Effect of laser radiation wavelength on explosives initiation thresholds

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Abstract. In this paper the initiation thresholds were measured and kinetics of decomposition was studied for pressed powders of FTDO (furansan-1,2,3,4-tetrazin-1,3-dioxide) at pulsed laser action by different laser wavelengths: 266 nm (zone-to-zone absorption), 532 nm (transparency range), 1.064 nm (transparency range) and 10600 nm (phonon absorption) that corresponds to absorption region (266 nm), transparency range (532 nm; 1064 nm) and phonon absorption (10600 nm) of these explosives.

1. Introduction
Heated centers of various configurations form at laser initiation of explosives. Thus, varying the radiation wavelength results in laser energy localization in a thin subsurface layer of < 10−4 cm (spectral range of “zone-to-zone” absorption), or in “hot spots” of ~10−5 cm (spectral range of transparency), or in cylindrical volume with the height of 10−3 cm (spectral range of phonon absorption). This brings to the question about the reactive effectiveness of heated centers of different shapes which can be answered after measuring the initiation energy thresholds and kinetic parameters of the explosive decomposition process. Previous studies were performed for primary explosives [1]. It was found that specific heat in heated centers of different shapes makes almost equal value of ~2700 J/cm³. These results suppose thermal heated center mechanism of heavy metal azides laser initiation [1]. This approach in secondary explosives studying has a significant interest for making of model representation of their initiation mechanisms, which is in its starting position. In this paper the given approach is used in PETN and FTDO initiation studying.

2. Experiments and methods
For the experimental works mount described in [2] was used. The base for this mount is YAG-laser LQ-929 with radiation on 1, 2 and 4 harmonics (wavelength 1064 nm, 532 nm and 266 nm at pulse duration of 10 ns), multimode beam structure with homogeneous central part. Mount includes pulse CO₂ laser (λ=10.6 µm) with pulse duration of 25 ns and energy ~ 0.1 J. This mount allows carrying out multiparameter process measurements at explosive decomposition of energetic materials.

As explosives powder samples energetic materials were used, such as PETN (tetryanitropentaerytrite) and FTDO (furansan-1, 2, 3, 4-tetrazin-1, 3-dioxide), pressed in tablets with 3 mm diameter into the press mold. Maximum pressure was 5•108 N/m², weighed amount was 6±1 mg. It is known that secondary explosives initiation from open sample surface is hampered or impossible because of gas-dynamic unloading of heated center through available surface. To exclude this, experiments were carried out from covered samples surface with the covering pressure of FTDO =...
108 N/m² and PETN = 3•108 n/m². Laser beam diameter made 1 mm and pulse duration made 10 ÷ 25 ns. In these conditions, threshold sensitivity of explosives initiation depends on the covering pressure. The experiments demonstrated optimal covering pressure. PETN optimal pressure was 3•108 n/m², whereas for FTDO this value was 108 n/m². At this covering pressure low-threshold mode of explosives initiation occurs.

Experiments determined samples initiation energy thresholds at different wavelengths within the range of 0.266-10.6 µm. Irradiation pulse from laser exposure zone [2] was determined and pressure pulse at samples initiation moment was registered. Initiation was accompanied by assembly destruction and strong bang. Sample rejection did not result in its structural changes and optical properties alteration [3]. Threshold level of laser exposure demonstrated pulse delay of explosive decomposition irradiation and delay of acoustic response with typical value of 4 ms for PETN and 1 ms for FTDO. Irradiation at 266 nm wavelength and 532 ns wavelength showed additional short irradiation peak, which permanent allocation corresponds to laser pulse allocation, what indicated luminescent character of this irradiation.

Threshold energy density and specific heat of micro heated centers are presented in Table 1. Average specific heat in zone-to-zone absorption (λ₀ = 266 nm) and phonon absorption (λ₀ = 10600 nm) was calculated by ω = H∙µ/(1 + µ√α∙τ∙i), where µ is explosive matrix absorption index (~10⁵ cm⁻¹ and ~10³ cm⁻¹ for 266 nm and 10600 nm respectively), α is thermometric conductivity. At matrix transparency range (λ₀ = 532 nm and λ₀ = 1064 nm) because of very small values of µ (~10⁴ cm⁻¹ – 10² cm⁻¹), average specific heat is negligible. In this case it stems from the fact that laser pulse energy localizes at microinhomogeneities which exist in explosives matrix (absorption nano-sized inclusions, structural defects) with forming of thermal centers (heating, optical-induced breakdown) typically sized 10⁻⁵ cm. Thermal center heat was estimated by ω = 3∙H∙R∙2/(R + √α∙τ∙i)³.

|          | 266 nm | 532 nm | 1064 nm | 10600 nm |
|----------|--------|--------|---------|----------|
| PETN     |        |        |         |          |
| H, mJ/cm²| 25±20  | 55±15  | 60±15   | 1800±20  |
| ω, J/cm³ | ~1900  | ~1900  | ~2100   | ~1800    |
| FTDO     |        |        |         |          |
| H, mJ/cm²| 8±2    | —      | 20±6    | 300±10   |
| ω, J/cm³ | ~600   | —      | ~700    | ~300     |

3. Results and discussions
Note that evaluated specific heat of different initiation centers (which correspond to different spectral ranges) for every explosive is almost equal when the initiation thresholds are significantly different. Critical value of specific heat for PETN comprised ~2.0 kJ/cm³ and that for FTDO comprised 0.4 kJ/cm³. It should be pointed out that laser initiation in phonon absorption is inherently thermal. It indicates thermal heated center character of PETN and FTDO initiation in different spectral ranges. Nevertheless, this brings to the question about the reactive effectiveness of heated centers with such specific heat, i.e. possibility of their development into explosives decomposition heated centers.

To clarify this statement, numerical simulation of PETN and FTDO initiation in zone-to-zone absorption and phonon absorption was made within the frames of thermal local initiation model, represented in [4]. Numerical simulation in transparency range was made by the method described in [5-6]. Simulation considers great alteration of absorption indices for these explosives at 266 nm, 532 nm, 1064 nm, and 10600 nm wavelengths. For that reason various light regime was made at given wavelengths in samples volume.
Thus, within transparency range of FTDO (1064 wavelength), matrix zone-to-zone made it difficult to explain experimentally the resulted initiation thresholds. The thickness of absorption layer is 7.7 cm, i.e. heating temperature for exposure period of laser pulse can be easily evaluated

$$\Delta T = \frac{Q}{\pi \cdot d^2 \cdot \left( h + \sqrt{\alpha \cdot \tau} \right) \cdot c \cdot \rho} = \frac{H}{\left( h + \sqrt{\alpha \cdot \tau} \right) \cdot c \cdot \rho} = \frac{w}{1 + \left( \frac{\sqrt{\alpha \cdot \tau}}{h} \right) \cdot c \cdot \rho}$$ (1)

According to the formula (1), heating temperature for 60 mJ thresholds is 0.003 K and for 40 mJ thresholds is 0.002 K.

In this case initiation mechanism can be explained by absorption microinclusions where radiation energy localization occurs. Thus, thermal local initiation model corresponds to the experiment well. Numerical simulation of light regime in FTDO matrix transparency range demonstrates 12 times more illumination enhancement in subsurface layer compared to surface illumination. Spectral beam is diminishing weakly while explosives basic layer is enhancing and it is estimated by absorption albedo. Any inclusion can be a heated center within the range of radiation penetration depth in the sample even up to 1 mm with its effective absorption crossing. As a result of inclusions ignition numerical simulation in active medium, initiation threshold was 40 mJ/cm$^2$ for FTDO and 80 mJ/cm$^2$ for PETN, what corresponds to experimental points of 20 mJ/cm$^2$ and 55 - 60 mJ/cm$^2$ by order of values. (Table 1). Effective absorption crossing for microinclusions particles with diameter 100 nm was calculated by Mie theory.

Edge of fundamental absorption at wavelength of CO2 laser (10600nm), sample refraction index becomes small, effect of full inner reflection stops contribute to light enhancement of subsurface explosive layer. Moreover, effective absorption crossing at this wavelength is approximately 4 times less than geometrical one for spherical inclusions. Thus, absorption particles 10-5 cm cannot be thermal centers of self-sustained decomposition, radiation is absorbed in sample volume with penetration depth 0.002 cm. As a result of numerical simulation of inclusions ignition at this wavelength with matrix absorption 500 cm$^{-1}$ initiation threshold is 400 mJ/cm$^2$, what corresponds to experimental data (Table 1).

In the range of zone-to-zone absorption (wavelength 256 nm), relevant thickness of FTDO sample optical layer is determined by absorption index:

$$\tau = \frac{1}{\mu},$$ (2)

Absorption index at this wavelength is considerably higher than dissipation index, which excludes volume light enhancement; all radiation energy localizes in volume of thin near surface layer. Light distribution on the sample volume can be described by Buger’s law.

Edge of zone-to-zone absorption preconditions a very high absorption index, where the thickness of near surface layer localizes l/e energy share of laser radiation will be several µm (1, 5 µm for absorption index 7000 cm$^{-1}$ by the 2 formula). Heated center with plane geometry has two times less heating unloading than that with spherical thermal field. Moreover, plane subsurface layer at short impacts (15 ns) and poor thermal conductivity of covering pressure made this center one-side limited by adiabatic wall and reduce thermal unload by 2 times more. According to numerical simulation, because of small volume and high laser radiation energy absorption efficiency in this layer, threshold is 10 mJ that corresponds to the experiments too (Table 1).

Thus, calculations based on thermal microcenter initiation model give desirable results describing macro- and micro centers of various configurations. Besides, by the formula (1) it is obvious that in a sample transparency range, initiation is impossible because of matrix volume heating. In conclusion, it is necessary to point out that the given results are preliminary and need to be confirmed. Numerical
simulation of FTDO thermo kinetic parameters demands special selection and validation because of their certain arbitrary character.

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