# Development of Mathematical Models to predict clad bead geometry deposited by GMAW in Stainless Steel Cladding

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## ABSTRACT

Weld Cladding is a process of depositing a thick layer of corrosion resistance material over carbon steel plate. The main problem faced in stainless steel cladding is the selection of optimum process parameters for achieving the required clad bead geometry. This paper highlights an experimental study carried out to develop mathematical models to predict clad bead geometry in Gas Metal Arc Welding (GMAW) process used in austenitic stainless steel cladding of low carbon structural steel plates. The experiments were conducted based on four-factor five level central composite rotatable design with full replications technique. The mathematical models was developed using multiple regression method.

**Keywords :** GMAW, Mathematical Model, Cladding, Austenitic Stainless Steel.

## INTRODUCTION

Corrosion is a problem which weakens the steel structure causing its failure. Though corrosion can not be eliminated fully, it can be reduced to certain extent. Corrosion resistance, protective layer is formed over the less corrosion-resistant substrate by a process called cladding. Cladding techniques are mainly employed to improve the service life of engineering components and to reduce their cost, either by rebuilding repeatedly or by fabricating in such a way as to produce a composite wall section, as in pressure vessels. In recent years, weld cladding processes have been developed rapidly and are now applied in numerous industries such industries as chemical and fertilizer plants, nuclear and steam power plants, food processing, petrochemical industries, and even in aircraft and missile components [2,11].

Various welding processes employed for cladding are shielded metal arc welding, submerged arc welding, gas tungsten arc welding, plasma arc welding, gas metal arc welding, flux cored arc welding, electroslag welding, oxy-acetylene welding and explosive welding [14]. The chief advantages of using GMAW for surfacing are [12]:

High reliability

All position capability

Ease of use

Low cost

High productivity

This paper highlights an experimental study carried out to develop mathematical models to predict clad bead geometry in GMAW process used in austenitic stainless steel cladding of low carbon structural steel plates. Experiments were conducted based on four factor five level central composite rotatable design with full replications technique and mathematical models developed using multiple regression method [3 -7]. Figure 1 shows the important clad bead geometry.

## EXPERIMENTAL WORK

The experiments were Conducted using THYRO µP 400 welding machine using DC electrode positive (DCEP). Test pieces of size 300mm × 200mm × 20 mm were cut from low carbon structural steel (IS: 2062) plate and its surfaces were ground to remove oxide scale before cladding [9]. Stainless steel solid welding wire (ER 308L) of 1.2mm diameter was used for depositing the weld beads. Chemical composition of the base metal and filler wire is given in Table 1. Mixture of 98% Argon and 2% of $O_2$ gas at a constant flow rate of 16.5 Litres/min was used for shielding. The experimental setup used consisted of a traveling carriage with a table for supporting the specimens. The carriage speed was continuously adjustable from 160 mm/min to 180 mm/min. The welding torch was held stationary in a frame mounted above the work table and it was provided with an attachment for both up and down movement with angular movement for setting the required nozzle to - plate distance and welding torch angle respectively.

## EXPERIMENTAL DESIGN PROCEDURE

The experimental design procedure used for this study and important steps are briefly explained below.

### Identification of factors and response

The chosen factors were wire feed rate (F), welding speed (S) nozzle-to-plate distance (N), and welding torch angle (T). The chosen responses were Weld bead width (W), Depth of Penetration (P) and Height of Reinforcement (R).

Figure 1

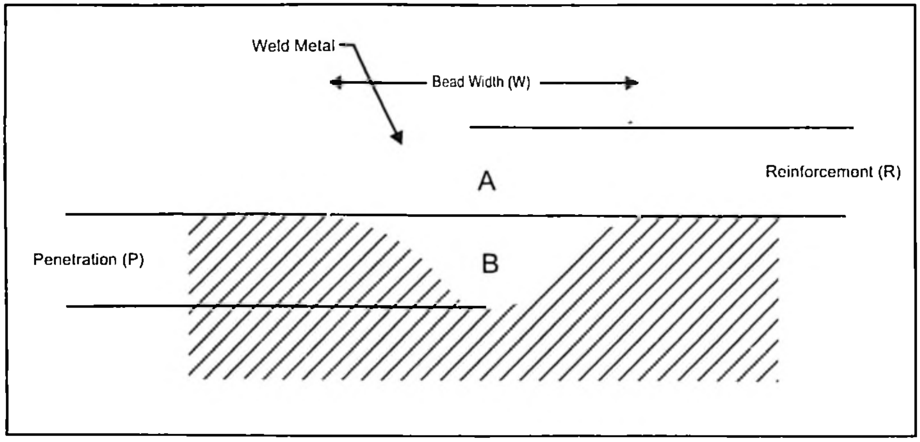

Table 1 Chemical composition of base metal and filler wire (%)

| Material | C | Si | Mn | P | S | Al | Cr | Mo | Ni |
|---|---|---|---|---|---|---|---|---|---|
| IS 2062 | 0.15 | 0.16 | 0.87 | 0.015 | 0.016 | 0.031 | - | - | - |
| ER 308L | 0.03 | 0.57 | 1.76 | 0.021 | 0.008 | - | 19.52 | 0.75 | 10.02 |

### Finding limits of the process variables

The working ranges of all selected factors were fixed by conducting trial runs. This was carried out by varying one of the factors while keeping the rest of them at constant values. The working range of each process parameters was decided upon by inspecting the bead for a smooth appearance without any visible defects such as surface porosity, undercut, etc. The upper limit of a factor was coded as +2 and the lower .limit was coded as -2. The coded values for intermediate values were calculated [10] using the Equation (1).

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

where $X_i$ is the required coded value of a variable X. X is the any value of the variable from $X_{min}$ to $X_{max}$, $X_{min}$ the lower limit of the variable and $X_{max}$ the upper limit of the variable. The chosen levels of the selected process parameters with their units and notations are given in Table 2

### Development of design matrix

The design matrix chosen to conduct the experiment was a central composite rotatable design [1, 8]. This design matrix comprised of a full replication of 24 (=16) factorial design plus seven center points and eight star points which is shown in Table 3. All welding variables at the intermediate levels (0) constituted the center points and the combination of each welding variables at either its highest value (+2) or lowest value (-2) with other three variables of the intermediate levels (0), constituted the star points. Thus the 31 experimental runs allowed the estimation of the linear, quadratic and two-way interactive effects of the process parameters on clad bead geometry.

### Conducting experiments as per the design matrix

In this work, 31 deposits were made using cladding conditions corresponding to each treatment combination of parameters shown in Table 3 at random.

### Recording the responses

To measure the clad bead geometry transverse sections of each weld overlays were cut using power hacksaw from the mid-length position of the welds and the end faces were machined. Specimen end faces were polished and

Table 2 Welding parameters and their levels

| PARAMETER | UNIT | NOTATION | FACTOR LEVELS | | | | |
|---|---|---|---|---|---|---|---|
| | | | -2 | -1 | 0 | + 1 | + 2 |
| Wire feed rate | m/min | F | 4 | 5 | 6 | 7 | 8 |
| Welding speed | mm/min | S | 160 | 165 | 170 | 175 | 180 |
| Welding torch angle | deg | T | 70 | 80 | 90 | 100 | 110 |
| Nozzle-to-plate distance | mm | N | 18 | 20 | 22 | 24 | 26 |

etched using a 2% nital solution and the bead profiles were traced using a reflective type optical profile projector at a magnification of 10. The profile images were imported to the software AutoCAD as raster image and profile are traced to a 2D form and then the clad bead geometry was calculated by using the same software .The calculated Weld bead width (W) Depth of Penetration (P) and Height of Reinforcement (R) for 31 trails are given in Table 3.

## Development of mathematical models

The response function representing any of the clad bead parameters can be expressed using Y = (F, S, T, and N) and the relationship selected being a second-degree response surface expressed as:

$$Y = b_0 + b_1 F + b_2 S + b_3 T + b_4 N + b_{11}F^2 + b_{22}S^2 + b_{33}T^2 + b_{44}N^2 + b_{12}FS + b_{13}FT + b_{14}FN + b_{23}ST + b_{24}SN + b_{34}TN$$

The values of the coefficients were calculated by regression analysis with the help of the following equation:

$$b_o = 0.142857\Sigma Y - 0.035714\Sigma\Sigma (X_i Y)$$

$$b_i = 0.041778\Sigma (X_i Y)$$

$$bii = 0.03125\Sigma (X_{ii} Y) - 0.035714\Sigma\Sigma (X_{ii} Y) - 0.035714\Sigma Y$$

$$b_{ij} = 0.0625\Sigma (X_{ij} Y)$$

Table 3 Design Matrix and the observed bead parameters

| S.NO. | F m/min | S mm/ min | T deg | N mm | W mm | P mm | R mm |
|---|---|---|---|---|---|---|---|
| 1 | -1 | -1 | -1 | -1 | 13.60 | 5.38 | 2.99 |
| 2 | +1 | -1 | -1 | -1 | 16.31 | 6.21 | 3.22 |
| 3 | -1 | +1 | -1 | -1 | 13.21 | 5.30 | 3.13 |
| 4 | +1 | +1 | -1 | -1 | 14.36 | 6.19 | 3.13 |
| 5 | -1 | -1 | +1 | -1 | 16.59 | 4.85 | 1.61 |
| 6 | +1 | -1 | +1 | -1 | 17.09 | 5.82 | 1.34 |
| 7 | -1 | +1 | +1 | -1 | 16.06 | 4.68 | 1.63 |
| 8 | +1 | +1 | +1 | -1 | 17.07 | 5.44 | 1.68 |
| 9 | -1 | -1 | -1 | +1 | 13.33 | 5.45 | 2.77 |
| 10 | +1 | -1 | -1 | +1 | 13.72 | 6.65 | 2.56 |
| 11 | -1 | +1 | -1 | +1 | 13.15 | 5.39 | 3.00 |
| 12 | +1 | +1 | -1 | +1 | 12.94 | 6.30 | 2.79 |
| 13 | -1 | -1 | +1 | +1 | 14.54 | 5.02 | 1.53 |
| 14 | +1 | -1 | +1 | +1 | 14.83 | 6.20 | 0.65 |
| 15 | -1 | +1 | +1 | +1 | 13.54 | 4.92 | 1.20 |
| 16 | +1 | +1 | +1 | +1 | 15.86 | 5.73 | 0.87 |
| 17 | -2 | 0 | 0 | 0 | 11.94 | 5.23 | 2.41 |
| 18 | +2 | 0 | 0 | 0 | 17.06 | 6.32 | 3.02 |
| 19 | 0 | -2 | 0 | 0 | 16.54 | 5.71 | 2.57 |
| 20 | 0 | +2 | 0 | 0 | 14.85 | 5.25 | 2.84 |
| 21 | 0 | 0 | -2 | 0 | 12.63 | 6.28 | 2.42 |
| 22 | 0 | 0 | +2 | 0 | 13.52 | 5.50 | 0.80 |
| 23 | 0 | 0 | 0 | -2 | 16.73 | 5.17 | 3.20 |
| 24 | 0 | 0 | 0 | +2 | 13.94 | 5.68 | 1.94 |
| 25 | 0 | 0 | 0 | 0 | 15.75 | 5.35 | 2.99 |
| 26 | 0 | 0 | 0 | 0 | 14.92 | 5.83 | 1.93 |
| 27 | 0 | 0 | 0 | 0 | 16.16 | 5.56 | 2.55 |
| 28 | 0 | 0 | 0 | 0 | 16.71 | 5.18 | 2.63 |
| 29 | 0 | 0 | 0 | 0 | 16.29 | 5.32 | 2.48 |
| 30 | 0 | 0 | 0 | 0 | 15.80 | 5.37 | 2.29 |
| 31 | 0 | 0 | 0 | 0 | 15.61 | 5.34 | 2.62 |

Table 4 Regression Coefficients

| S. No. | Coefficient | W | R | P |
|---|---|---|---|---|
| 1 | b0 | 15.75 | 5.419 | 2.488 |
| 2 | b1 | 0.766 | 0.406 | - |
| 3 | b2 | -0.3 | -0.107 | - |
| 4 | b3 | 0.698 | -0.24 | -0.679 |
| 5 | b4 | -0.748 | 0.117 | -0.244 |
| 6 | b11 | -0.315 | 0.081 | - |
| 7 | b22 | - | - | - |
| 8 | b33 | -0.671 | - | -0.266 |
| 9 | b44 | - | - | - |
| 10 | b12 | - | -0.051 | - |
| 11 | b13 | - | - | - |
| 12 | b14 | - | - | -0.103 |
| 13 | b23 | - | - | - |
| 14 | b24 | - | - | - |
| 15 | b34 | -0.232 | - | - |

The response coefficients were calculated using QA six sigma software (DOE-PCIV).This is shown in Table 4. After determining the coefficients the mathematical models were developed. The insignificant coefficients were eliminated without affecting the accuracy of the developed model by using t-test. This was done by back elimination technique, which is available in QA six sigma software (DOE-PCIV).The final mathematical models were constructed by using only significant coefficients [13]. The developed final models with welding variables in coded form are given below.

**BEAD WIDTH** =
$15.75+0.766F-0.3S + 0.698T - 0.748N - 0.315F^2-0.671T^2-0.232TN$

**REINFORCEMENT**=
$5.419 + 0.406F - 0.107S - 0.24T+0.117N+0.081F^2 + 0.11T^2 - 0.051FS$

**PENETRATION =**
$2.488-0.679T-0.244N-0.266T^2-0.103FN$

## Conducting Conformity Test

Conformity tests were conducted using the same experimental setup to confirm the results of the experiment and demonstrate the reliability of the predicted values and the claddings deposited during conformity test are shown in the Figure 2. The conformity test shows the accuracy of the developed models which is above 96%. This is shown in Table 5.

## CONCLUSIONS

A five level four factor full factorial 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 using GMAW.

The models developed can be employed easily in automated or robotic welding in the form of a program, for obtaining the desired weld bead dimensions. The prediction results are very close to the experimental results.

Accuracy of the developed models is above 95%.

Developed Mathematical models can be used to optimize the process parameters.

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Table 5 Results of Conformity Tests

| Process parameters in coded form | | | | Predicted values of clad bead parameters | | | | Actual values of clad bead parameters | | | | Error, % | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| I | S | N | T | W | P | R | D | W | P | R | D | W | P | R | D |
| -0.90 | -1.81 | 1.34 | 1.94 | 13.03 | 5.33 | 0.80 | 10.33 | 12.95 | 5.22 | 0.78 | 10.47 | -0.58 | -2.12 | -2.92 | 1.32 |
| 0.38 | 0.77 | 1.42 | -0.67 | 16.11 | 5.29 | 1.17 | 10.74 | 16.21 | 5.37 | 1.21 | 10.98 | 0.61 | 1.51 | 3.41 | 2.24 |
| 0.27 | -1.40 | 1.25 | -0.45 | 16.64 | 5.52 | 1.35 | 10.11 | 16.42 | 5.43 | 1.37 | 10.27 | -1.34 | -1.70 | 1.47 | 1.53 |

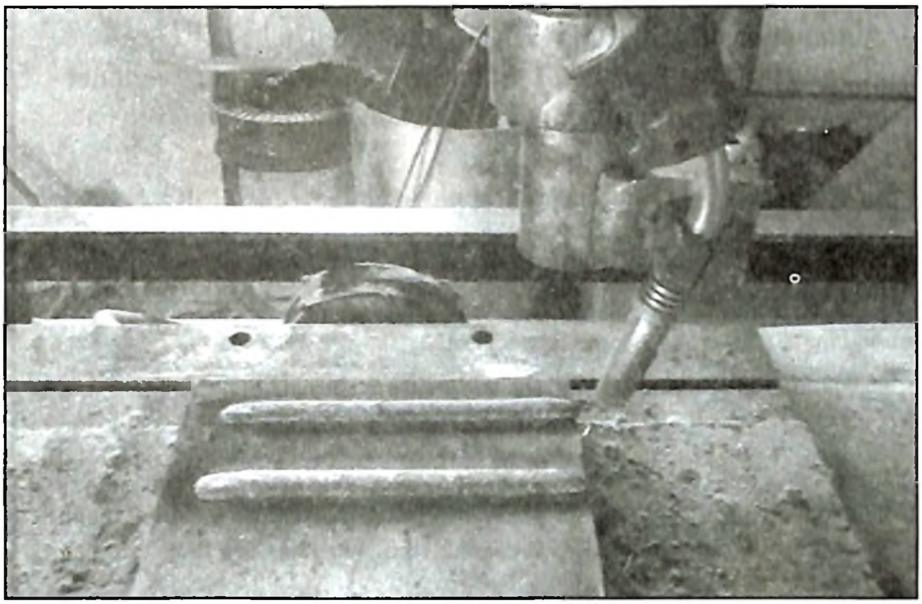

Figure 2 Claddings deposited during conformity test

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