Applied Thermal Engineering 30 (2010) 2396–2402

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Application of optimization techniques and the enthalpy method to solve a 3D-inverse problem during a TIG welding process

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ARTICLE INFO

Article history:
Received 22 May 2009
Accepted 13 June 2010
Available online 19 June 2010

Keywords:
Enthalpy method
Phase change
Inverse problems
Welding
temperature

ABSTRACT

Tungsten inert Gas (TIG) welding takes place in an atmosphere of inert gas and uses a tungsten electrode. In this process heat input identification is a complex task and represents an important role in the optimization of the welding process. The technique used to estimate the heat flux is based on solution of an inverse three-dimensional transient heat conduction model with moving heat sources. The thermal fields at any region of the plate or at any instant are determined from the estimation of the heat rate delivered to the workpiece. The direct problem is solved by an implicit finite difference method. The system of linear algebraic equations is solved by Successive Over Relaxation method (SOR) and the inverse problem is solved using the Golden Section technique. The golden section technique minimizes an error square function based on the difference of theoretical and experimental temperature. The temperature measurements are obtained using thermocouples at accessible regions of the workpiece surface while the theoretical temperatures are calculated from the 3D transient thermal model.

1. Introduction

Welding processes that involve material phase change are used in a large number of metallic structures such as buses, airplanes, reactors or oil ducts. Since these structures require a high level of safety, the manufacturing processes, in special welding, must be considered carefully. TIG is one of the most widely employed welding processes applied with success for welding of stainless steels and non-ferrous materials. In this process, a tungsten electrode is shielded by a flow of inert gas such as argon (normally employed), helium, nitrogen, hydrogen or mixtures. The union of two or more workpieces is obtained through a voltaic arc which is a moving heat source.

The analysis of the thermal behavior of the physical phenomenon that takes place in the process is crucial for understanding of the width and depth of weld penetration, the microstructure changes in the thermally affected base metal or the residual stress that appear in the welding process.

Transient heat transfer problems involving melting or solidification, such as a TIG welding process, are usually referred to as phase change or moving-boundary problems. The solution of such problems is inherently difficult because the interface between the solid and liquid phases is moving as the latent heat is absorbed or released at the interface. As a result, the location of the solid–liquid interface is not known a priory and must follow as a part of the solution Crank [1]. For obtaining the temperature field of welding processes either the actual heat flux or the interface position of the weld pool has to be known. Once these parameters are known, a direct problem is established and the temperature field can, then, be calculated. Several papers, analytical [2–4], numerical [5–9] or parametric model [10,11] that deals with this direct problem can be found in the literature. Besides the hypothesis of knowing the heat flux, important phenomena like metallic phase changes, thermal properties dependence on temperature or heat losses by convection or radiation are neglected or considered known. It also can be observed from the literature that the arc constriction and the reversed Marangoni convection can affect the penetration of weld pool of some process [8,9]. For example, this fact can occur for A-Tig process when quantity of the flux is low. However, in the literature, most of the works that takes in account the convection in liquid region does not solve the inverse problem nor consider the heat flux *delivered to the workpiece* as a known quantity in non transient models [8,9]. Although the convection effect in the liquid region is important in some specific conditions of welding it is not considered here.

It must be observed that the identification of heat flux or the weld pool geometry is not trivial in real welding. The main difficulty, in this case, is that these parameters are not easily available or they are not so easily measured directly. A mean of overcoming this difficulty is to use inverse techniques [12–17]. However, the

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doi:10.1016/j.applthermaleng.2010.06.009

Nomenclature

A_p	area of heat supply, m^2
c	specific heat capacity, J/kg K
$f(x,y,z,t)$	massic fraction of liquid phase
F_q	least square function, K^2
h_i	heat transfer coefficient, W/m^2 K
H	enthalpy function, J
k	thermal conductivity, W/m K
k_a	thermal conductivity of the air, W/m K
L_x, L_y, L_z	plate dimensions, m
L_c	characteristic length of the sample, m
L	latent heat solidification, J/kg K
Nu_l	local Nusselt number
Pr	Prandtl number
q''	moving point heat flux source, W/m^2
q_p	moving point heat source of constant strength, W
Q_m	latent heat source term, W/m^3
$\boldsymbol{r}$	vector position in the rectangular coordinate system (x,y,z)
Ra_l	Rayleigh number
R_l	liquid region, m^3
R_s	solid region, m^3
$\Re$	interface region, m^2
t	time, s
T	temperature, °C
T_0	initial temperature, °C
T_{sat}	saturation temperature, °C
T_∞	ambient temperature, °C
T_m	fusion temperature, °C
x, y, z	Cartesian coordinates, m
Y	measured temperature, °C

Greek symbols

α	thermal diffusivity, m^2/s
θ	temperature difference, °C
ρ	density, kg/m^3

Subscripts

e	experimental data
l	relative to liquid region
s	relative to solid region
m	relative to fusion
M	related to discrete time

majority of work that deals with inverse problem techniques in welding problems only uses simulated studies [12–14] or quasisteady assumptions [15] or simplified models [17].

Keanini and Desai [15] have presented an inverse finite element method that is developed for simultaneous solution of multi-dimensional solid–liquid phase boundaries and associated three-dimensional solid phase temperature fields. The technique, applicable to quasisteady phase change problems, fixes element nodes at known temperature locations and uses a coarse, spatially limited mesh.

In a previous work, Goncalves et al. [17] have presented a procedure to solve the direct and inverse problem related to GTA welding process considering a 2D transient phase change model. In that work, the molten pool radius and interface position were estimated by using gold section method. The molten pool shape was supposed to be circular and the objective of the inverse procedure was to estimate the radius of the weld pool as well as the temperature field within the solid region. Once the geometry and interface position of weld pool are known, a direct problem was established and the temperature field could be, then, calculated.

A new inverse procedure considering a 3D transient phase change model is proposed here. Besides the 3D thermal model be more complete than the previous work [17] the main objective of this study is to develop a method to recover the front surface heat source that is supplied by the welding process. Since the heat source is known, the interface position can be easily identified at each instant by solving the direct phase change model. This procedure seems to be simpler and more efficient than estimate the molten pool radius and interface position.

Thus, the main goal of this study is to contribute to the welding related studies on heat flux and temperature field by presenting a solution based on inverse technique to estimate the heat rate supplied and the interface position of the weld pool using a 3D transient phase change model and practical experiment data. The thermal fields at any region of the plate or at any instant are determined from the estimation of the heat rate that is delivered to the workpiece. The direct problem is solved by an implicit finite difference method. The system of linear algebraic equations is solved by Successive Over Relaxation method (SOR) and the inverse problem is solved using the Golden Section technique. The model developed is based on the enthalpy method described by Al-Khalidy [12] applied to a two-dimensional model.

2. Direct problem

2.1. Moving-boundary problem formulation

Fig. 1 presents the transient heat transfer problems involving phase change due to a TIG welding process in a AISI 304 sample. The moving-boundary problem can, then, be described by diffusion equation considering a three-dimensional system and nonlinear temperature-dependent thermal conductivity $k(\theta)$ and specific heat $c(\theta)$ in the solid region as

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

subjected to the following boundary conditions:

In the regions exposed to the environment

$$-k_i\frac{\partial T}{\partial \eta} = h_i(T - T_\infty) \tag{1b}$$

and at the region of heat supply

$$-k_i\frac{\partial T}{\partial \eta} = q''(t) \tag{1c}$$

where $\partial/\partial\eta$ denotes differentiation along the outward-drawn, normal to the boundary surface S, h_i is the heat transfer coefficient, T_∞ is the ambient temperature and q'' is a moving point heat source of constant strength q_p (W), that releases its energy continuously over the time as it moves with a constant velocity u in the positive × direction.

In Fig. 1 all surfaces are exposed to the environment except the area of heat supply, A_p. This area is subjected to the heat flux q'' generated by welding, Fig. 1b.

Equation (1) refers to the fixed coordinated system (x,y,z). However, depending on the value of the power supply a fusion zone in the region where the heat is delivered can occur. In which case,