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INVERSE THERMAL ANALYSIS FOR WELDING PROCESS

Summary. The aim of this work is to determine the mathematical model capable to predict the temperature distribution in the work piece, the position of the solid-liquid interface as well as to the study of the different parameters on the welding process to obtain a higher welding quality. The mathematical model is solved directly by the use of numerical solution employing the data at eight arbitrary sensors in the solid region. The numerical solution of the inverse steady state two dimensional advection-diffusion controlled phase change problem is developed.

ODWROTNA METODA ANALIZY CIEPLNEJ PROCESU SPAWANIA

Streszczenie. Praca dotyczy wyznaczania pola temperatury i położenia granicy faz dla blach spawanych. Metoda odwrotna wykorzystuje informację o temperaturze w materiale spawanym i pozwala uniknąć rozwiązywania równań przepływu ciepła dla fazy ciekłej

ОБРАТНЫЙ АНАЛИЗ ДЛЯ ПРОЦЕССА СВАРКИ

Резюме. Работа посвящена проблеме идентификации температуры тела для процеса сварки обратных методом. Метод требует унформаций о температуре в некоторых точках твердой фазы и потому можно избегнуть от проблема теплообмена жидкой фазе. Проблем решен числено.

1. INTRODUCTION

The solidification or phase change problem is required to analyze heat and mass transfer in many physical problems, especially in material process. Example of this casting[1], welding[2] where the application of the moving source must be considered, laser cutting and drilling[3]. Because of the complexity involved these problems, the analytical solutions are very limited[4]. The difficulties due to the combination of essentially elliptic and parabolic natures in the advection diffusion equation are well treated by the use of upwind scheme[5]. The grid transformation method performed remarkably well when it is compared with 20 different method[6].

Heat conduction is only the mechanism occurring in laser spot welding while the continuous welding stands as being on the boundary between heat conduction limited and non heat conduction limiting problems[3]. Enthalpy scheme is proposed to solve the conduction equation in both solid and liquid region to predict the location of the phase change[7]. A new enthalpy transformation scheme is used to solve the problem and to protect the work piece surface from burning out when the surface is subject to an intensive moving heating flux[8]. The experimental surface temperature shows agreement within $\pm 8\%$ with the best transient computational model of stationary gas tungsten arc welding when the convection equation is considered in the welding pool[9]. The problem was envisaged by an Eulerian-Lagrangian approach[10]. The numerical solution showed excellent agreement with the analytical solution of one dimensional problem and with experiment data for two dimensional problem. The infinite element method[11] based on Gauss-Laguerre quadrature showed an accurate near field solution to phase change situations on deforming meshes. The time dependent finite element model using the front tracking technique was used[12] to solve the linearized obtained equation and to locate the position of the phase change front into two dimension.

Inverse heat conduction is the estimation of the surface temperature distribution or heat flux history from the temperature measurement at specified location inside the body. Inverse technique is very important for this problem to avoid solving a very expensive and difficult direct problem or measuring the temperature inaccurately in the fusion zone while the temperature measurements in the solid region can be performed more easily. The one dimensional Stefan problem is presented successfully [13] to calculate the velocity or position of the moving interface. Also the analysis and design of welding process is examined [14] for front tracking one dimensional finite element method. An inverse finite element is developed to solve the two dimensional stationary arc welding [15]. The inverse analysis required the solution of the energy equation in solid region is the major advantage of this technique. The Newton-Raphson interpolation is used to predict the transient temperature history in the solid region and the position of the interface.

In all previous studies, inverse phase change problem with moving heat source is not considered for both steady and unsteady state. In this paper a detailed steady state analysis for two dimensional advection diffusion problem controlled welding process in a plate made of AISI-304 stainless steel is presented. The numerical solution is based on control volume discretization[16].

2. DEFINITION OF THE PROBLEM TO BE MODELLED

The physical problem in this study is defined as follows. A laser beam or electrical arc welding strike the surface of the work piece having infinite width and length in the positive x-direction. The heat is absorbed by the material and penetrating through a keyhole which acts as a black body. The experimental results show that the keyhole shape is circular [2,17]. The temperature of the keyhole is equal to the boiling temperature of the material and its radius is equal to the radius of the intersected beam. The welding pool is developing while the torch moves with a constant velocity. Some of the absorbed energy is lost by convection and radiation from the upper and lower surface while the rest is conducted through the work piece. The overall heat transfer coefficient used in calculating the heat loss from the plate to surrounding varies with the temperature . Two dimensional temperature variation is presented due to small metal thickness or Biot number. Non-linear temperature dependent properties in the solid region is considered with the exception of the density which is assumed to be constant in both solid and liquid region. The temperature distribution reaching steady state with respect to the coordinate system moving with the arc.

3. MATHEMATICAL FORMULATION

The governing equation may considering a region $\boldsymbol{R}$ of pure material separated into liquid region $\boldsymbol{R_l}$ and solid region $\boldsymbol{R_s}$. The boundary $\boldsymbol{dr}$ separate between these region. The inverse approach allows to avoid determining temperature distribution within the liquid region. As a result only governing equation for the solid region is considered. The advection-diffusion can be written as follows

$$\rho C_s u \frac{\partial T(x,y)}{\partial x} = \nabla . \ K_s \ \nabla T_s(x,y) - \frac{h(\bar{x},T)}{H} + Q \qquad (x,y) \subset R_S \qquad (1)$$

Where C, h, H, K, Q, U and ρ denote the specific heat, overall heat transfer coefficient, plate thickness, conductivity, internal heat source, velocity and density. The subscript s denotes the solid phase.

$$h(\bar{x},t) = h_c + h_r \qquad (2)$$

$$h_c = h_{up} + h_{lo} \qquad (3)$$

The characteristic length $\bar{x}$ is defined as the ratio between the surface area and perimeter. The subscripts c, r, lo and up denote the convection losses, radiation losses, lower surface and upper surface.
The initial condition are:

$$u = U \qquad (4)$$

where U is the torch velocity.

$$T(x,y) = 0. \ ; \quad x \to \infty \ ; y \to \infty \qquad (5)$$

The boundary condition are:

$$\frac{\partial u}{\partial y} = 0 \ ; \frac{\partial T_l}{\partial y} = 0 \ ; \frac{\partial T_s}{\partial y} = 0 \quad at \ y=0 \qquad (6)$$

$$T_s=0 \quad at\ x\to\infty \vee y\to\infty \tag{7}$$

The interface condition include the isothermal condition is

$$T_l(x,y)= T_m-T_\infty \quad at\ (x,y)\subset \partial r \tag{8}$$

where T_m is the reference temperature for an isothermal phase change.
The local internal source is calculating from these equation

$$Q=I_s-I_l \tag{9}$$

$$I_l=I_l+Q_l \quad during\ solidification \vee I_l=I_l-Q_l \quad during\ melting. \tag{10}$$

where I and Q_l denotes the enthalpy and the phase change heat respectively.
The temperature measurements at the specified interior sensors in the solid region is defined by the following equation

$$T(x_i,y_i)=T_{sen}.(i) \quad i=1,2,....,n \quad (x,y)\subset R_s \tag{11}$$

Where n is the number of the measurement points.

4. DISCRETIZATION

The solution domain is broken up into fine,medium and coarse zones. Each small rectangular region corresponds to a control volume. The associated nodes are located at the center of the control volume except at the first row, the associated nodes are located in the surface because the geometrical boundary of the work piece is included. The semidiscrete form of the advection-diffusion equation is obtained by approximating the spatial terms with central difference. For the internal node the governing equation can be discreting as follows

$$\begin{gathered}K_{i,j+1}T_{i,j+1}+K_{i,j-1}T_{i,j-1}+[K_{i-1,j}+(1-\mu)\ C_{i,j}]T_{i-1,j}+[K_{i+1,j}-\mu\ C_{i,j}]T_{i+1,j}+Q=[K_{i-1,j}+\\+K_{i+1,j}+K_{i,j-1}+K_{i,j+1}+C_{i,j}]T_{i,j}+\frac{h}{H}T_{i,j}\end{gathered} \tag{12}$$

where μ is the upwind factor. It takes values between 0 and 1.

5. SOLUTION PROCEDURE

The straight forward solution is not possible because of the unknown location of the solid-liquid interface. An iterative procedure is developed to find this location as well as to the temperature distribution in the solid region from the history of a number of specified sensors in the solid region. The solution procedure was:

1. The location of the interface is assumed arbitrary by setting up a grope of nodes on the interface. The radial distance from the origin (center of the keyhole) and the angular direction is assumed.
2. The initial conditions (equations 4 and 5) and the boundary conditions (equations 6 through 10) are used to appropriate matrix equations for the nonlinear problem.
3. The set of the obtained equations is solved by fully upwind back substitution procedure.
4. The new obtained nodes in the interface is linked by the least square method.
5. The boundary condition (equation 11) is used to compare the estimated and measured temperatures.
6. The above steps are repeated till convergence. The Powell optimization method is used to minimize the summation of the least square error between the measured and estimated temperature.

6. RESULTS AND CONCLUSION

Some exemplary results for a welding velocity of 0.5mm/s and keyhole radius of 2mm on a 12.7mm thick stainless steel are displayed in figure 1 and 2. These parameters are chosen to compare the results with the steady state two dimensional finite element model controlled fluid flow velocities in the welding pool[2]. The behavior of the temperature field and the location of the interface which is shown in figure 1 and 2 is in a good agreement with the above study. There are,in fact, no differences between results obtain from inverse and direct approach.

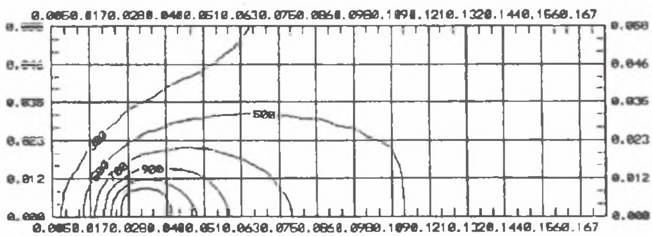

Fig.1. Temperature isotherms at U=0.5 mm/s
Rys. 1. Rozkład izoterm dla U=0.5 mm/s

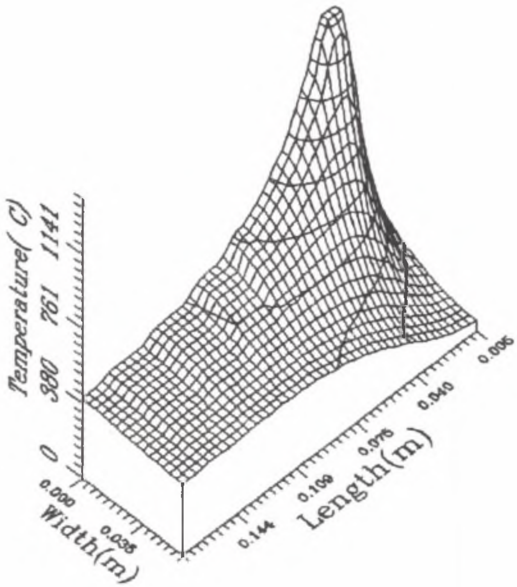

Fig. 2. Temperature distribution at U=0.5mm/s
Rys. 2. Rozkład temperatury dla U=0.5 mm/s

This work is a step towards using the inverse technique for the analysis of two dimensional moving heat source. This analysis can be used to improve welding quality by studying the maximum welding speed, the overall utilization of energy within the welding process and the different parameters. The feature of this method is the possibility of using the experimental procedure therefore controlling the parameters that concern with the welding or material process. The mechanism of the heat transfer in the phase change problems can be understanding well without any analysis in the fusion zone.

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