Representation of gas metal arc pulsed welding process behavior on bead geometry: a study of leading variables

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Abstract. Gas metal arc welding is one of the most influential processes in the production and repair of structures and equipment; therefore, the need to improve the productivity and quality of welded joints has led to the development of techniques for good control of welding parameters. Also, the development of semi-automatic welding processes led to the control of one of the variables such as pulsed current; this technique is characterized by a lower heat input and lower energy expenditure, which directly influences the structural quality of the welded joint and the geometry of the weld bead. This work focused on evaluating the effects of various welding operating parameters using the central composite design tool based on the response surface methodology; next, the experimental development employed an inverter type power source for weld depositions, a commercial grade Stargold clean 96% Ar and 4% CO₂ shielding gas at the rate of 15 L/min stationary arc, a 1.2 mm metal cored wire for welding deposit and a carbon steel base plate with a thickness of 6 mm. During the welding process, the torch was kept at a 90º inclination and a 16 mm stroke. To examine the adequacy of the empirical models and the significance of the regression coefficients, the variance analysis was employed. Consequently, the graphs were obtained through the determination of the model; from the statistical results obtained, it was shown that the above models were adequate to predict the weld width, bead height, and penetration within the range of variables studied. Furthermore, it was observed that the wire feed rate it has a very marked effect on weld bead geometry, followed by frequency pulse and peak current; finally, the effectiveness of employing these methodologies for the management of variables attributing to the execution of welding tasks with higher accuracy was demonstrated.

1. Introduction
Pulsed gas metal arc welding (GMAW-P) process is one of several types of welding processes, frequently employed in industry. This welding process is performed in two ways, as a manual process that depends on the welder's skills and as an automated robotic process [1,2]. Despite the advantages of this process with the conventional gas metal arc welding (GMAW), it is still not widely used because of the high complexity in the selection of its multiple variables. Joseph, et al. [3] reported that, this type of transfer is obtained when a pulsed current is used, which is alternated between a low intensity current, and a set of high intensity pulses called peak current. It is a spray type transfer mode that is produced by pulses at regularly spaced intervals with a given frequency.

The pulses allow the average current to be lower, keeping the arc stable at higher wire feed speeds and reducing the heat input [4,5]. If adequate welding parameters are chosen, the bead is expected to present an excellent appearance with little spatter and can be used for welding any type of material and...
in any welding, position including overhead. In this sense, the pulsed mode is more complex compared to the GMAW type due to the number of variables in the welding process [6]. In the case of the GMAW-P process, the bead geometry characteristics are dependent on input variables (control parameters) which are peak current, base current, peak time, base time, frequency, welding speed, wire feed speed, wire diameter, welding voltage, shielding gas composition, gas flow rate, and material composition [5]. The combination of these variables directly influences the weld bead geometry. Given this, in the present work the most influential variables were chosen as follows: peak current, base current, peak time, frequency and wire feed speed [7].

The present study investigated the empirical representation of the behavior of metal transfer in pulsed mode on the geometry of the weld deposition. For this purpose, this work focused on evaluating the effects of various welding operating parameters using the central composite design (CCD) tool based on the response surface methodology, since it is widely studied due to its significance in the control of variables.

2. Methodology and materials

La GMAW-P is technically a modified spray transfer process [3,4]. This allows the arc energy to be used efficiently by reducing the heat input in the welded zone [4]. It is characterized by a base current that keeps the arc stable and the peak current that forms and releases the molten droplets. Figure 1 shows a sketch of the time dependent welding current signal. By using the appropriate parameters, the average current and consequently the heat-affected zone can be reduced, improving transfer stability and out of position welding performance [8].

The heat input is a relative measure of the energy transferred per unit length of weld. The mechanical and microstructural properties of the weld and the heat-affected zone (HAZ) can be affected by high heat input. The wire feed speed and the parameters in pulsed mode directly influence the overheating of the welded joint [5]. The rate of heat input for a given welding condition is estimated by dividing the product of time-averaged current and voltage with the welding speed. Each pulsed GMAW wave is composed of four variables: peak current, background current, pulse time and pulse frequency. The pulse parameters have significant influence on wire feed rate [4,9]. Among the pulse parameters, the peak parameters have more influence on the wire feed rate.

The GMAW-P is versatile, and easily automated [3]. Therefore, the pulsed mode in areas of robotics and industry is increasingly employed [6]. Pulsed current contributes to good mechanical and microstructural properties especially in grain refinement of the affected area [8]. When a wire feed speed and pulsed current parameters are chosen, the pulsed mode produces a stable arc over a wide range of current and voltage parameters, and at the same time reduces spatter [6]. The spatter reduction will result in less cleaning of the parts after welding as spatter buildup on the base material and the gas nozzle of the welding gun [7]. In many applications, 98 % transfer efficiencies can be obtained, which reduces wasted filler metal [6,8].

![Figure 1. Schematic representation of a current-time diagram in GMAW-P (Ip = peak current; Tp = pulse on-time; Ib = background current; Tb = pulse off-time) [8].](image-url)
2.1. Response surface methodology
Response surface methodology (RSM) involves the application of mathematical and statistical techniques with the purpose of fitting experimental data to a polynomial equation, which allows describing the behavior of a set of values in order to make statistical predictions [10,11]. It can be applied when there is a response of interest or a set of responses that are influenced by several variables. The intention is to simultaneously optimize the levels of these variables to achieve the best performance in the welding process [12]. Prior to the application of the RSM methodology, it is necessary to choose an experimental design that defines the tests to be performed in the experimental study region [13].

For this purpose, designs for first order models (factorial) can be used when the data set does not present curvature [14]. However, for experimental data that cannot be described by linear functions, there are designs for quadratic surface responses. The CCD always contains axial points representing new extreme values (-α, α) for each factor in the design [15].

2.2. Literature review
Based on the literature survey [4,5] the most influencing parameters on the bead geometry are the peak current (Ip), the background current (Ib), the pulse frequency (f), the peak current time (tp) and the wire feed speed. Other parameters such as welding speed, voltage and distance between the SAE 1020 steel plate and the welding gun were kept constant.

To get a more satisfactory polynomial model, a CCD experimental design was applied to examine the five variables chosen, the independent variables were initial peak current (X1), background current (X2), peak time (X3), frequency (X4), and wire feed rate (X5). Table 1 shows the selected variable levels to be used for the factorial design runs.

| Peak current (X1, A) | Background current (X2, A) | Peak time (X3, ms) | Pulse frequency (X4, s⁻¹) | Wire feed rate (X5, m/min) |
|---------------------|---------------------------|-------------------|---------------------------|---------------------------|
| 360 (-1)            | 60 (-1)                   | 2.0 (-1)          | 190 (-1)                  | 7.5 (-1)                  |
| 375 (0)             | 80 (0)                    | 2.5 (0)           | 200 (0)                   | 8.0 (0)                   |
| 390 (+1)            | 90 (+1)                   | 3.0 (+1)          | 210 (+1)                  | 8.5 (+1)                  |

2.3. Factorial design
The design matrix was sixteen factorial combinations corresponding to the CCD rotatable design with five input variables; the upper limits of the design were set at +2 and -2, with ten axial points. The central point was replicated six times; a total of 32 experiments were run in the present work.

2.4. Experiment development
The base material for the development of the experiments was a SAE 1020 steel of 200 mm long, 50 mm wide with 6 mm thickness, and the filler material was 410NiMo MC wire with a diameter of 1.2 mm. The shielding gas was 96% Ar and 4% CO₂ with a flow rate of 15 L/min. The welding gun was maintained at 90° to the base metal and a distance of 16 mm using an inverter welding power source. Each of the assays were cut in cross section and underwent a polishing process.

They were then prepared for macrographic analysis by chemically etching with 2% nital solution for 20 s [16]. An Olympus confocal laser scanning microscope was used to measure weld bead characteristics, weld width (W), bead height (H) and penetration (P). The dimensioned macro image of one of the beads on plate welds is given in Figure 2.

2.5. Mathematical model
Using the polynomial regression method contained in the Design-Expert version 9.0.5 program, the relationship between five variables that describe the bead geometry of the GMAW-P process was analyzed. The resulting mathematical models with their respective graphs are the product of all the measured values of each of the samples that represent the 32 experimental combinations and the subsequent analysis that allowed obtaining the polynomial mathematical equations that were applied to the model [17].
The analysis of variance determined the significance of the model and the regression coefficients. In addition, Fisher's F test and the coefficient of determination (R^2) verified the quality of the polynomial equation.

Figure 2. Schematic representation of weld bead geometry parameters measured in GMAW-P.

3. Results and discussions
Using central composite design, in rotatable mode, the experiments were performed by the interaction of the variables of peak current, background current, peak time, frequency and wire speed rate were performed. The analysis of variance (ANOVA) in the factorial test was applied to the measurements of the variables, with the purpose of observing the significant differences between them. The probability value (p-value) indicates that the association of the variable is statistically significant and by consensus it is 0.05. A 95% confidence implies a p-value of less than 0.05.

Initially, most of the variables were statistically significant, except for variables X2 and X3. These two variables registered values below the critical level of 95% confidence. These considerations can be confirmed by the probability p-value interpretation shown in Table 2, Table 3, and Table 4, respectively. The results of the analysis of variance for the weld bead height H model are shown in Table 2.

Table 2. Analysis of variance for response surface model for bead height.

| Source   | Sum of squares | Degree of freedom | Mean square | F-value | P   |
|----------|----------------|-------------------|-------------|---------|-----|
| Model    | 7.1264         | 20                | 0.3563      | 07.10   | 0.001 |
| X1       | 1.3099         | 1                 | 1.3099      | 26.10   | 0.000 |
| X4       | 0.6975         | 1                 | 0.6975      | 13.90   | 0.003 |
| X5       | 2.6421         | 1                 | 2.6421      | 52.65   | 0.000 |
| X4X4     | 0.1936         | 1                 | 0.1936      | 03.86   | 0.075 |
| X4X5     | 0.3347         | 1                 | 0.3347      | 06.67   | 0.025 |
| S = 0.240 | R2 = 92.81%    | R2(adj) = 79.74%   | —           | —       | —    |

From the analysis of variance, it was verified that there is a strong first order relationship between variables X4 and X5, which were significant terms for the model. Likewise, the main variables such as peak current (X1), frequency (X4) and wire speed (X5) were significant. The same explanation cannot be stated for background current (X2), peak time (X3) and interaction terms (X1X2, X1X3, X1X4, X1X5, X2X3, X3X4 and X3X5), which did not show significance in the model height responses. However, second order of frequency (X4X4) could affect bead height. Thus, the F value of 7.10 indicated that the model was significant. In order to visualize the interaction effects for bead height, the response surface was generated in Figure 3.

The analysis of variance for the model of weld width is listed in Table 3. From the analysis of variance, the F value of 6.93 indicated that the model of weld width is significant. For this model the variables that were significant are X1, X4, X5 and the first order interaction effect (X1X4, X4X5). The other two variables such as background current (X2) and peak time (X3), as well as their interactions,
were not significant for the bead height model. Figure 4(a) shows the interaction effect between frequency and wire feed speed and Figure 4(b) shows the interaction between peak current and frequency.

![Figure 3](image)

**Figure 3.** Response surface of the effect of the factors on bead height.

**Table 3.** Analysis of variance for response surface model for bead width.

| Source | Sum of squares | Degree of freedom | Mean square | F-value | P     |
|--------|----------------|-------------------|-------------|---------|-------|
| Model  | 35.5969        | 20                | 0.17798     | 06.93   | 0.001 |
| X1     | 04.6807        | 1                 | 0.6807      | 18.22   | 0.001 |
| X4     | 01.6255        | 1                 | 0.6255      | 06.33   | 0.029 |
| X5     | 10.4426        | 1                 | 10.4426     | 40.64   | 0.000 |
| X1X4   | 01.3201        | 1                 | 01.3201     | 05.14   | 0.045 |
| X4X5   | 01.0112        | 1                 | 01.0112     | 03.94   | 0.073 |

$S = 0.507 \quad R^2 = 92.64\% \quad R^2(adj) = 79.27\%$

![Figure 4](image)

**Figure 4.** Response surface of the effect of the factors on bead width (a) frequency vs wire feed rate and (b) peak current and frequency.

The analysis of variance for the weld bead penetration model is shown in Table 4. As with the previous two models, peak current (X1), frequency (X4) and wire feed speed (X5) are statistically significant variables here. Significance is also apparent for the second order of frequency (X4X4), as well as the interaction effects of (X1X4, X4X5). In contrast, variables such as background current (X2) and peak time (X3) recorded values above the p-value, indicating to be statistically insignificant variables. The F-value of 5.95 revealed that the model was significant. Figure 5(a) shows the interaction between peak current, and frequency and Figure 5(b) shows the interaction effect between frequency and wire feed speed for weld bead penetration.
Table 4. Analysis of variance for response surface model for weld penetration.

| Source    | Sum of squares | Degree of freedom | Mean square | F-value | P   |
|-----------|----------------|-------------------|-------------|---------|-----|
| Model     | 6.298          | 20                | 0.314       | 0.002   |     |
| X1        | 1.331          | 1                 | 1.331       | 0.000   |     |
| X4        | 0.841          | 1                 | 0.841       | 0.002   |     |
| X5        | 2.103          | 1                 | 2.103       | 0.000   |     |
| X4X4      | 0.277          | 1                 | 0.277       | 0.043   |     |
| X1X4      | 0.280          | 1                 | 0.280       | 0.042   |     |
| X4X5      | 0.417          | 1                 | 0.417       | 0.017   |     |

\[S = 0.230\] \[R^2 = 91.54\%\] \[R^2(a) = 76.17\%\]

Figure 5. Response surface of the effect of the factors on bead penetration (a) peak current vs frequency and (b) frequency vs wire feed rate.

The R\(^2\) value was 0.928, 0.926 and 0.915 for each variable respectively. This expressed that for the cord height model, 92.8% was attributed for the variables studied. For the cord width model, 92.6% was assigned and for penetration, 91.5% was attributed. The quality of the models was judged by the coefficient of determination, the closer it is to 100% and the lower the standard deviation, the closer it is to the true value of the response. Under these considerations, the model for bead height recorded one of the lowest standard deviations of 0.240, thus expressing a more approximate value of the response than compared to the model for weld bead width and penetration. However, the statistical results indicated that the three models found were adequate to predict the geometrical dimensions of the bead such as height, width, and penetration of the weld.

The five variables studied had a large effect on bead geometry, except for the variables, (X2) background current and (X3) peak time. The three main variables such as peak current (X1), frequency (X4) and wire speed (X5) were significant for all three models. In the model for weld bead penetration, significance was observed for the second order with frequency (X4X4). Among the interaction effects, wire feed speed had the greatest effect on bead geometry, followed by frequency and peak current. To visualize the interaction effects on bead height, weld width and weld penetration, the respective response surface plots were generated.

4. Conclusions

From the statistical results obtained, it was shown that the above models were adequate to predict the weld width, bead height, and penetration within the range of variables studied. The absolute value of the coefficients of each variable reflecting the importance of the same in terms of their effect on welds bead geometry, whereby all the responses had R\(^2\) of above 0.9. In this case, the wire feed rate it has a very marked effect on weld bead geometry, followed by frequency pulse and peak current. The models were calculated using response surface methodology based on central composite design. For the experimental design, several tests were initially carried out in order to find the maximum and minimum range of the selected welding variables, avoiding the presence of problems such as arc extinction,
material waste and porosity in the weld bead, that is to say, maintaining the obtaining of welds of good appearance and quality. Wire feed rate had a significant positive effect on most of the important weld bead parameters, results indicate that the wire feed rate increases as the peak parameters is increased. Finally, the effectiveness of employing these methodologies for the management of variables attributing to the execution of welding tasks with higher accuracy was demonstrated and, in this way, a solution to the problem a solution to the problem was obtained in an agile and systematic way.

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