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Forming Dynamics of Temperature Stress Fields in the Process of Parallel Thermosplitting

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Growing demands to the quality and accuracy of the articles produced for digital and medical techniques and equipment creates the necessity to improve the knowledge and production of new treatment technologies of glass and ceramic stuff. In this case laser technologies are most effective. Their development and optimization need the solution of theoretical tasks in the area of thermoelasticity.

One of the most interesting kinds of laser division of brittle nonmetal materials is the laser parallel thermosplitting which consists in the appearance and development of a parallel plane surface of the treated material that divides cracks in the active zone of the moving laser beam. Finding out of the physical mechanism of this process and studying its technological potentialities is a problem of today.

This research describes the forming dynamics of temperature stress fields in different types of thermosplitting finding out their mechanisms and studying experimentally and theoretically the changing range of the main technological parameters. To understand the mechanism of the laser thermosplitting, it is necessary to solve the problem of the determination of temperature stresses moulding in the semi-infinite medium when it is being exposed to radiation by moving an elliptical laser beam with a Gaussian distribution of intensity. Let the axis of the beam coincide with coordinate axes and moving in the positive direction of the X axis. Absorption is considered to be shallow that corresponds to the usage of a continuous CO_2 - laser with the length of wave 10.6mcm as heat source. Ignoring the heat flow in the sample in the direction of the X axis, we will limit ourselves to a two-dimension task. In this case the dependance of the density of emission on time in the founding condition of the heat equation

$$-\lambda\frac{dT}{dz} = P_0 exp\left[-\frac{(2A-Vt)^2}{A^2} - \frac{y^2}{B^2}\right], \; z=0 \qquad (1)$$

will model the motion of a real laser beam.In the relation (1) λ is the heat diffusivity coefficient of the material from the point of view of a three-dimensional task the moment of time t =0, considering the transit of the beam centre at the surface point the distance of which to the plane X = const is equal to 2A. The laser beam moves to plane X = const, passes it and goes to infinity.

The solution of the homogeneous two-dimensional heat equation fulfilling condition (1) is given in [1]

$$T(y,z,t) = \frac{P\sqrt{a}}{\pi^{3/2}\lambda A}\int_0^t \frac{exp\left(-\frac{[2A-V(t-\tau)]^2}{A^2} - \frac{y^2}{4a\tau+B^2} - \frac{z^2}{4a\tau}\right)}{\sqrt{\tau(4a\tau+B^2)}}d\tau \qquad (2)$$

where $P=P_0 \pi AB$ is the capacity of the continuously acting laser beam, a is the thermal diffusivity coefficient of the material.

Defining the temperature stress, we ignore the inertia absolute terms of the equation of motion that coincides the solution of the task in a quasi-statistical situation.

In an isotropic and homogeneous elastical body heated by a heat source, the distribution of intensity of which does not depend on the coordinate X, there appears a flat deformated state which is characterized by moving $\bar{U} = (0, U_2, U_3)$. Because one of the moving vector component is equal to zero the components σ_{12} σ_{13} of the tensor of elastic stresses are equal to zero. Proceeding the two-dimensional equation of travel of the quasi-statistical theory of elasticity

$$[\mu\nabla_1^2 + (\lambda_1 + \mu)\, grad\, div]\, \overline{U} = (3\lambda_1 + 2\mu)\alpha_T grad\, T. \qquad (3)$$

Here μ, λ_1 - Lamé coefficients, $\nabla_1^2 = \frac{d^2}{dy^2} + \frac{d^2}{dz^2}$ two-dimensionaly Laplasian operator, α_T -coefficient of thermal expansion of the material.

We will also demand the observation of founding condition meeting the absense of load on the body surface:

$$\sigma_{23} = \sigma_{33} = 0, \; z = 0. \qquad (4)$$

The solution of the equation (3) results in the sum $\tilde{U} = \tilde{U}^{*} + \tilde{U}^{**}$ of the partial solution $\tilde{U}^{*} = \text{grad}\,\Phi$ of inhomogeneous equation and the general one of the homogeneous equation

The stresses σ^{*}_{ij} which coincide the mean $\tilde{U}^{*}$ are connected with the thermoelastic potential by the relation [2]:

$$\sigma^{*}_{ij} = 2\mu(\nabla_i \nabla_j \Phi - \delta_{ij}\nabla^2_1 \Phi),\ i,j = 2,3.$$

Here δ_{ij} is the two-dimensional Kronecker symbol.

Using the known methods and the Laplace transform, stress field σ^{*}_{ij} can be found:

$$\sigma^{*}_{22} = -K\int_0^t d\tau\,\left[-I/(2a\tau) + z^2/(2a\tau)^2\right] F_1F_2,$$

$$\sigma^{*}_{23} = -K\int_0^t d\tau\,(yz\beta/(a\tau))\,F_1F_2,$$

$$\sigma^{*}_{33} = -K\int_0^t d\tau\,(4y^2\beta^2 - 2\beta)\,F_1F_2, \tag{5}$$

$$F_1 = exp\left(-y^2\beta - z^2/(4a\tau)\right)(\beta/\tau)^{1/2},\ \beta = (4a\tau + B^2)^{-1}$$

$$F_2 = erf\left[V(t-\tau)/A - 2\right] + erf(2).$$

$K = \mu(1+v)a^{3/2}\alpha P/\pi_T\lambda v(1-v)$, where v - Poisson's ratio.

If the stress σ^*_{23} on the body surface is equal to zero, then to look for stress fields σ^{**}_{ij} that coincide the slip vector $\bar{U}^{**}$ under the bounding conditions (4), it is necessary to solve the homogeneous (3) with the bounding conditions

$$\sigma^{**}_{23} = 0,\ \sigma^{**}_{33} = -\sigma^{*}_{33},\ z = 0. \tag{6}$$

In (6) σ^*_{33} (y,0)= σ^*_{33} (y) is considered to be an external load. The method of finding the stresses in semi-infinite media loading on the bound z = 0 forces, depending only on the variable y, is well known and presented, for example in [2]. Following this method, we get the expression for the stress fields σ^{**}_{ij}

$$\sigma^{**}_{22} = K\int_0^t d\tau\,[N_+ + N_- - z(F_+ + F_-)]\,F_2,$$

$$\sigma^{**}_{23} = iKz\int_0^t d\tau(F_+ - F_-)F_2,$$

$$\sigma^{**}_{33} = K\int_0^t d\tau\,[N_+ + N_- + z(F_+ + F_-)]\,F_2, \tag{7}$$

$$N_\pm = (\beta^{3/2}/\sqrt{\pi\tau})\left(2\sqrt{\beta}(z\pm iy) + \sqrt{\pi}\left[1 + 2\beta(z\pm iy)^2\right]\times\right.$$
$$\left.\times exp\left[(z\pm iy)^2\beta\right] erfc\left[\sqrt{\beta}(z\pm iy)\right]\right),$$
$$F_\pm = (-4\beta^2/\sqrt{\pi\tau})\left(1 + \beta(z\pm iy)^2 - \sqrt{\pi}\left[3/2\sqrt{\beta}(z\pm iy)+\right.\right.$$
$$\left.\left.+\beta^{3/2}(z\pm iy)^3\right] exp\left[(z\pm iy)^2\beta\right] erfc\left[\sqrt{\beta}(z\pm iy)\right]\right).$$

The sum $\sigma_{ij} = \sigma^{*}_{ij} + \sigma^{**}_{ij}$ defines the stress field appearing in a semi-infinite body under the action of moving a laser beam on its surface.

The results of the numerical analysis of temperature stress fields that appear in glass when subjected to laser parallel thermosplitting are given here. Calculations were made for a beam with effective capacity P= 22Vt, moving at a speed of V=18mm/s. The size of the beam was A=0.5 mm, B=4.25 mm. Thermal and physical characteristics of the glass were defined by the following values: $a = 0.4 \cdot 10^{-6} m^2/s$, $\lambda = 0.81$ Vt/m, $\alpha_T = 0.89 \cdot 10^{-5}$ 1/K, v=0.22, $E = 68 \cdot 10^9$ Pa ($E = 2\mu(1+\nu)$)- Young's modulus).

The stress σ_{33} (fig.1) grows with the increasing of depth from zero value on the surface to a maximum value and is reduced to zero with a further growth of the coordinate z. As seen from the chart, when time elapses the component σ_{33} of the stress tensor (fig.2) also changes from zero to a maximum value and from the moment t=6A/v=0.17 s at begins slowly diminish. So, the normal stress σ_{33} receives its maximum value not on the surface of the plate, where it is because of the bounding conditions equal to zero. but at a definite depth.

The stresses σ_{33} being spread on the surface become quickly reduced with growth of the coordinate z and at different moments of time at depths of 0.2-0.4 mm they are passing through a zero value and change from being spread to compressed, preventing in this way the development of a crack from the surface of a sample.

Beside the fact that in the considered regime the laser beam has an elliptical shape oriented with the small axis forward the direction of motion, (B/A =8.5) increases the area of affective influence of the stress σ_{33} . So the stress σ_{33} plays a decisive role in developing a microcrack in the plane parallel to the surface of the sample.

It is worth while mentioning that the theoretical evaluation of the depth at which the microcrack should spread was slightly lower down. It could be explained by the approximation made in the task. First of all it is affected by the fact of not taking into account the three-dimensional structure of the temperature stress fields and assuming the linearity in the model of the heat transfer processes.

The considered method of the laser parallel thermosplitting of glass can be of great interest in getting thin flat parallel plates, for example, glass plates for liquid cristal indicators, where it helps to exclude in some cases labour-consuming and expensive traditional processes of grinding and polishing of glass on the surface up to a pre-assigned thickness.

References

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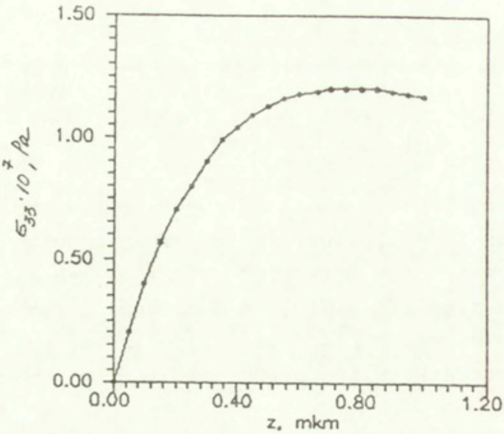

Fig.1. The dependence of the normal stress σ_{33} , acting in the direction that is perpendicular to the surface of the sample from coordinate z.

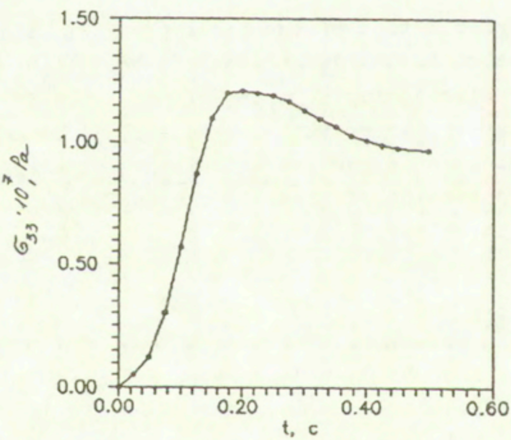

Fig. 2. The dependences of the normal stress σ_{33} on the surface of the sample from time t.