Investigation Of Dynamic Positioning Of The Electron Beam On The Chemical Composition Of Weld In Electron Beam Welding

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Abstract

The paper describes the numerical model of the processes of evaporation, condensation and diffusion of alloy components 5056 in electron beam welding with a tandem three electron beam, which allows you to predict the chemical composition of the weld. When building the model, we adopted the following the assumptions: the shape of the keyhole is approximated by a cylinder, the surface of the keyhole is considered to be isothermic, heat and mass transfer of material along the keyhole axis are considered insignificant, the diffusion coefficient in the melt depends on temperature, the depletion of alloying elements in the melt takes place in a thin layer on the surface of the keyhole and due to high pressure in the keyhole, the speed of metal vapour at
the outlet reaches the local sonic speed. Thus, the problem reduces to two dimensions and the computational domain contains only the liquid phase. To solve the problem, we can use a numerical method that takes into account the evaporation, condensation and diffusion of elements in the melt. Investigated macrosections sectional passages using X-ray fluorescence analysis, the results of which coincide with the calculated values.

**Keywords:** electron beam welding, diffusion processes, dynamic positioning electron beam, losses of alloying elements.

**Introduction**

For decades electron beam welding (EBW) is widely used in automobile, aircraft, space, power, shipbuilding industries and other ones. The facilities of the improvement of EBW technologies occurred with the development of modern methods of electron beam controlling [1], in particular, with the use of oscillation and electron beam dynamic positioning. EBW with electron beam oscillation allows to obtain more homogeneous macro-and microstructure of welded joints [2]. Dynamic positioning of electron beam with the formation of several heat sources provides heat input to specimens in some areas apart from each other [3-5], which allows to product high-quality welded joints from dissimilar materials [6], increase the efficiency of EBW and decrease the porosity of a joint [1].

Physical processes occurring during interaction of electron beam with a metal are complex. At EBW deep and narrow steam-gas channel is formed in the area of interaction of a concentrated electron beam with a metal. The liquid is hold on the channel walls by vapor pressure [7-10]. At EBW with the dynamic positioning of electron beam several steam-gas channels are formed (Fig. 1), where an intensive metal evaporation takes place, which may lead to the depletion of some alloying elements in molten metal. Such process can be observed in metal alloys containing alloying elements having low melting points.

![Fig. 1. The calculation scheme. 1-front boundary; 2-lateral boundary; 3-output boundary; 4-an axis of symmetry; 5-keyholes](image-url)
At present significant progress is achieved in simulating of a welded joint formation process at EBW [11-15] and evaporation processes. Two evaporation mechanisms, connected with concentration and pressure gradients [16], are known, and a theory of the evaporation processes at energy beam welding has been developed [17]. When simulating laser welding, which is close to electron beam processes, the temperature in weld penetration channel is generally accepted to be equal to boiling point at atmospheric pressure, but this assumption is inadmissible when simulating electron beam welding because this process is carried out in vacuum.

**Formulation of the problem: defining equation and boundary conditions**

When building the model, we adopted the following the assumptions: the shape of the keyhole is approximated by a cylinder, the surface of the keyhole is considered to be isothermic, heat and mass transfer of material along the keyhole axis are considered insignificant, the diffusion coefficient in the melt depends on temperature, the depletion of alloying elements in the melt takes place in a thin layer on the surface of the keyhole and due to high pressure in the keyhole, the speed of metal vapour at the outlet reaches the local sonic speed. Thus, the problem reduces to two dimensions and the computational domain contains only the liquid phase. To solve the problem, we can use a numerical method that takes into account the evaporation, condensation and diffusion of elements in the melt. The calculation scheme is shown in Fig. 1.

The system of equations describing the processes of evaporation in EBW includes the momentum transport equation (Navier-Stokes):

\[(\vec{U} \cdot \nabla)\vec{U} = -\frac{\nabla P}{\rho} + \nu \nabla^2 \vec{U},\]  

(1)

the energy transport equation:

\[\rho c_p \vec{U} \cdot \nabla T = \nabla (\lambda \nabla T),\]  

(2)

and the impurity transport equation:

\[\vec{U} \cdot \nabla S = D(\nabla^2 S),\]  

(3)

where \(\vec{U}\)-the velocity field of the melt; \(P\)-the pressure in the melt, \(\rho\) is the melt density, Pa; \(\nu\)-the kinematic viscosity coefficient, m\(^2\)/sec; \(c_p\)-the heat capacity at constant pressure J/K; \(\lambda\)-the heat conduction coefficient, V/m·K; \(S\)-the concentration of component \(i\) in the alloy, %; \(T\)-the temperature of the keyhole walls, K; \(\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\)-Laplace operator;

Index \(i\)-hereinafter omitted.

In accordance with [18], the diffusion coefficient adopted depends on the temperature:

\[D = D_0 \exp(-Q/8,31 \cdot T),\]  

(4)

where \(D_0\) the diffusion factor for element \(i\) of the alloy;

\(Q\)-the activation energy of element \(i\) in the alloy (Table 1).

The mass flux density of the \(i\)-th alloying element on the wall of the keyhole is determined by the sum of the flux densities due to evaporation \((J_{ev})\) and condensation \((J_c)\):

\[J = J_{ev} + J_c.\]  

(5)
Table 1. Components of the characteristics of the diffusion coefficient for the alloy components 5056 [18]

<table>
<thead>
<tr>
<th>Components of the diffusion coefficient</th>
<th>Basic alloying elements in the alloy components 5056</th>
</tr>
</thead>
<tbody>
<tr>
<td>D_0, m²/s</td>
<td>Al (liquid/solid)</td>
</tr>
<tr>
<td>0.1·10⁻⁵ / 17·10⁻⁵</td>
<td>9.9·10⁻³ / 1·10⁻⁴</td>
</tr>
<tr>
<td>Q, kJ/mol</td>
<td>128.0 / 143.0</td>
</tr>
</tbody>
</table>

The flux density due to evaporation J_{ev} is directly proportional to the concentration of impurities:

\[ J_{ev} = J_0 \left( \frac{S}{S_0} \right), \]

where \( J_0 \) is the evaporation flux density for the pure i-th element; \( S_0 \) and \( S \) are the initial and actual concentrations of element i in the alloy, the latter is determined by solving equation (3).

In turn, the diffusion flux density for the evaporation of element i is determined according to [14] from the formula:

\[ J_0 = \mu \cdot J_v = \mu \cdot A \cdot \left( \frac{P(T)}{\sqrt{\mu \cdot T}} \right), \]

where \( \mu \) is the mass of element i of the alloy in moles; \( J_v \) is the mole flow of element i of the alloy; \( A \) is a dimension factor; \( P(T) \) is the pressure of element i of the alloy under the melt.

At thermodynamic calculations the content of each chemical element C_i in vapor-gas phase of penetration channel was determined on the basis of the chemical composition of metal sample (Table 2) according to the equation [19, 20].

Table 2. Thermal characteristics of alloy components 5056

<table>
<thead>
<tr>
<th>Data used for the calculation for EBW of alloy components 5056</th>
<th>liquid phase</th>
<th>solid phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density ( \rho, (kg/m^3) )</td>
<td>2490</td>
<td>2640</td>
</tr>
<tr>
<td>Thermal conductivity (W/(m·K))</td>
<td>110</td>
<td>155</td>
</tr>
<tr>
<td>Heat capacity at constant pressure (kJ/(kg·K))</td>
<td>1,050</td>
<td>0,922</td>
</tr>
<tr>
<td>Temperature (K)</td>
<td>911</td>
<td>783</td>
</tr>
<tr>
<td>The initial concentration of elements in the alloy prior to welding, %</td>
<td>Al=93.6</td>
<td>Mg=5.84</td>
</tr>
</tbody>
</table>

The flux density is nonuniform evaporation on the surface of the keyhole and is proportional to the concentration of the element. Assuming complete mixing of the keyhole mixture in the flow keyhole density take on the condensation wall constant. We introduce the condensation coefficient k (0 < k < 1 for saturated steam k=1).

\[ k \cdot \int j_{ev} \, dS = J_c \cdot S_{keyhole}, \]

where \( S_{keyhole} \) it's area keyhole; \( dS \)-elementary surface area of the keyhole.

Then, the flux density of the condensing vapor phase on the keyhole wall \( J_c \), propor-
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\[ J_c = J_0 \cdot k \cdot \langle S \rangle / S \]  \hspace{1cm} (9)

where and \( \langle S \rangle \) is the average concentration of element i of the alloy on the surface of the keyhole.

Thus, the problem reduces to the simultaneous solution of equations (1-3) and ensuring the balance of the total mass flux on the walls of the vapor-gas channel \( \Sigma J \) mass flux carried away through its outlet section (condition (10) in conjunction with (11)):

\[ \sum_{i=1}^{N} (J_{ev} + J_c) \cdot S_{keyhole} = \frac{\partial m}{\partial t}, \]  \hspace{1cm} (10)

where \( S_{keyhole} \) is the cross-sectional area of the keyhole and \( \partial m/\partial t \) is the mass flow of metal vapour entrained by the keyhole outlet section. This mass flow is determined from the condition at the output of the keyhole for the local speed of sound [14]:

\[ \frac{dm}{dt} = \sqrt{\gamma P_k \rho_k \left( \frac{2}{\gamma + 1} \right)^{2\gamma/(\gamma-1)}} \cdot S_{keyhole}, \]  \hspace{1cm} (11)

where \( \gamma \) is the adiabatic index and \( P_k \) and \( \rho_k \) are the vapour pressure and density in the critical section at the exit of the keyhole, respectively [20].

The system of differential equations is written as follows. The boundary conditions at the inlet boundary are constant concentration \( S_i(x=0, L; y)=S_0 \) and temperature \( T(x=0, L; y)=T_b \). At the outflow boundary, the condition for constant heat flux density is:

\[ \frac{\partial^2 T}{\partial x^2} (x = L,y) = 0. \]  \hspace{1cm} (12)

and the mass flow density

\[ \frac{\partial^2 S_i}{\partial x^2} (x = L,y) = 0 \]  \hspace{1cm} (13)

lateral boundary 2 and symmetry axis \( (y=0) \) are adiabatic and closed, they are given zero values of the heat flux

\[ \frac{\partial T(x,y = H)}{\partial y} = 0; \frac{\partial T}{\partial y} = 0 \]  \hspace{1cm} (14)

mass flow and density, respectively,

\[ \frac{\partial S(x,y = H)}{\partial y} = 0; \frac{\partial S}{\partial y} = 0. \]  \hspace{1cm} (15)

The surface of the keyhole (border 5) adopted by the isothermal, with a given mass flux density.

\[ T = T_{m}, \ D \frac{\partial S}{\partial x} = J. \]  \hspace{1cm} (16)

To solve the problem of heat and mass transfer, including the transport equation of momentum, energy, mass, unused package Comsol Multiphysics. One of the input parameters of the model is the wall temperature vapor-gas channel. For each value of the parameter of the solution of the adjoint system of equations describing evaporation, condensation, diffusion, heat and mass transfer, determined by the concentration of alloying elements in the melt, pressure and concentration of chemical elements in pairs, determined by the temperature field, concentration and velocity.

**Results**

The numerical investigation of the evaporation processes for chemical elements on the walls of the keyhole, the condensation processes of the elements on the keyhole
walls and the diffusion of the elements in the melt was carried out with $H=1.5 \cdot 10^{-3}$ m, $L=3 \cdot 10^{-3}$ m, $r=2.5 \cdot 10^{-4}$ m and $l=1.6 \cdot 10^{-3}$ m. The data used are shown in Table 2. For the calculation of the task used mesh refinement in all the estimated volume of the body.

Fig. 2 shows the results of calculations of concentration of chemical elements in the liquid and the solidified keyhole portion along the weld.

**Fig. 2.** Calculated values of changes in the concentration of Mg along the seam weld

The length of the computational domain (the axis OX), m

The graph in Fig.2 can be divided into four areas along the x-axis. The first area being from -0.02 to 0 m is the base metal. The second area being from 0 to 0.004 m is responsible for the vaporization processes. The liquid weld pool exists in the third area being from 0.004 to 0.01 m. And the solid welded joint is in the fourth area. In the second area, where the keyhole exist, the concentration of magnesium decreases from 0.058 to 0.048 relative units (rel. un.), this is caused by an intensive evaporation process. Then in the weld pool the concentration of magnesium increases due to the diffusion processes in the liquid, but magnesium concentration planes in the solid phase and becomes equal to 0.052 rel. un.

The aim of the experimental procedure was to determine the temperature in the keyhole during EBW according to the chemical composition of the vapour formed over the welding zone. For the guarantee of high speed of electron beam deviation at the dynamic positioning the deflectors of an electron gun were connected to the broadband current amplifier having the top limit of the pass band being equal to 200 kHz. The signals were input through the digital-to-analogue interface from the computer system to the ports of these amplifiers, the system being functioned under the developed program which provided given space-time characteristics of the heat interaction on the specimens.

The weld parameters (welding speed, energy distribution in the beam, the distance
between dynamically positioned beams) have been varied in accordance to the matrix of the planning an experiment.

The resulting coating was analysed using roentgen fluorescence, performed on mode of 6 (Table. 3). The data obtained are presented in Table 4 and Fig. 3.

**Table 3: Parameters modes EBW**

<table>
<thead>
<tr>
<th>Number Weld</th>
<th>Welding current, mA</th>
<th>The distance between the beams, mm</th>
<th>Welding speed, mm / sec</th>
<th>The energy distribution (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>40</td>
<td>4 мм</td>
<td>5</td>
<td>1:2:1 (40:80:40)</td>
</tr>
</tbody>
</table>

**Table 4: The data obtained**

<table>
<thead>
<tr>
<th>№</th>
<th>Al, rel. un.</th>
<th>Mg, rel.un.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.948</td>
<td>0.0440</td>
</tr>
<tr>
<td>2</td>
<td>0.935</td>
<td>0.0515</td>
</tr>
<tr>
<td>3</td>
<td>0.934</td>
<td>0.0572</td>
</tr>
<tr>
<td>4</td>
<td>0.933</td>
<td>0.0584</td>
</tr>
</tbody>
</table>

The average value of the concentration

0.937

The concentrations of the reference data

0.911-0.936 0.058-0.068

**Fig. 3.** The welded joint obtained by EBW dynamic splitting of the electron beam; 1-4-zone determination of chemical composition

Roentgen fluorescent analysis of the cross-section of the penetration area obtained during the operation 6 shows the significant depletion of the volatile component of the alloy (Mg) to 0.044 rel. un. in the top part of the joint. Magnesium concentration increases to the root part of the joint and reaches the acceptable values being 0.058-0.068 rel. un. Consequently mean value of magnesium concentration in the welded joint is 0.0528 rel. un., which is in accordance with the mean value of magnesium concentration obtained at the process simulation (0.052 rel. un.). The developed simulator describes heat-and-mass transfer during EBW with the dy-
namic positioning of electron beam and allows to predict the chemical composition of welded joints at EBW. Verification of the simulator has been carried out by the comparing with the results of the chemical analysis of the welded metal penetration areas.

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References:


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