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A thermal analysis in laser welding using inverse problems

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A B S T R A C T

The heat flux inverse analysis is significantly affected by the heat flux distribution in laser welding simulation. This work proposed a different approach for the heat distribution which predicts the temperature and the weld bead in laser welding. The influence of the heat flux distribution in an inverse heat conduction problem applied on laser welding simulation is studied by comparing different heat distribution models. An inverse heat conduction algorithm based on the three-dimensional (3D) heat diffusion equation and the enthalpy function to model the phase change problem are used to estimate the heat flux under different heat distributions. The Time Traveling Regularization is applied with the Golden Section method to estimate the heat flux in the studied cases. The proposed cubic root and square root of the volumetric heat distribution presented a good agreement between the weld profile and the experimental temperatures. The heat rate estimation proves to be dependent on the heat distribution. The proposed methodology is an alternative to predict the weld bead profile and the thermal efficiency in low penetration laser welding.

1. Introduction

Welding is an important process for the assembly stage in many industries. Inadequate parameters can induce joint defects, which affect integrity of the structure and hinder its application. To optimize these parameters, the empirical approach is usually preferred. However, this involves numerous experimental trials, intended to investigate the influence of each variable involved. Considering the recurrent demand for better productivity and quality, the laser based welding processes have gained higher relevance relative to arc processes. However, this limits the experimentation efforts due to the high cost involved in equipment and consumables, in addition to the need for specialists to operate the systems and the highly restrictive safety requirements. Besides that, experimental procedure is time-consuming. Ayoola et al. [1] suggested minimizing these disadvantages through the replacement of usual adopted variables such as laser power and welding speed, by others based on spatial and temporal energy, as power density, interaction time and energy density. Thus, the same choice of parameters can be used for many problems and not only for specific ones. However, it still requires a considerable number of experiments to reach a reliable optimization.

Recently, heat transfer mathematical models have been used to predict the resulting weld geometry as a function of the input process variables. For example, Hadi [2] applied analytical equations to determine the behavior trends in temperature distribution during laser remelting process. These equations were useful to determine optimal parameters as well as to perform intelligent control. However, the majority of these methodologies considers simplified hypothesis such as infinite workpiece [3]. Although many authors continuously study these methodologies [4–7], the solutions are found mainly for simple conditions.

Complex joint geometries and the three-dimensional nature of the problem lead to the preference for numerical models over others. Ai et al. [8] demonstrated the feasibility of the numerical approach to predict laser welding results. This is also used to solve the multiphysics phenomena, which correlate heat transfer and solid mechanics differential equations numerically [9–12]. From these models, metallurgical information such as phase formation and grain refining can be extracted, as well as those related to mechanical behavior, due to the dependence of resultant strength on microstructure. One way to obtain

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this information is through the use of Inverse Problems [13]. The Inverse Problems are used to determine the casual factor from the observed effects. Usually in welding, the temperature data are collected and used as an observed effect. In heat transfers studies applied to welding process, the casual factor may be reported by the heat flux, thermal properties, and heat transfer coefficients. For instance, Magalhães et al. [14] proposed an Inverse methodology to estimate the heat flux for a Gas Tungsten Arc welding process. In their work, the authors proposed a combination of the temperature moving sensor technique and the Time Traveling Regularization. This new technique allowed the thermal efficiency curve determination. This cited work concentrated on the voltage arc process GTAW. There is currently not much information available covering the use of this approach of the focused heat sources, as the light beam originated from a laser. It must be emphasized that laser heat source shows distinct characteristics when compared to arc processes, which require the development of an appropriate model for this approach.

The joining of materials that are susceptible to undesirable metallurgical transformations, as in structures where deformation and residual stresses are not tolerated, usually leads to a coherent light beam as the process heat source, the laser. The equipment has a set of optical components such as optical fibers, mirrors and lenses, able to focus the energy, and as a result promote localized fusion over the surface of the processed material. Besides the benefits regarding the narrow Heat Affected Zone (HAZ), which is a typical feature of this process, it is important to mention the significant raise in productivity compared to arc voltage processes, as well as the feasibility to weld in difficult access areas, as it does not require torches or tools near the workpiece [15,16].

Considering the variation of parameters such as energy density and welding speed, the user can choose between two possible operation modes. The keyhole mode, known as deep penetration mode, dependent on metallic vaporization [17] and consequent gas ionization on the incidence laser point over the workpiece leading to plasma formation. Then, the weld pool surface breaks allowing direct radiation transfer from laser beam to the solid-liquid interface, resulting in a deep cavity. This reaches the maximum height when the laser energy is no longer sufficient to melt the rear material, causing a stabilization of the keyhole regime after the forces are balanced. As the laser beam progresses over the workpiece surface, a propagation front is induced and the fused metal fills the initial cavity, originating beads with penetration/width ration around 10:1 [16]. Even though this laser processing mode is suggested for joining applications, the metallic vaporization hinders its control and stability, which increases the defect susceptibility. Therefore, in critical circumstances, the conduction mode is preferred [18,19].

In conduction welding mode, metallic vaporization is not expressive. Then, the melting pool has a much more stable behavior, with a lower defect incidence [1,20,21]. The energy emitted by the laser is partially absorbed by the material, and, conduction heat transfer governs this situation [22]. Thus, contrary to keyhole mode, the weld bead exhibits a wider width and a shallow penetration, similarly to arc welding beads. Comparing these results to those obtained through conventional welding, the main gain is due to higher processing speeds and lower deformation levels in the structure. This paper concentrates on conduction welding mode behavior.

In order to determine the best approach for the heat flux distribution in a laser welding process, 4 (four) volumetric heat flux distributions for the laser welding process are proposed. The volumetric heat flux distributions are compared to the classical model proposed by Goldak and Akhlaghi [23]. The best approach is expected to predict the experimental temperatures and the transversal weld bead profile. The heat flux was estimated through the methodology proposed by Magalhães et al. [14]. In this methodology, the inverse methodology Time Traveling Regularization (TTR) and the temperature moving sensor technique are applied together to determine the average thermal efficiency of the analyzed cases.

2. Methodology

2.1. Thermal model

This work considered a non-linear three-dimensional heat transfer model with phase change modeled by the enthalpy equation and temperature-dependent thermal properties. Those equations have been solved through the Finite Difference method. Details of the software theoretical development and boundary conditions have been reported in Magalhães et al. [24].

2.2. Heat flux distribution

In laser welding, the weld is done through the heat delivered by the laser welding head. In welding simulation, this heat can be distributed according to some mathematical models. The heat distribution can be analyzed by two and three-dimensional approaches. Usually, the two-dimensional (2D) heat distribution can be obtained in two ways: a linear or Gaussian. The linear heat flux distribution over a circular area can be written as:

$$q''(x,y,t) = \frac{Q(t)}{\pi\ R^2}((x-u\ t)^2+y^2) \tag{1}$$

where q'' is the heat flux, Q is the gross heat rate, R is the weld radius and u is the welding speed. The Gaussian heat distribution is defined by:

$$q''(x,y,t) = \frac{Q(t)}{\pi\ R^2}e^{-3\frac{(x-ut)^2}{r^2}}e^{-3\frac{y^2}{r^2}} \tag{2}$$

The three-dimensional heat distribution applied in this work is based on a conical distribution of power density. This approach was suggested by Goldak and Akhlaghi [23] for the laser welding process. It has a radial Gaussian distribution and an axial linear distribution. Fig. 1 presents the distribution scheme, where h is the welding penetration.

A radial Gaussian distribution and a rational function for the heat distribution are proposed in this work. The linear heat flux distribution simulates the barrier effect that the laser beam is subject while it penetrates the sample. Although this model can predict the width and penetration size of the weld bead, it cannot predict its shape. The proposed model considers that the heat flux is distributed following a polynomial function distribution. Four approaches are considered. The two first approaches consider the heat distribution as a square and cubic function. The two others consider the heat flux distribution as a square and cubic root. These approaches consider the heat flux distribution higher on the surface than when it approaches the penetration coordinate h. Fig. 2 presents the difference between the heat flux distributions in coordinate z for the linear and all the cases proposed. Eqs.

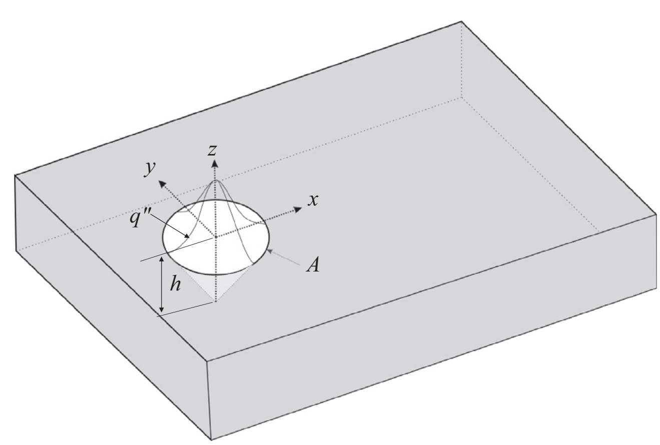

Fig. 1. Conical heat flux distribution in the laser welding process.