove of 30° on 100 mm side of the plate are prepared. The land and root gap of 2 mm are provided between the two workpieces. The Central Composite Design (CCD) matrix [14] is used for experimentation which consists of fraction points, star points and center points which depend on number input welding parameters (k). The CCD matrix consists of sixteen factorial points (2k), where 2 is the number of levels, eight star points (2k) and four center points (k). The first 16 rows correspond to factorial points; the rows from 17 to 24 correspond to star points and last 4 rows from 25 to 28 correspond to center points. Hence, final experimental design consists of 28 points as given in Table 3[A & B] and the welded samples are shown in Fig. 1.

TABLE 3 [A] CENTRAL COMPOSITE DESIGN MATRIX (CODED)

Expt. No.	Voltage V (Volt)	Current I (Amp.)	Feed Rate S (m/min.)	Gas Flow Rate G (lit/min)
R1	-1	-1	-1	-1
R2	-1	-1	-1	1
R3	-1	-1	1	-1
R4	-1	-1	1	1
R5	-1	1	-1	-1
R6	-1	1	-1	1
R7	-1	1	1	-1
R8	-1	1	1	1
R9	1	-1	-1	-1
R10	1	-1	-1	1
R11	1	-1	1	-1
R12	1	-1	1	1
R13	1	1	-1	-1
R14	1	1	-1	1
R15	1	1	1	-1
R16	1	1	1	1
R17	-2	0	0	0
R18	2	0	0	0
R19	0	-2	0	0
R20	0	2	0	0
R21	0	0	-2	0
R22	0	0	2	0
R23	0	0	0	-2
R24	0	0	0	2
R25	0	0	0	0
R26	0	0	0	0
R27	0	0	0	0
R28	0	0	0	0

TABLE 3 [B] CENTRAL COMPOSITE DESIGN MATRIX (UNCODED)

Expt. No.	Voltage V (Volt)	Current I (Amp.)	Feed Rate S (m/min.)	Gas Flow Rate G (lit/min)
R1	21	105	3.5	10
R2	21	105	3.5	20
R3	21	105	4.5	10
R4	21	105	4.5	20
R5	21	235	3.5	10
R6	21	235	3.5	20
R7	21	235	4.5	10
R8	21	235	4.5	20
R9	31	105	4.5	10
R10	31	105	4.5	20
R11	31	105	4.5	10
R12	31	105	4.5	20
R13	31	235	3.5	10
R14	31	235	3.5	20
R15	31	235	4.5	10
R16	31	235	4.5	20
R17	16	170	4	15
R18	36	170	4	15
R19	26	40	4	15
R20	26	300	4	15
R21	26	170	3	15
R22	26	170	5	15
R23	26	170	4	5
R24	26	170	4	25
R25	26	170	4	15
R26	26	170	4	15
R27	26	170	4	15
R28	26	170	4	15

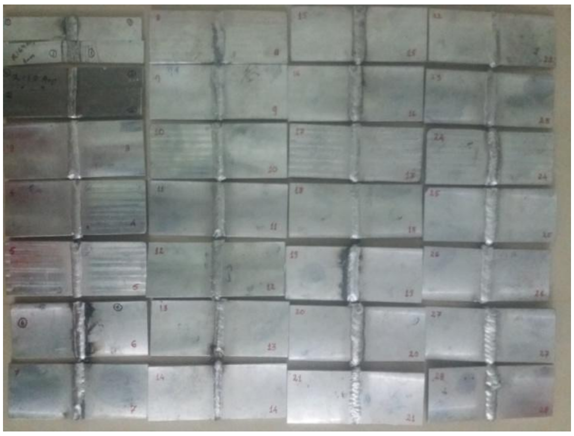

Fig. 1.Welded samples

After welding, each of these samples is cut for the measurement of bead geometry parameters. The samples are prepared as per American Society of Testing Materials (ASTM) E3-11 standards. The bead geometry is revealed by metallurgical polishing process as per ASTM standard for measuring the BH, BW and BP. The weld bead geometry parameters are measured at three different places and the average values are calculated.

3.3. Record the Responses: Twenty eight experimental results were conducted as per the CCD matrix at random to avoid any symmetric error creeping into the system. The weld bead profiles were traced by using an optical microscope and the bead geometry dimensions like bead height, bead width and bead penetration were measured. The measured values are given in the Table 4.

TABLE 4 MEASURED VALUES OF WELD BEAD PARAMETERS

Measured Bead Geometry Parameters			
Expt. No.	**BH** (mm)	**BP** (mm)	**BW** (mm)
R1	1.120	2.340	4.232
R2	1.250	2.325	3.520
R3	1.515	2.492	4.560
R4	1.670	2.481	5.150
R5	1.650	2.485	5.225
R6	1.920	2.510	5.125
R7	2.152	2.623	5.100
R8	2.112	2.600	5.213
R9	1.952	2.425	4.892
R10	1.838	2.484	4.896
R11	1.821	2.515	5.215
R12	1.732	2.525	5.180
R13	1.835	2.524	5.320
R14	1.935	2.610	5.225
R15	2.252	2.492	4.928
R16	2.214	2.498	4.980
R17	2.018	2.480	5.060
R18	3.010	2.482	5.982
R19	3.184	2.510	6.180
R20	2.984	2.612	5.990
R21	2.986	2.594	6.020
R22	3.218	2.624	6.021
R23	3.918	2.596	6.142
R24	3.028	2.610	6.122
R25	2.981	2.520	6.068
R26	2.994	2.542	6.234
R27	2.020	2.480	6.214
R28	2.128	2.446	5.982

3.4. Developing the Mathematical Model: For modeling and analysis of particular problem, a collection of mathematical and statistical techniques called Response surface methodology (RSM) is most useful. In RSM, response of interest is influenced by several variables and the objective is to optimize this response [15]. The purpose of choosing RSM model is to establish a relationship between input and output parameters that can used to predicts response values for given setting of control parameters.

In the present work, RSM's central composite design matrix consisting of twenty eight experiments are conducted to develop the mathematical models showing the relationships between the response / output parameters Y (BH, BW and BP) and the welding input process parameters (V, I, S and G). The second order response surface model for the four selected parameters is given by the equation [16]:

$$Y = b_0 + \sum_{i=1}^{4} b_i x_i + \sum_{i=1}^{4} b_{ii} x_i^2 + \sum_{\substack{i,j=1 \\ j \neq i}}^{4} b_{ij} x_i x_j$$

The second order response surface model for the four selected parameters is given by the equation [12]. Second order response surface model could be expressed as;

$$Y = b_0 + b_1S + b_2V + b_3F + b_4G + b_{11}S^2 + b_{22}V^2 + b_{33}F^2 + b_{44}G^2 + b_{12}SV + b_{13}SF + b_{14}SG + b_{23}VF + b_{24}VG + b_{34}FG$$

Where, b_0 is free term coefficient, b_1, b_2, b_3 and b_4 are Linear coefficients, b_{11}, b_{22}, b_{33} and b_{44} are quadratic coefficients and b_{12}, b_{13}, b_{14}, b_{23}, b_{24}, b_{34} are interaction coefficients.

3.5 Calculating the Coefficients of the Polynomials and Checking the Adequacy of the Models Developed: The values of significant coefficients for full and residual models for different responses were calculated with the help of SYSTAT13 statistical software [17]. Adequacy of the models was then tested by analysis of variance technique (ANOVA). It is found that the full model is better for bead penetration than the half models because multiple R, multiple R^2, adjustable square R are maximum, F-ratio is more in ANOVA table and standard error is minimum.

3.6 Arriving the Final Mathematical Models: The final mathematical models developed are given below. The process control parameters are in their uncoded form.

$$B.H. = -12.568 + 1.009V - 6.016I + 1.637S - 0.067G - 0.006V^2 - 0.000I^2 - 0.002S^2 + 0.004G^2 - 0.001VI + 0.009IS + 0.000IG - 0.123VS - 0.005SG - 0.002VG$$

$$B.W. = 0.149 + 0.142V + 0.003I + 0.135S - 0.017G - 0.001V^2 + 0.000I^2 + 0.067S^2 + 0.001G^2 - 0.000VI + 0.000IS + 0.000IG - 0.024VS - 0.003SG - 0.001VG$$

$$B.P. = -30.747 + 1.412V + 0.030I + 7.894S - 0.036G - 0.012V^2 - 0.000I^2 - 0.655S^2 - 0.005G^2 - 0.001VI + 0.001IS + 0.000IG - 0.146VS + 0.051SG - 0.001VG$$

4. RESULTS and DISCUSSION

The mathematical models so obtained can be used to study the effects of process parameters on weld bead geometry and are discussed below.

1. *Interaction effect of V and I on BP:* To provide good weld strength, Bead Penetration (BP) is required to be maximum. Therefore, we need to study the effects of process parameters on it. Following fig. 2 shows that increase in voltage from 10 to 30 keeping current below 200, BP increases. Beyond 32 volts BP is decreasing. While BP is increasing, if voltage is kept constant (below 30 volts) and current is raised. It will be interesting to know that if voltage is kept higher than 30, rise in current will have no effect on BP. Therefore it is desirable to keep voltage below 30. Further if we draw a line joining highest values of current and voltage (diagonal from top-left to downright) we are getting maximum BP. That means either voltage or current has to be higher than another and must follow the diagonal. In other words, going away from the centre of the diagonal we can have maximum bead penetration.

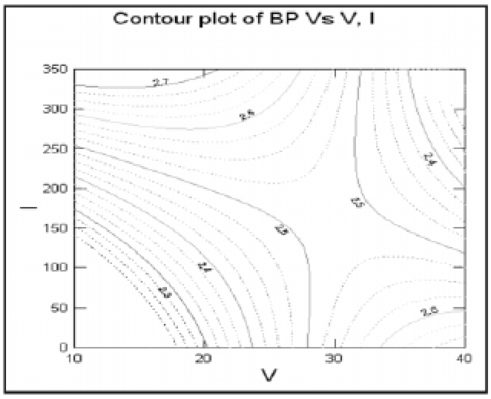

Fig. 2. Contour Plot (BOVs V,I)

2. *Interaction effect of I and S on BP:* It is seen from the Figure **3** that if current is increased from 150 to 300 amps then BP will increase from 2.5 to 2.6 at speed of 4. But here it will be interesting to know that same maximum penetration is obtained at current sufficiently below 50 and with the speed of 2.5. If at the same current, speed is increased then BP reduce first up to 4 and then again rise. Speed has to be kept below 3.5 as in this case.

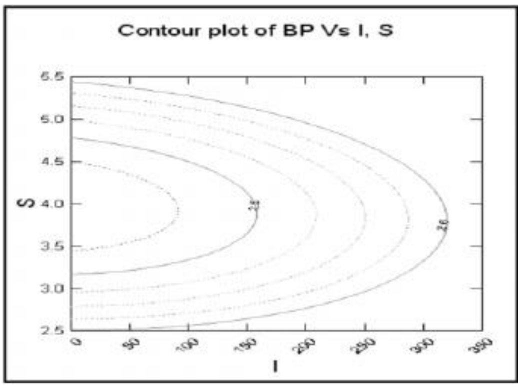

Fig. 3

3. *Interaction effects of S and G on BP:* From the Figure 4 it can be seen that maximum bead penetration will be obtained at speed below 3. From gas speed 10.3 to 20 and welding speed below 3 and more than 5.2; BH value is obtaining minimum which is desirable.

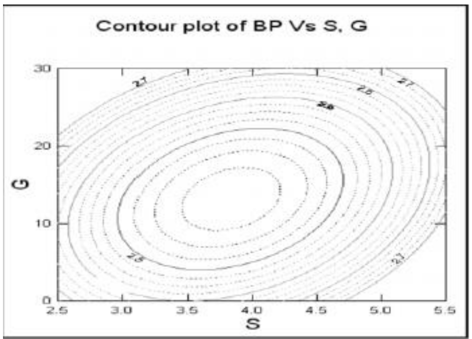

Fig. 4

4. *Interaction effect of V and I on BW:* This interaction plots (Figure 5) shows that current is having almost no effect on BW as seen from approx. straight vertical lines. While if voltage is kept below 20 or more than 35 with current below 75 will give minimum BW which our objective. But as said earlier that for maximizing BP we need to increase voltage than 35, therefore here it will be adequate to have voltage more than 35 rather lower than 20; so both objectives will be full-filled.

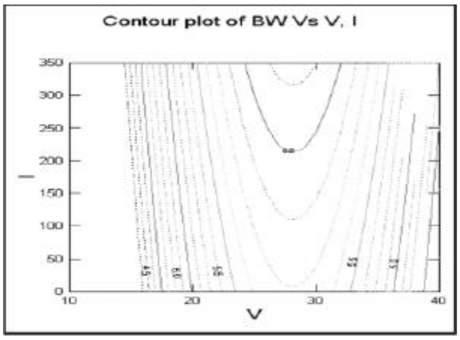

Fig. 5

5. *Interaction effects of I and S on BW:* This Figure 6 also results into desirable parameters as required in previous objectives. Here current will be less effective than that of Speed. For minimum bead width speed can be kept below 3.5 or above 4.75 at current below 60.

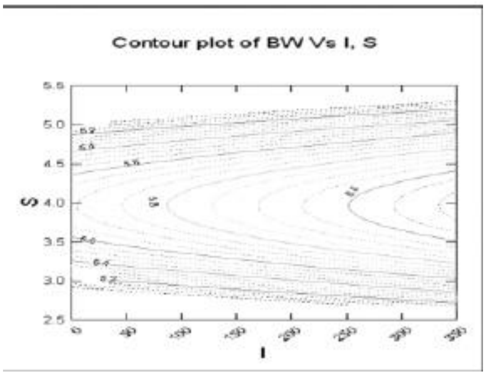

Fig. 6

6. *Interaction effect of V and I on BH:* As seen from the contour plot in figure 7, voltage has dual effect on BH and current has positive effect. Voltage between 25 to 32 volts and current more than 200 gives maximum BH, while to optimize welding process parameters it is desirable to reduce BH as to reduce net volume of weld bead. Therefore, to reduce BH; voltage has to be kept below 20 volts or more than 35 volts where we get 1.5 mm BH on the condition that current will remain constant. It is seen that current is not having sharp effect like voltage on BH, therefore, voltage must be deciding factor for BH.

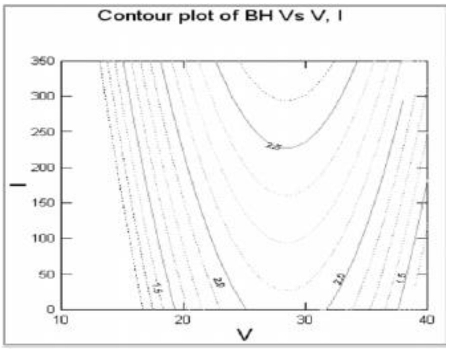

Fig. 7

7. *Interaction effect of G and S on BH:* As shown in graph 7 above appearing word like 'x' has a complimentary effect. As speed (S) starts increasing from 2.5 to 4.6, BH is increasing and then it starts decreasing. But comparatively it has less effect than that of 'G' gas speed. From 10.3 to 20 gas speed and welding speed below 3 and more than 5.2; BH value is obtaining minimum which is desirable.

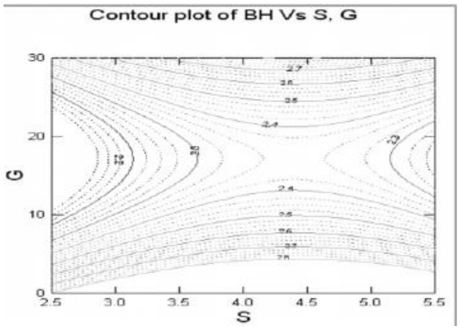

Fig. 7

8. *Interaction effect of I and S on BH:* Current has a positive effect, its raise constantly increasing BH value. As shown in figure 8, for minimum BH value current must be as less as possible and speed can be kept between ranges as it has little effect. Minimum BH is obtained at speed below 3.2 and current below 60.

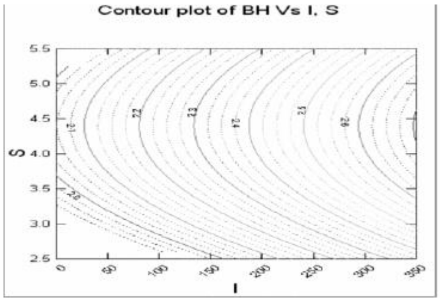

Fig. 8

5. Conclusion

Based on the detailed study of Gas Metal Arc welded joints of AA7020, mathematical models are developed to predict the weld bead geometry parameters and analysis the following conclusions are drawn,

- Mathematical models for bead geometry parameters are developed using response surface methodology and the models are tested using analysis of variance.
- Mathematical models easily predict dimensions bead geometry parameters (bead height, bead width and bead penetration) can give direct values without going for long design process, thus it saves designer's time and efforts.
- In GMAW process, essential interrelationships between input process parameters and output / responses are shown by the developed model.

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