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Measuring the Temperature of PETN Explosion Products with Iron Inclusions

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Abstract: The spectral-kinetic characteristics of luminescence of PETN with iron nanoparticle inclusions are measured in real time in the case of a laser initiated explosion (the wavelength is 1064 nm, and the pulse duration is 14 ns). During the action of the laser radiation pulse, the luminescence of the samples is observed, and the explosive decomposition occurs in a microsecond time interval. The spectral pyrometry method is used to establish the thermal nature of explosive luminescence. The explosion temperature is estimated to be 3400 ±100 K.

Keywords: laser initiation, PETN, explosion products, spectral pyrometry, streak camera.

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INTRODUCTION

The inclusion of nano- and ultradisperse metal particles in the composition of PETN (pentaerythritol tetranitrate) reduces the threshold of laser initiation of a composite material tens of times [1–5]. This opens up the prospect of using such materials as detonators for standard explosives initiated by laser radiation.

The thresholds of laser initiation of composites were previously studied in [6] on the basis of PETN with iron nanoparticle inclusions 75 nm in size in the distribution maximum in the case of initiation by the first (1064 nm) and second (532 nm) harmonics of a Q-switched YAG:Nd^{3+} laser. The critical radiation energy densities corresponding to the 50% possibility of explosion are as follows: $H_{\rm cr} = 0.6 \pm 0.1$ J/cm^2 for the first harmonic with the 0.4% mass concentration of inclusions and $H_{\rm cr} = 0.5 \pm 0.1$ J/cm^2 for the second harmonic with the 0.15% concentration.

This paper describes the measurements of the spectral-kinetic characteristics of explosive decomposition of samples identical to those in [6] in the case of initiation by the first laser harmonic and the determination of the temperature of the explosion products by the spectral pyrometry method [7].

OBJECTS AND RESEARCH TECHNIQUE

The samples were prepared by a PETN powder with narrow granulometric distribution. The grain size in the distribution maximum amounted to 1–2 μm. The additives were iron powder with a particle size of 75 nm in the distribution maximum, manufactured by means of electric explosion. The iron particles were covered by a FeO film about 5 nm in thickness and resistive to further oxidation [6].

The technique for preparing the powder mixture and pressing the experimental samples is described in detail in [3–5]. The samples are pressed into an opening 3 mm in diameter at the center of a 1-mm thick copper plate. The sample density after pressing is $\rho = 1.7$ g/cm^3.

The spectrum of the luminescence arising in the explosion of the sample in real time is measured via spectrophotochronograph, whose basic elements are polychromator that decomposes the luminescence into spectral components and a VZGLYAD-2A photochromograph based on an electron-optical converter (EOC) that operates as a streak camera.

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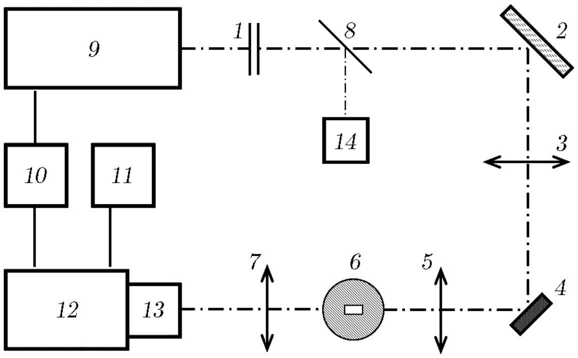

Fig. 1. Functional diagram of the experimental device: (*1*) neutral light filters; (*2*) rotary mirror; (*3*) lens (25 cm); (*4*) experimental assembly with a sample; (*5, 7*) lenses (10 cm); (*6*) space–time gap (in the figure; it is rotated by 90^0); (*8*) beam splitter plate; (*9*) Nd:YAG pulsed laser; (*10*) synchronization unit; (*11*) computer; (*12*) streak camera; (*13*) polychromator; (*14*) photodiode.

The device is illustrated in Fig. 1. The laser luminescence is focused on the assembly with the sample via the rotary mirror and the lens ($F = 25$ cm). The assembly is arranged as follows. The plate with the sample is placed on an aluminum substrate and covered by a 2-mm thick plate of optical glass from the side of radiation. The structure is supplemented with a copper plate with an opening at its center for the introduction of radiation, which tightly pressed the glass plate against the sample surface with the help of screws. The assembly is placed at an angle of 45° to the laser beam and optical axis of the measuring scheme. As a result of such geometry, there is an elliptical spot with the axes of 2 and 2.8 mm, and the irradiation of the copper plate is excluded.

The image of the sample is constructed with the help of the lens in the dimension of the gap. The 0.1×0.2 mm gap determines the spectral and temporal resolution of the recording system of 10 nm and 10 ns on the used sweep of the streak camera. The image of the space–time gap is transmitted to the polychromator input, which unfolds the luminescence into spectral components. The spectrum band 0.2 mm in width falls into the EOC converter of the photochronograph. At the output screen, the EOC spectrum unfolds in time with the help of the photochronograph sweep. On the output screen of the EOC, the spectrum is unfolded in time via the photochronograph sweep. The light matrix from the output screen of the EOC is read by the CCD matrix and transferred to a storage device in the computer for subsequent digital processing. The laser and the sweep of the streak camera begin operating at respective times with the help of a G5-56 pulse generator.

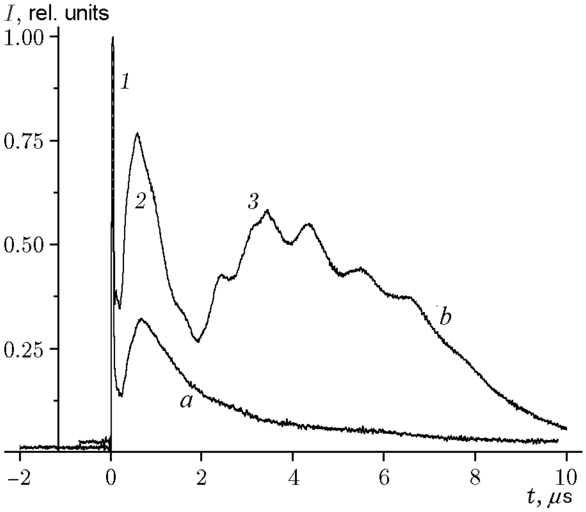

Fig. 2. Luminescence intensity arising from the explosion of the sample versus time for energy density of the laser radiation $H = 0.7$ (curve *a*) and 1.3 J/cm^2 (curve *b*): (*1*) luminescence peak occurring at the time of the laser pulse action; (*2*) luminescence peak arising at the time 0.5–0.8 μs; (*3*) luminescence peaks observed at 2–10 μs.

A detected signal is a matrix whose vertical elements allow constructing a luminance spectrum of the sample within the wavelength of 350–750 nm at a certain time and whose horizontal elements are the luminance kinetics of the sample at a chosen wavelength within the spectrum specified above.

The recovery of the true luminescence spectrum of the samples was carried out by the reference lamp method [8]. A TRSh-2850-3000 lamp was used. The observed spectrum was detected in a sweep mode, and the known color temperature can be used to calculate its true spectrum via the Planck formula (with account for grayness of tungsten) and determine the sensitivity of the optical path at any point of the experimental spectrum of the lamp. For the recovery of the true spectrum, the detected luminescence intensity of the sample should be split into the path sensitivity at the corresponding points of the spectrum at a given time or various times at this wavelength.

RESULTS AND DISCUSSION

Figure 2 illustrates the luminescence kinetics that accompanies the explosive decomposition of the sample at various energy densities of the laser radiation H. The first luminescence peak arises at the time of the laser pulse action when the sample is still in the condensed phase. The luminescence in a microsecond range results from the development of the chemical reaction and accompanies the explosive decomposition of the sample, i.e., the condensed phase transforms into gaseous products.

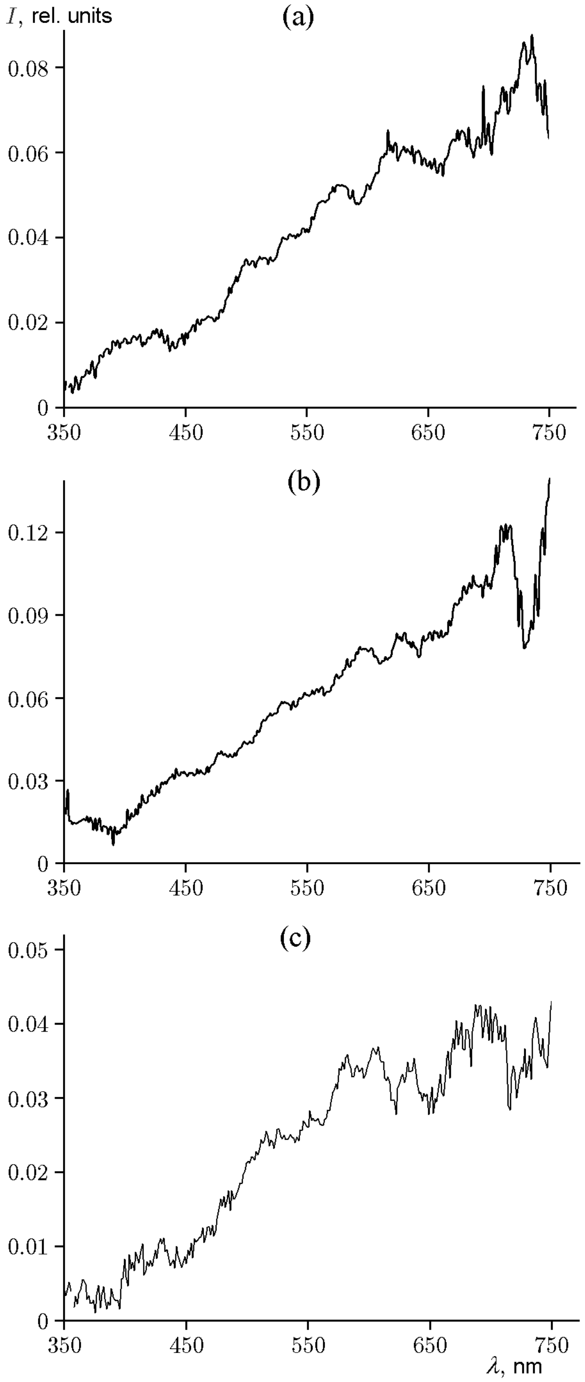

Fig. 3. Luminescence spectra: (a) $t = 0.7$ μs and $H = 0.7$ J/cm^2; (b) $t = 0.7$ μs and $H = 1.3$ J/cm^2 (see Fig. 2); (c) $t = 3.5$ μs and $H = 1.3$ J/cm^2 (see Fig. 2).

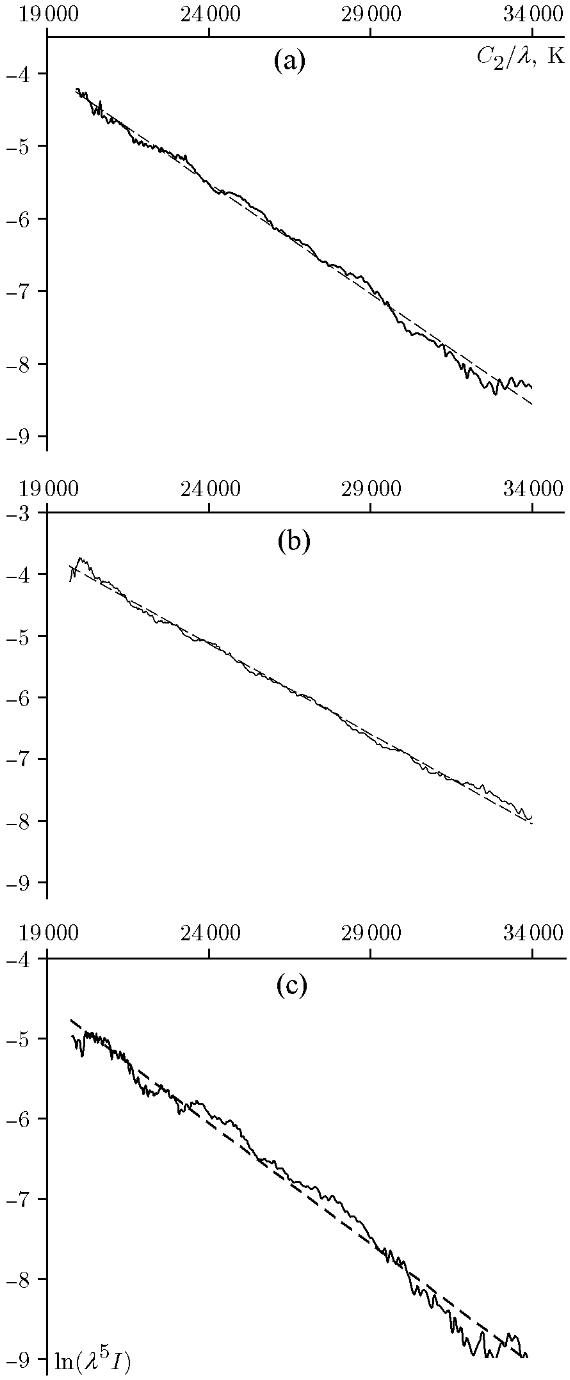

Fig. 4. Luminescence spectra from Fig. 3 given in the Wien coordinates: solid curve refers to the experimental data, and the dashed curve shows the linear regression.

The purpose of this work is to establish the nature of the luminescence arising at the stage of explosion. The luminescence spectra at $t = 0.7\ \mu$s (for curves a and b in Fig. 2) and $t = 3.5\ \mu$s (for curve b in Fig. 2) are presented in Fig. 3. The luminescence intensity increases monotonically in the direction of the long-wavelength range.

The nature of the luminescence can be associated with two processes: nonequilibrium luminescence of excited fragments of PETN molecules formed during the explosion, i.e., luminescence and equilibrium (in this case, quasi-equilibrium) thermal luminescence of the explosion products during the exothermic reaction. In the general case, both types of luminescence can be present in the spectra if their contributions are commensurable.

To validate whether the observed luminescence is thermal or not, one can apply the spectral pyrometry method with the use of the Wien coordinates [7]. The spectral intensity of the thermal radiation of the real object is described by the Planck formula

$$I = \varepsilon C_1 \lambda^{-5}/[\exp(C_2/\lambda T) - 1], \qquad (1)$$

where ε is the degree of blackness, λ is the wavelength, $C_1 = 37\,418\ \mathrm{W}\cdot\mu\mathrm{m}^4/\mathrm{cm}^2$, and $C_2 = 14\,388\ \mu\cdot\mathrm{K}$. In the Wien range, with $C_2/\lambda T \gg 1$, Eq. (1) can be represented in the form

$$\ln(\lambda^5 I) - \ln(\varepsilon C_1) = -C_2/\lambda T. \qquad (2)$$

If we take the value $x = C_2/\lambda$ is taken on the abscissa axis and the value $\ln(\lambda^5 I)$ is taken on the ordinate axis, the linear law should be satisfied in the case of thermal luminescence. In this case, the slope of the line can help one determine the temperature of the luminescent body [7].

Figure 4 illustrates the spectra from Fig. 3 in the Wien coordinates. Due to the linearity of the observed spectra, it is highly probable that the luminance arising during the explosion of the sample is thermal. The temperature at the spectrum range 430–730 nm that is determined according to the slope of the curve equals 3400 ± 100 K for all three spectra presented. (The standard temperature measurement error is determined from the root-mean-square deviation of the linear approximation from the experimental data and mean temperature measurement in five samples.)

Note that a similar result was obtained in the initiation of hexogen single crystals by an electron beam, where it was also established that luminance at the stage of explosion is thermal [9].

REFERENCES

1. V. B. Ioffe, A. V. Dolgolaptev, V. E. Aleksandrov, et al., “Laser Pulse Ignition of Condensed Systems Containing Aluminum,” Fiz. Goreniya Vzryva **21** (3), 51–55 (1985) [Combust., Expl., Shock Waves **21** (3), 316–320 (1985)].
2. V. E. Aleksandrov, A. V. Dolgolaptev, V. B. Ioffe, et al., “Ignition of Condensed Media with Absorbing Additives upon Concentrated Application of Radiant Energy,” Fiz. Goreniya Vzryva **19** (4), 17–20 (1983) [Combust., Expl., Shock Waves **19** (4), 384–386 (1983)].
3. B. P. Aduev, D. R. Nurmukhametov, R. I. Furega, et al., “Adjusting the Sensitivity of Pentaerythritol Tetranitrate to Laser Exposure with Additives of Nickel and Aluminum Metal Nanoparticles,” Khim. Fiz. **33** (6), 37–41 (2014).
4. B. P. Aduev, D. R. Nurmukhametov, and R. I. Furega, “Initiation of Explosive Decomposition of Tetranitropentaerythritol with Additives of Ultrafine Particles by Laser Pulses,” Khim. Tverd. Topliva, No. 6, 41–45 (2012).
5. B. P. Aduev, G. M. Belokurov, and D. R. Nurmukhametov, “Photosensitive Material Based on PETN Mixtures with Aluminum Nanoparticles,” Fiz. Goreniya Vzryva **48** (3), 127–132 (2012) [Combust., Expl., Shock Waves **48** (3), 361–366 (2012)].
6. B. P. Aduev, D. R. Nurmukhametov, A. A. Zvekov, et al., “Laser Initiation of Composite Materials Based on PETN and Iron Nanoparticles,” Khim. Fiz. **35** (7), 38–43 (2016).
7. A. N. Magunov, “Spectral Pyrometry (Review),” Prib. Tekh. Eksp., No. 4, 5–28 (2009).
8. L. V. Levshin and A. M. Saletskii, *Luminescence and Its Measurements* (Izd. Mosk. Univ., Moscow, 1989) [in Russian].
9. B. P. Aduev, G. M. Belokurov, S. S. Grechin, et al., “Explosive Decomposition of Hexogen Single Crystals Initiated by a Pulsed Electron Beam,” Pis’ma Zh. Tekh. Fiz. **40** (23), 16–20 (2014).