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CHARACTER OF THE FAST JET EFFLUX UPON DETONATION OF SHAPED CHARGES

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The space-time structure of fast jets flowing out from the cumulative groove of the detonating charge of a brisant explosive has been investigated. The velosity field of the jet and the flow of detonation products have been determined. We have revealed a change in the structure of the front end of the jet followed by an increase in its luminescence intensity and a decrease in the efflux velocity upon introduction into the cumulative groove of mixtures of metals and graphite. The sizes of the jet inhomogeneities reflecting the spatial scale of zones of selective change in its thermodynamic parameters have been estimated.

Introduction. Starting in the 1960s, the explosion energy has been widely used to strengthen and weld metals and pressing powder materials [1]. The last few years have seen a rising interest in explosion technologies due to the development of methods of detonation synthesis and consolidation of superhard ultradispersed powders [2, 3] based on a short-time action of high pressures ($P \sim 16–23$ GPa) and temperatures ($T \sim 3000$ K) on the initial material followed by rapid cooling of the metastable phase formed. It has been shown that explosion-consolidated polycrystalline compacts with ultrafine grains have the highest mechanical strength and fracture toughness [4]. The use of comparatively cheap explosives makes it possible to considerably lower the cost of synthesized products and widen the field of application of conversion of conventional kinds of ammunition and make it profitable.

A special place among explosives being converted is occupied by shaped charges. The detonation products of this type of charge flow out through the cumulative groove surface in the form of fast energy-saturated jets. Changing the charge characteristics and the groove shape, one can control the distribution of parameters in fast jets.

The basic data on cumulative jets are associated with their practical applications as punchers, metal-cutting facilities, and hitting elements in the weapon field [5-11]. Investigations of the characteristics of reacting powder jets formed by the detonation of cumulative explosives are scarce. The present work is devoted to the investigation of the spatial structure, the character, and the propagation velocity of such jets formed by the detonation of shaped charges based on trinitrotoluene and RDX as the most stable suitable explosives for the synthesis of ultradispersed materials [3].

Experimental. The investigated fast jet was formed by the explosion of a TG-70 charge of weight ~350 g. The charge had the form of a cylinder of diameter D = 50 mm and length L = 130 mm and a conical $\varphi = 58^{\circ}$ groove of depth ~50 mm on the face. In a series of experiments, the side walls of the groove were lined with a mixture from a prepressed or jelly-like mass based on glycerin, carbon black, and metallic powder. The detonator was positioned on the lateral surface of the charge near the flat face.

The space-time structure of the jet was investigated by the methods of photochronography with the use of an SKS-1 high-speed cine camera and a VFU-1 high-speed photographic set-up capable of operating in the frame-by-frame and continuous regimes of recording [12]. Jet radiation recording was carried out from a spatial zone of diameter ~300 mm near a cut of the cumulative funnel. The image was projected by means of a long-distance objective on a photographic film with reduction by a factor of 30.

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Initiation of the detonation process was realized by a remote explosion control system. The pulsed character of the investigated processes required synchronous (with the explosion detonation commencement) operation of an SKS-1 camera and an VFU-1 set-up. In the case of using the SKS-1 in starting the control program of the mainframe computer of the explosion complex, an electric signal was generated for remote turning on of the cine camera power. As the nominal rate of motion of the cine film in the SKS-1 was attained, initialization of the explosive charge detonator occurred. At the end of recording, a signal for turning off the cine camera power was applied. In using the VFU-1, at the beginning of the experiment electric power was applied to the set-up, and then, by a signal from the control program, an electric signal for starting the VFU-1 was generated. As soon as the set-up began to operate, the camera shutter opened, the control unit of the VFU-1 generated a pulse for the initialization of the explosion charge detonator, and the jet radiation was recorded. Then the shutter closed and the computer gave a signal for turning off the VFU-1 power.

Results of the Investigation of the Space-Time Structure and the Efflux Velocity of Jets. The survey photograms obtained with the aid of the SKS-1 cine camera in the frame-by-frame regime with a recording frequency of 3500 frames/sec gave a general idea on the character of the propagation of detonation products (DP) arising from the charge detonation. Analysis of the photograms has shown that during 25 msec a gradually decaying luminescence of DPs is observed. The duration of the main (bright) phase of the process is of the order of 0.3 msec, after which individual luminescent local zones are observed.

Detailed studies of the process of formation of the main phase of the jet were made with the use of the VFU-1 super-speed cine camera that permitted filming at a speed of 500,000 frames per second. Analysis of the photograms obtained in the frame-by-frame regime with time intervals between frames t = 29 and 6 μsec has shown that at the initial stage of detonation there occurs a transverse "cloud-like" expansion of the great bulk of DPs. Simultaneously with this, from the cumulative groove along the cone axis a fan-like jet flows out, which gradually increases in length and diameter and after $t \sim 60$ μsec separates from the expanding main "cloud" of DPs.

The spatial structure of the cumulative jet in the transverse x and longitudinal l directions was investigated by its luminescence intensity $I(x, l)$ distributions obtained by computer densimetry of the photograms. Figure 1 presents individual photograms of the luminescence intensity I of the DPs and the jet from a series of frames recorded subsequently after t = 29 μsec and their corresponding luminescence intensities II depending on the distance l from the charge face. Dashes show the size and the initial position of the charge. For the "zero" reading along the l coordinate, the plane at the base of the conical cumulative groove of the explosive was taken. As is seen from Fig. 1, I, the jet incipient in the cumulative groove is a spatially inhomogeneous but fairly symmetric (about the longitudinal expansion axis) luminescent object. The lateral maxima on the luminescence intensity distributions near the charge face (Fig. 1, II) pertain to the luminescence of the cloud of the main DPs. At the initial stage of formation (Fig. 1, IIa), along the full length of the jet the profile half-width of the luminescence intensity distribution is $\Delta x \sim 40$ mm. After $t \approx 29$ μsec (Fig. 1, IIb) the jet acquires a "fan-like" structure with a bright luminescent zone on the axis $x \approx 0$ having a half-width $\Delta x \sim 40$ mm. As the jet develops, at distances $l \approx 60$, 100, 150, 190, 230, and 280 mm the luminescence intensity and profile half-width of its spatial distribution decrease. The axial maximum breaks up into several segments with half-width $\Delta x \sim 10$–20 mm and distance between them $x \sim 20$–30 mm. Such a "multisegment" kind of fast jets was noted in [5, 8]. The observed local spatial inhomogeneities in the luminescence intensity distributions in the cumulative jet investigated by the authors of [5] are, in their opinion, trajectories of intersection of oblique shock waves formed in the explosive because of the asymmetry of the initiating shock wave caused by the extra-axial position of the detonator in the explosive body. Subsequently ($t \approx 87$ μsec, Fig. 1, IIa), because of the separation and turbulization of the jet, the distributions $I(x, l)$ acquire a Π-like form with an oscillating peak.

The time photoscans of the jet image obtained with a resolution $\tau \approx 5$ μsec by means of the SKS-1 cine camera in the continuous recording regime are given in Fig. 2. In the field of view of the SKS-1 camera, there was a segment of the jet of width $\Delta x \sim 4.5$ mm and length $l \sim 300$ mm adjoining the charge section. Analysis of the continuous photoscans obtained has shown their similarity to the photoscans of cumulative jets given in [8–11] and confirmed the conclusion drawn from the results of processing frame-by-frame photograms on the effluence from the conical groove of a bright luminescent jet having a complex structure.

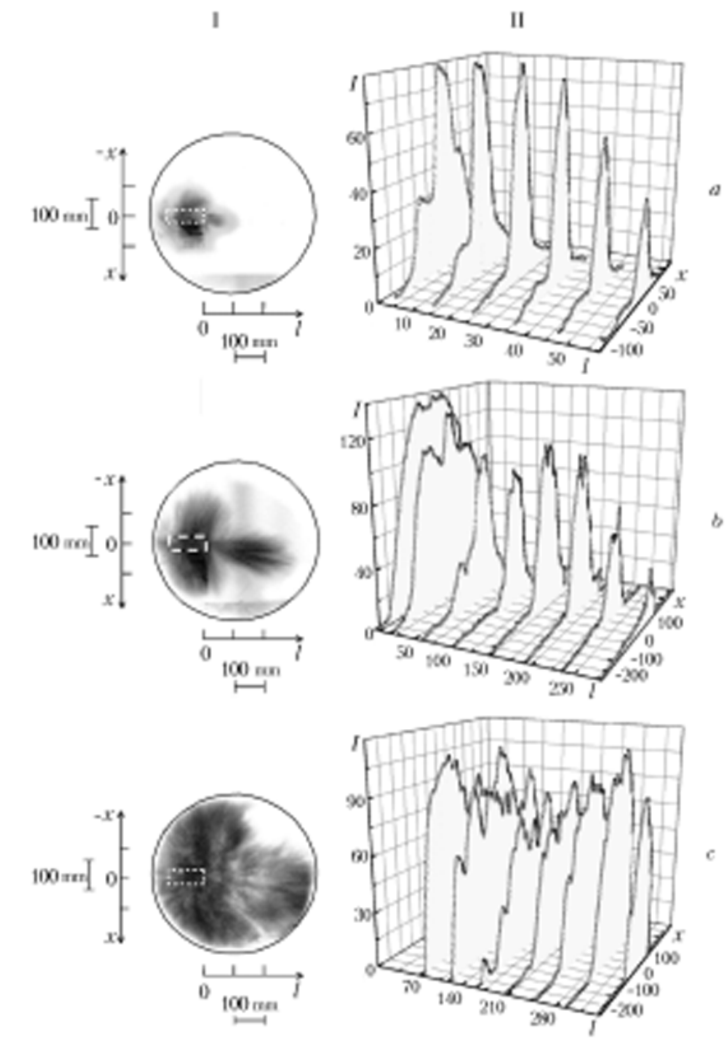

Fig. 1. Luminescence photograms (I) of the DPs and the jet and corresponding transverse distributions of the luminescence intensities (II) depending on the distance from the explosive charge face at the initial instant of jet development (a) recorded after 29 μsec (b) and 87 μsec (c).

Complex consideration of the results of the frame-by-frame and continuous recording permits the following interpretation of the detonation process: during the initial 5 μsec the fastest bright luminescent front end of the jet flows out of the cumulative groove and propagates for distance $l > 250$ mm. Next to the front end of the jet, during 60 μsec, its less fast segments and fragments of the main DP cloud entrained by them flow out and their luminescence gradually decays at distances $l \sim 100$–200 mm. In the presence of the lining mixture on the inner surface of the conical groove the velocity of the jet flowing out of it decreases.

A characteristic feature for all photoscans obtained is an increase in the luminescence intensity of the front end of the jet at distances $l \approx 100$–200 mm from the charge face, which is particularly pronounced in the case where the lining mixture is applied to the surface of the cumulative groove (Fig. 2b). As the x-ray microspectrum analysis of the detonation products has shown, this is due to the initiation of exothermal physicochemical reactions and phase transformations between the DP and lining components. Moreover, the photograms show a slightly luminescing (for 5–10 μsec) region preceding the front end of the jet. It is likely caused by the electron flux ahead of the jet [11], as well as by the ultraviolet radiation from its front end [13].

The numerical values of the measured velocities of jets v are presented in the field of photoscans (see Fig. 2). The lines mark the tangents to the regions of jets whose velocities were determined by computer processing of con-

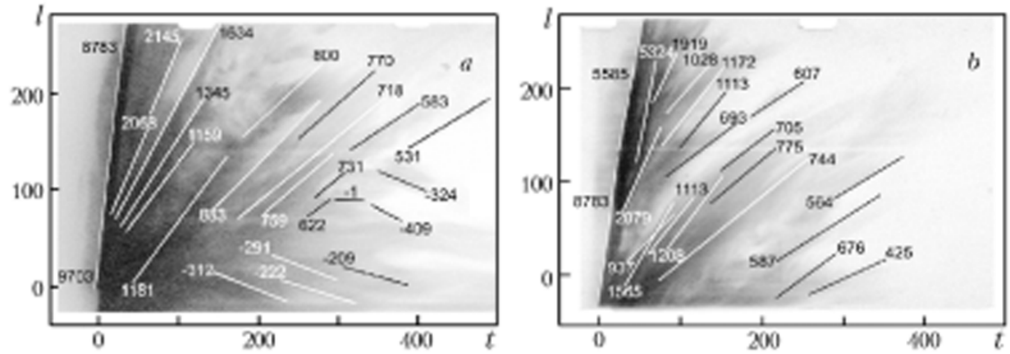

Fig. 2. Photograms of the DP radiation recorded by the SKS-1 camera in the continuous regime and velocity distribution of jet fragments: a) "pure" charge; b) charge with a lined cumulative groove.

tinuous photoscans with the use of the methodological data of [12]. The estimated rms error in determining the jet velocity taking into account the errors in measuring the velocity of motion of the cine film and in determining the reduction factor of the optical system and the values of the slope angles of the tangent to the jet path was $\Delta v / v \sim 5\%$. In the case of the "pure" charge detonation (Fig. 2a), the maximum velocity of the front end of the jet near the charge face is $v \approx 9700$ m/sec and gradually decreases, as it moves away from it for distance $l \sim 250$ mm, to $v \sim 8700$ m/sec, which is in qualitative agreement with the data of [10, 11], where a decrease in the velocity of cumulative jets as they propagate from the charge section into the surrounding gaseous environment rarefied to 100 Torr was noted. The slower segments of the jet following the front end move with velocities of 500–2000 m/sec. The propagation velocity of the main DP cloud is 2000 m/sec.

Unlike the "pure" charge detonation, in the case of detonation of a lined charge of the explosive (Fig. 2b), the velocity of a fast jet near the charge face is $v \approx 8800$ m/sec and decreases to $v \approx 5500$ m/sec at distance $l \sim 250$ mm. In so doing, the slow parts of the jet move with velocities from 2000 to 800 m/sec.

The observed velocity distributions of DPs agree, in general, with the data on cumulative jets formed in charges with metallic funnels. Since the detonation wave arrives at different instants of time to different parts of the groove surface, the greatest impulse is received by the region of the charge near the vertex of the cone which forms the fast front end of the jet. As the detonation wave moves to the base of the cone, the energy flux transferred by it to the explosive elements decreases and, accordingly, there is a decrease in the velocities of the jets formed. A characteristic feature of cumulative jets upon detonation of charges with a metallic funnel is the presence at some distance from the groove base of a cumulative focus, in which the greatest densification of the jet occurs. In our case, such a zone is absent.

The photoscans obtained show no tracks of the dispersed phase present in the jet, which is due to the small (of the order of dozens of nanometers) particle sizes and the limited spatial resolution of the photographic materials and projectors used. However, it may be suggested that their velocity corresponds to the jet velocity. The conclusion drawn follows from the data [14–16], where adequacy has been established of the velocities of the gas and microparticles with a larger diameter (~1 μm) in turbulent flows of different pressures pulsing up to frequencies of a few kilohertz. Taking this into account, we have estimated the residence time of the dispersed phase particles in the fast jet, $t^* \approx (l/v) \approx 40$ μsec.

Conclusions. As a result of the investigations of the gas-dynamic characteristics of fast jets formed by the detonation of shaped charges, we have noted a fan-like character of the flow of a jet with a luminescence intensity modulated along its length and transverse coordinate as a consequence of the interaction in the jet body of oblique shock waves caused by the extra-axial position of the detonator and the asymmetry of the initiating wave. It has been established that at the initial stage of formation of a jet, the velocity of its bright luminescent front end reaches $v \approx 9700$ m/sec and then a number of less fast rapidly turbulizable jets follow. At distances $l \sim 100$–200 mm from the funnel section there is an increase in the luminescence intensity and a change in the structure of the front end of the jet connected with the occurrence of exothermal carbide-forming reactions with compression and sputtering of the reacting mixture. The residence time of dispersed phase particles in the fast jet equal to $t^* \approx 40$ μsec has been estimated. The data obtained have been used to optimize the detonation synthesis of ultradispersed chemical compounds.

NOTATION

D, charge diameter, mm; $I(x, l)$, relative luminescence intensity of the jet; L, charge length, mm; l, longitudinal spatial coordinate, mm; P, pressure, GPa; T, temperature, K; t, time, μsec; t^*, residence time of dispersed phase particles in the fast jet, μsec; v, velocity of jets, m/sec; x, transverse direction of the spatial structure of the jet, mm; $\Delta v/v$, rms error in determining the jet velocity, %; Δx, profile halfwidth of the luminescence intensity distribution, mm; τ, exposure of individual frames (temporal resolution), μsec; φ, angle of the conical groove on the charge, deg.

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