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Initiating Aluminized High Explosives by Laser Radiation

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Abstract: A number of physical and chemical processes occurring under the action of a laser pulse in nanosized aluminum and aluminized explosives on the basis of fine-grained PETN and benzotrifuroxane along with estimates of the effect of aluminum of the explosive transformation dynamics in these explosives conclude that it is possible to initiate aluminized explosives by laser radiation. The estimated and experimental results show that the main source of hot spots capable of causing an explosive transformation in aluminized explosives under the action of a laser pulse can be a compression wave that forms as a result of rapid evaporation of a sufficient number of aluminum particles. It is shown experimentally that aluminized explosives based on fine-grained RDX and HMX can be initiated by a laser pulse whose source is no more powerful than that in the case of PETN and benzotrifuroxane.

Keywords: explosive, laser initiation, compression wave, detonation, PETN, benzotrifuroxane, RDX, aluminum.

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INTRODUCTION

All mechanisms for initiating an explosive transformation in high explosives under the action of a laser pulse, which are considered today in the literature, assume that it is created in local small regions that eventually leads to a generally accepted hot-spot mechanism. The hot-spot formation mechanism is described differently.

Two main mechanisms of formation of hot spots in explosives under the action of a laser pulse: selective photoinitiation and a thermal hot-spot mechanism.

Selective photoinitiation excites molecules of explosives under the action of a laser pulse and then begins their fragmentation (photodissociation). This mechanism is dominant in PETN initiation by neodymium laser radiation on the first harmonic (a wavelength of 1064 nm) [1–7]. A threshold density of PETN initiation by neodymium laser radiation is $H_{\text{thres}} \approx 90$ J/cm^2 [8–10]. Thresholds of initiation by neodymium laser equal to 30–40 J/cm^2 [11] are determined in experiments previously carried out at VNIIEF with fine-grained PETN obtained through thermovacuum recrystallization. The spread in the results of these two groups of experiments is apparently due to experimental conditions. In particular, it is shown in [12] that explosives subjected to thermovacuum recrystallization have a higher detonation ability.

Hot-spot initiation is considered as a main mechanism for initiating high explosives with light-absorbing inclusions. It is regarded that such inclusions are components of an explosive composition that absorb a laser pulse energy and transmit it to explosives in the form of a heat pulse [13]. In [8–10], a threshold density of initiation energy is $H_{\text{thres}} \approx 5$ J/cm^2 for PETN with Ni–C and Al–C carbide additives with a particle

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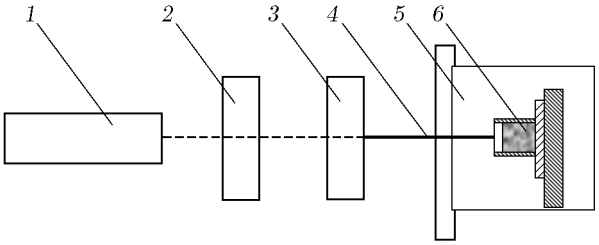

Fig. 1. Laboratory laser device: ((*1*) laser; (*2*) variable attenuator; (*3*) system for introducing the laser pulse into the optical fiber; (*4*) optical fiber; and (*5*) shielding chamber; (*6*) target.

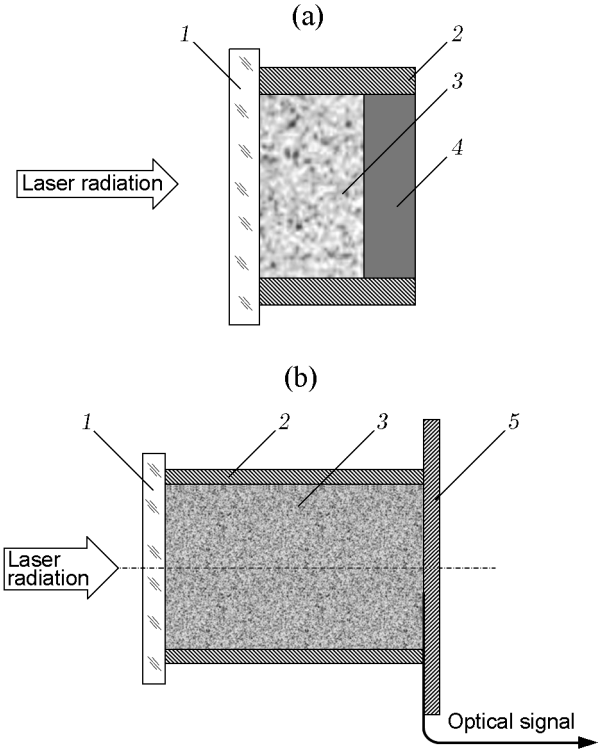

Fig. 2. Experimental devices for studying the interaction of the laser radiation with the nanosized aluminum powder (a) and aluminized explosives (b): (*1*) quartz glass; (*2*) ∅5-mm aluminum tube; (*3*) nanosized aluminum powder (a) and an aluminized explosive (b); (*4*) substrate; (*5*) witness plate.

size of ≈100 nm and $H_{\text{thres}} \approx 1.4$ J/cm^2 for PETN with Al additives with a particle size of ≈200 nm [14]. In the experiments carried out at VNIIEF, the threshold densities of laser pulse initiation energy do not exceed 1 J/cm^2 for PETN and benzotrifuroxane (BTF) with an Al additive and an average particle size of 50 nm.

Clearly, the change of the initiation mechanism in the examples under consideration yields a tenfold energy effect. Moreover, metallic aluminum and other studied light-absorbing additives are significantly different in the efficiency of their use. A significant decrease in the threshold density of the initiation energy under the action of a laser pulse on explosives with aluminum additives as opposed with explosives containing other light-absorbing additives makes one think that explosion inducing physical and chemical processes have their specific features in each case.

The laboratory technology for preparing aluminized explosives developed at the Institute and based on mixing components in a liquid medium with the use of a sonicator [16] makes sure that the distribution of components is highly homogeneous. The preparation of aluminized explosives by this technology makes it possible to investigate physical and chemical processes occurring in PETN and BTF based aluminized explosives under the action of a laser pulse and estimate the effect of nanosized aluminum on the development dynamics of explosive transformation in explosives. On the basis of the results obtained, conclusions are made on the possible mechanism of hot-spot formation in the case of initiating aluminized explosives by a laser pulse.

This study touches upon aluminized explosives based on fine-grained PETN, BTF, RDX, and HMX. The average particle size of Al is 50–200 nm.

EXPERIMENTAL DEVICE

Experiments are carried out on a laboratory laser device (Fig. 1) with the use of a neodymium solid pulse laser with an energy of ≈0.3 J, a wavelength of 1 064 nm, and a pulse duration of ≈6 ns (manufactured by "Polyus," Moscow). The interaction of a laser pulse with nanoaluminum and aluminized explosives is studied using experimental devices illustrated in Fig. 2.

ROLE OF ALUMINUM IN INITIATING AN EXPLOSIVE TRANSFORMATION BY A LASER PULSE

The temperature up to which nanosized Al is heated in the experiment under the action of laser radiation with an energy density close to the initiation threshold of aluminized explosives (0.5 J/cm^2 is the failure level, and 1 J/cm^2 is the initiation level) is calculated using a model given in [13] and describing the heating of small Al particles in the assumption that the coefficient of radiation absorption by aluminum is 0.3:

$$\delta T = Q_{\text{abs}}(r)\frac{Hr/4c_v}{rh + h^2 + r^2 + r^2/K^2}, \qquad (1)$$

Here T [°C] is the temperature, H [J/cm^2] is the laser pulse energy density, Q_{abs} is the radiation energy absorption coefficient, r [mm] is the metal particle radius,

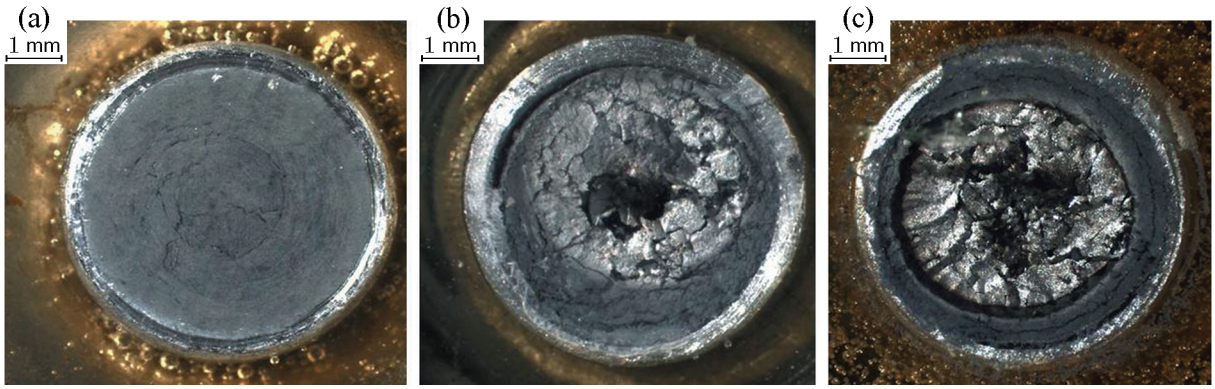

Fig. 3. Aluminum powder with an average particle diameter of 50–200 nm before (a) and after exposure to the laser pulse through a quartz glass with an energy density of ≈0.5 (b) and ≈1 J/cm^2 (c).

c_v [J/cm^3] is the heat capacity of the explosive with a constant volume, h [mm] is the thickness of the heated layer, (the value of h^2 is proportional to the pulse duration of the laser radiation), and $K = 3(c/c_1)$ is the coefficient determined by the ratio of the volumetric heat capacities of the dispersion medium and Al.

There are indications of melting and evaporation of the Al sample under study in the experiments on the effect of laser pulse on an Al powder with an average particle size of 50–200 nm (see Fig. 2a). The photographs of characteristic results of these experiments are given in Fig. 3. The image of the sample before exposure to the laser pulse is added for comparison (Fig. 3a).

Figures 3b and 3c show that there are three regions in the sample after exposure to laser radiation. The central region is apparently where Al evaporates, which is confirmed by the formation of a characteristic "crater". There are also regions where Al melts, which is seen from changes in the color and structure, and where it remains intact. As the laser pulse energy reduces from a level at which the aluminized explosive is initiated (≈1 J/cm^2) to a level below its initiation threshold (≈0.5 J/cm^2), the area of this "crater" formed due to aluminum evaporation becomes two times smaller (approximately from 0.04 to 0.02 cm^2). In this case, the areas of the regions where Al melts remain almost intact (≈0.05–0.06 cm^2).

The calculation carried out according to Eq. (1) with a laser pulse energy density of ≈1 J/cm^2 and a laser pulse duration of 6 ns and with account for the energy density distribution over the radiation spot, which is studied in [12], shows that the size of the Al evaporation region corresponds to the calculated temperature on the edges of the region 2600–3000°C (5000–6000°C at the center of the region). On the edges of the melting region, the estimated temperature is 650–900°C. Reaching these temperatures in aluminum should be accompanied with a pressure rise and the formation of a compression wave.

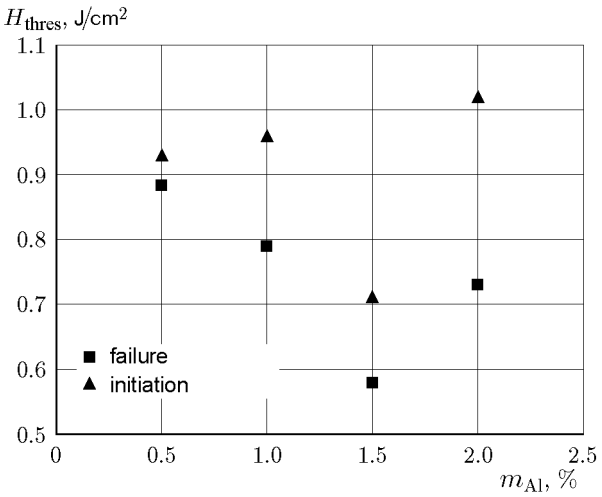

Fig. 4. Initiation thresholds and failure under the action of the laser pulse on the BTF based aluminized explosive charge versus the mass fraction of Al in the explosives

The study of the dependence of the threshold density of the laser pulse energy on the mass fraction of Al (m_{Al}) in the explosives (the experiment is illustrated in Fig. 2b), shown in Fig. 4, demonstrates that, if the Al content is optimized, the laser pulse energy with which detonation is initiated in the explosives under study is within the interval 0.6–0.7 J/cm^2. The temperature of heating of the Al inclusions is calculated using Eq. (1) with account for the heat conductivity and charge density, which concludes that the Al particle temperature with these energy values can reach 2500–2800°C, which is much higher than a boiling point.

Thus, it can be logically assumed that the source of hot spots capable of triggering an explosive decomposition of high aluminized explosives is the evaporated Al particles and a compression wave formed in this case. The probability of this process transitioning to detonation is apparently determined by the amount of evaporated Al.

It is shown by analyzing the development kinetics of the explosive transformation in the explosives in the same formulation for various Al content (Fig. 5) that the operation time of the aluminized explosive charge in the entire range of energy densities of the laser pulse exponentially decreases with increasing energy density. In this case, as the energy density of the laser pulse exceeds ≈2 J/cm^2, the time difference in the operation of the explosive charges for all the mass fractions of Al under study decreases. If the energy density exceeds ≈3 J/cm^2, the initiation time of the explosives with an Al content of 0.25–3% and a charge length of 3 mm lies in the range 1.15–1.25 μs. Thus, the operation time of the charge is changed by less than 10% with the mass fraction of Al changing by almost an order of magnitude.

Moreover, the detonation delay is estimated on the basis of the extrapolation results of x–t diagrams of operation of the explosive charges, and it is equal to ≈0.2–0.6 μs.

In this formulation of the experiment, these results virtually exclude the domination of the excitation mechanism of explosive transformation in aluminized explosives under the action of the laser pulse due to heat conduction between the Al particles and explosives because the initiation time of the charge in this case is more dependent on the aluminum content, while the detonation delay is longer than 1 μs.

Consequently, in the experiments conducted, the role of a dominant mechanism of hot spot formation in initiating aluminized explosives on the basis of heat-resistant high explosives by a laser pulse should be played by the formation of a compression wave due to quick evaporation of Al.

If this assumption turns out to be valid, it can be predicted that the use of a laser pulse to initiate aluminized explosives on the basis of heat-resistant high explosives with a sensitivity lower than that of PETN and BTF does not require a more intense impact.

INITIATING HEAT-RESISTANT ALUMINIZED EXPLOSIVES BY A LASER PULSE

The initiation threshold of the aluminized explosives based on finely-grained RDX and HMX is determined for devices similar to those in Fig. 2b. The Al powder with an average particle size of 100 nm is used, which demonstrated the best efficiency in previous studies. The working section of the aluminized explosive in the target is ensured by vibration compaction, and it is equal to ≈1 g/cm^3. The mass fraction of aluminum is chosen to be 1.5% from previously obtained results for mixtures based on finely-grained PETN and BTF. A positive result is excitation in the experimental charge of the detonation, which is indicated on the basis of the state of the witness plates after exposing the target to laser radiation, whose appearance is shown in Fig. 6. The obtained values of H_{thres}, which ensure the initiation of the explosives under study, are given in Table 1. For comparison, Table 1 shows the values of H_{thres} of PETN and BTF based aluminized explosives in a similar formulation. The operation time of the charge is controlled, it equals ≈2–3 μs (the charge length is ≈5 mm).

As seen from Table 1, all the explosives under study have comparable thresholds of initiation by a laser pulse

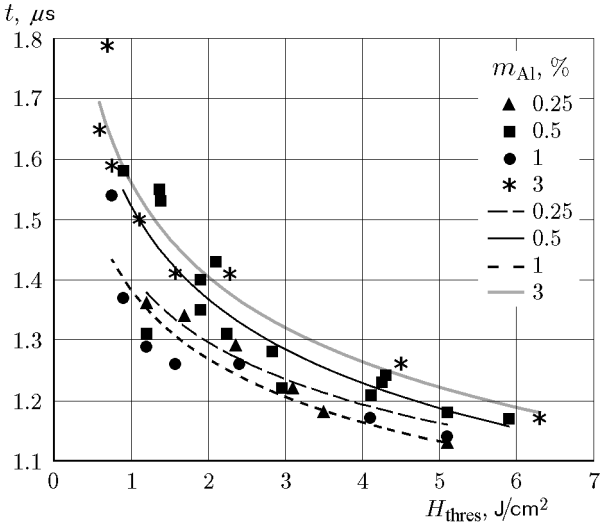

Fig. 5. Operation time of the BFT based aluminized explosive charge versus the energy density of the laser pulse for various mass fractions of Al in the explosive.

Table 1. Thresholds of initiation of aluminized explosives by a laser pulse

Aluminized explosive based on	H_{thres}, J/cm^2
PETN	0.8
BTF	0.7
RDX	0.4
HMX	1.0

Fig. 6. Visual appearance of the witness plates after exposing the target to laser radiation that initiates the aluminized explosive.

(at the level of ≈0.5–1.0 J/cm^2). Thus, the possibility of creating RDX and HMX based light-sensitive aluminized explosives with a sensitivity to a laser pulse close or even higher than that of PETN and BTF considered previously.

The obtained experimental results on the sensitivity of the aluminized explosives under study to a laser pulse do not correlate with any of the following characteristics of the corresponding individual explosives:
sensitivity to mechanical impact;
shock-wave sensitivity;
resistance to heat.

One of the reasons affecting the sensitivity to a laser pulse is apparently the nature of Al nanoparticle distribution on the surface of the explosive crystals (Fig. 7).

Even though there are many other specific features considered below, it is quite clear that one does not need a significantly more powerful laser radiation source for initiating aluminized explosives based on high explosives and whose sensitivity to mechanical and shock-wave impacts is lower than that of PETN and BTF.

DISCUSSION OF RESULTS

As shown by the results of determining the heating temperature of nanosized Al powders under the action of laser radiation with an energy density close to the initiation threshold of aluminized explosives (0.5–1 J/cm^2), the source of hot spots capable of initiating an explosive transformation in them is the evaporated Al particles.

Assuming that this mechanism is predominant, the dependence of the threshold density of the laser radiation energy triggering the aluminized explosive charge on the mass fraction of Al is easily explained.

In the case of this mechanism of explosion transformation, the density of the density of the threshold initiation energy of aluminized explosives is bound from the bottom by a necessity for a large number of Al particles to reach a boiling point and cannot be much lower than ≈0.5 J/cm^2, which is shown by the study of H_{thres} of aluminized explosives with different mass fractions of Al.

For the left branch of the experimental dependence given in Fig. 4, H_{thres} decreases in a reverse dependence on the Al concentration, whose growth is accompanied an increase in the number of heating hot spots.

If the optimal value of the mass fraction of Al in the explosives is exceeded, there are heat-conducting "bridges" formed from metal particles, because of which heat losses (the right branch of the dependence) increase and the heating temperature of the Al particles with a set energy density in the laser radiation drops rapidly. The threshold energy density increases proportionally to the mass fraction of Al.

One should probably exclude the domination of the mechanism of hot spot formation due to heat transfer between the Al particles and the explosives because an explosion delay in this case would be longer than 1 μs rather than ≈0.2–0.6 μs as obtained in the experiments. The reason for the short detonation delay in the initiation of aluminized explosives can be the possibility of a compression wave formation due to rapid (not larger than ≈10 ns) evaporation of a large amount of Al. The results showing that the evaporation of a solid matter under the action of a powerful laser radiation can lead to a pressure pulse transfer have been known for a long time. Thus, if metal targets are exposed to a powerful laser radiation based on a Q-switched neodymium glass, peak pressures of tens of kilobars are obtained [15], and the values of laser intensity that ensures the transition of Al into low-density

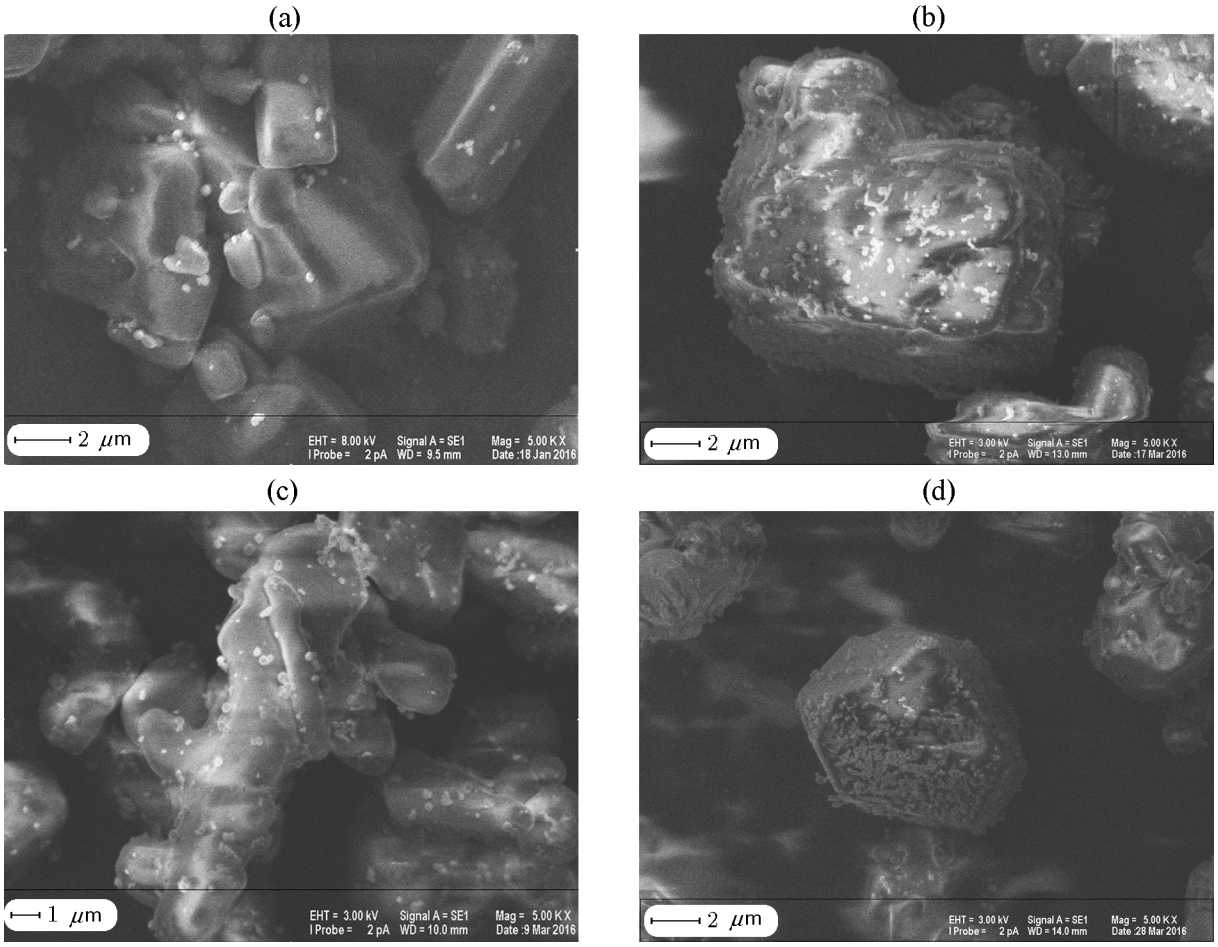

Fig. 7. Typical electronic images of samples of aluminized explosives based on PETN (a), BTF (b), RDX (c), and HMX (d).

Table 2. Thermal and physical characteristics of the explosives under study

Explosive	c_p, J/(mol · K)	λ, 10^{-2} W/(m · K)
RDX	277	10.6
BTF	316.3	29
PETN	529	25.8

plasma, which are given in [15] ($2.2 \cdot 10^8$ W/cm^2), correspond to threshold levels of impact, implemented in these experiments (≈ 0.8–$1.7 \cdot 10^8$/cm^2).

In all regards, RDX is more resistant, but it demonstrates a higher sensitivity to laser radiation than PETN or BTF, and the reasons for that are described below.

One of the reasons, as noted above, is the nature of distribution of Al nanoparticles on the surface of the explosive crystals.

It should also be noted that, even though heat transfer between the Al particles and explosive crystals is not a predominant source of excitation of explosive transformation according to the results presented, it still affects the temperature reached in the aluminum within the laser pulse duration. Because of the fact that aluminum loses some of its thermal energy in this case, its temperature drops, which, according to Eq. (1), is accounted for when calculating the coefficient defined as a ratio of volumetric heat capacities of the dispersion medium and Al. Possibly, this is the reason that, in the case of RDX whose heat conductivity and temperature conductivity λ are much lower than that of PETN and BTF (Table 2), the temperature of aluminum particles is much higher than in the case of these explosives, which is why the parameters of the arising compression wave are higher and the initiation threshold is lower.

On the other hand, accounting for initiation mechanisms with excitation of electronic states, as noted in [18] with a reference to calculations of the electronic structure of RDX carried out in [19], there could be ad-

ditional local narrowing of the bandwidth near dislocations during compression in the shock front, which may increase the possibility of electronic excitation. Consequently, the sensitivity of RDX itself to laser radiation could be increased under the action of a compression wave from evaporated Al.

CONCLUSIONS

As shown by the calculations, the main source of hot spots capable of causing an explosive transformation in aluminized explosives under the action of laser radiation is evaporated Al particles and a compression wave formed in this case. The experimental results obtained are in good agreement with the given assumptions that quick evaporation of Al under the action of laser radiation is a necessary condition for the formation of explosive transformation in aluminized explosives. The dominance of the hot spot formation due to heat transfer between the Al particles and explosives should be excluded, and the formation of a compression wave should be explained by quick evaporation of a sufficient amount of Al. With this mechanism of explosive transformation, the density of the threshold initiation energy of aluminized explosives is bound from the bottom by a necessity for a sufficient number of Al particles to reach a boiling point and should not be much lower than ≈ 0.5 J/cm^2.

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