Predicting Weld Bead Geometry in the Novel CW-GMAW Process

The regressive analysis showed that dilution and penetration are negatively correlated with the welding current in Cold Wire GMAW


ABSTRACT

One of the major concerns in welding is achieving an adequate weld bead with a geometry that is capable of resisting imposed stresses. Hence, predicting the geometrical features of a new welding process is of fundamental importance. Statistical methods are the most commonly used for predicting such geometries, and they provide particular confidence regarding the accuracy of the obtained regression. In this study, the geometries of weld beads produced using cold wire gas metal arc welding (CW-GMAW) were predicted using regressive and sensitivity analyses. This new process aims to increase the productivity of GMAW through the addition of a cold wire in the arc region, thereby increasing the deposition rate. The influence of the cold wire addition on the final weld bead geometry was investigated using curvilinear regressive and sensitivity analyses. The inputs considered in this study were the electrode feed rate, electric current, and nonelectrode feed rate ratio. The measured geometric parameters of the resulting weld were the bead penetration, bead width, bead height, and dilution. The results demonstrated that the regressive analysis could predict the geometry of the weld bead with good accuracy, with an error of less than 15%, and the sensitivity analysis indicated that dilution and penetration have a negative sensitivity to the welding current in CW-GMAW.

KEYWORDS

• Geometry • Cold Wire Gas Metal Arc Welding (CW-GMAW) • Regressive Analysis • Sensitivity Analysis • Analysis of Variance (ANOVA)

Introduction

One of the main issues concerning the conventional arc welding processes is the fact that to improve their productivity and deposition rate, the welding current imposed on the base metal must increase, then subjecting the workpiece to higher temperatures that cause distortions and oblige the welded product to be reworked to remove the distortions occasioned by the excessive heat input. This increases the postprocessing total costs.

To increase the deposition without subjecting the workpiece to excessive heat inputs or decrease the heat input without compromising deposition rates, modifications on conventional gas metal arc welding (GMAW) were proposed as alternative processes.

With the purpose of increasing deposition, some modifications of conventional GMAW were created such as tandem GMAW (Ref. 1) and variable polarity GMAW (VP–GMAW) (Ref. 2). Tandem GMAW consists of two welding guns united into one using two energized wires. One particular feature of the tandem process is that the maximum current could be selected to one particular welding gun. In addition, VP–GMAW presents a variation of polarity of the electrode that is still melted when positive, but during the negative polarity phase can be melted more rapidly, increasing deposition.

Those processes achieve the aim of increasing the productivity through an increase in the deposition rate. However, they offer increased amounts of heat input to the base metal.

In applications such as welding high-strength low-alloy (HSLA) steels, pipeline steels for example, those processes are not suitable because high heat inputs deteriorated the fine structure of the base metal in the heat-affected zone (HAZ) and therefore make this region the weakest in the structure and likely to be the point where the failure of the structure will take place.

To overcome this issue of increasing the deposition rate without increasing the heat input to the workpiece, there were technology developments. One of those welding processes recently developed to control the heat input on the workpiece while not compromising the deposition is double-electrode GMAW (DE-GMAW), a variant of conventional GMAW. This process was...
originally developed at the University of Kentucky (Ref. 3) and subsequently studied in a series of papers (Refs. 4–8).

Double-electrode GMAW was originally developed using a nonconsumable gas tungsten arc welding (GTAW) second torch as a bypass torch, called nonconsumable DE-GMAW. In this system, the existence of the current bypass allows control of the heat input on the base metal used in welding operations because the current flowing through the base metal is decoupled into the base metal current (I\textsubscript{bm}) and bypass current (I\textsubscript{bp}), which implies that the base metal current is less than the melting current (total current, I = I\textsubscript{bm} + I\textsubscript{bp}). Decreasing the heat input without a reduction in the deposition changes the former features of conventional GMAW.

Knowing that much of the heat generated by the electric arc is lost, a second variant of DE-GMAW with a consumable electrode (Refs. 5, 6) was proposed to increase even more deposition while the heat input is controlled by decoupling the melting current, as mentioned earlier. In this version, the second bypass torch, originally GTAW (Refs. 3, 4), is replaced by a GMAW gun with a consumable electrode (Refs. 5, 6).

More recently, another modification of the conventional welding processes was proposed and developed by ESAB. ICE technology (Ref. 9), applied to submerged arc welding (SAW), conjugates three wires, two energized and one nonenergized, making possible the deposition increase without increasing the heat input in the workpiece.

Following the efforts to increase productivity of the welding process (deposition rates) without increasing the heat input into the base metal, the Laboratory of Materials Characterization (LCAM) from the Federal University of Pará (UFPA) developed cold

<table>
<thead>
<tr>
<th>Material</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Mo</th>
<th>Ni</th>
<th>Cu</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTM A131-A</td>
<td>0.21</td>
<td>0.50</td>
<td>2.5C</td>
<td>0.035</td>
<td>0.035</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>AWS ER70S-6</td>
<td>0.06–0.15</td>
<td>0.80–1.50</td>
<td>1.40–1.85</td>
<td>0.025</td>
<td>0.035</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
<td>0.50</td>
</tr>
</tbody>
</table>

Single values are the maximum levels, and the copper content in the welding consumable is due to the coating on the electrode plus the copper present in the filler metal itself (Refs. 12, 13).
wire GMAW (CW–GMAW).

Since the heat generated by the electric arc in conventional GMAW is used to melt the electrode and the rest of it is wasted, a nonelectrode consumable wire (cold wire) was introduced into the arc, increasing the deposition regarding conventional GMAW. By the introduction of this cold wire, the original GMAW is changed into a new process, presenting intrinsic features such as different arc stability dynamics and, no less important, the effect of this cold wire on the geometry of weld beads. The configuration for the introduction of the cold wire in the region of the arc in CW-GMAW is illustrated in Figs. 1 and 2.

Regarding the final geometry of weld beads performed by CW-GMAW, it is necessary to understand how the amount of cold wire affects the geometric bead characteristics such as bead width, height, penetration, and dilution. Furthermore, it is necessary to investigate whether those geometric features are influenced in the same way by welding parameters such as welding current, voltage, travel speed, and feeding speed when compared to conventional GMAW.

Only once the input parameter’s influence on the final weld geometry is completely understood can a model to predict the geometry be built, and the process can be applied in a fully automated setup in manufacturing industries such as shipbuilding. Therefore, it is necessary to complete a modeling treatment to build a model that can predict the final geometry of weld beads generated by this process, which in turn will enable an alternative method that allies all the strong features of conventional GMAW to an increased deposition with fairly the same apparatus of GMAW.

**Weld Bead Geometric Parameters and Their Prediction**

An important consideration in welding is to achieve an adequate weld bead with a geometry that is capable of resisting imposed stresses. Geometric characteristics such as the width (W), height (H), and penetration (P), as shown in Fig. 3, as well as the dilution (D), as shown in Equation 1, are fundamental for assessing the quality of a weld bead.

In general, these characteristics are functions of the input parameters, such as current and voltage, among others. Hence, predicting and understanding how the input parameters influence these characteristics is of fundamental importance for a new welding process. Penetration refers to how the bead penetrated into the original base metal. In this paper, bead-on-plate welds were performed to primarily assess the geometric characteristics and weld cladding quality.

The width is a measure of how much the bead spreads over the plate, height refers to how much metal is above the plate surface reference line,
and dilution corresponds to the quantity of base metal incorporated into the weld bead. Dilution is mathematically defined in Equation 1. The mathematical definition of dilution (%) measures the amount of the weld bead cross-sectional area that came from the base metal; in other words, the quantity of the base metal that was incorporated into the weld bead. The parameters A and B are shown in Fig. 3.

\[ D = \frac{B}{A+B} \times 100 \]  

(1)

Statistical methods are the most commonly used approaches for predicting such geometries, and they provide particular confidence regarding the regression accuracy. However, the efforts to model weld bead geometry are not confined to the use of statistical techniques. The use of dimensional analysis is also employed with such intention.

Reference 10 represents an approach to model penetration using dimensionless numbers, based on a general assumption that it can be related to heat and mass transfer to the weld pool. Reference 11 represents the same dimensionless approach to model experimental data to determine analytical relations to determine the stable ranges of welding parameters to control weld bead geometry.

Kim (Ref. 12) performed a multivariate regression analysis (MRA) using the least squares method to estimate the regressors for identifying which parameters influence the bead penetration on a 12-mm SS400 plate using GMAW. These authors concluded that current, voltage, welding speed, and welding angle affect the penetration based on the comparison of two regression models, linear and curvilinear.

In another study, Kim (Ref. 13) determined the relationships of penetration, width, and height with all of the aforementioned variables except the welding angle. Furthermore, a sensitivity analysis was conducted to understand how a discrete change in the variables would discretely affect the output variables. The authors concluded that width and height were more affected than penetration by changes in the input variables during conventional GMAW.

Sangül (Ref. 14) stated that the sensitivity analysis is a very useful tool due to its simplicity in implementing all mathematical models and the inclusion of information about cross correlations between the process parameters. Therefore, considering that welding is highly dependent on the input variables and the increasing industrial need to implement new methods that combine adequate economic advantages in automated versions, this statistical analysis can guarantee that the resulting geometry would be in accordance with the design requirements.

Furthermore, in an optimization process, this sensitivity analysis can indicate which variable has the greatest influence on the objective parameters, as well as the variables that are not affected by the input variables, thereby providing a very clear indication of what must be performed to obtain a specific geometry for the manufacturing requirements. Additionally, this sensitivity analysis also provides an indication of how much the objective variable is affected, in contrast to the one-factor-at-a-time approach, which consists of incrementally increasing the input variables to determine their effects on the objective output functions (Ref. 15).

Palani (Ref. 16) developed a model for predicting the weld bead geometry in cladding produced using flux cored arc welding (FCAW). In another study, Karaoğlu (Ref. 17) performed the same sensitivity analysis for SAW and concluded that the width of the weld bead is very sensitive to the applied current, voltage, and welding speed; the height is primarily affected by the voltage; and the penetration is primarily affected by current.

The sensitivity information should be interpreted using mathematical defi-
tivation of derivatives. Namely, positive sensitivity values imply an increment in the objective function by a small change in design parameter, whereas negative values state the opposite (Ref. 17).

Therefore, a positive sensitivity value indicates that the dependent parameters increase as the independent parameters increase, whereas a negative sensitivity value indicates that the dependent variables decrease as the independent variables increase.

Furthermore, Saltelli (Ref. 18) stated the sensitivity analysis can be defined as “the study of how the variation in the output of a model (numerical or otherwise) can be apportioned, qualitatively or quantitatively, to different sources of variation.” It can also be inferred from Ref. 17 that a parameter is said to be nonsensitive when the absolute value of its sensitivity is less than 0.2.

Luo (Ref. 19) utilized regression analysis to predict and analyze the features of resistance spot welding (RSW) on galvanized steel sheets. Huang (Ref. 20) used the neural network and multiple regression methods to characterize and study the relationship between the weld penetration depth and acoustic signal acquired during laser welding (LW) of high-strength steels.

Models to predict the geometry of weld performed by GTAW have been investigated as well by several approaches. Zhang et al. (Ref. 21) used a visual identification procedure to obtain images of the weld pool in GTAW, then reconstructed these images using image processing algorithms to obtain a 3D image of it. After image processing, through experimentation, the following input parameters were selected: width, length, and convexity of the welding pool. Then, a least-square method was applied to establish regression equations between the backside bead width, which is proportional to the penetration of the weld bead, and the selected parameters as input, taken independently and in a combined way.

Liu et al. (Ref. 22) used the same visual acquisition system to generate a 3D image of the weld pools in GTAW and then correlate backside width to correct predicted penetration, but instead of using a least-square method to calculate the equations, it uses a neuro-fuzzy inference system (ANFIS) due the nonlinearity of the phenomenon studied.

Liu et al. (Ref. 23) also modeled the GTA weld pool to predict its width, length, and convexity to obtain equations to predict these parameters taking into account the welding current and speed as characteristic parameters. A predictive control algorithm is developed to control the aforesaid features of the weld pool, which does not need online optimization.

More recently, Shi (Ref. 24) employed the multiple curvilinear regression method and sensitivity analysis to investigate the influence of welding parameters on the geometry of the resulting weld bead in underwater wet flux cored arc welding (FCAW).

Xiong (Ref. 25) used a statistical approach consisting of a neural network model and a second-order regression analysis to predict the bead geometry for robotic GMAW-based rapid manufacturing.

Although MRA and sensitivity analysis have long been used for predicting the weld bead geometries of several welding processes, such as GMAW

Table 4 — Geometric Parameters Calculated Using the Curvilinear Regressive Model

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Bead Width (mm)</th>
<th>Bead Height (mm)</th>
<th>Bead Penetration (mm)</th>
<th>Dilution (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>14.77</td>
<td>3.21</td>
<td>3.29</td>
<td>49.26</td>
</tr>
<tr>
<td>2</td>
<td>14.42</td>
<td>3.69</td>
<td>2.80</td>
<td>39.79</td>
</tr>
<tr>
<td>3</td>
<td>14.21</td>
<td>4.01</td>
<td>2.55</td>
<td>35.12</td>
</tr>
<tr>
<td>4</td>
<td>13.69</td>
<td>4.29</td>
<td>2.44</td>
<td>32.18</td>
</tr>
<tr>
<td>5</td>
<td>13.25</td>
<td>4.53</td>
<td>2.37</td>
<td>30.08</td>
</tr>
<tr>
<td>6</td>
<td>15.81</td>
<td>3.54</td>
<td>4.30</td>
<td>49.58</td>
</tr>
<tr>
<td>7</td>
<td>15.66</td>
<td>4.05</td>
<td>3.61</td>
<td>40.02</td>
</tr>
<tr>
<td>8</td>
<td>15.44</td>
<td>4.40</td>
<td>3.29</td>
<td>35.32</td>
</tr>
<tr>
<td>9</td>
<td>16.21</td>
<td>4.56</td>
<td>2.92</td>
<td>32.23</td>
</tr>
<tr>
<td>10</td>
<td>15.17</td>
<td>4.88</td>
<td>2.92</td>
<td>30.18</td>
</tr>
<tr>
<td>11</td>
<td>16.19</td>
<td>3.90</td>
<td>5.56</td>
<td>49.93</td>
</tr>
<tr>
<td>12</td>
<td>16.44</td>
<td>4.42</td>
<td>4.57</td>
<td>40.25</td>
</tr>
<tr>
<td>13</td>
<td>16.21</td>
<td>4.80</td>
<td>4.16</td>
<td>35.53</td>
</tr>
<tr>
<td>14</td>
<td>16.49</td>
<td>5.04</td>
<td>3.79</td>
<td>32.47</td>
</tr>
<tr>
<td>15</td>
<td>16.14</td>
<td>5.30</td>
<td>3.65</td>
<td>30.34</td>
</tr>
</tbody>
</table>

Fig. 9 — Values estimated by the curvilinear regression model plotted against the measured values. A — Width; B — height; C — penetration; and D — dilution.
Experimental Procedures

Cold Wire Gas Metal Arc Welding (CW-GMAW)

The CW-GMAW process essentially consists of introducing a nonelectrode wire into the electric arc region, which is subsequently melted and deposited on the base metal. According to Ref. 26, the primary advantages of CW-GMAW are that it has all the advantages of GMAW plus a cooler weld pool, it can be utilized in all welding positions, the additional wire can be conventional or flux-cored, and it can achieve good weld bead quality and high deposition rates.

The general scheme for CW-GMAW is illustrated in Fig. 4.

This process consists of the following input variables: welding speed, shielding gas flow rate, contact tip-to-workpiece distance, plus current, voltage, and feed rate of the electrode and cold wire. However, in this study, only the electrode feed rate, current, and nonelectrode feed rate ratio will be considered as input variables. The cold wire feed rate ratio is a percentage of the electrode feed rate, and it is called the nonelectrode feed rate ratio (%), defined as follows:

\[ R = \frac{W_s}{E} \times 100 \] (2)

where \( W_s \) is the cold wire feed rate in m/min and \( E \) is the electrode feed rate in m/min. These variables and the arc current in amperes (A) play a major role in the geometry of the resulting weld.

Still, regarding the process, it is worthy to mention that wires can be different in diameter, and the cold wire is thinner than the hot wire. As the cold wire is melted by the heat that otherwise would be lost and/or transmitted to the base metal, it is believed that having a minor diameter would improve the melting, while having a larger diameter would decrease the heat input to the workpiece.

An interesting feature of CW-GMAW is that the process just needs an independent wire feeder to inject the cold wire into the arc, so the welding apparatus is slightly conventional and does not represent a huge impact.
on costs regarding the welding system configuration.

Figure 5 illustrates the actual CW-GMAW experimental setup used to perform the experiments for the present study.

**Equipment and Materials**

In this study, a Digiplus A7 electronic welding power supply operated at a current of 400 A was used to produce the weld bead. The electrode feeder was an IMC STA-20D, and an additional wire feeder (ESAB MEF 30) was used to feed the cold wire. The employed welding gun was an automated, water-cooled GMAW TBi 511 with a maximum current of 400 A. The shielding gas was a mixture of 25% CO$_2$ and 75% argon (Ar) with a constant volumetric flow rate of 15 L/min.

The base metal used in this work was a normalized structural steel with an ASTM A131 grade A classification, which is normally used in ship construction. This steel possessed a low level of carbon, and its chemical composition is shown in Table 1 (Ref. 27). The wires had an AWS ER70S-6 classification, and two different diameters of wires were used. The electrode wire had a diameter of 1.2 mm, and the nonelectrode wire had a diameter of 1.0 mm. The chemical composition of the wires is shown in Table 1 (Ref. 28).

**Experimental Procedure**

The experiments were conducted using an average constant voltage of 37 V; electrode feed rates of 10, 12, and 14 m/min; and nonelectrode rate ratios of 20, 40, 60, 80, and 100%, as shown in the fluxogram presented in Fig. 6. Average current levels of 300, 340, and 380 A were used during the experiments. It was performed as 15 experimental runs with one replicate for each, totaling 30 experiments.

The welding position was flat (1G) with automatic horizontal displacement in the wire feed direction, which guaranteed the injection of wire in front of the electric arc and welding pool. The angle between the welding gun and cold wire feeder tip was $\beta = 61$ deg, and the work angle and the angle of attack were 90 deg, as measured relative to the metal base plate; this configuration is illustrated in Fig. 2.

To measure the output variables, transverse cross sections were created in every weld using a Powermaq BS-912B hacksaw from the mid-length of the welds. The cross sections were polished and etched with 6% Nital to measure the width, height, penetration, and dilution. Note that dilution is an important parameter in deposition welding because a coating with excessive dilution could alter the chemical composition of the deposited metal and consequently change its mechanical behavior during service. Therefore, accurately predicting the dilution of a weld bead produced using CW-GMAW is fundamental for guaranteeing the quality of the process. Hence, this paper provides a regression for predicting dilution.

The influences of the volumetric

**Table 6 — Residuals Between the Measured Values from the Verification Experimental Runs and the Predicted Values**

<table>
<thead>
<tr>
<th>Residuals Width (mm)</th>
<th>Residuals Height (mm)</th>
<th>Residuals Penetration (mm)</th>
<th>Residuals Dilution (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.34</td>
<td>–0.07</td>
<td>1.53</td>
<td>8.67</td>
</tr>
<tr>
<td>0.92</td>
<td>–0.15</td>
<td>0.87</td>
<td>3.90</td>
</tr>
<tr>
<td>0.35</td>
<td>0.10</td>
<td>1.10</td>
<td>3.97</td>
</tr>
<tr>
<td>1.31</td>
<td>–0.14</td>
<td>1.04</td>
<td>8.51</td>
</tr>
<tr>
<td>2.47</td>
<td>0.62</td>
<td>–0.53</td>
<td>13.53</td>
</tr>
<tr>
<td>1.52</td>
<td>–0.02</td>
<td>0.82</td>
<td>8.65</td>
</tr>
<tr>
<td>0.94</td>
<td>–0.04</td>
<td>0.39</td>
<td>4.34</td>
</tr>
<tr>
<td>1.99</td>
<td>–1.08</td>
<td>1.89</td>
<td>13.47</td>
</tr>
<tr>
<td>1.48</td>
<td>0.05</td>
<td>0.45</td>
<td>–5.43</td>
</tr>
<tr>
<td>0.20</td>
<td>1.13</td>
<td>–1.35</td>
<td>–5.09</td>
</tr>
</tbody>
</table>
flow rate, welding speed, and welding angle were not investigated in this study and thus maintained constant during the experiments.

Mathematical Model

Chandel (Ref. 29) was the first to propose such mathematical models for investigating the relationships between the bead geometry and process parameters for GMAW. Regarding the curvilinear model, according to McGlone (Ref. 30) and Kim (Refs. 12, 13), the relationship between the input and the output variables follows a relation such as that in Equation 3.

\[ f = b_1 R^{b_2} E^{b_3} I^{b_4} \] (3)

where \( f \) might be any of the output weld bead geometric parameters mentioned earlier, \( I \) is the current in amperes (A), \( E \) is the electrode feed rate in (m/min), \( R \) is the nonelectrode (wire) feed rate ratio in (%), as defined by Equation 1 in the introduction, and \( b_1, b_2, b_3, \text{and } b_4 \) are the regressor coefficients to be estimated by the regressive method.

Equation 3 can be written as follows:

\[ \ln(f) = b_1 + b_2 \ln(I) \]
\[ + b_3 \ln(E) + b_4 \ln(R) \] (4)

Equation 4 is linear and can be rewritten as follows:

\[ F = b_1 + b_2 K(I) \]
\[ + b_3 K(E) + b_4 K(R) \] (5)

where \( F = \ln(f) \) and \( K \) is the natural log of the input variables. The \( b \) coefficients can ultimately be estimated using a linear regressive method. In the present work, Microsoft® Excel® software was used to perform this analysis.

ANOVA was also performed to determine how realistic the models are, and similar to the regressive relations, ANOVA was performed using Microsoft Excel.

Results and Discussion

Multivariate regressive curvilinear analysis was performed based on the results shown in Table 2.

Figure 7 shows the macrograph for all the samples from where the measurements presented in Table 2 were taken.

Applying the above-described procedure yielded the following equations for predicting the geometric features of the weld bead:

Penetration (P) [mm]:

\[ P = 11.6279 - \frac{E^{2.0247}}{I^{0.9166}R^{0.2324}} \] (6)

Width (W) [mm]:

\[ W = 0.0847 + \frac{I^{1.0230}}{E^{0.2472}R^{0.0349}} \] (7)

Height (H) [mm]:

\[ H = 2.6191 - \frac{I^{-0.3840}}{E^{-0.7756}R^{0.2026}} \] (8)

Dilution (D) [%]:

\[ D = 140.8586 - \frac{I^{-0.0486}}{E^{-0.0486}R^{0.3061}} \] (9)

Table 3 presents the statistical output indices from the regression analysis and ANOVA. The RSS is the sum of the squares of the residuals and indicates a better fit when it is closer to 0. The MRS is the mean root square of the residuals and indicates the model is good as it approaches 0. The significance F value is an indication of how strong the regression is, and a small significance F value confirms the validity of the regression output.

As shown in Table 3, although the \( R^2 \) values for penetration and dilution are less than 0.90, the significance F values for these two parameters are still small, which indicates a meaningful correlation.

Furthermore, according to Montgomery (Ref. 15), it is better to check the model adequacy based on the analysis of variance only after exam-
in the vast majority of this predicted geometric feature investigated, both the measured and predicted value of width, height, penetration, and dilution. Although there are points of high relative residual error, this does not invalidate the model, because in the majority of the weld’s geometry was cases predicted with regular accuracy.

**Sensitivity Analysis**

Using Equations 6–9, sensitivity analyses were performed for the independent process variables investigated in this study. To calculate these relations, Equations 6–9 were differentiated with respect to the independent process variables.

The sensitivity equations for width are as follows:

\[
\frac{dW}{dE} = 0.08661 \frac{1}{E^{0.2472} R^{0.0349}}
\]

(12)

\[
\frac{dW}{dR} = -0.00291 \frac{1}{E^{0.2472} R^{1.0349}}
\]

(13)

The sensitivity equations for height are as follows:

\[
\frac{dH}{dE} = 2.0313 \frac{1}{E^{0.2244} R^{1.3840}}
\]

(14)

\[
\frac{dH}{dR} = -1.0057 \frac{1}{1.3840 R^{0.0206}}
\]

(15)

\[
\frac{dH dR}{dI} = 0.5306 \frac{1}{E^{0.7756} R^{0.7974}}
\]

(16)

The sensitivity equations for penetration are as follows:

\[
\frac{dP}{dE} = 23.543 \frac{1}{E^{0.9166} R^{0.2324}}
\]

(17)

\[
\frac{dP}{dR} = -10.6581 \frac{1}{E^{0.9166} R^{0.2324}}
\]

(18)

\[
\frac{dP}{dI} = -2.7023 \frac{1}{E^{0.9166} R^{0.2324}}
\]

(19)

The sensitivity equations for dilution are as follows:

\[
\frac{dD}{dE} = 9.1276 \frac{1}{E^{0.4868} R^{0.3081}}
\]

(20)

\[
\frac{dD}{dI} = -6.8457 \frac{1}{E^{1.0488} R^{0.3081}}
\]

(21)

\[
\frac{dD}{dR} = -43.3985 \frac{1}{E^{0.0488} R^{1.3081}}
\]

(22)

Figure 12 shows the sensitivity of the bead width to each of the input pa-
As shown in Fig. 12A, the width has a negative sensitivity to \( E \), and it is approximately constant for each value of \( R \) but decreases with increasing current.

Figure 12B shows the sensitivity of the bead width to current, which is positive, indicating that an increase in current increases \( W \), but it is approximately constant for variations in \( R \).

Figure 12C shows the sensitivity of the bead width to \( R \), which is negative, indicating that an increase in \( R \) will decrease \( W \). In addition, the sensitivity decreases as \( R \) increases. However, according to the criterion established above, the sensitivity is negligible when its absolute value is less than 0.2. Therefore, the width is said to be nonsensitive to \( I \) and \( R \).

Figure 13 shows the sensitivity of the bead height to \( E \), \( R \), and \( I \).

Figure 13A shows the sensitivity of the bead height to \( E \), which is positive, and it increases as \( R \) increases but decreases as the average current increases.

Figure 13B shows the sensitivity of the bead height to \( I \), which is negative and practically equal to that of \( R \).

Figure 13C shows the sensitivity of the bead height to \( R \), which is positive as \( R \) decreases but practically constant with different levels of \( E \) and average current. The absolute values of the sensitivity of the bead height to \( I \) and \( R \) are small, < 0.2, which can be considered nonsensitive.

Figure 14 shows the sensitivities of penetration to each of the input variables.

Figure 14A shows that penetration is more sensitive to \( E \) than to \( R \) and \( I \), indicating that \( I \) and \( R \) practically do not affect penetration.

Figure 14B shows the sensitivity of penetration to current \( I \), which is practically constant and equal to zero.

Figure 14C shows the sensitivity of penetration to \( R \), and it can be observed that penetration is more sensitive to the lowest value of \( R \); furthermore, this sensitivity is negative, indicating that \( P \) decreases as \( R \) increases.

Figure 15 shows the sensitivity of dilution to \( E \), \( I \), and \( R \).

Figure 15A shows the sensitivity of dilution to \( E \), which is positive and decreases as \( R \) and \( E \) increase. It can be observed that dilution is more sensitive to lower values of \( E \) and \( R \).

Figure 15B shows that the sensitivity of dilution to current is negative, this negative sensitivity increases as \( R \) increases, and dilution is more sensitive to higher values of \( R \) and to lower values of \( E \).

The sensitivity of dilution to \( R \) is shown in Fig. 15C and is negative, which indicates a negative relation among dilution and \( R \) that diminishes as \( R \) increases, indicating that the sensitivity of dilution to \( R \) is higher for lower values of \( R \) and is approximately nonsensitive after a certain value of \( R \). It can also be observed that the sensitivity of dilution to \( R \) is almost not influenced by the value of \( E \).

As previously mentioned, in CW-GMAW, dilution has a negative sensitivity to current, as shown in Fig. 15B. This is a characteristic of CW-GMAW. Note that this increase in current is used to melt the extra wire being fed rather than to provide more heat directly to the base metal. Furthermore, because the power supply used was a constant voltage machine and due to the dynamic control of arc length, the introduction of the second wire in the electric arc region shortened the arc length and decreased its voltage. Therefore, the power supply was required to increase the current to establish the previously set welding voltage.

**Conclusions**

In this study, the input variables current, electrode feed rate, and non-electrode (wire) feed rate ratio were investigated to establish a regression between them that could explain or predict the geometric features of a weld bead.

The regressions in this study resulted in good accuracy between the calculated data and measured data, and the regressions were submitted to a sensitivity analysis to determine how the objective functions are influenced by the independent variables.

The errors of the regressions used in this study were less than 15% for the majority of the specimens, indicating that the results obtained in the present study are trustworthy and can be employed in engineering applications to predict the geometries of weld beads.

The relationship between the penetration and electrode feed rate showed a positive sensitivity, which decreased with the increasing nonelectrode ratio.

Regarding CW-GMAW, it was found that the current has an inverse relationship to the penetration, which could be explained by the introduction of another wire that must be heated to be deposited on the plate, thereby taking heat from the electric arc, acting as a heat sink, and consequently decreasing the energy transferred to the base metal compared with that in conventional GMAW.

There are sensitivities, such as the width to \( E \) (\( dW/dE \)), width to \( I \) (\( dW/dI \)), height to \( I \) (\( dH/dI \)), and dilution to \( E \) (\( dD/dE \)), that are minimally influenced by the values of \( R \), remaining essentially constant for the range of \( R \) investigated in this study.

According to the criterion inferred from Ref. 17, the sensitivity is negligible if its absolute value is less than 0.2. The width, height, and penetration are only sensitive to the electrode feed rate \( (E) \), whereas dilution is sensitive to all three input variables investigated in this study. Dilution is most influenced by the welding current and nonelectrode feed rate ratio \( (R) \).

The novelty of this study is the application of already consolidated statistical methods used to predict the resulting weld geometry of well-established welding processes to predict the geometries of weld beads produced using CW-GMAW, which is still under development. Thus, this study contributes to a better understanding of how the process variables influence the resulting weld bead geometry.

The results of the present study can be used as a basis for optimizing the geometries of weld beads produced using CW-GMAW in a future study, considering that one of the major concerns in industry is the optimization of welding processes to obtain high productivity, similar to how CW-GMAW achieves high productivity through a second wire being melted and deposited.

The analyses performed in the present work are also a necessary step toward automation of CW-GMAW, as prediction is the first step for implementing a closed-loop feedback system.

In the present study, the influence of parameters such as the type of gas...
and its volumetric flow rate, welding speed, welding angle, angle of injection of the cold wire, and plate thickness were not included as variables in the regressive model. Therefore, they represent limitations of the study and should be addressed in future studies.

As the present study configures an initial work on the prediction of CW-GMAW, the authors recognize that a deeper investigation on the prediction of the final geometry generated by CW-GMAW should be conducted for the development of more precise prediction models. The new study should include variables such as welding speed and voltage, and employ the design of experiments (DOE) technique.

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