A THERMAL EFFICIENCY ANALISYS OF GTAW PROCESS IN STAINLESS STEEL

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Abstract. *This work presents a global model to determine the time dependent thermal efficiency in a GTAW process. With the purpose of estimating the amount of heat delivered by the GTAW torch, a previously developed homemade C++ code was improved. The new model proposes the heat flux estimation through the Golden Section optimization with Temperature Moving Sensor technique. An innovative methodology based on Time Traveling concept is proposed to regularize the Golden Section technique. In order to test the capacity of the model to adapt to a range of conditions, a set of lab-controlled experiments were performed under different welding conditions based on a Robust Project matrix (Taguchi). The objective function was determined based on to the fourth power between the experimental and the calculated values. Moreover, the work also presents an analysis of the cooling rate of the process by convection and radiation. An empirical correlation based on the local Nusselt number for flat plates was used to estimate the local heat transfer coefficient. The proposed model proved to be a first-class method to determine the thermal efficiency in a welding process.*

Keywords*: Inverse problems, Heat Transfer, Thermal Analysis, Numerical and Experimental Methods*

1. INTRODUCTION

An easy way to determine the melting efficiency represents a big challenge in all kinds of welding processes. A welding thermal model might allow the precise determination of the welding efficiency and the optimum welding parameters configuration without the need for experimental validation. This configuration may improve significantly the process and reduce costs. The optimum thermal process configuration may be determined by a statistical approach (Koleva, 2005). Although the statistical method can determine the best configuration for a random welding process, it cannot present the heat delivered to the welded plate numerically. Consequently, the welding efficiency cannot be determined.

The thermal models usually have a heat input equation with an efficiency term. We can find several references about the use of an efficiency term on the heat distribution equation; however this value is not frequently presented, for example, Wahab et al. (1998). Other authors only use tabulated literature values as Piekarska and Kubiak (2011), where they assume the laser-arc hybrid welding process efficiency as 75%, or Sudheesh and Prasad (2015) who applied an efficiency of 70% for a TIG welding process. The empirical character of the thermal efficiency determination limits the precision of those models. Consequently, the results achieved by these authors may be doubtful. As a matter of fact, the welding efficiency does not depend just on the welding process itself, but it depends on the welded material, electric current, voltage, pointing angle, distance between the electrode and the plate, among others.

One method to directly measure the process efficiency is by using a calorimeter (Nasiri et al., 2014). However, due to the price of the equipment, this method is usually put aside. Another way is by using numerical models. Rosenthal (1946) first presented a model for the heat input estimation of a welding process. Although this model is still largely used today for instance, Xia et al. (2008), Pham (2013) and Han et al. (2014), the welding energy is concentrated in only one point and this limits the calculation of the temperature in the region close to the fusion zone. Another weakness is the linearity presented in the model. Indeed, it assumes the material thermal properties as constant values (Goldak, 2005). Due to the presented limitations of the Rosenthal model, it should not be used for efficiency analysis.

An efficient methodology to determine the heat input of the model is inverse analysis. The use of inverse problems allows the precise determination of the heat input with optimization techniques. In those analyses, the numerical temperature is minimized through an objective function until it reaches the measured temperature. For instance, in order to estimate the average heat input in the Tungsten Inert Gas (TIG) welding process, Gonçalves et al. (2010) used the Golden Section technique to minimize an error square function based on the difference of theoretical and experimental temperature. However, in this case the authors could only estimate the average heat input due to the fact that their model was not linked to a regularization method. Yang et al. (2011) applied the conjugate gradient method and the discrepancy principle to determine the heat generation in a friction welding process. Magalhães et al. (2015) developed an inverse code based on the Broydon-Fletcher-Goldfarb-Shanno (BFGS) optimization technique to estimate the heat input in a Gas Tungsten Arc (GTA) welding process in aluminum.

This work proposes a new methodology to determine the temporal efficiency curve of a GTA welding process. Thereunto, the Golden Section minimization technique (Vanderplaats, 2005) was used as an inverse technique to minimize the heat input during the welding process. Furthermore, this work proposes a model based on the Time Traveling idea as a methodology for regularization of the Golden Section technique. As innovation, the Temperature Moving Sensor technique is proposed as a new methodology for the welding efficiency curve estimation. In addition, nine experiments were performed to verify the efficiency variation in accordance with the electrical current, shielding gas, arc length and the pointing angle in the GTAW process of AISI 304 stainless steel.

2. METHODOLOGY

A Finite Difference model based on the three-dimensional heat diffusion equation with moving heat source and the Enthalpy function was developed in an in-house C++ code. The direct problem applied in this model is based on the code developed by Magalhães et al. (2015). Details on the software theoretical development as well as the boundary conditions were reported in Magalhães et al. (2015).

2.1 Time Traveling Methodology

The heat flux estimation technique proposed in this work is based on the Time Traveling concept. Therefore, it consists of an initial guess which analyses a hypothetical timeline. Then, it compares the parameter to be minimized in a future time. If the analyzed timeline does not suit the optimum condition, the method goes back to the present time and changes the guess. In all kinds of experimental measurements there are a response time between excitation and measure. This methodology allows minimize this response time in order to maximize the estimation. Therefore, this configuration reduces the number of required future time steps in the conventional regularization techniques. Figure 1 presents the schematic representation of the Time Traveling methodology, where *nft* represents the number of future time steps, *i* is the counter for the Time Traveling methodology and *j* is the counter for the analyzed model.

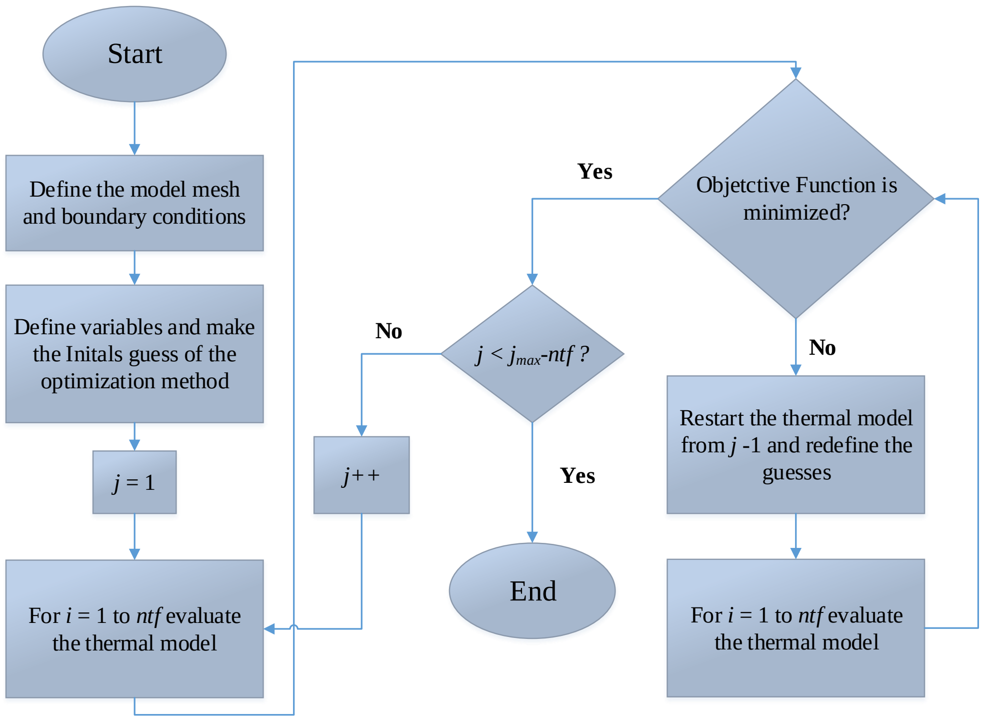


Figure 1. Flowchart for the Time Traveling methodology.

This methodology could be applied in a welding problem. A method for solution is presented in Magalhães *et al.* (2015). In the mentioned work, the numerical model based on the three-dimensional heat diffusion equation with mobile heat source is solved by the Finite Difference method. The thermal properties are assumed as temperature dependent. Therefore, the only variable to be analysed is the heat flux. The optimization technique will require an initial guess for the heat flux. From this guess, the heat flux will be considered as a constant value in the interval 1 and *ntf* (number of future time steps). The objective function will then be compared at time step $j+ntf$. If the guess is not the optimum value, the optimization technique will redefine the heat flux guess and restart the model from time $j-1$. The interactive procedure will remain until the sensitivity criterion is satisfied.

2.2 Objective Function

In order to estimate the heat input, in this work, the Golden Section Technique was applied. This estimation technique requires an objective function. Due to the characteristic high thermal gradient of the process, the objective function based on the temperature difference to the fourth power was used. The objective function adopted in this work is defined by:

$$F_{obj} = \left(T_e^{j+ntf} - T_n^{j+ntf}\right)^4 + \alpha_{reg}\left(q_j - q_{j-1}\right)^2 \tag{1}$$

where F_{obj} is the objective function, T_e^{j+ntf} and T_n^{j+ntf} are the experimental and numerical temperatures respectively at time step $j + ntf$, α_{reg} is the regularization parameter, q_j is the estimated heat flux and q_{j-1} the last estimated heat input.

2.3 Thermal Properties

The thermal conductivity, diffusivity and emissivity were considered as temperature dependent. The thermal conductivity and diffusivity curves were built from fitting data presented in Touloukian et al. (1975). And the emissivity was taken from Roger et al. (1979). Equations (2-4) present the fitted curves for the thermal properties data from Touloukian et al. (1975) and Roger et al. (1979):

$$\lambda(T) = -7.52\times10^{-11}T^4 + 1.95\times10^{-7}T^3 - 1.80\times10^{-4}T^2 + 8.43\times10^{-2}T + 1.73\,[\mathrm{W/mK}] \tag{2}$$

$$\alpha(T) = 1.41\times10^{-9}T + 3.10\times10^{-6}\,[\mathrm{m/s^2}] \tag{3}$$

$$\varepsilon(T) = 8.47\times10^{-2}\ln(T) - 39.32\times10^{-2} \tag{4}$$

where λ is the thermal conductivity, α is the thermal diffusivity, ε the emissivity and T the local temperature.

2.4 Temperature Moving Sensor

In order to maximize the heat input estimation, this work also proposes heat flux estimation with a mobile temperature sensor. The proposed approach allows the determination of the torch efficiency curve during the welding process. Likewise, it allows the heat estimation on the maximum sensitivity point. Figure 2 presents the problem approach. In this work, the GTA torch applies boundary condition of heat flux q'' (x, y, t) with velocity u_x. The minimization point P also moves with an u_x velocity towards the x. The joint use of Moving Sensor and Time Traveling methodology allows the torch efficiency curve determination for the welding process.

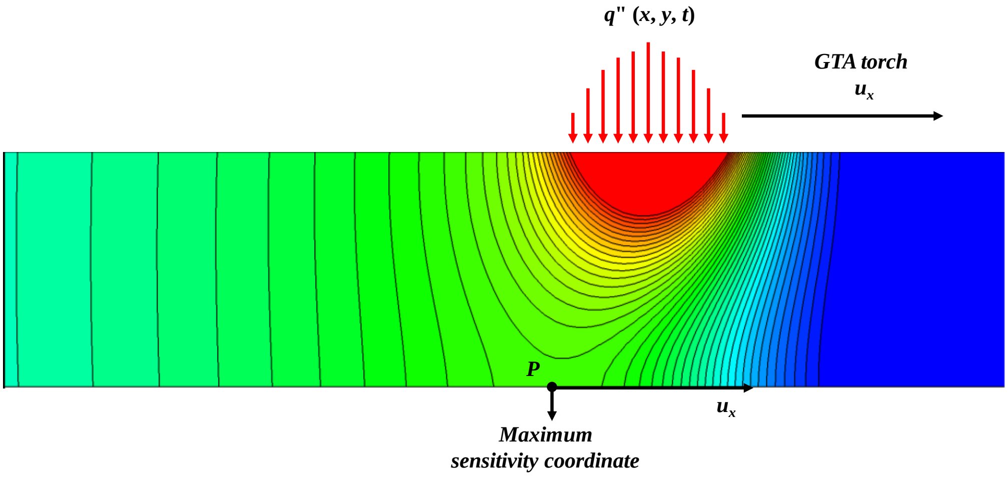


Figure 2. Moving Sensor scheme.

3. EXPERIMENTAL PROCEDURE

Figure 3 presents the equipment apparatus used in the laboratory for the heat flux determination experiments of a GTA welding process. 200 × 50 × 4 mm stainless steel 304 plates were used. 10 type K thermocouples were welded by capacitive discharge opposite the surface where the heat flux was applied on the sample. The thermocouples were positioned 16.7 mm apart as displayed in Fig. 3. The large number of temperature sensors allows the linear approximation of the temperature peaks on the opposite surface of the heated plate. This approach is required due to the application of Temperature Moving Sensor method. An HP75000 series B was connected to a computer for the data acquisition of the temperature history on the plate. A coordinate table was used for the automated process.

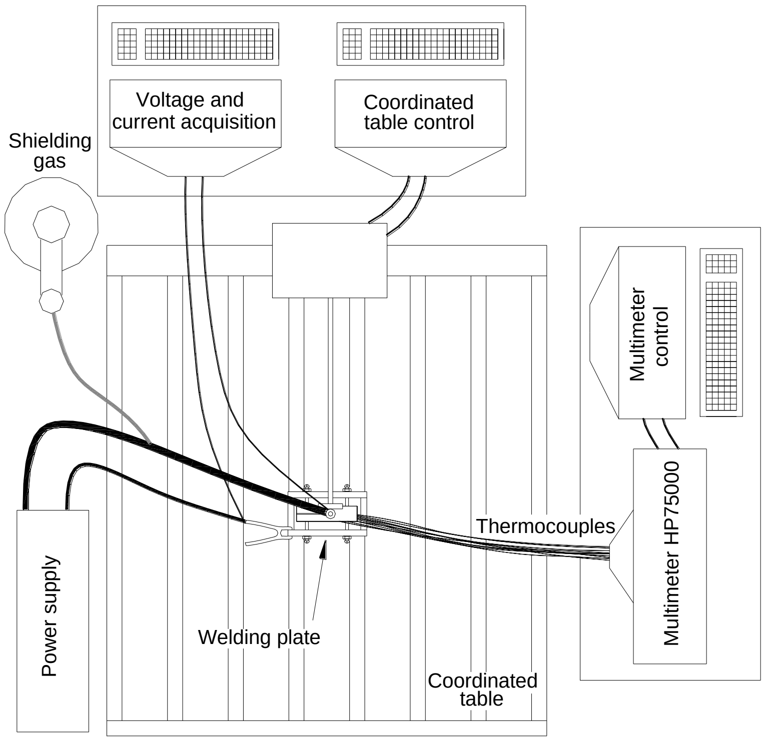


Figure 3. Experimental apparatus displacement.

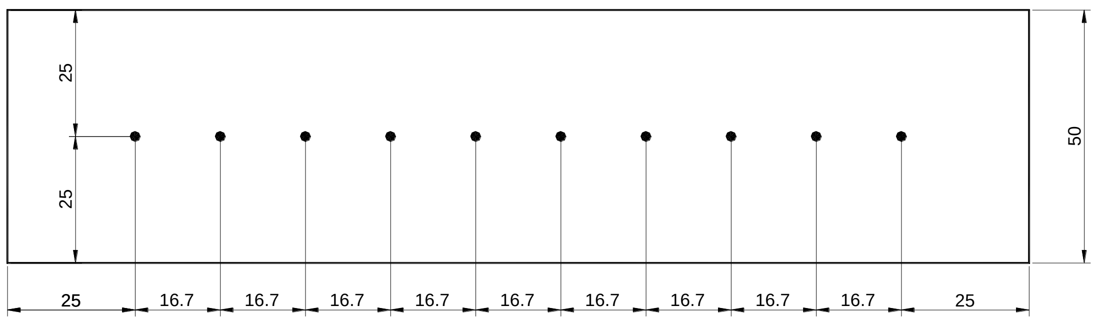


Figure 4. Positions of the Thermocouples on the 304 stainless steel.

Table 1 presents the tested experimental conditions. In addition, the pointing angle, the distance between the welding torch and the sample, current, shielding gas and weld bead width, were presented. The set of experiments were planned following the Taguchi statistical approach (Robust Project). The weld bead width was obtained for each experimental condition from image analyzer.

Table 1. Experimental conditions tested

Test	Pointing angle (± 1°)	La [mm] (± 0,1 mm)	Current [A] (± 0,1 A)	Shielding Gas	Weld Bead width[mm] (± 0,1 mm)
A01	30º	2	40	Ar	2
A02	30º	3	70	Ar+25%He	3
A03	30º	4	100	Ar+25%He	4
A04	60º	2	70	Ar+25%He	3
A05	60º	3	100	Ar	4
A06	60º	4	40	Ar+25%He	2
A07	90º	2	100	Ar+25%He	4
A08	90º	3	40	Ar+25%He	2
A09	90º	4	70	Ar	3

4. NUMERICAL ANALYSIS

Due to the high computational cost of simulation (at least 74 hours each simulation), only the results for case A02 from Tab. 1 are presented. Figure 5 presents the measured temperature curves for test A02. Notice that for this experimental condition, the maximum measured temperature on the opposite surface of the heat is about 315°C.

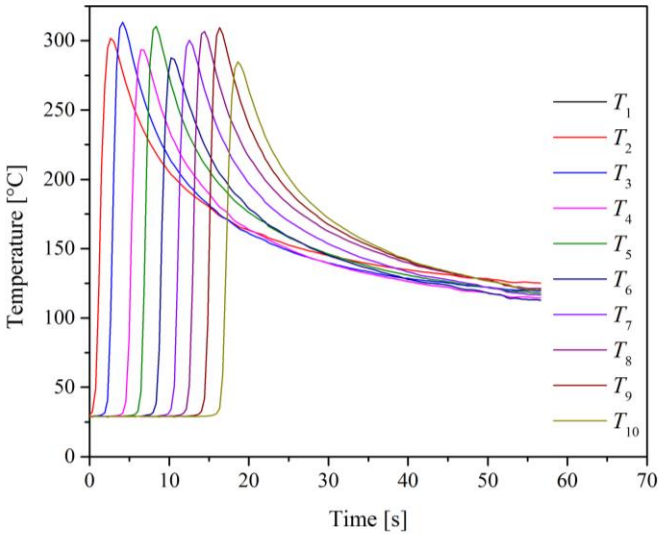
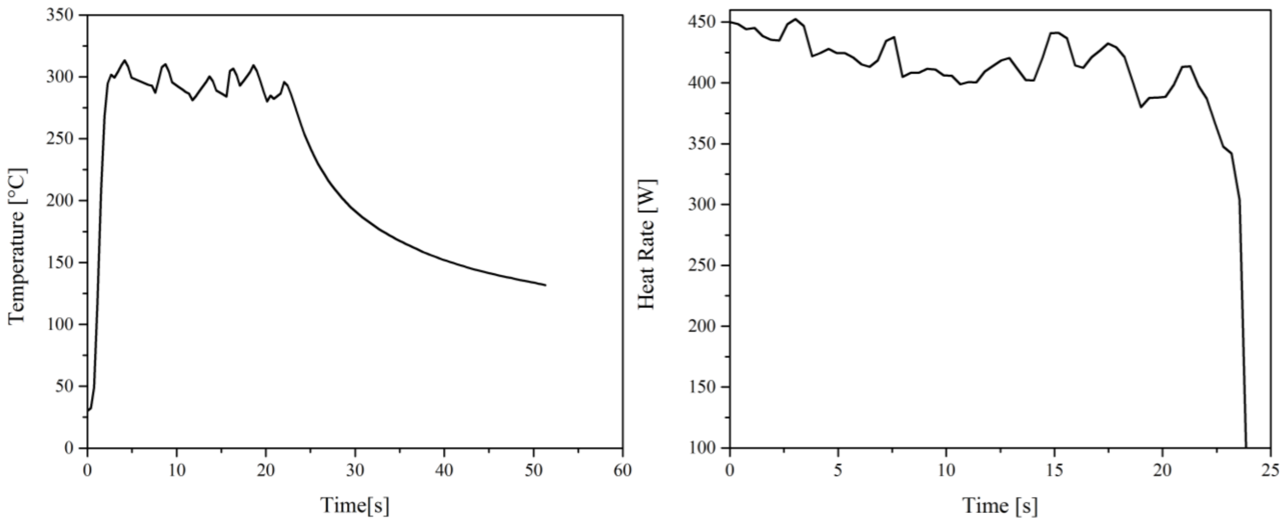


Figure 5. Experimental temperatures on the surface opposite the heated surface for test A02.

The large number of temperature sensors allows the determination of an efficiency curve for the moving sensor which is represented by the point P (Fig. 2). Figure 6a presents the temperature curve of sensor P ($u_x \times t$, t) used for the heat flux estimation. Therefore, for each point of the curve on the Fig. 6a, P presents a different position in relation to x. Notice that although the temperature is about 300° C, the temperature in the heated region is not well established. This oscillation may be associated to some causes: the welding velocity could be irregular, the welded material is not homogeneous or the thermocouples are not adequately fixed. The experiments were conducted on an automated coordinate table which minimizes the welding speed oscillations. To precisely determine how homogenous the material is a microstructural analysis is required. However, this factor has a low impact on the temperature distribution. The most probable cause of the non-uniformity of the temperature on the heated region is the thermocouple attachment. For this evaluation, more experiments for each condition are required.

The non-uniformity of the temperature curve on the heated region implies on similar oscillations on the heat estimation of the welding process. The heating rate of the plate in relation to time in test A02 (Tab. 1) is presented in Fig. 6b. Notice that there is no noise of the estimated heat rate in the output data on the heating region. In the mentioned case, the simulation took only three time steps of the method Time Traveling.



a) b)

Figure 6. a) Temperature in the moving sensor *P* region and b) Estimated heat rate for case A02.

The welding torch thermal efficiency is obtained by dividing the heating rate estimated values by the power supply. Figure 7 presents the welding efficiency for test A02. The thermal efficiency of the welding is defined as the percentage of generated heat effectively delivered to the welded plate. Notice that the thermal efficiency of the torch in relation to time tends to decrease as time increases. This may be explained: During the welding process heat diffusion occurs continuously on the sample. This energy storage leads to the increase in temperature in the points which are going to be welded as the torch moves. As these points have a higher energy level, they tend to reflect more heat than was imposed. Therefore, there is a decrease in the thermal efficiency of the welding as the plate becomes hotter.

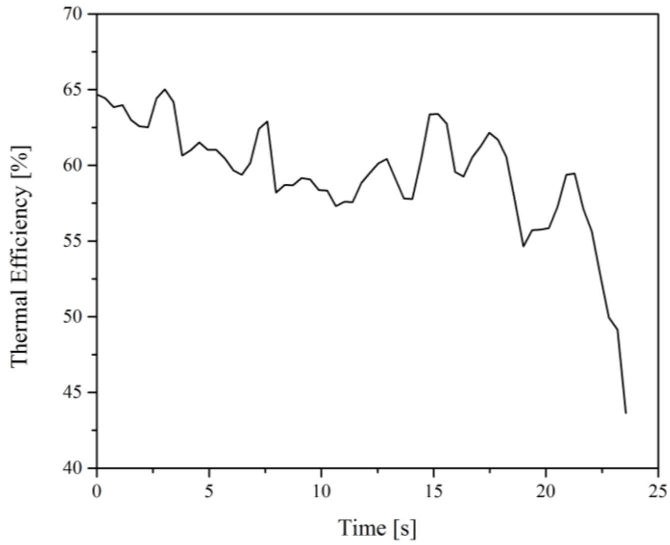


Figure 7. Thermal efficiency curve of the GTA welding process for test A02.

As presented by Magalhães *et al.* (2015), the developed computational code also accurately predicts the numerical temperatures. A comparison between the experimental temperature values for thermocouple T_1 (Fig. 5) and the obtained values on the software is displayed on Fig. 8. A good agreement between the curves may be observed. However, the temperature peak tends to be a little lower when compared to the experimental temperature. This difference is correlated to the inherent error of the attributed values of the thermal properties. For a higher precision of the calculated data at high temperatures, an estimation of the thermal conductivity and diffusivity for the stainless steel AISI 304 is required, mainly on the liquid phase. Unfortunately, there is a lack of technology development on this area. Therefore, those values are not easily found in literature.

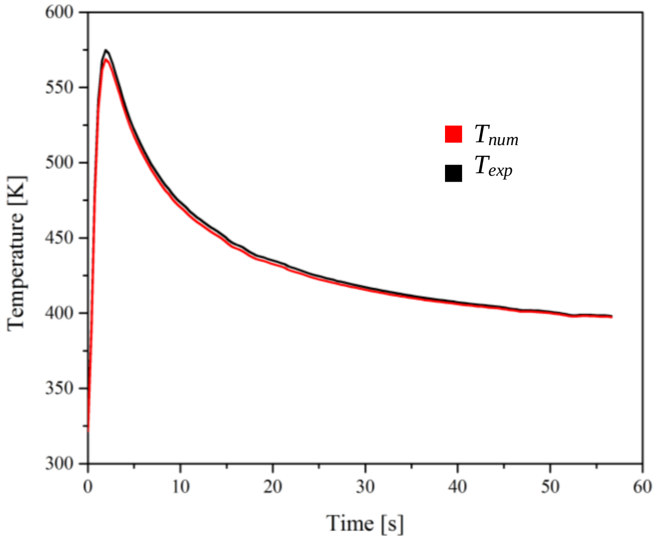


Figure 8. Numerical and experimental temperatures for test A02.

Figure 9 presents the temperature field obtained for the experimental test A02 (Tab.1) for time instant t=19s. The temperature field differs from the case presented by Magalhães *et al*. (2015), in which the authors obtained circular isothermals due to the high conductivity of the aluminum. For the AISI 304 stainless steel, the isothermals presented oval shape layout. This fact is intrinsically connected to a lower thermal conductivity value of stainless steel when compared to the aluminum. With a lower thermal conductivity, the heat tends to be stored in the welding region which reduces the cooling process.

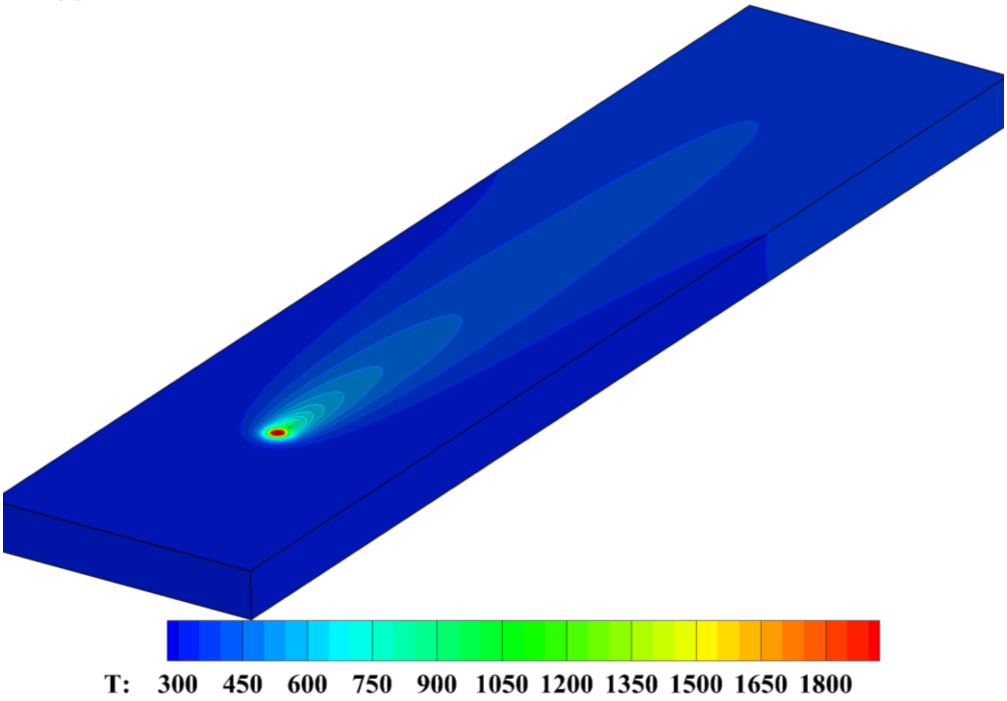


Figure 9. Temperature field in [K] of the GTA welding process for case A02 at t = 19s.

5. CONCLUSIONS

This work presents a low cost and accessible model to determine the thermal efficiency of a welding process. The couple between the proposed model of Time Traveling and the Temperature Moving Sensor technique proved to be a high class method to determine the efficiency of the GTA welding process. The same methodology may be applied to the heat flux estimation in other welding processes. The application of the Golden Section minimization technique allowed the heat flux estimation on the sample. Through the estimated heat flux, the welding efficiency could be determined. The similarity between the estimated and the measured temperatures validated the methodology. A proposition for future work in this area is the application of the developed model for the estimation of the welding efficiency in other manufacturing process, for instance the cutting process.

6. ACKNOWLEDGEMENTS

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