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Modeling of formation of deep 2D channels in metal targets via laser irradiation

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ABSTRACT

The method of dynamic adaptation is applied for the solution of a multifront Stephan problem in an arbitrary 2-D domain with explicit tracking of interphase fronts. Method of solution is based on the idea of dynamic adaptation of the computational grid by means of the transition to an arbitrary non-stationary coordinate system. The results of computational experiments of the modeling of the processes of metal treatment by intense energy flows are presented.

Keywords: laser irradiation, material removal, 2D channels

1. INTRODUCTION

The processes of material removal by means of intense energy flows (laser radiation, electron and ion beams) are the basis of many technological operations like cutting, drilling, surface modification and dimensional processing of condensed media.¹⁻³ The necessity of clear understanding of the peculiarities of the involved processes stimulates fundamental research of the kinetics of fast phase transformations⁴ simultaneously with the processes of macrotransfer underlying the procedures of the technological treatment. Notice that theoretical investigations are especially urgent in the consideration of the pulsed treatment regimes.

The main difficulties of the mathematical modeling of the Stephan-type problems are associated with the presence of the moving boundaries, what makes these problems essentially nonlinear. Further complications are due to the fact that the processes of the energy release and relaxation are spatio-temporal non-uniformly scaled. Analytical solution of such problems is rather an exception due to significant simplifying assumptions.

In the problems of the pulsed material processing by means of intense energy flows, the nonequilibrium behavior of the fast phase transitions may play the dominant role and therefore requires an explicit interphase front tracking mechanism and account of the related processes. The dominating position of the algorithms of the homogeneous computations in multidimensional problems is mainly due to the absence of the effective methods with the explicit moving phase front tracking.

This paper considers a method of numerical solution of multifront non-stationary 2-D Stephan problems with explicit front tracking in arbitrary domains. The solution is performed by means of the dynamic adaptation method⁵⁻⁷, which is widely used for non-stationary and spatially 1-D problems of mathematical physics.

The basis of the dynamic adaptation method is the idea of the transition to an arbitrary non-stationary coordinate system using the sought solution. In an arbitrary non-stationary coordinate system the problem is described by the extended differential system of equations, one part of them describes the physical phenomenon and another part determines the dynamics of the computational grid. The description of the motion of the computational grid in 2-D non-stationary problems is performed using two equations in partial differences.

This paper presents the results of the numerical experiments for the solution of the problems typical for the intense energy flows material processing. The main peculiarities of the similar problems are: the processes of melting-crystallization, evaporation, significant difference between the typical sizes of the considered domain and the energy release zone (focal spot).

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2. PROBLEM STATEMENT

Melting and crystallization of the pure materials in the simplest approximation is described by means of the classical Stephan problem, considering this process as a motion of the media with a strong discontinuity corresponding to the location of the phase front. The internal energy, density and thermophysical properties of the material (thermal capacity and conductivity) discontinuously change at the interphase boundary. The mathematical statement of the 2-D Stephan problem is reduced to a quasi-linear heat conduction equation

$$\left[\frac{\partial H}{\partial t} = -\frac{\partial W_1}{\partial x} - \frac{\partial W_2}{\partial y} + g \right]_k, \quad k = s, \ell, \quad (1)$$

$$H_k = c_p \rho_k T, \quad (W_1)_k = -\lambda_k(T) \frac{\partial T}{\partial x}, \quad (W_2)_k = -\lambda_k(T) \frac{\partial T}{\partial y}$$

in two domains $\bar{\Omega}_s(t)$ and $\bar{\Omega}_\ell(t)$ of an arbitrary domain Ω_{xy} , separated by an unknown beforehand moving boundary $\Gamma_{s\ell}(t)$. Stephan differential condition holds at $\Gamma_{s\ell}(t)$, and continuous temperature is assumed:

$$L_m \rho_s \nu_{s\ell}^n = W_\ell^n - W_s^n, \quad T_s = T_\ell = T_m. \quad (2)$$

Here superscripts n and τ stand for the normal and tangential component, s and ℓ signify the solid and liquid phase, T_m , L_m are the melting (crystallization) temperature and melting (crystallization) heat, $\nu_{s\ell}$ is the velocity of the interphase front. Boundary conditions are set at the boundary $\partial\Omega_{xy}$ of the domain $\Omega_{xy} = \Omega_s(t) \cup \Omega_\ell(t)$ in the form

$$\left(\bar{W}, \bar{n} \right) \Big|_{\partial\Omega_{xy}} = f, \quad (3)$$

where $\bar{W} = (W_1, W_2)$ is the vector of the heat flow, \bar{n} is the outward perpendicular for $\partial\Omega_{xy}$, f is a function, given at $\partial\Omega_{xy}$.

The inclusion of evaporation is performed in terms of a single-phase type of Stephan problem and is characterized by the presence of the moving interphase front $\Gamma_{\ell v}(t)$ liquid-vapor in the domain $\Omega_{x,y}(t) = \Omega_s(t) \cup \Omega_\ell(t)$. The process of the developed surface evaporation is described by means of three conservation laws (mass, pulse and energy) at this boundary

$$\rho_k \nu_{kv}^n = \rho_v (\nu_{kv}^n - u), \quad (4)$$

$$P_k + \rho_k (\nu_{kv}^n)^2 = P_v + \rho_v (\nu_{kv}^n - u)^2, \quad (5)$$

$$-\lambda \frac{\partial T}{\partial n} = G^n - \sigma T^4 - L_v \rho_k \nu_{kv}^n \quad k = s, \ell \quad (6)$$

and two additional relations, characterizing the kinetics of the phase transition and being determined using the Knudsen layer approximation⁸:

$$T_v = T_v(T_k, M), \quad \rho_v = \rho_v(\rho_{sat}, M), \quad (7)$$

where $G = (G^n, G^r)$ is the energy flow, v_{k0}'' is the velocity of the evaporation front, l_v is the evaporation heat, u is the gas-dynamic velocity, M is the Mach number, ρ_{sat} is the density of the saturated vapor.

Here

$$M = u/u_c, \quad u_c = (\gamma RT_v)^{1/2}. \quad (8)$$

Temperature and density of the vapor (7) functionally depend on the Mach number M , adiabatic exponent γ and additional parameter m

$$T_v = T_k \frac{2\gamma M^2 (m^2 + 0.5)^2}{(1 + \gamma M^2)^2 m^2 t^2}, \quad (9)$$

$$\rho_v = \rho_{sat} \frac{1}{\exp(-m^2) + \pi^{1/2} m (1 + \operatorname{erf}(m))} \frac{(1 + \gamma M^2) m^3}{\gamma M^2 (m^2 + 0.5)^3}, \quad (10)$$

If M is known the value of m is found from the equation

$$F(M)(m^2 + 0.5)^2 - m^2(m^2 + 1.5 + \alpha) = 0, \quad (11)$$

where $F(M) = 1 + \frac{3\gamma M^2 - 1}{(\gamma M^2 - 1)^2}, \quad \alpha = 2t^2 - 0.5\pi^{1/2} m t - 1,$

$$t = \frac{2m}{\pi^{1/2}} + \frac{1 + \operatorname{erf}(m)}{\exp(-m^2) + \pi^{1/2} m (1 + \operatorname{erf}(m))}, \quad \operatorname{erf}(m) = \frac{2}{\sqrt{\pi}} \int_0^m e^{-v^2} dv.$$

The value of $M=1$ corresponds to $T_v = 0,633T_k, \quad \rho_v = 0,326\rho_{sat}^{8,9}$.

The magnitude ρ_{sat} is determined using the equation of state

$$\rho_{sat} = P_{sat}/(RT_k), \quad \text{where} \quad P_{sat} = P_0 \exp\left(\frac{l_v}{R} \left(\frac{1}{T_b} - \frac{1}{T_k}\right)\right). \quad (12)$$

Here P_{sat} is the pressure of saturated vapor, P_0 is the atmospheric pressure, T_b is the boiling temperature, R is the gas constant.

3. STATEMENT OF THE PROBLEM IN AN ARBITRARY NON-STATIONARY COORDINATE SYSTEM

When solving multidimensional boundary problems in the domains with arbitrary shape, it is more convenient to use curvilinear coordinates for partial-difference approximation of differential equations. The type of the curvilinear system depends on the requirements and limitations for the computational grid from the solution of the particular problem. By convention, all the limitations can be divided in two classes. One of them is caused by the physical peculiarities of the considered processes, the other part of limitations is associated with the shape and geometrical parameters of the domain. Both these classes are often interdependent. For the problems with an arbitrary shape of the domain, the strictest limitations are associated with the approximation of the boundary conditions. Curvilinear coordinate systems

having the domain borders coincident with the coordinate lines are the most reasonable for such problems. Consequent to the borders coordinate lines deliver from additional interpolation required for the approximation of the boundary conditions of any type.

The solution of the combined type of the Stephan problem consists in determination of the temperature fields $T_s(t)$, $T_\ell(t)$ and movement velocities $v_{s\ell}$ and $v_{k\nu}$ of the phase fronts $\Gamma_{s\ell}(t)$, $\Gamma_{k\nu}(t)$. The algorithm of numerical solution of real Stephan problems, describing the processes of evaporation and melting - solidification naturally splits in two qualitatively different stages. The first one is dedicated to the determination of the temperature fields in a domain with one moving border $\Gamma_{k\nu}(t)$. It considers surface evaporation and covers the stages of the solid phase heating up to the equilibrium melting temperature T_m with further cooling to the initial temperature T_0 at the end of the solidification process. The temperature fields in the two subdomains Ω_s , Ω_ℓ and the velocity $v_{s\ell}$ of the interphase boundary $\Gamma_{s\ell}(t)$ are determined during the second stage.

Each of the stages has its own special features. The main feature of the first stage is the possibility of the appearance of high gradients near the zone of heating by a static external source. The peculiarities of the second stage are associated with the interaction of the two moving interphase fronts $\Gamma_{s\ell}(t)$ and $\Gamma_{k\nu}(t)$ and are determined by the behavior of the velocities $v_{s\ell}''$ and $v_{k\nu}''$. These features should be taking into account during the construction of the computational grid. The peculiarities of the first stage for a problem with an arbitrary shape of the domain can be taken into consideration during transition to curvilinear coordinates by means of a simple concentration of the coordinate lines in the heating zone. Considering the specialties of the second stage the situation is more complicated. Besides the problems, associated with the moving front, further complicity arises due to the change in the typical size of the phases. At the onset of the melting the thickness of the phase can be equal to several interatomic distances which is about 10\AA . The thickness of a new phase can increase with time by $3\div 6$ orders of magnitude. The same but in the reverse order can happen with the initial phase. In these situations, it can turn out that the computational grids used at the beginning of the computations, become ineffective in a period of time. The grids should be radically reconstructed in order to continue the computations. Considering the peculiarities mentioned above, the construction of effective computational grids in Stephan-type problems is possible only using adaptive approaches when the grid is dynamically connected with the basic solution.

The method of dynamic adaptation^{5,7}, in which the motion of any element of the physical space is tracked by means of an arbitrary non-stationary curvilinear coordinate system, is suited in full measure to the mentioned requirements. The arbitrariness of the coordinate system means that the laws of motion of the coordinate system are not predefined like, for example, when using Lagrangian coordinates, but are determined simultaneously with the solution. As a result, the motion of the nodes of the grid depends on the evolution of the numerical solution of the physical problem. In particular, the dynamics of the nodes in the Stephan problem is associated with the velocity of the phase front propagation. The reverse transformation for the spatial variables in the dynamic adaptation method is performed using two equations in partial differences. Thus, the sought grid functions and grid nodes coordinates are determined jointly from the solution of the united differential model.

Consider a computational space $\Omega_{\xi\eta}$, with an arbitrary non-stationary curvilinear coordinate system (ξ, η, t) . Assume that for each moment of time a biunique non-degenerate transformation exists $\xi = \xi(x, y, t)$, $\eta = \eta(x, y, t)$, $\tau = t$, mapping the physical domain with arbitrary shape Ω_{xy} onto a rectangle $\Omega_{\xi\eta}$ in the plane of curvilinear coordinates (ξ, η) . The domain borders and interphase fronts $\Omega_{\xi\eta}$ are coincident with the corresponding coordinate lines and remain unchanged with time. The Jacobian for such transformation is the function J

$$\rho J^{-1} = \rho \left(\frac{\partial x}{\partial \xi} \frac{\partial y}{\partial \eta} - \frac{\partial x}{\partial \eta} \frac{\partial y}{\partial \xi} \right) = \psi.$$

The mathematical formulation of the problem (1)-(6) in an arbitrary curvilinear coordinate system (ξ, η, τ) takes the form:

$$\left[\frac{\partial(\psi H)}{\partial \tau} = -\frac{\partial}{\partial \xi} \left\{ (\rho W_1 + H Q_1) \frac{\partial y}{\partial \eta} - (\rho W_2 + H Q_2) \frac{\partial x}{\partial \eta} \right\} - \frac{\partial}{\partial \eta} \left\{ -(\rho W_1 + H Q_1) \frac{\partial y}{\partial \xi} + (\rho W_2 + H Q_2) \frac{\partial x}{\partial \xi} \right\} \right]_k, \quad k = s, \ell, \quad (13)$$

$$\left[\frac{\partial x}{\partial \tau} = -\frac{Q_1}{\rho} \right]_k, \quad (14)$$

$$\left[\frac{\partial y}{\partial \tau} = -\frac{Q_2}{\rho} \right]_k, \quad (15)$$

where

$$W_1 = -\frac{\lambda \rho}{\psi} \left(\frac{\partial y}{\partial \eta} \frac{\partial T}{\partial \xi} - \frac{\partial y}{\partial \xi} \frac{\partial T}{\partial \eta} \right), \quad W_2 = -\frac{\lambda \rho}{\psi} \left(-\frac{\partial x}{\partial \eta} \frac{\partial T}{\partial \xi} + \frac{\partial x}{\partial \xi} \frac{\partial T}{\partial \eta} \right),$$

with corresponding boundary conditions at the phase transition line

$$(\xi, \eta) \in \Gamma_{s\ell} : \quad \left[\left(-\frac{\partial y}{\partial \xi} W_1 + \frac{\partial x}{\partial \xi} W_2 \right)_\ell - \left(-\frac{\partial y}{\partial \xi} W_1 + \frac{\partial x}{\partial \xi} W_2 \right)_s \right] \gamma^{-1/2} = -L_m Q_{s\ell}^n, \quad (16)$$

$$(\xi, \eta) \in \Gamma_{k\nu} : \quad Q_{k\nu}^n = -\rho_\nu \left(u + Q_{k\nu}^n / \rho_k \right), \quad (17)$$

$$P_\ell + \left(Q_{k\nu}^n \right)^2 / \rho_k = P_\nu + \rho_\nu \left(u + Q_{k\nu}^n / \rho_k \right)^2 \quad (18)$$

$$\left(-\frac{\partial y}{\partial \xi} W_1 + \frac{\partial x}{\partial \xi} W_2 \right)_k \gamma^{-1/2} = G^n + L_\nu Q_{k\nu}^n, \quad \eta = const, \quad (19)$$

$$\left(\frac{\partial y}{\partial \eta} W_1 - \frac{\partial x}{\partial \eta} W_2 \right)_k \alpha^{-1/2} = G^n + L_\nu Q_{k\nu}^n, \quad \xi = const, \quad (20)$$

$Q_{s\ell}^n, Q_{k\nu}^n$ are the material flows through the boundaries $\Gamma_{s\ell}, \Gamma_{k\nu}$, Q_1, Q_2 are arbitrary transformation functions,

$\frac{\partial x}{\partial \xi}, \frac{\partial y}{\partial \xi}, \frac{\partial x}{\partial \eta}, \frac{\partial y}{\partial \eta}, \alpha = \left(\frac{\partial x}{\partial \eta} \right)^2 + \left(\frac{\partial y}{\partial \eta} \right)^2$ and $\beta = \left(\frac{\partial x}{\partial \xi} \right)^2 + \left(\frac{\partial y}{\partial \xi} \right)^2$ are metric coefficients of the transformation.

4. TRANSFORMATION FUNCTION Q

Like during the solution of other problems of mathematical physics, the main difficulties in the generation of the computational grid for the Stephan problem are related to the determination of the form of the transformation, mapping the physical space onto the computational one. Since the solution of the full Stephan problem consists of two qualitatively different stages, two types of transformations are used for the grid generation. The both transformations map a domain with arbitrary shape Ω of the physical space onto a rectangle Ω in the plane of curvilinear coordinates

(ξ, η) . At the same time, mutually orthogonal coordinate lines in the computational space form a uniform grid with rectangular cells. In the physical space these cells correspond to the ones formed by the intersection of the non-uniformly placed non-orthogonal coordinate lines. All the boundaries including the moving ones are coincident in the computational space with the coordinate lines.

The solution of the problem (1)-(3) at the heating-cooling stage without phase transitions does not differ from the solution of typical non-stationary problems of mathematical physics. To construct a static and non-reconfigurable grid we use a relatively simple and prevailing method of determination of the required transformation by means of the numerical solution of a special system of the elliptic equations of the Poisson type¹⁰. Thus, the solution of the first stage of the problem is performed on a static grid, constructed before the beginning of the computation. The nodes of the grid are concentrated in the heating zone by means of specially chosen functions P_1 and P_2 placed in the right-hand member of the Poisson equations.

The second stage is associated with the appearance and propagation of the phase front $\Gamma_{s\ell}(t)$. Because of the usage of a non-stationary coordinate system, the line of the phase transition $\Gamma_{s\ell}(t)$ in the computation space remains stationary and coincident with the coordinate lines. The mass flow between two subdomains is calculated using the boundary conditions (8): $Q_{s\ell} = -\rho_s v_{s\ell}''$. In the physical space, the grids for the two subdomains $\bar{\Omega}_s, \bar{\Omega}_\ell$ are reconstructed at each time step depending on the magnitude and sign of the mass flow. The arbitrariness of the transformation functions Q_1, Q_2 means that all the points of the physical space may move with its own speed, and the computation grid can adapt according to any peculiarities of the sought solution. In the Stephan-type problems, it is reasonable to require that the nodes of the grid are semi-uniformly distributed in every direction. To achieve this objective it is appropriate to choose the functions Q_1, Q_2 in the form:

$$Q_1 = -\rho \left(D_\xi \frac{\partial^2 x}{\partial \xi^2} + D_\eta \frac{\partial^2 x}{\partial \eta^2} \right), \quad Q_2 = -\rho \left(D_\xi \frac{\partial^2 y}{\partial \xi^2} + D_\eta \frac{\partial^2 y}{\partial \eta^2} \right),$$

where D_ξ, D_η depend on the velocity of the nodes at the phase front and the degree of the domains transformation.

5. GRID GENERATION

Grid generation is aimed at establishing a relation between the points (ξ, η) of a regular computational domain $\Omega_{\xi\eta}$ and the points (x, y) on the domain Ω_{xy} , (Fig. 1).

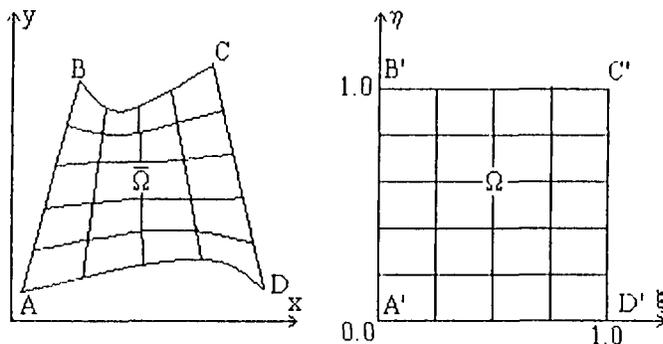


Figure 1.

Stage 1. To construct a moving grid in an arbitrary 2-D domain, we use a method based on the solution of the elliptic equations¹⁰

$$\frac{\partial^2 \xi}{\partial x^2} + \frac{\partial^2 \xi}{\partial y^2} = P_1(\xi, \eta), \quad \frac{\partial^2 \eta}{\partial x^2} + \frac{\partial^2 \eta}{\partial y^2} = P_2(\xi, \eta), \quad (x, y) \in \Omega_{xy}. \quad (21)$$

Here $P_1(\xi, \eta)$, $P_2(\xi, \eta)$ are the functions to control the concentration of the internal nodes of the grid.

The equations (21) are solved in the domain $\Omega_{\xi\eta}$, where they take the form

$$\alpha \frac{\partial^2 x}{\partial \xi^2} - 2\beta \frac{\partial^2 x}{\partial \xi \partial \eta} + \gamma \frac{\partial^2 x}{\partial \eta^2} + (J^{-1})^2 \left(P_1 \frac{\partial x}{\partial \xi} + P_2 \frac{\partial x}{\partial \eta} \right) = 0, \quad (22)$$

$$\alpha \frac{\partial^2 y}{\partial \xi^2} - 2\beta \frac{\partial^2 y}{\partial \xi \partial \eta} + \gamma \frac{\partial^2 y}{\partial \eta^2} + (J^{-1})^2 \left(P_1 \frac{\partial y}{\partial \xi} + P_2 \frac{\partial y}{\partial \eta} \right) = 0, \quad (23)$$

where

$$J^{-1} = \frac{\partial(x, y)}{\partial(\xi, \eta)} = \frac{\partial x}{\partial \xi} \frac{\partial y}{\partial \eta} - \frac{\partial x}{\partial \eta} \frac{\partial y}{\partial \xi}.$$

The system of equations (22), (23) is closed by the specification of the boundary conditions determining distribution of the nodes at the boundary $\partial\Omega_{xy}$ of the physical domain.

The concentration of the nodes in the source region is achieved by means of concentration at the border $\partial\Omega_{xy}$ and inside the domain Ω_{xy} . The nodes distribution at the boundary $\partial\Omega_{xy}$ is performed using a two-parameter extension function of Vinokur¹¹. The functions P_1 and P_2 controlling the nodes concentration inside the domain Ω_{xy} , are chosen as in ref.¹⁰.

The differential equations (22)-(23) at the uniform grid in the domain are approximated by difference schemes with central differences. An iterative process of Newton type is used to solve the obtained equations.

At the second stage of the solution of the Stephan problem associated with the appearance of a new subdomain Ω_ℓ and the propagation of the phase fronts $\Gamma_{s\ell}(t)$ and $\Gamma_{k\omega}(t)$ the generation of the computation grid was performed by means of numerical solution of the non-stationary equations (14), (15) used in the form:

$$\frac{\partial x}{\partial \tau} = D_\xi \frac{\partial^2 x}{\partial \xi^2} + D_\eta \frac{\partial^2 x}{\partial \eta^2}, \quad \frac{\partial y}{\partial \tau} = D_\xi \frac{\partial^2 y}{\partial \xi^2} + D_\eta \frac{\partial^2 y}{\partial \eta^2}.$$

The following formulas are used to determine the diffusion coefficients:

$$D_\eta = \left(\frac{L_\eta}{L_\eta^0} \right)^2 \left(\frac{\Delta l_\eta^0}{\Delta l_\eta} \right)^2 \frac{1}{h_\eta} v_{s\ell}^n, \quad D_\xi = \left(\frac{L_\xi}{L_\xi^0} \right)^2 \left(\frac{\Delta l_\xi^0}{\Delta l_\xi} \right)^2 \frac{1}{h_\xi} |v_{s\ell}^r|,$$

where

$$\Delta l_{\eta,(i,k)} = \begin{cases} \Delta l_{\eta,(i,k+1)(i,k)}, & m = \ell, \\ \Delta l_{\eta,(i,k-1)(i,k)}, & m = s, \end{cases} \quad \Delta l_{\xi,(i,k)} = \min \left\{ \Delta l_{\xi,(i+1,k)(i,k)}, \Delta l_{\xi,(i-1,k)(i,k)} \right\}.$$

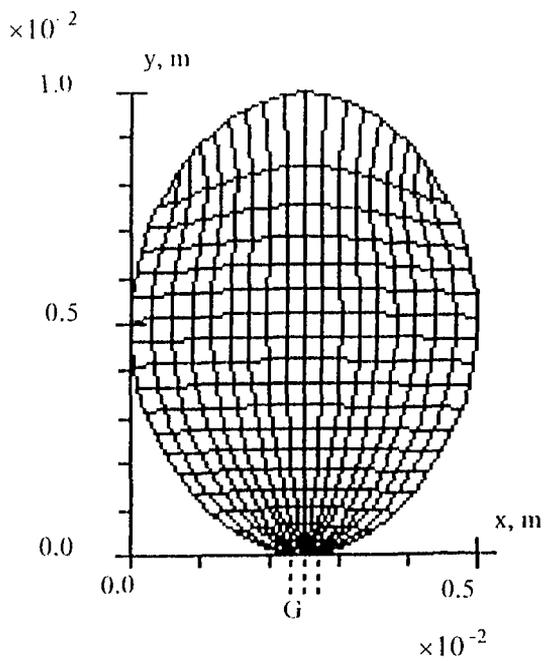


Figure 2a: $t = 0.00$

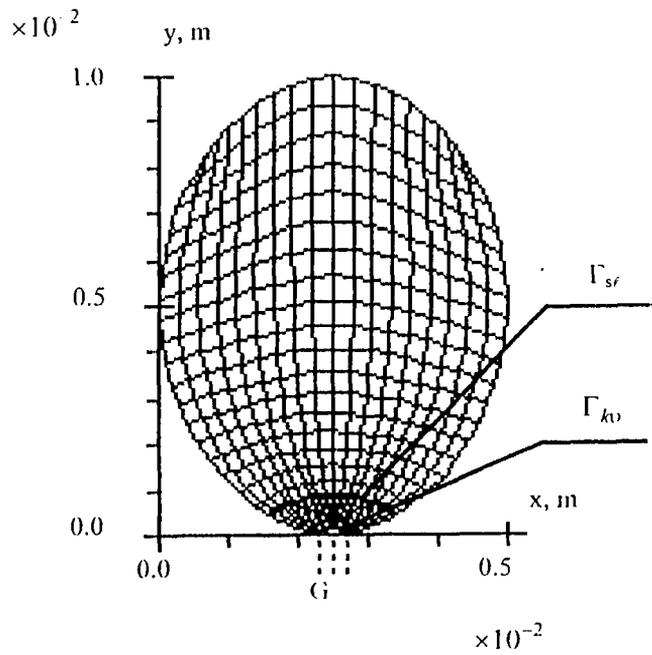


Figure 2b: $t = 5.55 \times 10^{-3}$

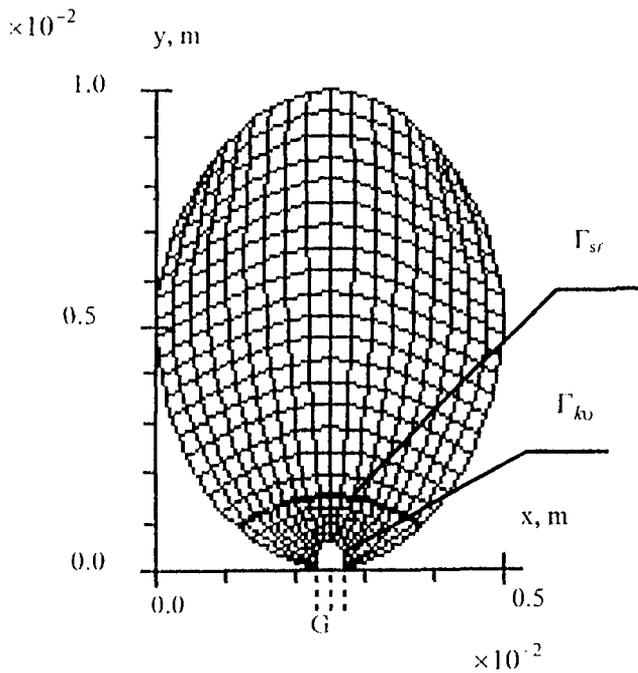


Figure 2c: $t = 2.23 \times 10^{-2}$

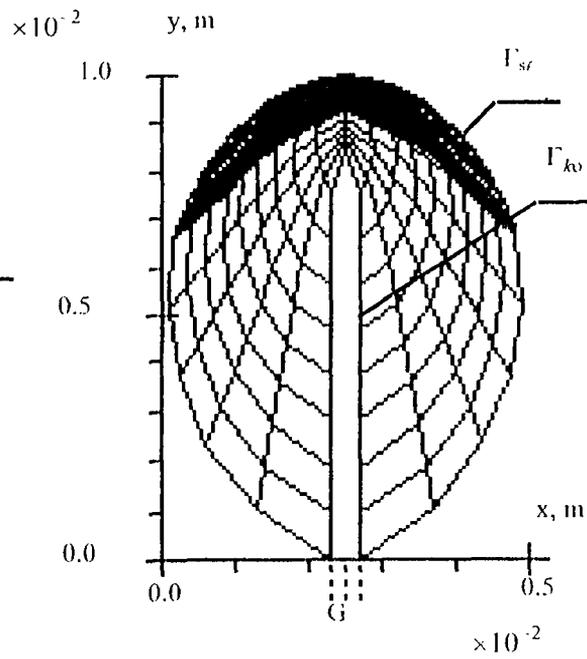


Figure 2d: $t = 2.80 \times 10^{-1}$

6. COMPUTATION EXPERIMENT

The developed methods were used to model the processes of melting and evaporation in 2-D statements. Many regimes of treatment were considered for the targets of various shape and material.

Figs. 2a – 2d show the results of the modeling of the laser treatment of an ellipsoidal lead target at the intensity $G=10^5 \text{ W/cm}^2$ and duration of a square pulse $\tau_L \cong 0.3 \text{ s}$. The grid in the domain $\Omega_{x,y}$ had 19×23 nodes total, 19×6 of them were in the subdomain Ω_ℓ .

Figure 2a shows the initial computational grid with 2-D concentration of the cells in the region corresponding to the initial period of the heating of the target. Fig. 2b corresponds to the initial stage of melting with the appearance of a new subdomain Ω_ℓ and semi-uniform nodes distribution. Fig. 2c corresponds to the stage of a developed melting and formation of a channel in the target. Fig. 2d shows the final stage of the treatment, which is characterized by almost complete melting of the target and formation of the deep channel with the depth-width ratio equal to 14. At such long period of treatment, the process relatively quick becomes stationary with constant values of the surface temperature $T_s \approx 2200^\circ \text{ C}$ and velocity $v_{s\ell} \cong v_{kv} \cong 0.03 \text{ m/s}$, Fig. 6.

Figs. 3 a, b show the results of the modeling of a similar treatment regime with Gaussian intensity distribution of a triangular shaped target. Fig. 3a corresponds to the initial stage of the heating with the significant concentration of the nodes, and Fig. 3b shows the final stage of the channel formation in the liquid phase.

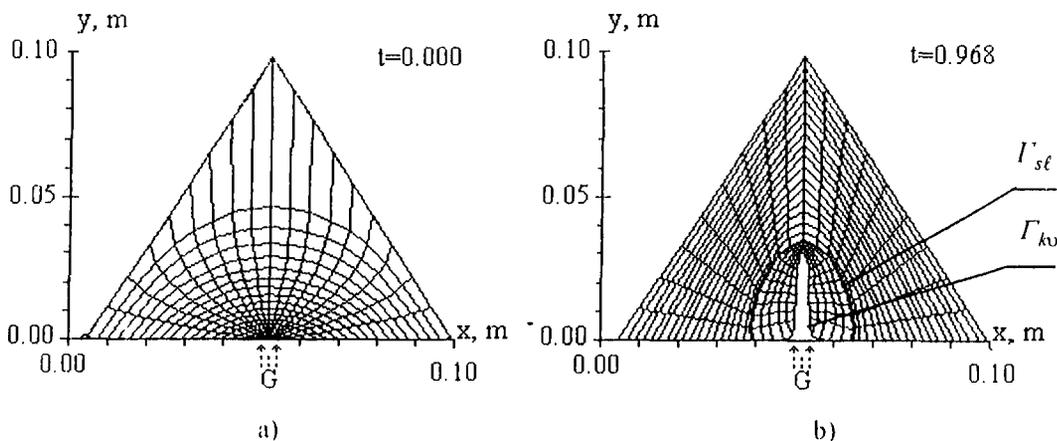
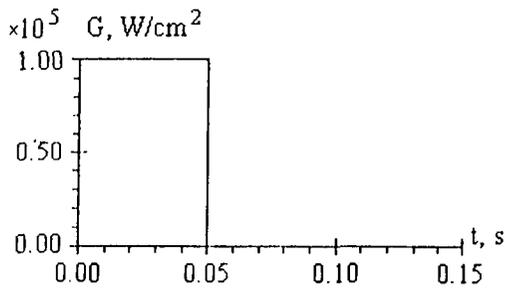


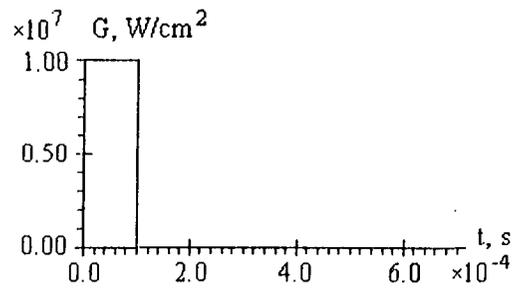
Figure 3a, b: A settlement grid in the initial and final moments of time.

For comparison, two treatment regimes were considered for an aluminum target. In the first one the parameters of the laser were equal to: $G=10^5 \text{ W/cm}^2$ and $\tau=5 \cdot 10^{-2} \text{ s}$ in the second — $G=10^7 \text{ W/cm}^2$ and $\tau=10^{-4} \text{ s}$ for a square pulse. The results of the modeling are shown at Figs. 4-7 a, b.

One can notice two peculiarities in these regimes. The first one is that the melting velocity will increase from $0,5 \text{ m/s}$ at $G = 10^5 \text{ W/s}^2$ up to 30 m/s as the intensity increases on two order. The second feature is associated with the fact that the velocity of evaporation is exponential depends on temperature of an irradiated surface. Therefore, the end of the pulse results in a sharp stop of evaporation, while the process of melting continues rather longer due to the large amount of energy stored in the condensed phase. This fact results in approximately two times increase of the thickness

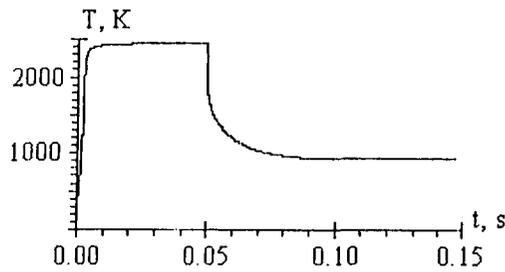


a)

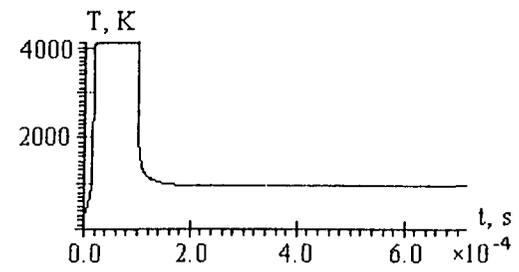


b)

Figure 4a, b: Time profile of the laser pulse.

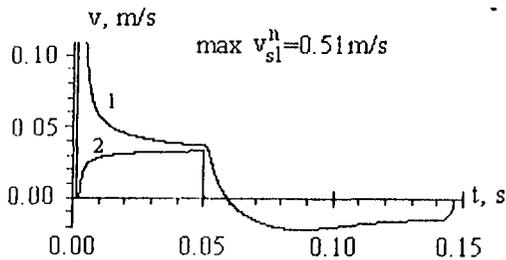


a)

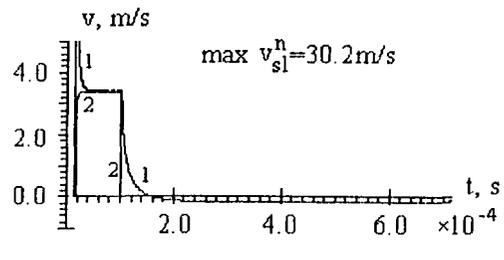


b)

Figure 5a, b: Time dependence of the surface temperature

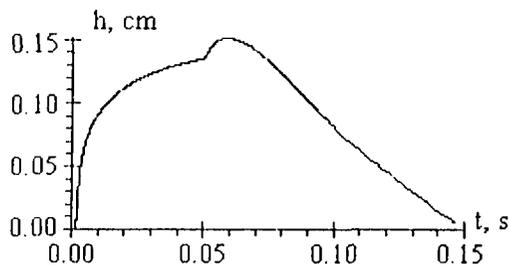


a)

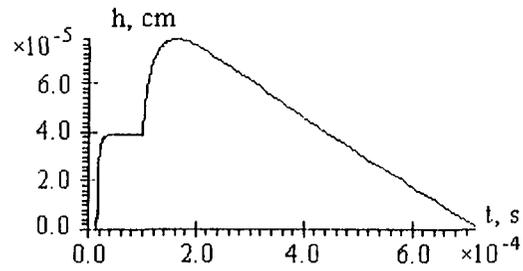


b)

Figure 6a, b: Melting v_{sl} and evaporation v_{kv} velocities.



a)



b)

Figure 7a, b: Liquid phase thickness.

7. CONCLUSION

The performed modeling indicates high efficiency of the method of dynamic adaptation for the considered problems of laser material processing.

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