HEAT TRANSFER WITH PHASE CHANGE APPLIED TO THE GTAW PROCESS

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Abstract. *One of the most widely used welding processes is the GTAW (Gas Tungsten Arc Welding). This process is used with success for stainless steels and non-ferrous materials welding. The welding of workpieces is obtained through a voltaic arc, which is a very intense heat source. The thermal behavior analysis of the physical problem that occurs during the welding process is crucial to understand, for example, the width and depth of the weld, microstructure changes and residual tensions. The numerical techniques are recognized as a convenient way to obtain the solution of the differential equations related to the heat transfer problem and identify the solid-liquid interface. In this sense, this work presents the numerical solution of the diffusion equation based on the enthalpy method. The objective is to study the phase change phenomenon during the GTAW of a cylindrical AISI 304 steel bar. The Golden Section technique is used to estimate the heat flux supplied to the sample. Experimental data are used to validate the thermal model proposed in this work. The methodology shows to be efficient to identify the thermal fields and the solid-liquid interface.*

Keywords: *inverse problems, heat conduction, phase change, welding*

1. INTRODUCTION

The heat transfer problem with phase change attracts a considerable attention of the mechanical engineering researchers due to its relevance and application in several industrial processes as casting and welding of metallic materials.

Many investigators have studied this thermal problem analytically, numerically and experimentally. It is possible to find in literature articles about the thermal analysis of GTAW process as in Rosenthal (1941), Tsai and Hou (1988) and Gonçalves (2004). Besides that, other authors are concerned about the study of the penetration of the welding pool (Liangyu and Ruidong, 2000), the heat conduction analysis of bi-directional multipass welding (Kasuya *et a.l*, 2000) and the thermal analysis of the flow and speed of the welding front of solidification (Flemings, 1974), among others problems. In the majority of these works, however, the value of the heat flux input is assumed to be known, that means, or it is taken from literature or determined by using calorimetric techniques. In fact, the heat flux that goes to the workpiece is unknown and its determination represents an inverse problem. In this sense, the use of techniques found in inverse heat conduction problems can represent an alternative way to obtain the heat flux that goes to the workpiece. This procedure is justified by the difficulties to obtain measurements in the thermally affected zone in the welding area. The inverse technique can then obtain the heat flux imposed in the weld face of the workpiece using temperatures measured on accessible locations of the workpiece.

Inverse heat conduction problems (IHCP) have been used recently in the studies of welding processes (Katz and Rubinsky (1984), Hsu *et al.* (1986) and Gonçalves *et al.* (2005). Katz and Rubinsky (1984) have used a finite element method called border attack with a one-dimensional treatment, while Hsu *et al.* (1986), also using finite elements, considered a two-dimensional model. In that case, the temperature data measured by thermocouple sensors in the solid region are used to calculate the interface solid-liquid position and the temperature field in the solid region of the workpiece. For this, a Newton-Raphson interpolation is used, assuming a stationary welding process. Another two-dimensional model can be found in the work of Gonçalves *et al.* (2005). In this case, a transient numerical model based on Al-Khalidy (1997) is used to derive the direct problem equation while the simulated annealing method is applied to obtain the heat flux input. It is noticed, however, that in the two-dimensional model the influence of heat diffusion through the plate thickness is neglected. Although this consideration is justified by practical results in GTA welding process with thin plates, it represents a limitation for other processes when welding thicker plates.

The inverse technique proposed in this work is based on a two-dimensional transient heat conduction model with heat source fixed. The inverse technique determines the heat imposed in the weld face of the workpiece using temperatures measured on the opposite face to the weld bead.

The direct problem, based on the heat conduction equation in cylindrical coordinates with phase change, is solved by the enthalpy method. In the numerical solution it was applied the Finite Volumes technique with irregular mesh and implicit formulation. The computational algorithm was implemented in C++ and allows obtaining the temperature profiles in the cylindrical model, liquid mass fraction, enthalpy and depth and length of the welding pool.

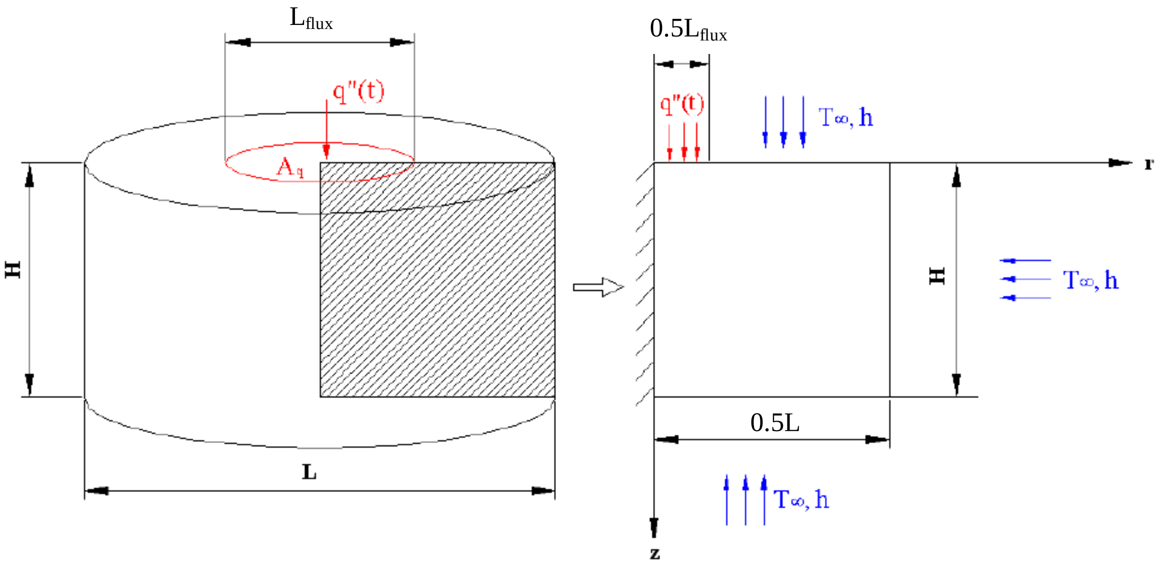
The objective of this work is to obtain a thermal solution of the welding problem that appears during a real GTAW welding process of austenitic stainless steel AISI 304 by using the inverse technique. In this sense, all the simulated results are compared to experimental data.

2. THEORETICAL FUNDAMENTAL

2.1. Physical model

In Fig. 1a the physical model of the thermal problem is presented. It consists of a cylindrical sample with a heat source $q''(t)$ applied in the area A_q(r,z). The remains' surfaces are submitted to the convection heat transfer.

Considering a constant heat flux for each step of time and the symmetries in Fig. 1a, the original model can be approximated by a bi-dimensional thermal model as presented in Fig.1b.



(a) (b)

Figure 1. a) The physical model in cylindrical coordinates. b) The simplified physical model.

Once the physical model is known, it becomes important to establish the mathematical model.

2.2. Mathematical model

To solve a realistic thermal problem it is necessary to consider the nonlinearity of the diffusion equation as well as the thermal properties of the materials varying with temperature. Besides that, one of the difficulties to solve the thermal problem for alloys and glassy substances is due to the phase change taking place over an extended temperature range from T_s (solid temperature) to T_l (liquid temperature), and the presence of a mushy zone between the solid and liquid regions (Ozisik, 1993).

The cylindrical thermal problem presented in Fig. 1b can be described by the heat diffusion equation in terms of enthalpy as:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(k(T)r\frac{\partial T(r,z,t)}{\partial r}\right)+\frac{\partial}{\partial z}\left(k(T)\frac{\partial T(r,z,t)}{\partial z}\right)=\rho\frac{\partial H}{\partial t} \tag{1}$$

where $k(T)$ is the thermal conductivity that varies with temperature T, and r is the cylinder radius.

It is noticed in the Eq. (1) that the problem is governed by a nonlinear differential equation due to the thermal properties depending on the temperature. In this case, the enthalpy is represented by the sum of the sensible and latent heat according to Ozisik (1993), in other words,

$$H = \begin{cases} C_p T & for \quad T < T_s \quad solid \;\; region \\ C_p T + \dfrac{T - T_s}{T_l - T_s} H_f & for \quad T_s \le T \le T_l \quad mushy \; region \\ C_p T + H_f & for \quad T > T_l \quad liquid \; region \end{cases} \tag{2}$$

where T_s and T_l are the solid and liquid phase temperatures, respectively. C_P is the specific heat, *L* is the latent heat, and *f* is the liquid mass fraction that can be obtained from:

$$f = \begin{cases} 0 & for \quad T < T_s \quad solid \;\; region \\ \dfrac{T - T_s}{T_l - T_s} & for \quad T_s \le T \le T_l \quad mushy \; region \\ 1 & for \quad T > T_l \quad liquid \; region \end{cases} \tag{3}$$

The boundary conditions imposed to the problem presented in Eq. (1) can be written by

$$-k(T)\frac{\partial T}{\partial \eta} = h(T - T_\infty) \tag{4}$$

on the regions exposed to the environment and

$$-k(T)\frac{\partial T}{\partial z} = q''(t) \tag{5}$$

in the area defined as A_q, where η represents the coordinates *r* and *z*, T_∞ is the room temperature, and *h* is the convective heat transfer coefficient. The initial condition is:

$$T(r,z,0) = T_o \tag{6}$$

where T_o represents the initial temperature of the sample.

In order to solve Eq. (1), a numerical modeling based on the Volume Finite method was developed (Maliska, 2004). According to the dimensions furnished in Fig. 1b, the sample was discretized from an irregular bi-dimensional mesh. The diffusion equation was integrated in the space and time. The transient problem was solved by the implicit methodology to avoid restrictions in the mesh and time step.

An irregular mesh was used in this work; hence the thermal properties must be calculated in the faces of the finite volume. In this case, a linear interpolation scheme was used as suggested by Patankar (1980). A more accurate approach for calculating the temperature dependent properties (mass fraction and specific heat) is the use of an extrapolation scheme as describe by Ozisik (1993). The linear algebraic equations system is solved by the Successive Over Relaxation method (SOR – Cângani *et al.* 2008).

In this work, the simulated results are compared to experimental data of the welding process of stainless steel AISI 304. Moreover, inverse problems based on the Golden Section technique are implemented in the computational code to estimate the heat flow supplied to the cylindrical sample.

2.3. Inverse problems in heat transfer

The heat flux in this work is obtained by Inverse Problems, which consist in minimizing an error function (*F*), defined by the square of difference between the experimental *Y(r,z,t)* and calculated *T(r,z,t)* temperatures. Thus, the objective function to be minimized can be written as:

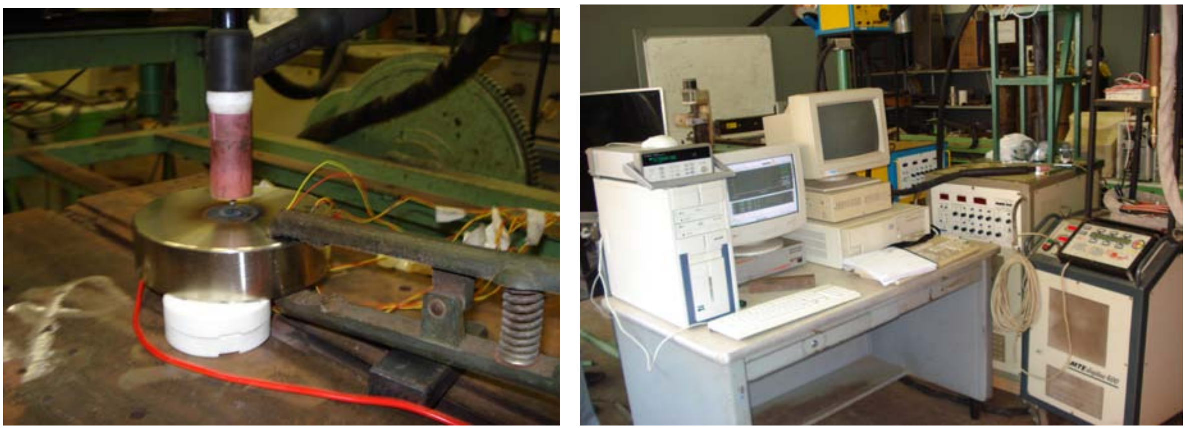
$$F = \sum_{t=1}^{nt} \sum_{i=1}^{N} (Y(r_i, z_i, t) - T(r_i, z_i, t))^2 \tag{7}$$

where *N* represents the number of thermocouples, and *nt* represents the period of heating or cooling of the sample.

The Golden Section (Carvalho, 2005) is proposed in this work to estimate the heat flux supplied to the sample. The choice of this technique is based on several reasons: First, the objective function is assumed to be unimodal, so it does not need continuous derivatives. Secondly, as opposed to polynomial or other curve fitting, the rate of convergence for the Golden Section is known. Finally, the method is easily programmed for obtaining the solution by the digital computer. The Golden Section Method is basically an iterative process in which the search interval reduces the previous iteration interval in approximately 60%, until finding the minor value of the objective function.

2.4. Experimental procedure

In order to obtain the experimental temperature *Y(r,z,t)* in the GTAW process, three thermocouples type K (chromel-alumel) are fixed by capacitor discharge in the bottom of the stainless steel AISI 304 cylinder. The experimental temperatures during the phase change were obtained by the data acquisition system HP Series (34970), as shown in Fig. 2.



a) b)

Figure 2. Experimental apparatus: a) Thermocouples and welding torch positioned in the sample; b) Data acquisition system.

In this case, three experiments were accomplished. The dimensions of each cylinder are presented in Tab. 1. C is the nomenclature adopted for each cylinder.

Table 1. Dimensions of each experimental cylinder AISI 304.

	Cylinder			Uncertainties
Measures	**C1**	**C2**	**C3**	
L [m]	0.102	0.101	0.102	± 0.001
H [m]	0.026	0.026	0.030	± 0.001

A general overview of the experimental bench of tests applied in the thermal analysis of the GTAW process is shown in Fig. 3.

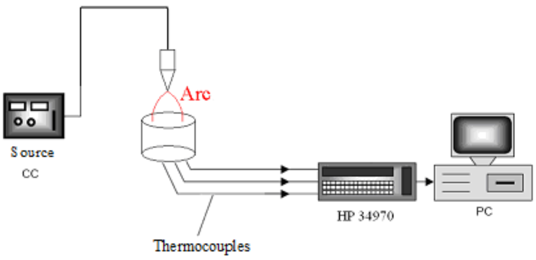


Figure 3. Experimental bench of tests.

The coordinate *r* of the thermocouples is showed in Tab. 2. All the sensor ones were positioned in the surface opposite to the heat flux, as presented in Fig. 1. TER is the nomenclature used for each thermocouple.

Table 2. Coordinate *r* of each thermocouple positioned in the bottom of the sample ($z = H$) according to Tab. 1 and Fig. 1.

	Cylinder			Uncertainties
Thermocouple	**C1**	**C2**	**C3**	
TER1, (m)	0.022	0.004	0.001	± 0.001
TER2, (m)	0.032	0.018	0.017	± 0.001
TER3, (m)	0.042	0.039	0.027	± 0.001

The welding conditions for each test are shown in Tab. 3.

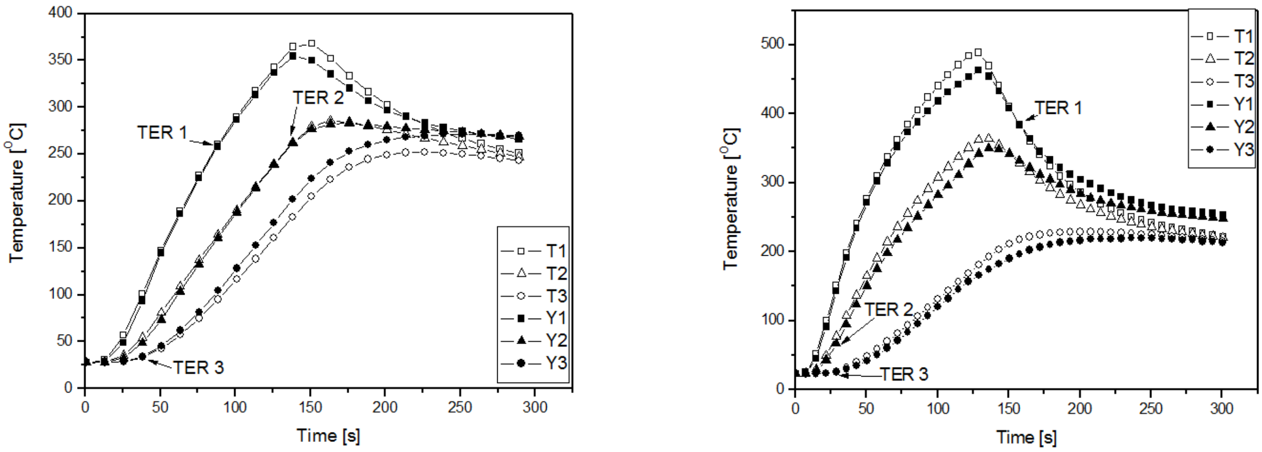
Table 3. Welding conditions for each experimental test

	Cylinder			Uncertainties
Welding conditions	**C1**	**C2**	**C3**	
***V*, voltage, (V)**	15.00	14.10	14.62	± 0.01
***I*, current, (A)**	205.0	203.0	204.2	± 0.1
$P_{Exp}=V.I$, power of the torch, (W)	3075.0	2862.3	2985.4	-
T_o, initial temperature of the sample, ($^{\circ}$C)	27.8	23.0	22.3	±0.1
T_{00}, ambient temperature, ($^{\circ}$C)	27.8	23.0	22.3	±0.1
Δt , interval of data acquisition (s)	0.502	0.286	0.289	± 0.001
t_H, time of heating (s)	128.512	118.976	119.935	± 0.001
t, time of data acquisition (s)	300.196	301.158	291.312	± 0.001
L , Final length of the welding pool (m)	0.010	0.010	0.010	± 0.001

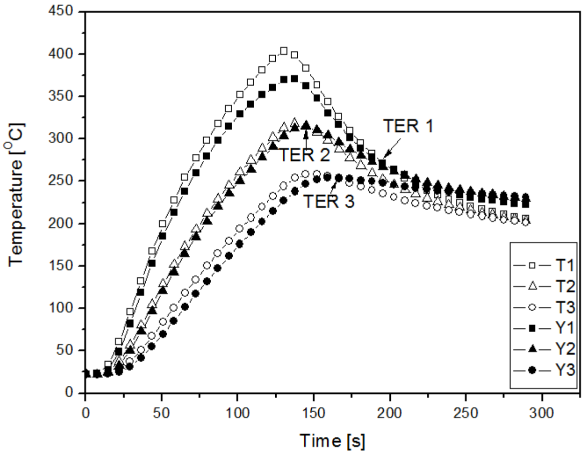
It is verified by the analysis of the experimental data presented in Tab. 3 that the experiments seen to be similar. In fact, the authors attempt to repeat the experimental conditions for each test. However, the difficulty of adjusting the experimental parameters and the uncertainties related to the dimensions of each cylinder make the tests different.

3. RESULTS AND DISCUSSION

Three independent runs were performed for each welding condition. The coefficient of heat transfer convection is considered 110 [W/m^2 $^{\circ}$C] in the surface submitted to the heat flux and 20 [W/m^2 $^{\circ}$C] in the remains' surfaces. In the simulation process it was used the thermal physical properties of the stainless steel AISI 304 according to Cângani *et al.* (2008). The heat flux supplied to the samples in each experiment was estimated by the Golden Section technique. Figure 4 presents the comparison between the experimental and calculated temperatures for tests C1, C2 and C3 according to the coordinates presented in Tab. 2.



(a) (b)



(c)

Figure 4. Comparisons between experimental and calculated temperatures. Welding conditions: a) C1, b) C2 and c) C3.

When analyzing Fig. 4 it can be noticed an excellent agreement among the experimental temperatures and those calculated by the inverse technique. The Tab. 4 presents the results for the heat flux estimation for the three tests defined in Tab. 3. The Thermal Efficiency (η) can then be calculated from the ratio between the useful heat flux to the workpiece (Q_{Est}) and the total power supplied by the torch (Q_{Exp}).

Table 4. Useful heat flux estimated and Thermal Efficiency for each test.

	$Q_{Est} \cdot 10^{-7}$ (W/m²), Useful Power	$Q_{Exp} \cdot 10^{-7}$ (W/m²),Total Power	η (%)
C1	2,4503	3,9152	62.55
C2	2,2475	3,6444	61.67
C3	2,3362	3,8011	61.46

It is seen in Tab. 4 that due to the similarity between the experiments carried out the Thermal Efficiency is practically constant. According to Easterling (1983), the typical values for the Thermal Efficiency for the GTAW process vary between 20% and 50% when using alternating current, and between 50% and 80%, for continuous current. Grong (1994) also ratifies that the band of typical values for η using the TIG process varies between 25% and 75%. In this case it is verified that the obtained results presented in Tab. 4 are in agreement with the literature.

Figures 5a to 5c represent the thermal fields during heating, and Fig. 5d shows the cooling of the sample. The temperature fields are obtained from the numerical solution of the direct problem given by Eq. (1) and solved using the estimated value of the useful power ($\boldsymbol{Q_{Est}}$) for test C1 as shown in Tab. 4.

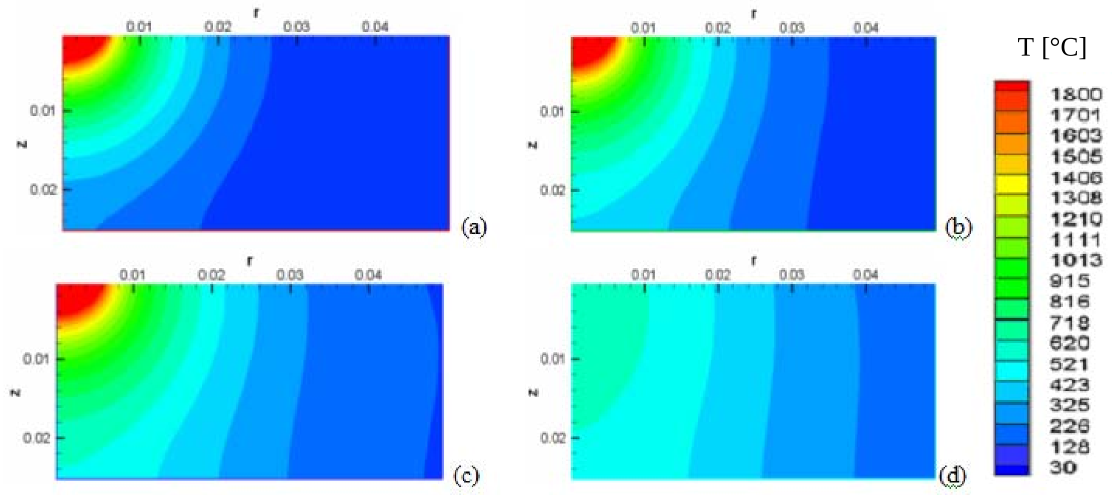


Figure 5. Thermal fields at: a) 37.5 [s]; b) 75.0 [s]; c) 112.5 [s] e d) 150.0 [s].

Figure 6 shows the mass fraction of liquid (f) considering the symmetry of the thermal model. In this case it is possible to identify the width (m) and the penetration depth (m) of the weld bead in the last time of heating (128 seconds) during test C1.

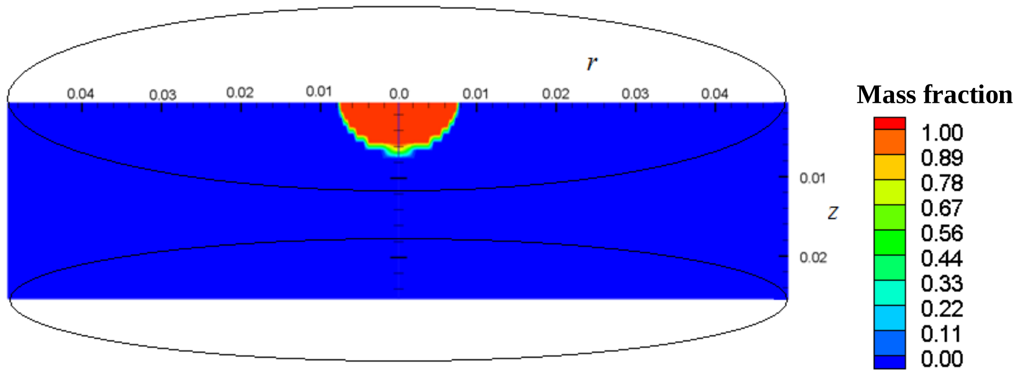


Figure 6. Simulation of the mass fraction for test C1.

In this work two procedures were used in order to validate the numerical methodology proposed. The first one was presented previously and consists in analyzing the calculated and the experimental temperature in the workpiece. The second one is to compare the width and depth of the weld bead with the calculated values obtained by Eq. (1).

In order to obtain experimentally the width and the penetration depth of the weld bead the workpiece was sectioned transversely in the plan r-z as presented in Fig. 7. In this case, these values were obtained using an image treatment system for the specific welding condition presented in test C1. In the simulation process, the width and depth of the weld bead were calculated from the information of the mass fraction of liquid as shown in Fig. 6.

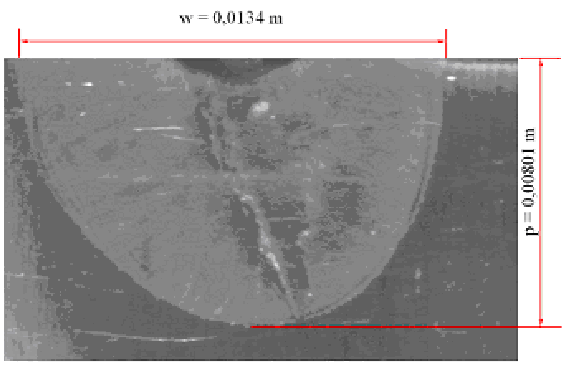
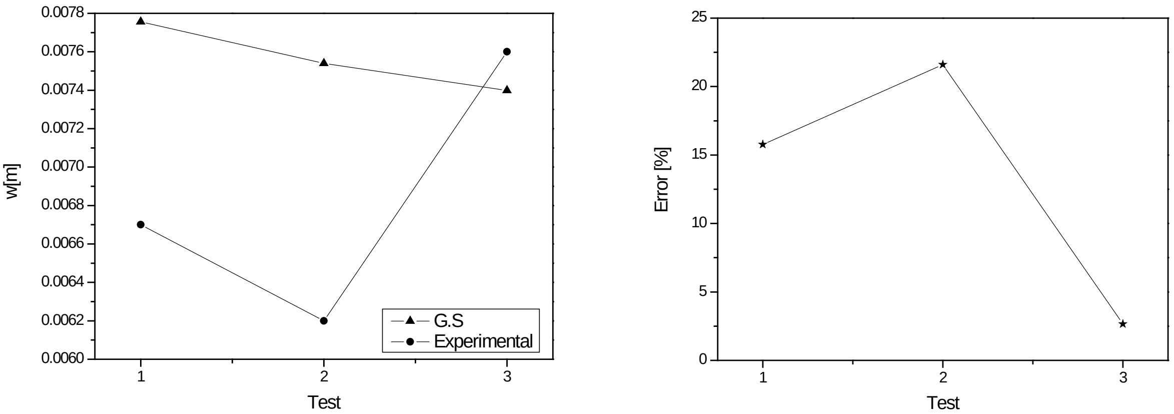


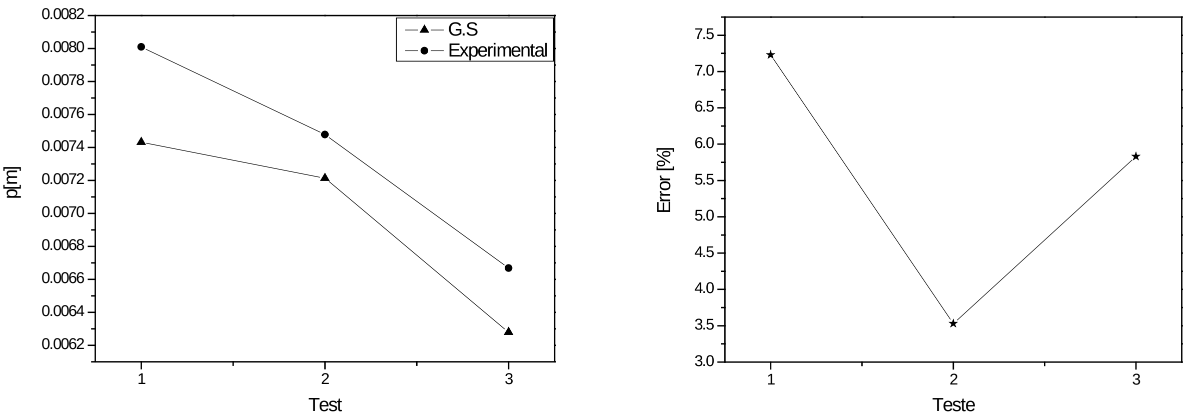
Figure 7. Width and depth of the weld bead for test C1.

Figures 8 and 9 present the comparison among the experimental width and penetration depth of the weld bead with the calculated values for the three tests presented in Tab. 3. The uncertainties related to the measurement of the experimental data are ± 0.0001 meters.



a) b)

Figure 8. Results: a) Comparison between the experimental and calculated width of the weld bead for the three tests. b) Error between the experimental and calculated results.



a) b)

Figure 9. Results: a) Comparison between the experimental and calculated penetration depth of the weld bead for the three tests. b) Error between the experimental and calculated results.

It can be seen in Figs. 8a and 9a a good agreement among the experimental and calculated values of the width and the depth of the weld bead. The maximum deviation for the width and depth was 22.0 % and 7.0 %, respectively. These discrepancies can be attributed to the thermal property that varies with temperature, the correct analysis of the convective heat transfer in the surface submitted to heat flux and the thermal radiation effects that have not been considered in the thermal model.

The two validation procedures presented in this work, in fact, assure that the technique proposed here can be used to estimate heat flux supplied to the sample and temperature field during the GTAW process.

4. CONCLUSIONS

It is presented the use of inverse heat conduction problem techniques to determine temperature fields and heat flux during the GTA welding process of three cylindrical AISI 304 workpieces. The heat flux imposed on the weld surface is estimated using the Golden Section technique. Two procedures were used in order to validate the numerical methodology proposed in this work. The first one consists in analyzing the calculated and the experimental temperature in the workpiece. The second one compared the width and depth of the weld bead with the calculated values. The thermal efficiency of the GTAW process was also calculated and the results were in agreement with the literature. The discrepancies presented in this work are attributed to the uncertainties related to the measurement of the experimental parameters, the simplified bi-dimensional thermal model adopted, the knowledge of the thermal property that varies with temperature, the correct analysis of the convective heat transfer in the surface submitted to heat flux and the thermal radiation effects that have not been considered in the thermal model. In general, the technique shows to be satisfactory to simulate and analyze the welding thermal problem.

5. ACKNOWLEDGEMENTS

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