MEASUREMENT OF TEMPERATURE FIELDS IN SPECIMENS OF QUARTZ CERAMIC DURING SURFACE ABLATION

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The authors propose a method of mounting thermocouples and have obtained temperature fields within specimens of pure and doped quartz ceramic. The linearity of the dependence $\Delta^* = f(\sqrt{\tau})$ for deep isotherms has been proved experimentally.

The temperature field inside a material is important initial information in determining its thermophysical characteristics and depth of heating. It is of especial interest to measure the temperature fields during intense one-sided heating, enough to cause thermal breakdown of the material surface. Under these conditions it was established in [1, 2] that the thickness of the heated and removed layer Δ^* depends linearly on $\sqrt{\tau}$ observed over the time range $\tau_T - \tau_\delta$. In these references they measured the path followed by the high temperature isotherms, in particular the phase transformation isotherm ($T^* \sim 1000$ K) and the isotherm corresponding to change of color in the doped quartz ceramic ($T^* = 1800$ K). However, in designing a surface heat shield one pays principal attention to determining the total depth of heating, which, as a rule, is taken to mean the position of the isotherm with temperature equal to 0.1 or 0.05 of $T_w - T_0$.

The aim of the present paper is to investigate the influence of surface ablation on the temperature distribution throughout the heated layer. It is advantageous to measure temperature inside the material with the aid of thermoelectric converters (thermocouples). The errors arising in such measurements have been examined in detail in [3-6]. Many of these can be reduced to a minimum by appropriate choice of thermocouple and method of installation in the specimen. Nevertheless, errors associated with deviation of the thermocouple characteristic from standard due to the action of products of decomposition of the material, with shunting of the thermocouple in an electrically conducting zone, and also with shrinkage of the material, always arise in measurements in sintered heat shield materials, and are not amenable to accurate calculation. For this reason the experiments were conducted on specimens of quartz ceramic in which the low-temperature component (binder) was missing.

For the investigations we used specimens of pure ceramic and ceramic doped with chromic oxide, fabricated from dross of transparent quartz glass using the technology of [7]. The porosity of the specimens was in the range 10-12%.

As is known, the accuracy of measurement of temperature inside the material depends to a considerable degree on the method of installing the thermocouples in the specimen. After examining existing schemes for locating thermocouples in specimens of composite materials [8], performing calculations and a series of test experiments, we proposed a scheme to achieve the required length of isothermal section, integrity of the material above the sensor temperature in the direction of application of the heat flux, reliable contact of the thermocouple with the material, high accuracy of measurement of the thermocouple coordinate during installation and at the end of the experiment, protection of the thermo-electrodes from the action of the high temperature gas stream, and also maintenance of the model of a semi-infinite insulated body.

A diamond wheel was used to cut four slots of different depths, of width $0.6 \cdot 10^{-3}$ m, separated by a distance of $3 \cdot 10^{-3}$ m, in specimens of glass ceramic of diameter $25 \cdot 10^{-3}$ m and length $30 \cdot 10^{-3}$ m. The depths of the slots were measured with a micrometer to an accu-

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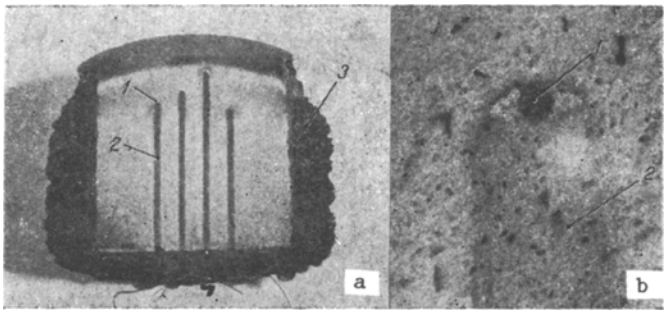

Fig. 1. Location of thermocouples in specimens of quartz glass ceramic: 1) thermocouple; 2) ceramic plate; 3) shield ring of asbestos textolite (a); magnified 50 times (b).

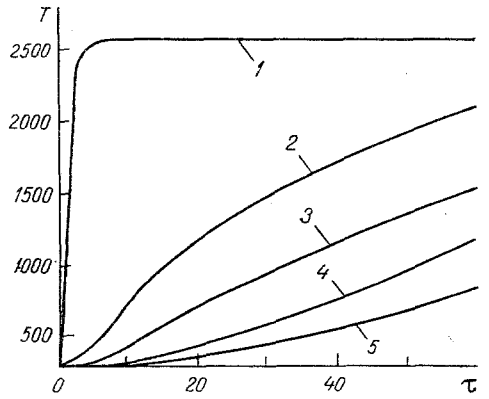

Fig. 2. Variation of temperature at the surface and inside of a doped ceramic as a function of heating time in the jet of the electric arc gas heater at q = 7260 kW/m^2: 1) on the surface; 2, 3, 4, 5) at distances $4.54 \cdot 10^{-3}$ m, $6.93 \cdot 10^{-3}$, $9.42 \cdot 10^{-3}$, and $11.65 \cdot 10^{-3}$ m from the original heater surface. The quantity T is in K, and τ is in sec.

racy of $0.01 \cdot 10^{-3}$ m. Temperature was measured with the aid of 5 thermocouples. The first of these was tungsten/tungsten-rhenium (VR 5/20) with thermoelectrode diameter $0.1 \cdot 10^{-3}$ m, and then there were three chromel–alumel thermocouples with thermoelectrode diameter $0.2 \cdot 10^{-3}$ m. The thermocouples were butt-welded and installed in such a way that the length of the isothermal section ℓ/d was ~50. The fifth thermocouple, made of the chromel–kopel was welded to a copper plate glued to the lower end of the specimen, and was used to ensure that the model of a semi-infinite insulated body was maintained. After the thermocouples were installed, they were sealed using molten glass and plates of the specimen material, which simultaneously guaranteed contact of the thermocouple with the material during congealing of the molten glass. Then the specimen was glued to an asbestos textolite substrate. The method error associated with using semi-infinite conditions was determined by comparing the solutions of the problem for a finite cylinder and a semi-infinite body with T_w = const [9]. We examined the most unfavorable regime of heat transfer where the heat transfer over the side surface of the cylinder and its lower end with a medium having the initial temperature and a heat transfer coefficient equal to ∞. For the thermocouple distant $10 \cdot 10^{-3}$ m from the surface (almost the greatest distance) and the least heating time (~60 sec) the deviation of the two-dimensional temperature fields from the temperature field of the semi-infinite body did not exceed 5%. Since the thermocouple installation scheme was intended to displace them relative to the specimen axis by $\pm 4.5 \cdot 10^{-3}$ m, heat shielding of the side surface of the specimen was accomplished with the aid of an asbestos-textolite ring. The coordinates of thermocouple installation were also monitored after the tests on the slotted specimen (Fig. 1).

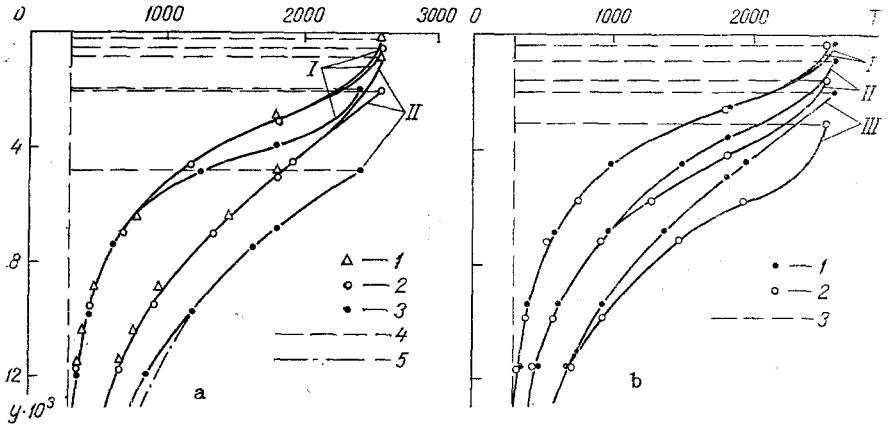

Fig. 3. Experimental temperature profiles in specimens of quartz glass ceramic: a – 1, 2, 3) doped ceramic with $\overline{V}_\infty$ = $0.02 \cdot 10^{-3}$, $0.04 \cdot 10^{-3}$, and $0.11 \cdot 10^{-3}$ m/sec; 4) position of the external surface at the heating time examined; 5) as computed from Eq. (1); I) 15, and II) 50 sec of heating; b – 1) doped ceramic, $\overline{V}_\infty = 0.04 \cdot 10^{-3}$ m/sec; 2) pure ceramic, $\overline{V}_\infty = 0.09 \cdot 10^{-3}$m/sec; 3) position of the external surface; I, II, III) 15, 30, and 50 sec of heating (all at a heat flux of 7260 kW/m²). y, m.

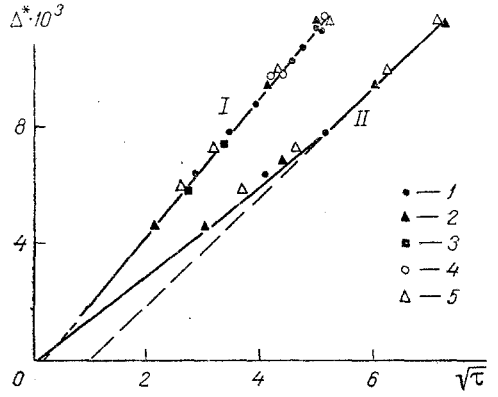

Fig. 4. Total thickness of the heated and ablated layers as a function of $\sqrt{\tau}$ for quartz glass ceramic: 1-3) doped; 4, 5) pure; 1, 4) q_k = 4130 kW/m²; 2, 5) 7260; 3) 9350 kW/m²; I) Θ^* = 0.05; II) 0.2. Δ^*, m; $\sqrt{\tau}$, $\text{sec}^{1/2}$.

The surface of the specimens was heated in the air jet of an electric arc gas heater in the heat flux range 4000-10,000 kW/m². The surface brightness temperature was measured in the visible spectral range ($\lambda = 0.65 \cdot 10^{-6}$ m) with a photoelectric pyrometer and was recorded along with the thermocouple readings, on a drift oscillograph. To calculate the true temperature we used values of emissivity from [10]. The error in determining T_w was indicated in [10]. The error in measuring the rate of removal of material in these experiments was ~15%.

Figure 2 shows an oscillogram of the measured temperature at different depth in a doped quartz glass ceramic specimen. From reduction of analogous oscillograms we constructed temperature profiles in specimens of doped and pure ceramic for various heat fluxes and rates of removal of material. Here also we used the depth of the heated layer to the $T^* = 1800$ K isotherm, which corresponds to the change of color of the doped quartz glass ceramic. As was noted in [10], by adding only up to 1% of chromic oxide we can obtain a sharp boundary. The location of this boundary ($T^* = 1800$ K) was monitored after the tests on the slotted specimens with the aid of a type MBS-9 microscope. Immediately after heating the specimen was cooled with air from a special vortex-type cooler to eliminate "post-heating."

Calculations using the formula

$$\frac{\tilde{T}-T_0}{T_w-T_0}=\exp\left(-\frac{\bar{V}_\infty}{a}y\right), \tag{1}$$

proposed in [4] for a quasisteady temperature profile show that for $\bar{V}_\infty = 0.1\cdot10^{-3}$ m/sec for 50 sec of heating the quasisteady profile should be established up to the isotherm $\Theta^* = 0.4$, which agrees with the experimental results (Fig. 3a, points 3). In the calculations the coefficient a was taken to be $0.65\cdot10^{-6}$ m^2/sec [11]. The good agreement between the calculated and experimental temperatures in the quasisteady heating regime confirms the high accuracy of the experiments.

It was shown earlier in [10] that in conditions of convective heating to a first approximation one can consider the ceramic doped with chromic oxide to be opaque, and the pure ceramic to be semi-transparent, the result being that, for the same heating conditions, the rate of ablation is roughly 70% less for the doped ceramic compared with the pure ceramic. By comparing the quasisteady sections of the temperature profiles in the specimens of these materials (Fig. 3b, curves III) one can reach the same conclusion, since the temperature profile in the pure ceramic is S-shaped, in contrast with the doped ceramic.

However, an S-shaped temperature profile in unsteady ablation conditions is also observed in specimens of doped ceramic. Apparently, in this case the S-shaped profile arises at the start of surface ablation, and as one approaches the quasisteady heating regime it becomes exponential (Fig. 3a). Hence it follows that in the unsteady ablation regime an S-shaped profile can arise from causes other than the radiant heat transfer component. For example, according to the thermal ablation model proposed in [12], there may be a certain zone with a small temperature gradient in the surface layer, since the temperature coefficient of the surface isotherms, in contrast with the classical solution with no removal of material, is not equal to zero, but to the ablation constant k_{T_a}.

As can be seen from Fig. 3, there is a range of temperature in which the depth of the heated layer does not depend on the rate of ablation and the heat flux. The numerical computations of [4] confirm that up to the temperature ratio $\Theta^* = 0.2$-0.3 the variation of dimensionless temperature inside the material should be the same with and without mass ablation.

By comparing the temperature profiles in the doped and pure ceramic for the same heating conditions (Fig. 3b) one can conclude that the deviation of the two profiles from one another due to different ablation rate increases as one approaches the quasisteady heating regime (the ablation rate of the pure ceramic is almost a factor of 2 greater than that of the doped ceramic).

From the measured temperatures in the specimens (see Fig. 2) we also constructed the dependence of the path followed by the deep isotherms ($\Theta^* = 0.05$ and 0.2) on the square root of the heating time (Fig. 4). From Fig. 4 it can be seen that the dependence $\Delta^* = f(\sqrt{\tau})$ for deep isotherms is practically linear in the heating conditions examined. Here the variation of heat flux, ablation rate and even surface temperature from T_a to T_w does not change the linear nature nor the slope of this dependence. It is only after enough time has elapsed that there is a change of slope, and the linear nature of the dependence is preserved (Fig. 4). It we consider, as was done earlier, that the coefficient $a = 0.65\cdot10^{-6}$ m^2/sec, then the straight lines $\Delta^* = f(\sqrt{\tau})$ on the left section can be represented by the equation

$$\Delta^* \approx K\sqrt{a\tau}, \tag{2}$$

where the temperature coefficient K is determined by solving the problem of heating a semi-infinite insulated body with T_w = const [13].

Thus, the question arises as to the reason why Eq. (2) holds from the start of surface ablation, in spite of the increase of temperature from T_a to T_w in this time period. This question requires further investigation.

NOTATION

Δ^*, total thickness of the heated and ablated layers; τ, heating time; τ_T, τ_δ, time to establish quasisteady values of surface temperature and depth of heating; T_w, T^*, surface and isotherm temperatures; T_0, temperature of the unheated material; $\tilde{T}$, ambient temperature;

λ, wavelength; a, thermal diffusivity; $\bar{V}_\infty$, quasisteady value of the ablation rate; y, distance from the heater surface; Θ^*, dimensionless isotherm temperature $(T^* - T_0)/(T_w - T_0)$; T_a, temperature at the start of surface ablation; q_k, calorimetric heat flux.

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COMPUTATIONAL METHOD OF THERMAL DESIGN OF SOLID STATE LASER QUANTRONS WITH NATURAL COOLING.

2. PARAMETRIC OPTIMIZATION

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Recipes and results of parametric optimization of a single-tube solid-state laser quantron with natural cooling are presented.

We consider parametric optimization method in an example of the determination of geometric dimensions of elements and parameters of their mutual disposition in the base construction of a quantron (Fig. 1) in whch GSGG or YAG crystals are used as active medium. Among the variatable parameters are the inner dimensions of the reflectors D_1 and D_2, the thickness of the leucosaphire tube δ_T, the magnitude of the gap between the active element and the tube δ_g, and the spacing between the axes of the active element and the pumping tube ℓ.

The nature of the influence of the variatable geometric parameters on the magnitude of the relative output energy η is clarified during design by performance of cycles of computations and the combination of their values is determined that will assure the maximal value of η at the end of the laser operation time interval.

Selection of the optimal values of the geometric parameters is executed in several stages. First, the parameters whose influence on the quantity η within the intervals of their variation is unsubstantial are disclosed. It is allowable to determine their values from considerations of simplicity of technical realization. Later quantities are found for

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