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A thermal efficiency analysis of a Gas Tungsten Arch Welding process using a temperature moving sensor

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A B S T R A C T

This works proposes an Inverse methodology to estimate the thermal efficiency of a Gas Tungsten Arch welding (GTAW) process as a time-dependent function. The direct model consists in solving the non-linear three-dimensional heat diffusion equation through the Finite Difference Method in a C++ code. As the inverse methodology, the Golden Section optimization technique was used together with the Time Travelling Regularization to estimate the applied heat rate in the GTAW process. The Time Travelling Regularization was used to reduce the noise on the estimated heat input. Furthermore, a numerical Temperature moving sensor is proposed to determine the heat input as a time-dependent function. The methodology was applied in lab-controlled experiments based on a Robust Project matrix. The numerical analysis revealed that the thermal efficiency decreased as the arch torch moves. The proposed methodology also presented a higher sensitivity than the usual methods for the heat rate estimation and is a cheaper way to determine the melting efficiency in welding processes.

1. Introduction

In welding, thermal efficiency is an important parameter to compare different kinds of processes. Indeed, there are many variations on the same welding process and comparing them to determine the optimum configuration is usually difficult. Likewise, the same welding apparatus can be used to weld with different parameters. The best setup configuration for a welding process may be by using a statistical approach [1,2]. However, the statistical approach usually requires many experiments, which makes it expensive. Another way to determine the best welding setup is the thermal efficiency analysis of the process. The thermal efficiency represents the amount of heat effectively delivered to the welded plate divided by the power supplied.

The numerical simulation is an efficient way to analyze welding processes. In such cases, an efficiency term is usually presented. Due to the empiric character of this term, some authors choose to omit it in their publications, for instance, Wahab et al. [3]. Other authors only use tabulated literature values as Yadaiah and Bag [4] who used a thermal efficiency of 60% for a GTAW (Gas Tungsten Arch Welding) process; Piekarska and Kubiak [5] assumed the laser-arc hybrid welding process efficiency as 75%; Sudheesh and Prasad [6] applied an efficiency of 70% for the same process; and Little and Kamtekar [7] used an efficiency of 80% for a similar case. As presented, the welding efficiency is not a fixed value that could be used in simulations. Many authors just assume it as a hypothetical value that many times does not suit the real thermal efficiency of the process. Consequently, a simple assumption of a fixed thermal efficiency value can conceal the real data output of a numerical simulation. Indeed, the welding efficiency relies on the kind of welded material, voltage, current, the distance between the electrode and the plate, etc. [8].

The thermal efficiency can be obtained experimentally through a calorimeter, which is expensive [9,10]. Another cheaper and more efficient way to estimate the heat input in a welding process is by using an inverse problem analysis. In a direct problem, the solution of partial different equations requires the knowledge of the boundary conditions of the domain and initial conditions. On the other hand, in the inverse methodology some of these conditions may be unknown. Therefore, discrete measurements of the dependent variable inside the domain are used to estimate the unknown parameters [11]. The use of Inverse Problems allows a faster estimation of parameters than the conventional experimental methods [12]. In heat transfer, the inverse methodology is commonly used to predict thermal properties, for example thermal conductivity, emissivity and specific heat, and boundary condition such as heat transfer coefficient by convection and heat flux [13].

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A parameter may be estimated through an iterative method. For instance, Alifanov [14] applied the conjugate gradient method to determine a nonstationary heat flux for a one-dimensional case. Likewise, Taler [15] applied two different methods to evaluate a nonlinear steady-state heat flux, the Gauss-Newton Method and the Space-Marching Technique. In addition to the conventional iterative methods, there are inverse techniques that were developed to estimate heat flux as the Sequential Function Specification Method [16]. The statistical approach can also be applied to the parameter estimation. For example, Cui et al. [17] applied the Bayesian approach to determine the temperature-dependent thermal properties in a transient inverse heat conduction problem. In order to improve the results in estimation, filters are also applied to smooth the output in Inverse Problems. For instance, Massard et al. [18] applied the Kalman filter into the Bayesian framework to determine the transient heat source term. There are still the regularization methods that can be used to determine parameters in Inverse Problems, as Bozzoli et al. [19] who applied a regularization method as a filtering technique to the restoration of the heat source field. The classical model was proposed by Tikhonov and Arsenin [20]. This regularization known as the Tikhonov regularization is widely used in the solution of Inverse Problems. For instance, Bozzoli et al. [21] applied the Tikhonov regularization to determine the local heat transfer coefficient in a laminar flow regime.

The Inverse Problems are often used to determine thermal efficiency in welding processes. For instance, Dal et al. [22] analyzed a static welding process using the conjugate gradient method for minimization. Yang [23] proposed an algorithm to estimate the temporal gross heat input in a Friction Stir Welding (FSW) process. Chen et al. [24] applied the Hooke-Jeeves direct search method to determine the combine heat source in a Metal Active Gas (MAG) welding. Magalhães et al. [25] estimated the gross heat input through the Broyden-Fletcher-Goldfarb-Shanno (BFGS) minimization technique in an aluminum GTAW process. Unnikrishnakurup et al. [26] applied the Levenberg-Marquardt algorithm to estimate the process efficiency and radial distribution of the heat flux in a static GTAW process.

In order to estimate the temporal heat input distribution a GTAW process, an inverse methodology based on the Time Travelling Regularization is proposed [27]. The Time Travelling Regularization (TTR) is an inverse methodology used with an optimization technique, in this case with the Golden Section method [28]. One of its great advantages is that it allows reducing the noise in the output data on inverse models. A numerical temperature moving sensor is also proposed to allow the temporal heat input estimation. It is a cheaper and more precise way to determine the heat input during a welding process, fundamental to improve welding quality.

2. Methodology

2.1. Thermal model

A finite difference model based on the non-linear three-dimensional heat diffusion equation with moving heat source and the Enthalpy function was used as the direct problem. Fig. 1 presents the GTAW problem where a torch applies heat flux on a plate. When the heating process starts, spontaneous heat loss by convection and radiation begins.

The heat diffusion equation with phase change problem may be expressed as:

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

where x, y and z are the Cartesians coordinates, λ is the thermal conductivity, T is the temperature, ρ is the density and t is the time. Equation (1) is applied in the domain: $0 \le x \le L$; $0 \le y \le H$; $0 \le z \le W$; $0 \le t \le t_f$, where L, H, and W are the dimensions of the sample in the directions x, y, and z and t_f is the experimental or simulated total time. The enthalpy function H may be defined as:

$$H = \int CdT + fL \tag{2}$$

where C is the specific heat, L is the latent heat and f is the Heaviside step function defined as a function of the melting temperature T_m

$$f(T) = 1 \quad T > T_m$$
$$f(T) = 0 \quad T < T_m \tag{3}$$

The boundary conditions of convection and radiation were defined as:

$$\text{BC1:} \quad \left.\frac{\partial T}{\partial x}\right|_{x=0} = h(T)(T - T_\infty) + \sigma\varepsilon(T)(T^4 - T_\infty^4) \tag{4a}$$

$$\text{BC2:} \quad \left.\frac{\partial T}{\partial y}\right|_{y=0} = h(T)(T - T_\infty) + \sigma\varepsilon(T)(T^4 - T_\infty^4) \tag{4b}$$

$$\text{BC3:} \quad \left.\frac{\partial T}{\partial z}\right|_{z=0} = h(T)(T - T_\infty) + \sigma\varepsilon(T)(T^4 - T_\infty^4) \tag{4c}$$

$$\text{BC4:} \quad \left.\frac{\partial T}{\partial x}\right|_{x=L} = h(T)(T - T_\infty) + \sigma\varepsilon(T)(T^4 - T_\infty^4) \tag{4d}$$

$$\text{BC5:} \quad \left.\frac{\partial T}{\partial y}\right|_{y=H} = h(T)(T - T_\infty) + \sigma\varepsilon(T)(T^4 - T_\infty^4) \tag{4e}$$

$$\text{BC6:} \quad \left.\frac{\partial T}{\partial z}\right|_{z=W} = h(T)(T - T_\infty) + \sigma\varepsilon(T)(T^4 - T_\infty^4) \tag{4f}$$

where h is the heat transfer coefficient, ε is the emissivity, σ the Stefan-Boltzmann constant, η is the normal direction and T_∞ the room temperature. The initial condition imposed for the entire domain was:

$$T(x, y, z, 0) = T_\infty \tag{5}$$

The boundary condition of imposed heat flux is applied in area A_{xy} defined in Fig. 1. In this area, the heat flux, distributed by the arch, followed a Gaussian distribution as presented by Goldak and Akhlaghi [29]. This boundary condition can be described as:

$$-\lambda(T)\frac{\partial T}{\partial z} = \frac{3Q(t)}{\pi \times r^2}e^{-3\frac{(x-u)^2}{r^2}}e^{-\frac{3y^2}{r^2}} \tag{6}$$

where Q is the estimated heat rate, u is the welding velocity and r is area A_{xy} radius. The direct model was solved through Finite Difference method in a C+ + code. Details on the code development have been reported in Magalhães et al. [30].

2.2. Temperature moving sensor

This proposed technique consists of having a temperature moving sensor on the opposite surface where heat is applied. It allows the determination of the torch efficiency curve during the welding process. Fig. 2 presents the problem approach. The GTA torch applies a heat flux $q''(x, y, t)$ with a velocity u_x. The temperature sensor also moves with velocity u_x towards coordinate x. As the temperature sensor moves continuously with the GTA torch, it allows the heat input estimation point by point along the sample.

Supplementary video related to this article can be found at http://dx.doi.org/10.1016/j.ijthermalsci.2018.02.023.

This proposed methodology allows the determination of the thermal efficiency curve of the welding. The temporal thermal efficiency curve is defined by:

$$\eta_T(t) = \frac{Q(t)}{P} \tag{7}$$

where P is the power supply, Q is the heat rate and $\eta_T(t)$ is the transient