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TEMPERATURE FIELD OF THE IRRADIATED MATERIAL IN THE LASER-INDUCED DAMAGE

O.V. Mkrtychev

Novorossiysk Branch of Belgorod State Technological University named after V. G. Shukhov,

Myskhakskoe shosse 75, Novorossiysk, 353905, Russia

e-mail: oleg214@ya.ru

Abstract. The use of powerful pulse lasers in various areas of science and technology requires an understanding of the physical mechanisms of laser-induced damage to the irradiated substance. In this paper, we consider the numerical solution of the one-dimensional non-stationary heat equation. The developed algorithm of the solution and the software, created with this application using a specialized application software package, allowed one to analyze the dynamics of a number of parameters of laser ablation destruction. It is possible take into account the differences and make calculations, based on the developed computer program for parameters, which can depend on time and coordinates in an arbitrary way. As the most significant application, one can point out the approximations of the solutions obtained for the sub-threshold radiation conditions.
Keywords: laser-induced damage; laser ablation; method of moments.

1. Introduction

The widespread distribution of laser technologies raises questions about the study of the mechanisms and parameters of the interaction of laser radiation with matter, in particular, the mechanisms of laser ablation destruction (LAD) of coating materials. These studies are carried out for a long time in various research groups and a large number of papers have been devoted to them [1 – 3]. The study of material destruction dynamics and the velocity of thermal wave propagation within the framework of various physical-mathematical models of ablation destruction, leads researchers to complex systems of partial differential equations, analytical solution of which is difficult or impossible. Therefore, the most acceptable is the numerical solution of such systems. The authors [4 – 7] have considered the method of moments in the thermal model of laser ablation.

2. Problem Statement and Solving Method

Consider the laser ablation one-dimensional model in which a flat surface laser ablation moves with velocity $v = v(t)$ along z-axis. In the coordinate system, associated with this surface, we formulate the heat equation:

$$\frac{\partial H}{\partial t} = v\frac{\partial H}{\partial z} + \frac{\partial}{\partial z}\left(\varkappa\frac{\partial T}{\partial z}\right) - \frac{\partial I}{\partial z},$$

where H is the solid enthalpy, $\varkappa(T)$ is its thermal conductivity, and I is the intensity of the laser radiation, absorbed by the solid, the distribution of which inside the solid is determined by the following equations:

$$\frac{\partial I}{\partial z} = -\alpha I, \qquad I|_{z=0} = I_S, \qquad I_S = I(t)A(T_S)e^{-\alpha_g h},$$

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where α is the absorption coefficient, and I_S is the intensity of the absorbed laser radiation at $z = 0$, which depends on the laser pulse form in time $I = I(t)$, the surface temperature $T_S = T(z = 0, t)$ and on the thickness of the layer of the removed substance: $h(t) = \int_0^t v(t_1)d\,t_1$, where $A(T_S) = 1 - R(T_S)$ is the absorption, R is the reflection, α_g is the absorption coefficient of the laser ablation products, normalized to the density ρ of the solid.

To solve this problem, we used the method of moments with a test function:

$$H_p(z,t) = \frac{1}{1-\alpha l}\left[\left(H_S - \frac{J_S l}{\chi_S}\right)e^{-\alpha z} - \left(\alpha l H_S - \frac{J_S l}{\chi_S}\right)e^{-\frac{z}{l}}\right].$$

The test function satisfies the boundary conditions for $z = 0$, $z = \infty$ and ensures the fulfillment of the obvious condition $H_p(z = 0, t) = H_S(t)$.

To obtain the equations for $T_S(t)$ and $l(t)$, the transformations, known from the method of moments, are performed. The system of equations for surface temperature and depth of heating was supplemented by an equation, describing the change in the thickness of the ablated layer:

$$\frac{dh}{dt} = v = v_0 \exp\left(-\frac{T_a}{T_S}\right).$$

This method reduces the problem to a system of differential equations for the functions $T_S(t)$, $l(t)$, $h(t)$ and $v(t)$, which should be numerically integrated with the appropriate initial conditions. This approach is quite flexible and convenient for analyzing the experimental data than the direct numerical solution of the boundary value problem of heat conduction using the finite differences or the finite elements. Studies of different problems on laser ablation show that the method of moments makes it easy, taking into account the functional dependence of various parameters.

The shape of the laser pulse is modeled by the function $(t) = I_0 \frac{t}{t_1} e^{-t/t_1}$, where the radiation dose is related to the characteristic time t_1 by using the formula of pulse energy: $\Phi = I_0 t_1$.

3. Numerical Simulation and Results

By applying the method of moments, we obtain a system of differential equations:

$$\begin{cases} m_{11}\dot{T}_S + m_{12}\dot{l} + m_{13}\dot{h} + m_{14}\dot{v} = n_1, \\ m_{21}\dot{T}_S + m_{22}\dot{l} + m_{23}\dot{h} + m_{24}\dot{v} = n_2, \\ m_{31}\dot{T}_S + m_{32}\dot{l} + m_{33}\dot{h} + m_{34}\dot{v} = n_3, \\ m_{41}\dot{T}_S + m_{42}\dot{l} + m_{43}\dot{h} + m_{44}\dot{v} = n_4, \end{cases}$$

where the coefficients m_{ij}, n_i do not depend explicitly on $\dot{T}_S$, $\dot{l}$, $\dot{h}$, $\dot{v}$.

This system of equations was solved using numerical methods on a computer.

One of the solutions is shown in Fig. 1. The upper left part of this figure shows dependence of sample temperature on time $T(t)$, and the upper right part demonstrates the dependence of the characteristic length of the temperature field $l(t)$ in the sample. In the lower row on the left, it is present the dependence of the depth of crater $h(t)$, formed as a result of ablative destruction of the material, and at the right hand, the dependence of the velocity $v(\mathrm{t})$ is depicted.

An important application of the obtained results is the approximations of the numerical solutions in some of the most interesting ranges of parameters of laser ablation. For example, under the sub-threshold approximation of laser ablation and assuming the constancy of the thermo-physical parameters ρ, c, $\varkappa$ and A, when $l << 1$ and $T_a >> T_s$, we will have the system of equations:

$$\begin{cases} \dot{T}_S = \frac{I_S\alpha}{c\rho} - \frac{1}{2}\frac{\alpha\varkappa}{lc\rho}\,(T_s - T_0), \\ \dot{l} = \frac{1}{2}\frac{\varkappa}{c\rho}\left(\alpha + \frac{1}{l}\right). \end{cases}$$

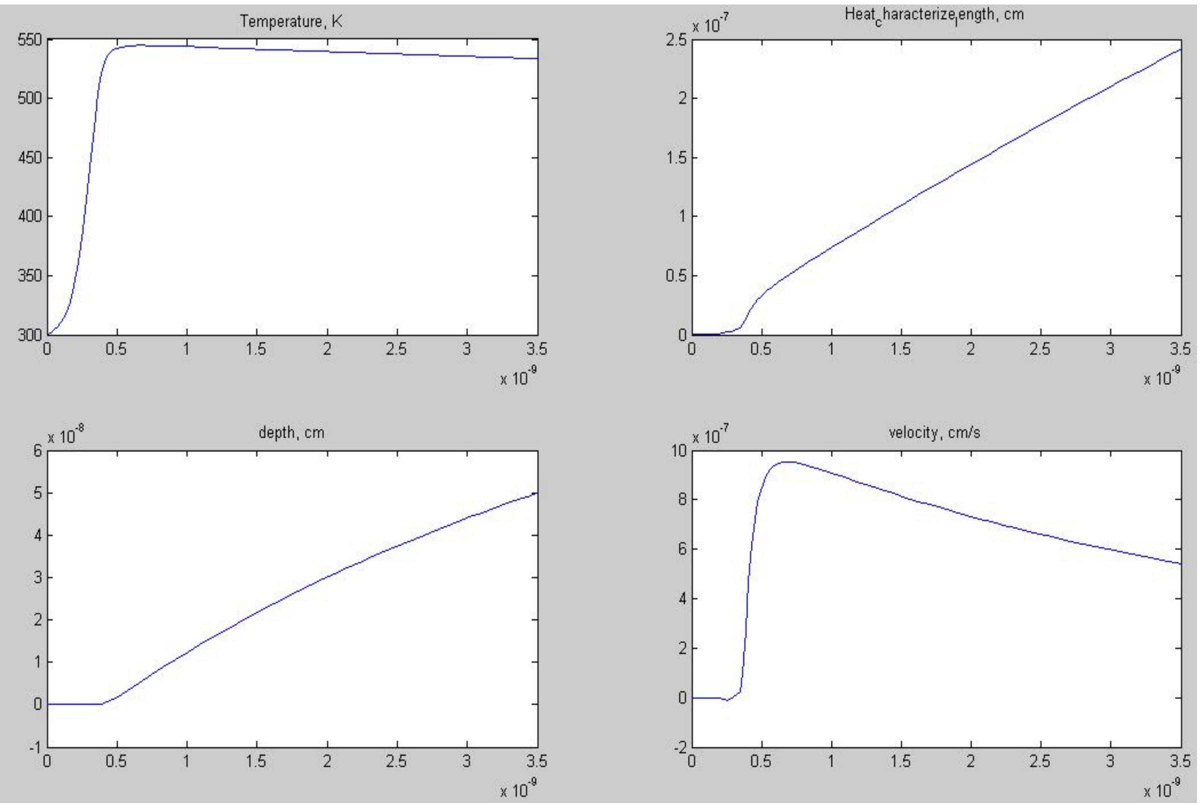

Fig. 1. Results of numerical simulation with the following values of the parameters:
$\alpha = 4.5\cdot10^5$ cm^{-1}, $\alpha_g = 0.5\alpha$ cm^{-1}, $A = 0.92$, $T_0 = 300$ K, $\varkappa = \varkappa_1\left(\frac{T}{\varkappa_2}\right)^{\varkappa_3}$,
where $\varkappa_1 = 1.8\cdot10^{-3}$, $\varkappa_2 = 300$, $\varkappa_3 = 0.3$, $L = 1000$ J·cm^{-3}, $T_a = 10000$ K,
$c = c_0 - c_1 e^{\frac{c_2 - T}{c_3}}$, where $c_0 = 2.7$ J·gr^{-1}·K^{-1}, $c_1 = 1.75$ J·gr^{-1}·K^{-1}, $c_2 = 300$ K,
$c_3 = 760$ K, $c_{0g} = 2.38$ J·gr^{-1}·K^{-1}, $c_{1g} = 1.67$ J·gr^{-1}·K^{-1}, $c_{2g} = 300$ K, $c_{3g} = 760$ K,
$\rho = 1.42$ gr·cm^{-3}, $\Phi = 100$ mJ, $t_1 = 14.24$ ns, $v_0 = 2.8\cdot10^6$ cm·s^{-1};
calculations were performed for a time range from 0 to 2 nanoseconds at i.c.
$T_S(0) = 300$ K, $l(0) = 10\cdot10^{-10}$ cm, $h = 0$, $v = 0$.

4. Conclusion

The computer simulation results were obtained for the thermal field distribution of the laser ablation of different nano-composites. This simulation was based on the thermal processes for which laws and methods of the heat conductivity theory were used. The method of moments has been chosen for solution of two differential equations system. The obtained numerical results are in good agreement with the experimental results of [4].

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