Thermal effects caused by action of powerful laser radiation on condensed matter

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The spatial and temporal temperature distribution on a solid's surface heated by laser interference pattern is calculated using integral transformation on coordinates x, y and Fourier transformation on coordinate z. Two-dimensional periodic structure consisting of circles with radii equal to a radius of the laser beam is considered. It is shown, that the maximal heating is observed in the center of a circle while diminishing to periphery. The area where the intensive surface heating is observed extends up to 0.8 r/a (a is a period of the grating, r is a radius of the laser beam).

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1. Introduction

Last time an interest to research of any sort of surface structures in solids created by means of laser radiation and laser beams interference pattern increased essentially [1-10]. Also, laser ablation becomes a perspective direction of researches, which can be in addition used to form nano-sized particles of a solid electrolyte [11]. Impulse laser ablation of solid targets in the gas phase has been widely used for the preparation of various nanostructure materials such as nanoparticles, nanotubes and nanocomposites [12-14]. The study of laser-induced heating and melting are of great importance for achieving high quality materials' processing with lasers [15-19]. However, till recently a question on features of spatial and temporal distribution of temperature on a surface produced by laser heating was investigated poorly. Most extensively this question has been analyzed in [20]. In this paper, the spatial and temporal temperature distribution in a material is calculated using Green's function method for various cases of laser radiation: pulsed laser and continuous laser wave. However, a question is to find a spatial and temporal distribution of temperature in various structures created by means of laser beam interference pattern, which now becomes the subject of intensive researches.

2. Formulation of the problem

Let us consider process of a solid's surface heating by two-dimensional laser beam interference pattern. It is supposed that laser beams are identical, fall normally to a surface and do not interact with one another. We shall assume that thermophysical characteristics of the medium not dependable on temperature and coordinates. In this case, the heat diffusion equation describing distribution of temperature T in a half-space $0 < z < \infty$ can be written as

$$\frac{\partial T}{\partial t} = \chi\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + \alpha I\left(x, y, z, t\right), \qquad (1)$$

where t is a time, x, y, z - Cartesian coordinates with x, y lying in the surface of the solid, χ is a thermal diffusivity, α is an absorption coefficient, I is a power density of the laser beam.

We assume that the laser beam can be presented by the Gaussian intensity distribution

$$I(x, y, z, t) = H(x, y) I_0 (1 - R) e^{-\alpha z} \exp\left\{-(x^2 + y^2)/r^2\right\} f(t), \qquad (2)$$

where I_0 is a maximal intensity of the laser beam, R is a reflection coefficient, r is the radius of a solitary laser beam, $H(x, y) = 1$ if $x^2 + y^2 \le r^2$, and $H(x, y) = 0$ in opposite case, $f(t)$ is a function which describes the distribution of the laser pulse in time.

Distribution of temperatures is subjected to the following initial and boundary conditions:

$$T\left(x, y, z, 0\right) = T_0,$$
$$\left.\frac{\partial T}{\partial x}\right|_{x=\pm a} = 0, \quad \left.\frac{\partial T}{\partial y}\right|_{y=\pm b} = 0, \quad \left.\frac{\partial T}{\partial z}\right|_{z=0} = 0, \quad \lim_{z\to\infty} T = T_0, \qquad (3)$$

where $2a, 2b$ are dimensions of the rectangular period, T_0 is an initial value of the temperature.

The solution of our problem can be constructed using Green's function as it has done by some authors [19, 20]. However, this appears to be not a trivial problem of calculating infinity integrals, so in the present work other approach is offered. Let us notice, that the linear equation (1) has constant coefficients, and variables are divided in the function of the source (2). Under such circumstances, for solving the equation (1) infinite integral transformation on coordinates x, y and Fourier transformation on coordinate z can be used. Consecutive performance of these transformations (independent of execution sequence) leads to systems of non-uniform differential equations of the first order over time. Its solving does not cause difficulties. After return to the space of originals we have to get an analytical solution of the problem in form of converging series and integrals.

3. Discussion of the general solution and numerical results

Two-dimensional periodic structures with sources operating within the limits of the circle of radius r with Gaussian intensity distribution in space are investigated. The cases considered when time function $f(t)$ represents Dirac function $\delta(t)$ or Heaviside function $H(t)$. One-dimensional periodical (strip) structure, which is created by action of instant laser impulse described by $\delta(t)$-function is considered also. Then, solutions for any impulse form can be obtained using the convolution operator. Some results of the calculations are presented as an illustration in the Fig. 1. The square cell ($b = a$) is considered. Dimensionless time is used $t = \chi t'/a^2$ (t'-dimensional time), also dimensionless temperature $\theta = T/T^*$, where $T^* = \alpha a^2 I_0/\chi$, and dimensionless space coordinates $x = x'/a$, $y = y'/a$, $z = z'/a$, where x', y', z' are the dimensional ones.

The distribution of dimensionless temperature on the surface of the solid in the middle section of cell for various radii of a beam at t = 0.005 is presented in the Fig. 1a. The distribution of temperature velocity on surface of the solid in a middle section of the cell when $r/a = 0.2$ and $f(t) = H(t)$ for various values of time is presented in the Fig. 1b.

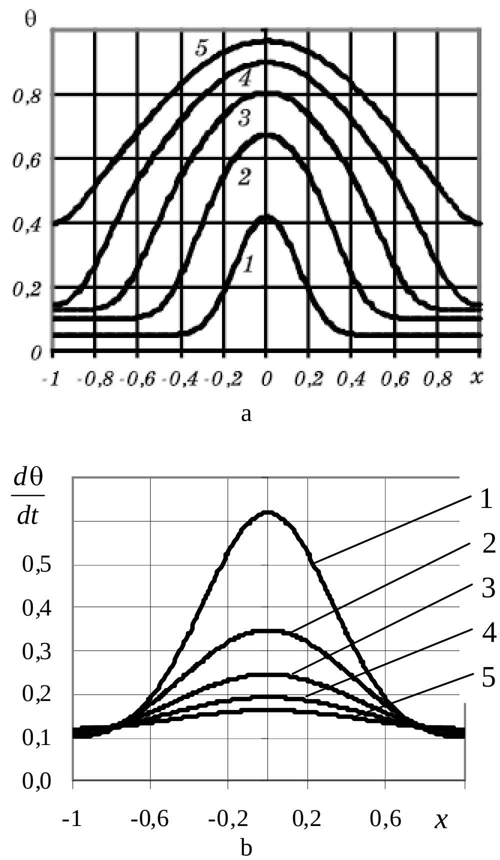

Fig.1. (a) Distribution of dimensionless temperature θ on a surface of the solid in the middle section versus dimensionless space coordinate x for various beam radii: 1- r/a =0.2; 2 – r/a =0.4; 3 – r/a =0.6; 4 – r/a =0.8; 5 - r/a =1.0; (b) Distribution of temperature velocity on a surface of the solid $(d\theta/dt)$ in the average section of two-dimensional periodic structure versus dimensionless space coordinate x for various moments of time: 1 – t = 0.05; 2 – t = 0.10; 3 – t =0.15; 4 – t =0.2; 5 – t =0.25.

The calculations show that the area of the maximal difference of temperatures coincides with the diameter of a laser beam. Outside of this area, the surface temperature remains practically constant (see the Fig.1a). In process of heating of the cell by laser radiation the temperature of its surface during the time t=0.2 stabilizes. The greatest heating is observed in a circle with radius $r/a = 0.8$ in the middle section and in diagonal ones ($x = y$). For instant laser impulse this process takes a greater place, but it substantially depends on the relation r/a.

From the analysis of temperature distribution time caused by a laser beam with radius $r / a = 0.2$ presented in the Fig. 1b follows, that stabilization of temperature occurs rather quickly (in the moment $t = 0.02$ its triple reduction is observed).

4. Conclusions

In this paper, research is carried out of spatial and temporal distribution of temperature on a surface of a solid, caused by heating the surface with a laser interference pattern beam. Two-dimensional periodic structure is analyzed consisting of circles with radii equal to the laser beam radius. The results obtained produce the following conclusions:

1. Stationary distribution of temperature occurs quickly enough (during the time period t=0.2) in two-dimensional periodic structures, the same way as in one-dimensional structures [21]. Though for one-dimensional structures this process goes a little bit more slowly.
2. The width of area in which the surface temperature is supported maximal in case of one-dimensional lattice, appears to be some times greater in comparison with two-dimensional one.

Thus, it is possible to approve that the heating of a solid surface by means of one-dimensional laser interference pattern appears to be more effective when it is necessary to achieve more uniform surface heating. Two-dimensional laser interference pattern is more useful in case when more local and fast heating of a surface is necessary.

It may be noticed in conclusion that the results obtained in the paper can be useful when interpreting experiments concerning analysis of the multilayer metallic films topography modified by laser interference irradiation [22, 23]. The results are confirmed completely by experimental investigations on temperature history of carbon steel samples [24].

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