THERMAL MECHANISM OF DESTRUCTION OF THE BARRIER OF A TRANSONIC JET OF COMBUSTION PRODUCTS OF ROCKET FUEL

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The work concerns the combined theoretical and experimental investigation of the cutting speed of thermally highly conducting alloys by a jet of combustion products flowing at supercritical pressure gradient from the transonic jet of oxygen–hydrogen and oxygen–propane gas generators.

In traditional oxygen cutting of materials, the fuel combustion in the heating gas circuit proceeds beyond the edge of the nozzle; as a result, the speed of the combustion products is low and the density of the thermal fluxes is insufficient, viz., $\sim(0.4\text{–}1.0)\cdot 10^6$ kW/m^2 [1, p. 101]. This makes it difficult to cut carbon steels up to 5 mm thick because there the role of the reaction of oxidation in the mechanism of parting the material is inconsiderable [1, p. 130]. Cutting of high-alloy steels is also rather complicated, and the cutting of thermally highly conducting nonferrous alloys, especially those containing more than 10% aluminum [1, p. 129], is altogether impossible.

This problem can be solved only by intensifying the heat supply to the cutting zone. This principle is put into practice in plasma arc cutting which makes it possible to cut materials up to ~10 mm thick at much higher speeds, viz., 27–75 mm/sec, with densities of the thermal fluxes $\sim(2.0\text{–}6.0)\cdot 10^6$ kW/m^2 [1, p. 218]. However, even in cutting with low-temperature plasma the temperature of the cutting jet attains ~5000–20,000°K; this causes buckling of thin sheets, and on account of recrystallization there is considerable loss of material in the subsequent processing; moreover, special safety measures have to be taken in cutting.

It is therefore highly desirable to limit the temperature level of the cutting jet to ~2500–3000°K, which is sufficient for melting aluminum, chromium and other oxides while maintaining high densities of the thermal fluxes. This led to the appearance of devices whose cutting instrument is a transonic high-temperature gas jet. In such devices the fuel combustion proceeds inside a special combustion chamber (Fig. 1); this ensures effective transformation of the fuel and supercritical pressure gradient on a limited minimum cross section of the nozzle. The endeavor to ensure long service life of the combustion chamber leads to the generation of jets with reducing properties in the gas cutting devices under examination.

The high speeds (~2 km/sec) and temperatures (~3000°K) of the combustion products make it possible to obtain densities of the thermal fluxes in the jet that are comparable with plasmotrons $\sim(2.0\text{–}3.0)\cdot 10^6$ kW/m^2, i.e., to cut highly thermally conducting materials including copper and aluminum alloys.

The interaction of the jet with the barrier may be represented in the form of two successive and interrelated stages: the heating and the cutting itself of the material. At the first stage the source of the jet is stationary, and the jet penetrates into the material in the direction x (Fig. 1), melting its surface layer of thicknesses dx which is in direct contact with the hot combustion products.

The combustion products liberate per unit time some amount of energy in the form of heat

$$\overline{Q} = I\dot{m}, \tag{1}$$

of which only part Q_1 heats and melts the material. It is impossible to determine the heat-transfer coefficient under such complex conditions [2, pp. 166, 193], and therefore it is advisable to specify the ratio between $\overline{Q}_1$ and $\overline{Q}$ by the empirical coefficient $K = \overline{Q}_1/\overline{Q}$. Then we can write for the mean thermal flux on the surface of active interaction F

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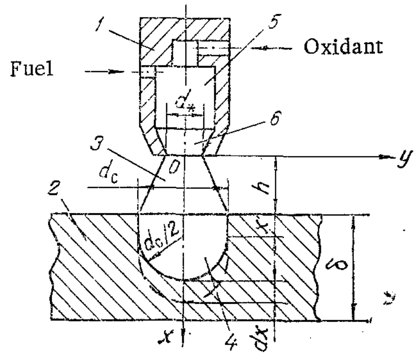

Fig. 1

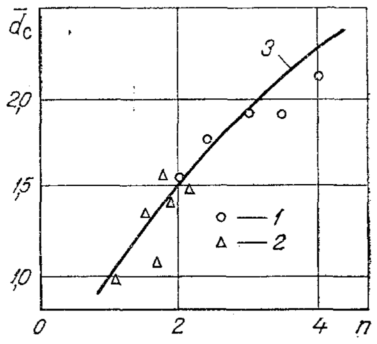

Fig. 2

Fig. 1. Diagram of burning out a hole: 1) gas generator; 2) material to be cut; 3) jet of combustion products; 4) burned-out hole; 5) combustion chamber; 6) critical nozzle.

Fig. 2. Dependence of the burned-through hole $\bar{d}_c$ on the underexpansion of the jet n on the gasdynamic section: 1) fuel $H_2 + O_2$; 2) fuel $C_3H_8 + O_2$; 3) calculation of $\bar{d}_{max}$ by the method of [3].

$$\bar{Q}_1/F = KI\dot{m}/\pi d_c\,(0.5\,d_c + x). \tag{2}$$

If we compare the energy supplied to the material during the period of time $d\tau$ by the combustion products through the fusion surface (the semisphere with radius $d_c/2$ in Fig. 1) with the energy expenditure on melting the elementary volume $\pi_c^2 dx/4$, we are able to find the instantaneous cutting speed in the direction x:

$$V_x = dx/d\tau = KI\dot{m}/\pi r\rho d_c\,(0.5 d_c + x). \tag{3}$$

Unlike [2, p. 215] we obtained that the speed of destruction of the barrier depends on the running depth x in connection with the decrease of the mean thermal flux when the running surface of interaction of the jet with the material increases. The correlation of the length of burning through of the material of the plate τ_n with its thickness δ is determined by integrating (3):

$$\tau_n = \pi r\rho\delta d_c^2\left(1 + \frac{\delta}{d_c}\right)/2KI\dot{m}\cdot \tag{4}$$

The diameter d_c of the burned hole in (4) is correlated in the general case with the size d_* of the gas generator nozzle by the distance to the barrier h, and when the jet flows into the flooded space, it depends on the underexpansion of the jet n and the exponent of the isentrope of expansion of the combustion products in the nozzle k.

The boundary of the examined jets within the limits of the gasdynamic section may be described by the approximate method of calculating the geometry of "cold" jets [3]. Experiments showed that in the range n = 1-4 the diameter of the burned hole $\bar{d}_c$ coincides (Fig. 2) with the maximum jet diameter $\bar{d}_{max}$ found in accordance with [3]:

$$\bar{d}_c = \bar{d}_{max} = n^{0,6}. \tag{5}$$

This indicates that the role of the heat exchange with the surrounding space is slight on the gasdynamic section, a characteristic feature of which is that the distances from the edge of the nozzle $\bar{h}$ are smaller than $\bar{s}$ calculated by the method of [3]:

$$\bar{s} = 2s/d_* = [2n/(1.20n + 0.30n)] + 8.4\sqrt{n} - 0.8. \tag{6}$$

The experiments were carried out using the method of probing the jets with thin foil-type aluminum lamina placed across the flow of combustion products of the fuels $H_2 + O_2$ and $C_3H_8 + O_2$, and with thermocouples types KhA, KhK, VR5/VR20 with secondary apparatus type KSP. The size d_c was determined by the diameter of the hole burned in the foil and the curve $T^* = 933°K$ corresponding to the melting point of aluminum.

Beyond the gasdynamic section, with $\bar{h} > \bar{s}$, the interaction of the jet with the surrounding space leads to an abrupt decrease of the temperature (proportionally to $\sim\bar{h}^{-0.52}$ for n = 4.0) on the axis of the jet, and to a substantial redistribution of the temperature curves in

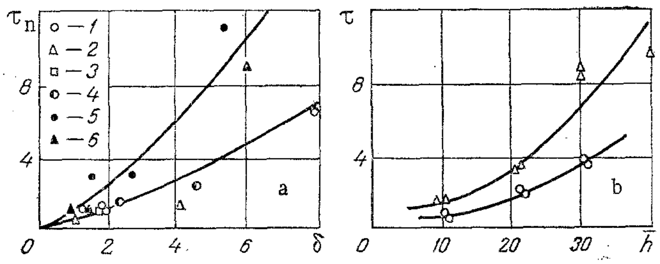

Fig. 3. Comparison of the calculation of the duration of burning through τ_n (c) by formula (11) with the experimental values: a) with different thickness of the plate δ (mm) ($K = 1\cdot10^{-2}$): 1) D16AT; 2) AMG; 3) AMTsM; 4) V95T; 5) 30KhGSA; 6) Kh18N10T; b) with different distances from the edge of the nozzle $\bar{h}$: lower curve ($K = 0.5\cdot10^{-2}$; upper curve) $1.0\cdot10^{-2}$.

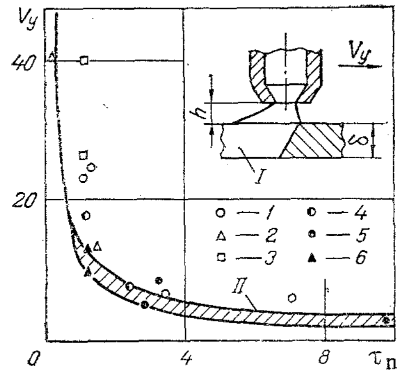

Fig. 4. Dependence of the cutting speed V_y (mm/sec) on the duration of burning a hole in the plate τ_n (sec) with $\bar{h} = 15$, $\delta = 1$-8 mm, fuel $H_2 + O_2$: I) jet of combustion products; II) calculation by formula (12); 1-6) the same as in Fig. 3a.

the jet. Assuming that the processes of interaction of the jets with the surrounding space for n = 1-4 and $\bar{h} > \bar{s}$ are similar, and transforming the coordinates of the temperature curve $T^* = 933°K$ into the form $h = (\bar{h} - \bar{s})/\bar{d}_{max}$ and $\tilde{d}_c = \bar{d}_c/\bar{d}_{max}$, we generalize the experiments in the form of the universal dependence $\tilde{d}_c = 0.1h + 1$, i.e., in the range $\bar{s} < \bar{h} < 10\bar{d}_{max} + \bar{s}$ we obtain

$$\bar{d}_c = \bar{d}_{max} + 0.1\,(\bar{h} - \bar{s}). \tag{7}$$

Expressions (5) and (7) may be combined in the form

$$\bar{d}_c = \bar{d}_{max} + 0.1\,(\bar{h} - \bar{s})\,\Theta\,(\bar{h} - \bar{s}), \tag{8}$$

where $\Theta(\bar{h} - \bar{s})$ is the Heaviside unit function.

Formula (8) may be used for calculating $\bar{d}_c$, beginning at the coordinate of the maximum cross section of the first "barrel" calculated by the method of [3], and ending with the distance $\bar{h} = \bar{s} + 10\bar{d}_{max}$. This range is of the greatest practical interest because when $\bar{h} \lesssim 1$, the effect of reverse thermal fluxes becomes impermissible for the material of the gas generator, and when $\bar{h} > \bar{s} + 10\bar{d}_{max}$, the cutting efficiency is impaired.

It is expedient to express the enthalpy of the fuel I contained in (4) by the flow rate complex $\beta = p_k F_*/\dot{m}$ characterizing the energetics of the fuel:

$$I \simeq \varkappa^2(k)\,\beta^2, \tag{9}$$

where $\varkappa(k) = [2/(k+1)]^{(k+1)/2(k-1)}\,(k-1)^{-0.5}$.

For most fuels, k lies within the range k = 1.1-1.3, and the expression for $\varkappa$ (k) may be simplified with an error not exceeding 1.6%:

$$\varkappa(k) = 0.59\,(k-1)^{-0.5} \tag{10}$$

The presented relations (8), (9), and (10) enable us to write (4) in a form suitable for analysis:

$$\tau_n = 5.75 r\rho\delta\,(k-1)\,\bar{d}_c^2 \left(1 + \frac{\delta}{d_* \bar{d}_c}\right) / K p_K \beta_T \varphi_K^2 , \tag{11}$$

where $\varphi_K = \beta/\beta_T$ is the efficiency of fuel transformation. Hence we can see the factors determining the efficiency of the gas generator at the first stage of operation: the physical properties of the material (r, ρ), the energetics of the fuel (k, β_T), the regime and design parameters of the gas generator (p_K, d_*), the degree of perfection of the work process (φ_K) and the conditions of cutting the material ($\bar{d}_c$, δ, K).

The duration of the burning-through process was investigated on plates with thickness δ = 1-8 mm of materials D16AT, AMG, AMTsM, V95T, 30KhGSA, and Kh18N10T in jets of combustion products of the fuels $H_2 + O_2$ and $C_3H_8 + O_2$. For these materials and fuels the value of K lies in the range $(0.5\text{-}1.5)\cdot 10^{-2}$. Figure 3a presents the experimental data and results of calculation by expression (11) obtained in the regime: fuel $H_2 + O_2$, $\dot{m}$ = 0.91 g/sec, α = 0.45, $p_K = 6.15\cdot 10^5$ Pa, d_* = 2.07 mm, $\bar{h}$ = 15. The dependence of the duration of burning through τ_n on the distance from the plate with thickness δ = 1 mm of alloy AMTsM (Fig. 3b) was obtained with a jet of the combustion products of fuel $C_3H_8 + O_2$ with $\dot{m}$ = 0.69 g/sec, α = 0.56, $p_K = 2.92\cdot 10^5$ Pa, d_* = 2.0 mm (curve 2) and $\dot{m}$ = 0.688 g/sec, α = 0.79, $p_K = 3.53\cdot 10^5$ Pa, d_* = 2.0 mm (curve 1).

Assuming that the mechanism of destruction of the barrier at the second stage of interaction remains analogous, and writing the heat balance equation over half the lateral surface of the cylinder formed after burning of the hole, we arrive at the following expression:

$$V_y = \frac{d_c + \delta}{\tau_n} = \frac{d_* \bar{d}_c}{\tau_n} + \frac{K p_K \beta_T \varphi_K^2}{5.75 r\rho\,(k-1)\,\bar{d}_c^2 \left(1 + \dfrac{\delta}{d_* \bar{d}_c}\right)} . \tag{12}$$

The second term in the expression for V_y in the range δ = 1-8 mm for steel and aluminum alloys affects only weakly the cutting speed V_y which amounts to 0.45-2.5 mm/sec. Therefore, the divergence from each other of the curves in Fig. 4 for materials with different δ is small, and this enables us to correlate the cutting speed V_y solely with the time τ_n.

Thus, with specified parameters of the material and selected fuel, the efficiency of the gas generator (in our case quivalent to the magnitude of V_y) is determined by the presence by the pressure in the combustion chamber p_K and the diameter of the minimum cross section of the nozzle d_*, whose combination in turn corresponds to the flow rate of combustion products $\dot{m}$. With a view to this circumstance, expression (12) limits the quotient space of the operating conditions of the gas generator. This makes it possible to design a gas generator taking into account the operating and other considerations and maintaining high values of V_y.

NOTATION

d_*, diameter of the minimum cross section of the nozzle, m; $\bar{d}_c = d_c/d_*$, relative diameter of the burned hole; $\bar{h} = 2\,h/d_*$, relative distance from the barrier; I, enthalpy, J/kg; m, mass flow rate per second of combustion products, kg/sec; F, surface area of the burned-through hole, m²; r, specific melting heat of the material of the barrier, J/kg; ρ, density of the material, kg/m³; $n = p_*/p_H$, degree of underexpansion of the jet; p_*, pressure at the edge of the gas generator nozzle, Pa; $\bar{d}_{max} = d_{max}/d_*$, relative maximum diameter of the gas dynamic section of the jet; $F_* = \pi d_*^2/4$, critical cross-sectional area of the nozzle, m²; p_K, pressure in the combustion chamber, Pa; β_T, theoretical flow rate complex, m/sec; $\alpha = \dot{m}_{OX}/\dot{m}_G K_{m.st}$, coefficient of oxidant excess; $K_{m.st}$, stoichiometric ratio of the components; δ, thickness of the barrier, m. Subscripts: Γ, fuel; OX, oxidant.

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AMPLIFICATION RATIO ON CO_2 GASDYNAMIC LASERS BEHIND NOZZLES OF WEDGE AND PROFILED GEOMETRIES.

2. MEASUREMENT RESULTS. COMPARISON OF EXPERIMENTAL AND CALCULATED DATA

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The optimum content of the components and parameters of the mixture are determined experimentally and the efficiencies of the nozzle apparatus are compared. The influence of local inhomogeneities on the amplification is estimated and satisfactory agreement between experimental and calculated data is noted.

In a homogeneous gasdynamic laser (GDL) the active medium is formed by the rapid expansion of the preheated and compressed working mixture in a supersonic nozzle. The achievement of supersonic stream velocities imposes very strict demands on the profiling of the flow channels. Heat release due to the relaxation of vibrationally excited CO_2 and N_2 molecules in the resonator creates the inhomogeneity in the supersonic stream characteristic of the active media of GDL, to which are added gasdynamic inhomogeneities, the source of which is, for example, incorrectness of the profiling of the flow channel [1].

The influence of these factors can be estimated by numerical calculations, making certain simplifications in solving the problem of the state of the active medium moving in the resonator. In the present work we used the well-known scheme of [2] for calculating CO_2 GDL for a gas mixture of 10% CO_2 + 45% N_2 + 45% He which expanded through a nozzle with a wedge geometry [3] and having the stagnation parameters $T_0 \simeq 1200$-2200°K and $P_0 = 1.5$ MPa. The vibrational modes of CO_2 and N_2 molecules were described within the framework of the model of a harmonic oscillator and it was assumed that relaxation of the deformation and symmetrical modes of carbon dioxide proceeds jointly, i.e., the corresponding temperatures are equal, while the relation $\theta_1 = 2\theta_2$ is satisfied for the characteristic temperature θ_1 of the vibrational level. The presence of equilibrium of rotational and translational degrees of freedom was also assumed, while variation of the chemical composition and effects of viscosity and heat conduction were ignored. The kinetic constants were chosen on the recommendations of [1]. The system of relaxation equations for vibrational levels of CO_2 and N_2 was solved jointly with the equations of one-dimensional gasdynamics [4]. The amplification ratio for a weak signal was calculated for the P(20) transition of the 00°1-10°0 band of the CO_2 molecule at the center of the line with allowance for the Doppler and collisional mechanisms of broadening.

For the case of the flow of an inverted medium in a resonator channel of constant cross section the gasdynamic parameters and amplification were calculated with allowance for the presence of an oblique compression shock inclined at a 13° angle to the vector of the oncoming stream; the angle of inclination was determined from an analysis of thermograms of gas flow behind a nozzle with a wedge geometry [3]. It was assumed that as the gas passes through the compression shock there is a change in the density and translational temperature of the gas, while the internal degrees of freedom of the molecules relax far more slowly than the translational ones, i.e., they are "frozen in." The kinetic and gasdynamic equations were integrated by the method of streamlines using the known pressure distribution for four stream filaments: boundary ($y_1 = 15$ mm), axial ($y_4 = 0$), and two intermediate ones (y_2 and y_3); the

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