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FORMATION OF AN ELECTRET STRUCTURE BY EXPOSURE OF A DIELECTRIC TO A LASER PULSE IN AN ELECTRIC FIELD

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The appearance of mechanical stresses on the surface of a dielectric exposed to a laser pulse is considered.

As is known, when the surface of a medium is exposed to laser radiation, a local heat source appears, which develops a rather high temperature that leads to the generation of a heat wave. Moreover, if an electric field is applied in this case to the surface, different situations appear, depending on the electrical conductivity of the medium. In the case of a conducting medium covered with a dielectric film, the effect of electromagnetic radiation leads to the appearance of a relief structure of the surface [1]. Besides, if physicochemical processes appear on the surface that bring about "swelling" of the surface layer, fracture of the surface can occur [2]. At the same time, during pulse heating in a field an electret structure is formed in the interior of the dielectric matrix. The arising electric forces can be rather large and can destroy the matrix. The objective of the present work was theoretical determination of the electret structure induced in the body of a dielectric on exposure of its surface to a laser pulse in a constant electric field applied to the surface, as well as to provide a sink for charges from the surface, for example, by depositing a thin conducting film on the surface. The laser pulse is short, and it can be considered instantaneous compared with the process of heat conduction. The propagation of heat after instantaneous heat liberation is described by the expression [3]

$$T(r, t) = T_1 \left(\frac{4\chi t}{R^2}\right)^{-3/2} \exp\left(-\frac{r^2}{4\chi t}\right), \qquad (1)$$

where R and T_1 are the radius and local temperature of the laser spot on the body surface, respectively; $T(\mathbf{r}, t)$ is the temperature at point $\mathbf{r}$ at time t; the vector $\mathbf{r}$ is reckoned from the spot center. In Eq. (1) it is assumed for simplicity that there is no heat release from the external surface.

The electrical conductivity of dielectrics σ usually increases in accordance with the Arrhenius law. Taking into account such a strong growth with temperature, the quantity is approximated by a step function [4]:

$$\sigma = \begin{cases} 0, & T < T_\sigma, \\ \infty, & T > T_\sigma, \end{cases}$$

where the boundary value of the temperature T_σ is fixed.

It is necessary to take into account that for any point $\mathbf{r}$ the temperature first increases and then drops, with its maximum value being equal to

$$T_m = T_1 \left(\frac{R}{r}\right)^3 . \qquad (2)$$

Taking into account that for all of the moments of time $\partial T(r, t)/\partial r < 0$, we isolate two phases in the formation of an electret structure in a dielectric:

1) the formation of a conducting sphere on whose surface the temperature T_σ is maximal; the radius of this sphere is equal to (see Eq. (2))

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$$r_n = R \left(\frac{T_1}{T_\sigma}\right)^{1/3} \tag{3}$$

and it is formed during a time determined by the equation $T(r_n, t_n) = T_\sigma$, which has an approximate solution

$$t_n \simeq \frac{r_n^2}{4\chi} \ln^{-1} \left[\frac{T_1}{T_\sigma} \left(\frac{R^2}{r_n^2} \ln \frac{T_1}{T_\sigma}\right)^{3/2}\right]; \tag{4}$$

2) at the stage $t > t_n$ the radius of the sphere on whose surface $T = T_\sigma$ decreases; electric charges are deposited on this boundary, in consequence of which a charge sphere of radius r_n appears.

The distribution of the charge in the sphere is determined by the rates of two processes: the decrease in the size of the sphere with a decrease in temperature T_σ on the surface and the supply of charges from without. Let us consider these processes. The decrease in the size of the conducting sphere is again described by Eq. (1), if on the left we substitute $T = T_\sigma$. Taking into account expressions (3) and (4), we rewrite the last equation in the form

$$r^2 = 4\chi t \left[\frac{r_n^2}{4\chi t_n} - \frac{3}{2} \ln \frac{t}{t_n}\right] \quad (t > t_n). \tag{5}$$

It is seen that as t increases, the value of r is descreased, $r \to 0$, as $t \to t_k$:

$$t_k = \frac{T_1}{T_\sigma} \frac{R^2}{4\chi},$$

the law of approximation of $r \to 0$ has the form

$$r^2 = 6\chi t_k \ln \frac{t_k}{t}. \tag{6}$$

Let us consider the process of the inflow of charges. The equation that describes the deposition of charges on a hemisphere is

$$\rho (r)\, 2\pi r^2 \left(-\frac{dr}{dt}\right) = J(t), \tag{7}$$

where $\rho(r)$ is the volumetric charge density at distance r from the point of heating; $J(t)$ is the total current to the hot point. The value of $J(t)$ depends on whether we have a constant-current or of a constant-voltage circuit. The greatest charges are accumulated when a constant-current circuit is used, $J(t) = J_0$; let us limit the discussion to this case, when the charge distribution is described by the formula (see Eq. (7)):

$$\rho (r) = \frac{J_0}{2\pi r^2 \left(-\frac{dr}{dt}\right)}, \tag{8}$$

where $(-dr/dt)$ is determined with the aid of Eq. (5). We can easily write a formula for the electric potential at the zero point on the surface:

$$\varphi = \varphi_0 + \varphi_1,$$

where $\varphi_0 = J_0 t_n / r_n$ is the potential created by charges on the surface of maximum radius for the electret structure (appearing at the time $t = t_n$),

$$\varphi_1 = 2\pi \int_0^{r_n} r^2 dr \frac{\rho (r)}{r} = 2J_0 \int_0^{r_n} \frac{dr}{\left(-\frac{dr^2}{dt}\right)}.$$

We can easily calculate the latter integral by using approximation (6) and the theorem of the mean:

$$\varphi_1 = \frac{2J_0 t_k}{\sqrt{6\chi t^*}},$$

where t^* is selected from the interval (t_n, t_k). Comparison shows that the potentials φ_0 and φ_1 have the same order of magnitude.

Let us estimate the mechanical stresses appearing in the matrix (on the surface) by the formula

$$\sigma_1 = \frac{1}{\pi r_n^2}\left[\frac{Q(r_n)\varphi_0}{r_n} + \int_0^{r_n} \frac{2\pi r^2 dr Q(r)\rho(r)}{r^2}\right],$$

where

$$Q(r) = 2\pi \int_0^r drr^2 \rho(r)\, dr$$

is the charge in a hemisphere of radius r; the first term in the brackets describes the force acting on the full volumetric charge from the side of the surface charge on a hemisphere of radius r_n, the second term stands for the volumetric forces. For $Q(r)$ we have

$$Q(r) = J_0 t_k \left[1 - \exp\left(-\frac{r^2}{6\chi t^*}\right)\right]$$

(about t^* see above). The estimating formula for σ_1 is

$$\sigma_1 = \frac{1}{\pi r_n^4}(J_0 t_k)^2 \left[1 - \exp\left(-\frac{r_n^2}{6\chi t^*}\right) + \frac{r_n^2}{6\chi t^*}\right].$$

Taking account of formulas (3) and (4), we write

$$\sigma_1 = \frac{J_0^2}{16\pi\chi^2}\left(\frac{T_1}{T_\sigma}\right)^{2/3}\left[1 - \exp\left(-\frac{r_n^2}{6\chi t^*}\right) + \frac{r_n^2}{6\chi t^*}\right].$$

The quantity in the square brackets depends weakly on the heating regime, which determines only the magnitude of the initial heating T_1, which substantially influences σ. The magnitude of the current J_0 is even more important.

Let us carry out the corresponding estimation. If $r_n \simeq 5 \cdot 10^{-4}$ m and $Q_0 = J_0 t_k \simeq 10^{-5}$ C, then $\sigma_1 \simeq 5 \cdot 10^{10}$ Pa, i.e., the value is quite sufficient to initiate fracture of the dielectric material surface. By selecting the laser pulse parameters and the magnitude of the current it is possible to apply a pattern of stresses (without disintegration), thus ensuring the creation of a electret memory of the image.

Thus, the combined use of laser pulse heating and an electric supply makes it possible to create electret structures in dielectrics. This opens new possibilities for mechanical treatment of materials without melting. We should note that electret structures in dielectrics are also formed by pulse heating in the absence of an electric field if the current of thermoelectronic emission from the surface of the heated dielectric is taken into account, but the determination of such a structure needs special consideration.

NOTATION

$T(r, t)$, temperature of the medium at point r at time τ; T_1, initial temperature of the laser spot; R, radius of the laser spot; χ, thermal diffusivity of the material; σ, electrical conductivity of the material; T_σ, temperature at the boundary; T_m, maximum temperature; r_n, radius of conducting sphere; t_n, time of formation of conducting sphere; J_0, constant value of total current; φ, potential at a zero point; φ_0, potential on the surface of maximum radius; σ_1, mechanical stress.

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