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THE NUMERICAL SIMULATION OF HEAT TRANSFER DURING A HYBRID LASER-MIG WELDING OF DUPLEX STEEL

Paper # 1905

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Abstract

The present study is dedicated to the numerical simulation of an industrial case of hybrid laser-MIG welding of high thickness duplex steel UR2507Cu with Y-shaped gap geometry. It consists on stimulating the heat transfer during the welding by COMSOL Multiphysics software using heat equivalent source approach. A numerical exploratory designs method is used to identify and to optimize the heat sources parameters in order to obtain a small relative error between the numerical results and the experiment.

Introduction

The coupling of laser with a second source of thermal energy has been attracting attention for a number of years. The approach of combining a laser beam and a welding arc into a compound welding process has been known since the 1970s, but for many years little commercial development took place. Recently, the demands for improved productivity and reduced thermal damage have prompted the application of the technique in industry. The aim is to combine the advantages of arc welding with those of laser to overcome the limitations of individual processes. The hybrid laser arc welding is reported as having the potential to increase penetration depth, width and so welding speed, whilst improving tolerance and controlling weld pool chemistry by means of filler addition. The process can be easily automated. The combination of the welding processes leads to the apparition of intrinsic features and characteristics, which increase the process capabilities, if the mutual interaction between the two energy sources is optimized. Although there is a growing interest in this process, the thermal cycles induced by the combination

of these two processes are still not well known. The precise knowledge of temperature history is essential for predicting accurately the distortions and residual stresses. Similarly, the metallurgical properties of welds also depend on the thermal cycles induced by the involved heat sources. More than that, the hybrid welding implicates a large number of complex physical phenomena. We know that each process alone is not already completely mastered or understood, nor is their combination. Therefore, the development of a mathematical modeling of this hybrid process that would take into account the main involved physical phenomena would be very useful tool for estimating the final parameters of the weld seam for a given set of operational parameters. We can mention the work of Wouters [1], who has developed a semi-analytical model to calculate the temperature field and melt pool shape during hybrid laser-MIG welding. Reutzel et al. have proposed a three dimensional thermal finite element model using a volumetric double ellipsoidal heat source to represent both laser and MIG [2]. A similar approach was recently used by Zhang for the hybrid laser GMAW welding process [3]. More sophisticated numerical models were proposed by Zhou and Tsai to investigate transport phenomena in hybrid welding [4]. It includes the calculation of the temperature field, pressure balance, melt flow, and free surface evolution. However, this model is limited to a two dimensional axial-symmetric approach. Recently, Le Guen [5] has presented a 3D quasi-steady thermal model for hybrid laser/MAG welding which calculates the temperature field and predicts the melt pool surface by taking into account the addition of filler metal and the effects of surface tension. In the same way, Bidi [6] has treated the heat transfer of the hybrid laser/MIG welding by the equivalent heat sources approach associated to numerical exploratory designs method.

In this paper, a numerical model is developed to calculate the thermal cycles in duplex steel UR2507Cu welded by the hybrid laser/MIG process for a given set of welding parameters. This model is able to determine the temperature field out of the weld pool and to reproduce the geometry shape of the melted zone. Therefore, the numerical modeling approach used in this work does not require the description of all phenomena that occur in the weld pool: it consists in determining the heat sources that provide the predetermined geometrical characteristics of fusion zone. This approach is called “equivalent source approach”. A main difficulty in this numerical approach is the choice of the heat sources which will give an adequate representation of each process and the identification of parameters for these sources, since they are not directly measurable. These parameters are calibrated using a numerical exploratory designs method; however, the goals of this method are to optimize the number of simulations and to determine the influence of several factors (heat sources parameters) on the chosen object functions, in this particular case, on the geometrical sizes of melted zone. The numerical results are compared with corresponding experimental macrographies and thermocouple measurements.

WELDING CONFIGURATION:

The experimental configuration is shown in Fig 1. The experiments consist in the realization of a one pass hybrid laser/MIG welding of duplex steel UR2507Cu (Euronorm 1.4507- X2CrNiMoCuN25.6.3) in Y-shaped gap geometry.

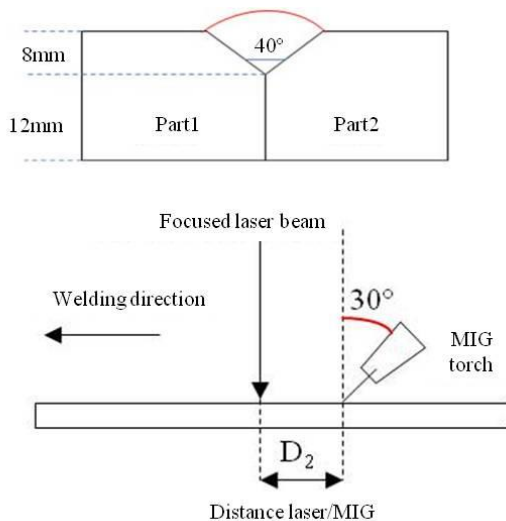


Fig.1: Experimental configuration and laser/MIG layout

The experimental work is carried out using a TRUDISK 6002 Yb YAG laser with a maximum output power of 6 kW, and a FRONIUS torch arc. A FRONIUS head design holds the laser and the MIG torch. The head is fixed on a six axes KUKA Robot. In this case, the laser focused position is in front of the arc, this position is defined by two parameters: laser-MIG distance (D_2) and angle between the laser beam and the vertical axis (30°). The welding parameters determined during a preliminary study are shown in table 1.

Table 1: Welding parameters

Parameters	Domain
Laser power [kW]	6
Laser beam diameter [mm]	[0,2 ; 0,6]
Wire speed [m.min ⁻¹]	[8 ; 12]
MIG power [kW]	12,6
Wire diameter [mm]	1,2
Speed welding [m.min ⁻¹]	[0,4 ; 0,5]
Distance laser-MIG [mm]	[20 ; 24]

Temperature measurements by thermocouples

The aim of this experiment is to obtain the temporal evolution of temperature at different points around the melted zone. In addition, these temperature records are used to validate the heat transfer model by comparing measured and calculated thermograms. We placed 10 K-type thermocouples ($T_{max}=1100^\circ\text{C}$) into holes (0.5mm diameter, 50mm deep) machined by electrical discharge (Fig 2). The thermocouples are inserted at the bottom of the holes and fixed with a heat conducting silver pad.



Fig. 2: Thermocouples layout

NUMERICAL MODELING

The present model was developed using COMSOL Multiphysics® 3.5a. This software uses the finite element method to solve partial differential equations governing several of physics and engineering problems. The numerical model setup is based on the following assumptions:

- Quasi-steady-state conditions: the heat equation is written for a moving coordinate

system which moves with the same velocity as the heat source.

- The filler material is supposed to have the same properties as UR2507Cu steel, and the latent heat of fusion is taken into account using the apparent heat capacity formulation [7] as shown in expression (1)

$$c_p^{eq} = c_p + L_f \frac{\exp\left(-\frac{(T-T_m)^2}{\Delta T^2}\right)}{\sqrt{\pi\Delta T^2}} \quad (1)$$

Where c_p is the specific heat capacity, L_f is the latent heat of fusion, T_m is the melting temperature and ΔT is the difference between solidus and liquidus temperature.

- Fluid flow in the weld pool is not considered, but thermal conductivity of the liquid phase is enhanced to take in account convective heat transfer in the weld pool. When convection occurs in the melt pool, thermal transport is accelerated by fluid flow and the isotherms are modified in the direction of the flow. An easy way to reproduce this effect using a conductive model is to assign artificially isotropic or anisotropic high thermal conductivity in this area.
- Metallurgical phenomena are not taken into consideration. The values of the latent heat of the metallurgical phase change are generally small compared to solid-liquid latent heat of fusion.
- The weld pool surface is assumed to be in a static equilibrium with respect to arc pressure, gravity and surface tension. The effect of fluid flow induced by Marangoni phenomena or electromagnetic forces is ignored.
- Finally, only half of the work piece is considered since the weld is symmetrical along the weld centerline. The temperature field is determined by solving the heat equation (2) where Q is a volumic heat source.

$$\rho(T)c_p(T)V_s \frac{\partial T}{\partial x} = \text{div}(\lambda(T)\overrightarrow{\text{grad}}T + Q(x, y, z)) \quad (2)$$

CHOICE OF THE EQUIVALENT HEAT SOURCE

The development of the numerical model is based on three steps. First, we define the sources which represent the laser alone. Then the heat sources corresponding to MIG process are identified. And finally, all of these sources are introduced into the hybrid laser\MIG model.

Laser

The focused laser beam is used in keyhole mode. The energy contribution of laser is assumed by a combination [6] of Gaussian source (3) and volume Goldak conic source (4)

- Gaussian source with parietal supply

$$q_{\text{surf1}} = \frac{P_L A_1}{2\pi r_{\text{surf1}}^2} e^{-\left(\frac{x^2+y^2}{2r_{\text{surf1}}^2}\right)} e^{-\left(\frac{w^2}{dz^2}\right)} \quad (3)$$

- Goldak conic volume source

$$Q_1 = \frac{9P_L \eta_w}{\pi h(r_0^2 + r_0 r_1 + r_1^2)} e^{-3\frac{x^2+y^2}{r_z^2}} [1-u(z+h)] \quad (4)$$

where $r_z = r_0 + \frac{r_0 - r_1}{h}z$, r_0 melted zone radius when $z=0$, h depth penetration, r_1 melted zone when $z=-h$ and $u(z+h)$ Heaviside function. (v,w) are coordinate system for q_{surf1} position is defined as follows (Fig 3).

$$v = z \sin \beta + y \cos \beta \quad w = -y \sin \beta + z \cos \beta$$

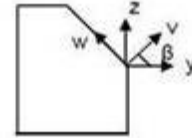


Fig.3: Coordinates system for q_{surf1}

Metal Inert Gas (MIG)

The power distribution of MIG is modeled in two parts. On the one hand, we consider that volumic energy is due to the heat input from melted droplets which is represented by a double-ellipsoid source proposed by Goldak et al [8]:

$$Q_{2f}(x,y,z) = f_f \frac{6\sqrt{3}\eta UI}{abc\pi\sqrt{\pi}} e^{-3\left(\frac{x-D_2}{a_f}\right)^2} e^{-3\left(\frac{y}{b}\right)^2} e^{-3\left(\frac{z-h_m}{c}\right)^2} \quad (x>0)$$

$$Q_{2r}(x,y,z) = f_r \frac{6\sqrt{3}\eta UI}{abc\pi\sqrt{\pi}} e^{-3\left(\frac{x-D_2}{a_r}\right)^2} e^{-3\left(\frac{y}{b}\right)^2} e^{-3\left(\frac{z-h_m}{c}\right)^2} \quad (x\leq 0) \quad (5)$$

As a second point the surface energy is associated to the arc. This heat source is assumed to have a Gaussian heat distribution (6):

$$q_{\text{surf2}} = \frac{A_2 UI}{2\pi r_{\text{surf2}}^2} e^{-\left(\frac{(x-D_2)^2 + y^2}{2r_{\text{surf2}}^2}\right)} \quad (6)$$

Hybrid Laser/MIG

The setup of hybrid numerical model is based on both previous cases. The heat sources chosen for laser alone and MIG alone were used for the hybrid case and the heat parameters were identified by using the numerical exploratory designs method. In this case we consider a predefined geometry for a filler metal with the inclination of the filling front. This geometry was determined from macrographies.

Identification for equivalent heat source parameters

The identification process is applied in the same way for three numerical models [11]. We have developed a method of parameter optimization, simple to implement and robust, founded on the numerical exploratory designs method. From the numerical model, we define a parameter list influencing factors (IF) and object functions (OF) which allow to determine (design matrix) all possible combinations of factors and to organize the simulations. Using a limited number of calculations, we evaluate the effects of IF (parameters of analytical expressions of equivalent heat sources) on OF (geometrical characteristics of the melted zone). The analysis of effects direction and amplitudes allows to make adjustments of the IF values in order to obtain differences between the experiments and calculation below a limit value defined before. The procedure can be represented by the following diagram (Fig 4):

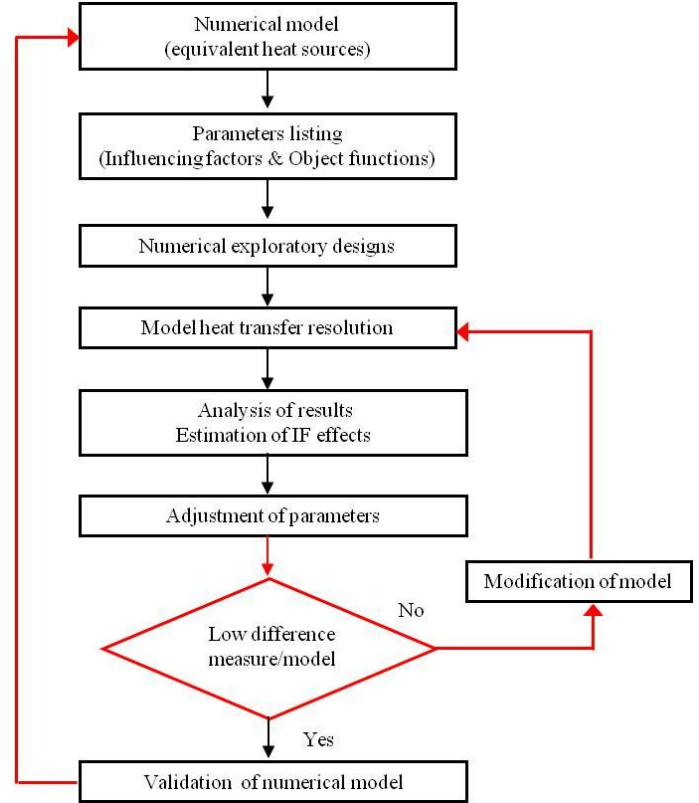


Fig.4: Diagram of adjustment for heat source parameters

This optimization method allows also to test the flexibility of model adjustment. In fact, if the modification of one IF changes mainly only one OF, the numerical model is very flexible towards the adjustments, however if by acting on a single IF, we change in the same proportion many OF, the numerical model is less flexible for the adjustments.

Results and discussion

A sensitivity study of equivalent heat source parameters is used to determine the influence of each parameters (a_f , a_r , b , c , ...) on the geometric dimensions (L_1 , L_2 , L_3 ...) which describe the shape of the weld macrographs in transverse direction, as shown in Fig 6. For the numerical design matrix we use a fractional design 2^{5-2} (which contains all the possible combinations between the two values of the three analyzed factors). As an example, Fig 5 shows the effect diagrams in the case of MIG only, which represent the amplitude and the direction of the influencing factors on each of object functions.

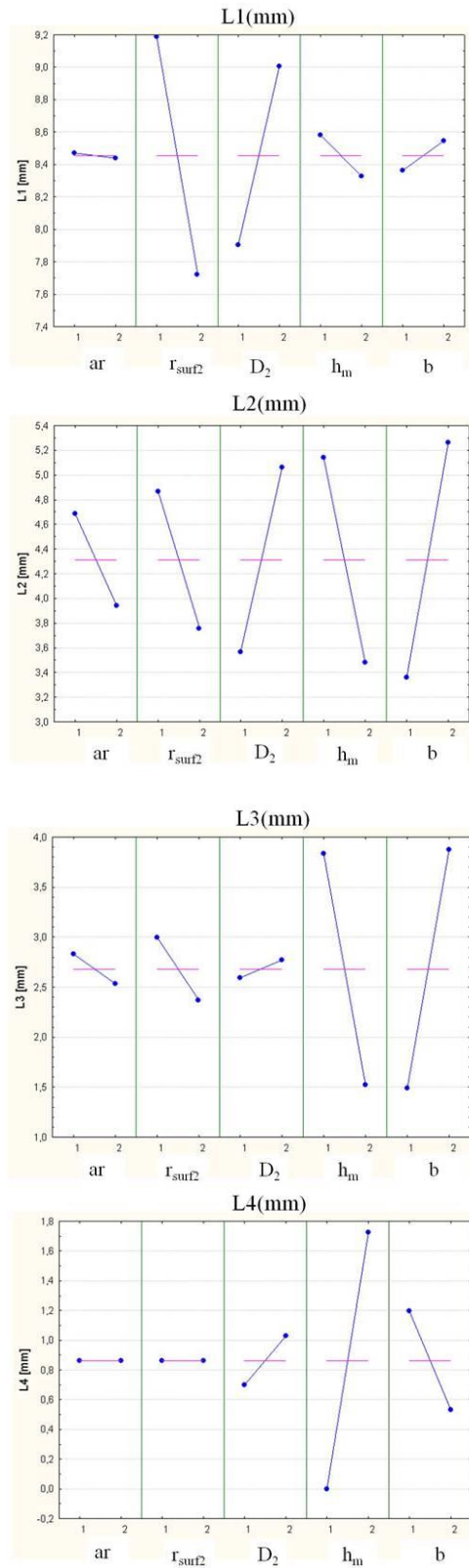


Fig. 5: Diagram of effects for influencing factors

The analysis of these effects indicates that:

- the OF L4 is strongly influenced by the factor h_m ;
- R_{surf2} has an inverse influence on L_1 and L_2 , if R_{surf2} increases L_1 and L_2 decrease;
- the factor D_2 affects also L_1 and L_2 , its influence is direct, if D_2 increases L_1 and L_2 also increase;
- generally, the a_r factor has a low influence on all the object functions.

The identification of heat source parameters in hybrid case is based on standalone models of laser and MIG. These parameters are given in table 2.

Table.2: Heat sources parameters

A_1 (%)	r_{surf1} (m)	dz (m)	η_v (%)	r_0 (m)
24	$7 \cdot 10^{-4}$	$7 \cdot 10^{-4}$	71	$2.4 \cdot 10^{-3}$
a_r (m)	a_f (m)	b (m)	c (m)	λ_{eq} ($W \cdot m^{-1} \cdot K^{-1}$)
$7 \cdot 10^{-3}$	$2 \cdot 10^{-3}$	$7 \cdot 10^{-5}$	$9 \cdot 10^{-3}$	70
r_1 (m)	r_{surf2} (m)	A_2 %	η %	
$1.45 \cdot 10^{-3}$	$7 \cdot 10^{-3}$	60	25.5	

The Fig 6 shows calculated and experimental transverse weld shape for hybrid (c), laser (b) and MIG (a) cases.

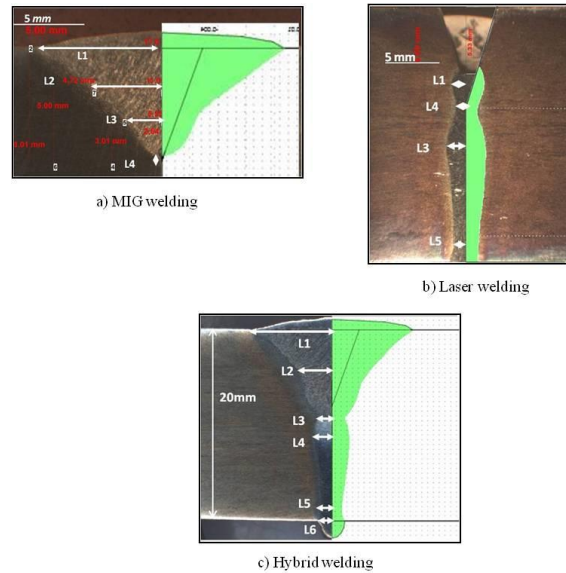


Fig.6: Comparison between calculated and experimental geometries of the melted zones

The dimensions of the fusion zone obtained from the heat transfer study have been compared to the measured

values. As it can be seen in Fig 6, the melted zone shape obtained from the numerical modeling correlates well with the experimental results. Table 3 gives an example of results obtained in hybrid welding case after fitting heat source parameters.

Table.3: Comparison between experimental and numerical values of melted zone dimensions

Quantities (mm)	L1	L2	L3	L4	L5	L6
Experimental (mm)	8.83	3.20	1.40	1.80	1.20	1.50
Uncertainty (mm)	0.06	0.10	0.04	0.16	0.04	0.02
Modeling (mm)	8.80	3.50	1.38	1.87	1.10	1.40
Relative difference%	0.4	8.5	1.4	3.7	9.0	7.0

Moreover, numerical modeling gives us an access to the temperature gradients inside the welded piece. We compared the temperature calculated with the measurement; the results are shown in Fig 7.

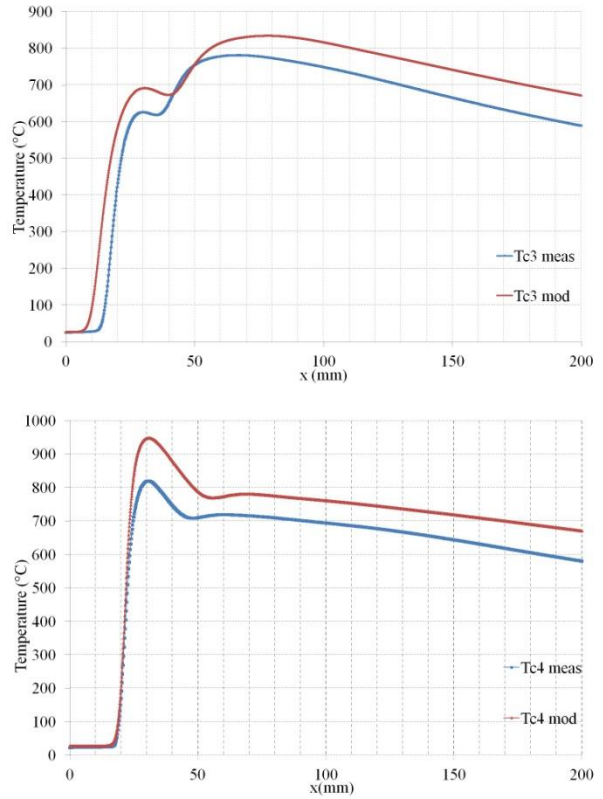
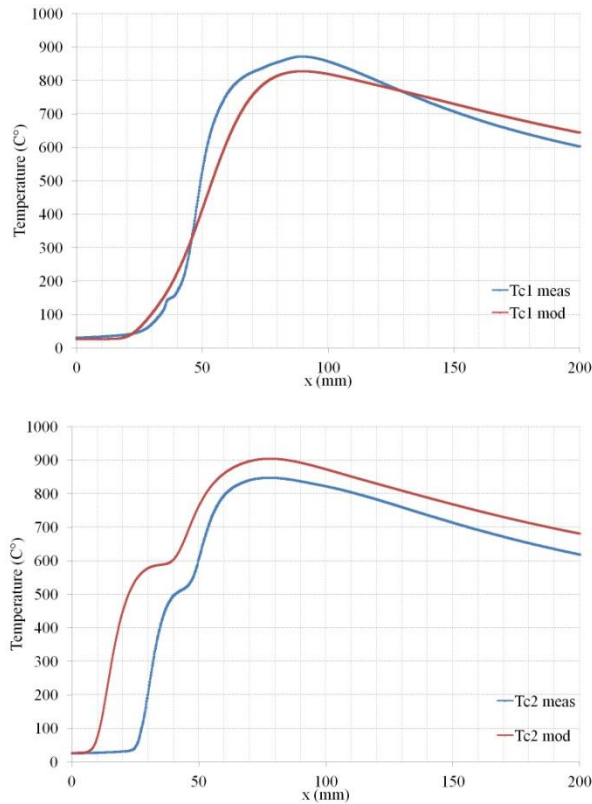


Fig.7: Comparison between measured and calculated thermograms

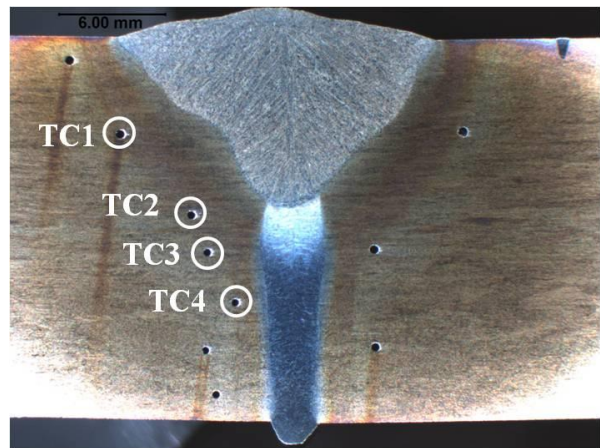


Fig.8: Transversal cut macrography with thermocouples layout

The layout of thermocouples (TC) (Fig 8) has been selected in order to record thermal gradients located around and closer to the limit of the melted zone. The TC1 measures the temporal evolution of temperature during the MIG source passage without detecting the laser source, contrary to the TC4 which is only sensible to laser source. However, TC2 and TC3 placed in the middle of work piece register two pikes: the first one

induced by laser is followed by the pike of MIG. The distance between the two pikes is related to the gap separating the laser head and the MIG torch $D_2 = [20\text{mm}, 24\text{mm}]$. Overall, we notice that the thermal levels are found by using the parameters defined before for the model conception which was initially validated by experimental macrographs. The difference between measured and calculated thermograms can be linked from one hand to the model errors as the numerical model does not take into account thermocouples holes and, in another hand, from the simplifying assumptions which present partially physical phenomena involved.

Conclusion

In the present study, a 3D quasi-steady state model of heat transfer for welding duplex steel UR2507Cu with Y shaped gap is developed to analyze hybrid laser/MIG welding. First of all, the information on the shape and dimensions of the melted zone was collected from preliminary tests. Then, using the numerical experimental designs method associated to the numerical model, the equivalent heat source parameters were estimated and adjusted to reproduce the characteristics of the melted zone. The model results are satisfying since we obtain low difference between model and measurements for the melted zone dimensions and also for the temperature inside the work piece. These results allow us to validate to choice of equivalent heat sources for heat supply of hybrid welding process. This information can be used to solve thermomechanical problem. In the following, we look for developing a methodology based on the experimental designs which gives the possibility to link the operating parameters (laser power, welding velocity ...) to simulated geometrical values of the melted zone.

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Author Autobiography

Mr. Issam Bendaoud is currently studying for a PhD thesis titled “Comprehension of hybrid laser/MIG welding: heat equivalent source approach and phenomenological approach” in the Interdisciplinary Laboratory Carnot of Burgundy, University of Burgundy under supervision of Prof. Simone Mattei, Prof. Eugen Cicala and Dr. Iryna Tomashchuk.