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**IDENTIFICATION OF THE GAUSSIAN HEAT SOURCE PARAMETERS IN THE
ELECTRON BEAM WELDING PROCESS.**

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NOMENCLATURE:

T temperature, $^{\circ}C$
 C_p specific heat, $J/kg/^{\circ}C$
 k , thermal conductivity, $W/m/^{\circ}C$
 x , space variable (cartesian), m
 y space variable (cartesian), m
 t time variable, s
 P_{α} phase α proportion
 $S(P,T)$ quadratic criterion
 W_{FE} electron beam parameter, m^2
 P_w power density, W/m
 V speed of the electron beam, m/s
 Y_s position of the heat source, m
 L_v vaporisation phase change, J/m^3
 L_f fusion phase change, J/m^3
 Y_i temperature measurements, $^{\circ}C$
 J sensitivity coefficients
 W diagonal matrix
 Ω^k diagonal matrix
 α steel phase α
 β steel phase β
 ϕ_E diameter of the electron beam, m
 ε emissivity coefficient
 σ Stefan constant
 ξ space variable (cartesian), m
 ρ mass density
 λ damping parameter

ABSTRACT

In this communication, a electron beam welding process is studied. The work focused on the identification of the power density and the position of a gaussian heat source. The Levenberg-Marquardt method is employed to solve the inverse heat source problem. The welded material is cut in several planes and the identification is performed for each planes. The, a pseudo 3D heat source is reconstructed from these results.

Keywords : electron beam welding process, heat conduction, inverse heat problem, levenberg-marquardt.

INTRODUCTION

The electron beam welding is a process used to assembly metallic materials under vacuum conditions. This technique allows to weld high thickness (until 16 cm) with a low width and narrow heat affected zone (HAZ). This operation affects both mechanical and structural properties. Several numerical studies has been made at the LET2E about

the simulation of the electron beam welding [1,2]. The understanding of complex thermo-metallurgical phenomena occurring in the electron beam welding process is difficult because of the liquid and vapor zone (Temperature superior to 1450 $^{\circ}C$). The temperature distribution is just known in the solid phase, so, thermal energy dissipated in liquid phase is unknown.

The objective of this work is the estimation of the heat source in the welding zone at different depth of the welded material. The temperature difference between the welding and solid zones is bigger, there is a strong damping effect in the solid zone. It is difficult to estimate correctly the heat source from temperature measurements taken at points which are too far from the welding zone. So, the temperature measurements are made at the frontier between solid and liquid domains, figure 2.

The heat source formulation (gaussian function) has been shown as representative of the energy dissipated in the matter [2]. The estimated heat source is obtained by the resolution of an inverse heat transfer problem (IHTP). The Levenberg-Marquardt method is employed to solve the IHTP [3,4,5]. This study has been performed in 2D quasi steady state. Each studied 2D plane corresponds to a depth in the welded material.

In this communication, the electron beam welding process is briefly presented. The main assumptions are established : the liquid phase is treated as a solid phase. So the problem considered here is the heat conduction equation only. The thermo-metallurgical transformations are considered in the specific heat coefficient for the phase changes $\alpha \rightarrow \gamma$. The latent heat fusion and vaporisation are taken in account in the specific heat [6].

After the formulation of the direct problem, we have stated the inverse heat source problem. The Levenberg Marquardt method (LM) is briefly presented.

The employed code for the estimation was both developed under MATLAB and FEMLAB softwares. The optimisation algorithm is programmed under MATLAB and the direct and sensitivities problems are solved with FEMLAB.

THE ELECTRON BEAM WELDING (EWB) PROCESS

Principle :

The electron beam welding is an assembling process in vacuum using a high density energy beam. This technique permits the welding of the high thickness (up to 16 cm) with a low width and a

narrow Heat Affected Zone (HAZ). At the beginning of the welding process, the high power density of the electron beam leads to an evaporation of the material and then to a keyhole (figure 1). It is this keyhole and its displacement which generate the welded joint. The high penetration capacity of the beam with a narrow fusion zone characterizes the electron beam welding in comparison with other weld methods. For these other methods, the penetration is limited by the heat conduction [7].

For this study, weld joints are realised at the DCN-propulsion (power of this electron beam: 100KW). The used sample are 18MnNiMo5 steel. The welding parameters are: voltage: U=60kV, current I = 0.29A, velocity v = 2.5mm/s, focus current I_f=2.46A. A partial part of the sample has been analyzed. The temperature measurements are taken near to the HAZ, figure 2 (dark colored domain). The temperature measurements are made at different depth and distance to the electron beam axis. Some temperature measurements are shown in figure 3.

Direct heat conduction problem :

Several works are concerned with the numerical simulation of the EB welding [1,2]. In a transient regime, the equations are the heat conduction equation (1) and the metallurgical kinetic equations (2) of the Leblond and Devaux [8] and Koistinen and Marburger type [9].

The studied domain is one half of the longitudinal section taken perpendicularly to the beam axis, figure 1.

$$C(T) \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(k(T) \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial \xi} \left(k(T) \frac{\partial T}{\partial \xi} \right) + \Delta PL + S(x, \xi, t) \quad (1)$$

$$\frac{dP}{dt} = \frac{P_{eq} - P}{\tau} f \left(\frac{dT}{dt} \right), P = P_{max} (1 - \exp(-b(T - M_s))) \quad (2)$$

In the Equation1, the thermophysical characteristics $C(T) = C_p(T) \rho(T)$ and $k(T)$ are calculated by a law of mixtures according to the temperatures:

$$C(T) = P_\alpha C_{p\alpha}(T) \rho_\alpha(T) + P_\gamma C_{p\gamma}(T) \rho_\gamma(T) \quad \text{and}$$

$$k(T) = P_\alpha \lambda_\alpha(T) + P_\gamma k_\gamma(T) \quad \text{with } P_\alpha \text{ and } P_\gamma \text{ the}$$

proportional phases obtained from the equation (2). A Continuous Cooling Temperature (C.C.T.) diagram is used for the definition of the parameters in the equation (2). During the metallurgical transformation, the phase change heats are L_f (J/m³) for the fusion heat, L_v (J/m³) for the vaporization heat and $L_{\alpha\gamma} = \rho_\gamma H_\gamma - \rho_\alpha H_\alpha$ (J/m³) for the solid transformations. For this last case, we consider only

two metallurgical phases: \mathcal{Y} (austenite) and α (ferrite, bainite or martensite). The enthalpies of the phase α and \mathcal{Y} are approximated with a good accuracy by polynomials between 100°C and 1450°C [10]. ΔP is the proportion of the transformed phase ($\Delta P < 0$ if $\partial T / \partial t \geq 0$).

The boundary and initial conditions are the following : at the lateral surfaces, only the radiative conditions are fixed because the welding process is carried out in vacuum. At the lateral surface in $x = x_{max}$, the boundary condition is :

$$-k(T) \partial T(x_{max}, \xi, t) / \partial x = \epsilon \sigma (T^4(x_{max}, \xi, t) - T_{inf}^4)$$

$$\text{On the symmetric axis : } \partial T(x=0, \xi, t) / \partial x = 0$$

$$\text{Initial conditions: } T(x, y, 0) = T_0, P_\alpha(x, y, 0) = 1.$$

For this study, we use a quasi stationary problem and we define moving coordinates (x, y) \mathcal{Y} , where $y = \xi + Vt$. In the stationary regime ($\partial T / \partial t = 0$), the heat conduction equation and the metallurgical kinetic equations become (3) and (4):

$$VC(T) \frac{\partial T}{\partial y} = \frac{\partial}{\partial x} \left(k(T) \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k(T) \frac{\partial T}{\partial y} \right) + \Delta PL + S(x, y) \quad (3)$$

$$(6)$$

$$V \frac{dP}{dy} = \frac{P_{eq} - P}{\tau} f \left(\frac{dT}{dy} \right), P = P_{max} (1 - \exp(-b(T - M_s))) \quad (4)$$

For this new problem, we take only a part of the longitudinal section. The boundary conditions in the beam direction "y" change and we impose these new conditions : at $y = y_{min}$: $T = T_0$ and at $y = y_{max}$: $\partial T / \partial y = 0$.

For the conditions in the transverse direction "x", we have the same boundary conditions.

In the equation (1), the term $S(x, y)$ is the source term which represents the energy of the electron beam. The form of this source term is a Gaussian function which corresponds to several studies carried out in our laboratory [1,2] :

$$S(x, y) = f(z_e) * \frac{8\eta U I_b}{h \pi \Phi^2} \exp \left(- \frac{8(x^2 + (y - y_s)^2)}{\Phi^2} \right),$$

$f(z_e) = 2(1 - z_e/h)$ where the parameters are : efficiency coefficient $\eta = 0,9$, voltage: $U = 60kV$, current: $I_b = 0,29A$, velocity: $V = 2,5mm/s$, penetration: $h = 71mm$, beam diameter: $\phi = 1mm$ and z_e : the depth of the longitudinal section.

The goal of this study is the estimation of the parameters describing the source term by the Levenberg-Marquardt method. So, first, the source

term which has been presented above is defined mainly by three parameters (P_w, W_{FE}, y_s) :

$$S(x, y) = (P_w / W_{FE}^2) \exp\left(-\left(x^2 + (y - y_s)^2\right) / W_{FE}^2\right) \quad \text{where}$$

P_w is the power density of the electron beam, W_{FE} , equal to $\sqrt{\phi^2 / 8}$, is the parameter of the Gaussian source and y_s is the position of the source in this quasi steady problem. Second, we analyse only a thermal problem without metallurgical transformations but the phase changes (fusion, vaporization) is taken in account in the specific heat according to Goldak method [6]. The thermophysical parameters are shown in the table 1.

Table 1 : steel thermophysical properties

ρ (kg / m ³)	7500
C_p (J / kg)	520 + $L_{\alpha \rightarrow \gamma}$ + L_v
k (W / m / K)	32
ε	0,6

THE INVERSE HEAT TRANSFER PROBLEM

Formulation :

The general formulation of the inverse problem is written as :

Find the unknown vector z such that the measured temperature $\hat{T}_{mes}(t)$ is equal to the calculated temperature $T_{cal}(x_i, t; z)$ at each sensors located and at points x_i , $i=1, n_c$ and for any time steps.

A second formulation is desirable. This formulation introduces a quadratic criterion [10] :

$$S(z, T) = \frac{1}{2} \int_{\Omega} \sum_{i=1}^{n_c} (T_{cal}(x, t; z) - \hat{T}_{mes}(t))^2 \delta(x - x_i) dt d\Omega$$

where n_c is the number of sensors, $\delta(x)$ is the Dirac function. So the second formulation of the inverse problem becomes:

Find the vector z which minimizes the cost function $S(z, T)$.

The resolution of the inverse problem under this form needs optimisation and/or regularisation methods [3,4,5,10]. Here, we use the Levenberg-Marquardt (LM) method [3,4,5].

The Levenberg-Marquardt method :

In the LM method, the expression of the cost function is formulated as:

$$S(z) = [Y_i - T_i]^T W [Y_i - T_i] \quad \text{where } Y_i \text{ are the measured temperatures and } T_i \text{ the calculated temperatures. The}$$

subscript T denotes the transpose : $[Y_i - T_i]^T = [Y_1 - T_1, Y_2 - T_2, \dots, Y_l - T_l]$.

To minimize the cost function $S(z)$, we need to equate to zero the derivatives of $S(z)$ with respect to the unknown parameters : $[z] : \partial S(z) / \partial z = 0$.

This necessary condition for the minimization of $S(H)$ can be represented normally in matrix (here a vector): $\nabla S(z) = 2 [\partial T_i^T(z) / \partial z] [Y_i - T_i(z)] = 0$ (5).

The sensitivity matrix $J(z)$ is defined as the transpose of the previous equation, that is $J(z) = [\partial T_i^T(z) / \partial z]^T$ (6). I is the total number of measurements. The elements of the sensitivity matrix are called the sensitivity coefficients. The sensitivity coefficient is thus defined as the first derivative of the estimated temperature at position Z with respect to the unknown parameters Z .

By using the definition of sensitivity matrix (5) in the equation (6), we obtain : $-2J^T(z) [Y_i - T_i(z)] = 0$ (7).

The solution of this equation for non linear estimation problems requires an iterative procedure, which is obtained by linearizing the vector of estimated temperatures, $T(z)$, with a Taylor series expansion around the current solution z^k at iteration k : $T(z) = T(z^k) + J^k(z - z^k)$ (8) where $T(z^k)$ and J^k are the estimated temperatures and the sensitivity matrix evaluated at iteration k respectively. Equation (8) is substituted into equation (7) and the resulting expression is rearranged to yield the Gauss iterative procedure method to obtain the unknown parameters Z : $z^{k+1} = z^k + [(J^k)^T J^k]^{-1} [(J^k)^T (T_i - Y_i)]$.

Inverse heat transfer problems are generally very ill-conditioned ($J^T J \approx 0$), especially near the initial guess used for the unknown parameters, creating difficulties. The Levenberg-Marquardt method alleviates such difficulties by utilizing:

$$z^{k+1} = z^k + [(J^k)^T W J^k + \lambda^k \Omega^k]^{-1} [(J^k)^T W (T_i - Y_i)]$$

where λ^k is positive scalar named damping parameter and Ω^k is a diagonal matrix. The goal of the term $\lambda^k \Omega^k$ is to damp the oscillations and instabilities due to the ill-conditioned character of the problem. This damping parameter is large at the beginning of the iterative procedure (and the method is like the steepest descent method) then it decreases when the procedure advances to the solution (and

the method tends to the Gauss method). W is a diagonal matrix where the diagonal elements are given by the inverse of the standard deviation of the measurement errors.

The Levenberg-Marquardt algorithm is the following :

Suppose that the temperature measurements Y_i are given at each abscissa y_i , $i=1,\dots,I$. We choose an initial set of parameters $P^0 = [P_w^0, y_s^0]$ and an initial value for the damping parameter $\lambda^0 = 0.001$. The iteration number is initialized ($k=0$).

- Step 1: Solve the direct problem with the available estimate P^k in order to obtain the temperature vector $T(P^k) = (T_1, T_2, \dots, T_I)$.
- Step 2: Compute $S(P^k)$.
- Step 3: Compute the sensitivity matrix J^k and then the matrix $\Omega^k = I$, by using the current values of P^k .
- Step 4: Calculate the new set of estimate P^{k+1} from the following equation:

$$P^{k+1} = P^k + \left[(J^k)^T W J^k + \lambda^k \Omega^k \right]^{-1} \left[(J^k)^T W (T_i - Y_i) \right]$$
- Step 5: Solve the direct problem with the new estimate P^{k+1} in order to find $T(P^{k+1})$. Then compute $S(P^{k+1})$, as defined in step 2.
- Step 6: if $S(P^{k+1}) \geq S(P^k)$, replace λ^k by $\lambda^{k+1} = 10\lambda^k$ and return to step 4.
- Step 7: if $S(P^{k+1}) \leq S(P^k)$, accept the new set of estimate P^{k+1} and replace λ^k by $\lambda^{k+1} = 0.1\lambda^k$. Check the stopping criteria. Stop the iterative procedure if it is satisfied; Otherwise, replace k by $k+1$ and go to step 3.

EXPERIMENTAL RESULTS

The welded material is compounded of four blocks of steel. The measurements are made at the interface of each blocks. Here, the results of the identification are made from two interfaces. The interfaces are referenced "black" and "red". 17 measurements for the black surface and 12 for the red surface were employed. Each measurements corresponds to a depth of the welded material. The estimation of the heat source at each depth has allowed us to estimate a pseudo 3D heat source distribution.

In the quasi stationary, the time axis is replaced by the longitudinal axis y . The temperatures reach values near to the fusion of the steel ($\sim 1450^\circ\text{C}$),

figure 3. We see that the peak of temperature is lower at the top of the welded material (the surface impacted by the electron beam) but the distribution of the temperature along the y axis is larger. In the depth of the material the peak of temperature increases to value near to 1250°C . The gradient of temperature are important in front of the electron beam ($0,012m \leq y \leq 0,016m$) whereas, for $y \geq 0,02m$, the temperature decreases more rapidly inside the material than in the surface. This behaviour is probably due to the convective movement of the liquid steel and, also to the phase change of the liquid phase to solid phase with liberation of latent heat fusion.

In the following, we have identified two parameters : the power density P_w and the source position y_s . The third parameter : the electron beam diameter is imposed to $1mm$. A sensitivity analysis has shown that the measurements taken near the HAZ are unable to identify this parameter : W_{je} . The power density parameter is initialized to $P_w^0 = 1000 \text{ W/m}$ and $y_s = 0.005m$. The damping parameter λ is initialised to 10^3 and the calculus are stopped to a estimated value. The stopping criterion is computed from the estimated error on the measurements at each step time. The error measurement is assumed to be equal to $J_{STOP} = \sum 4\% * T_i$, $i=1,1000$. Only the curves of one measurements in the black block is presented here, figures 4,5, 6 and 7.

The stopping criterion is rapidly reached, about 5-6 iterations. The power density converge towards a value of $6e4 \text{ W/m}$ and the source position seems to be around $y=16,9 \text{ mm}$. The difference between calculated and measured temperature are not important except for the peak of temperature, fig. 7.

All the results of the parameters estimation are reported on the figures 8, for the power density, and 9 for the source position. The power density seems to be constant in the depth of the material (for $z \geq 10mm$) and decreases slowly at the bottom of the welded material. The power density is bad estimated at the top of the welded material that is probably due to the convective movement of the liquid phase. For the two surface, black and red, the power density is of the same order of magnitude. The source position seems to be stable with the depth for the black interface, figure 9. The source position moves to forwards in the red case.

These results give good results for measurement performed away from the surface of the electron

beam treatment. We have established a distribution of the power density in the depth of the welded material. The choice of a given electron beam diameter and not to take in account of the liquid phase may be the cause of the variations of the source position.

CONCLUSION

We have studied a process of welding in this communication. We have estimated the thermal dissipated energy under the form of a gaussian heat source depending of two parameters : power density and source position. The power density and the source position have been estimated for a fixed diameter of the electron beam. Then, the distribution of the power density in the depth of the welded material has been reconstructed. These results will be used in more complex simulations (thermo-convective model) where the heat source is an input data.

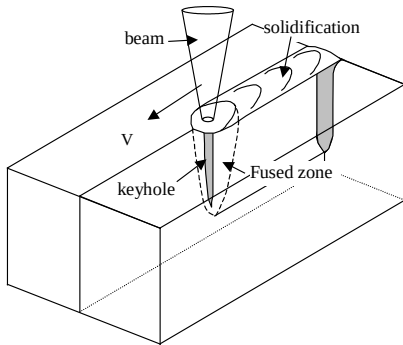


Figure 1 : Electron beam welding process.

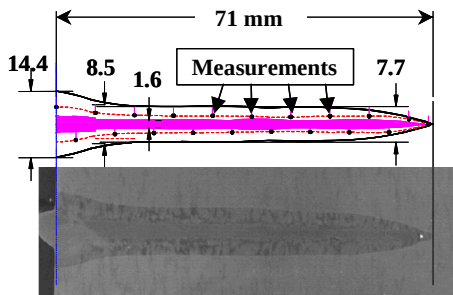


Figure 2 : Welded joint dimensions (mm) and sensors location.

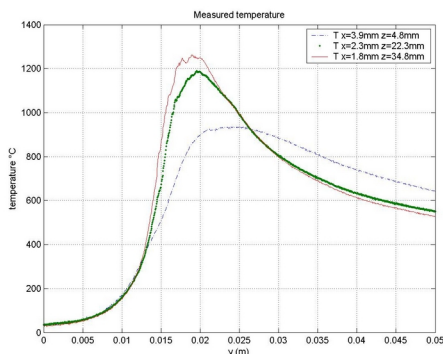


Figure 3 : Temperature measurements in the welded sample at different depth (Red).

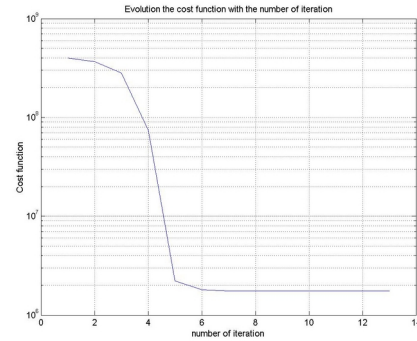


Figure 4 : Cost function evolution for measurement at $x = 2mm$ and $z = 22,3mm$ (red).

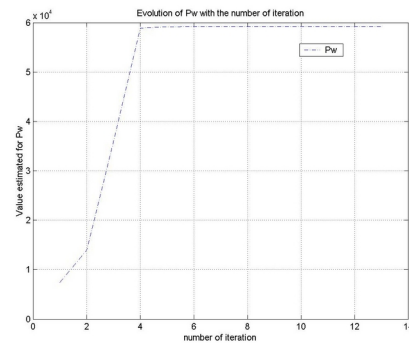


Figure 5 : Estimated power density for measurement at $x = 2mm$ and $z = 22.3mm$ (red).

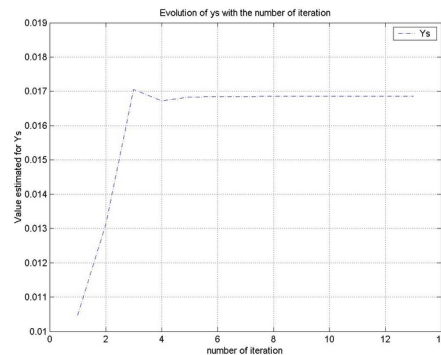


Figure 6 : Estimated position for measurement at $x = 2mm$ and $z = 22.3mm$ (red).

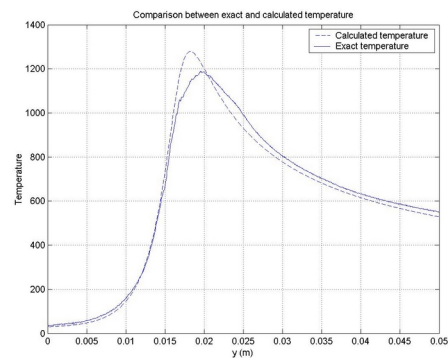


Figure 7: Comparison between experimental and calculated temperature at $x = 2mm$ and $z = 22.3mm$ (red).

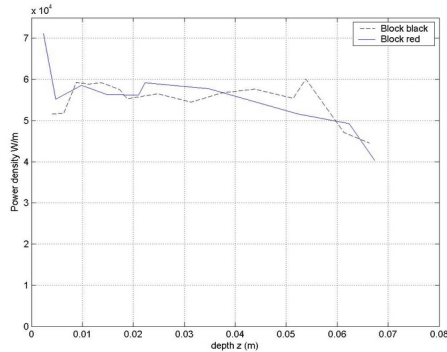


Figure 8 : Estimated power density at different depth.

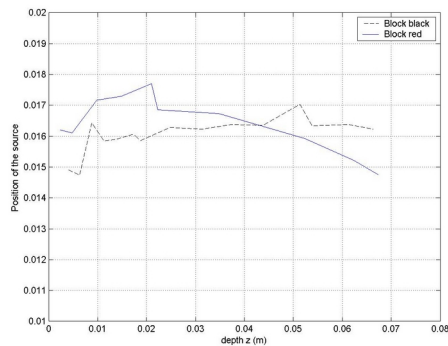


Figure 9 : the estimated source position at different depth of the welded material.

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