THERMOELASTIC STRESSES PRODUCED IN AN ABSORBING LAYER BY THE ACTION OF A LASER PULSE

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Current technology often employs laser pulses for drilling and scribing of semiconductors and dielectric materials. If the material being processed is partially transparent to laser radiation, processing modes are possible in which thermoelastic stresses are the dominant factor in the process. Thus study of such stresses is of practical interest. The thermoelastic stresses produced in a material upon laser pulse irradiation have been considered theoretically in a number of studies [1-5]. In [1, 2] the thermoelasticity problem was solved for an isotropic semispace with a radiant energy flux incident on its surface. The complexity of the equations describing the stresses which develop hinders use of the solutions obtained in [1, 2] for practical purposes.

In [3-5] the stresses produced in a semispace upon laser heating were found by numerical solution of the gasdynamic equations simultaneously with a generalized equation of state. By analysis of the space-time stress distributions obtained in [3, 5] it was concluded that destruction of the material (including glasses) by exfoliation on the irradiated surface was possible. This conclusion was later confirmed experimentally [6]. In [7-9] surface destruction of dielectrics was related to development of thermoelastic stresses.

In the present study, by solving the thermoelasticity problem for a semispace, the dimensionless parameter range characteristic of the material and laser action will be determined, in which exfoliation of the irradiated surface is possible. It is obvious that with other conditions being equal the thermoelastic stress will be highest if cooling of the absorbing layer of material over the duration of energy liberation can be neglected.

At high values of laser radiation flux density for which exfoliation destruction is characteristic, the role of convective heat exchange with the irradiated surface is negligibly small. The cooling of the absorbing layer due to thermal conductivity during the time of laser pulse action τ_i will be small when the following condition is satisfied:

$$\sqrt{a\tau_i} \ll 1/\varkappa, \tag{1}$$

where a is the thermal diffusivity coefficient and $\varkappa$ is the absorption coefficient of the material at the laser wavelength.

When heat loss from the absorbing layer is neglected the system of equations for the free thermoelasticity of the semispace has the form

$$c_0^2\partial^2\sigma/\partial x^2 - \partial^2\sigma/\partial t^2 = 3K\alpha\partial^2T/\partial t^2, \quad \rho c\frac{\partial T}{\partial t} = q\varkappa e^{-\varkappa x}, \tag{2}$$

where c_0 is the speed of sound, σ is the stress along the normal to the surface; K is the modulus of omnidirectional compression, Π is the linear expansion coefficient, T is the temperature, ρ is the density, c is the specific heat, and q is the laser radiation thermal flux on the surface of the semispace.

We write the boundary and initial conditions in the following manner:

$$\begin{gathered} T(0,\ x) = T_0,\ \sigma(0,\ x) = 0,\ \partial\sigma/\partial t|_{x=0} = 0, \\ T(t,\ \infty) = T_0,\ \sigma(t,\ \infty) = 0,\ \sigma(t,\ 0) = 0. \end{gathered} \tag{3}$$

We assume that the laser radiation flux incident on the surface of the semispace is completely absorbed in the material. The solution of Eq. (2) with boundary and initial conditions (3) can be represented in the form

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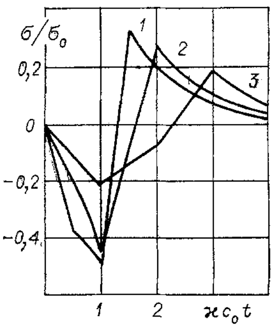

Fig. 1

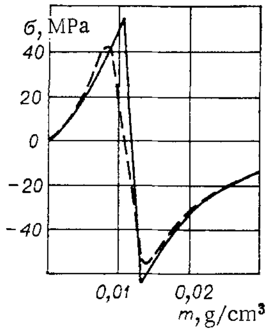

Fig. 2

$$\sigma(x,\ t)=\frac{3K\alpha\varkappa}{\rho c}\left[\operatorname{sh}\varkappa x e^{-\varkappa c_0 t}\int\limits_0^{t-x/c_0} q(\tau)\,e^{\varkappa c_0\tau}d\tau-e^{-\varkappa x}\int\limits_{t-x/c_0}^{t} q(\tau)\operatorname{ch}\varkappa c_0(t-\tau)\,d\tau\right]. \tag{4}$$

It follows from Eq. (4) that:

1. For $t \leqslant x/c_0$ (rarefaction wave from irradiated surface has not reached the section x) the first term is identically equal to zero, and at such times only compressive stresses develop at the section x, with magnitude described by the expression

$$\sigma^{+}=-\frac{3K\alpha\varkappa}{\rho c}e^{-\varkappa x}\int\limits_0^t q(\tau)\operatorname{ch}\varkappa c_0(t-\tau)\,d\tau.$$

The minus sign denotes a compressive stress.

2. At $t \geqslant \tau_i + x/c_0$ the second term in solution (4) vanishes, and in this interval at section x extensive stresses are produced, with magnitude decaying exponentially with time:

$$\sigma^{-}=\frac{3K\alpha\varkappa}{\rho c}\operatorname{sh}\varkappa x e^{-\varkappa c_0 t}\int\limits_0^{\tau_i} q(\tau)\,e^{\varkappa c_0\tau}d\tau.$$

In the time interval $x/c_0 \leqslant t \leqslant \tau_i + x/c_0$ at the section x there is a transition from compressive to extensive stresses, while at $t = \tau_i + x/c_0$ the extensive stress reaches its maximum value σ_m^-, equal to

$$\sigma_m^{-}=\frac{3K\alpha\varkappa}{\rho c}\operatorname{sh}\varkappa x e^{-\varkappa c_0(\tau_{\text{и}}+x/c_0)}\int\limits_0^{\tau_i} q(\tau)\,e^{\varkappa c_0\tau}d\tau. \tag{5}$$

The time t, corresponding to transition at section x from compression to extension, can be found by solution of the integral equation

$$\operatorname{sh}\varkappa x\int\limits_0^{t-x/c_0} q(\tau)\,e^{-\varkappa c_0(t-\tau)}d\tau-e^{-\varkappa x}\int\limits_{t-x/c_0}^{\tau_i} q(\tau)\operatorname{ch}\varkappa c_0(t-\tau)\,d\tau=0.$$

Analytical expression (5) allows us to evaluate the maximum value of extensive stress produced in an elastic body with consideration of the time dependence of the laser pulse.

For the case of "instantaneous" energy liberation ($\tau_i \ll x/c_0$) the solution obtained here, Eq. (4), coincides with that presented in [10]:

$$\hat{\sigma}=\begin{cases}-\dfrac{3K\alpha\varkappa E_0}{\rho c}e^{-\varkappa x}\operatorname{ch}\varkappa c_0 t, & x\geqslant c_0 t,\\[2mm] \dfrac{3K\alpha\varkappa E_0}{\rho c}e^{-\varkappa c_0 t}\operatorname{sh}\varkappa x, & x\leqslant c_0 t.\end{cases}$$

Here $E_0 = \int\limits_0^{\tau_i} q(\tau)\,d\tau$ is the specific energy of the laser pulse. We will analyze solution (4) further with the assumption that the laser pulse is rectangular in form, i.e.,

$$q(t)=\begin{cases} q_0, & 0 \leqslant t \leqslant \tau_i, \\ 0, & t > \tau_i. \end{cases}$$

In this case, for the maximum value of the compressive σ_m^+ and extensive σ_m^- stresses at section x we have

$$\sigma_m^+ = -\frac{3K\alpha q_0}{2\rho c c_0}\left(1-e^{-2\varkappa x}\right), \quad \sigma_m^- = \frac{4K\alpha q_0}{2\rho c c_0}\left(1-e^{-2\varkappa x}\right)\left(1-e^{-\varkappa c_0 \tau_и}\right).$$

For a fixed radiant energy density on the surface of the semispace $E_0 = q_0\tau_i$ the maximum possible extensive stress value at section x, σ_m^-, is achieved for the case of "instantaneous" energy liberation and is equal to

$$\sigma_m^- = \frac{3K\alpha\varkappa E_0}{\rho c}\left(1-e^{-3\varkappa x}\right).$$

With increase in τ_i the maximum extensive stress value σ_m^- decreases in accordance with the expression

$$\sigma_m^- = \hat{\sigma}_m\left(1-e^{-\varkappa c_0 \tau_i}\right)/(\varkappa c_0 \tau_i).$$

This is illustrated by Fig. 1, which shows a calculation with Eq. (4) of stress as a function of time, the former referenced to a value $\sigma_0 = 3K\alpha\varkappa E_0/(\rho c)$ in the section $\varkappa x = 1$ at fixed energy density E_0 for three values of the dimensionless parameter ($\varkappa c_0 \tau_i$ = 0.5, 1.0, 2.0; lines 1-3).

For a fixed moment in time ($t = 9.1 \cdot 10^{-8}$ sec), Fig. 2 shows the distribution of normal stresses σ, found by numerical solution of the gasdynamic equations simultaneously with a generalized equation of state (dashed line) [5], compared with the same values calculated from the analytical Eq. (4) (solid line). The σ distribution [5] shown in Fig. 2 corresponds to the action on tinted ice ($\varkappa \approx 10$ cm^{-1}) of a rectangular laser pulse of duration $\tau_i = 2 \cdot 10^{-8}$ sec.

It is evident from Fig. 2 that there is marked divergence between the numerical calculation of [5] and the analytical solution (4) only in the range of large σ gradients, i.e., where the numerical calculation is least accurate.

The extensive stresses which develop under laser action within the body may produce fractures (exfoliations).

Exfoliation destruction at the section x may occur if the maximum extensive stress value in that section proves to be equal to the dynamic fracture strength σ_f, i.e.,

$$\sigma_f = \frac{3K\alpha q_0}{2\rho c c_0}\left(1-e^{-\varkappa c_0 \tau_i}\right)\left(1-e^{-2\varkappa x}\right). \tag{6}$$

If the energy density E_0 is sufficient for fracture to develop within the material, then the thickness of the exfoliated layer x_0 (coordinate of the section where the fracture occurs) can be estimated from the following expression:

$$x_0 = -\frac{1}{2\varkappa}\ln\left[1-\frac{2\rho c c_0 \sigma_p}{3K\alpha q_0\left(1-e^{-\varkappa c_0 \tau_i}\right)}\right]. \tag{7}$$

The region in which exfoliation is possible can be defined conveniently in the plane of the dimensionless parameters a_1 and a_2, which completely characterize the body and laser pulse within the framework of the problem in question

$$a_1 = \varkappa c_0 \tau_i, \quad a_2 = 3K\alpha\varkappa E_0/2\rho c \sigma_f. \tag{8}$$

The parameters introduced have physical meaning: a_1 is the ratio of the laser pulse duration to the time required for a sound wave to traverse the energy liberation zone; a_2 is the ratio of the maximum possible extensive stress value E_0 (for "instantaneous" energy liberation) to the dynamic fracture strength of the material.

Using parameters a_1 and a_2, Eqs. (6), (7) take on the form

$$a_2 = \frac{a_1}{\left(1-e^{-a_1}\right)\left(1-e^{-2\varkappa x}\right)}; \tag{9}$$

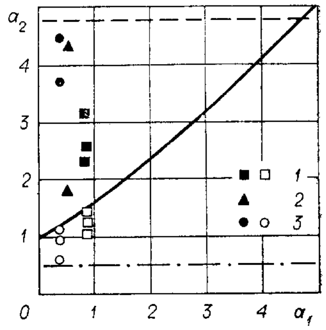

Fig. 3

$$2\varkappa x_0 = -\ln\left[1 - \frac{a_1}{a_2\left(1 - e^{-a_1}\right)}\right]. \tag{10}$$

The lower limit for exfoliation corresponding to the minimum energy (power) density of the radiation leading to destruction has the following form in the plane of the parameters a_1, a_2L

$$a_2 = a_1/\left(1 - e^{-a_1}\right). \tag{11}$$

Equation (11) is universal for all elastic materials. Since Eq. (10) implies that the maximum extensive stress value σ_m^- asymptotically (as $\varkappa x \to \infty$) approaches σ_f, the section in which the fracture occurs is undefined (see Eq. (10)) and depends on random causes.

With removal from the lower boundary (11) (by increasing radiant energy (power) density) the thickness of the exfoliated layer decreases rapidly. For example, if the value of the left side of Eq. (11) exceeds unity by 0.1, which corresponds to a 10% increase in E_0, the thickness of the exfoliated layer becomes $\sim 1/\varkappa$. Since in real situations there is always a certain spread in local parameter values characterizing the radiation and material, the maximum fractured material layer thickness found in experiments will obviously be $\sim 1/\varkappa$.

The solution obtained above is valid only for relatively low energy concentrations in the absorbing layer, where the material has not yet lost its elastic properties, and evaporation of the material is negligibly small. A numerical solution of disintegration of a plane layer with consideration of its possible two-phase nature was carried out in [4].

Using the example of vitreous material, we will derive an explicit upper limit for the applicability of Eq. (4). Due to the exponential dependence of vitreous material viscosity on temperature it becomes possible [11] to introduce the concept of the transformation temperature T_f, the temperature at which the material loses its elastic properties. Based on this fact, the condition for applicability of Eq. (4) can be written as

$$\varkappa q_0 \tau_i \leqslant \rho c T_f. \tag{12}$$

In the plane of the parameters a_1, a_2, Eq. (12) has the form

$$a_2 \leqslant 3K\alpha T_f/2\sigma_f.$$

In Fig. 3, in terms of the parameters a_1 and a_2 we show the lower limit for exfoliation destruction, Eq. (11), (solid line) and the limit of applicability of Eq. (4) for K-8 glass (dashed line) and for fused quartz (dash-dot line). The physical constants characterizing the K-8 glass and fused quartz were taken from [11, 12].

As is evident from Fig. 3, for K-8 glass there is a fully defined range of the parameters a_1 and a_2 in which the solution obtained herein is applicable. In the case of fused quartz the material softens before the extensive stress reaches the dynamic fracture strength of the material, so that Eq. (4) cannot be used to analyze destruction by fracture.

Experiments were performed to observe exfoliation phenomena occurring on the irradiated surface of vitreous materials under laser pulse action. The experiments employed a neodymium glass laser operating in the modulated-Q mode with pulse duration at the half-power level $\tau_i \simeq 80$ nsec.

A 50-cm focal length lens was used to direct the laser radiation onto the specimen surface in the form of a spot $\sim$0.2-0.5 cm in diameter. The laser radiation energy was measured

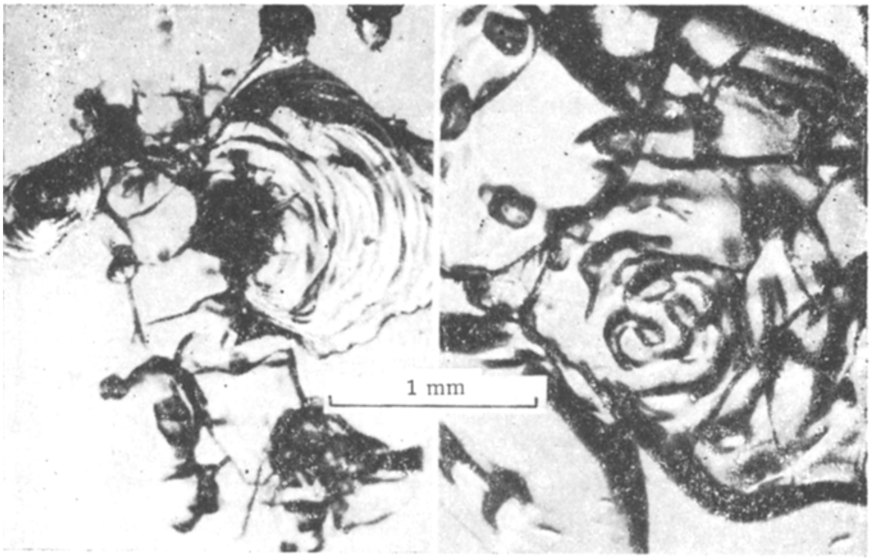

Fig. 4

by an IKT-1M calorimeter device, and the variation in generation over time was measured with an FEK-14 photocell and I2-7 oscilloscope. The energy distribution over the specimen surface was not controlled, and the phenomena observed were related to the average energy density $\bar{E}$ over the spot area.

The specimens were prepared from type NS-12, NS-10, and SZS-23 glasses, which are used in industrial production of colored glasses. The glass specifications give an absorption coefficient at 1.06 μm of 17.1, 11.1, and 8.1 cm^{-1} respectively.

It was established that there exists a threshold energy density value $\bar{E}_t$, dependent on the type of glass, at which fracture phenomena begin to occur on the glass surface. The experimental value of E_t for NS-12 glass was ~30 J/cm^2. At such an $\bar{E}_t$ value sickle-shaped pits appeared on the surface of the NS-12 glass.

Further increase in $\bar{E}$ led to formation of cone-shaped craters on the specimen surface. For NS-12 and NS-10 glasses the crater depth lay in the ranges 0.03-0.09 and 0.05-0.1 mm.

Destructure of SZS-23 glass occurred with pulverization of the material in the irradiated region to a depth of 0.2-0.5 mm, although the pulverized material was not expelled from the specimen.

Photographs of laser-irradiated NS-10 (left) and SZS-23 (right) glasses are shown in Fig. 4.

Since condition (1) was fulfilled in the experiments, while the time for arrival of an unloading wave from the edge to the center of the irradiated spot was 2-3 times longer than the laser pulse duration, from the viewpoint of stress development the data obtained can be compared to the one-dimensional theory developed here.

In the coordinates a_1, a_2 in Fig. 3 shows the experimental results for specimens of NS-12, NS-10, and SZS-23 glass (points 1-3 respectively) with the shaded points indicating experiments where exfoliation destruction was observed. In calculating the a_1 and a_2 values corresponding to the experimental conditions it was assumed that the physical constants of the glasses used, with the exception of the absorption coefficient, were the same as those of K-8 glass, with values equal to [11, 12]: $\rho = 2.5 \cdot 10^3$ kg/m^3, $c_0 = 5.7 \cdot 10^3$ m/sec, $c = 0.76$ kJ/(kg·°K), $K = 4 \cdot 10^{10}$ Pa, $\alpha = 7.6 \cdot 10^{-6}$ deg^{-1} K, $\sigma_f = 6 \cdot 10^7$ Pa.

As is evident from Fig. 3, exfoliation destruction of the glasses occurred in the a_1 a_2 range predicted theoretically.

Thus, the evaluations performed in the present study may be used for analysis of destruction in elastic materials which are partially transparent to radiation.

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EFFECT OF LOADING PREHISTORY ON MECHANICAL PROPERTIES OF STEEL IN SINGLE-AXIS EXTENSION

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Rational design of structures operating under intense dynamic loads requires a detailed study of material properties in various modes of high speed deformation. Maximum exploitation of the material's strength properties requires a knowledge of the parameters of the equation of state in the deep plasticity region with significant shifts in deformation rate. In such cases [1, 2] the material's loading prehistory can have a significant effect on the properties [3]. For example, it is known that hardening is greater with high speed deformation than with deformation at lower rates [4, 5].

The goal of the present study is an experimental investigation of the effect of loading prehistory on the mechanical properties of stainless steel. The literature is lacking in data from such studies on important structural materials such as steels.

The studies were performed at a temperature of 293 ± 3°K on specimens of 12Kh18N10T sheet steel, quenched in air ($\sigma_{0.2}$ = 0.33 GPa, σ_B = 0.63 GPa, δ = 61.5%). In the experiments

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