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CONSIDERATION OF REFLECTION FROM THE BACK SURFACE DURING LASER ANNEALING OF OPTICAL GLASS PLATES WITH HIGH REFRACTIVE INDEX VALUES

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Within the framework of the quasi-static unrelated problem of thermoelasticity, a criterion for the thermal strength of a freely pinched plate during pulsed laser annealing is obtained, taking into account the reflection of laser radiation from the back surface of the plate. The possibility of reducing the maximum tensile stresses in the plate by 15 – 65% and energy costs for annealing by 8 – 30% is shown. It was established that consideration of the reflection of laser radiation from the back surface of the plate leads to a decrease in the interval of variations of the dimensionless parameter ÷*h* (the product of the absorption index by the plate thickness), in which thermoelastic stresses may cause plate destruction.

Keywords: optical glass, laser annealing, refractive index, reflection coefficient, quasi-static thermoelasticity problem, thermal strength criterion.

INTRODUCTION

At present, laser annealing of glass and semiconductor wafers, as well as thin-film coatings and glass waveguides, is increasingly finding application [1 – 7]. In [1 – 4], semiconductor wafers were subjected to laser annealing after ion-implantation processing to improve the damaged structure of the semiconductor and to change the implant concentration across the wafer thickness. In [2], laser annealing of wafers was carried out with a CdTe laser with a wavelength of 1.064 μm, operated in continuous mode. For the same purpose, laser annealing of glass wafers was carried out after ion implantation with metals to create new optical media with specified properties for use in photonics [5, 6]. In addition, laser annealing of optical glass plates operated as transmission optics in high-power laser installations was found to increase their radiation resistance in the passband due to relaxation of residual stresses that arise in the surface layer of annealed glass during grinding and polishing.

In [8], non-destructive modes of pulsed laser annealing of glass plates were substantiated for cases of laser radiation applied to one and both surfaces of the plate. The studies were carried out without taking into account the reflection of laser radiation from the back surface of the plate. This assumption is valid for the majority of optical glasses whose refractive index does not exceed 1.50 – 1.65. In this case, the reflection coefficient from the back surface of the plate, which is about 0.04 – 0.06, can be neglected in the calculations. For example, for light crown-, crown-, heavy crown-, crown flint-, light flint-, barite flint-, and other optical glasses [9], the reflection coefficient from one surface of the plate varies within the specified range. However, for heavy flint-, super-heavy flint-, and heavy barite flint TBF14 glasses, the refractive index comprises 1.64 – 1.90, more than 1.9, and 1.96, respectively. For these types of glasses, the reflection coefficient of the incident laser radiation from the back surface of the plate equals about 0.1, thus affecting significantly the temperature distribution across the thickness of the plate and, consequently, the thermoelastic stresses therein.

Recent years have seen the emergence of aluminosilicate glasses [7, 10, 11] developed with the addition of up to 27 mol.% lanthanum and niobium oxides, with the refractive

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index of more than 1.8. These glasses are used in the development of informational, optical, and laser systems to compensate for spherical and chromatic aberrations [11]. The researchers in [12] studied glasses based on PbO–Ga$_2$O$_3$, which have a wide passband from 0.5 to 7.5 μm and a high refractive index of about 2.2. These glasses are intended for use in optics and photonics for devices in the infrared spectrum.

Note should be made of specific groups of gallate, chalcogenide, halogen chalcogenide, and oxyhalide glasses [13 – 18], intended for optical systems operating in the infrared spectrum and having a refractive index of about 2.4 – 3.8 depending on the glass composition. For these glasses, the reflection coefficient of laser radiation from the back surface of the plate equals up to 0.34, thus requiring its consideration in calculations.

CALCULATION MODEL AND ANALYSIS OF RESULTS

The temperature field in the plate by the end of the laser pulse, taking into account reflection from the back surface, is determined by the relation [1]

$$T(z)=T_0+\frac{(1-R)\chi W(e^{-\chi z}+e^{-\chi(2h-z)}R)}{c\gamma}, \qquad (1)$$

where z is the coordinate measured from the irradiated surface into the bulk of the plate; T_0 is the initial temperature of the plate; R is the reflection coefficient of the plate material from one surface of the plate; χ is the absorption coefficient of the plate material at the wavelength of laser radiation; W is the energy density of laser radiation; c and γ are the specific heat capacity and density of the plate material, respectively; h is the plate thickness.

Formula (1) is valid provided that the condition $\chi\sqrt{a\tau} \ll 1$ is met (a is the thermal diffusivity of the plate material, τ is the duration of the laser pulse).

Under the action of a temperature field, which changes only within thickness, thermoelastic stresses arise in the plate [19]:

$$\sigma_x(z,t)=\sigma_y(z,t)=\frac{E}{1-\nu}\left(\varepsilon_T-\alpha_T\left[T(z,t-T_0)\right]\right); \qquad (2)$$

$$\varepsilon_T=\frac{1}{h}\int_0^h \alpha_T\left[T(z,t)-T_0\right]\mathrm{d}z, \qquad (3)$$

where $\sigma_x(z,t)$, $\sigma_y(z,t)$ are thermoelastic stresses in the plate; E is Young's modulus of the plate material; ν is Poisson's ratio; α_T is the temperature coefficient of linear expansion; ε_T is the average temperature across the plate thickness; $T(z,t)$ is the temperature.

From equations (1) – (3), taking into account the reflection of laser radiation from the back surface of the plate and after carrying out mathematical transformations, we obtain:

$$\sigma_{\max}(\chi h,R)=\frac{E\alpha_T(1-R)\chi W}{(1-\nu)c\gamma}\left(\frac{1-(1-R)e^{-\chi h}-R(e^{-2\chi h})}{\chi h}-(1+R)e^{-\chi h}\right); \qquad (4)$$

$$W_T=\frac{\sigma_{Bp}(1-\nu)c\gamma}{E\alpha_T(1-R)\chi\left(\dfrac{1-(1-R)e^{-\chi h}-R\left(e^{-2\chi h}\right)}{\chi h}-e^{-\chi h}\right)}; \qquad (5)$$

$$W_f(\chi h,R)=\frac{\left(T_f-T_0\right)c\gamma}{(1-R)\chi\left(1+e^{-2\chi h}R\right)}; \qquad (6)$$

$$\frac{\sigma_{Bp}(1-\nu)}{E\alpha_T\left(T_f-T_0\right)}\geq\frac{1-(1-R)e^{-\chi h}-e^{-2\chi h}R-\chi he^{-\chi h}}{\chi h\left(1+e^{-2\chi h}R\right)}=f(\chi h,R), \qquad (7)$$

where $\sigma_{\max}(\chi h,R)$ are the maximum tensile stresses in the plate; W_T is the energy density of laser radiation required to destroy the plate by thermoelastic stresses; $W_f(\chi h,R)$ is the energy density of laser radiation required for the plate surface to reach the annealing temperature; T_f is the plate annealing temperature; σ_{Bp} is the ultimate tensile strength of the plate material.

Formula (4) can be used to obtain the ratios of the maximum tensile stresses in the plate, both taking into account the reflection of laser radiation from the back surface of the plate and without its consideration:

$$\frac{\sigma_{\max}(\chi h,R)}{\sigma_{\max}}=\frac{\left(1-(1-R)e^{-\chi h}-R\left(e^{-2\chi h}\right)-\chi h(1+R)e^{-\chi h}\right)}{\left(1-e^{-\chi h}-\chi he^{-\chi h}\right)}, \qquad (8)$$

where $\sigma_{\max}$ is the maximum tensile stress in the plate without taking into account the reflection of laser radiation from the back surface.

In a similar manner, we find the ratio

$$\frac{W_f(\chi h,R)}{W_f}=\frac{1}{\left(1+e^{-2\chi h}R\right)}, \qquad (9)$$

where W_f is the energy density of laser radiation required for the wafer surface to reach the annealing temperature without taking into account reflection from the back surface of the wafer.

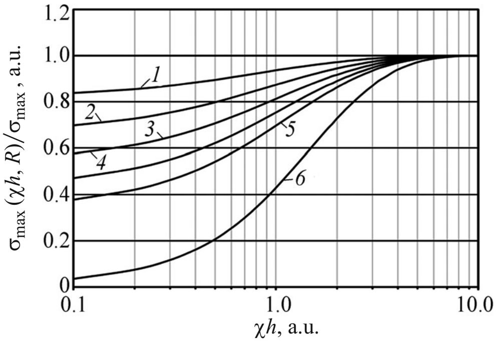

Fig. 1. Dependence of the ratio $\sigma_{\max}(\chi h, R)/\sigma_{\max}$ on the reflection coefficient for the following values: *1*) $R = 0.1$; *2*) $R = 0.2$; *3*) $R = 0.3$; *4*) $R = 0.4$; *5*) $R = 0.5$; *6*) $R = 1$.

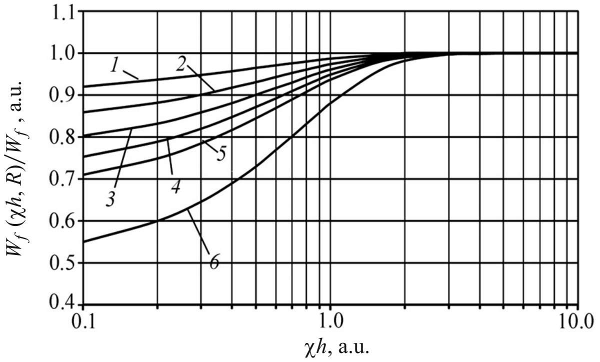

Fig. 2. Dependence of the ratio $W_f(\chi h, R)/W_f$ on the dimensionless parameter χh and the reflection coefficient for the following values: *1*) $R = 0.1$; *2*) $R = 0.2$; *3*) $R = 0.3$; *4*) $R = 0.4$; *5*) $R = 0.5$; *6*) $R = 1$.

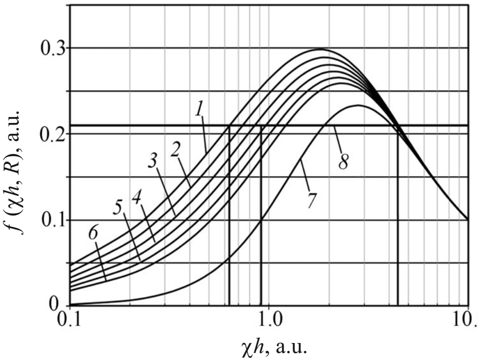

Fig. 3. Graphical solution of expression (7) for IKS32 optical glass: *1*) $R = 0.1$; *2*) $R = 0.2$; *3*) $R = 0.3$; *4*) $R = 0.4$; *5*) $R = 0.5$; *6*) $R = 1$; *8*) is left-hand side of expression (7) for IKS32 chalcogenide optical glass.

Figure 1 shows a graphical solution of equation (9) for the reflection coefficients in the interval of variation of the dimensionless parameter χh from 0.1 to 10.0. It can be seen that the consideration of reflection coefficient from the back surface of the plate unambiguously leads to a decrease in tensile stresses by a maximum of 15 – 65% at the χh values $\chi h < 5$.

Figure 2 shows the dependence of the ratio $W_f(\chi h, R)/W_f$ on the dimensionless parameter χh and the reflection coefficient of laser radiation from the back surface of the plate in the interval of variation of the dimensionless parameter χh from 0.1 to 10.0. The dependence is nonlinear. The reduction in energy costs for annealing can be from 8 to 30%, depending on the reflection coefficient value and the specific value of the χh parameter for the plate under treatment. A positive effect is observed for values of the dimensionless parameter $\chi h \leq 2$.

Let us analyze formula (7) using the example of IKS32 chalcogenide optical glass. Figure 3 shows a graphical solution of formula (7) for IKS32 optical glass. For $R = 0$, the function reaches its maximum value of 0.2984 at $\chi h = 1.7933$. When carrying out an extremum analysis, for reflection coefficients of 0.1, 0.2, 0.3, 0.4, 0.5, and 1, the function reaches maximum values of 0.2891, 0.2806, 0.2728, 0.2657, 0.2591, and 0.2333 at $\chi h = 1.899$, 2.004, 2.1076, 2.2099, 2.3103, and 2.7741, respectively. An increase in the reflection coefficient of laser radiation from the back surface of the plate leads to a decrease in the function maximum and its shift towards higher values of the dimensionless parameter χh. For example, for IKS32 optical glass, without considering the reflection of laser radiation from the back surface of the plate, its destruction under the action of thermoelastic stresses is possible at $0.63 < \chi h < 4.40$. Taking into account the reflection coefficient, which is 0.25 for a laser radiation wavelength of 1.06 μm [12, 14, 15], this region lies within the limits $0.93 < \chi h < 4.40$ (see Fig. 3). In other words, a significant shift of the left boundary of the region of possible destruction of the plate under the action of thermoelastic stresses and its decrease are observed.

In a similar way, equations for the maximum tensile stresses and the thermal strength criterion of a plate subjected to simultaneous annealing of its both surfaces can be obtained:

$$\sigma_{\max}(\chi h/2) = \frac{2E\alpha_T(1-R)\chi W}{(1-\nu)c\lambda}\left[\frac{1-(1-R)e^{-\chi h} - R(e^{-2\chi h})}{\chi h} - e^{-\chi h/2}(1+e^{-\chi h}R)\right]; \tag{10}$$

$$\frac{\sigma_{Bp}(1-\nu)}{E\alpha_T\left(T_f - T_0\right)} \geq \frac{[1-(1-R)e^{-\chi h} - e^{-2\chi h}R - \chi h e^{-\chi h/2}(1+e^{-\chi h}R)]}{\chi h[1+e^{-\chi h}(1+e^{-\chi h}R)]} = f_2(\chi h, R), \tag{11}$$

TABLE 1. Dependence of the $f_2(\chi h, R)$ Function on χh Parameter and Reflection Coefficient

χh	1	2	3	4	5	6	7	8	9
$R = 0$	0.0374	0.1135	0.1783	0.2162	0.2316	0.2323	0.2248	0.2132	0.1999
$R = 0.2$	0.0393	0.1162	0.1800	0.2169	0.2318	0.2324	0.2248	0.2132	0.1999
$R = 0.4$	0.0412	0.1189	0.1817	0.2177	0.2321	0.2325	0.2249	0.2132	0.1999

TABLE 2. Study of the $f_2(\chi h, R)$ Function for Extrema

R	0	0.1	0.2	0.3	0.4
$f_2(\chi h, R)_{\max}$	0.2333	0.2334	0.2335	0.2336	0.2337
χh	5.55	5.54	5.53	5.52	5.51

Let us analyze the obtained relationships. Table 1 presents the calculation results of the right-hand side of equation (11) for reflection coefficient values of 0, 0.2, and 0.4. It can be seen that, despite the apparent similarity, equations (9) and (11) differ significantly. The function $f_2(\chi h, R)$ depends weakly on the reflection coefficient of the plate material. The difference is no more than 10% for highly small values of the χh parameter. It should be noted that for small χh values, an increase in the reflection coefficient causes an insignificant increase in the value of the $f_2(\chi h, R)$ function. For $\chi h > 7$, the reflection coefficient has virtually no effect on the calculation results. The study of the extrema of the $f_2(\chi h, R)$ function shows that an increase in the reflection coefficient leads to a highly insignificant increase in the extremum of the function and its shift toward smaller values of the χh parameter. These differences are explained by the fact that the average temperature of the plate, taking into account the reflection coefficient from the back surface of the plate, increases somewhat more than the temperature in the $\chi h/2$ section. The study of extrema of the $f_2(\chi h, R)$ function are presented in Table 2. Hence, when calculating non-destructive laser annealing modes for the case of simultaneous action of laser radiation on both surfaces of the plate, the influence of the reflection coefficient from the back surface can be ignored.

CONCLUSIONS

The calculation method was used to establish the following. Consideration of the reflection of laser radiation from the back surface of the plate during annealing of one of its surfaces, the maximum tensile stresses in the plate decrease by approximately 15 – 65% depending on the reflection coefficient and the dimensionless parameter χh. A positive effect is achieved at $\chi h < 5$.

Consideration of the reflection of laser radiation from the back surface of the plate during annealing of one of its surfaces makes it possible to reduce the energy density required for annealing the plate by approximately 8 – 30% at $\chi h < 2$.

Using the example of IKS32 optical glass, a shift in the boundary of possible plate destruction under the action of thermoelastic stresses is shown from $\chi h = 0.63$ to $\chi h = 0.93$.

When carrying out simultaneous laser annealing of two surfaces of the plate, the influence of the reflection coefficient from the back surface of the plate can be neglected.

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