Letter

The influence of aluminum and ammonium perchlorate dispersion on characteristics of the laser ignition

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Abstract

Laser ignition of the stoichiometric mixtures based on aluminum and ammonium perchlorate has been experimentally studied. A laser with a radiation wavelength of 1.06 μm and a pulse duration of 0.8 ms was used to initiate ignition. The ignition thresholds were determined for samples with different degree of dispersion of both aluminum and ammonium perchlorate. The samples were exposed to laser radiation in confined conditions in order to prevent gas pressure relief. The difference in the mixture sensitivity to laser radiation is discussed within the theory of thermal ignition and light scattering.

Keywords: ammonium perchlorate, aluminum, laser ignition

1. Introduction

Laser ignition of energetic materials has been widely studied[1)−8)]. Laser radiation allows precise control of the amount of energy, pulse duration and the affected zone.

The patterns and mechanisms of primary and secondary explosives laser ignition has been actively investigated since the last quarter of the past century. The ignition of multicomponent mixtures is more challenging to investigate. However, some methods and approaches allow extended use of common models of ignition for such materials.

The interaction of well-known oxidizer ammonium perchlorate (AP)[9), 10)] and aluminum (Al) (including nanosize Al[11)−13)]) initiated by laser radiation need to be investigated in terms of thermal ignition theory and optics.

This study aims to estimate the effect of Al and AP particle size on the sensitivity of the mixture made of these components to laser exposure.

2. Materials and methods

Al powders with different particle size distribution were used as components of the tested mixtures. The particle size distribution maxima are summarized in Table 1. Nanosize Al (n-Al) was produced using the technique described by Yavorovskiy[14)]. Analytical-grade AP was milled in an agate mortar and sieved through a brass sieve with a mesh size of ~85 × 85 μm for one group of mixtures and of ~40 × 40 μm for another group.

Near stoichiometric mixture (at ratio 60 : 40 for AP and Al, respectively) samples of ~20 mg were pressed into a hole with an inner diameter of 3 mm and a depth of 3 mm in a polymethyl methacrylate (PMMA) capsule up to pressure of 74 MPa using a puncheon with a diameter of 3 mm.

Neodymium laser with $\lambda = 1.06$ μm was used to conduct the experiment[15)]. It generates a quasicontinuous laser pulse with the modulation depth not greater than 10 % and duration of 0.8 ms. The laser beam was formed into a spot with a diameter of 2 mm on the sample surface.

The ignition of the samples through the transparent PMMA capsule was performed in accordance with the scheme shown in Figure 1. The ignition thresholds were determined using the methods reported by Medvedev et al.[16)].

3. Results and discussion

The samples were observed to burn out simultaneously with a blast sound and complete disruption of the PMMA

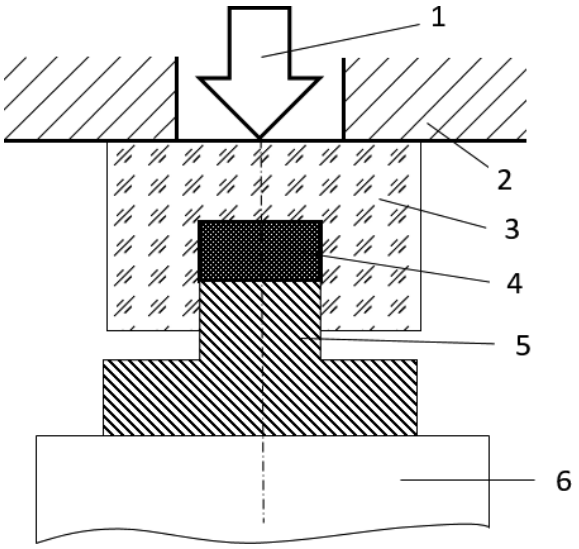

Figure 1 Scheme of laser ignition of the Al/AP mixture sample: 1. Laser radiation; 2. Upper press stop; 3. PMMA capsule; 4. Sample; 5. Puncheon; 6. Press forcer.

capsule. This indicates that combustion develops into explosive decomposition. The obtained ignition threshold data is listed in Table 1.

According to this data, the sensitivity of the samples increases as the Al particle size reduces. To interpret this dependence, the heating of the near surface layer is to be estimated at the end of laser pulse action τ. The thickness of the layer is $Z_l = \mu^{-1} + \sqrt{\alpha \cdot \tau}$, where μ is the absorbance index of the mixture, and α is thermal diffusivity (according to Rosser et al.[9], $\alpha \approx 10^{-3}$ cm^2·s^{-1}).

μ can be calculated from the equation:

$$\mu = \pi \cdot R_0^2 \cdot k\,(R_0, \lambda_0) \cdot C\,, \tag{1}$$

where $k\,(R_0, \lambda_0) = \sigma \cdot (R_0, \lambda_0) / \left(\pi \cdot R_0^2\right)$ is relative absorption cross-section at laser wavelength λ_0 (for Al particles size $2 \cdot R_0$, we consider $k\,(R_0, \lambda_0) \approx 0{,}1$[17]); C is Al particle concentration ($C = \eta \cdot \rho_m / (M_{pat} \cdot (1 - \eta))$; η is the weight percentage of Al particles; ρ_m is mixture density; M_{pat} is the mass of one Al particle). The values of μ for different mixtures are listed in Table 2.

The temperature of the heated layer can be found from the equation:

$$\Delta T_l = \frac{F \cdot (1 - \rho_d) \cdot E_{50}}{Z_l \cdot c \cdot \rho_m}, \tag{2}$$

where ρ_d is diffusion reflection coefficient, c is specific heat, F is coupling coefficient of illumination on the sample surface and in the bulk sample[18]. The values of the heated layer temperature are listed in Table 2.

As can be seen in Table 2, the surface layer temperature increases as the Al particle size and the thickness of the heated layer Z_l reduce.

Nevertheless, the reactivity of the flat hot spot with a temperature of 1650 °C and a layer thickness of about 10^{-3} cm (AP/n-Al mixture) is significantly higher than the reactivity of the hot spot with a temperature of 845 °C and a layer thickness of about 10^{-2} cm (AP/Al-4 mixture). This situation corresponds to classic ideas of thermal hot spot ignition and in particular, it corresponds to the critical

Table 1 The obtained ignition threshold data.

Mixture type	Typical size of Al particle 2·R$_0$, [μm]	Ignition energy density threshold for mixture with AP 85 μm E$_{50}$, [J·cm^{-2}]	Ignition energy density threshold for mixture with AP 40 μm E$_{50}$, [J·cm^{-2}]
AP/Al-4	8–10	16.9 ± 0.9	8.34 ± 0.23
AP/Al-8	3–4	11.8 ± 0.7	6.54 ± 0.12
AP/Al-10	2–3	8.33 ± 0.24	6.54 ± 0.07
AP/n-Al	0.14	3.25 ± 0.07	3.29 ± 0.05

Table 2 The values the heated layer temperature.

Mixture type	Al particle concentration, [particle /cm^3]	Layer absorbance index μ, [cm^{-1}]	Thickness of the heated layer Z_l [cm]	Heated layer temperature ΔT_l, [°C]
AP/Al-4	1×10^9	74	1×10^{-2}	845
AP/Al-8	5×10^9	185	6×10^{-3}	983
AP/Al-10	1.5×10^{10}	370	4×10^{-3}	1037
AP/n-Al	3×10^{13}	3700	1×10^{-3}	1650

Table 3 The results of Λ calculation.

Mixture type	Single-scattering albedo Λ for Al particles	Single-scattering albedo Λ for 85 μm AP particles	Single-scattering albedo Λ for 40 μm AP particles
AP/Al-4	0.9	0.64	0.78
AP/Al-8	0.9	0.42	0.59
AP/Al-10	0.9	0.27	0.42
AP/n-Al	0.9	0.04	0.07

Frank-Kamenetskii parameter[19].

Through the result analysis, we also need to call attention to the fact that the investigated mixtures are a diffuse scattering medium. The light conditions within the diffuse scattering medium (the distribution of spatial illumination deep in the sample) can be determined using the absorbance index μ and scattering β indices for both AP and Al particles. The scattering index for Al can be calculated by Equation (1) in case the relative absorption cross-section is replaced by the relative scattering cross-section.

To find β for AP, the correlation $\beta \approx 0.35 \cdot S$ can be used, where S is dispersiveness of explosive powders[20]. In this regard, single-scattering albedo Λ—the ratio of scattering efficiency to total extinction efficiency should be determined by equation $\Lambda = \beta/(\beta+\mu)$[21]. The results of Λ calculation are listed in Table 3. The data reported by Tsipilev et al.[17] was used to calculate μ and β for Al particles.

It is obvious that the single-scattering albedo in mixtures with smaller Al particles mostly depends on Al light scattering since AP light scattering is small to negligible. For mixtures with larger Al particles, the AP light scattering is commensurable with that of Al, consequently, the size of AP particles can affect the light conditions, which can be proved by the difference in the sensitivity of mixtures with different AP particle sizes (as shown at Table 1).

4. Conclusion

It is shown that AP/Al mixture sensitivity to laser radiation (pulse length 0.8 ms, wavelength 1.06 μm) grows simultaneously with the decreased Al particle size. This behavior can be interpreted in terms of heating the near surface layer hot-spot limited by the diameter of the laser spot, light attenuation depth and thermal front propagation into the sample within laser pulse duration.

The dependence between the AP particle size and the mixture sensitivity to laser radiation can be attributed to the growth of light scattering and the change in illumination in the bulk sample.

The mixtures with AP particle size that significantly exceeds that of Al particles was investigated; however, the mixtures with commensurable particle sizes are of special interest. In this case, a significant change in patterns and characteristics of laser ignition is expected. Further studies, which consider this issue, will need to be performed.

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