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Ignition study of high-energy materials containing Al, B, AlB_2 and TiB_2 powders

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Abstract. Boron and its compounds are considered as possible high efficiency fuel components for high-energy materials (HEMs), since they have high gravimetric and volumetric heats of oxidation in comparison with aluminium powder. This work aims to modify a commercial 99.5% pure boron and AlB_2 or TiB_2 powders to improve the ignition and combustion characteristics for solid propellants. The ignition parameters for the model HEM sample based on ammonium perchlorate, ammonium nitrate and energetic binder, containing Al, B, AlB_2 and TiB_2 powders are presented. It was found that the greatest effect at the laser ignition is achieved at a full replacement of Al by B powder, at which the ignition time and the activation energy of HEM are reduced by 2.1–2.7 and 1.8 times, respectively. When replacing Al by AlB_2 powder in HEM the ignition time is reduced by 1.7–2.4 times, and the activation energy is increased by 1.4 times.

1 Introduction

Boron and its compounds are considered as possible high efficiency fuel components of solid propellants for solid fuel rocket and ramjet engines [1–3]. Boron hydrides and organic derivatives have high burning rate, varying in a wide range at changing the air relation and pressure in the combustion chamber. The combustion heat of 1 kg boron in the oxygen more than 1.9 times in comparison with the combustion heat of aviation kerosene and 1 kg aluminum.

Note that solid propellants are widely used, which contain up to 22 wt.% aluminum micropowder. According to the study [4, 5] the aluminum oxidation during the combustion of composite solid propellants strongly influence by the presence on the burning surface the refractory layer containing the aluminum oxide particles and carbonaceous resudues. Melting point of alumina significantly above the melting point of aluminum. The aluminum particles combustion possible at the high temperature gradient of high-energy materials (HEMs) reaction layer near the burning surface with occurrence of cracks and destruction of the oxide layer resulting in the oxidation of active metal. It is well known [6] that the destruction of the aluminum oxide layer on the particle surface may react with the carbon particles to form aluminum carbide.

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However, HEMs, containing aluminum micropowders, have a long delay ignition time and low burning rate compared to HEMs, containing nanopowders of aluminum or other metals [7–10].

This paper presents the experimental dependences of the ignition time on heat flux density, values of the ignition temperature and activation energy for the model HEMs based on ammonium perchlorate and nitrate, energetic binder, containing powders of aluminum, boron, aluminum diboride and titanium diboride.

2 Experimental

2.1 HEM samples

To study the main ignition characteristics we used four tested compositions of HEM. The first – the basic composition, containing ammonium perchlorate (fraction with particle size 160–315 μm), ammonium nitrate (fractions with particle size less than 50 μm), the energetic binder of MPVT-ASP type, and 30 wt.% Al micropowder of ASD-4 type [7]. In other tested compositions the Al powder is completely replaced by the amorphous boron, aluminium diboride and titanium diboride powders (Fig. 1).

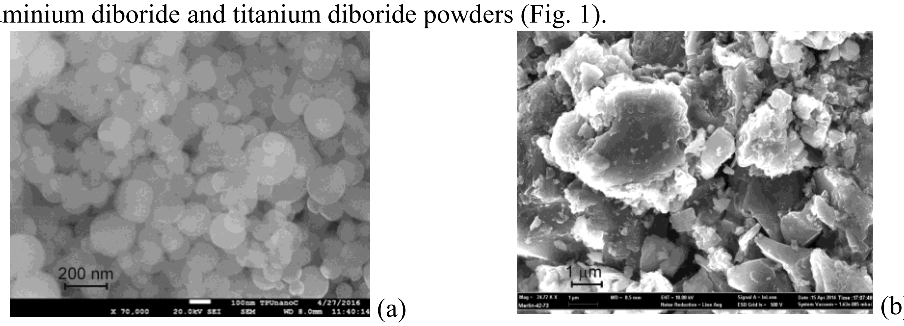

Fig. 1. SEM images of amorphous boron (a) and aluminium diboride (b) powders.

2.2 Ignition of HEM

The ignition process was studied with the use of setup for the radiant heating on the basis of CO_2-laser with the wavelength of 10.6 μm and power of 200 W (Fig. 2). Prior to testing the samples were cut into tablets of 5 mm in height.

The test HEM sample (6) was attached to the substrate of recoil force transducer (8) to register the gasification products outflow from the burning surface. When opening the shutter (4) the radiation was focused by the sodium chloride lens (5) to the HEM sample (6). Signals from the recoil force transducer (8) and photodiodes (7) were transmitted to the L-card-E 14-440 ADC (9) and recorded in the personal computer (10), and then processed with the software application LGraph2. The time delay of start gasification t_{gas} of HEM sample was determined as time interval between the moments of signals change of photodiode near the shutter (7) (or a thermocouple installed in the laser beam behind the shutter), and the recoil force transducer (8). Photodiode (7) registered the moment of opening the shutter, transducer (8) recorded the appearance of recoil force signal of gasification products flowing from the front (irradiated) sample surface. The ignition time t_{ign} of HEMs was determined by difference between the moments of signals from two photodiodes (7), one of which registered the appearance of flame near the end surface of HEM sample. The relative error of delay times measuring of t_{gas} and t_{ign} was equal 5–12 % at the value of confidence probability 0.9.

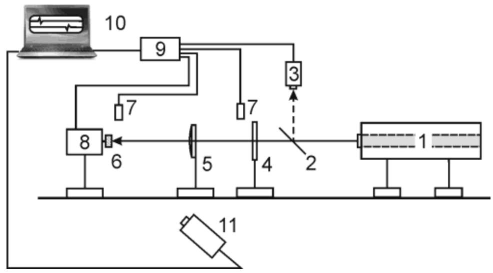

Fig. 2. The scheme of experimental setup based on CO_2-laser: 1 – CO_2-laser; 2 – beam-splitting mirror; 3 – thermoelectric sensor of radiation power; 4 – shutter; 5 – lens; 6 – HEM sample; 7 – photodiodes; 8 – transducer; of recoil force; 9 – ADCs; 10 – PC; 11 – thermal imager.

The radiation power and heat flux density of CO_2-laser beam was measured by the thermoelectric sensor of radiation power (3). The maximum radiation power was defined in the center of the laser beam using a diaphragm with diameter 2 mm. The diameter of the laser beam incident on a HEM sample was 10 mm.

3 Results and Discussion

The ignition time of tested HEM samples was determined in atmospheric conditions. The approximation dependences for HEMs ignition time vs. the heat flux density were determined (Fig. 3).

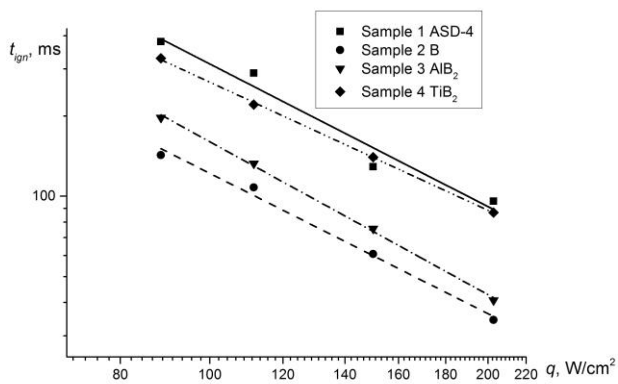

Fig. 3. The ignition time vs. the heat flux density for tested HEMs containing powders:

Al – t_{ign}=9.90·10^5·$q^{-1.75}$; B – t_{ign}=2.02·10^5·$q^{-1.61}$; AlB_2 – t_{ign}=7.39·10^5·$q^{-1.83}$, TiB_2 – t_{ign}=4.71·10^5·$q^{-1.62}$.

It was found that a complete replacement of aluminum by boron powder in HEM leads to a decrease of the ignition time by 2.1–2.7 times in the heat flux density range of 90–200 W/cm^2. Replacement of aluminum by aluminum diboride micropowder in the HEM basic composition reduces the ignition time of sample by 1.7–2.4 times. At the same time, the ignition time of the HEM containing TiB_2 is 1.05–1.2 times lower in comparison with the basic composition.

The kinetic constants and ignition temperature of HEM were determined according to [11] and with use of the t_{ign} and T_{ign} equations. The ignition data for tested HEM samples are presented in Table 1. Here there are experimental values of the average $\overline{T}$ and the maximum T_{max} surface temperature on the HEM reaction layer at appearance of visible flame which obtained using a thermal imager Jade J530 SB at q = 114 W/cm^2.

Table 1. The activation energy, specific heat of reaction, ignition temperature and surface temperature on the reaction layer for tested HEMs.

Parameter	HEM sample containing metal powder			
	ASD-4	**B**	**AlB_2**	**TiB_2**
E_a, kJ/mol	219	120	307	136
Qz, W/g	$8.32\cdot10^{10}$	$3.77\cdot10^{8}$	$4.81\cdot10^{18}$	$3.84\cdot10^{7}$
T_{ign}, K	1203	859	935	1139
$\bar{T}$, K	1040±30	949±110	1009±90	897±20
T_{max}, K	1516±80	1531±120	1600±170	971±30

4 Conclusions

The ignition parameters for the HEMs based on ammonium perchlorate, ammonium nitrate and energetic binder of MPVT-ASP type, containing powders of aluminium, boron, diboride aluminum or titanium diboride are presented. It was found that the greatest effect at the laser ignition is achieved at a full replacement of the Al micropowder by 99.5% pure boron, at which the ignition time and the activation energy of HEM sample are reduced by 2.1–2.7 and 1.8 times, respectively, in the heat flux density range of 90–200 W/cm^2.

When replacing the Al micropowder by the AlB_2 powder in HEM the ignition time is reduced by 1.7–2.4 times, and the activation energy is increased by 1.4 times. For HEM containing TiB_2 powder the ignition time is slightly reduced by 1.05–1.2 times. Thus boron powder and its compounds can be used to improve the ignition characteristics for HEMs.

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