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Laser initiaion of PETN-based composites with nano-sized absorbing additives of carbon and aluminum under conditions of various volume compression

The energy thresholds and the kinetics of explosive decomposition of pentaerythritol tetranitrate (PETN) and its composites induced by the laser pulse (λ_0 = 1064 nm; $\tau_и$ = 12 ns) in dependence on the concentration of absorbing additives and different volume compression within the range from 40 to 600 MPa are experimentally studied. The sensitivity of pure PETN and its composites increases along with the volume compression value. For low pressures (less than 200 MPa) with the increase of additives concentration the sensitivity of mixtures to laser pulse exposure increases and for higher pressures (more than 300 MPa) — it decreases. Such behavior is explained from the perspective of both diffuse light scattering and the thermal micro-spot model of initiating the transparent explosive components (the "hot spot" model), according to which the reactive capacity of hot spots is determined by their heat reserve, their concentration and the scale of gas dynamic unloading in the neighboring to hot spots pores and through the sample surface pressed by the input window (the area of low pressures), as well as by the heat conducting unloading of hot spots in the explosive components matrix and the covering glass (the area of high pressures).

Keywords: PETN, laser pulse initiation, nano-sized particles, optical breakdown, hot spots.

Introduction

The goal of this work is to identify the combined effect of absorbing nano-sized additives and volume compression pressure on the energy thresholds of pulsed laser initiation of pentaerythritol tetranitrate (PETN) and to improve model concepts of the mechanism of laser initiation of explosive decomposition of composites based on PETN powders. The objectives of the study included determining the value of spatial illumination in the sample volume at different concentrations of absorbing additives (up to 1 % by weight) and different compression pressures (from $2.5 \cdot 10^7$ Pa to $4 \cdot 10^8$ Pa), determining the coupling coefficient between spatial illumination and surface illumination specified by the laser beam, obtaining experimental dependencies of the energy thresholds of initiation of explosive decomposition of mixtures, developing and describing the mechanisms of explosive decomposition of PETN.

The studies of the laser pulse ignition of the secondary explosive components are conducted since the 60s of the previous century [1–6]. However, until now the united opinion about the initiation mechanisms has not been formed. The main cause for this is the absence of the unified methodology of research conducted by different research teams which is discussed in [6]. The most informative direction of research to discover the ignition mechanisms is the experiments of the impact of the volume compression pressure on the ignition energy thresholds. The pioneering experiments in this direction were described in [2], where the volume compression of powders of PETN, hexogen and octogen was achieved by the positioning of the samples into metallic compression mold with the transparent input window placed into the hydraulic press. In the experiments there was used the compression pressure of the input window from 10 MPa (0.1 kbar) to 2000 MPa (20 kbar). At that, with the compression pressure increase there was observed the monotonous increase of sensitivity (the ignition threshold decrease). Thus, with the laser pulse irradiation with the pulse duration of 40 ns on the wave length of 1064 nm the threshold energy density comprised about 600 J/cm^2 under the pressure of 10 MPa, while under the pressure of 2000 MPa — it is about 20 mJ/cm^2, that is, it decreased approximately in 30000 times.

The studies of PETN mixtures with absorbing additives were conducted in [3–5], where it was demonstrated that with introduction of additives the ignition energy decrease is recorded and it depends on the additive material. The maximum decrease of energy was discovered in [3, 4] with introduction of aluminum particles with the size of 2 μm.

In the study [6] there were measured the ignition thresholds for pure PETN with the dispersion of 6000 cm^2/g and PETN with additives of carbon nanopowder particles (the typical size of the particles is 75 nm) with the additives' concentration from 0.1 % to 1 % on the mass. The compression pressure of the input window (the plexiglass thickness 5 mm) did not change and was $1.76 \cdot 10^8$ Pa (1.76 kbar) with the laser beam diameter equal to 0.6 mm. It was demonstrated that with the increase of additives concentration the threshold energy (the energy density) decreases monotonically. Thus, under zero concentration (pure PETN) the threshold energy comprises 6.5 mJ (the threshold energy density 2.3 J/cm^2), under the concentration 0.1 %C — 2.4 mJ (0.85 J/cm^2); under the concentration 0.5 %C — 1.8 mJ (0.64 J/cm^2); under 1 %C — 1.3 mJ (0.46 J/cm^2). It was discovered that the sensitivity under 1 % additive of carbon nanopowder increases in 5 times in comparison with the PETN sensitivity which does not contain additives. In [7] there was sufficiently detailed study of the PETN behavior with additives of coarse particles of different metals (the size 20–100 μm) and with the additives of aluminum fine particles (the average size is about 1 μm) in dependence on their concentration (up to 10 % on the mass). The specifics of the methods of the experiments were the low density of mixture (less than 1 g/cm^3) and the input window (the sheet glass) tightly pressed to the surface avoiding the pressuring force. There were obtained the dependences of the ignition thresholds on the irregularities' concentrations. In both cases the minimum of the ignition threshold was discovered under certain values of concentration. The similar results were obtained in the studies [8-9], but under high densities of PETN mixtures with nano-sized aluminum particles (1.75 g/cm^3).

In the study [10] there was investigated PETN with the additives of aluminum nano-sized particles from 0 to 1.0 of the weight percentage under different pressures of the input window. At that, the typical size of the particles comprised 140 nm with the aluminum content in the particle about 90 %. In these experiments the quantities of mixture powders were preliminary pressed under the pressure of 1800 MPa, while the compression pressure of the input window was changed from 17 MPa up to 288 MPa with the side lever press. It was demonstrated that with the compression pressure increase and increase of additives concentration the ignition thresholds are decreasing monotonically, at that in the area of low pressures the additives decrease the thresholds in more than 3 times, while in the area of high pressures — in only 1.4 times.

Some different results were obtained earlier in the study [11] on PETN with carbon nanopowder additives (75 nm) under the compression pressures from 200 to 600 MPa avoiding the preliminary pressing. The concentration of carbon particles changed from 0 to 1.0 of the weight percentage. In the area of low pressures (about 200 MPa) there was discovered the sensitivity increase approximately in 1.85 times in the mixture with one percentage of carbon nanopowder in comparison with pure PETN. However, in the area of high pressures (about 600 MPa) 1 % mixture turned out to be less sensitive (there was observed the threshold increase in comparison with pure PETN in 1.37 times).

It is evident that the impact of the sensitivity increase in the area of low pressures with the concentration growth is dependent on the energy localization of the laser pulse on the absorbing additives and formation of supplementary hot spots distributed throughout the sample volume. Introduction of the additives leads to hot spots concentration in comparison with concentration of hot spots formed in self-generating defects in pure samples. This conclusion is trivial and does not require any proof; however, based on the given contradictory data [7–9, 11] it is difficult to explain the decrease of additives efficiency under high compression pressure. To solve this problem, it is necessary to conduct the research of impact of carbon nanopowder and aluminum particles concentration on the behavior of mixture compositions in the same interaction conditions. It requires the measurements for different composites performed using the same set-up which constitutes the goal of this study.

Experiment

The measurements of the ignition thresholds under different compression pressure of the input window. The measurements were performed within the compression pressure range from 40 to 600 MPa. Pure PETN and PETN with nano-sized carbon and aluminum particles were under investigation. The substance quantities with the weight of 10 mg were positioned into the metallic compression mold with the diameter of d_n = 1.15 mm, and were located in the hydraulic press and pressed against the input window. The sheet glass with the thickness of 10 mm was used as the input window. The kinetic characteristics of the decomposition process were determined with the photomultiplier H5773 Hamamatsu with the time resolution about 1 ns and the force wave detector on the piezoelectric ceramic PZT-19 with the time resolution about 10 ns. Figure 1 represents the obtained by us results (with consideration of [11, 12]) the experimental dependences of the PETN energy ignition threshold on the compression pressure of the input window under different concentra-

tions (in the weight percentage) of carbon nanopowder particles (the curves 1–4) and aluminum (the curve 5). At that, the typical size of carbon and aluminum nanopowder particles was 75 nm and 140 nm respectively. It is highlighted that with the pressure increase of the pure PETN powder sensitivity increases not monotonically but there is observed the rapid leap of the sensitivity under the pressures exceeding 200 MPa. The quality of mixtures behavior remains the same as of pure PETN. The ignition threshold decreases under low compression pressures of the input window with the additives' concentration increase. While under the pressure of 100 MPa the threshold decreases in 5 times. With the pressure increase the additives' impact decreases and under the pressures exceeding the break-down point of PETN crystals the impact becomes unperformed. Under the pressures higher than $3 \cdot 10^8$ Pa their impact becomes negative (Fig. 1, the curves 1–5); that is, with the additives concentration increase the threshold increases and under the pressure of 600 MPa it reaches the value of 100 mJ/cm^{2}and 60 mJ/cm^2 against 50 mJ/cm^2 for pure PETN.

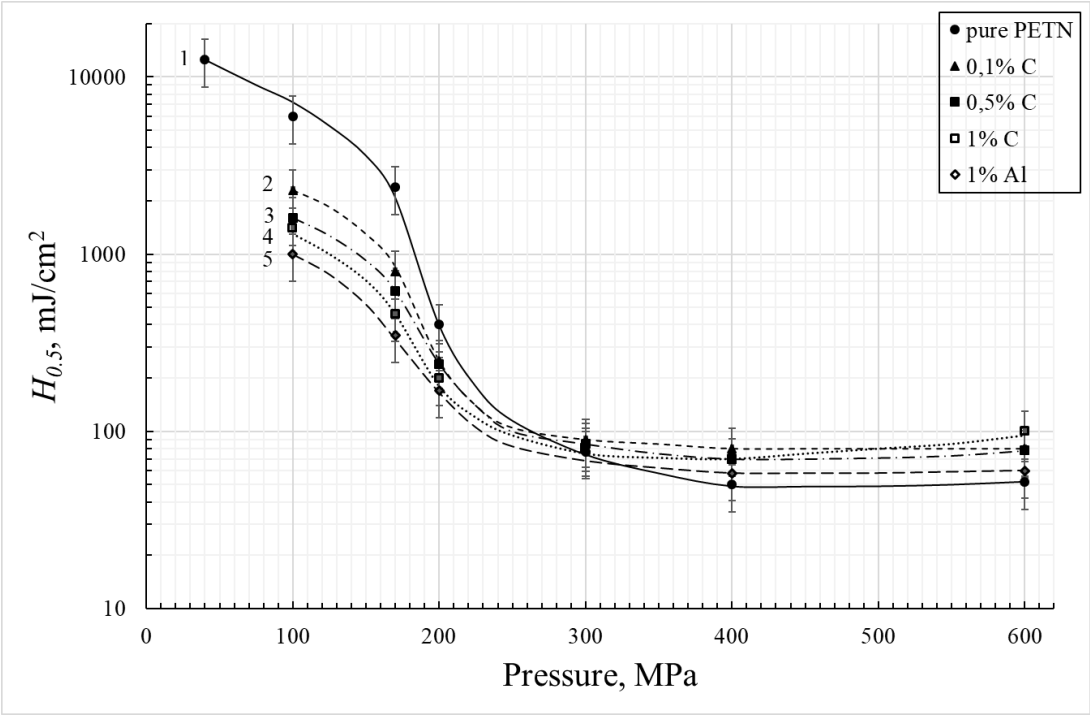


Figure 1. Dependence of PETN ignition energy threshold on the pressure P with different concentrations of carbon nanopowder and aluminium additives. Pure undoped PETN (1); with additives 0.1 % of carbon nanopowder (2); with additives 0.5 % of carbon nanopowder (3); 1 % of carbon nanopowder (4); PETN with additives 1 % of aluminium (5).

PETN with aluminium additives (the typical size 140 nm) was studied in less detail and only with the maximum concentration of additives, that is, with the same weight coefficient, following the hypothesis that in the area of low compression pressures with this concentration it is possible to obtain significant decrease of the threshold. In fact, the threshold decrease under the compression pressure of 100 MPa comprised 6 volumes (please see the curve 5). It should be mentioned that the ignition thresholds for the mixture with aluminium additives are slightly lower than the thresholds for the mixture with carbon nanopowder additives. Thus, under the pressure 100 MPa the ignition energy threshold density for the ignition of PETN with aluminium additives comprised 1050 mJ/cm^2 against 1400 mJ/cm^2 for PETN with carbon nanopowder additives. In the area of 300 MPa this ratio comprised 82 and 80 mJ/cm^2, correspondingly. Certain measurement data with carbon nanopowder additives is given in Table 1. In Table 2 there is given the data on the ignition thresholds for PETN mixture with aluminium additives obtained in the study [10] under slightly different conditions comparing to our experiments (samples were pre-pressed), which are partly used by us in discussion of the results. It is evident that in the area of high compression pressures of the input window the mixture porosity in our experiments and in the experiments from [10] is minimal that is the experimental conditions are almost similar while the thresholds are of near value. In the area of low pressures the mixture porosity in the experiments of [10] still remains minimal while in our experiments it is maximum. It is possible to suggest that the ignition thresholds are determined by the mixture porosity and explain high ignition thresh-

olds in our experiments (1050 mJ/cm^2) in comparison with low thresholds obtained in the study [10] (100 mJ/cm^2).

Table 1

The ignition thresholds of PETN $H_{0,5}$ (mJ/cm^2) with carbon nanopowder additives under different volume compression pressure (the compression pressure for the input window)

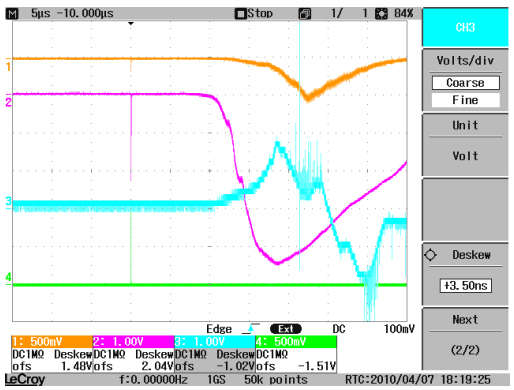
P, MPa	C, %				Al, %
	0.0	0.1	0.5	1.0	1.0
40	12000±3000	–	–	–	–
100	6000±1700	2300±800	1600±400	1400±200	1000±150
170	2299±700	849±200	640±160	460±110	300±100
200	370±150	250±100	210±70	200±50	200±30
300	80±20	80±15	75±15	82±12	80±10
400	50±10	80±10	-	73±10	62±10
600	55±10	80±15	-	100±20	60±10

Table 2

The ignition thresholds for PETN H0,5 (mJ/cm2) with the additives Al, obtained in the study [10] on the samples preliminary pressed up to 1800 MPa under different compression pressures of the input window

P, МПа	Al,%			
	0,0	0,1	0,5	1,0
17	2700	900	450	400
120	320	150	80	80
288	70	50	50	50

The kinetics of the explosive decomposition is given in Figure 2. Earlier we have demonstrated in [12], that for pure PETN the kinetics of the explosive decomposition are characterized by greater length of the induction period. In this respect, the interest represents the comparison of the kinetics of the mixture composites decomposition with the kinetics of pure PETN decomposition. With this objective Figure 2 provides the kinetics of the explosive decomposition of the composites under study. Comparison of Figure 2 with the pictures from the study [12] points to the quality conformity of the kinetics of the explosive decomposition in both cases. In particular, it is evident that under the threshold levels impact there is always observed the ignition delay in PETN composites containing carbon nanopowder and aluminium, that is, there is the induction period. The delay length depends on the compression pressure of the input window, laser spot size, and the mixture concentration and reaches 60 μs under certain conditions (please see Fig. 2 *a*, *b*, *c*); it can also exceed the length of the laser pulse in 4 orders of value. With multiple orders exceeding of the threshold levels the delay effects become shorter up to the values of microseconds.



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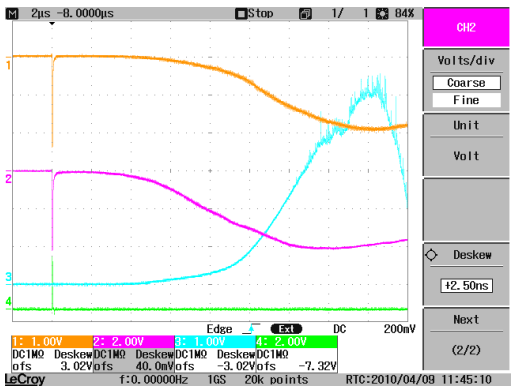

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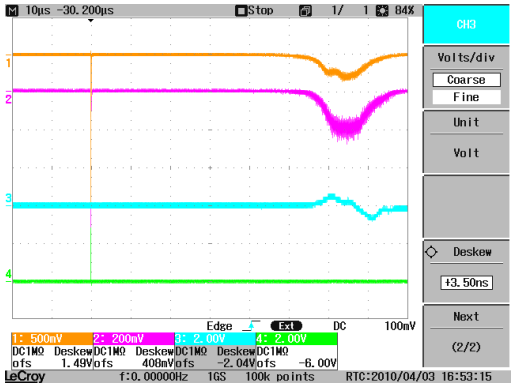

Fig. 2. Oscillograms of the process of explosive decomposition of PETN with additives 0.1 % of carbon nanopowder (a, b) and 0.1 % aluminium (c). 1 — laser pulse duration τ = 12 ns; 2 — the light signal of explosive decomposition in the radiation zones; 3 — the same at the all-round view; 4 — the pressure pulse registered by the acoustic transducer. λ0 = 1064 nm. d_n = 1.15 mm. H = 300 mJ/cm2, P = 200 MPa (a); H = 80 mJ/cm2, P = 300 MPa (b); H = 50 mJ/cm2P = 600 MPa. (c).

в)

Discussion of Results

Despite the differences in optical and thermo-physical properties of these additives (carbon nanopowder and *Al*), their impact is the same from the quantitative perspective, in particular, the additives concentration increase leads to the sensitivity increase (please see Fig. 1). This is especially evident in the areas of low compression pressure. Such behavior of the curves is determined by a number of factors. We will analyze these factors from the standpoint of heating the absorbing additives, the formation of thermal micro hot spots in their volume and surroundings.

One of these factors is strong change of optical properties of powders under pressures exceeding the material breaking down point (visually observed is contrast darkening of the mixture with its high compression pressure). The optical characteristics change under different concentrations of additives of carbon nanopowder and aluminium and different volume compression pressure of PETN powder were measured by us in separate experiments. There were experimentally determined the diffuse-reflection factors for the pressed tablets with the thickness h = 2 mm and based on their values there was determined the distribution of spatial luminance through the sample volume, using the Monte Carlo method. It was demonstrated that the spatial luminance E_0 in the volume of pressed powders may significantly increase the luminance E_n of the sample surface. It should be noted that spatial illumination (the saturation of a point in space with light) determines the heating temperature of the "hot spot". Table 3 gives the values of relative increase of the spatial illuminance $F_0 = E_0/E_n$ in the near-surface layer in comparison with the illuminance on its surface defined by the incident laser beam.

The estimated value F_0^{max} for PETN with the dispersion 6000 cm^2/g under different compression pressures P and different concentrations of absorbing nano-sized additives γ the weight percentage. The layer thickness h = 2 mm (semi-infinite layer from the optical perspective)

Table 3

γ, %	$P = 2{,}5 \cdot 10^7$ Pa		$P = 10^8$ Pa		$P = 2 \cdot 10^8$ Pa		$P = 4 \cdot 10^8$ Pa	
	Al	*C*	*Al*	*C*	*Al*	*C*	*Al*	*C*
0,0	8,9	8,9	8,9	8,9	7,8	7,8	6,46	6,46
0,05	8,5	5,6	7,0	3,7	5,9	3,2	4,6	2,7
0,11	7,5	4,1	5,1	2,7	4,1	2,6	3,0	2,4
0,25	5,0	2,9	3,6	1,7	2,6	1,5	2,0	1,4
0,33	4,4	2,5	3,1	1,5	2,4	1,4	1,9	1,2
0,5	3,6	2,0	2,5	1,4	2,1	1,3	1,5	1,2
0,66	3,2	1,8	2,3	1,2	1,9	1,2	1,5	1,1
1,0	2,9	1,5	2,0	1,2	1,5	1,1	1,4	1,02

The data from Table 3 informs that the luminance in the powder volume decreases with increase of concentration of absorbing additives and the compression pressure increase. From the perspective of micro hot spots ignition mechanism [6, 11, 12] and hot spots formation separately this factor does not explain the sensitivity increase with the increase of pressure and concentration as decrease in the spatial luminance, on

the contrary, is to lead to lesser heating of hot spots, hindering the ignition process and the threshold increase. The experiment shows the opposite, so it is necessary to take into account the heating of the matrix.

The second, in our opinion, key factor is the following. In the area of low (for example, 100 MPa) volume compression pressures (the area of high values for the ignition threshold, H_{05} = 6 J/cm^2) the mixture porosity is high. The temperature of heat micro hot spots may reach tens of thousands Kelvin degree, due to this, the intensive gasification of PETN takes place in the vicinity of hot spots. In such situation the interest represents the processes of heat averaging through the illuminated sample and formation of high temperature macro hot spot capable of igniting the explosive decomposition.

When evaluating the heating temperature for irregularities as well as the temperature for energy material matrix heating with different additives concentration, it is necessary to take into consideration the relative cross-section of particles absorption k (λ_0, R_0, N_0, N_p) and the luminance increase coefficient $F_{max}(R_\partial, h, \gamma)$ in the vicinity of the absorbing center. Thus, with the impact on the surface of the thick (semi-infinite layer from the optical perspective) tablet of pure PETN by the neodymium laser beam (λ_0 = 1064 nm; τ_p =10 ns) the temperature of single irregularity T_p in approximation of the adiabatic heating conditions comprises:

$$T_c \sim T_н + 3HkF_0/(4c_1\rho_1R_0) \quad (1)$$

(where H — the laser pulse energy density; $c_1\rho_1$ — the particle thermal capacity; R_0 — the particle radius, T_0 — the initial temperature),

while the temperature for the matrix heating T_m of PETN

$$T_м \sim T_н + \mu HF_0/c_2\rho_2 \quad (2)$$

(where μ — the index of absorption ($\mu = k\pi R_0^2 n$); $c_2\rho_2$ — the thermal capacity of energy material; n — the particles concentration ($n = 3\cdot10^{-2}\rho_2\gamma/4\rho_1\pi R_0^3$); γ — the additives weight percentage).

For clarity, we present the calculated dependences of the heating temperature of the hot spots and matrix and their distribution over the depth of the sample at a laser energy density of 100 mJ/cm^2 under adiabatic heating conditions (see Fig. 3). From (1) and (2) it is clear that the heating temperature is directly related to the coefficient F_0, which was calculated by the Monte Carlo method in three different ways [13], giving slightly different results. In this work, taking into account the importance of F_0 and the accuracy of its determination, the Monte Carlo algorithms were improved, and the F_0 values were obtained more reliable. Taking into account the duration of the laser pulse, the temperature values will be significantly less than the estimates from (1) and (2). Modeling and numerical calculation of the problem of heating a single spherical absorbing particle (carbon, aluminum) of different radii at different durations of the laser pulse in a transparent scattering medium are described in detail in the article [14–16]. Using the results of [14], the data of Table 1 and Table 3, we will estimate the heating temperatures of the hot spot in the region of low and high pressures of volume compression of the samples. The calculation data are shown in Figure 3.

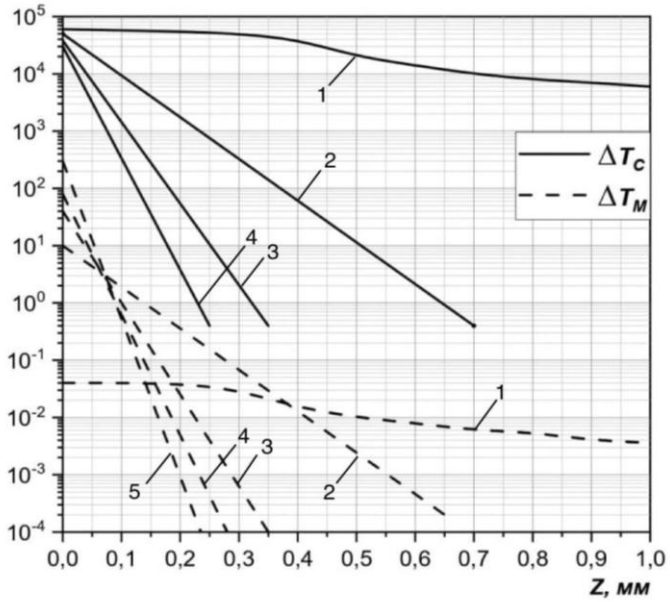

Fig. 3. Calculated dependence of the heating temperature of carbon nanopowder inclusions ΔTc (solid curves) and the heating temperature of PETN matrix ΔTм (dashed curves) along the layer depth z on the weight percentage of carbon nanopowder additives γ. Radiation wavelength λ0 = 1064 nm; h → ∞. Relative particle absorption cross section k = 1.5. Weight percentage of carbon (C) nanopowder additives γ.= 0.0 % (1); 0.1 % (2); 0.5 % (3); 1 % (4); 10 % (5). The energy density on the surface (Hs= 100 mJ/cm2) is close to the threshold value.

Let's consider the initiation mechanism in the low pressure region (about 100 MPa). Here the samples have high porosity and high initiation thresholds (from 1 to 6 J/cm^2). It can be assumed that possible gas-dynamic unloading from the hot spot volume will significantly reduce their temperature, however, the addition of impurities from the standpoint of the initiation process from the hot spot volume cannot explain their effect on the threshold reduction observed in the experiments. From Figure 3 it is evident that the temperature in the hot spot volume decreases with increasing concentration of additives and this should lead to an increase in the threshold, but this contradicts the experimental results. Ignition due to heating the matrix and averaging on the mechanism of heat transfer is not realized as the averaging time $\tau = d_n^2/\alpha$, where $\alpha = 6{,}77 \cdot 10^{-4}$ cm^2/s [16] comprises about 10 s which exceeds the maximum time for ignition delay observed in the experiment, in 5 orders of the value (Fig. 2).

However, in the areas of low volume compression pressures, another mechanism for heating hot spots is feasible. The possibility of ignition from its volume and impact of the irregularities concentration in this process will be considered further. Each PETN microcrystal is surrounded by pores in which gas break-through in the neighboring pores takes place. With the minimum expansion velocity of gas v_n (about 1 km/s) in the time of laser pulse the gases break-through will comprise the distance from hot spot up to 100 μm, which significantly exceeds the average distances between hot spots (with irregularities concentrations of 1 %, the average distance equals to 0.4 μm). Thus, during the laser impact each hot spot may receive additional energy from the neighboring hot spots. At that, the greater irregularities concentration is, the greater number of hot spots will give additional energy into the considered hot spot and the more its heating will be as well as the better conditions for ignition will be. In this mode, the temperature averaging is possible on the volume limited by the crosswise size of the laser spot on the samples surface and by the light penetration depth. The time of this averaging comprises the volume of $d_n/v_n \approx 10^{-6}$s. The averaging on this mechanism may lead to formation of reactive capable hot spot with the heat reserve necessary for development of explosion decomposition of the total mass of the sample. The higher the additives concentration is, the higher the heat reserve in hot spot is, the higher its reactive capacity and the lower the ignition threshold which was observed in experiment.

The necessary additional energy reserve in macro hot spot may be formed in the following way. In the vicinity of hot spots after the laser impact completion along with gasification the reaction of decomposition takes place in the gaseous phase with great energy production and growth of heat micro hot spots. Due to this, the average temperature of macro hot spot is determined not only by heat reserved by a hot spot as a result of laser-induced heating and of heating from micro hot spots, in the vicinity of which the chemical reaction of decomposition took place and heat storage of which increased in many times.

Let's consider the initiation mechanism in the high pressures region (more than 300 MPa). In this mode, the initiation thresholds are about 0.1 J/cm^2, pores are practically absent, gasification in the vicinity of the hot spot is difficult due to their relatively low temperature, the vapor pressure is insufficient to destroy the heating element matrix and break through gases into cracks. For the most, unloading of thermal micro hot spots has thermal conductivity nature. At that, the typical heat transit during the laser pulse comprises about $3 \cdot 10^{-6}$cm, which is much less than the average distance between the particles of carbon nanopowder and aluminium (for carbon nanopowder with the concentration 1 % this distance comprises about $3 \cdot 10^{-5}$cm, while for aluminium it is about $3.8 \cdot 10^{-5}$ cm). With the irregularities concentration 0.1 % the distances between the particles will be greater in approximately 2.15 times. Taking this into consideration it is possible to think that hot spots development takes place without the neighboring particles impact, that is the collective impact is absent in this situation. Due to this, the ignition process develops in the vicinity of single particle and is determined only by its temperature and initial heat reserve in micro hot spot which decrease with the particles concentration increase. This, with the collective impact absent, is to lead to increase of the ignition threshold and it is observed in the experiment under the pressure more than 300 MPa (please see Fig. 1).

It is necessary to point out that this conclusion is made without considering the heating of the explosive components matrix in dependence on absorbing irregularities concentration. However, it is obvious that with the maximum concentration of carbon nanopowder particles (in the experiment up to 1 %) the matrix temperature according to (2) does not exceed 350 K, while in aluminium composite it may be even less. Considering the minimum temperature of PETN self-ignition comprises 515 K [17–19], it is possible to state that under the conditions of heating the near surface layer of the matrix up to the temperature 350 K PETN ignition is known to be impossible. Further to that, it is also possible to neglect the matrix heating impact on hot spots reactive capacity due to the difference in their temperatures almost in 3 orders of value as well as due

to long (about 10 s) time of heating the illuminated volume in comparison with the experimentally measured time of the ignition delay (tens of μs, see Fig. 2).

Important from our perspective result is to be mentioned; it goes from comparison of the experimental data on carbon nanopowder particles and *Al* impact on the quantitative and qualitative levels. It is obvious that the mixture with aluminium additives is more sensitive than the mixture with carbon nanopowder particles that is in the vicinity of aluminium particles there are formed more reactive capable hot spots. However, the computing simulation and calculation of carbon nanopowder and *Al* particles heating in PETN matrix in [14] demonstrates that heat reserve in the hot spot with heating carbon nanopowder particle located in PETN matrix exceeds the heat reserves in the vicinity of aluminium one. And this is due to the fact that the relative cross-section of carbon particles has a value of $k = 1.5$, and of aluminum — $k = 0.2$. To explain this phenomenon in the area of high pressures it is necessary along with understanding the heating of carbon nanopowder and aluminium particles due to absorption to engage the understanding about the possibility to form hot spots as a result of optical breakdown and localization of the laser pulse energy in the vicinity of particles. In case of realization of the optical breakdown in the vicinity of the absorbing metal and dielectric particles the hot spots parameters (temperature, heat reserve) are in weak dependence on the particle material and determined by the matrix properties. As it goes from here the ignition thresholds for PETN mixtures with carbon nanopowder and PETN with aluminium are to be near in their values. In the experiment there is observed higher sensitivity of PETN with additives of aluminium, and possibly, with higher concentration of free electrons in aluminium, their thermal emission under the laser heating of aluminium particles and, consequently, with lower threshold of optical breakdown.

Conclusions

In general, the behavior of PETN and composites based on it is easily described from the standpoint of the thermal focal theory of ignition by an external pulse. It can be argued that laser action leads to the formation of reactive hot spots as a result of optical micro breakdowns in the vicinity of intrinsic or introduced absorbing inhomogeneities.

In the low-pressure region of volume compression, the initiation process occurs from a macro hot spot limited by the diameter of the laser beam on the sample surface and the depth of light penetration, the temperature of which and its reactivity are proportional to the concentration of absorbing impurities. The macro hot spot is created by the breakthrough of gases from the volume of the micro hot spot into the surrounding pores. Unloading of the macro hot spot through the irradiated surface (interface), which occurs mainly during the induction period, determines the high level of initiation thresholds.

In the region of high values of input window pressing pressures, the initiation process occurs from the volume of the micro hot spot, the temperature of which and reactivity decrease with increasing concentration due to the decrease in spatial illumination and, consequently, the energy thresholds of initiation grow, i.e. the effect of absorbing additives is negative. The absence of pores excludes the possibility of gas breakthrough and rapid gas-dynamic formation of a reactive macro hot spot. Gas-dynamic unloading in this mode is insignificant, which determines the low level of initiation thresholds.

The indicated patterns and features must be taken into account in theoretical and experimental studies of the sensitivity of mixed compositions, as well as explosives containing their own optical inhomogeneities, to the action of laser pulsed radiation.

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Жан-жақты қысудың әртүрлі қысымдары жағдайында көміртекті қара және алюминийдің наноөлшемді сіңіргіш қоспалары бар лазерлік инициацияға негізделген композиттер

Лазерлік импульстік әсерде (λ0 = 1064 нм; және τ= 12 нс) 40-тан 600 МПа-ға дейінгі диапазондағы әртүрлі көлемді ұнтақты қысу қысымдарындағы (мөлдір кіріс терезесінің қысу қысымы) сіңіргіш қоспалардың концентрациясына байланысты оның негізіндегі қыздыру элементі мен композиттердің жарылғыш ыдырауының энергетикалық шектері мен кинетикалық сипаттамалары эксперименталды түрде зерттелді. Таза қыздыру элементі мен оның негізіндегі композиттер үшін көлемді қысу қысымының жоғарылауымен сезімталдық тұтастай жоғарылайды, бірақ монотонды емес. Сонымен қатар төмен қысым аймағында (200 МПа-дан аз), қоспалар концентрациясының жоғарылауымен аралас композициялардың лазерлік импульстік әсеріне сезімталдығы жоғарылайды, ал жоғары қысым аймағында (300 МПа-дан жоғары) ол төмендейді. Бұл тәртіпті авторлар диффузиялық жарық шашырауын мөлдір ВВ инициациясының микроошақтық жылу моделі («ыстық нүктелер» моделі (ЫН)) тұрғысынан да түсіндіреді; осыған сәйкес «ыстық нүктелердің» реактивтілік қабілеттілігі олардың көлеміндегі жылу қорымен, олардың концентрациясымен, КТ-ға жақын тіректерге газдинамикалық түсіру және үлгінің кіріс саңылауының басылған беті (төмен қысым аймағы), сондай-ақ ВВ матрицасына және жабын шыныға (жоғары қысым аймағы) ГТ жылу өткізгіштік түсіру арқылы анықталады.

Кілт сөздер: қыздыру элементі, лазерлік импульсті инициация, наноөлшемді бөлшектер, оптикалық сыну, ыстық нүктелер (ЫН).

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Лазерное инициирование композитов на основе тэна с наноразмерными поглощающими добавками сажи и алюминия в условиях различных давлений объемного сжатия

Экспериментально исследованы энергетические пороги и кинетические характеристики взрывного разложения тэна и композитов на его основе при лазерном импульсном воздействии (λ_0 = 1064 нм; $\tau_и$ = 12 нс) в зависимости от концентрации поглощающих добавок при различных давлениях объемного сжатия порошков (давлениях прижатия прозрачного входного окна) в диапазоне от 40 до 600 МПа. Показано, что для чистого тэна и композитов на его основе с ростом давления объемного сжатия чувствительность, в целом, увеличивается, но не монотонно. При этом в области малых давлений (менее 200 МПа) с возрастанием концентрации добавок чувствительность смесевых составов к лазерному импульсному воздействию увеличивается, а в области больших (более 300 МПа) — уменьшается. Такое поведение объясняется авторами с позиций как диффузного светорассеяния, так и с позиций тепловой микроочаговой модели инициирования прозрачных ВВ (модель «горячих точек» (ГТ)), согласно которой реакционная способность «горячих точек» определяется запасом тепла в их объеме, их концентрацией, газодинамической разгрузкой в близлежащие к ГТ поры и через прижатую входным окном поверхность образца (область малых давлений), а также теплопроводностной разгрузкой ГТ в матрицу ВВ и покровное стекло (область высоких давлений).

Ключевые слова: тэн, лазерное импульсное инициирование, наноразмерные частицы, оптический пробой, горячие точки.

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