Prediction of bead geometry on filling cavities in hydroelectric turbine blades by means of robotic welding

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Abstract. This paper presents a methodology of mapping the bead geometry, deposited on a fillet like joint, as a function of the input parameters of the synergic pulsed gas metal arc welding process and the welding position, to allow the planning of repairing hydroelectric turbine runner blades by means of robotic welding. The challenges of automating the repair process; further, to choosing the best welding parameters, include the definition of the path that the robot must follow during the metal deposition, such that it is able to fill completely the damaged blade cavity, by means of producing overlapped layers from several individual weld beads. Thus, this research focused on developing statistical prediction models that could map the geometric variations of the weld bead section as function of the input parameters (wire feed speed, welding speed and bead face rotation angle). For this purpose, the bead section was approximated by a parallelogram whose height, width and inclination angle were considered as dependent variables. Several welding trials were carried out according to a central composite experimental design and three multiple regression models were obtained. Here, the physics is used to interpret the influence of the input parameters on the output results.

1. Introduction
Hydroelectricity is considered as a renewable energy source, clean and inexpensive [1]. Hydroelectric turbines are equipment designed to transform hydraulic energy into mechanical work; for the generation of electrical energy, the turbines are coupled to an electrical generator, maintaining its rotation in constant value to guarantee the frequency to the network. Depending on the energy potential of the river, the geometry of the blades of hydroelectric turbines are different; as a consequence of the mechanical stress, which arise during its operation, various types of mechanical wear occur more frequently in the blades of electric turbines [2].

Among the possible wear, is the progressive loss of original material from the solid surface of the blade, due to continuous exposure to cavitation erosion; another possible wear is the development of fatigue cracks in regions of high stress concentration, which occurs in a localized and progressive way [1]. To restore the original geometry of the blade surface, the welding process is the best option. A metal of chemical composition that is like the metal of the damaged region is deposited [1,2]. Pulsed gas metal arc welding (GMAW-P) process is one of the methods used for this type of repair, because it presents better levels of productivity [3,4].

Goyal, et al. [5] concluded that GMAW-P is a welding process that keeps the arc stable at higher wire feed speeds and at the same time requires less energy for the welding process. Thomsen [6] reported
that this pulsed process allows the arc energy to be used efficiently, reducing the heat input in the welded area and in this way the deformations with the base material are reduced. Likewise, it is used for the welding of almost any type of material and in any welding position, including the overhead [5].

According to Tham, et al. [7] and Joseph, et al. [8] for out-of-position welding it is necessary to reduce the heat input in such a way that the weld pool size is kept small enough such that the combination of the arc pressure and the molten metal surface tension overcome the gravity force acting on the liquid metal, which tends to spill it out of its position. As defined by Alegasan, et al. [9] to oppose the effect of gravity, the welding gun must be controlled, and the optimal parameters selected to obtain weld beads with the desired geometry.

The fact of being able to interact on a great diversity of welding parameters generates a wide range of possibilities during the process. Therefore, the welding variables that directly influence the geometry of the weld bead are chosen. In this way, statistical methods make it possible to relate the main variables of the process with the shape of the weld bead. The response surface methodology (RSM) is one of the techniques that allows establishing the relationship between the response variables (output) and the input factors. Xu, et al. [4] obtained four mathematical models on the geometry of the bead for different welding positions, by means of the gas metal arc welding (GMAW) process.

Likewise, Kim, et al. [10] included the welding position input variable to determine three empirical models, selecting the optimal conditions in root pass welding of pipes. The GMAW was applied for root pass welding in three kinds of welding positions 0° (1G - butt groove joint in flat position), 90° (3G - butt groove joint in vertical position), and 180° (4G- butt groove joint in overhead position). Koleva [11] adjusted four mathematical models which allowed him to empirically establish the type of relationship that exists between thermal efficiency and geometric characteristics in the electron beam welding process.

The quality of the equation of other mathematical models developed to predict the dimensions of the weld bead as a function of the operational variables were verified using the coefficient of determination and the Fisher test [4,12,13]. Although several statistical designs have been developed to predict the geometry of the bead, only two authors mentioned the welding position within the input variables of their experiments [4,10]. In line with this, this study aims to define statistical models that can predict the geometry of the weld bead based on operational variables such as the bead face rotation angle and the main GMAW-P parameters, applied to welding fillet joints. To achieve different welding positions, it was decided to rotate the joints from 1F to 2F and to 4F position [14].

The experiments were carried out based on a factorial design to define the weld runs necessary to determining mathematical models that would map and the output geometric bead dimensions as compared with the shape of a parallelogram. The responses of the models such as height, width, and angle of inclination of the parallelogram were developed as a function of the operational variables of welding and the face rotation angle.

2. Methodology and materials
In order to fulfill the central purpose of this work, the experimental research was developed in several stages. The stages were distributed as follows. Stage 1: initial parameters, stage 2: experimental procedure and stage 3: model of the geometry of the weld bead.

2.1. Initial parameters
The welding variables directly influence the geometry of the bead; according to the research works of Palani, et al. [15] and Alagesan [9], main variables such as wire feed speed, welding speed and bead face rotation angle, were chosen. Several weld depositions were carried out on the AISI 1020 base material in order to observe the behavior of each of the variables. The welding variables allowed the tests to be carried out in various welding positions, such as flat, horizontal, and overhead. The variables that registered a stable arc in the weld beads and maintained a minimum of weld spatter and porosities were selected as the subject of study.
Additionally, the weld gun was oriented in such a way as to counteract the effect of gravity on the molten metal of the weld pool, by means of providing a component of the arc pressure in the opposite direction of the gravity acceleration vector [7,9,16]. Figure 1 presents the front view of a fillet like joint in the flat position (face rotation angle = 180° relative to the gravity acceleration vector) and six other face rotation angles, corresponding to the variations of 30° starting from 180° (flat position) up to 360° (overhead position).

![Figure 1. Schematic diagram of welding flat position.](image)

To study the influence of the three independent welding variables on the geometry of the bead, a central compound design (CCD) was applied. Design and their levels are listed in Table 1. The CCD experimental design was chosen since it normally delivers more satisfactory polynomial models [17]. The independent variables were wire feed speed (X1), welding speed (X2), and weld face rotation angle (X3).

| Wire feed speed (X1, m/min) | Welding speed (X2, mm/s) | Weld face rotation angle (X3, °) |
|---------------------------|--------------------------|---------------------------------|
| 6.5 (-1)                  | 9.0 (-1)                 | 216.5 (-1)                      |
| 7.0 (0)                   | 10.0 (0)                 | 270.0 (0)                       |
| 7.5 (+1)                  | 11.0 (+1)                | 323.5 (+1)                      |

Table 2 presents the welding parameters selected for the pulsed GMAW metal transfer mode used in the welding trials [18]. As reported by Lázaro [18], these welding parameters resulted in weld beads with good appearance and quality in any position.

![Table 2. Pulsed GMAW welding parameters.](image)

| Wire feed speed (m/min) | Average current (A) | Period (ms) | Peak time (ms) | Background current (ms) | Peak current (A) | Background current (A) |
|-------------------------|---------------------|-------------|----------------|-------------------------|------------------|------------------------|
| 7.0                     | 186                 | 6.9         | 2.4            | 4.45                    | 380              | 80                     |
| 7.5                     | 195                 | 6.4         | 2.4            | 3.97                    | 380              | 80                     |
| 8.0                     | 204                 | 6.0         | 2.4            | 3.60                    | 380              | 80                     |

2.2. Experimental procedure
To carry out the experiments, a lap joint was assembled from two 6 mm thick mild steel plates (50 x 200 mm); the top plate was chamfered with an angle of 45 deg, the opening angle between the two plates resulted in 135°. The shielding gas (mixture of 96% Ar + 4% CO₂) flow rate was set at 15 liters/min and kept constant during the welding process; as filler material, a 1.2 mm diameter metal cored tubular wire (AWS 410 NiMo) was used. In all experiments, a workpiece to contact tip distance (CTWD) of 16 mm was used. Each of the resulting weld beads were cut in cross section and went through a polishing process.
The samples were prepared for macrographic analysis by etching with 2% NITAL solution for 20 seconds [19]; an Olympus confocal laser scanning microscope was used to measure the characteristics of the weld beads. The geometric characteristics of the weld bead such as the height (H), the width (W) and the angle of inclination (α) of the weld bead, were compared with the shape of a parallelogram as shown in Figure 2.

![Figure 2. Representation of weld bead geometry parameters measured in GMAW-P.](image)

2.3. Model of the geometry of the weld bead

Using the polynomial regression method contained in the Design-Expert r. 13 software [20], the effects of the three independent variables (wire feed speed, welding speed and face rotation angle) on the geometry of the weld bead were analyzed. The bead height (H), the bead width (W) and the angle of inclination (α) were considered as dependent variables (responses). The analysis allowed obtaining initially three full second order polynomial multiple regression models.

The analysis of variance determined the significance of each of the factors (zero order, first order and second order factors). Factors that presented low levels of significance were removed from the models and new regression models were obtained until all the factors considered presented the acceptable significance level [17]. In addition, using Fisher’s F test and the coefficient of determination (R²), the quality of the polynomial equations was verified.

3. Results and discussions

The experimental trials made it possible to define whether the studied factors have statistically significant effects on the response variable; gravitational force has a direct relationship on the bead geometry. The geometry of the weld bead changes when the parameters are varied, and the sample is rotated; therefore, the welding gun was positioned in such a way that it can counteract the effect of gravity on the weld bead. To analyze the results obtained derived from the central composite design, the response surface methodology was used. The probability value (p-value) was used as a tool to check the significance of the model and each coefficient. The p value indicates that the association of the variable is statistically significant. A 95% security implies a p less than 0.05; with these considerations, factors with a p value greater than 0.05 were eliminated.

Considering the significant factors and their interactions, a new mathematical model was produced for each of the dependent variables. The second order polynomial model can be used to estimate the mathematical relation between the three independent variables. Second order regression models are shown in Equation (1), Equation (2), and Equation (3), where $\xi_1$ is the wire feed speed (m/min), $\xi_2$ is the welding speed (m/min), and $\xi_3$, the weld face rotation angle (degrees). Equation (1) shows the resulting regression model that approximates the relationship between the input variables on the bead height (H).

\[
H = 28.88 - 6.364\xi_1 + 1.031\xi_2 - 0.072\xi_3 + 0.348\xi_1^2 + 0.00015\xi_3^2 + 0.0064\xi_1\xi_3 - 0.0045\xi_2\xi_3.
\]
Equation (2) shows the resulting regression model that approximates the relationship between the input variables on the bead width (W).

\[
W = 51.325 - 9.238\xi_1 - 4.177\xi_2 + 0.046\xi_3 + 0.751\xi_1^2 + 0.188\xi_2^2 - 0.000109\xi_3^2. \tag{2}
\]

Equation (3) shows the resulting regression model that approximates the relationship between the input variables on the inclination angle (\(\alpha\)).

\[
\alpha = 171.928 - 0.815\xi_1 + 2.56\xi_2 - 1.033\xi_3 + 0.00179\xi_3^2 + 0.018\xi_1\xi_3. \tag{3}
\]

Such models do not have a physical meaning at first, since they were obtained by a statistical method and their validity can only be assured within the studied range of variation used for the input variables; however, it is possible to analyze them considering the known effects of the input variables on the bead geometry. For a stable process to be achieved, it is imperative that the wire feed speed is equal to the wire fusion rate; this, in turn, is knowingly a function of the welding current, which strongly influences the heat input the process imposes to the base material.

A higher wire feed speed implies in a greater amount of heat transferred to the weld pool as well as in a greater amount of filler material; these can interact with the gravity action, thus making it more difficult to stabilize the weld pool. From the models in Equation (1) and Equation (2), it is possible to observe that the coefficients for the first order effects of the welding speed (\(\xi_2\)) agree with the above explanation, since increasing the welding speed tend to increase the bead height (H) and to decrease the bead width (W). It might be important to notice that both the bead height and the bead width are affected not only by the wire feed speed and the welding speed, but also by the face rotation angle, which, together with the weld pool size, has a strong effect on the bead geometry, as stated before.

The inclination angle, on the other hand, is related not only to the direction to which the molten metal flows out as a result of the combined action of the gravity and the contrary arc pressure component, but also to the weld pool wettability on the base material, which is influenced by both the temperatures of the molten metal and the base metal, that are also dependent on the rate at with the heat is transferred from the arc to the weld pool and from this to its vicinities.

After obtaining the mathematical models, seven experimental tests were carried out, to validate the equations. The tests were carried out considering various positions of the workpiece, from position 1F to position 4F. As defined by Xu, et al. [3], the percentage of error (\(\%\)) can be calculated using the Equation (4). Where AV represents the actual value, and PV is the predicted value.

\[
(\%) = 100 \times (AV - PV)/PV. \tag{4}
\]

Table 3 shows the new tests for each of the dependent variables; the estimate of the measured and predicted value of the weld bead was calculated. The quality of the polynomial equation was verified using the coefficient of determination (\(R^2\)). The \(R^2\) value was 0.95, 0.92, and 0.74 for the variables of the height of the bead (H), the width of the weld (W) and the angle of inclination (\(\alpha\)), respectively; this expressed that 95% of the variables studied were attributed to the weld bead height model. For the mathematical model the width of the weld bead was assigned 92% and for the polynomial equation of the angle of inclination it was assigned 74%.

A coefficient of determination close to 100% and a lower standard deviation, the results are closer to the real value [19]. Under these considerations, the model for the height of the weld bead registered one of the smallest standard deviations of 0.17. Therefore, the height model expressed a more approximate value of the response, compared to the width model (0.32) and angle of inclination of the weld bead (3.44); however, the statistical results indicated that the three models found were adequate to predict the geometric dimensions of the chord such as height, width, and angle of inclination.

The three variables studied had a great effect on the geometry of the weld bead. Figure 3 presents the effect of wire feed speed on the geometry of the weld bead. An increase in wire feed speed means...
an increase in the height and width of the weld bead. Figure 3(a) shows the effect of welding speed and wire feed speed on weld bead height. In the same way, Figure 3(b) reflects the effect of welding speed and wire feed speed on the width of the weld bead.

The mathematical models found allow to calculate the geometry of the weld bead. The dependent variables were related to the shape of a parallelogram; it was possible to observe that, the value of the width of the weld bead (W) increased from position 1F to position 2F. The opposite case occurred with the height of the weld bead; it decreases from position 1F to position 2F. However, he showed an increase from position 2F to position 4F. Observation that agrees with other authors [7,9,16] and can be explained by the expected effects the gravity might have on the weld pool as its face rotation angle varies from the flat to the overhead position, passing through the horizontal position.

Table 3. Estimation of the measured and predicted value of the weld bead.

| Variable | Run | 1   | 2   | 3   | 4   | 5   | 6   | 7   |
|----------|-----|-----|-----|-----|-----|-----|-----|-----|
| ξ₁ (m/min) |     | 7.5 | 7.5 | 7.5 | 7.5 | 6.5 | 6.5 | 6.5 |
| ξ₂ (mm/s)  |     | 11.0| 11.0| 11.0| 11.0| 11.0| 11.0| 11.0|
| ξ₃ (deg)   |     | 180.0| 210.0| 240.0| 270.0| 300.0| 330.0| 360.0|
| Predicted  |     |     |     |     |     |     |     |     |
| H (mm)     |     | 3.6 | 3.0 | 2.6 | 2.5 | 2.5 | 2.8 | 3.4 |
| W (mm)     |     | 5.0 | 5.2 | 5.1 | 4.3 | 3.9 | 3.4 | 2.6 |
| α (deg)    |     | 23.8| 21.5| 20.2| 19.4| 18.0| 19.9| 22.8|
| Measured   |     |     |     |     |     |     |     |     |
| H (mm)     |     | -2.8| 10.0| -7.7| 4.0 | -8.0| 3.6 | -8.8|
| W (mm)     |     | 8.0 | -5.8| -5.9| 9.3 | 10.3| 8.8 | 3.8 |
| α (deg)    |     | -8.0| -11.2| -13.4| 15.5| 10.6| 17.6| -10.5|
| Error (%)  |     |     |     |     |     |     |     |     |
| H (mm)     |     | -2.8| 10.0| -7.7| 4.0 | -8.0| 3.6 | -8.8|
| W (mm)     |     | 8.0 | -5.8| -5.9| 9.3 | 10.3| 8.8 | 3.8 |
| α (deg)    |     | -8.0| -11.2| -13.4| 15.5| 10.6| 17.6| -10.5|

Figure 3. Effect of welding speed vs wire feed speed on weld bead geometry; (a) bead height; (b) bead width.

4. Conclusions
This research focused on developing statistical prediction models that could map the geometric variations of the weld bead section as function of the input parameters. The validation of the models indicated that the predictions of the height and width of the weld bead are closer to the true value. In the case of the inclination angle model, it presented greater errors, values above 10%. The independent variables reflected their importance, as main effects and as interaction effects. The quality of each of the polynomial equations was verified using the coefficient of determination. For the height of the bead and width of the bead, the responses had a coefficient of determination greater than 0.9.

On the other hand, for the angle of inclination, the responses had a completion coefficient lower than 0.9 but higher than 0.75. it was observed that the height of the weld bead increases as the wire feed speed increases. This same increase was observed when measurements were made in the position from position 2F to position 4F. However, the height of the weld bead decreased with the change of position...
from position 1F to position 2F. When the same parameters were used, weld position 1F achieved difference in height and width in the weld bead, compared to weld position 2F. Position 4F generated a greater height of the weld bead. It was observed that the direction of gravity has a direct relationship on the bead geometry.

The metal deposited to the joint tends to sag on the plate, resulting in a bead with a reduction in the height and an increase in the width. Therefore, the welding gun was positioned in such a way that it can counteract this effect of gravity on the weld bead. To prevent this, in future research a possible solution is to keep the molten puddle small. The pulsed mode welding process was chosen, the selection of its parameters allowed to obtain weld beads with an excellent appearance and with little material spatter. In addition, this process is used for the welding of any metallic material and in any welding position, including the overhead.

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