CHAPTER 3

DEVELOPMENT OF REGRESSION EQUATION AND
OPTIMIZATION OF WELD BEAD GEOMETRY

3.1 INTRODUCTION

By conducting real time experiments it is possible to study the effect of GMAW process variables of weld bead geometry like weld bead width, penetration, reinforcement and weld bead area. From design of experiments (Montgomery 2008) the basic information and knowledge about the various parameters to be studied, and how the data is to be collected are obtained. The experimental design must be planned with minimum time and effort. Thus the designs of experiments were used for selecting the number of trails and conditions for doing experiments.

In the present work, three factors, five levels central composite design technique was used for the development of design matrix to conduct the required experiments. In this chapter the experimental work was carried out to develop regression models for the prediction of weld bead geometry using response surface methodology (RSM) is discussed. The detailed report of direct and interactive effect of GMAW process parameters on weld bead geometry is presented in detail. The developed regression models are optimized using design expert software to minimize the weld bead area.
3.2 WELD JOINT SPECIFICATIONS

The base metal SS409M of size 150 mm X 150 mm X 4 mm were butt welded in a single pass with a root gap of 2 mm by using ASS 308L electrode. Argon is used as a shielding gas with a gas flow rate of 14 lpm.

3.3 GMAW EXPERIMENTAL SETUP

![Schematic diagram of GMAW process](image)

**Figure 3.1 Schematic diagram of GMAW process**

The schematic diagram of GMAW process is shown in figure 3.1. The GMAW setup shown in figure 3.2 is available at the welding research lab of Coimbatore Institute of Technology, Coimbatore. Experiments were conducted using the setup. The welding setup consists of a welding
Welding manipulator is an equipment which helps in relative movement between the welding torch and work-piece. The work-table with fixture is shown in figure 3.3. The GMAW gun is fixed on the manipulator and the work-piece is clamped on the fixture. By using variable speed electric motors the work-table could be moved at the desired speed in both x and y
directions. The speed of working-table and wire feed rate were calibrated before welding.

Figure 3.3  Work-Table with fixture

3.5  CALIBRATION OF THE WELDING PARAMETERS

3.5.1  Calibration of Wire Feed Rate

308L filler wire of 1.2 mm diameter was used for welding of SS409M plates using GMAW process and spool of filler wire is shown in figure 3.4 and figure 3.5 shows the filler wire feeding unit setup. The success of the GMAW process is based on the wire feed rate and it is responsible for the burn off rate to obtain constant arc length. Good arc stability is achieved by good metal transfer condition. Calibration of knob position and wire feed is shown in figure 3.6.
Figure 3.4  Spool of filler wire

Figure 3.5  Filler wire feeding unit
3.5.2 Calibration of Work-Table Speed

The speed of working-table along x direction and y direction is adjusted by rotating the knob. The welding speed (mm/sec) of the working-table is calibrated by using a stop-watch and scale. Calibration of knob position and welding speed is shown in figure 3.7.
3.5.3 Calibration of Welding Torch Angle

Welding torch angle is the angle relative to the gun in a perpendicular position to the welding plate. The welding gun in all positions can travel an angle of 5 to 15 degrees. Travel angles beyond 20 degree results in more spatter, less penetration and general arc instability. The calibration of torch position and welding angle is shown in figure 3.8.

Figure 3.7 Calibration of knob position and welding speed
Figure 3.8  Calibration of torch position and welding angle

3.6 SEQUENCE OF THE INVESTIGATION

The investigation has been carried out as per the following order (Cochran & Coxz 1987):

1. Calibration of input process parameters
2. Selection of the significant GMAW input process parameters
3. Identifying the limits and range of the GMAW process parameters
4. Developing the experimental design matrix
5. Conducting the experiments based on design matrix
6. Recording the response
7. Developing the regression models by using RSM approach
8. Results and discussion
3.6.1 **Selection of the GMAW Input Process Parameters**

The quality of weld joint depends on wire feed rate, welding speed, welding torch angle, open circuit voltage, electrode stick-out, gas flow rate and nozzle to plate distance (Benyounis & Olabi 2008). In the welding Process, the quality and joint strength is based on the weld bead geometry. The weld bead geometry mainly depends on the input process parameters. Welding speed, wire feed and torch angle were selected as the input process parameters.

In analog welding machines the current readings are always fluctuating. If the wire feed rate is selected as the one of the process parameter, the accurate value of current supplied was easily measured and also it is the indirect way of measuring the actual current supplied while welding. Productivity factor is mainly based on welding speed of the process.

Based on the position of the welding torch the amount of shielding gas applied is varied, and it will reflect in bead dimension and weld strength. These are the reason for selecting wire feed, welding speed and torch angle as the input process parameters.

3.6.2 **Identifying the Limits and Range of the GMAW Process Parameters**

By conducting trial runs the working ranges of the selected parameters are fixed. Working range is identified by varying one of the process parameters and keeping the other two parameters as constant. By inspecting the smooth appearance of the weld bead the working range of GMAW parameter was decided.
The natural variables were transformed into dimensionless coded variables (Carley et al. 2004). The upper limit and lower limit of the factor were +1.682, and -1.682 respectively. The intermediate values can be calculated by using the following equation (Giridharan & Murugan 2007):

\[ X_i = 1.682 \frac{2X - (X_{\text{max}} + X_{\text{min}})}{(X_{\text{max}} - X_{\text{min}})} \]  

where

- \( X_i \) is expected coded value of the variable of \( X \);
- \( X \) is any variable between the value from \( X_{\text{min}} \) to \( X_{\text{max}} \);
- \( X_{\text{min}} \) is the lowest level of variable
- \( X_{\text{max}} \) is the highest level of variable

The input process parameter and their levels of GMAW process with their units and notations are given in table 3.1

<table>
<thead>
<tr>
<th>S.No</th>
<th>Process Parameters</th>
<th>Units</th>
<th>Factor Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>-1.682</td>
</tr>
<tr>
<td>1</td>
<td>Wire feed (f)</td>
<td>(mm/sec)</td>
<td>6.5</td>
</tr>
<tr>
<td>2</td>
<td>Welding speed (s)</td>
<td>(mm/sec)</td>
<td>2.7</td>
</tr>
<tr>
<td>3</td>
<td>Torch angle (θ)</td>
<td>(°)</td>
<td>69.9</td>
</tr>
</tbody>
</table>
3.6.3 Developing Design Matrix

Experiments were conducted for all the possible combinations as per the design matrix given in table 3.2. The selected design matrix is a three-factor five-level central composite rotatable design consisting of 20 sets of a full-factorial \(2^3 = 8\) plus, 6 center points and 6 star points.

If the factorial is a full factorial, then

\[
\alpha = [2^k]^{1/4} = [2^3]^{1/4} = 1.682
\]

\[
\alpha = \text{[Number of factorial runs]}^{1/4}
\]

3.6.4 Conducting the Experiments

For all the 20 specimens the responses measured were weld bead width, reinforcement, penetration and weld bead area. Design matrix with observed values of bead dimensions was shown in table 3.2. The GMAW welded plates was shown in figure 3.9. The typical bead geometry measured was shown in figure 3.10.
Table 3.2  Design matrix with observed values of bead dimensions

<table>
<thead>
<tr>
<th>Specimen No</th>
<th>Design Matrix</th>
<th>Weld Bead Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F (mm/sec)</td>
<td>S (mm/sec)</td>
</tr>
<tr>
<td>1</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>-1</td>
</tr>
<tr>
<td>3</td>
<td>-1</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>-1</td>
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<tr>
<td>7</td>
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<td>11</td>
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<tr>
<td>12</td>
<td>0</td>
<td>1.682</td>
</tr>
<tr>
<td>13</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>14</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>15</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>16</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>17</td>
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<td>18</td>
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<td>0</td>
</tr>
<tr>
<td>19</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>20</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

F = Wire Feed; S = Welding Speed; θ = Welding torch angle; W = Weld Bead Width;

R = Reinforcement; P = Penetration; WA = Weld Bead Area:
3.6.5 Recording the Responses

All the 20 samples were sectioned with a specimen size of 12 mm x 150 mm x 4 mm by using the power hacksaw. Specimens were prepared by using the standard metallurgical polishing procedure to measure weld bead profile. The profile was exposed by etching the specimen in the
etchant 5% nital solution (1/20 of nitric acid in ethanol) is applied on the surface of the weld bead. In their work by (Lightfoot et al. 2007), weld bead profile was measured by using photogrammetry. Height of the weld bead was measured by the vernier height gauge (Parmar 2010). In the present investigation weld bead profile was measured by using Rapid – I vision measuring system (V 2015J LX) model and it is given in figure 3.11. Transverse section of a welded plate is shown in figure 3.12.

Figure 3.11  Rapid – I vision measuring system (V 2015J LX) model

Figure 3.12  Transverse section of a welded plate
3.6.6 Development of Regression Model

The response function denoting the weld geometry can be expressed as

\[ Y = f(F, S, \theta) \]  

where,

- \( Y \) = Responses weld bead width (mm), reinforcement (mm), penetration (mm) and weld bead area (mm\(^2\))
- \( F \) = Wire feed (mm/sec), \( S \) = Welding speed (mm/sec) and \( \theta \) = Torch angle (°).

The second order polynomial equation used to represent the response surface for \( k \) factors is given by

\[
Y = a_0 + \sum a_i X_i + \sum a_{ij} X_i X_j + \sum a_{ii} X_i^2 \\
\quad i = 1 \quad i.j = 1 \quad i = \pm j
\]  

(3.3)

For three factors, the selected polynomial could be expressed as

\[
Y = a_0 + a_1 F + a_2 S + a_3 \theta + a_{12} FS + a_{23} S\theta + a_{31} F\theta + a_{11} F^2 + a_{22} S^2 + a_{33} \theta^2
\]  

(3.4)

Where \( a_0 \) . Coefficient of free term of the regression equation

- \( a_1, a_2 \) and \( a_3 \) . Coefficient of linear terms
- \( a_{12}, a_{13} \) and \( a_{23} \) . Coefficient of interactive terms
- \( a_{11}, a_{22} \) and \( a_{33} \) . Coefficient of quadratic terms
The flow chart for the regression models is shown in figure 3.13.

**Figure 3.13 Flowchart for the regression models**

W – Weld bead width  P – Penetration  R – Reinforcement and
WA - Weld bead area  FC - Calculated values of F- ratio
FT - Tabulated values of F- ratio
### 3.6.6.1 Estimated Values of the Co-efficient of Models in Coded Form

The design expert software was used to calculate the values of the coefficients for different responses. The calculated values of the coefficient of models are given in table 3.3. Calculation for weld bead width, reinforcement, penetration and weld bead area are given in equations (3.5) to (3.8) respectively.

#### Table 3.3 Calculated values of the coefficient of models

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Weld Bead Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Weld Bead Width (mm)</td>
</tr>
<tr>
<td>a₀</td>
<td>13.4477</td>
</tr>
<tr>
<td>a₁</td>
<td>-1.3698</td>
</tr>
<tr>
<td>a₂</td>
<td>5.9570</td>
</tr>
<tr>
<td>a₃</td>
<td>0.2767</td>
</tr>
<tr>
<td>a₁₂</td>
<td>-0.1410</td>
</tr>
<tr>
<td>a₁₃</td>
<td>0.0020</td>
</tr>
<tr>
<td>a₂₃</td>
<td>-0.0437</td>
</tr>
<tr>
<td>a₁₁</td>
<td>0.1223</td>
</tr>
<tr>
<td>a₂₂</td>
<td>-0.2140</td>
</tr>
<tr>
<td>a₃₃</td>
<td>-0.0008</td>
</tr>
</tbody>
</table>
Weld bead width = 13.4477 - 1.3698 F + 5.9570 S + 0.2767 \theta - 0.1410 FS + 0.0020 F\theta - 0.0437 S\theta + 0.1223 F^2 - 0.2140 S^2 - 0.0008 \theta^2 \tag{3.5}

Reinforcement = 1.5480 + 0.1047 F - 0.0903 S + 0.0202 \theta - 0.0181 FS + 0.0812 F\theta - 0.0975 S\theta - 0.0039 F^2 - 0.0075 S^2 - 0.0095 \theta^2 \tag{3.6}

Penetration = 4.679 - 3.3633 F - 0.5654 S - 0.0590 \theta + 0.2071 FS + 0.0186 F\theta - 0.0277 S\theta - 0.0824 F^2 + 0.1102 S^2 + 0.0001 \theta^2 \tag{3.7}

Weld bead area = 30.9235 + 7.4495 F + 50.4085 S - 0.2146 \theta - 7.7273 FS - 0.2262 F\theta - 0.2158 S\theta + 3.0088 F^2 + 2.4525 S^2 + 0.0178 \theta^2 \tag{3.8}

The models were verified by using scatter diagram. Measured values and predicted values of weld bead width, reinforcement, penetration and weld bead area are shown in figure 3.14 (a) to figure 3.14 (d). It is observed from the scatter diagrams, the measured values are almost nearer to the predicted value.

![Figure 3.14 (a) Scatter diagram of weld bead width](image-url)
Figure 3.14 (b) Scatter diagram of reinforcement

Figure 3.14 (c) Scatter diagram of penetration
3.6.6.2 Checking the Adequacy of the Developed Models

The adequacy of the regression model is verified by using the Analysis Of Variance (ANOVA). ANOVA for testing adequacy of the models was given in table 3.4. The calculated values of the F-ratio exceeds the standard tabulated value of the F – ratio for a desired level of confidence (say 95%), then the model was considered adequate within the confidence limit. From the results it was observed that, all the models were adequate.
### Table 3.4 ANOVA for testing adequacy of the models

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Weld Bead Geometry</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Weld bead width</td>
</tr>
<tr>
<td>Regression</td>
<td>SS</td>
</tr>
<tr>
<td></td>
<td>DF</td>
</tr>
<tr>
<td>Residual</td>
<td>SS</td>
</tr>
<tr>
<td></td>
<td>DF</td>
</tr>
<tr>
<td>Lack of fit</td>
<td>SS</td>
</tr>
<tr>
<td></td>
<td>DF</td>
</tr>
<tr>
<td>Error Term</td>
<td>SS</td>
</tr>
<tr>
<td></td>
<td>DF</td>
</tr>
<tr>
<td>F – ratio (Calculated)</td>
<td></td>
</tr>
<tr>
<td>$R^2$ Value</td>
<td></td>
</tr>
<tr>
<td>Adjusted $R^2$ Value</td>
<td></td>
</tr>
<tr>
<td>Remarks</td>
<td>Adequate</td>
</tr>
</tbody>
</table>

SS : Sum of Squares, DF: Degree of Freedom

SS/DF = Mean Square

F- ratio = Mean Sum of Squares for Regression/ Mean Sum of Squares of Error

#### 3.6.6.3 Development of Final Regression Model

The final regression model was developed by using a significant coefficient without change in the accuracy of the models. The selected input parameters wire feed, welding speed and torch angle were substituted in coded form to calculate the weld bead width, reinforcement, penetration and weld bead area and it is given in equation (3.9) to (3.12) respectively.
Final Regression Equation in Terms of Coded Factors:
Weld bead width = 3.25 + 0.15 F - 0.12 S - 0.037 θ - 0.049 θ²  (3.9)
Reinforcement = 1.55 + 0.10 F - 0.090 S + 0.020 θ + 0.081 Fθ - 0.098 S0  (3.10)
Penetration = 2.07 + 0.037 F - 0.026 S + 0.037 θ + 0.0071 F²  (3.11)
Weld bead area = 5.55 + 0.53 F - 0.44 S + 0.14 θ - 0.20 FS  (3.12)

3.6.6.4 Conformity Test

By using the same experimental setup conformity test was conducted to find the accuracy of the models.

Table 3.5 Conformity test results

<table>
<thead>
<tr>
<th>Input / Response Parameters</th>
<th>Conformity Test No</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Wire feed (f)</td>
<td>0</td>
</tr>
<tr>
<td>Welding speed (s)</td>
<td>1</td>
</tr>
<tr>
<td>Torch angle (θ)</td>
<td>-1</td>
</tr>
<tr>
<td>Weld bead width (mm)</td>
<td>10.658</td>
</tr>
<tr>
<td>Reinforcement (mm)</td>
<td>2.088</td>
</tr>
<tr>
<td>Penetration (mm)</td>
<td>4.779</td>
</tr>
<tr>
<td>Weld bead area (mm²)</td>
<td>34.669</td>
</tr>
</tbody>
</table>

MV - Measured Value  PV - Predicted Value  % E - % of Error

% of Error = [(Measured Value – Predicted Value) / Predicted Value] x 100
By using different sets of process variables other than the values given in design matrix, conformity test was conducted. The conformity test results were given in table 3.5. The percentage errors, gives the deviation of predicted results of response from the measured values.

3.7 RESULTS AND DISCUSSION

To predict the weld bead geometry regression model was used. From the models, the direct effects of the process parameters on weld bead geometry were estimated and plotted graphically in figure 3.15 to figure 3.18. Figure 3.19 to 3.22 show the interactive effects of the process parameters. The graphs plotted by using the regression models provide the cause and effect of welding variables on weld bead geometry.

3.7.1 Direct Effect of GMAW Process Parameters on Weld Bead Geometry

3.7.1.1 Direct Effect of Welding Parameters on Weld Bead Width

Figure 3.15 shows the direct effect of welding parameters on weld bead width. If the wire feed increases the width also gradually increased because the wire fused per unit of time increased resulting in more deposition of metal. In the case of welding speed, the same thing occur in vice-versa and leads to a narrow thin bead. At the vertical position of the torch better weld bead width was obtained.
Figure 3.15  Direct effects of welding parameters on weld bead width

3.7.1.2 Direct Effect of Welding Parameters on Reinforcement

Figure 3.16 shows the direct effect of welding parameter on reinforcement. If the wire feed increases the reinforcement also increased. This is due to high deposition rate of metal per unit length. But in the case of welding speed, reinforcement decreases when the speed was increased, the reason is at high speed the metal melting rate is low. Similarly for width at vertical position of the torch, better reinforcement was obtained due to the edge preparation and root gap even melting occurred at both the plates.
3.7.1.3 Direct Effect of Welding Parameters on Penetration

In the figure 3.17 the direct effects of welding parameters on penetration is shown. It is observed that maximum penetration was attained at high feed rate because more current was supplied that results in better penetration. To attain better penetration minimum speed is preferred because at slow speed only the metal fuses in the required area and propagate up to the bottom of the plate. Due to this reason multiple passes of the weld was avoided.

Figure 3.16 Direct effects of welding parameters on reinforcement
3.7.1.4 Direct Effect of Welding Parameters on Weld Bead Area

The direct effect of welding parameters on weld bead area is shown in figure 3.18. The algebraic sum of penetration and reinforcement is defined as weld bead area. High metal deposition rate is attained when the feed is high and speed is slow, due to this minimum weld bead area is attained with reduction in production cost.
Interactive Effect of GMAW Process Parameters on Weld Bead Geometry

3.7.2.1 Interactive Effect of Wire Feed and Welding Speed on Weld Bead Width

Figure 3.19 shows the interactive effect of wire feed rate and welding speed on weld bead width and in 3.19, a 3-D surface graph of wire feed and welding speed on weld bead width is shown. If the wire feed rate increases, width increases for all values of speed. It was observed that, increasing tendency of bead width was due to increase in wire feed rate and decrease in welding speed. This is because the wire feed rate has a positive effect whereas welding speed has a negative effect on bead width.
Figure 3.19 Interactive effects of wire feed and welding speed on weld bead width

Figure 3.20 (A) 3-D surface graph of wire feed and welding speed on weld bead width
3.7.2.2 Interactive Effect of Wire Feed and Welding Speed on Reinforcement

Interactive effects of wire feed and welding speed on reinforcement is shown in figure 3.20 and the 3-D surface graph of wire feed and welding speed on reinforcement is shown in 3.20 (a). The reinforcement decreases with an increase in welding speed at all the levels of the wire feed rate. The reason is due to the fact that, when welding speed is increased the metal deposition per unit length is reduced. However, the rate of decrease in reinforcement decreases with the increase in wire feed rate.

Figure 3.21 Interactive effects of wire feed and welding speed on reinforcement
3.7.2.3 Interactive Effect of Welding Speed and Torch Angle on Penetration

Interactive effects of welding speed and torch angle on penetration is shown in figure 3.21 and the 3-D surface graph of welding speed and torch angle on penetration is shown in figure 3.21,a. From the graph it is observed that better penetration is achieved when the weld torch is at a vertical position and the welding speed rate is at a minimum level. At minimum welding speed, metal fusion rate was high which results in better penetration. At 90° of the welding torch for the given root gap and edge prepared, even heat is applied on both plates result in better penetration.
Figure 3.23 Interactive effects of welding speed and torch angle on penetration

Figure 3.24 (A) 3-D surface graph of welding speed and torch angle on penetration
3.7.2.4 Interactive Effect of Wire Feed and Welding Speed on Weld Bead Area

The interactive effect of wire feed rate and welding speed on weld bead area is shown in figure 3.22 and the 3-D surface graph of wire feed and the welding speed on weld bead area is shown in figure 3.22 (a). The weld bead area increases with the increase in wire feed rate at the all levels of welding speed but the rate of increase in weld bead area decreases with the increase in welding speed. This is due to more metal deposition is occurring at higher feed rate and lower welding speed.

![Graph showing the interactive effect of wire feed and welding speed on weld bead area.](image)

**Figure 3.25** Interactive effects of wire feed and welding speed on weld bead area.
3.8 OPTIMIZATION OF THE GMAW PROCESS PARAMETERS USING DESIGN EXPERT SOFTWARE

3.8.1 Introduction

In welding process, the weld bead area is the most important parameter to be considered for optimization (minimization). By observing the interdependence of various weld bead parameters, weld bead area is the most important parameter to be controlled. Minimizing the weld bead area apparently minimizes other bead parameters such as width and the reinforcement. The consumable cost can be minimized by having the minimum size of the weld bead area. The productivity rate in welding could be
improved through moderate welding speed. Due to these advantages weld bead area should be optimized. Regression equation is needed for optimization, for predicting the values of weld bead geometry such as weld bead width, reinforcement, penetration and weld bead area. By using the regression analysis, models were developed to optimize the GMAW process to attain minimum weld bead area. (Allen et al 2002) in their research work, systematic and scientific approach in welding procedure was established, by efficient usage of design of experiment techniques and other optimization techniques. In this problem design expert software was used to optimize the gas metal arc welding parameters.

3.8.2 Optimization of the GMAM Process Parameters using Design expert software

Weld bead area is selected as a objective function for optimization. Other parameters like weld bead width, reinforcement and penetration were given as the constraints of the objective function. The input parameters are maintained within the maximum and minimum range. By using design expert software optimization was carried out. The design expert software was directly or indirectly related, to the objective function from regression modeling in a target cell. The software manages the values in the changing cells called the adjustable cells to bring out the results. By using the constraints the variables are restricted in the objective function.

The objective function for optimization

The objective function and the constraints are given in the following equation:
Weld bead area = 30.9235 + 7.4495 F + 50.4085 S - 0.2146 θ - 7.7273 FS - 0.2262 Fθ - 0.2158 Sθ + 3.0088 F^2 + 2.4525 S^2 + 0.0178 θ^2

The objective function was optimized with the following constraints:

-1.682 < Wire Feed < 1.682
-1.682 < Welding Speed < 1.682
-1.682 < Weld Torch Angle < 1.682

Weld bead width = 13.4477 - 1.3698 F + 5.9570 S + 0.2767 θ - 0.1410 FS + 0.0020 Fθ - 0.0437 Sθ + 0.1223 F^2 - 0.2140 S^2 - 0.0008 θ^2 - 10

(3.14)

Reinforcement = 1.5480 + 0.1047 F - 0.0903 S + 0.0202 θ - 0.0181 FS + 0.0812 Fθ - 0.0975 Sθ - 0.0039 F^2 - 0.0075 S^2 - 0.0095 θ^2 - 2.2

(3.15)

Penetration = 4.679 - 3.3633 F - 0.5654 S - 0.0590 θ + 0.2071 FS + 0.0186 Fθ - 0.0277 Sθ - 0.0824 F^2 + 0.1102 S^2 + 0.0001 θ^2 - 4.9

(3.16)

The pair of optimum solution for minimum weld bead area is

F = -1.682, S = 1.682, θ = -1.682

W = 10.227 mm, R = 2.235 mm, P = 3.132 mm, WA = 29.1235 mm^2

3.8.3 Conformity Test

By using the same experimental setup the conformity tests was performed with a optimal parameter. Weld trials was conducted for the
optimum parametric values. Results of the conformity test with optimized process parameters is given in table 3.6.

**Table 3.6  Results of the conformity test with optimized process parameters**

<table>
<thead>
<tr>
<th>Trial No</th>
<th>Optimized Process Parameters</th>
<th>Weld Bead Area (mm²)</th>
<th>% error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F (mm/sec)</td>
<td>S (m/sec)</td>
<td>θ (°)</td>
</tr>
<tr>
<td>1</td>
<td>-1.682</td>
<td>1.682</td>
<td>-1.682</td>
</tr>
</tbody>
</table>