# Simulation Evaporation Processes in Electron Beam Welding

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*In this paper the method of experimental estimation of the temperature in a keyhole in electron beam welding is described on the basis of chemical elements concentration in the vapors above welding zone. The temperature of a vapor-gas phase in the keyhole is determined when equating calculated and experimental concentrations of the elements. Thermodynamic calculations are based on diffusion processes in the melt around the keyhole wall.*

***Моделиране на процесите на изпарение при електроннолъчево заваряване (Д. Н. Трушников, Е. С. Саломатова, А. И. Цаплин, В. Я. Беленкий).*** *В тази статия е описан метод за експериментална оценка на температурата в канала на проникване на снопа при електроннолъчево заваряване, основан на измерване на концентрацията на химическите елементи в парите над зоната на заваряване. Температурата на парната фаза на газа в канала на проникване се определя при равенство на изчислените и експерименталните концентрации на елементите. Термодинамичните изчисления се основават на дифузионни процеси, протичащи в течния метал около стените на канала на проникване.*

## Introduction

Electron-beam bonding plays a special role among welding methods due to its high power concentration in electron welding beam and because of its capability to penetrate deep in the metal. These characteristics cause wide application of electron-beam welding in the production of critical parts from different alloys.

At electron-beam welding vapour and gas keyhole is formed, where an intensive evaporation of the material occurs. This may lead to the depletion with some elements in the melt metal comparing with the base metal. One can observe such process for metal alloys containing low-melting impurities. In turn, the pressure of the vapour leaving the melting zone at evaporation deflects the surface of a molten pool and the deep and narrow keyhole is formed, which liquid walls are hold by vapour pressure [1-3]. Therefore evaporation processes in electron-beam welding are interesting for the development of theoretical models of a weld joint formation process [4-5].

Evaporation processes are considered in the works [6], but the diffusion of impurities in the melt bulk is the base limiting process for the determination of the alloying components loss at electron-beam welding. The diffusion processes will occur in a thin layer near the keyhole. The problem becomes nonlinear in the case of the strong (exponential) correlation between the diffusion coefficient and the temperature of the melt.

The purpose of the work is the construction of a theoretical model describing the chemical composition of a weld joint being in a liquid state at electron-beam welding. Such processes like the evaporation of the chemical elements from keyhole walls, condensation of elements of the alloy on the keyhole walls and the diffusion of the elements in the melt will have a great influence on the chemical composition of a weld joint.

## Used data

A number of simplifications are introduced to construct the model. Firstly, the shape of a keyhole is approximated to a cylinder. The surface of the keyhole is considered to be isothermic at a given temperature being equal the temperature of the environment. Secondly, heat and mass transfer along the keyhole axis are neglected. Thus the problem comes to tow-dimensional formulation. Thirdly, the diffusion coefficient is used in the dependence of the melt temperature. Fourthly, whole medium is considered to be liquid because the depletion with alloying elements in the melt occurs in a thin layer near the keyhole surface. Fifthly, the pressure in the keyhole is different from the pressure under the

keyhole by several orders of magnitude, and metal vapour reaches sonic speed c in the outlet of the keyhole.

Thus the numerical method is used for the solution of the problem. This allows to solve quasistationary problem of evaporation, condensation and diffusion of the elements in the melt more accurately. Calculated geometry of the problem is represented in the Figure 1.

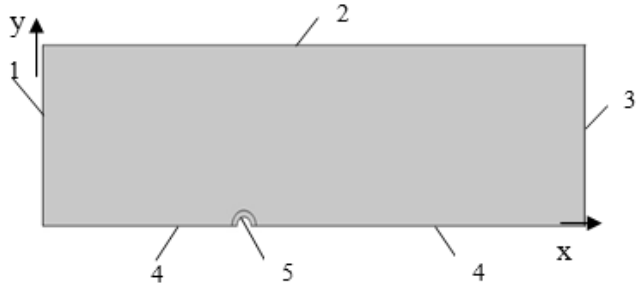


*Fig. 1. Calculated geometry of the problem*

To solve energy transfer equation (convective diffusion) it is necessary to know the velocity field in a molten pool. Hydrodynamic movement of a melt is described by Navier-Stokes equation:

$$\left(\vec{U}\cdot\nabla\right)\vec{U} = -\frac{\nabla P}{\rho} + \nu\Delta\vec{U} \quad (1)$$

where $\vec{U}$ is a velocity field of the melt; $P$ is a pressure in the melt; $\rho$ is a melt density; $\nu$ is kinematic viscosity coefficient.

The solution of a heat problem comes to nonstationary energy transfer equation:

$$\rho C_p \vec{U}\cdot\nabla T = \nabla\cdot\lambda\nabla^2 C_i \quad (2)$$

where $\rho$ is a melt density; $\vec{U}$ is a liquid velocity; $C_p$ is a heat capacity at constant pressure; $\lambda$ is heat conduction coefficient; $C_i$ is the concentration of an i-component in the alloy.

Convective diffusion equation for each element of the alloy has the following expression:

$$\vec{U}\cdot\nabla C_i = D_i\cdot\nabla^2 C, \qquad \nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \quad (3)$$

where $\vec{U}$ is a liquid velocity vector in the point (x, y); $C_i$ is the concentration of an i-component in the alloy; $D_i$ is the diffusion coefficient of an i-element of the alloy, being determined in terms of the equation (4).

$$D_i = D0_i\cdot\exp\left(\frac{Q_i}{8{,}13\cdot T}\right) \quad (4)$$

where $D0_i$ is the diffusion factor of an i-element of the alloy (Table 1); $Q_i$ is the activation energy of an i-component in the alloy (Table 1).

**Table 1.**

*Component characteristic of the diffusion coefficient [7]*

| Component characteristic of the diffusion coefficient | Basic alloying elements in the steel X12CrNiTi 18-10 | |
|---|---|---|
| | Cr | Mn |
| $D0_i\left[\frac{m^2}{c}\right]$ | $1{,}318\cdot10^{-7}$ | $2{,}515\cdot10^{-7}$ |
| $Q_i\left[\frac{kJ}{kg}\right]$ | 3,92 | 3,99 |

The solution of the problem of element condensation is carried out with the use of flow density of the alloying elements on the keyhole wall, which is determined by sum of flow densities caused by evaporation ($Jev_i$) and condensation ($Jc_i$):

$$J_i = Jev_i + Jc_i \quad (5)$$

Flow density of condensation $Jev_i$ is directly proportional to impurity concentration and flow density of evaporation under an i-element $J0_i$:

$$Jev_i = J0_i\cdot\frac{C_i}{C0_i} \quad (6)$$

where $J0_i$ is the diffusion flow density of an i-element evaporation; $C0_i$, $C_i$ is the initial and current concentrations of an i-element in the alloy, respectively.

Current concentration of an i-element of the alloy on the keyhole wall is determined taking into account chemical composition of the sample with the use of the method described in the works [8].

In turn, the diffusion flow density of an i-element evaporation was determined on the basis of the works [9] according to equation:

$$J0_i = \mu_i\cdot Jv_i = \mu_i\cdot A\cdot\frac{P_i(T)}{\sqrt{\mu_i\cdot T}} \quad (7)$$

where $\mu_i$ is the mass of an i-element of the alloy taken in moles; $Jv_i$ is the mole flow of an i-element of the alloy; A is a dimension factor; $P_i(T)$ is the pressure of an i-element of the alloy under the melt, being determined with the use of the method described in the works [9]; T is the temperature on the keyhole walls.

Flow density $J_{ci}$, being condensed from the vapour on the keyhole walls, is proportional to the average concentration of the elements in the vapour:

$$J_{ci} = \kappa \cdot f\frac{(C_i)}{C0_i} \quad (8)$$

where $\kappa$ is the coefficient illustrating the part of the condensed vapour in respect to the evaporated one (for the saturated vapour $\kappa$ is equal 1); $f(C_i)$ is a calculation function of the average concentration of an i-element of the alloy on the keyhole surface.

The coefficient $\kappa$ is determined by the method of the successive approximation on the basis of the equation of evaporated element mass:

$$(Je\gamma - Jc_i)\cdot S_{channel} = \frac{\partial m_i}{\partial t} \quad (9)$$

where $S_{channel}$ is a keyhole surface; $\frac{\partial m_i}{\partial t}$ is the mass flow of an i-element of the alloy.

The mass flow is determined in terms of the fifth assumption and it is expressed the following way:

$$\frac{\partial m}{\partial t} = \rho \cdot c \cdot \pi \cdot r_k^2 \quad (10)$$

where $r_k$ is radius of a keyhole.

Specify the following boundary conditions:

On the boundaries 1 and 3 (Fig. 1) the boundary conditions of the first type are $C_i = C_{0i}$ and $T = T_0$, where $T_0$ is the temperature of medium.

$$q = const \qquad -\lambda\frac{\partial T}{\partial n} = q \qquad \frac{\partial q}{\partial n} = 0 \quad (11)$$

.

Also the condition of continuability ( $q = const$ ) is kept on these boundaries:

$$\frac{\partial^2 T}{\partial n^2} = 0 \quad (12)$$

2. The boundary 2 is adiabatic:

$$\frac{\partial T}{\partial n} = 0 \quad (13)$$

3. The solutions being symmetric on x-axis, mass and heat energy flows on the boundary 4 are defined like zero:

$$\frac{\partial T}{\partial n} = 0 \quad \text{и} \quad \frac{\partial C_i}{\partial n} = 0 \quad (14)$$

4. Constant temperature is defined on the keyhole surface which corresponds with the boundary 5:

$$T = T0 \quad (15)$$

where T0 is the temperature on the keyhole surface.

And the constant mass flow density is expressed:

$$D_i\frac{\partial C_i}{\partial n} = J_i \quad (16)$$

**Solution algorithm**

Take an initial value $\kappa$ in the equation (8) being equal 0.9 (the coefficient $\kappa$ is 0.9 at vapour condensation being equal 90%). Carry out the calculation of the coupled problem of heat and mass transfer, which the solutions of hydrodynamic equation and energy transfer and conductivity equations for some defined temperatures on the keyhole walls are included in. On the basis of the solution of the coupled problem one determines the concentrations of alloying elements and pressures against the temperature. The cross point of the curves of the experimental and calculated concentration determines the temperature (T1) on the keyhole l walls. Also the cross point of the curves of the initial and calculated mass flow determines the temperature (T2). The process continues till reaching the required accuracy, i.e. till the approaching of T1 and T2.

**Results**

The numerical investigation of the evaporation process of chemical elements from the walls of the keyhole, condensation processes of the elements on the keyhole walls and the diffusion of the elements in the melt was carried out with the use of data represented in the Tables 2, 3.

Two curves are represented in the Figure 2, 3, including vapour pressure in the keyhole without regard for the diffusion and taking into account the diffusion processes in the melt. Vapour pressure in the keyhole including the diffusion processes is lower than vapour pressure in the keyhole without diffusion.

**Table 2.**

*Data used for the calculations in welding of X12CrNiTi 18-10*

| Property/ Parameter | Value |
|---|---|
| Density (kg/m$^3$) | 7810 |
| Thermal conductivity (W/(m·K)) | 30.6 |
| Heat capacity at constant pressure (J/(kg·K)) | 830 |
| Dynamic viscosity (Pa·s) | $10^{-3}$ |
| Condensation coefficient | 0.9 |
| Ratio of specific heat | 1.4 |
| Medium temperature ($T_0$, K) | 200 |
| Surface temperature of the keyhole (T0, K) | 1400 |

**Table 3.**

*Parameters of alloying elements*

| Enthalpies of evaporation of alloying elements [a] | | |
|---|---|---|
| Element | Enthalpy (kJ/kg) | |
| Iron | 19.60 | |
| Manganese | 12.07 | |
| Chromium | 18.14 | |
| Experimental concentration of elements in vapour | | |
| Element | Concentration (%) | atomic mass (g/mole) |
| Iron | 0.676 | 55.85 |
| Manganese | 0.02 | 54.94 |
| Chromium | 0.19 | 51.99 |

(a) Ref.10

Then the results of thermodynamic calculation, made with the use of the [10] were compared with the results of chemical analysis of the deposited coating to estimate the temperature of a vapor-gas phase in keyhole. Calculation results for the chemical composition of vapor-gas phase within the electron beam welding zone are represented in Figure 4 (only for iron, chrome and manganese, because the content of the other elements can be neglected), and the concentrations of chemical elements obtained with the use of roentgen fluorescent analysis at experimental research (horizontal lines) are also shown in the figure.

The temperature of a vapor-gas phase in the penetration channel is determined when equating calculated and experimental concentrations of the elements, and it was 2220 K (for Fe), 2250 K (for Cr) and 2300 K (for Mn). As it is clear from the data obtained the difference between the temperatures is insignificant (about 5 %) and it can be caused by indirect character of the applied method which accuracy is still difficult to estimate.

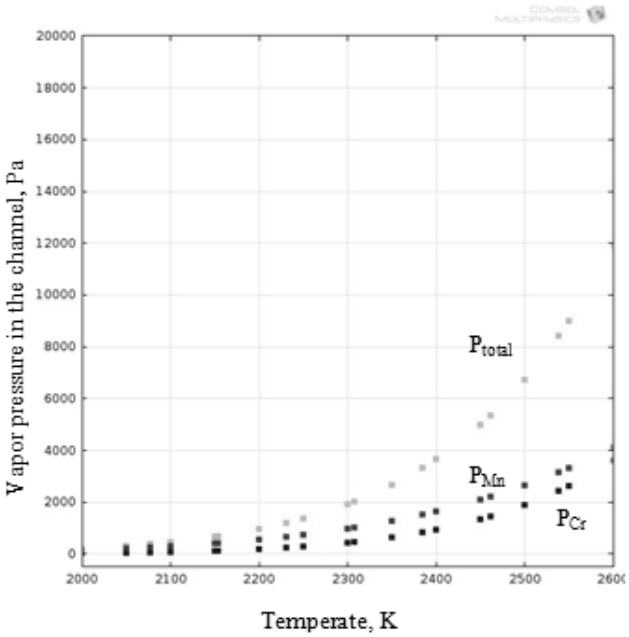


*Fig. 2. Correlation between vapor pressure in the keyhole and the temperature for X12CrNiTi 18-10, where $P_{Cr}$ is chrome vapor pressure; $P_{Mn}$ is manganese vapor pressure; $P_{total}$ – total vapor pressure.*

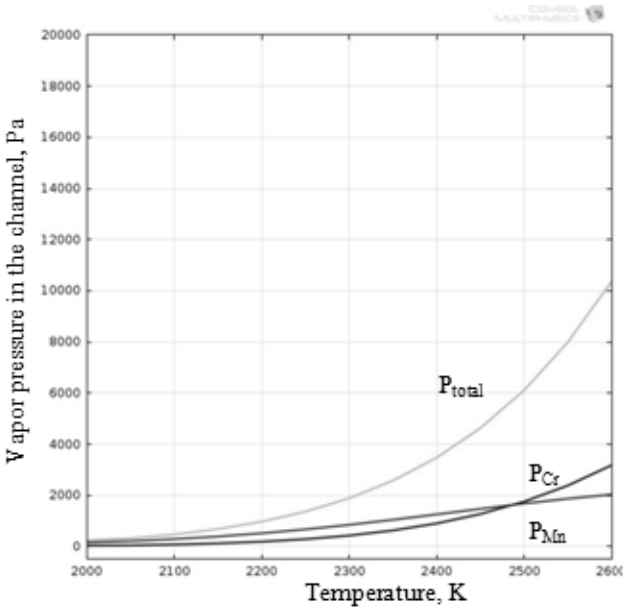


*Fig. 3. Vapour pressure in the keyhole including the diffusion processes and the temperature for X12CrNiTi 18-10, where $P_{Cr}$ is chrome vapor pressure; $P_{Mn}$ is manganese vapor pressure; $P_{total}$ – total vapor pressure*

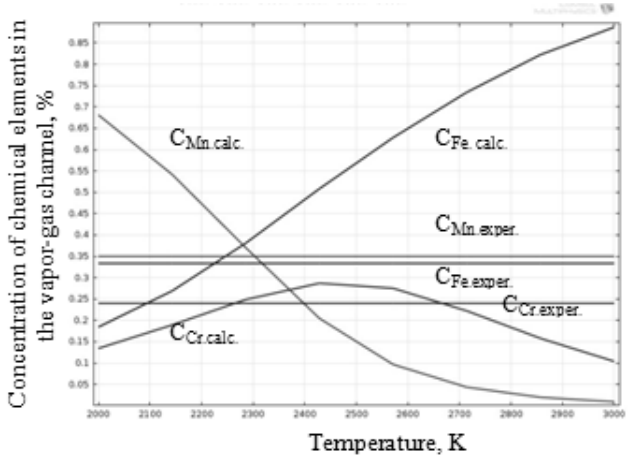


*Fig.4. Correlation between iron, manganese and chrome concentrations in the channel for the X12CrNiTi 18-10 and the temperature*

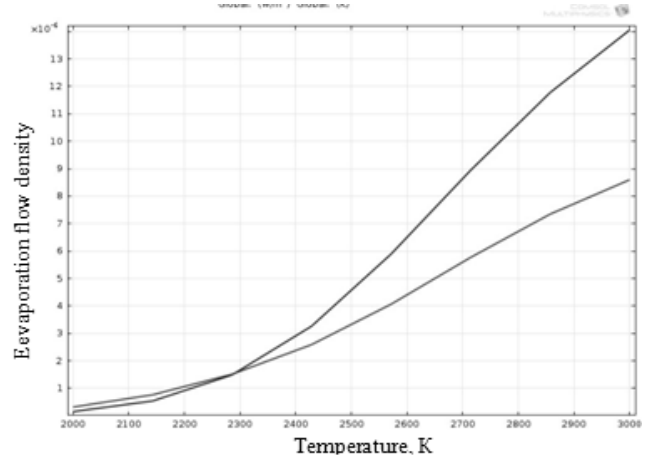


*Fig.5. Eevaporated element mass (Mn) in the channel for the X12CrNiTi 18-10 and the temperature*

The cross point of the curves of the initial and calculated mass flow determines the temperature 2290 K (Fig.5).

**Conclusions**

1. The method of experimental estimation of the pressure and temperature in the keyhole is given. The method is based on experimental determination of the element concentration in vapour and the numerical solution of thermal conductivity, hydrodynamic and diffusion problem.

2. The experimental results together with the results of numerical simulation show that the temperatures obtained with an allowance for the diffusion processes have a low influence in the comparison with the temperatures obtained without regard for the diffusion.

3. It was stated that vapour in the keyhole was almost saturated. The mass flow removed from the outlet channel section was about 10% taken from total flow evaporated from the walls of the penetration channel.

4. In further work it is necessary to specify the interpretation of pressures and temperatures obtained and if these values refer to the top area of the keyhole near outlet section or they are effective characteristics of the whole channel. In further work it is projected to spread the described model to three-dimensional statement in order to take into account the convective transfer in vertical direction, which is caused by the convective and thermocapillary phenomena.

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