TRANSIENT REGIME IN THE THERMAL AND EROSIONAL DESTRUCTION OF MATERIALS

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It is shown that at the moment a quasisteady disintegration regime is established, the thickness of the layer of material carried off from the surface is roughly equal to the depth of heating.

One feature of the thermal and erosional destruction of materials is the presence of two fronts: a surface front, determining linear ablation; an internal front, characterizing the depth of the heated and degenerated layers. In erosional destruction, certain properties of the material change during the repeated collisions of particles with the obstacle. In particular, there is a reduction in the energy associated with the rupture of internal bonds. The depth of the degenerated layers also increases as mass loss proceeds. Given certain external conditions, it is necessary to answer the question of selecting the optimum thickness of coating which will ensure the requisite thermally protective and strength characteristics.

In both erosional and thermal disintegration of materials, there is a certain period of time during which a quasisteady regime is established. The completion of the transient period will be marked by the attainment of certain characteristic values of the depth of the heated and degenerated layers. From this moment on, their lower bounds move at the same rate as the surface undergoing destruction.

In the quasisteady regime, it is not necessary to study the internal processes in detail. For example, in the case of thermal destruction, it is sufficient to know the total amount of heat absorbed by the material before it is heated to the disintegration temperature. Conversely, to determine the depth of heating in the transient regime, it is necessary to know not only the thermophysical properties, but also the dependence of the rate of displacement of the external surface and its temperature on the heating time. Since it is during the transient regime that constant thicknesses of the degenerated and heated layers are established, it is extremely important to find a simple and unambiguous relationship between these quantities and the size of the layer of material removed from the surface.

The studies [1, 2] introduced the notion of the relative intensity $\bar{\bar{G}}$ and effective enthalpy of erosional destruction H_{er}:

$$\bar{\bar{G}} = dm_{er}/dm_p \approx G_{er}/G_p, \tag{1}$$

$$H_{er} = \frac{V_p^2}{2\bar{\bar{G}}}. \tag{2}$$

The linear dependence of the total loss of mass m_{er} on the mass of the incident particles m_p is established at m_p^* (Fig. 1). Here

$$\frac{m_p^* V_p^2}{2} = A, \tag{3}$$

$$m_{er}^* H_{er} = B, \tag{4}$$

where A and B are constants.

Analysis of the experimental data shows that in the range $0 < m_p < m_p^*$, m_{er} can be found from the formula

$$m_{er} = Cm_p^2. \tag{5}$$

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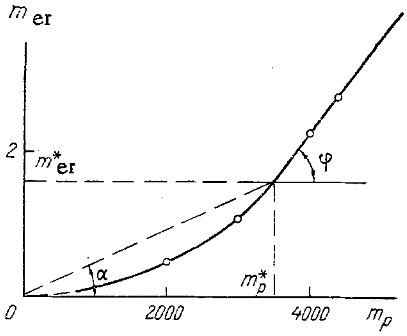

Fig. 1. Dependence of the loss of mass m_{er} of a nickel plate on the integral mass of incident particles of quartz sand m_p at a collision velocity of 82 m/sec. $\tan\varphi = dm_{er}/dm_p = \bar{\bar{G}}$; $\tan\alpha = 1/2 \tan\varphi$. m_{er}, mg; m_p, kg/m^2.

From here we can write

$$\frac{m_{er}}{m^*_{er}} = \left(\frac{m_p}{m^*_p}\right)^2 \text{ and } \frac{dm_{er}}{dm_p} = 2\,\frac{m_p}{m^*_p}\,\frac{m^*_{er}}{m^*_p}.$$

At $m_p \to m_p^*$

$$\bar{\bar{G}} = \frac{dm_{er}}{dm_p} \to 2\,\frac{m^*_{er}}{m^*_p}. \tag{6}$$

Inserting the expressions for m_p^* and m_{er}^* from (3) and (4) into (6), we find

$$\bar{\bar{G}} = \frac{B}{A}\,\frac{V_p^2}{H_{er}} \tag{7}$$

and

$$B = \frac{A}{2}. \tag{8}$$

Since

$$\mathrm{tg}\,\alpha = \frac{m^*_{er}}{m^*_p} = \frac{B}{H_{er}}\,\frac{V_p^2}{2A} = \frac{1}{2}\,\bar{\bar{G}},$$

then

$$\mathrm{tg}\,\alpha = \frac{1}{2}\,\mathrm{tg}\,\varphi. \tag{9}$$

It follows from Eq. (9) that at the end of the transient period the thickness of the degenerated layer should be equal to the ablated layer.

The study [4] proposed a model of disintegration of a material under the influence of a constant thermal load. In accordance with this model, the path of an isotherm in the transient heating regime, reckoned from a stationary surface, can be represented by the expression

$$\Delta^*(\tau) = K\sqrt{a}\,(\sqrt{\tau} - \sqrt{\tau_\xi}), \tag{10}$$

while the linear removal of material from the surface can be represented by the relation

$$S(\tau) = (K^2_{T_p} + 1)\,\bar{V}_\infty(\tau - \tau_e) - K^3_{T_p}\,\sqrt{a}\,(\sqrt{\tau} - \sqrt{\tau_e}). \tag{11}$$

At the end of the transient period, the rate of disintegration is determined by the formula

$$S(\tau_v) = \frac{K^2_{Tp}}{4(K^2_{Tp} + 1)}\,\frac{a}{\bar{V}_\infty}. \tag{12}$$

The following expressions were obtained in this study for the times to establish steady-state values τ_v and τ_δ

$$\tau_v = \frac{K^2_{Tp}\,a}{4\bar{V}^2_\infty}, \tag{13}$$

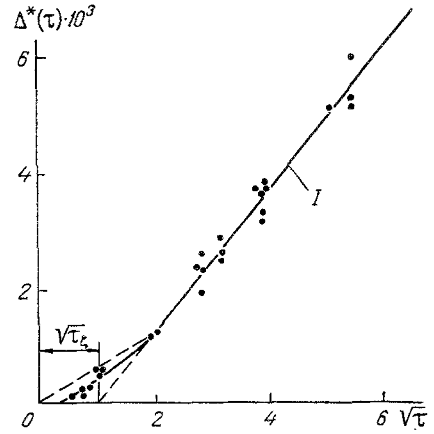

Fig. 2. Dependence of the path travelled by the 1800°K isotherm in the alloyed glass-ceramic on the heating time: The points represent experimental results. Curve I shows the results of analysis by the least squares method. $\Delta^*(\tau)$, m; $\sqrt{\tau}$, $\sqrt{\text{sec}}$.

$$\tau_\delta = \frac{K^2 a}{4\bar{V}_\infty^2}\,. \tag{14}$$

It was then shown that if the time equality $\tau_T = \tau_e = \tau_\zeta$ is allowed, then at $\tau = \tau_v$ the ratio of the path of the isotherm corresponding to the temperature at which linear ablation begins to $S(\tau_v)$ will be equal to 2.

However, in thermal disintegration, the entrainment of material from the surface normally begins considerably earlier than the establishment of T_w = const and the time $\tau_e < \tau_T$ [5]. Also, in this case, the heating depth means the distance from the heated surface to a certain isothermal plane T^* = const. It is normal to take $T^* - T_0 = 0.1(T_w - T_0)$ from the set of all isotherms. In dimensionless coordinates, this expression corresponds to $\Theta^* = 0.1$. The position of this isotherm nearly coincides with the required thickness of the thermally insulated layer. Numerical calculations performed in [6] for this isotherm show that throughout the investigated range of the parameter m, the thickness of the entrained layer is scarcely greater than half the corresponding value of the total thickness $\Delta^*(\tau_\delta)$.

The path covered by the isotherm at the moment τ_δ can be found from (10). The linear ablation of material at this moment of time will be

$$S(\tau_\delta) = S(\tau_v) + \bar{V}_\infty(\tau_\delta - \tau_v). \tag{15}$$

Having inserted (12), (13), and (14) into (10) and (15), we find

$$\frac{\Delta^*(\tau_\delta)}{S(\tau_\delta)} = 2\,\frac{K(K\sqrt{a} - 2\bar{V}_\infty\sqrt{\tau_\xi})}{\sqrt{a}\left(K^2 - \dfrac{K_{\text{тр}}^4}{K_{\text{тр}}^2+1}\right)}\,. \tag{16}$$

The results of calculation of the deviation of $\Delta^*(\tau_\delta)/S(\tau_\delta)$ from (2) in accordance with (16) for $\Theta^* = 0.1$ are shown in Table 1.

To determine the effective thermal conductivity of pure and alloyed glass-ceramics, we used oscillograms showing the change in surface temperature. The oscillograms were analyzed to find the time at which the melt formation temperature — about 2000°K [5] — was reached. Knowing this, we were able to use the formula obtained in [6]

$$\tau_{T_\text{p}} = \pi\lambda\rho c\,\frac{(T_\text{p} - T_0)^2}{4\,(q'_{\text{av}})^2}$$

to calculate λ_{ef}. Here, q'_{av} is the mean integral heat flux [7]. Values of heat capacity were taken from [8]. The time τ_ζ was determined from empirical relations (see Fig. 2, for example).

A good illustration of the satisfaction of the law $\Delta^*(\tau_\delta)/S(\tau_\delta) \approx 2$ is the experimental data shown in Fig. 3 for alloyed and pure quartz glass-ceramics. It is evident that at the

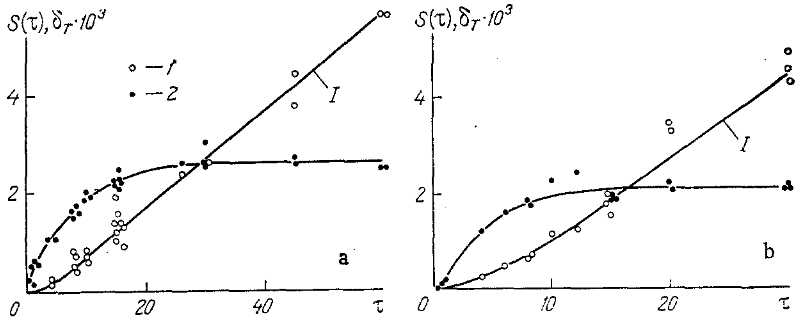

Fig. 3. Dependence of linear ablation $S(\tau)$ and depth of heating δ_T on heating time (a and b show results for alloyed and pure glass-ceramics tested in regime I): 1) linear ablation; 2) depth of heating ($T^* = 1800°K$); I) analysis by the least squares method.

TABLE 1. Parameters of the Destruction of an Alloyed Quartz Glass-Ceramic and the Deviation of $\Delta^*(\tau_\delta)/S(\tau_\delta)$ from 2 at $\Theta^* = 0.1$

No. of regime	q_c, kW/m²	I_e, kJ/kg	T_w, K	$\overline{V}_\infty \cdot 10^3$, m/sec	m	$\frac{2-\Delta^*(\tau_\delta)/S(\tau_\delta)}{2}$, %
I	7650	8600	2620	0,1	0,46	6
II	7000	3500	2400	0,09	2,3	8
III	11500	12300	2800	0,18	0,36	9
IV	14700	4700	2600	0,19	2,6	9
VI	19500	15000	2900	0,3	0,36	12

moment of establishment of a constant rate for the 1800°K isotherm corresponding to a color change in the ceramic [5] (δ_T = const), the heating depth determined from this isotherm is roughly equal to the linear ablation. Approximate calculations performed with (16) in the range of Θ^* from 0.05 to 1 show that the deviation of $\Delta^*(\tau_\delta)/S(\tau_\delta)$ from 2 increases with an increase in the ablation rate. However, as can be seen from the table, this deviation is no greater than 12% throughout the investigated range of disintegration rates for $\Theta^* = 0.1$.

We should point out that the law $\Delta^*(\tau_\delta)/S(\tau_\delta) \approx 2$ does not depend on the parameter m, i.e., on the thermal efficiency of the material. The latter is determined mainly by the temperature of the surface and the stagnation enthalpy of the gas flow [6, 7]. It can be seen from (11) that the linear ablation and its rate are not associated with the law of change or the temperature during the period from τ_e to τ_v.

This conclusion is supported by experimental data [4, 7]. Despite the fact that the stagnation enthalpy of the supersonic jet of a gas generator is lower than the stagnation enthalpy of the jet of an electric-arc gas heater by a factor of three, the rate of removal of material is nearly the same for identical mean integral heat fluxes [7]. This is due to the fact that eight times more heat is absorbed in the second case than in the first case as a result of the heat of vaporization. As the temperature increases from T_p to T_w, there is an increase in the fraction of vaporization and an increase in the thermal efficiency of the material. However, this process does not evidently have an effect on linear ablation.

Thus, at the moment of establishment of the quasisteady regime in both the erosional and thermal destruction of materials, it can be assumed that the thicknesss of the layer of material carried away from the surface is roughly equal to the thickness of the degenerated (heated) material.

NOTATION

$\overline{\overline{G}}$, H_{er}, relative intensity and effective enthalpy of erosional destruction; m_{er}, total mass loss in erosional destruction; m_p, mass of incident particles; m_p^*, mass of incident particles at which the quasisteady regime of erosional destruction is established; V_p, velocity of particles; τ, heating time; τT_p, time until attainment of melt formation temperature; τ_T, τ_v, τ_δ, time to establishment of quasisteady values of surface temperature, ablation rate, and heating depth; τ_e, time of initiation of linear ablation; $\Delta^*(\tau)$, path of isotherm reckoned from the stationary surface; τ_ζ, time determining the hypothetical point of intersection of the curve of the isotherm path and the x axis; K, temperature coefficient; a, diffusivity; T_w, T^*, temperature of surface of material and isotherm under consideration; T_0, temperature of unheated material; V_∞, quasisteady value of surface velocity; KT_p, material disintegration constant; $S(\tau)$, linear ablation; q_c, calorimetric heat flux; I_e, stagnation enthalpy; q'_{mn}, mean integral heat flux during the period from 0 to τ_T; λ, thermal conductivity; ρ, density; c, heat capacity; m, parameter of thermal efficiency of the material; δ_T, depth of heating.

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EXPERIMENTAL VERIFICATION OF MODELS OF TRIPLE MIXED CORRELATION BETWEEN VELOCITY AND TEMPERATURE AS APPLIED TO THE CALCULATION OF JET FLOWS

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The optimum values of the constants in the well-known approximation of the moment $\overline{u_2^2\theta}$ are determined from the results of experimental investigations of nonisothermal wakes.

Multiparameter differential $\overline{u_iu_j}-\varepsilon_u-\overline{u_i\theta}-\overline{\theta^2}-\varepsilon_\theta$ models of turbulence are now being used ever more extensively in practical engineering calculations. They are suitable for calculating a broad class of complicated flows and enable one to obtain information about the pulsation characteristics, which is important in a number of technical applications (e.g., in problems of the propagation of radiation in a turbulized medium, in the construction of mixing devices, the calculation of thermal stresses in heat-releasing elements arising from the presence of temperature pulsations in the oncoming stream, etc.).

It is obvious that the reliability of the calculation depends on the soundness of the closing hypotheses for the unknown moments, each of which requires careful verification. In fact, a situation is possible when the individual terms of the equations of turbulent transport are roughly modeled but the end result of the calculation is still found to be close to the experimental data. But if there is no agreement, it is unclear just which hypotheses laid at the foundation of the model do not accord with reality.

The results of an experimental test of various approximations used in models of momentum transfer are given, in particular, in [1-3]. The dynamics of the turbulent field of a passive admixture (temperature) has been studied in less detail, however, both theoretically and experimentally. The development of experimental technique and the surmounting of a number of methodological difficulties now make it possible to measure different mixed moments of velocity and temperature pulsations and thereby estimate the reliability of approximations

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