Abstract

The mathematical model of capillary thermal-concentration convection is proposed; on its basis, a numerical simulation of the process of metal surface alloying with the aid of pulse laser radiation was done. The influence of the pulse intensity on melt hydrodynamics and distribution of the alloying substance was evaluated. In the published works on this theme results of researches are not full enough and the extremely limited. For the substrate material, the data of titanium and iron were used, including the dependence of the surface tension on the melt temperature and admixture concentration.

Keywords: metal alloying; pulse laser radiation; convective heat- and mass-transfer; numerical simulation

1. Introduction

The history of the study of the influence imposed by the surface tension gradient on the convection character at metals melting by laser radiation extends over several decades [1-10]. However, many fundamental aspects still remain unexplained. Among them are the mechanisms of capillary thermal-concentration convection manifestation and resulting instability of microflows at laser alloying [2,3]. The laser alloying is widely applied for the modification of units surface and improvement of their operation properties such as hardness, thermal and wear resistance, antifrictionality, corrosion resistance, etc. Alloying elements are either preliminary applied on the material surface (as a coating or powder layer) and then penetrate into it during the fusion, or are injected into the melt by a gas flow. The processes in the surface layer of metals initiated by the laser radiation have been studied for quite a long time [2-10]. The thermal-capillary convection so called “Marangoni convection” is commonly known to be one of the governing factors dictating the laser alloying quality. At the same time, some investigations prove the influence of admixtures in the melt on the surface tension temperature gradient; in turn, the character of thermal hydrodynamic flows, admixture distribution in the resulting liquid casting pipe, this pipe shape, and surface layer structure after cooling highly depend on this gradient.

In this work, we study theoretically the processes of alloying material penetration into a metal substrate from the substrate surface under the pulse laser action. Under consideration is the axisymmetrical non-stationary process
which includes the metal heating-up, melting, heat- and mass transfer in the melt, and melt cooling and solidification after the pulse ending. The proposed mathematical model of the capillary thermal and concentration convection is based on Navier-Stokes equations at the Boussinesq approximation. The results of numerical simulation of the alloying component with the substrate material are presented. We evaluated the influence of the surface tension factor dependence on the temperature and admixture concentration on the hydrodynamics of the melt pool and alloying substance distribution. The substrates of iron-carbon (Fe+0.42%C) and titanium (Ti) alloy were used as the study object. The Gaussian and plane spatial distribution of energy flow was used.

2. Mathematical model

Under consideration is the physical task of the action of a laser beam with the radius \( R_0 \) on the substrate surface. The pulse duration is of \( t_H \), and the density of its intensity is described by the Gaussian distribution. Under the action of the laser energy, the metal heat and melts. In the formed molten pool which eventually increases, the thermal-capillary convection develops. For the melt, the non-slip conditions of the solid crystallization front are used. It is expected that the studied heating modes result in the moderate convective speeds, which makes for the flat shape of the free liquid surface. At the initial instant, the substrate surface is covered with some layer of doping material, which contacts with the melt and, due to the forming flows, penetrates into the molten pool. Upon the pulse ending, the molten pool cools down and solidifies.

Let us write the mathematical formulation of the considered task in dimensionless quantities. The temperature field distribution over the substrate in the cylindrical system of coordinates with the axial symmetry is described by the equation:

\[
\frac{c_e f}{\frac{\partial \theta}{\partial t}} + \frac{1}{r} \frac{\partial u \theta}{\partial r} + \frac{\partial w \theta}{\partial z} = \frac{1}{\text{Pr}} \left( \frac{1}{r} \frac{\partial r}{\partial r} + \frac{\partial^2 \theta}{\partial z^2} \right), \quad 0 \leq r \leq r_g, -z_g \leq z \leq 0. \tag{1}
\]

Here, \( r_g, z_g \) are the boundaries of the considered domain; \( u, w \) – the components of the velocity vector in the radial (\( r \)) and vertical (\( z \)) directions, respectively (in the solid metal \( u \equiv 0, w \equiv 0 \)); \( \theta \) is the temperature (\( \theta = T / T_s \)); \( \text{Pr} = v / a \) – Prandtl number, where \( v \) is the kinematic viscosity, \( a \) is temperature conductivity. The dimensionless parameters are defined with the aid of a characteristic size \( R_0 \), time \( t_0 = R_0 / v_0 \), velocity \( v_0 = v / v_0 \), \( T_s \) – temperature of liquid solidification. The effective heat capacity is described by the relation \( c_{ef} = 1 + \delta(\theta) \kappa / (T_s c_p) \), where \( \delta(\theta) = 1 \) at \( \theta \in [1 - \Delta \theta / 2, 1 + \Delta \theta / 2] \) and \( \delta(\theta) = 0 \), if \( \theta \not\in [1 - \Delta \theta / 2, 1 + \Delta \theta / 2] \), \( \Delta \theta \) is the temperature gap, within the phase boundary is “smeared”. \( \kappa \) is the hidden heat of the phase transition, \( c_p \) – the specific heat capacity.

The boundary conditions for the equation (1) are the following.

On the symmetry axis:

\[
\frac{\partial \theta}{\partial r} = 0, \quad r = 0, -z_g \leq z \leq 0. \tag{2}
\]

On the external side boundary of the calculation domain:

\[
\frac{\partial \theta}{\partial r} = 0, \quad r = r_g, -z_g \leq z \leq 0. \tag{3}
\]
On the top boundary of the calculation domain \((z = 0)\). Being heated by the heat source \(t \leq t_H\):

\[
\frac{\partial \theta}{\partial z} = \bar{q}(r), \quad 0 \leq r \leq 1; \quad \frac{\partial \theta}{\partial z} = \bar{\alpha}(\theta_c - 0), \quad 1 \leq r \leq r_g. \tag{4a}
\]

At the off heat source \((t > t_H)\):

\[
\frac{\partial \theta}{\partial z} = \bar{\alpha}(\theta_c - 0), \quad 0 \leq r \leq r_g. \tag{4b}
\]

On the bottom boundary of the calculation domain:

\[
\frac{\partial \theta}{\partial z} = 0, \quad 0 \leq r \leq r_g, \quad z = -z_g. \tag{5}
\]

Here \(\bar{\alpha} = \alpha r_0 / \lambda\), \(\bar{q}(r) = q_0 \exp\{-2r^2\}/\lambda T_s\), \(\alpha = \varepsilon \sigma_0 (T_s^2 + T_c^2)(T_s + T_c)\), \(\bar{q}(r)\) is the power density of the heat source, \(\sigma_0\) – the Stephen-Boltzmann constant, \(\varepsilon\) – the emissivity factor, \(\lambda\) is the heat conductivity, \(T_c\) is the ambient temperature.

As the metal melts in the area \(0 > 1\) with the «melt- solid phase» boundary \(f(r,z,t)\), the flow in the liquid is described by the Navier-Stokes and Boussinesq equations:

\[
\frac{\partial u}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} \left( ru^2 \right) + \frac{\partial}{\partial z} \left( uw \right) = -\frac{\partial p}{\partial r} + \frac{1}{r} \frac{\partial}{\partial r} \left( ru \frac{\partial u}{\partial r} \right) + \frac{\partial^2 u}{\partial z^2} - \frac{u}{r^2},
\]

\[
\frac{\partial w}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} \left( rw^2 \right) + \frac{\partial}{\partial z} \left( wv \right) = -\frac{\partial p}{\partial r} + \frac{1}{r} \frac{\partial}{\partial r} \left( rw \frac{\partial w}{\partial r} \right) + \frac{\partial^2 w}{\partial z^2} + \text{Gr}(\theta - 1), \tag{6}
\]

\[
\frac{1}{r} \frac{\partial}{\partial r} \left( ru \right) + \frac{\partial}{\partial z} \left( w \right) = 0.
\]

Here \(p\) is the pressure \((p_0 = \rho v_0^2)\), \(\text{Gr} = \beta_p g r_0^3 T_s / \nu^2\) is the Grashof number, \(g\) is the free-fall acceleration, \(\beta_p\) is the coefficient of cubic expansion, \(\rho\) – the melt density.

The boundary conditions for the equations (6) are the following.

On the «melt – solid phase» surface \(f(r,z,t)\):

\[
u |_f = 0, \quad w |_f = 0. \tag{7}
\]
On the symmetry axis $r=0$, $-z_f \leq z \leq 0$ ($z_f(t)$ are the coordinates of the phase transition at $r=0$):

$$u = 0, \quad \frac{\partial w}{\partial r} = 0. \quad (8)$$

On the liquid surface $z = 0$, $0 \leq r < r_f$:

$$\frac{\partial u}{\partial z} = \frac{Mn}{Pr} \frac{\partial \theta}{\partial r}, \quad w = 0, \quad (9)$$

where $r_f = r_f(t)$ is the radius of the free surface of the melted metal pool, $Mn = \frac{\left(\frac{\partial \sigma}{\partial T}\right)T_z r_0}{\rho v a}$ is the Marangoni number, $\sigma$ – the surface tension.

The condition (9) is defined from the relation:

$$\mu \frac{\partial u}{\partial z} = \frac{\partial \sigma}{\partial T} \frac{\partial T}{\partial r} + \sum_i \frac{\partial \sigma}{\partial C_i} \frac{\partial C_i}{\partial r},$$

where $\mu$ is the dynamic viscosity ($v = \mu/\rho$), $C_i$ is the $i$-element of the mixture in the melt. According to the physical properties of most melts

$$\left| \frac{\partial \sigma}{\partial T} \frac{\partial T}{\partial r} \right| \gg \left| \sum_i \frac{\partial \sigma}{\partial C_i} \frac{\partial C_i}{\partial r} \right|,$$

and hence the variation of the surface tension value regarding the admixture concentration is usually neglected. However, in [7] the authors describe the dependence of the value $\frac{\partial \sigma}{\partial T}$ in the melt regarding the varying value of admixture. Let us present the expression which describes the surface tension as

$$\sigma = \sigma_0 - k_{\sigma}(T - T_s) - TR\Gamma_s \ln(1 + K_{seg} C), \quad K_{seg} = S_I \exp\{-\Delta H^0/(RT)\},$$

where $\sigma_0$ is the surface tension in the pure metal in the melting point ($J/m^2$), $k_{\sigma} = -\frac{\partial \sigma_0}{\partial T}$ - for the pure metal ($J/(m^2 \cdot K)$), $R$ is the universal gas constant ($J/(mole \cdot K)$), $C$ is the admixture concentration on the melt surface (% of the mass), $S_I$ – the constant corresponding to the segregation entropy, $\Delta H^0$ is the standard variation of the enthalpy at the reaction ($J/mole$), $\Gamma_s$ is the excessive admixture in the surface layer per a surface unit ($mole/m^2$).
Then
\[
\frac{\partial \sigma}{\partial T} = -k_\sigma - R \Gamma_\sigma \ln(1 + K_{\text{seg}} C) - \frac{K_{\text{seg}} C}{1 + K_{\text{seg}} C} \frac{\Gamma_s \Delta H^0}{T}.
\] (10)

Taking into account the value $\Delta H^0 < 0$, it follows from (10) that $\partial \sigma / \partial T$ can take the values not only below, but also above 0 regarding the values $T$ and $C$.

The distribution of the concentration $C$ of the admixture substance which is involved by the flowing melt from its free surface, is described by the equation of convective diffusion.

\[
\frac{\partial C}{\partial t} + \frac{1}{r} \frac{\partial ruC}{\partial r} + \frac{\partial wC}{\partial z} = \frac{1}{Sc} \left( \frac{1}{r} \frac{\partial C}{\partial r} \frac{\partial C}{\partial r} + \frac{\partial^2 C}{\partial z^2} \right),
\] (11)

where $Sc = \nu / D$ is the Schmidt number, $D$ is the diffusion coefficient.

The boundary conditions for (11)

\[
\frac{1}{Sc} \frac{\partial C}{\partial n} = 0 \quad \text{on the “melt – solid phase” surface } f(r,z,t),
\]
\[
\frac{1}{Sc} \frac{\partial C}{\partial r} = 0 \quad \text{at } r = 0, \quad -z_f \leq z \leq 0,
\]
\[
\frac{1}{Sc} \frac{\partial C}{\partial z} = Bi_D (C_{ls} - C) \quad \text{on the melt mirror } z = 0, \ 0 \leq r < r_f,
\]

here $Bi_D$ reflects the velocity of interaction between the admixture substance and the melt, $C_{ls}$ is the amount of the admixture substance on the substrate surface.

Note that the results of the diffusion task must be a qualitative model, since we do not consider the mechanism of the interaction of the melt and admixture material particles which are located on the surface. For this reason we assume that $C_{ls} = 1$.

The initial conditions: $\theta = \theta_0$. In the just-melted metal, $u = w = 0, \ C = 0$.

3. The task solution algorithm

To realize the model (1)–(10) which includes the Navier-Stokes and convective heat- and mass-transfer equations, the finite-difference algorithm was applied. The spatial mesh was used for the equation approximation in the calculation domain:

\[
r_i = \Delta x \cdot i, \quad i = 0, \ldots, I, \quad z_k = \Delta z \cdot k, \quad k = 0, \ldots, K, \quad \Delta r = r_g / I, \quad \Delta z = z_g / K.
\]
This mesh breaks the calculation domain in $I \times K$ of cells. Along the time variable, the uniform mesh is used $t = n \cdot \tau$, $n = 0, 1, 2, \ldots$ with the pitch of $\tau$. The differential equations were constructed by means of the approximation of the balance relations obtained by the integration of the equations (1), (6), (10) with the corresponding boundary conditions.

Note that under consideration is such a mode of liquid convection, when the flow is laminar and the boundary layer is absent. At the approximation (6), in the melted metal area, similar to the methods like MAC and SIMPLE [11, 12], the components of the velocities $u, w$ were determined in the middles of the side edges of the cells, and the pressure $p$ was calculated in the cells centers. The temperature distribution and concentrations of the diluted substance in the calculation domain are described by their values in the mesh nodes.

The calculation procedure is as follows. Initially, the substrate heat-up under the laser beam energy is calculated. Upon the molten pool occurrence, the temperature field is to be calculated at each time pitch. Substituting the calculated values of temperature in the momentum equations enables to determine the velocity field components. Then, using the method of artificial compressibility [13], the pressure is calculated. We perform several iterations to match the pressure and velocity distributions. The condition of calculation ceasing is the satisfaction of the inequation $\max |\nabla \cdot \mathbf{u}| \leq \Delta$, where $\Delta$ is the assigned small number. Finally, the distribution of the alloying admixture in the melt is calculated.

The solution of the algebraic systems obtained at the implicit approximation of the momentum and heat- and mass-transfer equations, is done by the iteration method of unitized successive overrelaxation [14].

Upon the end of the laser pulse, the calculations are continued up to the full solidification of the substrate material.

4. Numerical experiments results

The numerical investigation of the process was carried out at the following parameters: geometrical sizes $r_0=0.001$ m, $z_g=0.0006$ m, $r_g=0.0015$ m; $I_\mu=0.0037$ sec; $T_c=300$ K; $T_0=300$ K; $\Delta T=10$ K; $Q_0=4.5 \times 10^8$ W/m$^2$.

Thermophysical properties of the alloy: $\rho=7065$ kg/m$^3$, $c_p=787$ J/(kg·K), $\lambda=27$ W/(m·K), $\kappa=2.77 \times 10^7$ J/kg, $T_s=1775$ K, $v=8.5 \times 10^{-7}$ m$^2$/s, $k_\sigma=4.3 \times 10^{-4}$ N/(m·K), $\beta_\rho=1.18 \times 10^{-4}$ 1/K, $D=2.5 \times 10^{-9}$ m$^2$/s, $\varepsilon=0.5$, $\Gamma_s=1.3 \times 10^{-8}$ mole/m$^2$, $\Delta H^0=-1.88 \times 10^8$ J/mole, $R=8314.3$ J/(mole·K), $S_f=3.18 \times 10^{-3}$ [1]. In addition in Table 1 are presented the physical parameters of titanium, iron and graphite.

The dimensionless parameters used in the calculations are: $Pr=0.175$, $Gr=2.848 \times 10^3$, $Mn_0=2.62 \times 10^4$ (for the pure iron), $\overline{\alpha}=7 \times 10^{-3}$, $Sc=340$, $Bi\beta=0.025-0.05$, $\Delta=10^{-4}$. The calculations were performed in the spatial meshes $I \times K$ from 120 x 150 to 240 x 300 (the difference of the obtained results did not exceed 2 %). The value of the time pitch $\tau=10^{-4}$ was chosen from the conditions of the numerical calculation stability and minimization of iterations quantity.

Figures 1 – 3 show the versions of the task solution at $Q_0=4 \times 10^8$ W/m$^2$. The Figures 1a,c illustrate the velocity fields in the melt at the instants 2.6 ms and 3.7ms (the laser pulse end), obtained at $Bi\beta=0.05$ and varying temperature gradient of the surface tension. It follows from the calculation results that from the time of substrate submelting (1.9 ms), a centrifugal flow occurs near the free surface; it exists within about 0.2 ms. Then the admixture concentration growth in the top layers of the liquid forms the thermocapillary flow directed toward the molten pool center, (Figure 1a).

The growing heating up to the moment of the pulse end promotes the formation of two toroidal vortices in the liquid (Figure 1c). The first one – with the intensive counterclockwise flow at the melt mirror near the phase transition boundary. The second one is less intensive with the counter (in respect to the first one) downflow and upflow in the central area of the liquid. The occurring near-surface centripetal flow results in the fact that the alloying admixture in the melt penetrates into a considerable depth in the central part of the molten pool (Figure 1c). Then the formed intensive flows stimulate the admixture distribution in the liquid (Figure 1d).
Figure 1. The structure of the velocity field (a,c) and admixture distribution in the melt (b,d); - - - – the schematic of the phase transition boundary.

Figure 2. The structure of the velocity field (a,c) and admixture distribution in the melt (b,d) in the instants 2.6 ms (a,b) and 3.7 ms (c,d); - - - – the schematic of the phase transition boundary.
Figure 2 presents the results obtained at $Bi_D=0.065$ and under otherwise equal conditions. It was determined by the calculation results that the initial period of the centrifugal flow existence near the free surface is approximately 0.1 ms. The growth of the admixture concentration causes the variation of the temperature gradient of the surface tension, which in turn results in the formation of the thermocapillary flow directed toward the system center, illustrated by Figure 2a for the instant of 2.6 ms. Being involved by this flow, the alloying admixture is brought inside the melt in the central part of the molten pool (Figure 2b). By the time of the pulse ending, the continuing heating of the liquid surface varies the value $\partial \sigma / \partial T$ and promotes the formation of five toroidal vortices in it (Figure 2c). Such a structure of the flow promotes the heat transfer inside the melt toward the phase transition boundary, which changes significantly its shape. The vortices position results in the fact that the doping admixture is transported inside the melt from the surface and is then distributed over the molten pool volume (Figure 2d). Non-monotone shape of molten pool (Figure 2c,d) is transformed into monotone one at solidification, when convective heat transfer becomes less intensive.

Figure 3(a) illustrates the variation of $\partial \sigma / \partial T$ within the pulse duration. Figure 3(b) shows the varying temperature gradient of the surface tension regarding the admixture temperature and concentration on the liquid surface, which is calculated by (10). This parameter governs the flow structure and takes positive and negative values. To form a centripetal flow near the free surface, the condition $\partial \sigma / \partial T > 0$ is necessary, which is possible when the admixture concentration in the liquid grows and the laser radiation power is limited.

Figure 4 shows the version of the task solution at $q_0 = 5 \times 10^8$ W/m$^2$, $Bi_D=0.05$. Figure 4a presents the velocity field in the melt at the time of laser pulse ending. It was defined that under the conditions of the substrate intensive heating, the dominating is the centrifugal flow with the downflow near the swirl in the melt mirror area, at the phase transition boundary. In the central part of the molten pool, the liquid goes upward and it results here in the fact that the admixture does not penetrate deeply (Figure 4b). Thus, though in the considered version, the flow intensity is high because of higher temperature of the melt, for the admixture distribution we see the considerable similarity with the calculation version at the constant $\partial \sigma / \partial T$. 

Figure 4. The structure of the velocity field in the melted metal (a) and admixture distribution in the melt (b); 
---- -- the schematic of the phase transition boundary.
Figure 5. Comparison of a vortex convection in a molten pool of iron (a,b) and titanium (c,d) under identical conditions of laser radiation: (a,c)-\( q_0 = 4 \times 10^6 \text{ W/m}^2, \text{BiD}=0.065; \) (b,d)- \( q_0 = 5 \times 10^6 \text{ W/m}^2, \text{BiD}=0.05. \)

Table 1. Physical parameters of substance of titanium, iron and graphite.

<table>
<thead>
<tr>
<th>Physical quantity, dimension</th>
<th>Titanium</th>
<th>Iron</th>
<th>Graphite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting temperature, K: ( T_m )</td>
<td>1943</td>
<td>1775</td>
<td>4118-4163</td>
</tr>
<tr>
<td>Thermal conductivity, W/(m K): ( \lambda_t )</td>
<td>30</td>
<td>27</td>
<td>120-190</td>
</tr>
<tr>
<td>Thermal diffusivity, ( \text{m}^2/\text{s} ): ( k\times10^5 )</td>
<td>3,15</td>
<td>2,77</td>
<td>122,0</td>
</tr>
<tr>
<td>Density, ( \text{kg/m}^3 ): ( \rho_t )</td>
<td>4208</td>
<td>7065</td>
<td>2090-2230</td>
</tr>
<tr>
<td>Specific heat capacity, J/(kg K): ( C_l )</td>
<td>962</td>
<td>787</td>
<td>840</td>
</tr>
<tr>
<td>Dynamic viscosity ( \text{m}^2/\text{s} ): ( \nu \times 10^7 )</td>
<td>10,5</td>
<td>8,5</td>
<td>-</td>
</tr>
<tr>
<td>Temperature coefficient of volumetric expansion 1/K: ( b_t \times 10^{-5} )</td>
<td>11,69</td>
<td>1,18</td>
<td>0,79</td>
</tr>
</tbody>
</table>

Figure 5 shows the results of comparison of the vortex-type convection in substrates of iron and titanium under identical conditions of laser radiation. Flow velocity in melted iron is appreciable higher. It is explain the predisposition to appearance of a flow with a multivortex convection in iron.

An effort was made to compare the calculation and experimental results for the pulse laser interaction with the titanium substrate onto which a thin graphite powder layer was applied preliminary [2, 3]. Table 2 presents the photos of the sample sections and the conditions under which they were obtained.

In these experiments, the graphite powder played the role of an admixture and marker, which was clearly seen on the sections. It permitted to visualize the vortex flow directions and to determine the degree of mixing and admixture penetration. We observe the structural The dark areas which contain the admixture particles enable to evaluate the degree of the admixture penetration into the melt, as well as the direction of the developing flows in the liquid pool during the time of the laser pulse action. variations in the melted area of the substrate material after the cooling, which characterize the size of the melt pool.
Table 2. Photos of the sample sections and the conditions under which they were obtained

<table>
<thead>
<tr>
<th>Photo of the section</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1. Ti + graphite; E= 24.4 J; $t_H = 6$ ms; Spot diameter - 0.72 mm; Simple sickness - 1.5 mm; Beam distribution – plane.</td>
</tr>
<tr>
<td></td>
<td>2. Ti + graphite + Ni; E= 30.0 J; $t_H = 10$ ms; Spot diameter - 0.72 mm; Simple sickness - 2.0 mm; Beam distribution – plane.</td>
</tr>
<tr>
<td></td>
<td>3. Ti + graphite; E= 40.4 J; $t_H = 10$ ms; Spot diameter - 1.08 mm; Simple sickness - 1.5 mm; Beam distribution – plane.</td>
</tr>
<tr>
<td></td>
<td>4. Ti + graphite; E= 30.5 J; $t_H = 8$ ms; Spot diameter - 0.72 mm; Simple sickness - 1.0 mm; Beam distribution – Gauss.</td>
</tr>
<tr>
<td></td>
<td>5. Fe + Mo; E= 8.4 J; $t_H = 7$ ms; Spot diameter - 0.18 mm; Simple sickness - 3.0 mm; Beam distribution – Gauss.</td>
</tr>
<tr>
<td></td>
<td>6. Ti + graphite; E= 32.0 J; $t_H = 10$ ms; Spot diameter - 0.72 mm; Simple sickness - 4.0 mm; Beam distribution – plane.</td>
</tr>
</tbody>
</table>
Note that the areas occupied by the admixture are not exactly symmetrical. This vindicates the 3D dynamics of
the processes. The cases when the presence of the dark areas with the admixture is observed simultaneously in the
molten pool center and periphery are of interest. The reasons of the development of such flows, as is shown above in
the calculations, are directly related with the character of the variation of the surface tension regarding the
temperature and local content of the admixture on the liquid surface.

Unfortunately, the detailed comparison of the calculation and experimental results remains undone. The presence
of lighter graphite admixture in the melted metal vindicates that it is necessary to regard the variation of the mixture
density as well as the there to related Archimedes force. Small sizes of the liquid pool, high temperature gradients,
short-time pulse action result in the fact that in the general case the laser induces three-dimensional non-stationary
fast microprocesses.

The state of the molten pool surface, its ability to absorb the laser radiation strongly varies during the pulse. This
causes the necessity to consider the dependence of the absorption coefficient on the admixture temperature and
concentration in the same way as it was done for the surface tension.

So long it is impossible to take all these factors into account. That is why, at the first stage of our investigations
we restricted ourselves by the demonstration of the calculation model, which is already quite complex.

5. Conclusion

The performed calculations present the qualitative peculiarities of the development of the thermocapillary
thermal-concentration microconvection in the laser molten pool. The results of the present work enable to make the
qualitative conclusion on the conditions needed to reach the desired alloying effect. The influence of the
characteristics of the pulse laser radiation on the penetration speed and distribution of the alloying component in the
melt pool is demonstrated.

The numerical experiments showed that, to apply the considered approach to the certain or specific system (the
material plus the alloying admixture), it is necessary to perform the systematic experimental and theoretical
researches to determine the process parameters governing the thermal and concentration convection.

The reasons of the development of such unstable distribution of the admixture, as is shown above in the
calculations and experiments, are related with the character of the variation of the surface tension regarding the
temperature and content of the admixture on the liquid surface.

The results of the experiments are given in order to present more comprehensively the problem of the really
performing microprocesses. Here, the comparison of the calculations and experiments can be only qualitative.

Further, it is assumed that the model will be complicated and, when possible, all above mentioned peculiarities of
the task will be regarded.

References

[1] Sahoo P.; DebRoy T.; McNallan M.J. Surface tension of binary metal-surface active solute systems under conditions relevant to welding


