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A NOVEL OPTIMIZATION METHODOLOGY APPLIED TO PARAMETERS OF HEAT SOURCES IN WELDING NUMERICAL SIMULATIONS

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Abstract. *Welding processes on plates involve complex physical and chemical phenomena, which make mathematical modeling difficult. Several types of heat sources are available to be used in numerical simulations of welding processes. However, to get accuracy, some heat sources have many geometry parameters to be set and it demands much computational time, even using optimization methodologies. In this paper, a welding numerical analysis of single pass butt joint weld, with square groove, of AISI 1020 carbon steel, using the conventional TIG process is shown. The plates are 3.2 mm thick, 100 mm long and 50 mm wide. The numerical simulations were performed by ANSYS® Multiphysics software, considering three types of moving heat sources distributions (Gaussian, Conical and Double Ellipsoid), convection and radiation heat transfers on the surfaces and temperature-dependent material properties. The fusion zone shapes of the plates obtained from the experiments developed at the laboratory of research in welding engineering (LAPROSOLDA – UFU), located in Uberlandia, MG, Brazil, are compared with numerical results. This data, obtained by macrography, were used by a new optimization methodology to find the optimal parameters of these heat sources, by using a Genetic Algorithm approach. Analysis of the computational time and the accuracy in relation to experiments was carried out. In general, thermal results obtained by numerical simulation are in good agreement with experimental ones. Besides, the use of the proposed methodology decreases strongly the computational time.*

Keywords: *optimization methodology, heat source, welding process, numerical simulation, reduced geometry*

1. INTRODUCTION

Welds are essential parts of the engineering structures. Residual stresses and metallurgical transformations due to thermal nonlinearities during welding processes can cause damage effects. An important tool to predict the behavior of welding structures is the numerical modelling (Yaghi et al., 2004). The application of the numerical simulation to the welding process has recently grown mainly due to the increase of the computer capacity and the availability of commercial numerical codes.

The complexity of phenomena involved in welding processes requires many assumptions and approximations in numerical simulations. Although thermo-mechanical-metallurgical effects are coupled, generally, numerical simulations are carried out in sequence (thermo-mechanics or thermo-metallurgic), due to the low dependence of the thermal field in relation to others (Goldak and Akhlaghi, 2005). However, the accuracy of structural and metallurgical results depends on the accuracy of the thermal solution. Lindgren (2001) and Dong (2003) have shown that thermal-mechanical decoupled analysis provides accurate results and simplifies the numerical solution. Similarly, other authors, such as Brickstad and Josefson (1998), Capriccioli and Frosi (2009), Coret and Combescure (2002), Wu *et al*. (2009) and El-Ahmar (2007) have stated that the influence of the mechanical model on thermal and metallurgical simulations is not significant in the welding process application.

In the welding process, the most interesting regions in the heat transfer analysis are the fusion zone (FZ) and the heat affected zone (HAZ), where high temperatures are reached (Iacobescu, 2006). These high temperature levels cause phase transformations and alterations in the mechanical properties of the welded metal. These effects influence significantly the behavior of the welded piece. Thus, the correct simulation of the temperature field in numerical simulations is fundamental.

The main difficulty of the thermal field simulation in a welding process is the heat source modeling. Although solutions considering distributed heat sources can be reached both analytically and numerically, there is an increasing tendency to use numerical methods. After Rosenthal (1941) proposed the analytical solution considering a punctual or a line heat source, several more realistic heat source distributions have been developed. Pavelic *et al*. (1969) developed a surface heat source model with a Gaussian distribution. Other researchers, such as Balasubramanian *et al*. (2008), Zaeh and Schober (2008) and Ziolkowski and Brauer (2009), proposed the combination of Gaussian distribution on the surface and the distribution along the thickness in order to consider a 3D model, by applying the conical Gaussian heat source. A classical volumetric heat source model is the double ellipsoid distribution that was developed by Goldak *et al*. (1984). Chukkan et al. (2015) tested several heat sources and analyzed their accuracy. Wahab *et al*. (1998) and Wu *et al*. (2009) combined the double ellipsoid with spherical and cylindrical volumes along the thickness.

Finding optimal welding parameters by using experimental procedures demands many test specimens (Moradpour et al., 2015; Nagesh and Datta, 2010). Besides, there is no confidence that values are optimal. However, the knowledge advance related to welding can grow significantly if welding simulations are combined with optimization techniques. This combination enables finding, computationally, optimal values of process parameters, with less cost and time (Islam *et al*., 2014).

The mathematical optimization is an area of the Computational Sciences which the main objective is to reach the best solution for problems whose the response quality can be measured by a number. The quality of available tools used for carrying out this task is as almost similar as the number of applications. Engineering designs can include optimization processes in which designers consider goals, such as resistance, distortion, weight, wear, corrosion, etc. Conventional optimization methods may require that objective functions are continuous and differentiable due to convergence conditions. However, the mapping of project variables for functions and constrains are strictly implicit in numerical optimizations. Thus, it is difficult to determine whether these functions have these characteristics. Therefore, optimization methods based on gradients are not adequate to be used in this type of problems (Rao and Savsani, 2012). Techniques free of derivation, with stochastic behavior and rules of the probabilistic transition, have more applicability for these problems; some of them include: Genetic Algorithms (GA), Differential Evolution (DE) and Particle Swarm Optimization (PSO).

The computational time is the main variable that restricts a more wide use of numerical simulations by using optimization methods. CFD simulations of welding processes, even in simple cases, can require more than 20 days (Cheon *et al.*, 2016), while simulations based on the *Finite Element Method* (FEM) can demand from one to more than 6 hours, depending on the mesh size and the time step (Farias *et al.*, 2016). It is worth emphasizing that subsequent simulations of the heat transfer (mechanical or metallurgical simulations) demand even longer computational time.

The computational time of CFD simulations is prohibitive if optimization techniques are used, since simulations must be carried out several times, with different parameters, to find the global or the local optimal values. However, optimization methods have been widely used in structural analysis based on FEM. Tajima *et al.* (2007) employed optimization techniques to investigate the optimal welding sequence that provides the lowest imposed heat flux and, consequently, the lowest residual stresses. Gannon *et al.* (2010) also used an optimization technique to study the influence of the welding sequence on the distortion distribution and residual stresses. Ertas e Sonmez (2011) applied optimization techniques to study fatigue in spot welded structures. In welding numerical simulations of Fu *et al.* (2016), parameters of Goldak's double ellipsoidal heat source model were predicted using optimization. Moghaddam *et al* (2017) used the hybrid neural network and PSO in weld bead geometry. Other authors (Moghaddam *et al.,* 2016) (Fu *et al.*, 2016) (García-García *et al.*, 2016) (Las-Casas *et al.*, 2017) have used optimization techniques, but the computational time is still high (several days).

In this paper, a welding numerical analysis of single pass butt joint weld, with square groove, of AISI 1020 carbon steel is carried out by the conventional TIG process. Numerical simulations were performed by ANSYS® Multiphysics software, considering three types of moving heat source. Convection and radiation heat transfer on the surfaces and temperature-dependent material properties were used in the thermal simulations. Fusion zone shapes, obtained from experiments, were used in a novel optimization methodology to determine optimal parameters of these heat sources by means of Genetic Algorithms coupled with a reduced geometry technique to diminish the computational time. Numerical results were compared with experimental ones.

2. THEORETICAL CONCEPTS

2.1 Thermal analysis

The thermal field is governed by the heat conduction equation given by

$$\frac{\partial}{\partial x}\left(k(T)\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k(T)\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k(T)\frac{\partial T}{\partial z}\right)+Q_V=\rho(T)C_p(T)\frac{\partial T}{\partial t} \tag{1}$$

where T is the temperature, $k(T)$ is the thermal conductivity, $\rho(T)$ is the specific mass, $C_p(T)$ is the specific heat and Q_V is the rate at which energy is generated per unit volume of the medium.

In the welding process, phase change, with melting and solidification phenomena, is involved. Enthalpy methods are some of several techniques to deal with this type of problems (Tamma and Namburu, 1990). The essential feature of the basic enthalpy methods is that the evolution of the latent heat is accounted by the enthalpy as well as the relation between the enthalpy and temperature. These methods are based on the heat conduction equation expressed in function of the enthalpy (H) as following:

$$\frac{\partial}{\partial x}\left(k(T)\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k(T)\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k(T)\frac{\partial T}{\partial z}\right)=\frac{\partial[H(T)]}{\partial t} \tag{2}$$

where the enthalpy H is the integral of the heat capacity with respect to temperature:

$$H=\int \rho(T)C_p(T)dT \tag{3}$$

In Eq. (2) and (3), the latent heat must be considered for the phase change region.

The thermodynamic boundary conditions on the external surfaces of the solid comprise heat transfer for convection and radiation. The heat flow density for convection (q_c) in the environment, gas or liquid, is given by Newton's heat transfer law

$$q_c = h_c(T-T_0) \tag{4}$$

where T is the temperature of the external surface, T_0 is the temperature of gas or liquid and h_c is the coefficient of convective heat transfer. This coefficient depends on the convection conditions on the solid surface, besides the properties of the surface and the environment. Some authors, such as Sorensen (1999), Teng *et al*. (2001) Gery *et al*. (2005) and Smith and Smith (2009), have proposed values of coefficient of convective heat transfer from 5 to 20 W/m^2K.

The heat flow density for radiation q_r is governed by the Stefan-Boltzmann law, as follows

$$q_r = \varepsilon_r \sigma_r (T^4 - T_0^4) \tag{5}$$

where ε_r is the emissivity of the material surface and σ_r is the Stefan-Boltzman constant. The value of the emissivity depends on the temperature in the welding process (Paloposki and Liedquist 2005), in which it ranges from room temperature to approximately the *solidus* temperature of the material. In general, in the solid state, the higher the temperature, the larger the emissivity.

2.2 Heat Sources

In this study, the heat of the welding arc was modeled by means of three different heat sources: Gaussian surface source, three-dimensional conical heat source and three-dimensional double ellipsoid heat source (Goldak *et al.*, 1984). In the two-dimensional distribution of a heat source with a Gaussian distribution, the heat flux distribution on the surface of the solid is related to the radial position r (whose origin is the arc center), as follows (Pavelic *et al.*, 1969):

$$q(r)=\frac{\eta UI}{2\pi\sigma^2}e^{-(r^2/2\sigma^2)} \tag{6}$$

where $q(r)$ is the surface flux at radius r, η is the thermal efficiency, U is the voltage, I is the current and σ is the radial distance from the center. The surface flux is reduced by 5% when $r = 2.45\sigma$ and it is practically null when $r = 3\sigma$ (Goldak and Akhlaghi 2005). A Fig. 1 shows this type of distribution.

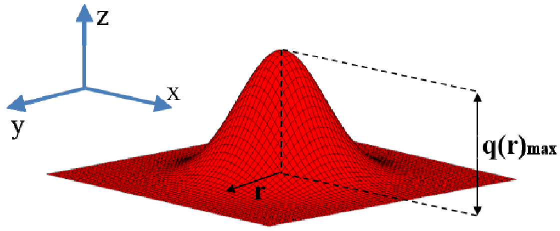

Figure 1. Gaussian distribution of a heat flux to simulate the electric arc of a welding process.

The three-dimensional conical heat source is a volumetric heat source that considers the heat intensity distribution along the workpiece thickness. As shown in Fig. 2, the heat intensity in the deposited region is maximum and minimum at the top and bottom surfaces of the workpiece, respectively. Along the thickness, the diameter of the heat density distribution region decreases linearly (Wu *et al*., 2006).

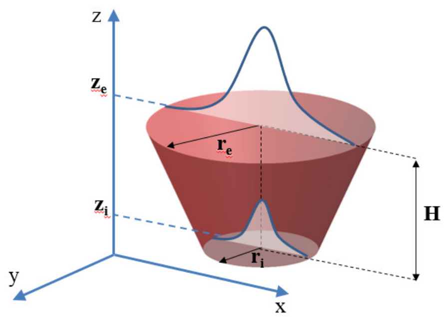

Figure 2. Three-dimensional conical distribution of a heat flux to simulate the electric arc of a welding process.

The heat density at the central axis (z-direction) is kept constant. At any plane perpendicular to z-axis, the heat intensity is distributed in a Gaussian form. At any plane perpendicular to the z-axis the heat intensity distribution may be written as

$$q(r,z)=\frac{9\eta UIe^3}{\pi(e^3-1)}\cdot\frac{1}{(z_e-z_i)(r_e^{\,2}+r_e r_i+r_i^{\,2})}e^{-(3r^2/r_0^{\,2})} \tag{7}$$

where r_0 is the distribution parameter, r is the radial coordinate. The distribution parameter r_0 decrease linearly from the top to the bottom surfaces of the conic region, and it can be expressed as

$$r_0(z)=r_e-(r_e-r_i)\frac{z_e-z}{z_e-z_i} \tag{8}$$

where the height of the conical heat source is $H = z_e - z_i$, the z coordinates of the top and bottom surfaces are z_e and z_i , respectively, and radius at the top and bottom are r_e and r_i, respectively.

The three-dimensional source proposed by Goldak *et al*. (1984) is a combination of two ellipses; one of them is in the front quadrant of the heat source and the other is in the rear quadrant. Equations (9) and (10) show the volumetric heat flux distributions inside the front and rear quadrants of the heat source, respectively:

$$q_r(x,y,z)=\frac{6\sqrt{3}f_r(\eta UI)}{abc_r\pi\sqrt{\pi}}\cdot e^{-3(x^2/a^2)}e^{-3(y^2/b^2)}e^{-3(z^2/c_r^{\,2})} \tag{9}$$

$$q_f(x,y,z)=\frac{6\sqrt{3}f_f(\eta UI)}{abc_f\pi\sqrt{\pi}}\cdot e^{-3(x^2/a^2)}e^{-3(y^2/b^2)}e^{-3(z^2/c_f^{\,2})} \tag{10}$$

where factors f_f and f_r are fractions of the heat imposed on front and rear quadrants, respectively (f_f+f_r=2); a, b, c_f and c_r are source parameters that define the size and shape of the ellipses and, consequently, the heat source distribution. The Fig. 3 shows this type of heat source.

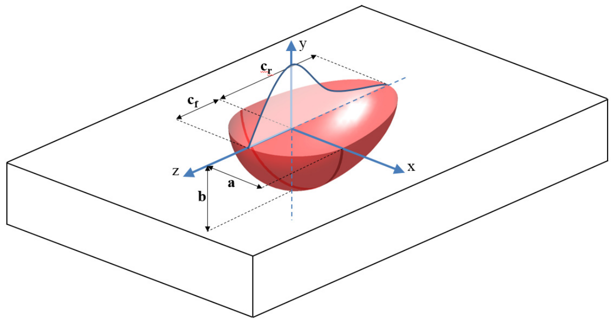

Figure 3. Three-dimensional double ellipsoid distribution of a heat flux to simulate the electric arc of a welding process.

3. CASE STUDY

The case study consist in a welding process of a single pass butt joint weld in AISI 1020 carbon steel plates, with square groove. The conventional TIG process, with Argon in a flow rate of 2.10^{-4} m^3/s (12 l/min), was used. Experiments were carried out at LAPROSOLDA – UFU. The two plates, initially positioned by two tack welds, are 3.2 mm thick, 100 mm long and 50 mm wide each. Welding processes were carried out on a coordinate table by using a welding power supply IMC MTE DIGITEC 600 model. Three experiments were carried out with the objective of assessing the repeatability of results. Welding speed was 1.67mm/s (100 mm/min) and the distance from the electrode to the plate surface (DEP) was 12 mm. Parameters of voltage and current (*RMS*), and instantaneous power of the welding process are shown in Table 1 for each test, and a sketch of the test is show in Fig. 4.

Table 1. Experimental values for each test.

Parameters	TEST 1	TEST 2	TEST 3
RMS Voltage U (V)	9.66	9.92	9.65
RMS Current I (A)	112.97	112.92	112.99
RMS Instantaneous Power (W)	1091.59	1120.31	1090.67

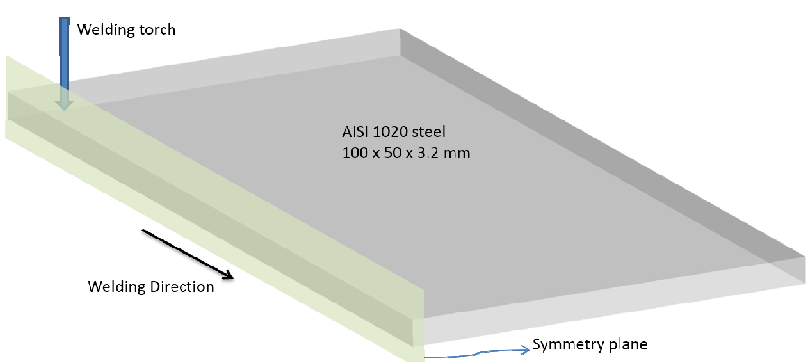

Figure 4. Sketch of the study case.

4. OPTIMIZATION METHODOLOGY

In this study, a computational methodology was developed, by means of stochastic optimization techniques (genetic algorithms) and other specific methods, to calibrate parameters of heat sources. The flow chart of the methodology is shown in Fig. 5. This methodology can be applied to several types of materials, welding processes and welded joints. The solution must be fast and able to reproduce approximately experimental results. Besides, the methodology must consider low level of interference of the user during the optimization process. Therefore, this methodology can contribute to increase the application of the numerical simulation on the welding process and, probably, its use in correlated processes, as coating and additive manufacturing by arc welding.

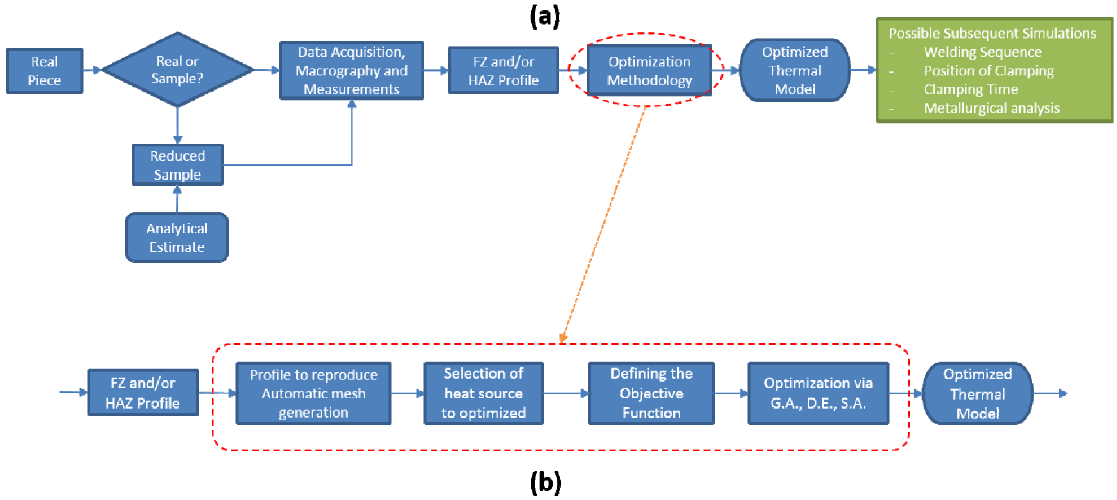

Figure 5. Flow chart of the proposed methodology: (a) process steps; (b) detail of the optimization methodology.

The available data of an experiment must be collected, such as voltage, current, welding velocity, dimensions of the fusion zone and/or the heat affected zone, thermocouple temperatures (if available), among others. These data are input in the model, in which the geometry is constructed automatically with established criteria in relation to element sizes and load steps. After the choice of the type of the heat source, the objective function is defined taking into account the welding geometry and/or thermal cycles. Then, several simulations, with different parameters of heat sources determined by the genetic algorithm, are carried out up to the optimal solution (not necessarily global one), that respect the acceptability criterion previously established.

A technique, named *Reduced Geometry*, was developed to circumvent difficulties related to the computational time and to facilitate the use of the optimization in the welding process. This technique is based on the fact that the fusion zone is a local phenomenon and distant regions do not influence significantly this phenomenon. Therefore, the mesh has large element sizes in these regions (Fig. 6) that reduce considerably the mesh element number and, consequently, reduce the computational time. Besides, the length of the bead is also reduced, enough to have a central zone with the regime fully developed.

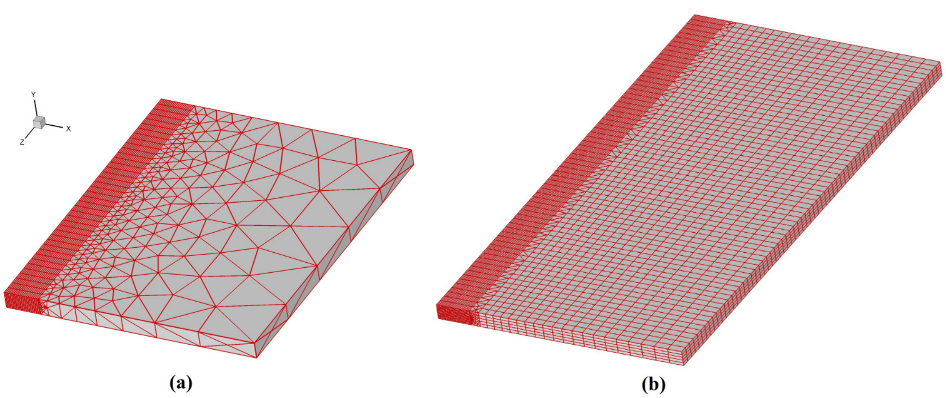

Figure 6. Mesh of the computational model, Reduced Geometry (a) and standard geometry (b).

The Reduced Geometry technique is fundamental in the step optimization methodology shown in Fig. 5. Large element sizes in regions distant of the weld bead can be used because, in these regions, temperature gradients are smooth and, consequently, low errors are expected. The Least Mean Square (LMS) method was employed to evaluate the objective function. This method quantifies the quadratic difference between experimental and numerical values. The heat sources showed at Section 2.2, available in the optimization algorithm, besides other numerical implementations, were written as a library of functions (*WeldLib*) used in *ANSYS Parametric Design Language* (APDL) of *ANSYS*© *Multiphysics*. The *WeldLib* library is been developed at LAPROSOLDA.

5. RESULTS AND DISCUSSION

In this Section, the optimization method, by using the reduced geometry technique, is applied in the case study. The objective is to obtain, by means of numerical simulation, the same geometry of the fusion zone of the experiment. Three points along the fusion limit line are chose as reference: on the top, on the bottom and on the middle of the plate along the thickness, as shown in Fig. 7. In the optimization process, temperatures of these points were used as objective function (LMS). The nearer the fusion temperature of the material (1467 ºC), lower is the objective function value.

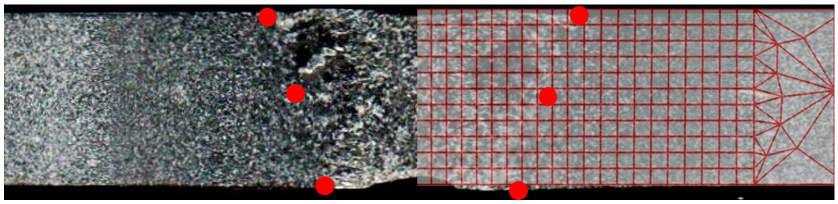

Figure 7. Points used for temperature monitoring on the simulation and the evaluation of the objective function.

The optimization process was repeated three times (for statistical assessment), with different initial population, for each heat source, to obtain optimal parameters of heat sources. The thermal efficiency was also considered as a parameter to be optimized during the optimization process. Lower and upper bounds for the thermal efficiency imposed in the process were obtained by the typical ranges for TIG, reported by Modenesi *et al*. (2012). The evolution of a population of 10 individuals along 20 generations was imposed as end criterion in the genetic algorithm for all cases. Therefore, computational time of each case can be compared. However, all optimal results were obtained before the 20th generation. Table 2 shows results obtained by using the Gaussian heat source.

Table 2. Numerical results for the optimization process using the Gaussian heat source.

	TG-T1	TG-T2	TG-T3
Objective function	749.6	810.61	21.56
Simulation time (h)	7,2	7,0	6,9
Number of simulations	124	116	118
Thermal efficiency (%)	66,5	66,3	66,1
Generation of the optimum	12	15	10
Heat source parameter			
Radial distance from center, σ (mm)	1,308	1,307	1,194

A maximum value of the objective function of 1875 was adopted to reach a satisfactory solution. It causes differences around 25ºC, which is 1.7% of the fusion temperature (1467ºC), in each three monitored points. Every values of the objective function for this case were lower than the maximum one.

Optimization process demanded a simulation time from approximately from 6 to 7 h, which is 85% lower than that obtained when the full geometry was considered, around 40 h. Figure 8 shows the fusion zones experimentally and numerically obtained in transverse section for the TG-T3 test, which presented the lowest value of the objective function. The numerical results were similar to the experimental ones in terms of coordinates of the monitored points and of the fusion shape (yellow line).

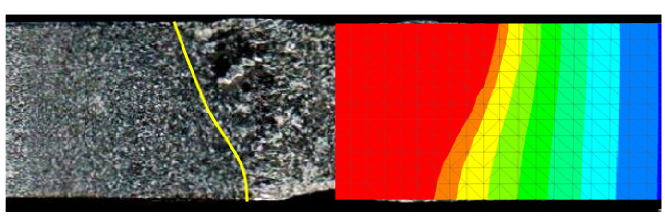

Figure 8. Fusion zone obtained in the TG-T3 test, which used the Gaussian heat source.

Table 3 shows results obtained by using the three-dimensional Conical heat source.

Table 3. Numerical results for the optimization process using the Conical heat source.

	TCT-T1	TCT-T2	TCT-T3
Objective function	1497,3	2136,8	47,0
Simulation time (h)	7,1	6,9	6,5
Number of simulations	128	126	118
Thermal efficiency (%)	67,4	68,9	66,9
Generation of the optimum	19	11	14
Heat source parameters			
Cone height H (mm)	1,140	1,202	1,544
Superior radius r_e (mm)	4,515	4,962	4,655
Inferior radius r_i (mm)	0,741	3,135	1,856

The optimization process demanded the same simulation time of the previous tests, approximately from 6 to 7 h. The maximum value of the objective function in the case TCT-T2 was higher than the allowed value. Values of the inferior radius were very different, while the other two parameters were similar. It indicates that the inferior radius had more influence on results

Figure 9 shows the fusion zones experimentally and numerically obtained in transverse section for the TCT-T3 test, which presented the lowest value of the objective function.

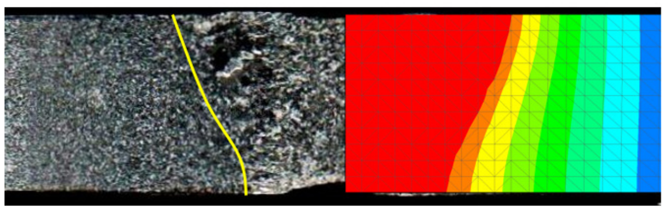

Figure 9. Fusion zone obtained in the TCT-T3 test, which used the Conical heat source.

In addition, Table 4 shows results obtained by using the three-dimensional double ellipsoid heat source.

Table 4. Numerical results for the optimization process using the Double Ellipsoid heat source.

	TGK-T1	TGK-T2	TGK-T3
Objective function	112,4	160,5	32,3
Simulation time (h)	5,75	6,4	6,1
Number of simulations	122	128	124
Thermal efficiency (%)	65,4	68,8	68,2
Generation of the optimum	7	17	11
Heat source parameters			
a (mm)	5,684	3,455	3,530
b (mm)	3,027	0,845	1,040
c_f (mm)	3,185	4,324	4,917
c_r (mm)	3,750	5,985	4,142

In these cases, optimization process demanded a simulation time from 5.5 to 6.5 h. In every case, values of objective function were lower than the maximum allowable one. Although parameters were smoothly different, the three tests showed a good approximation. TGK-T3 test presented the best result (Fig. 10).

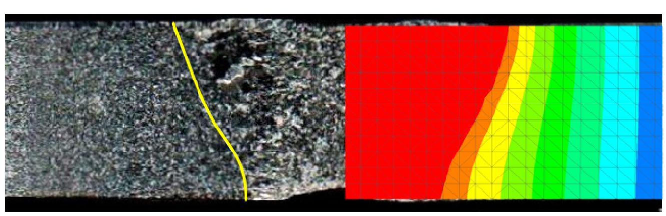

Figure 10. Fusion zone obtained in the TGK-T3 test, which used the Double Ellipsoid heat source.

The values of thermal efficiency for the three heat sources tested are very similar, around 67%. It means that simulations for all heat sources found practically the same required energy to generate the expected fusion zone, where the role of the heat source was to "manage" the distribution of this energy in the best possible way. Differences between them were related to each mathematical proposal to distribute the heat flux in the piece.

6. CONCLUSIONS

In this work, a welding numerical analysis of single pass butt joint weld, of AISI 1020 carbon steel was carried out by the conventional TIG process. Numerical simulations were performed, considering three types of moving heat source. Fusion zone shapes, obtained from experiments, were used in a new optimization methodology to determine optimal parameters of these heat sources by means of Genetic Algorithms.

Numerical results were in good agreement with experimental ones. The computational time demanded to determine the heat source parameters was 85% lower than that of a conventional simulation. In future researches, this methodology will be applied to other heat sources, welding processes and materials, as stainless steels and aluminum alloys.

7. ACKNOWLEDGEMENTS

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