Modelling and Simulation of Austenitic Stainless Steel Claddings deposited by GMAW

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Abstract- This paper presents the development of mathematical models for austenitic stainless steel (316 L) cladding deposited by gas metal arc welding (GMAW).The weld quality depends on the welding process parameters like welding voltage, welding current, welding speed, bead offset, etc. The heat input to the cladding process influences bead geometry, composition, ferrite content, microstructure and corrosion properties. The bead geometry influences the number of welding passes required to deposit the given surface area. The percentage of offset influences the dilution of filler metal and thickness of the deposited layer. Dilution reduces the alloy content of the deposited later and degrades corrosion resistance properties. The simulation results shows that the parameters wire feed rate and welding speed has significant impact on the bead width and height of reinforcement.

Key words- Weld bead geometry, Austenitic stainless steel, Response Surface, offset, bead width, height of reinforcement

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1 INTRODUCTION

THE engineering applications require high strength with inherent corrosion resistance for long-term reliability and performance. Low carbon steel meets the requirements of the industrial applications but lacks on corrosion resistance. Cladding is one of the surface modification processes developed to impart corrosion resistance to low-carbon steel substrate. Cladding offers significant cost and energy savings over the conventional bulk material components. Claddings can be produced by using various techniques such as laser welding, tungsten inert gas (TIG) welding, metal inert gas welding (MIG), electron-beam welding (EBW), plasma arc welding (PAW), etc. [2-5] . Welding is a potential candidate for the cladding process because of the availability wide range of processes to cater the needs of the different industries. Cladding is based on the objective of matching the microstructure and composition of the deposit to that of the electrode [5, 6].

The GMAW process preferred because of its:

i) All position capability

ii) Absences of fluxes

iii) Cleanliness and ease of mechanization

iv) GMAW Suitable for both ferrous and nonferrous metals

v) High productivity

vi) Low cost

vii) High reliability

The heat input to the process alters the composition and microstructure of the deposit leading to the deterioration of corrosion properties [2, 5]. The relationship between the welding process parameters and the properties of the deposited layer is essential to maximize the durability of the components [10]. This relationship can be expressed by the mathematical model. The simulation of the welding cladding process using the models helps to understand the various welding processes were developed with the objective of matching the process parameters on the responses. The mathematical models can also be used to quantify the influence of the process parameters by analysing the sensitivity of the process parameter on the responses [7-11]. The weld cladding process is essentially a multi-objective, where it is desirable to maximize the bead dimensions like width.

This experimental study is carried out to develop mathematical models to predict bead geometry in stainless steel claddings deposited by GMAW process. The experiments were conducted based on the five - factor, five-level central composite rotatable design and the models were developed using regression analysis [3]. The adequacy and significance of the models were checked statistically. The

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validated models helps in predicting the responses as the function of input process parameters to achieve the desired weld bead geometry.

2 Experimental Procedure

The experimental setup consists of multi process arc welding machine (Lincoln Electric Invertec V350 PRO®) coupled with Wire feeder (LF-74) and Welding manipulator. Fixed torch and moving plate configuration were used for conducting the experiments. Filler material Austenitic stainless steel wire of 1.2 mm diameter (ER-316L) was used for the cladding. The mixture of 80% argon and 20% of CO_2 shielding gas was used. The test plates of Size 300 x 100 x 10 mm were cut from the IS-2062 mild steel as base plate.

Table 1 presents the chemical composition of the electrode and the base metal. The shielding gas mixture was supplied at a rate of 25 lit/min. Figure 2 shows the experimental setup. The experimental procedures followed for the development of mathematical models were presented in the following sections.

2.1 Identification of Process Parameters and their Responses

The chosen input process parameters were welding voltage (X1), wire feed rate (X2), welding speed (X3), nozzle-to-plate distance (X4) and pinch (X5). The chosen responses were weld bead width (W) and height of reinforcement (H).

2.2 Finding the working range of the process variables and coding

Trial runs were conducted by varying one of the process parameters at a time while keeping the rest of them at a constant value. The working range was established by in the absence of visible defects such as cracks and lack of fusion. The upper and lower limit of the working range was coded as +2 and −2, respectively. The intermediate values can be coded using the equation 1.

$$X_i = \frac{2[2X - (X_{\max} + X_{\min})]}{(X_{\max} - X_{\min})} \qquad (1)$$

Where *Xi* is the required coded value of a variable *X*, when *X* is any value of the variable from *X*min to *X*max;

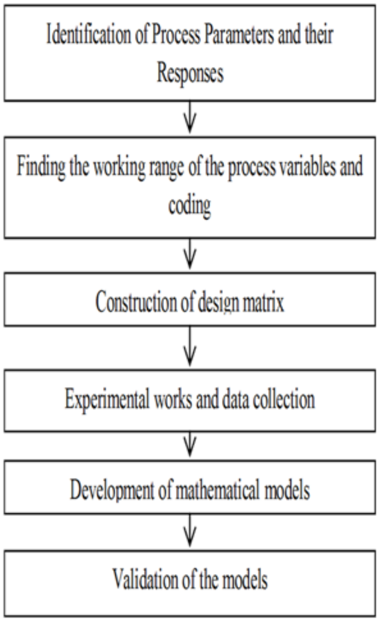

Fig. 1. Experimental design procedure

*X*max and *X*min are the maximum and minimum levels of the variables. The selected process variables and their upper and lower limits together with units are given in Table 2.

2.3 Construction of design matrix

The experimental data required for the development of simulation models for the GMAW process were collected from the experiments based on the central composite rotatable design. The design matrix consists of 2^5 (=32/2=16) factorial combinations with 10 star points and 6 center points. All welding variables at the intermediate (0) level constitute the center points while the combination of each welding variables at either its lowest value (−2) or its highest value (+2) with the other four variables at the intermediate levels

TABLE 1

CHEMICAL COMPOSITION OF ELECTRODE AND BASE METAL

Material	C	Si	Mn	P	S	Al	Cr	Fe	Ni
IS: 2062	0.175	0.287	1.05	0.029	0.017	0.0067	0.0910	98.33	~0.00
ER 316L	0.030	0.450	2.00	0.030	0.030	-	18.00	-	12.00

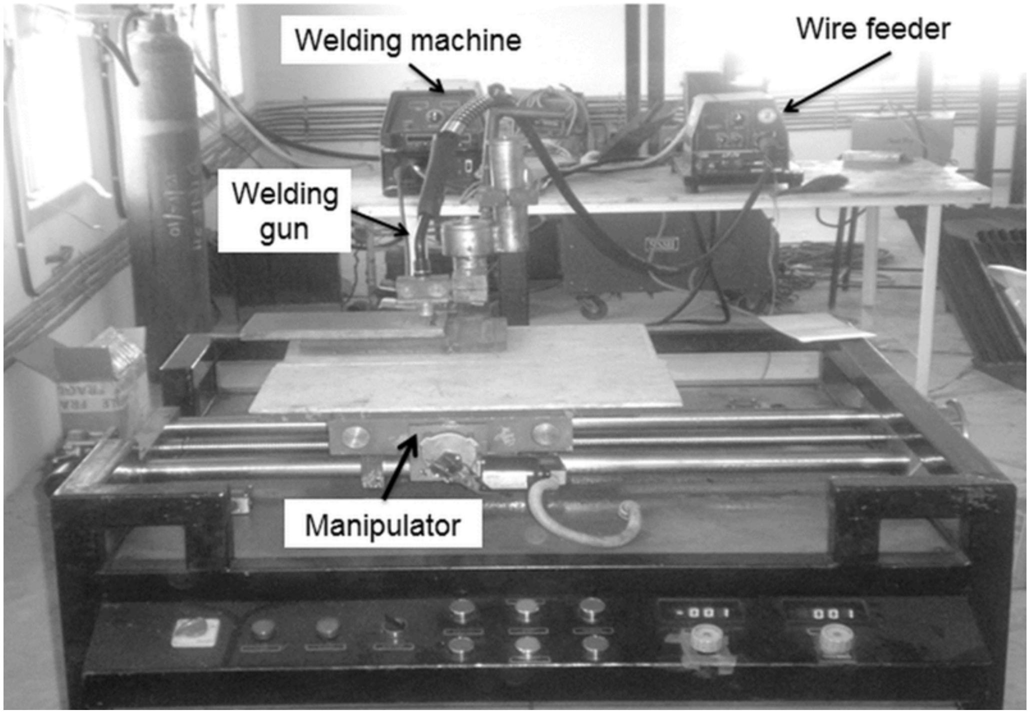

Fig. 2. Experimental Setup

TABLE 2
PROCESS PARAMETERS LEVELS AND CODING

Parameters	Units	-2	-1	0	1	2
Welding voltage	V	7	9	11	13	15
Wire feed rate	Inch/min	250	275	300	325	350
Welding speed	mm/min	120	140	160	180	200
NTPD	mm	15	17	19	21	23
Pinch	-	-10	-5	0	5	10

TABLE 3

DESIGN MATRIX WITH MEASURED RESPONSES

Trial No	Welding Voltage	Wire Feed Rate	Welding Speed	NTPD	Pinch	Responses	
						Height	Width
	X1	X2	X3	X4	X5	mm	mm
1	-1	-1	-1	-1	-1	25.595	8.115
2	-1	-1	-1	1	1	27.48	7.85
3	-1	-1	1	-1	1	21.785	7.49
4	-1	-1	1	1	-1	21.635	8.845
5	-1	1	-1	-1	1	29.05	8.86
6	-1	1	-1	1	-1	32.655	8.05
7	-1	1	1	-1	-1	24.94	7.835
8	-1	1	1	1	1	24.24	7.745
9	1	-1	-1	-1	1	26.055	7.385
10	1	-1	-1	1	-1	27.21	7.78
11	1	-1	1	-1	-1	22.52	7.93
12	1	-1	1	1	1	22.165	7.625
13	1	1	-1	-1	-1	28.325	8.9
14	1	1	-1	1	1	27.78	9.275
15	1	1	1	-1	1	22.6	8.235
16	1	1	1	1	-1	21.9	7.8
17	-2	0	0	0	0	21.83	7.495
18	2	0	0	0	0	23.695	8.27
19	0	-2	0	0	0	21.83	7.495
20	0	2	0	0	0	27.41	8.185
21	0	0	-2	0	0	32.715	8.815
22	0	0	2	0	0	20.345	7.525
23	0	0	0	-2	0	24.1	8.555
24	0	0	0	2	0	27.02	8.2
25	0	0	0	0	-2	25.055	8.28
26	0	0	0	0	2	25.52	7.75
27	0	0	0	0	0	24.28	8.72
28	0	0	0	0	0	24.095	8.225
29	0	0	0	0	0	24.71	8.49
30	0	0	0	0	0	23.42	8.81
31	0	0	0	0	0	23.625	8.36
32	0	0	0	0	0	24.81	8.92

constitute the star points. The experimental parameter combinations in coded form with measured responses were presented in the Table 3.

2.4 Experimental works and data collection

The experiments were conducted at Welding Research Center of Kumaraguru College of Technology, Coimbatore. The base plate cleaned thoroughly using the finest grade sand paper. The experimental combinations were selected from the Table 3 at random basis to introduce variance in the experimental settings error. At the end of each run, the plates were allowed to cool in open air. The settings of the five parameters were disturbed and reset for the next deposit.

The weld beads were sectioned perpendicular to its length and its two end faces were polished and etched with 5% initial solution. The bead profile was generated using reflective type optical profile projector with 10X magnification. Then the responses like reinforcement height (H) and bead width (W) were extracted from the weld bead profile. The Figure 3 shows the bead overlap specimen number 11 and 25.

2.5 Development of mathematical models

The response function represented the clad bead geometry with the process variables as its components and it is given by the equation (2).

$$Y = f\ (X_1, X_2, X_3, X_4, X_5) \qquad (2)$$

Where Y is the response variable, X_1, X_2, X_3, X_4 and X_5 are the process parameters.

The equation (3) presents the second-order response surface model of the five factors.

$$Y = \beta_0 + \sum_{i=1}^{5} \beta_i X_i + \sum_{i=1}^{5} \beta_{ii} X_i^2 + \sum_{\substack{i=1 \\ i<j}}^{5} \beta_{ij} X_i X_j \qquad (3)$$

Above the second-order response surface model equation can be represented by the following equation (4)

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 + \beta_{11} X_1^2 + \beta_{22} X_2^2 + \beta_{33} X_3^2 + \beta_{44} X_4^2 + \beta_{55} X_5^2 + \beta_{12} X_1 X_2 + \beta_{13} X_1 X_3 + \beta_{14} X_1 X_4 + \beta_{15} X_1 X_5 + \beta_{23} X_2 X_3 + \beta_{24} X_2 X_4 + \beta_{25} X_2 X_5 + \beta_{34} X_3 X_4 + \beta_{35} X_3 X_5 + \beta_{45} X_4 X_5 \qquad (4)$$

Where β_0 is the free term of the regression equation, the coefficients β_1, β_2, β_3, β_4 and β_5 are linear terms, the coefficients β_{11}, β_{22}, β_{33}, β_{44} and β_{55} quadratic terms, and the coefficients β_{12}, β_{13}, β_{14}, β_{15}, β_{23}, β_{24}, β_{25}, β_{34}, β_{35}, β_{45} are the interaction terms. The coefficients were calculated by the regression analysis. After the determination of the coefficients, the mathematical models were developed. The developed mathematical models with the coded form of welding parameters are given as follows.

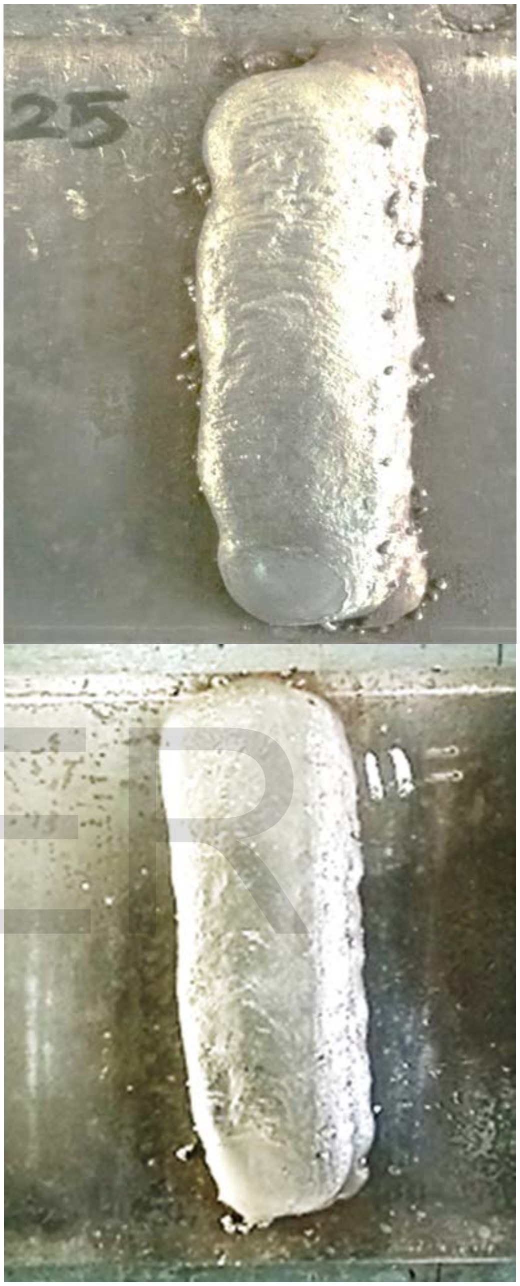

Fig. 3. weld bead specimen

Bead width (W) in mm

$$= 24.220 - 1.186X_1 + 2.331X_2 - 5.612X_3 + 0.816X_4 - 0.198X_5 + 0.693X_1^2 + 0.208X_2^2 + 2.118X_3^2 + 1.148X_4^2 + 0.876X_5^2 - 2.993X_1X_2 + 0.439X_1X_3 - 1.331X_1X_4 + 0.308X_1X_5 - 1.414X_2X_3 - 0.159X_2X_4 - 1.248X_2X_5 - 1.942X_3X_4 + 0.725X_3X_5 - 0.040X_4X_5 \qquad (5)$$

TABLE 4
STATISTICAL VALIDATION OF THE MODELS

Response	First order terms		Second order terms		Lack of Fit		Error terms		F - ratio*	R – ratio**	R Square	Adequacy of the model
	SS	**DF**	**SS**	**DF**	**SS**	**DF**	**SS**	**DF**				
W	4.148	5	27.894	15	4.124	6	1.577	5	2.179	41.783	0.979	Adequate
H	2.594	5	4.767	15	0.360	6	0.370	5	0.810	4.831	0.907	Adequate

SS – Sum of Squares, DF – Degree of Freedom,
F ratio = MS of lack of fit / MS of error term,
R ratio = MS of first order and second order term / MS of error terms,
* Critical value of F ratio $F_{(6, 5, 0.05)} = 4.95$, ** Critical value of R ratio $R_{(20, 5, 0.05)} = 4.56$

Height of Reinforcement (H), in mm

$$= 8.579 - 0.042X_1 + 0.451X_2 - 0.412X_3 - 0.012X_4 - 0.149X_5 - 0.209X_1^2 - 0.714X_2^2 - 0.384X_3^2 - 0.176X_4^2 - 0.539X_5^2 + 0.912X_1X_2 - 0.111X_1X_3 + 0.047X_1X_4 + 0.267X_1X_5 - 1.144X_2X_3 - 0.623X_2X_4 + 0.947X_2X_5 + 0.120X_3X_4 - 0.475X_3X_5 + 0.192X_4X_5 \quad (6)$$

2.6 Validation of the models

The adequacy of the developed model was tested using the analysis of variance technique. The criteria used to validate the models are the lack of fit F-ratio should be less than the critical value at a 5% level of significance. The adequacy of the models has been checked. The details of the statistical validation of the developed models were presented in the table IV. Both models were found to satisfy the adequacy requirements. The models can be used to predict the responses with reasonable accuracy.

3 RESULTS AND DISCUSSION

Experiments were conducted using GMAW to produce cladding of austenitic stainless steel material on the low carbon structural steel plate. From the experimental results a mathematical model was developed using regression models. The validity of these models was again tested by drawing scatter diagrams as shown in figure 4 and 5, which show the observed and predicted values of weld bead geometry and also the figure 6 and 7 shows the main effects of process parameters on the responses such as weld bead width and the height of reinforcement. Both Weld bead width and height of reinforcement increases with increase in wire feed rate.

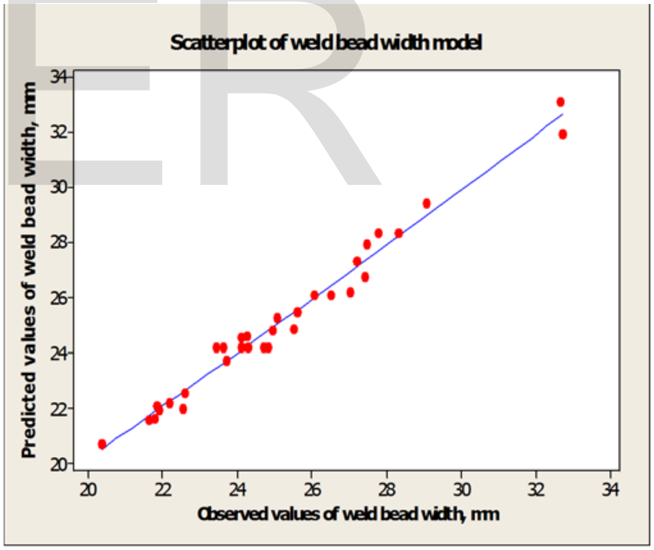

Fig. 4. Scatter diagram of weld bead width model

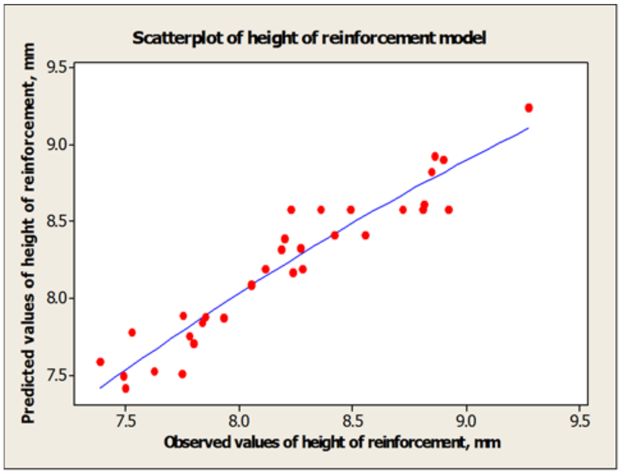

Fig. 5 Scatter diagram of height of reinforcement model

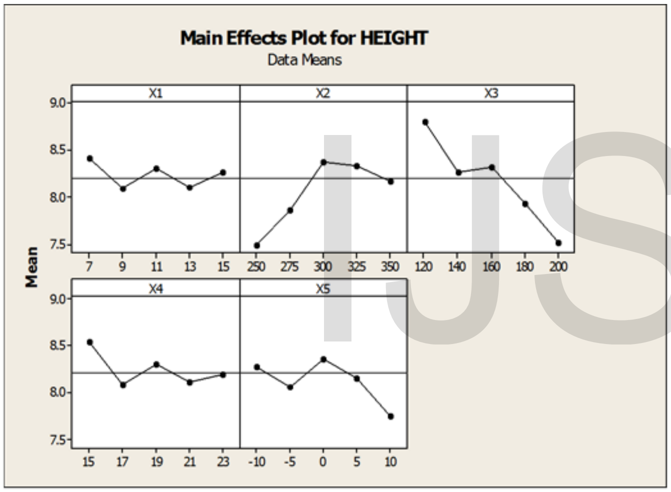

Fig. 6 Main effects plot for height of reinforcement

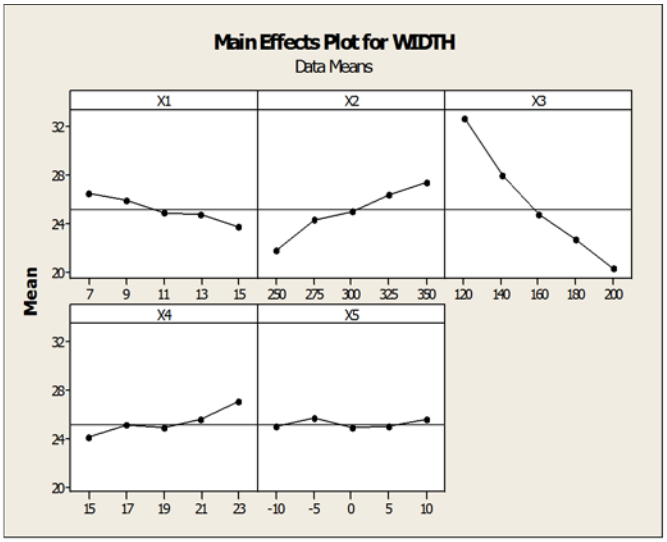

Fig. 7 main effects plot for weld bead width

4 CONCLUSION

A five-level, five-factor design matrix based on the central composite rotatable design technique was used for the development of mathematical models to predict the clad bead geometry for austenitic steel cladding deposited by GMAW. The predicted results using mathematical models are very close to the experimental results which are shown in the scatter plots. Weld bead width and height of reinforcement increase with increase in wire feed rate. Weld bead width and height of reinforcement decrease with the increase in welding speed. Weld bead width and height of reinforcement increase with increase in nozzle-to-plate distance. Height of reinforcement increases with the increase in the wire feed rate for all values of welding speed.

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