FAILURE OF MATERIAL DUE TO NONSTEADY THERMAL EFFECT OF GAS STREAMS

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The article presents the results of numerical calculation of the failure of materials upon linear change of heat flux.

In optimizing heat protection, it is indispensable to investigate the destruction of the heat protecting coating when a gas stream has a nonsteady thermal effect on it.

As a result of numerical calculations of the entrainment of sublimating materials at the stage of establishment of the characteristics of failure upon constant thermal action, Dul'nev et al. [1] obtained the dependences of the depth of heating on the time and the properties of the material. In the heat balance on the surface, the authors took into account the heat that passed inside the body due to heat conduction and the heat absorbed in the sublimation of the material.

For a plate, the authors of [2] took into account the gaseous products of destruction being blasted into the boundary layer, and they discovered a lag of the surface temperature and of the rate of entrainment behind the periodically changing heat supply. On the other hand, for the model of destruction of coking material, on the assumption that its properties are constant, it was concluded that there is no difference in principle between the characteristics of entrainment when the heat flux increases and when it decreases [3]. Investigations [4] showed that the dependence of such properties of composites as thermal conductivity and specific heat on the temperature is affected by the heating rate; this has to do with the shift of the zones of physicochemical transformations.

The problem of failure of a semibounded body at constant surface temperature was examined in [5]. The following boundary conditions were adopted: $q_0 = \text{const}$ and $q_0 = \alpha(T_e - T_w)$. The properties of the material were assumed to be constant. The authors remarked that in spite of the simplicity of the model, this model expresses the principal features of nonsteady failure of a heat protecting coating of sublimating materials, and also of materials fusing upon intense entrainment of the melt. For the nonsteady stage of failure (from the onset of the process to the instant of establishment of a constant rate of destruction), numerical calculation yielded the dependences of the thickness of the entrained layer on time for a number of values of m characterizing the properties of the material. Expressions were found for determining the times of establishing the temperature of failure τ_T, the constant rate of failure τ_V, and the depth τ_δ to which the material is heated. It was shown in [6] that the results of calculation of these times agree satisfactorily with the experimental data for different types of material; this confirms that the model of the process adopted in [5] is correct.

Experimental investigation of nonsteady failure of teflon and organic glass in a jet of air plasma upon increase and decrease of the heat flux at the rate of 0.03-0.15 $\text{kW/cm}^2\cdot\text{sec}$ in the range 0.6-1.3 kW/cm^2 showed that the rates of entrainment do not differ from the quasi-steady-state values [7].

It follows from the literature under examination that the characteristics of entrainment under nonsteady conditions differ from the quasisteady characteristics in some cases, in other cases such a difference was not found. The conclusions reached by various authors are not always in agreement with each other, and this makes further investigations necessary. Most authors examined the initial stage of the process of failure.

In practice there may be cases of the heat flux to the surface of a coating beginning to change after the quasisteady regime of failure has been established.

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Investigation of the characteristics of entrainment of some materials in the above-mentioned case with changes of the heat flux, different in rate and sign, for the above-described model of the process [1, 5], with the blast of gaseous products into the boundary layer is the subject of the present work. As in [5], the heat flux is the difference between the external thermal effect and the radiation from the surface. Depending on the type of material and the conditions of entrainment, the effective heat of the process of failure ΔQ may contain the heat of sublimation, of fusion, of depolymerization, of burning, etc.

The heat conduction in the region of the stagnation point of a semibounded body in the process of destruction with mobile boundary is described by the equation

$$\frac{\partial\theta}{\partial t} = \frac{\partial^2\theta}{\partial z^2} + W(t)\frac{\partial\theta}{\partial z}, \tag{1}$$

where $\theta = (T - T_0)/(T_p - T_0)$; $t = (\tau - \tau_v)/\tau_v$; the dimensionless rate of entrainment is $W(t) = v_\infty/\sqrt{a/\tau_v}$; $z = (y - S(\tau))/\sqrt{a\tau}$; $\tau_v = (\lambda c\rho/q_0^2)(T_p - T_0)^2F(m)$. Below we use the notation for magnitudes adopted in [1, 5]. The value $F(m)$ is determined by the curves in Fig. 3.11 of [5], $m = c(T_p - T_0)/\Delta Q$.

The initial conditions are the characteristics of the quasisteady regime of failure

$$t = 0,\ W(0) = \frac{c(T_p - T_0)[\sqrt{F(m)} + (\partial\theta/\partial z)|_{z=0}]}{\Delta Q + \frac{q_0\gamma}{(\alpha/c_p)}} \tag{2}$$

and

$$\bar{\theta} = \exp[-W(0)z], \tag{3}$$

where α/c_p is determined by the expression $q_0 = (\alpha/c_p)(I_e - I_p)$, and the coefficient of blast γ by the dependence $q_{bl} = \gamma\rho\bar{v}_\infty(I_e - I_p)$.

The boundary conditions assume the form

$$W(0,\ t) = \frac{c(T_p - T_0)[\sqrt{F(m)} + \sqrt{F(m)}\,b\tau_v t/q_0 + (\partial\theta/\partial z)|_{z=0}]}{\Delta Q + \gamma b\tau_v t/(\alpha/c_p) + q\gamma/(\alpha/c_p)}, \tag{4}$$

where b is the rate of change of the heat flux,

$$q(0,\ t) = b\tau_v t/q_0, \tag{5}$$

$$\theta(0,\ t) = 1, \tag{6}$$

$$\theta(\infty,\ t) = 0. \tag{7}$$

When there is no blast, $\gamma = 0$, and the problem (1)-(7) is simplified. With the blast taken into account, the steady-state problem has the form

$$\frac{d^2\theta}{dz^2} + W(0)\frac{d\theta}{dz} = 0, \tag{8}$$

$$W(0) = \frac{c(T_p - T_0)[\sqrt{F(m)} + (d\theta/dz)|_{z=0}]}{\Delta Q + q_0\gamma/(\alpha/c_p)}, \tag{9}$$

$$\theta(0) = 1, \tag{10}$$

$$\theta(\infty) = 0. \tag{11}$$

The solution of problem (8)-(11) is

$$\theta = \exp[-W(0)z], \tag{12}$$

where

$$W(0) = \frac{c(T_p - T_0)\sqrt{F(m)}}{\Delta Q + c(T_p - T_0) + q_0\gamma/(\alpha/c_p)}.$$

From (12) the rate of entrainment in quasisteady regime is equal to

$$\rho\bar{v}_\infty = \frac{q_0}{\Delta Q + c(T_p - T_0) + q_0\gamma/(\alpha/c_p)} \tag{13}$$

and the effective enthalpy of the material is

TABLE 1. Values of the Parameters of Materials Adopted for the Calculation (the denominator contains the literature source)

Material	ρ, g/cm³	$c \cdot 10^3$, kJ/g·°K	$\lambda \cdot 10^5$, kW/cm·°K
Teflon	2,2 [2, 5, 8, 9]	0,125 [2, 5, 8, 9]	0,26 [5, 8, 9]
Glass-fiber reinforced plastic	1,65 [9, 12—15]	0,11 [9, 12—14]	0,4 [9, 12, 14—16]
Technical-grade graphite	1,73 [5, 17]	0,2 [5, 17]	45 [5, 17]
	T_p, K	ΔQ, kJ/g	γ
Teflon	800 [2, 5, 8, 9]	1,7 [2, 5, 8, 10]	0,38 [11]
Glass-fiber reinforced plastic	2800 [5]	8 and 4 [5]	0,182 [5]
Technical-grade graphite	3800 [5, 17]	26 [5, 18]	0,4 [5, 18]

$$I_{\mathrm{ef}} = \Delta Q + c(T_p - T_0) + \gamma q_0/(\alpha/c_p). \tag{14}$$

It is interesting to compare the solution of the steady-state problem (13), (14) with the experimental data from the literature.

The thermophysical parameters, and also other magnitudes contained in the theoretical formulas, for three types of material are presented in Table 1.

The results of measurements and of calculations of the dimensionless entrainment of teflon in dependence on the stagnation enthalpy [5, 10, 19] for quasisteady conditions are presented in Fig. 1. The same figure also contains the curve calculated by Eq. (14) with the use of published values of the parameters that agree satisfactorily in the enthalpy range 5000-20,000 kJ/kg with the available data.

The experimental and theoretical dependences for teflon are most accurately described by the expressions

$$I_{\mathrm{ef}} = 1000 + 0.46 I_e \tag{15}$$

and

$$\bar{G} = I_e/(1000 + 0.46 I_e) \tag{16}$$

for I_e = 4000-22,000 kJ/kg. The nature of the experimental dependences of effective enthalpy and entrainment coincides with the calculation by Eqs. (14) and (15), obtained on the basis of the model of the process of failure used in the present work.

For glass-fiber reinforced plastic the mechanism of failure includes heating, melting, partial evaporation, chemical decomposition, etc. In the general case the dependence of the

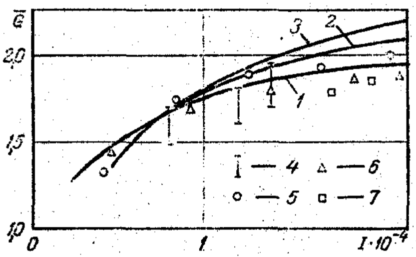

Fig. 1. Dependence of the dimensionless entrainment of teflon on the enthalpy of the gas stream: 1) calculation [5]; 2) calculation [19] for M_2 = 200; 3) calculation by Eq. (14); 4) experiment [5]; 5) experiment [10]; 6) [20]; 7) experiment by the present author. I, kJ/kg.

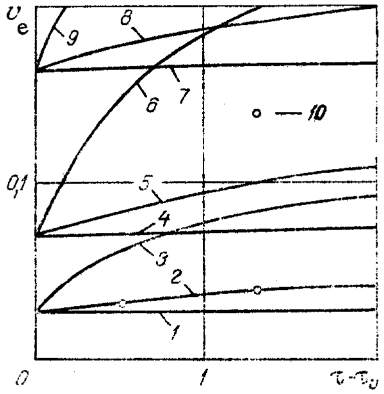

Fig. 2.

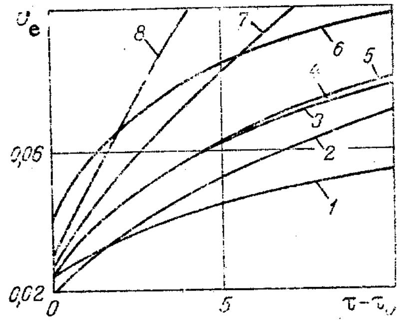

Fig. 3.

Fig. 2. Dependences of linear entrainment on time upon change of heat flux for various materials: 1, 2, 3) graphite; 4, 5, 6) glass fiber-reinforced plastic; 7, 8, 9) teflon; 1, 4, 7) $b = 0.05$ kW/cm²·sec; 2, 5, 8) 0.5; 3, 6, 9) 5; 1-9) $M = 200$; 10) $M = 100$. v_e, cm/sec; $\tau - \tau_v$, sec.

Fig. 3. Effect of various factors on nonsteady entrainment ($b = 0.5$ kW/cm²·sec): 1) $\gamma = 0.7$; 2) $\Delta Q = 36$ kJ/g; 3) $\gamma = 0.4$, $T_p - T_0 = 3500$°K, $\Delta Q = 26$ kJ/g, $\lambda = 0.45 \cdot 10^{-3}$ kV/cm·°K, $(\alpha/c_p) = 0.05$ gf/cm²·sec; 4) $\lambda = 1 \cdot 10^{-3}$ kW/cm·°K; 5) $T_p - T_0 = 2000$°K; 6) $\Delta Q = 10$ kJ/g; 7) $(\alpha/c_p) = 0.1$ gf/cm²·sec; 8) $(\alpha/c_p) = 1.5$ gf/cm²·sec. For 1, 2, 4-8 the remaining parameters are the same as for curve 3.

effective enthalpy of material on stream enthalpy is therefore not linear. However, it follows from published data ([5], Figs. 6.12 and 9.22, [20]) that in certain ranges of change of enthalpy, the dependences under examination may be approximated by straight lines. In particular, for $q \cong 0.5\text{–}2$ kW/cm² and $(\alpha/c_p) = 0.05$ gf/cm²·sec, the effective enthalpy of glass-fiber reinforced plastic on the basis of experimental data is equal to

$$I_{ef} = [6800 + 0.182\,(I_0 - I_w)] \pm 15\,\%. \tag{17}$$

If we take the surface temperature, which varies between 2700 and 2850°K in the range of applicability of Eq. (17), as equal to 2800°K, then the amount of heat expended on heating the material is approximately equal to 2.8 kJ/g, and the total thermal effect of the processes on the surface is 4 kJ/g. The coefficient of blast for glass-fiber reinforced plastic is ∿0.18.

The principal processes determining the destruction of graphite in a stream of hot air are burning, sublimation, radiation, heating. Depending on the external conditions, the contribution of some process or other changes. In that case, however, the dependence of the effective enthalpy of the material on the enthalpy of the stream may be represented by rectilinear functions [18] whose possible coefficients are given in Table 1.

Expression (14) may be used for evaluating the contribution of individual "absorbers" of the heat supplied to the coating. For instance, for glass-fiber reinforced plastic with $q_0 = 1$ kW/cm² and $(\alpha/c_p) = 0.1$ gf/cm²·sec, the proportion of heat expended on heating the material to the temperature of destruction is 9%, the heat absorbed in consequence of phase transitions and chemical reactions amounts to 24.5%, and the effect of blasting amounts to 66.5%.

Let us examine the results of the solution of the nonsteady problem (1)-(7), obtained by a numerical method with the aid of an ES 1022 computer. Preliminary calculations showed that a change of the step Δt from 0.0002 to 0.0025 and of Δz from 0.025 to 0.1, and also of the number of steps along the coordinate M from 100 to 200, did not substantially affect the results.

Examples of the dependences of the nonsteady rate of entrainment on time for three materials with three rates of change of heat flux are given in Fig. 2. A tendency toward stabilization of the speed of entrainment with time may be noted. The initial points represent the contributions in quasisteady regime, determined by the initial heat flux, which is equal to kW/cm².

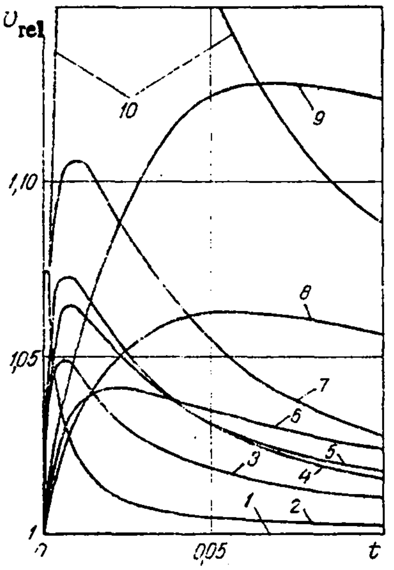

Fig. 4. Dependence of relative entrainment on dimensionless time (graphite): 1) $b = 0$, $q_0 = 1$ kW/cm^2; $b = -0.05$ and -0.5 kW/cm^2·sec, $q_0 = 10$ kW/cm^2; 2) $b = 5$; 3) $\gamma = 0.7$; 4) $\gamma = 0.4$, $T_p - T_0 = 3500$°K, $\Delta Q = 26$ kJ/g, $\lambda = 0.45 \cdot 10^{-3}$ kW/cm·°K, $(\alpha/c_p) = 0.05$ kg/cm^2·sec, $b = 0.5$ kW/cm^2·sec; 5) $\Delta Q = 36$; 6) $T_p - T_0 = 2000$; 7) $(\alpha/c_p) = 0.1$; 8) $b = 0.05$; 9) $b = 0.05$, $(\alpha/c_p) = 1$; 10) $b = 0.5$, $(\alpha/c_p) = 1.5$; 2-10) $q_0 = 1$. For 1-3, 5-10 the remaining parameters are the same as for curve 4.

By the example of graphite, Fig. 3 shows the effect of the principal parameters determining destruction of the material on the speed of entrainment. A substantial effect on the increase of v_e with time is exerted by the parameter α/c_p which is connected with the velocity head of the stream. An increase of the coefficient of blast from 0.4 (for turbulent flow) to 0.7 (for laminar flow) [18] noticeably decreases the speed of entrainment. An increase of the total thermal effect ΔQ influences v_e in the same way. A change of the surface temperature and of the thermal conductivity, which may greatly change depending on the variety of graphite, had a small effect on the unsteady flow velocity.

Calculations of the relative speed v_{rel}, which is the ratio of the unsteady to the quasisteady speed at the instantaneous value of the heat flux, showed (Fig. 4) that it has a maximum depending on the time, and after that v_{rel} tends to unity. With increasing rate of change of the heat flux, the magnitude of the maximum increases, and it shifts toward shorter times. A substantial influence on v_{rel} is exerted by the temperature of destruction, the coefficient of blast, and by the overall thermal effect.

For the conditions of heating materials obtaining in subsonic plasma jets at pressures close to atmospheric, the model under examination yields a nonsteady effect of about 10-15% for graphite when the heat flux changes linearly. For glass fiber reinforced plastic this effect does not exceed a few percent, and with teflon it is practically imperceptible.

Calculations (Fig. 4) show that with increasing α/c_p, v_{rel} may increase substantially. With $(\alpha/c_p) = 1.5$ gf/cm^2·sec and $b = 0.5$ kW/cm^2·sec, the ratio of the speeds for graphite attains 1.2, and it noticeably (>10%) exceeds unity within 45 sec.

Thus we investigated the influence of a number of parameters that are important to the process on the nonsteady rate of destruction determined by a change of the heat flux.

It was shown that unsteady effects may arise expressing themselves in the difference between the linear speed of entrainment and the corresponding quasisteady speed (according to the instantaneous values of the heat flux). Under certain conditions this difference in the speeds of entrainment may be considerable.

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