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Optimization of Heat Source Parameters in Numerical Simulations of the GTAW Welding Process of AISI 1020 Lap Joints

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Abstract. *Welding processes involve complex physical and chemical phenomena, which make mathematical modelling 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 they demand much computational time, even using optimization methodologies. In this paper, a welding numerical analysis of a fillet weld in a lap joint, of AISI 1020 carbon steel, using the autogenous GTAW process is shown. The plates are 3.2 mm thick, 150 mm long and 50 mm wide. Numerical simulations were performed in ANSYS® Multiphysics software, considering three types of heat sources distributions (Gaussian, Conical and Double Ellipsoid). The fusion zone shapes of the plates obtained from the experiments developed at the Laboratory of Research in Welding Processes (LAPROSOLDA – UFU), are compared with numerical results. This data, obtained by macrography, were used by a novel optimization methodology to find the optimal parameters for these heat sources, by using the Genetic Algorithm method. Analyses of the computational time and accuracy in relation to experiments were carried out. In general, thermal results obtained by numerical simulation show good agreement with experiments. Thus, the proposed methodology strongly decreases the computational time.*

Keywords: optimization, heat source, welding, numerical simulation, reduced geometry

1. INTRODUCTION

Welds are essential parts of the engineering structures. Residual stresses and metallurgical transformations due to thermal non-linearities during welding processes can cause damage effects. An important tool to predict the behaviour of welding structures is the numerical modelling (Yaghi and Becker, 2004).

The complexity 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). 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 cause phase transformations and alterations in the mechanical properties of the welded metal. Those consequences impact notably on the behaviour of the welded piece. Consequently, the correct simulation of the temperature field in numerical simulations is essential.

Mathematical optimization is a field of the Computational Sciences which the main goal is to achieve the best solution for problems whose response quality can be measured by a number. The quality of available tools used for carrying out this challenge is as nearly similar as the quantity of applications. Engineering designs can include optimization processes in which designers consider goals, such as resistance, distortion, weight, wear, corrosion, and so on. Typical optimization strategies may require that objective functions are continuous and differentiable due to convergence conditions. Still, the mapping of project variables for functions and constrains are strictly implicit in numerical optimizations. For this reason, it is difficult to determine whether or not these functions have these characteristics. Therefore, optimization methods primarily based on gradients are not adequate to be used in this type of problems (Rao and Savsani, 2012). Methods free of derivation, with stochastic behaviour have more applicability for these problems; some of them include: Genetic Algorithms (G.A.), Differential Evolution (D.E.) and Particle Swarm Optimization (P.S.O.).

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). 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 residual stresses. Gannon *et al.* (2010) also used an optimization technique to study the influence of the welding sequence on the distortion distribution . Fu *et al.* (2016), predicted parameters of Goldak's double ellipsoidal heat source model using optimization. Azadi Moghaddam *et al.* (2016) used the hybrid neural network and PSO in weld bead geometry. Other authors (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 work, a welding numerical analysis of a fillet weld in a lap joint, of AISI 1020 steel, using the autogenous GTAW is carried out. Numerical simulations were performed considering three types of moving heat sources. This type of joint is chosen to test the accuracy of the proposed optimization methodology, since the heat flux in the transverse direction to the weld is asymmetric, which makes it difficult to obtain optimum parameters for the heat sources. Convection and radiation on the surfaces and temperature-dependent material properties were used in the 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.

2. THEORETICAL CONCEPTS

2.1 Thermal analysis

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. 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 as following:

$$\frac{\partial}{\partial x}(k(T)\frac{\partial T}{\partial x}) + \frac{\partial}{\partial y}(k(T)\frac{\partial T}{\partial y}) + \frac{\partial}{\partial z}(k(T)\frac{\partial T}{\partial z}) = \frac{\partial[H(T)]}{\partial t} \quad (1)$$

where *T* is the temperature, *k(T)* is the thermal conductivity, and *H* is the enthalpy, as the integral of the heat capacity with respect to temperature as following:

$$H = \int \rho(T) C_p(T) dT \quad (2)$$

where ρ is the density and C_p is the specific heat.

The thermodynamic boundary conditions on the external surfaces of the solid comprise heat transfer for convection and radiation.

2.2 Heat Sources

In this study, the heat of the welding arc was modelled 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):

$$q(r) = \frac{\eta U I}{2\pi\sigma^2} e^{-(\frac{r^2}{2\sigma^2})} \quad (3)$$

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 (Goldak and Akhlaghi, 2005). Figure 1 shows this type of distribution.

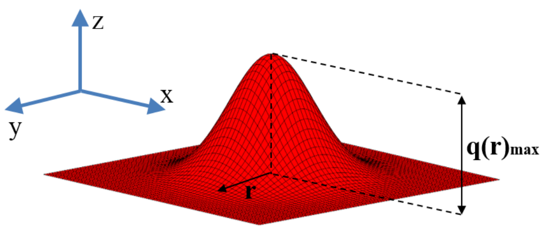

Figure 1: Gaussian distribution of a heat flux to simulate the energy input of a welding process.

The three-dimensional conical heat source is a volumetric heat source that considers the heat intensity distribution along the workpiece thickness. 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). 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

$$q(r,z) = \frac{9\eta U I e^3}{\pi(e^3-1)} \frac{1}{(z_e - z_i)(r_e^2 + r_e r_i + r_i^2)} e^{-(\frac{3r^2}{r_0^2})} \tag{4}$$

where r_0 is the distribution parameter, *r* is the radial coordinate, 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. Figure 2 shows this type of distribution.

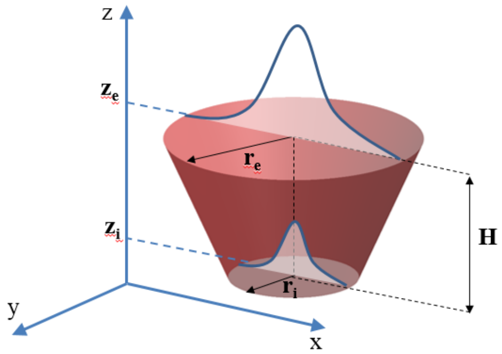

Figure 2: Three-dimensional conical distribution of a heat flux to simulate the energy input of a welding process.

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 5 and 6 show the volumetric heat flux distributions inside the front and rear quadrants of the heat source, respectively:

$$q_r(x,y,z) = \frac{6\sqrt{3} f_r (\eta U I)}{abc_r \pi\sqrt{\pi}} e^{-3(\frac{x^2}{a^2})} e^{-3(\frac{y^2}{b^2})} e^{-3(\frac{z^2}{c_r^2})} \tag{5}$$

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

where factors f_f and f_r are fractions of the heat imposed on front and rear quadrants, a, b, c_f and c_r are source parameters that define the size and shape of the ellipses. Figure 3 shows this type of distribution.

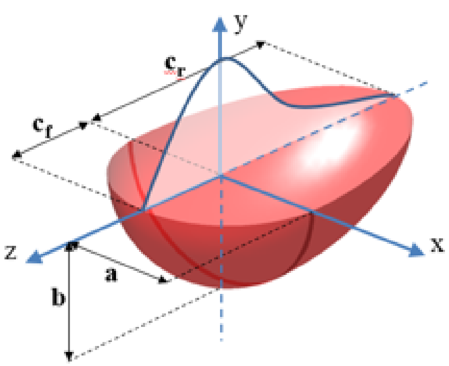

Figure 3: Three-dimensional double ellipsoid distribution of a heat flux to simulate the energy input of a welding process.

3. CASE STUDY

The case study consist in a welding process of a fillet weld in a lap joint in AISI 1020 carbon steel plates. The autogenous GTAW process with Argon in a flow rate of 2.10-4 m3/s (12 l/min), was used. The two plates, positioned by three tack welds, are 3.2 mm thick, 150 mm long and 50 mm wide each, with a overlap of 25 mm. Welding processes were carried out on a coordinate table by using a welding power supply *POWERWAVE® 455M/STT* model, from *LINCOLN®*. Three experiments were carried out with the objective of assessing the repeatability of results. Welding speed was 2mm/s and the distance from the electrode to the plate (DEP) was 4 mm. Parameters of voltage and current (RMS) of the welding process were acquired. The obtained voltage (RMS) was 10.7 V, the current (RMS) was 123.7 A and the instantaneous power (RMS) was 1322.9 W. The work angle was 30^o and the travel angle 0^o. A sketch of the test plates is show in Fig 4.

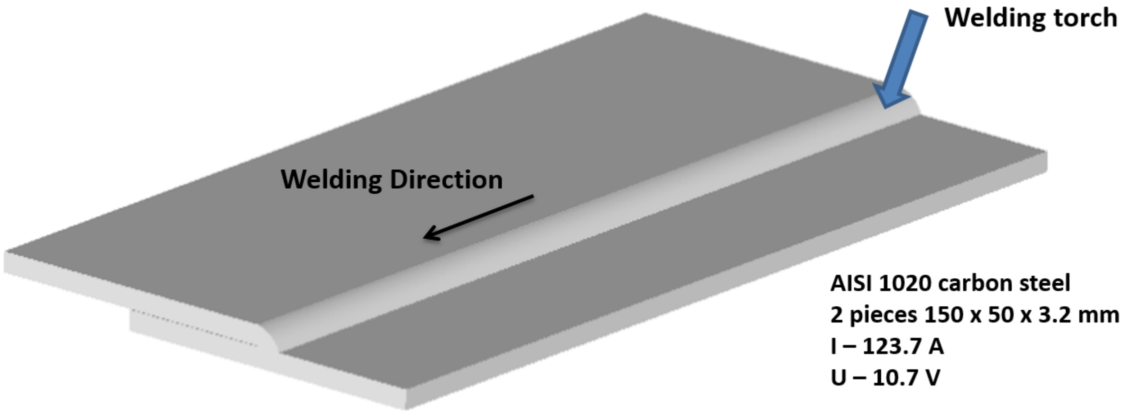

Figure 4: Sketch of the study case.

Thermal properties used in numerical simulations are temperature dependent. Latent heat during the phase change is taken into account by varying the enthalpy abruptly. Figure 5 shows the relation between thermal conductivity and enthalpy with temperature. An equivalent thermal conductivity, higher than the one at room temperature is used above the fusion temperature to consider the convection of melted material (Deng and Murakawa, 2006) (Liang and Murakawa, 2014). The coefficient of convective heat transfer is h_c = 10 W/m^2.^{o}C.

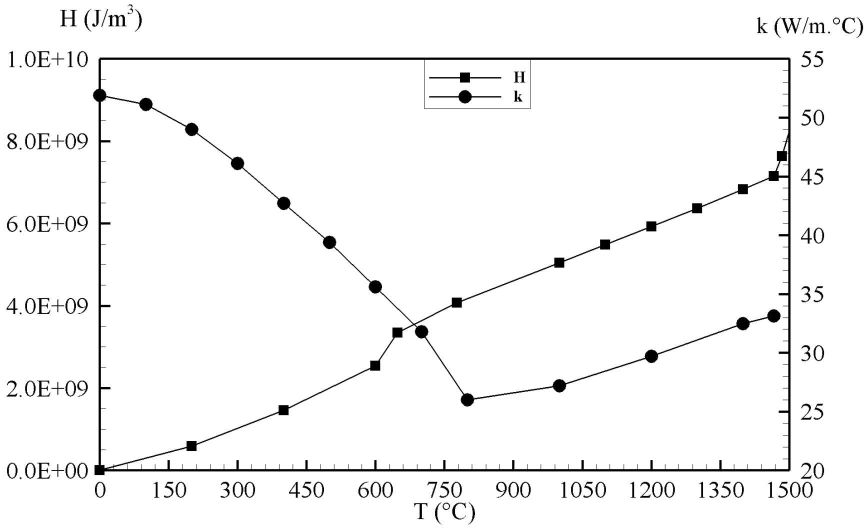

Figure 5: Thermal properties of AISI 1020 carbon steel (Miettinen, 1997).

The algorithm of the optimization process was done in the *Matlab®/Octave* language, using a open source implementation of a Genetic Algorithm (Houck *et al.*, 1995). A modification was implemented to allow parallelization of the process, to help speed up the solution. The heat sources showed, besides other numerical implementations, were written as a library of functions called *WELDLIB* used inside ANSYS® *Multiphysics*.

4. OPTIMIZATION METHODOLOGY

In this study, a computational methodology was developed, by means of evolutionary optimization techniques (Genetic algorithms) and other specific methods, to calibrate parameters of heat sources. The flow chart of the methodology is shown in Fig 6. 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.

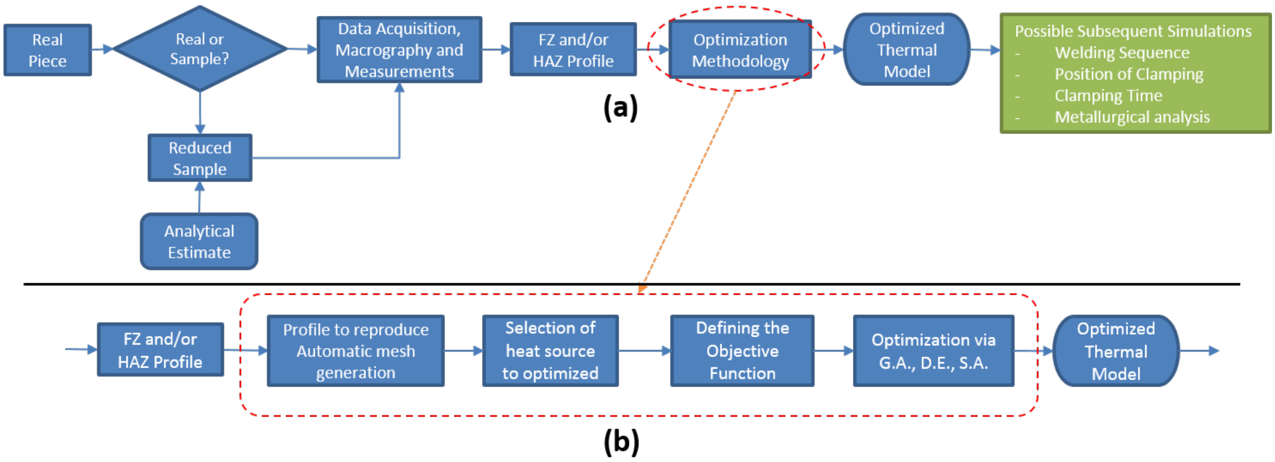

Figure 6: Flow chart of the proposed methodology: (a) process steps; (b) detail of the optimization methodology.

The available data of an experiment must be collected, such as voltage, current, dimensions of the fusion zone and/or the heat affected zone, thermocouple temperatures (if available), among others. These data are input in the model. After the choice of the type of heat source, the objective function is defined taking into account the welding geometry and/or thermal cycles. The optimization is carried out up to a optimal solution (not necessarily the 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 optimization process. This technique is based on the fact that the fusion zone is a local phenomenon and distant regions do not influence it significantly. Therefore, the mesh has large element sizes in these regions that reduce considerably the mesh size and, consequently, reduce computational time. Besides, the length of the bead is also reduced, enough to have a central zone with the regime fully developed.

The Reduced Geometry technique is fundamental in the optimization methodology shown in Fig. 6. 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 traditional *Least Square* function was employed as to evaluate the objective function. This method quantifies the quadratic difference between experimental and numerical values.

The optimization method described is applied to 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 line are chose as reference.In the optimization process, temperatures of these points were used as input in the objective function. The nearer the fusion temperature of the material on this points, the lower is the objective function value.

The optimization process was repeated three times (for statistical assessment), with different initial population, for each heat source. 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 from Modenesi *et al.* (2012). The evolution of a population of 10 individuals along 20 generations was imposed as end criterion in the G.A. for all cases. Therefore, computational time of each case can be compared. However, all optimal results were obtained before the 20th generation.

5. RESULTS AND DISCUSSION

For this heat sources, considering all the runs of the process, the optimization process had a simulation time ranging from 9.5 to 10.5 hours, which is around 86% lower than that obtained when the full geometry is considered, around 70 h. Table 1 presents a summary of the main results obtained from these simulations.

For the Gaussian heat source the optimization process demanded a simulation time around 10.2 h, which is 86% lower than that obtained when the full geometry is considered, around 70.0 h. Figure 7 shows the fusion zones experimentally and numerically obtained in transverse section for one of the runs, which presented the lowest value of the objective function. The numerical results (black dashed line) were similar to the experimental ones in terms of coordinates of the monitored points and of the fusion shape (yellow line), but this heat source did not achieved the same penetration as the experiment. A possible explanation for this, as mentioned before, is that since the heat flux in the transverse direction to the weld is asymmetric for this type of joint, an area heat source may not be sufficient to achieve the desired results.

	Gauss	Conical	Goldak
Objective function	45363	9355	198
Simulation time (h)	10.2	9.9	10.3
Number of simulations	119	107	109
Thermal efficiency (%)	79.3	65	79
Generation of the optimum	14	18	18
Heat source parameters			
σ (mm)	1.44	-	-
H (mm)	-	1.50	-
r_e (mm)	-	2.60	-
r_i (mm)	-	3.43	-
a (mm)	-	-	0.95
b (mm)	-	-	1.22
c_f (mm)	-	-	2.65
c_r (mm)	-	-	4.42

Table 1: Numerical results for the optimization process.

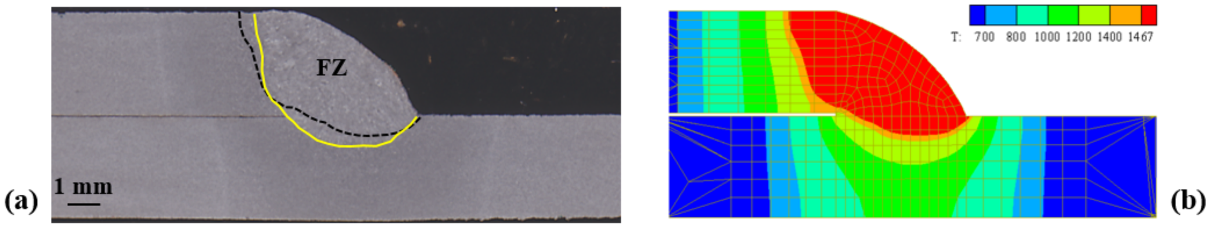

Figure 7: Experimental (a) fused zone and numerical (b) optimal fused zone obtained in one test, for the Gaussian heat source.

For the Conical heat source, optimization process demanded a similar time, around 9.9 h. Figure 8 shows the fusion zones experimentally (yellow line) and numerically (black dashed line) obtained in transverse section. Regarding the Gaussian heat source, the Conical heat source obtained a more adequate result in relation to penetration.

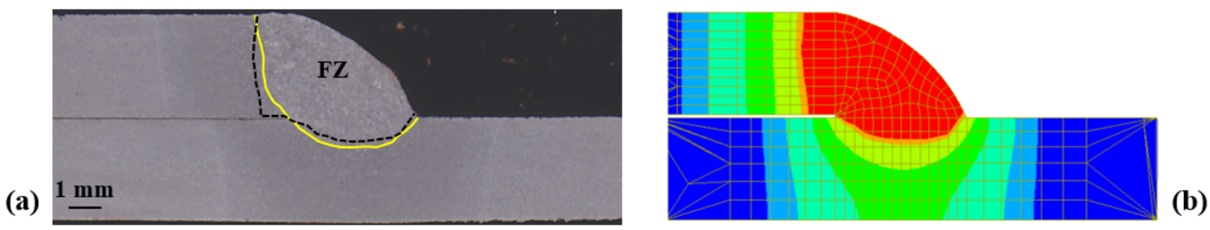

Figure 8: Experimental (a) fused zone and numerical (b) optimal fused zone obtained in one test, for the Conical heat source.

Regarding the Goldak heat source, optimization process again demanded a similar time, around 10.3 h. Figure 9 shows the fusion zones experimentally (yellow line) and numerically (black dashed line) obtained in transverse direction of the weld. This heat source had the lowest value of the objective function, when comparing all heat sources.

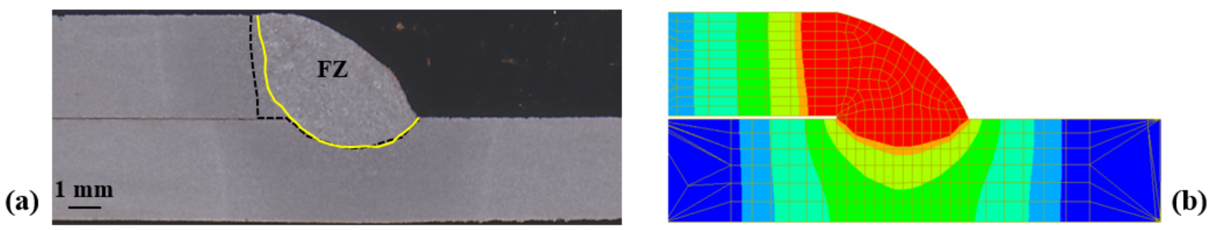

Figure 9: Experimental (a) fused zone and numerical (b) optimal fused zone obtained in one test, for the Goldak heat source.

6. CONCLUSIONS

In this work, a welding numerical analysis of a fillet weld in a lap joint in AISI 1020 carbon steel plates was carried out. Numerical simulations were performed, considering three types of moving heat sources. Fusion zone profiles, obtained from experiments, were used in a new optimization methodology to determine optimal parameters of these heat sources.The lap joint was chosen to verify the accuracy of the proposed methodology, since the heat flux in the transverse direction to the weld is asymmetric, making it more difficult to obtain optimum parameters for the tested heat sources. Numerical results were in good agreement with experimental ones. Computational time demanded to determine the heat source parameters was around 86% lower than that of a conventional simulation. In additional researches, this methodology will be applied to other heat sources, welding processes and materials, like stainless steels and aluminum alloys.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

Azadi Moghaddam, M., Golmezergi, R. and Kolahan, F., 2016. "Multi-variable measurements and optimization of GMAW parameters for API-X42 steel alloy using a hybrid BPNN–PSO approach". *Measurement: Journal of the International Measurement Confederation*, Vol. 92, pp. 279–287. doi:10.1016/j.measurement.2016.05.049.

Cheon, J., Kiran, D.V. and Na, S.J., 2016. "Cfd based visualization of the finger shaped evolution in the gas metal arc welding process". *International Journal of Heat and Mass Transfer*, Vol. 97, pp. 1–14.

Deng, D. and Murakawa, H., 2006. "Numerical simulation of temperature field and residual stress in multi-pass welds in stainless steel pipe and comparison with experimental measurements". *Computational Materials Science*. doi: 10.1016/j.commatsci.2005.07.007.

Farias, R.M., Teixeira, P.R. and Araújo, D.B., 2016. "Thermo-mechanical analysis of the mig/mag multi-pass welding process on aisi 304l stainless steel plates". *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, pp. 1–14.

Farias, R.M., Teixeira, P.R. and Vilarinho, L.O., 2018. "A Novel Optimization Methodology Applied to Parameters of Heat Sources in Welding Numerical Simulations". In *17th Brazilian Congress of Thermal Sciences and Engineering*. ABCM, p. 10.

Fu, G., Lourenço, M.I., Duan, M. and Estefen, S.F., 2016. "Influence of the welding sequence on residual stress and distortion of fillet welded structures". *Marine Structures*, Vol. 46, pp. 30–55. doi:10.1016/j.marstruc.2015.12.001.

Gannon, L., Liu, Y., Pegg, N. and Smith, M., 2010. "Effect of welding sequence on residual stress and distortion in flat-bar stiffened plates". *Marine Structures*, Vol. 23, No. 3, pp. 385–404.

García-García, V., Reyes-Calderón, F. and Camacho-Arriaga, J.C., 2016. "Optimization of experimental temperature measurement in GTAW process by means of DoE technique and computational modeling". *Measurement: Journal of the International Measurement Confederation*, Vol. 88, pp. 297–309. doi:10.1016/j.measurement.2016.03.049.

Goldak, J., Chakravarti, A. and Bibby, M., 1984. "A New Finite Element Model for Welding Heat Sources". doi: 10.1007/BF02667333.

Goldak, J.A. and Akhlaghi, M., 2005. "Computational welding mechanics". *Springer*.

Houck, C.R., Joines, J.A. and Key, M.G., 1995. "A Genetic Algorithm for Function Optimization: A Matlab Implementation". Technical Report 5.

Iacobescu, G., 2006. "A theoretical model for welding process with gaussian heat source- part. 1". *University" Politehnica" of Bucharest Scientific Bulletin, Series D: Mechanical Engineering*, Vol. 68, No. 4, pp. 45–50.

Las-Casas, M.S., Bracarense, T.L.D., Queiroz, A. and Lima, E.J., 2017. "Weld parameter prediction using artificial neural network: FN and geometric parameter prediction of austenitic stainless steel welds". *Journal of the Brazilian Society of Mechanical Sciences and Engineering*.

Liang, W. and Murakawa, H., 2014. "Predicting Welding Distortion in a Panel Structure with Longitudinal Stiffeners Using Inherent Deformations Obtained by Inverse Analysis Method". *Scientific World Journal*, Vol. 2014. ISSN 1537744X. doi:10.1155/2014/601417.

Miettinen, J., 1997. "Calculation of solidification-related thermophysical properties for steels". *Metallurgical and Materials Transactions B: Process Metallurgy and Materials Processing Science*. ISSN 10735615. doi:10.1007/s11663-997-0095-2.

Modenesi, P.J., Marques, P.V. and Santos, D.B., 2012. "Introdução á metalurgia da soldagem". Universidade Federal de Minas Gerais, Belo Horizonte, Brasil.

Pavelic, V., Tanbakuchi, R., Uyehara, .A. and Myers, 1969. "Experimental and computed temperature histories in gas tungsten arc welding of thin plates". *Welding Journal Research Supplement*.

Rao, R. and Savsani, V., 2012. *Mechanical Design Optimization Using Advanced Optimization Techniques*. Springer Series in Advanced Manufacturing. Springer London. ISBN 9781447127482.

Tajima, Y., Rashed, S., Okumoto, Y., Katayama, Y. and Murakawa, H., 2007. "Prediction of welding distortion and panel buckling of car carrier decks using database generated by fea". *TRANSACTIONS-JWRI*, Vol. 36, No. 1, p. 65.

Wu, C., Wang, H. and Zhang, Y., 2006. "A new heat source model for keyhole plasma arc welding in fem analysis of the temperature profile". *WELDING JOURNAL-NEW YORK-*, Vol. 85, No. 12, p. 284.

Yaghi, D.A. and Becker, A., 2004. "State of the art review - weld simulation using finite element methods". Technical report, University of Nottingham, UK.

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