Sensitivity analysis and multi-objective optimization of tungsten inert gas (TIG) welding based on numerical simulation

Luiz Eduardo dos Santos Paes1 · João Rodrigo Andrade1 · Fran Sérgio Lobato1 · Elisan dos Santos Magalhães2 · Volodymyr Ponomarov1 · Francisco José de Souza1 · Louriel Oliveira Vilarinho1

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Abstract
In welding processes, many factors contribute in achieving a required quality of the welds. Those factors are numerous and they may interact with each other, affecting response parameters such as welding penetration and the heat-affected zone (HAZ) size. Some factors are more important while the influence of others is negligible. To find an optimum factor combination in order to maximize penetration and minimize the HAZ is not an easy task. This contribution is aimed to evaluate the influence of welding energy \( E \) versus the influence of current \( I \) and welding speed \( V_w \) on the penetration and HAZ volume in the autogenous tungsten inert gas welding process. For this purpose, two numerical models are proposed. The first considers an in-house finite volume numerical model, and the second is based on response surface method. A sensitivity analysis of the proposed numerical model using two strategies is also performed. In addition, to determine the best-operating conditions, a multi-objective optimization problem is proposed and solved. The presented numerical models were found to provide good concordance in terms of coefficient of determination and p-value, indicating its significance. Each model (with one or more independent variables) represents detailed information about the physical process and can be used for optimization. The sensitivity analysis demonstrates that the current affects penetration and HAZ volume much stronger than the welding speed does. Physically, this is due to the fact that the current has linear (arc coupling) and non-linear (Joule effect and pressure gradient) influence, and the welding speed contributes linearly, modulating the heat conduction. Finally, it was demonstrated a compromise between the penetration and the HAZ volume by addressing multi-objective optimization. In this context, point C \(( I = 250 \text{ A}; V_w = 24.8 \text{ cm/min})\) of the Pareto curve is the optimal option for operation since it provides a lower relative HAZ volume while keeping the same penetration and higher productivity (welding speed).

Keywords  Design of experiments · Response surface method · Parametrization · Modeling · Heat input

1 Introduction

Welding processes are very important for material joining in different industrial sectors. The welds should have required mechanical properties and geometrical characteristics, being the former partially depending on the latter. Therefore, it is crucial to know the input parameters that result in the desired geometrical characteristics. This knowledge is not a trivial assignment since the number of parameters is large and may interact with each other.

Several methodologies have been proposed to predict the main weld bead dimensions, such as penetration and heat-affected zone (HAZ). Liu et al. [1] applied the neuro-fuzzy artificial intelligence technique. Menaka et al. [2] and Chokkalingham et al. [3] selected infrared thermal imaging. Bhattacharya et al. [4] implemented a novel graph approach. Sharma et al. [5] developed a “multiple-input single-output” each providing an index that represents the overall geometric fitness of weld bead.

Despite these advances, the weld bead geometry prediction is based on the welding energy \( E \), because of its simplicity. In practice, \( E \) is defined by the relation between electric power to maintain the arc and the welding speed. It represents the energy amount per unit length (J/mm) as...
shown by Eq. (1). Similar parameters are also used, such as the energy density \( (J/mm^2) \) and the volumetric energy density \( (J/mm^3) \).

\[
E = \frac{q}{L} = \frac{q}{t/V} = \frac{P}{V} \tag{1}
\]

where \( E \) is the energy supplied by the power source, \( q \) is the energy generated by the power source, \( L \) is the joint length, \( t \) is the welding time, \( P \) is the generated power, and \( V \) is the welding speed. Alcock and Baufeld [6], Tan and Shin [7], Quintino et al. [8], and Paes et al. [9] reported a direct correlation between penetration and welding energy.

However, selecting the welding energy to parametrize the welding process is not appropriate as not all arc energy is employed to melt the material. The so-called heat input should be used instead, because it is “free” from losses by conduction, convection, and radiation [10, 11]:

\[
HI = \eta_T E \tag{2}
\]

where \( \eta_T \) is the thermal efficiency, which can be determined through calorimetry [12] or numerical simulations [13].

Although some standards use the heat input to define the quality limits, a part of the heat still diffuses to the base metal but does not contribute to melting. The effective heat input \( (EHI) \) represents the portion that heats the material up to its melting point after subtracting the part diffused to the base metal [14], shown in Eq. (3).

\[
EHI = E \eta_T \eta_m \tag{3}
\]

where \( \eta_m \) is the fusion efficiency.

It is worth mentioning that the thermal and the fusion efficiency depend on the welding conditions. Thus, despite the observed correlation between welding energy, heat input, or effective heat input and the weld geometrical characteristics from other, each parameter affects the former and the latter. Even the welding position can influence the final result [15]. Therefore, with the same process and energy, it is possible to find welds with different shapes due to the individual parameter influence [10, 16]. Maybe it is the reason why the American Welding Society defines heat input as the full energy generated by the arc [17], calculated according to Eq. (1). Onwards in the present paper, the term “welding energy” or “heat input” will be used whether it is calculated according to Eq. (1) or (2), respectively.

According to Cao et al. [18], full penetration can be reached in a 3.2-mm thickness titanium plate with 80 J/mm welding energy. However, for the same welding energy, depending on the selected power, the weld bead presented defects such as porosity. They concluded that intermediate powers are recommended in this case since they result in higher metallurgical integrity. Prashanth et al. [19] discussed the role of the volumetric energy density for the selective laser melting process and found that for the same value of 55 J/cm³, the tensile curves diverged significantly considering the Al-12Si alloy. The amount of porosity in the samples increased with decreasing the power and the scanning speed, which culminated in lower strength. Then, they varied the power, keeping the same scanning speed, and found the same trend, while this was not observed when the scanning speed was varied for the same power. Power has demonstrated to be the most influential parameter for porosity formation and consequent strength. Bertoli et al. [20] also investigated the volumetric energy density. They stated that decreasing this parameter below 100 J/mm³ leads to a degradation. However, they did not consider the volumetric energy density to quantify the weld pool depth. The reason for that is that this parameter is generally a thermodynamic quantity and is therefore unable to capture the complex physics such as Marangoni flow and hydrodynamic instabilities that drive heat and mass transport in different portions of the weld pool. Despite this, Ayoola et al. [21] were able to correlate the penetration depth with the energy density, whereas other authors [6–8] recognize that the “welding energy density–weld geometry” phenomenon needs more studies.

The way power is delivered also influences the results, as demonstrated by Neto et al. [22, 23]. Keeping the same welding energy during laser welding, but varying the power wave shape (trapezoidal, square, and step), higher penetration was found when compared to the constant power wave.

One should know that is not enough to achieve just a needed penetration. The HAZ must be minimized since it may present brittle phases [24] and grain growth regions [25]. Grajcar et al. [26] reported a direct relation between welding energy and HAZ width.

Given the presented challenge to predict penetration and the HAZ volume based on the welding energy, heat input, or effective heat input, many authors prefer to use multiple regression models [27], which can be associated with artificial intelligence techniques [15] and optimization [28–33]. These are empirical models that correlate a geometrical output variable such as penetration \( (Pe) \) or the HAZ volume \( (V_{HAZ}) \), with process variables such as current \( (I) \) and welding speed \( (V_w) \).

In this case, only the current and the welding speed were selected, but other parameters can be added if they prove to have influence, such as the pulsation frequency [34]. These models can predict the weld geometry with greater accuracy but do not explain the process physically. Without such explanations, there is no chance to select between current and welding speed values. One question is still missing an answer. Which variable is more efficient? Kumar et al. [35] experimentally found that penetration is more sensible to current than welding speed but did not provide convincing reasons. Assefa et al. [36], by means of the Taguchi-based
desirability function analysis, found that the current is a highly influential parameter on the TIG procedure. When evaluating the bead depth and width in a TIG process, Karganroudi et al. [37] also discovered opposing effects for welding current and speed. However, they found the welding speed as the most significant factor. The sensitivity analysis associated with numerical simulation is the most appropriate tool for answering these questions. It is possible to rank the most influential input parameters considering a defined output [38]. After developing empirical equations, several authors used sensitivity analysis in their welding experiments.

Kim et al. [39, 40] found that in the metal inert gas/metal active gas (MIG/MAG) welding process, the most influential variable on penetration is the current. Palani and Murugan [41] reached the same conclusion, but for the flux-cored arc welding and Karaoglu and Seçgin [42] for the submerged arc welding process. Therefore, this seems to be a trend, at least for processes with filler metal. This is not an obvious result. A high feeding rate requires a high current. If this is associated with low welding speed, it can result in lower penetration [43–45]. Other authors applied the sensitivity analysis to correlate the input process parameters with the mechanical strength [46–48].

The present paper proposes a sensitivity analysis of electric current and welding speed relative to penetration and HAZ volume in the TIG welding process without filler metal (autogenous) using a finite volume numerical model and response surface method. It also discusses the viability of the welding energy as an input parameter compared to current and welding speed in regression models. The proposed work is accomplished by establishing statistical regression models for the HAZ volume and the weld penetration. Two distinct methodologies are used to assess the model sensitivity to the independent variables. Finally, a multiobjective optimization problem for determining the coded independent variables is suggested and solved. This issue involves minimizing the HAZ volume and maximizing the weld penetration.

## 2 Methodology

### 2.1 Materials and welding parameters

Among the main types of welding, the TIG is given by an arc generated between a non-consumable tungsten electrode and the workpiece. Its main advantage is the higher quality when compared to other welding processes, such as the MIG/MAG welding. The main reason for its good welding quality relies on a high process controllability. In this case, the welding energy is independent of the filler metal; consequently, it is possible to heat the workpiece before adding the material. Additionally, the added metal can be supplied according to the joint needs, using the same amount for different levels of welding energy. This does not occur in the MIG/MAG process since the amount of material must be proportional to the welding energy. Then, when heat and material are combined in a “cold” workpiece, the result is more prone to defects. Even when the workpiece is preheated, the defect rate remains high since it is impossible to halt the feeding to enhance melting. One of the main drawbacks of the TIG process is its low productivity. However, recent works have shown that this limitation can be solved [49].

To validate the numerical model, experiments were conducted using a multiprocess IMC Digiplus A7 welding power source on a carbon steel plate SAE 1020, with 250-mm length (Lx), 100-mm width (Ly), and 6.42-mm thickness (Lz). A robotic manipulator SPS Taritilope V4 was used to control the welding speed. Argon was selected as shielding gas. The tungsten electrode was doped with 2% thorium and had a 3.2-mm diameter and 30° tip angle. The distance between the electrode tip and the workpiece (DEP) was 2 mm. Transversal sections were prepared using a metallographic procedure that includes sandpaper classifications of 80, 320, 400, 600, and 1200, besides 1.0-µm alumina polishing. Nital 10% was used during 7 s to reveal the HAZ. Table 1 presents the welding parameter values.

### 2.2 Numerical model

#### 2.2.1 Governing equations

The following four-dimensional differential equation for the transport of the thermal energy is used to predict the temperature field depending on spatial and temporal domains:

\[
\frac{\partial H}{\partial t} = \nabla \cdot (k \nabla T)
\]  

(4)

where \( T(t, X) \) is the temperature, \( t \) is the time, \( X \) is the spatial position vector \( X = xi + yj + zk \), and \( k(T) \) is the thermal diffusion coefficient. Additionally, according to Crank [50], the considered enthalpy function is defined by:

\[
H(T) = \int_{T_0}^{T} [\rho c + \rho H_2 \delta(\theta - T_m)] d\theta
\]  

(5)

### Table 1 Welding parameters for validation of the numerical model

| Parameter | Value |
|-----------|-------|
| I         | 200 A |
| U         | 11.5 V|
| \( V_w \) | 15 cm/min|
where $\theta$ is an integration variable, $T_0$ is the reference temperature, $T_m$ is the melting temperature, $\rho$ is the specific mass, $c(T)$ is the specific heat, $H_L$ is the latent heat of fusion, and $\delta$ is the Dirac impulse function.

### 2.2.2 Initial and boundary conditions

Setting boundaries and initial conditions are crucial to solve Eq. (4). Therefore, convection and radiation effects are imposed, and a moving surface heat source describes the welding process' thermal effects. The applied initial condition is $T(0, X) = 30 \, ^\circ\text{C}$, and the mathematical model for the boundary condition involving convection and radiation [51] is given by:

$$\left. \frac{\partial T}{\partial \xi} \right|_{S_n} = \frac{1}{k} \left[ h(T_\infty - T) + \sigma \varepsilon (T_\infty^4 - T^4) + \omega q'' \right] \quad (6)$$

where $\xi$ is the normal direction to the boundary surface $S_n$, $h$ is the convective heat transfer coefficient, $\sigma$ is the Stefan-Boltzmann constant, $\varepsilon$ is the emissivity, $T_\infty$ is the room temperature, $q''$ is the welding heat flux, and $\omega$ is a condition parameter, $(\omega = 1$ for the top domain surface and $\omega = 0$ for all the others). It is worth mentioning that the convective heat transfer coefficient determination is based on free convection calculations and depends on $T$ and the domain surface direction, $h = h(T, S_n)$. The surrounding air temperature is $T_\infty = 30 \, ^\circ\text{C}$.

### 2.2.3 Welding heat source

The welding boundary condition depends on time and position, i.e., $q'' = q''(X,t)$. The imposed heat flux is given by a homogeneous heat surface distribution restricted by a circular region with a radius $R$ on the top surface, as given below:

$$q'' = \begin{cases} \eta I U / (\pi R^2) & \text{if } d \leq R \\ 0 & \text{if } d > R \end{cases} \quad (7)$$

where $R$ stands for the weld radius in $xy$-plane; $I$ and $U$ are the electric current and voltage, respectively; $\eta$ is the thermal efficiency; and $d$ is the distance from the heat source in the $xy$-plane, which is given by:

$$d = \sqrt{(x - x_0 - V_w t)^2 + (y - y_0)^2} \quad (8)$$

where $(x, y, z)$ are the spatial coordinate and $(x_0, y_0)$ are the welding source’s initial position on the top surface. The mathematical welding heat flux spatially moves according to the torch displacement in the experimental procedure at welding speed $V_w$ in the $x$-direction. Figure 1 displays the mathematical form of the welding heat source.

Regarding the thermal efficiency, its value has been considered based on the following empirical relation provided by Ferro et al. [52]:

$$\eta = 71.8 + 0.006 I + 0.36 U \quad (9)$$

In the TIG welding process, the power source static characteristic is constant current. This means that current is the input variable, whereas voltage is a function of current and the DEP distance. By varying the welding current in the welding power source, it is then possible to experimentally determine the maximum arc voltage variation, which resulted in 10.2 V and 12.7 V, and an average of 11.3 V.

### 2.2.4 Material properties

Most of the physical properties of the AISI 1020 steel are based on the work of Li et al. [53], i.e., $k(T)$, $c(T)$, $\rho = 7870 \, \text{kg/m}^3$, and $T_m = 1538 \, ^\circ\text{C}$. It was considered an average emissivity $\varepsilon = 0.5$. 

---

Table 2 Mesh refinement information

| Dimension                      | Symbol | Value  |
|--------------------------------|--------|--------|
| Minimum length in $x$-direction | $\Delta x_{\text{min}}$ | 0.66 mm |
| Minimum length in $y$-direction | $\Delta y_{\text{min}}$ | 0.25 mm |
| Minimum length in $z$-direction | $\Delta z_{\text{min}}$ | 0.25 mm |

---

Fig. 1 Welding heat distribution on the top surface
2.2.5 Meshing

Calculations were performed using an “in-house” algorithm with a Cartesian non-uniform mesh. A grid independence analysis was performed on different meshes until convergence was achieved. A mesh with 403,000 elements was the most efficient in terms of processing cost and numerical convergence. Table 2 presents the dimensions of the most refined elements located in the welding path region.

Mesh refinement was applied in the region around the welding heat source path. Figure 2 illustrates a three-dimensional mesh applied, as well as its top view. One can observe the different refinement regions, namely gradual refinement and refined regions. Moreover, considering time integration, the time step was $\Delta t = 3 \cdot 10^{-4}$ s. The numerical domain was set to have the same dimensions as the experiments.

2.3 Validation

The similarity between the experimental data and the numerical simulation’s temperature field is shown in Fig. 3. The figures illustrate the radius of the HAZ and the melted zone. It can be seen that the numerical and experimental values are quite close, indicating that the model has been quantitatively validated. Additionally, it can be noted that the HAZ and FZ zones (highlighted in the software picture) exhibit a high degree of coherence, which corresponds to the expected behavior of simulations. As it is well known, the penetration is the maximum melted depth. Therefore, it is given by the maximum linear distance from the surface to the region where the temperature reaches the melting temperature (1538 °C). The HAZ is a region subjected to temperatures below the melting point yet high enough to induce microstructural changes. For carbon steels, this temperature is around 727 °C, where austenitization starts. Therefore, the HAZ comprises the region with temperatures in the range between 727 °C and 1538 °C. The experimental sample was sanded and then chemically etched with a 10% Nital. The measurements were performed using ImageJ image analysis software after the acquisition in a LEICA DM750M optical microscope. In a recently published work, a detailed validation of the present software was performed [54].

2.4 Design of experiments

In order to represent the optimal combination of factors and their interactions between dependent and independent variables in the TIG welding process, the response surface method approach is applied. For this purpose, the welding penetration ($P_e$) and the HAZ volume ($V_{HAZ}$) are employed as the dependent variables, and the electric current ($I$) and welding speed ($V_w$) are chosen as the independent ones. It is important to emphasize that voltage was not chosen as an
independent variable because U and I are interdependent (Sect. 2.2.3). Although Kim et al. [39] and Karaoglu and Seçgin [42] used voltage and current as input parameters, both are present in the welding energy. However, it is impossible to set simultaneously current and voltage in a power source. In the TIG welding case, the current is regulated, and the voltage is a variable depending on the current, the distance between the electrode tip and the workpiece. Because of that, we chose to discard the voltage as variable. Instead, it was considered a constant ($U = 11.3 \text{ V}$), determined experimentally. The usual current range for TIG welding is between 50 and 250 A, and the welding speed ranges from 5 to 25 cm/min. Outside these limits, the weld usually presents defects [55]. The values of the independent variables used to build the experimental design are presented in Table 3.

Regarding the levels $−1$ and $+1$ of each parameter in Table 3, they were chosen so that the difference between the extreme values of the interval ($−\alpha$ and $\alpha$) and the central level did not exceed 10% of the original parameter value. The experimental design’s value of $\alpha$ (extreme dimensionless level) was 1.4142. This value leads to an orthogonal central composite design, i.e., a design in which the variance and covariance matrices are diagonals, and the parameters are uncorrelated [56].

According to central composite design (CCD), by taking two control factors, 12 numerical experiments with four replicates at the center levels were performed, as presented in Table 4. In this table, both current and welding speed variables are coded as:

\[ X_1 = 2 \frac{(I - 150)}{(220.72 - 79.28)} \]

\[ X_2 = 2 \frac{(V_W - 15)}{(22.07 - 7.93)} \]

It is important to emphasize that both answers (penetration and HAZ volume) in the CCD are obtained employing the finite volume numerical model depicted earlier.

### 2.5 Regression models

The relation between input parameters and answers is based on the multiple regression analysis (MRA). For this purpose, a general second-order polynomial equation is presented:

\[ Y = b_0 + \sum_{i=1}^{k} b_i X_i + \sum_{i=1}^{k} b_{ii} X_i^2 + \sum_{i=1,j\neq i}^{k} b_{ij} X_i X_j \]

where $b_0$ is the regression equation constant, $\{b_1, ..., b_k\}$ are the linear terms, $\{b_{11}, ..., b_{kk}\}$ are the quadratic terms, and $\{b_{12}, ..., b_{k-1,k}\}$ are the interaction terms, and $X_i (i = 1, ..., k)$ represents the dimensionless forms for the independent parameters. This model allows to quantify the main effects of the input variables, their interactions, and their quadratic contributions.

In the present work, $Pe$ and $V_{HAZ}$ are fitted as a function of the coded variables $X_1$ (electric current) and $X_2$ (welding speed). For this purpose, an inverse problem is formulated. Mathematically, this consists on determining the design variables $\{b_{0p}, b_1, ..., b_k, b_{11}, ..., b_{kk}, b_{12}, ..., b_{k-1,k}\}$ in order to minimize the functional objective function (OF), which is given by:

\[ OF = \sum_{i=1}^{n} (Y_i^{exp} - Y_i)^2 \]

where $Y_i^{exp}$ and $Y_i$ stand for the “experimental” and simulated values, respectively, and $n$ is the number of experimental
data. The classical sequential quadratic programming (SQP) iterative method is employed to solve the proposed inverse problem [57].

Alternatively, \( Pe \) and \( V_{HAZ} \) also can be fitted as a function of welding energy \( (E) \), defined as \( UI/V_w \). For this purpose, a classical second-order polynomial equation is considered, i.e.,

\[
Y = c_0 + c_1E + c_2E^2
\]

where \( c_0 \) is the regression equation constant, \( c_1 \) and \( c_2 \) are the linear and quadratic terms. It is important to mention that an averaged value for the voltage \( (U = 11.3 \, \text{V}) \) is considered to calculate the energy. In this case, an inverse problem is also formulated to determine the design variables \( \{c_0, c_1, c_2\} \) to minimize the functional OF given by Eq. (13).

The obtained formulated models are then validated by analyzing the predicted values. In addition, the coefficient of determination \( (R^2) \) and the model’s significance are determined through an analysis of variance. The significance was determined using the \( p \)-value of the lack of fit, where the significance level was set as 0.05.

### 2.6 Sensitivity analysis

In order to evaluate the sensitivity of the answers regarding the electric current and the welding speed, the MRA strategy is applied. Two different approaches are used. The first approach considers the perturbation of each answer by using five different levels. Nominal values (without perturbation) are defined. Thus, for each level of perturbation, the models based on response surface method are simulated. The second form consists of determining the Sensitivity Index (SI), defined by [58] as:

\[
SI_j(\theta) = \frac{\gamma_{\theta+\Delta\theta} - \gamma_{\theta-\Delta\theta}}{\gamma_{\theta}}
\]

where \( SI_j (\gamma = [Pe \, V_{HAZ}] \) is the sensitivity index for the answer \( \gamma \), \( \theta (\theta = [I \, V_w]) \) is the set of independent variables, and \( \Delta \) is the level of perturbation considered for each \( \theta \) value (concerning nominal values). This dimensionless parameter allows to evaluate the influence of the weighted independent variables, i.e., all \( SI \) values for different answers can be presented in the same figure. Thus, the variables which reach the highest amplitudes are the most sensitive [58].

### 2.7 Optimization

Knowing the degree of influence of the input parameters and the equations that models the relationship between input and output is essential for correct selection but is not sufficient. A weld with integrity must reach the required penetration for joining and simultaneously present the minimum HAZ possible. Rafieazad et al. [24] and Chen et al. [25] mentioned that this region is critical due to brittle phases and grain growth.

In such a manner, through the formulation and solution of multiobjective optimization, one can compute the current and welding speed values (coded variables) for which the penetration is maximized, and the HAZ volume is minimized. Mathematically, this problem is formulated as:

\[
\begin{align*}
\max_{x_1, x_2} & \quad V_{HAZ} \\
\max & \quad Pe \\
\end{align*}
\]

where both the \( V_{HAZ} \) and \( Pe \) depend on the coded current \( (X_1) \) and welding speed \( (X_2) \) variables. The regression models representing these answers are obtained as described earlier in Sect. 2.4. The following design space is considered to guarantee the limits of each variable’s domain: \( -\alpha \leq X_1, X_2 \leq \alpha \) (where \( \alpha \) refers to the extreme dimensionless level).

The Multiobjective Optimization Differential Evolution (MODE) algorithm, proposed by Lobato and Steffen [59], is considered to solve the proposed problem. This procedure is based on associating the differential evolution algorithm [60] with two different operators, namely, fast non-dominated sorting [60] and crowding distance [61]. The main steps of the MODE algorithm are described below:

(I) Initially, a population of \( N \) individuals is randomly generated, limited by the design space defined by the user.

(II) A new population is then generated with the differential evolution operators. This new population is incorporated into the current population. In this case, the population of \( 2N \) individuals is classified according to the fast non-dominated sorting operator, i.e., the dominated candidates are removed from the population, and the remaining points are ranked on several Pareto fronts.

(III) Next, the current population is truncated according to the crowding distance operator. This step is necessary to avoid the increase of the population size for the next generation; i.e., along the evolutionary process, only \( N \) individuals belong to the non-dominated solutions set.

(IV) Finally, this iterative procedure goes on until a maximum number of generations is reached. At the end of the generations, it is expected that MODE has converged on an approximate Pareto set, with adequate diversity of solutions.

A complete description of MODE is presented by Lobato and Steffen [59].
3 Results and discussions

3.1 Regression models

As previously mentioned, the answers (penetration and HAZ volume) for each experiment are obtained employing a finite volume numerical model; i.e., for each input (current and welding speed), both penetration and HAZ volume in the TIG welding process are calculated. The obtained numerical results are presented in Table 5.

The SQP algorithm is applied to solve the proposed inverse problem (Eq. (15)). For this purpose, the algorithm was run 1000 times considering random initial estimates within the domain $[-2000,2000]$ for each design variable $\{b_0, b_1, \ldots, b_k, b_{11}, \ldots, b_{k-1,k}\}$. The same regression coefficients for penetration and HAZ volume were found, what indicates that the optimization algorithm always converged to the same optimal solution, and is independent of the initial estimate. These results can be found in Table 6.

The regression results show that 98.9% and 92.1% of the variability of $P_e$ and $V_{HAZ}$, respectively, were obtained for each fitted model. The model $p$-value ($< 0.05$) indicates that the model’s probability of being incorrect is less than 5%.

According to the hypothesis test of the Student’s distribution, the regression coefficients presenting a significance level higher than this value are neglected. Thus, as observed in Table 6, the quadratic coefficients ($b_{11}$ and $b_{22}$) and interaction coefficient ($b_{12}$) for $V_{HAZ}$ can be disregarded. On the other hand, regarding the penetration output, all parameters were significant to the model; i.e., the significance levels did not exceed 5.

A good compromise is observed for both the answers in Fig. 4 (3D curves). As expected, the highest penetration and HAZ volume values were achieved with the highest values of current ($I$) and lowest values of welding speed ($V_w$). It is important to mention that the response surfaces seem to be flat because the quadratic and interaction coefficients are orders of magnitude smaller than the linear coefficients. In addition, in this figure, the projections of each three-dimensional graph in ($I,V_w$) plane (contour lines) are presented. These curves make it possible to observe the regions where $P_e$ and $V_{HAZ}$ have a constant value.

To estimate the vector of design variable $\{c_0, c_1, c_2\}$ and to obtain both the quadratic equations for the penetration and the HAZ volume depending on the welding energy, the SQP algorithm was applied. In this case, the algorithm was run

### Table 5 Penetration and HAZ volume based on RSM

| Experiment | $X_1$ | $X_2$ | $I$ (A) | $V_w$ (cm/min) | $E$ (kJ) | $P_e$ (mm) | $V_{HAZ}$ (cm$^3$) |
|------------|-------|-------|---------|----------------|---------|------------|------------------|
| 1          | −1    | −1    | 79.28   | 7.93           | 113.034 | 1.064      | 0.257            |
| 2          | −1    | 1     | 79.28   | 22.07          | 40.614  | 0.651      | 0.147            |
| 3          | 1     | −1    | 220.72  | 7.93           | 314.693 | 3.537      | 1.509            |
| 4          | 1     | 1     | 220.72  | 22.07          | 113.072 | 2.203      | 0.694            |
| 5          | −α    | 0     | 50      | 15             | 37.687  | 0.195      | 0.085            |
| 6          | α     | 0     | 250     | 15             | 188.437 | 2.957      | 1.074            |
| 7          | 0     | −α    | 150     | 5              | 339.187 | 3.266      | 1.674            |
| 8          | 0     | α     | 150     | 25             | 67.837  | 1.495      | 0.385            |
| 9          | 0     | 0     | 150     | 15             | 113.062 | 1.882      | 0.647            |
| 10         | 0     | 0     | 150     | 15             | 113.062 | 1.882      | 0.647            |
| 11         | 0     | 0     | 150     | 15             | 113.062 | 1.882      | 0.647            |
| 12         | 0     | 0     | 150     | 15             | 113.062 | 1.882      | 0.647            |

### Table 6 Regression coefficients for the penetration and HAZ volume as a function of current and welding speed considering 95% confidence bounds

| Coefficient | $P_e$ (mm) | $p$-value | $V_{HAZ}$ (cm$^3$) | $p$-value |
|-------------|------------|-----------|--------------------|-----------|
| $b_0$       | 1.8828     | 1.0653E-07| 0.6477 (0.4434, 0.8521) | 0.0002 |
| $b_1$       | 0.9915     | 6.1515E-07| 0.3994 (0.2549, 0.5439) | 0.0005 |
| $b_2$       | −0.5314    | 2.3960E-05| −0.3435 (−0.4880,−0.1989) | 0.0011 |
| $b_{11}$    | −0.1817    | 0.0118    | −0.0721 (−0.2336, 0.0894) | 0.3167 |
| $b_{22}$    | 0.2205     | 0.0049    | 0.1528 (−0.0086, 0.3144) | 0.0598 |
| $b_{12}$    | −0.2303    | 0.0117    | −0.1760 (−0.3804, 0.0282) | 0.0795 |
| $OF$        | 0.0996     | −        | 0.1674 (cm$^3$) | −         |
| $R^2$       | 0.9881     | −        | 0.9205 | −         |

*95% confidence
1000 times considering random initial estimates within the domain [−2000,2000] for each design variable. The obtained results are presented in Table 7.

These results demonstrate that 90.4% and 94.7% of the variability of $Pe$ and $V_{HAZ}$, respectively, were obtained for each fitted model in terms of energy. As mentioned earlier, the model $p$-value lower than 0.05 indicates that the model’s probability of being incorrect is less than 5%. As observed in Table 7, the intercept term for both the answers can be disregarded. In addition, the quadratic coefficients for $V_{HAZ}$ also can be disregarded.

Mathematically, considering the $R^2$ values for each model fitted (see Tables 6 and 7), it is possible to conclude that the model with current and welding speed is more appropriate for penetration prediction than the model with energy, which is more interesting for prediction of the HAZ volume. However, it should be noted that as these models present different independent variables, the simple comparison is not trivial. Thus, these models represent complementary information to understanding the physical process. In addition, the model with two independent variables has a greater number of degrees of freedom than the model with one independent

![Table 7](https://example.com/table7)

**Table 7** Regression coefficients for the penetration and HAZ volume as a function of energy

| Coefficient | $Pe$ (mm) | $p$-value | $V_{HAZ}$ (cm$^3$) | $p$-value |
|-------------|-----------|-----------|-------------------|----------|
| $c_0$ | $-0.4223$ (mm) | 0.2940 | $-0.15482$ (cm$^3$) | 0.3002 |
| $c_1$ | 0.0248 (mm/kJ) | 0.0008 | 0.0074 (cm$^3$/kJ) | 0.0035 |
| $c_2$ | $-4.0136E-05$ (mm/kJ$^2$) | 0.0125 | $-6.2842E-06$ (cm$^3$/kJ$^2$) | 0.2227 |
| OF | 1.0663 (mm$^2$) | – | 0.1473 (cm$^6$) | – |
| $R^2$ | 0.9044 (90.4%) | – | 0.9467 (94.7%) | – |
variable. This means that a priori, with the model with more independent variables tends to be more accurate, although the values of the objective functions for HAZ volume are similar.

Figure 5 presents the penetration and HAZ volume depending on the welding energy. In these figures, a good compromise is observed for both the answers. As expected, the highest values of penetration and HAZ volume were achieved with the highest energy values.

These figures show that the same energy levels may lead to significantly different results, as indicated in the blue squares. The fitting considers an average. This occurs since current and welding speed have different effects on penetration and HAZ, as mentioned by other authors [10, 16, 17]. According to Scotti and Ponomarev [14], the weld bead is mainly influenced by thermal and mechanical effects, which seem to be critical for accurate welding physics prediction. These effects are implicitly taken into consideration in the thermal efficiency equation applied in this study since it comes from an experimental correlation. The former term works through the coupling of the electric arc and the workpiece, where a high current density is found in the anodic regions and then internal energy is directly conducted to the material. The latter, on the other hand, is caused by the stagnation pressure. As the current increases, the magnetic field also becomes higher, forcing the weld pool down and maximizing penetration. Then, whereas electric current contributes to both thermal and mechanical effects, welding speed is primarily responsible for thermal effects. Furthermore, the current has linear (arc coupling) and non-linear (Joule effect and pressure gradient) effects, and the welding speed contributes linearly to the heat conduction, modulating it.

As a result, when the penetration is examined, the respective current and welding speed sensitivity effects are different.

### 3.2 Sensitivity analysis

As previously mentioned, two approaches are considered to evaluate the numerical model’s sensitivity. Figure 6 presents the sensitivity analysis for $P_e$ and $V_{HAZ}$ considering 5 different levels of perturbation $[-10\% -5\% 0\% +5\% +10\%]$ to each independent variable. The nominal value is 150 A and 15 cm/min for $I$ and $V_W$, respectively. It is possible to observe that $I$ has a stronger influence over both the penetration and HAZ volume than the $V_W$. The influence of $V_W$ becomes more evident for higher values of $I$. In addition, the increase in current implies an increase in the outputs. In Fig. 6, it is also possible to notice that the minimum values of the answers are reached, as expected, with the highest values of the welding speed. Regarding the welding speed, an opposite behavior is observed; i.e., the highest values for both answers are computed with the highest current values.

Figure 7 depicts the sensitivity index ($SI$) for penetration and HAZ volume considering a perturbation equal to 5% of the independent variables. In addition, for each analysis, the following nominal values are employed: $I$ ([100 150 200] A) and $V_W$ ([10 15 20] cm/min). For the welding current sensitivity index (see Fig. 7a), one can observe that the HAZ volume model is more sensible than the penetration model. This difference becomes more evident when the electric current intensity is increased. Similar behavior also is found for the sensitivity index regarding the welding speed for both the answers; i.e., the HAZ volume model is more sensible than the penetration model, as observed in Fig. 7b, where
the central area of the figure is zoomed in such a way that one can distinguish between the curves.

### 3.3 Optimization

In order to solve the proposed optimization problem given by Eq. (16), the MODE algorithm is considered. For this purpose, according to Lobato and Steffen [59], the following parameters must be employed: population size (100), a maximum number of generations (100), crossover probability (0.8), perturbation rate (0.8), rand/1/bin strategy [60], and a maximum number of generations as a stopping criterion. In each case, considering these parameters, the number of objective function evaluations is equal to 100 + 100 × 100.

Figure 8 presents the Pareto’s curve for the maximization of the penetration and the minimization of the HAZ volume requirements. The result of the relationship between the two data output objectives shows that these variables exhibit concurrent behavior: the higher is the HAZ volume, the deeper is the penetration. From the mathematical point of view, this curve presents points having the same significance, which implies that they all are equally important and, a priori, can be applied in a welding process.

Table 8 presents some key points belonging to the Pareto’s curve. The points were chosen because they belong to the Pareto curve and are spaced, allowing for various possible outcomes for the optimized process.

As previously stated, the Pareto’s curve denotes the region of compromise for the optimized variables. Since the response behavior is incompatible, the optimum combinations are given as a continuous curve spanning the studied interval. To better understand this curve’s behavior, six points were chosen with various combinations of $P_e$ and $V_{HAZ}$, denoted by the letters A, B, C, D, E, and F.

Simulations in finite volumes were run on each of the indicated combinations. The produced data aids in the

![Fig. 6 Sensitivity analysis for penetration and HAZ volume is considering the first approach](image-url)
comprehension of the observed occurrence. Figure 9 depicts the temperature field for each simulation and the penetration values. It is worth noting that the results for the combinations A, B, C, D, and E are pretty close to the values in Table 8, demonstrating that the statistical model is accurate. However, point F deviates significantly from the statistical model; this may be explained because this combination point lies on the boundary of the analyzed domain, which might result in extrapolation errors. Additionally, the heat generated by the welding source is sufficient to penetrate the component and reach the underside, significantly altering the model’s patterns and showing a divergence in its behavior.

To determine the best point of the Pareto graphic (Fig. 8), it is necessary to consider the manufacturing requirements. The specification for penetration is determined by the plate thickness. Based on this criterion, only point F would be acceptable since it presented full penetration. However, it also presented a higher HAZ volume, which is not positive. Choosing this parameter for a joint could lead to a lack of integrity due to problems such as grain growth [24, 25]. Therefore, the best application would be for a partial penetration joint (A to E).

Analyzing the Pareto curve (Fig. 8) and Table 7, it is noticed that the straight line that includes points A to C is more inclined than the straight line that determines points C to F. Then, points A to C show a higher penetration increment for the same variation of the HAZ volume. This means a higher penetration gain for the same value of HAZ volume variation, which is more advantageous for the process. By dividing the value of penetration by the value of the HAZ volume, we get $5.5 \times 10^3$ for point A, 3.6 for B, 4.0 for C, 2.8 for D, 2.3 for E, and 2.1 for F.

Since the penetration in A is not useful for most practical applications, the second point with the largest value for the ratio between penetration and HAZ volume is point C. Therefore, this point is more advantageous if the objective is to obtain higher penetration with productivity (welding speed) for the same relative HAZ volume.
Conclusion

This work studied the influence of welding energy, current, and welding speed concerning penetration and HAZ volume in the TIG autogenous welding process was studied. The aim was to develop a tool to help specialists in optimizing this welding process. For this purpose, two numerical models (finite volume and response surface) were considered. In addition, the sensitivity analysis concerning current and welding speed is performed. A multiobjective optimization problem was formulated and solved, considering the maximization of the penetration and the minimization of the HAZ volume to determine the best operating conditions.

Based on the obtained results, the next main conclusions can be drawn:

- In terms of coefficient of determination and p-value, both numerical models demonstrated high concordance, i.e., each model is statistically significant.
- Each proposed model (with one or more independent variables) represents particular information about the physical process. Thus, each one can be used to understand the process. In addition, these models can be used as a tool to help welding specialists during the parametrization process.
- The sensitivity study shows that the current influences penetration and HAZ volume more than welding speed. Physically, this is due to the fact that the current has linear (arc coupling) and non-linear (Joule effect and pressure gradient) influence, and the welding speed contributes linearly, modulating the heat conduction.
- Based on the multiobjective optimization, a good choice to be implemented in practice is the point C \((I = 250 \text{ A}; V_W = 24.8 \text{ cm/min})\) of the Pareto’s curve because it has greater penetration relative to the same HAZ volume and higher productivity (welding speed). The same methodology can be applied for other processes and parameter’s range.

**Author contribution** Luiz Eduardo dos Santos Paes: supervision, project administration, conceptualization, methodology, formal analysis, investigation, writing—original draft; João Rodrigo Andrade: software, formal analysis, investigation, writing—original draft; Fran Sérgio Lobato: software, formal analysis, investigation, writing—original draft; Elisan dos Santos Magalhães: formal analysis, writing—review and editing.

**Table 8** Some points of the Pareto’s curve for the maximization of the penetration and the minimization of the HAZ volume

|   | \(X1\)  | \(X2\)  | \(I\) (A) | \(V_W\) (cm/min) | \(P_e\) (mm) | \(VHAZ\) (cm³) | \(P_e/VHAZ\) (mm/cm³) |
|---|---------|---------|----------|----------------|-------------|-------------|---------------------|
| A | -1.4142 | 1.0136  | 50       | 22.17          | 0.1352      | 2.4353E-05  | 5.5516E03           |
| B | -0.5639 | 0.6795  | 110      | 19.80          | 1.0948      | 0.3042      | 3.5989              |
| C | 1.4142  | 1.3905  | 250      | 24.83          | 2.1563      | 0.5401      | 3.9924              |
| D | 1.4142  | 0.0537  | 250      | 15.38          | 2.8761      | 1.0370      | 2.7735              |
| E | 1.4142  | -0.7032 | 250      | 10.03          | 3.6334      | 1.5607      | 2.3280              |
| F | 1.4142  | -1.4142 | 250      | 5.00           | 4.5749      | 2.2121      | 2.0681              |

**Fig. 9** Temperature field for the FV simulation for combination point A, B, C, D, E, and F together with the penetration values
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Declarations

Competing interests The authors declare no competing interests.

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