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# Features of thermal behavior and ignition of HEM with bimetal powders

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**Abstract.** The use of metal fuel in high-energy materials (HEM) for propulsion is the most energy efficient method allows to the combustion characteristic increase for solid propellants and specific impulse. Aluminum powder is used in original HEM. To improve the ignition characteristics of HEM advisable to use the catalyst (nonmetals, metals or their oxides). Paper presents the experimental data of the thermal behavior and ignition for HEM based on AP and butadiene rubber, containing bimetal powders: aluminum/iron and aluminum/boron. The use of Alex/Fe powder in HEM decreases the ignition time by 1.3–1.9 times under initiation by $CO_2$ laser in air at the range of heat flux density of 55–220 W/cm$^2$ and increases of the recoil force of gasification products outflow from burning surface by 27 % during combustion of propellant due to possible of the catalytic effect, which reduces the beginning temperature of AP high-temperature decomposition by ~20 °C, and interaction of thermite mixture of aluminum and iron particles in the reaction layer of propellant. Then the use of Alex/B in HEM the ignition time is decreased by 1.2–1.4 times, the recoil force of gasification products outflow from burning surface is slightly increased by 9 %.

## 1 Introduction

According to the study [1] on the aluminum oxidation at combustion of composite solid propellants considerable influence renders the presence on the surface particles of refractory layer of aluminum oxide. Melting point of alumina is significantly above the aluminum melting point. The combustion aluminum particles is possible at the high temperature gradient near the reaction layer of high-energy materials (HEM) near the combustion surface with occurrence of cracks and destruction of the oxide layer resulting in oxidation of the active metal. It is well known [1, 2] the destruction of the aluminum oxide layer of particles is possible in cooperation with the carbon particles to form aluminum carbide.

Analysis of obtained results [3] showed that the main role of iron powder additive is reduced to acceleration of thermal decomposition process of oxidizer and combustible binder occurring in condensed phase of HEM. Furthermore, the iron and titanium powders used for the intermetallic compounds by heating with aluminum powder reacts with high

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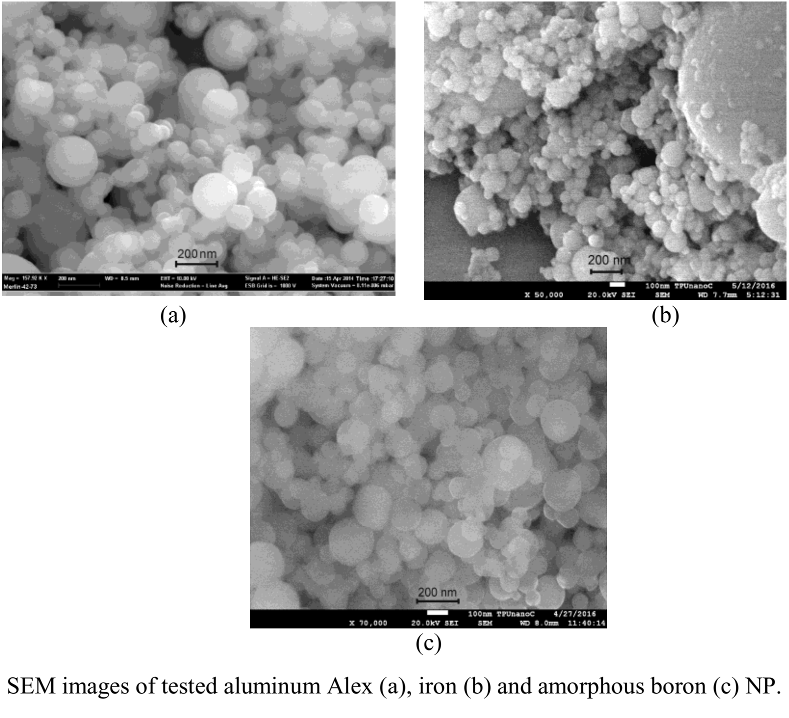
exothermic effect. This indirect to confirming is the reduction of the plate surface temperature at the same value of the ignition time of sample under introduced into the HEMs these metal additives [4]. Additive of boron powder can change the agglomeration of aluminum nanoparticles on the HEM reaction layer surface then combustion composite solid propellants [5]. Moreover according to the thermodynamic calculations and experimental data [6] the additives of boron and iron powders allows to reduce of the mass fraction of condensed combustion products of HEM.

This paper presents the experimental data of thermal decomposition and the ignition characteristics for the HEM samples based on ammonium perchlorate (AP) and butadiene rubber, containing metal: aluminum, aluminum/iron and aluminum/amorphous boron.

## 2 Experimental

### 2.1 The HEM samples

We studied the HEM samples on the basis of bidispersed AP (fraction less than 50 μm and 160–315 μm in the ratio of 40/60), inert combustible-binder (19.7 wt. %) – butadiene rubber plasticized by transformer oil, and ASD-4 micron or Alex aluminum NP (15.7 wt. %) obtained in argon using electric explosion of conductors. In the second and third compositions 2 wt. % of the Alex nanopowder (NP) was replaced by aluminum/iron and aluminum/amorphous boron NP in the ratio of 87/13. According to the measurements on the BET analyzer Nova 2200e in nitrogen the specific surface area of Alex amounts to 7.04 m$^2$/g, iron – 1.08 m$^2$/g, amorphous boron – 8.63 m$^2$/g. Micrographs of scanning electron microscope Jeol JSM-7500F of aluminum, iron and boron nanopowders are shown in Fig. 1. According to the manufacturers data the metal content in the tested NP Alex comprised 85 wt. %, iron – 92 wt. %, and boron – 99.5 wt. %.



(a) (b)

(c)

**Fig. 1.** SEM images of tested aluminum Alex (a), iron (b) and amorphous boron (c) NP.

The studied cylindrical samples of HEM in diameter 10 mm and height 30 mm produced in the laboratory by extrusion pressing with the subsequent curing. The density of solid samples was in an interval of 1.53–1.59 g/cm$^3$ depending on the component composition.

### 2.2 Ignition of HEM

The ignition study of tested HEM was carried using the setup of 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 HEM samples were placed in the hollow cylinder of 10 mm depth made of ebonite for inhibiting the lateral surface and making one-dimensional flow of gasification products.

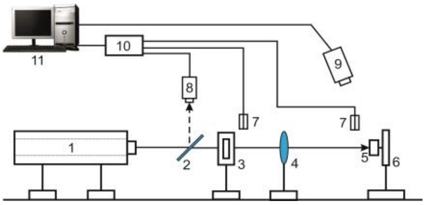


**Fig. 2.** The scheme of experimental setup based on $CO_2$ laser: 1 – $CO_2$ laser; 2 – beam-splitting mirror; 3 – shutter; 4 – lens; 5 – HEM sample; 6 – holder; 7 – photodiodes; 8 – thermoelectric sensor of radiation power; 9 – video camera; 10 – ADCs; 11 – PC.

The 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 HEM 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 to 5–12 % at the value of confidence probability of 0.95.

The values of recoil force of gasification products outflow from the end surface of HEM sample during the heating of reaction layer, ignition and combustion of HEM were determined using recoil force transducer [7].

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.

## 3 Results and discussion

### 3.1 Thermal decomposition of HEM

Thermal analysis of HEM samples containing metal ultrafine powders was carried out using a Netzsch Simultaneous Analyzer STA 449 F3 Jupiter at the heating rate range of 2–

10 °C/min. A set of TG measurements performed for the tested HEM samples in argon at the heating rate of 10 °C/min. is presented in Fig. 3.

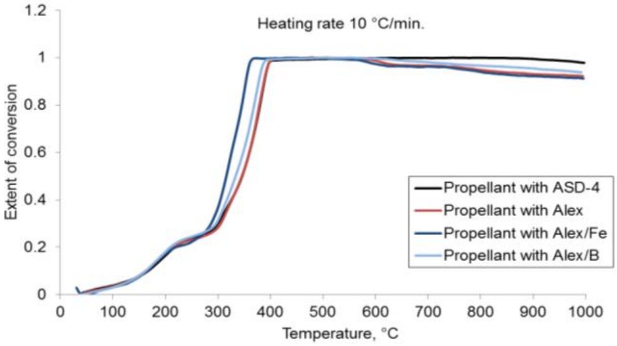


**Fig. 3.** The extent of conversion for tested HEM samples vs. the temperature.

The results of DSC-TG measurements show that the tested HEM samples have two stage decomposition. The use of Alex/Fe in HEM reduces the starting temperature of intensive decomposition by ~20 °C and increases the rate of intensive decomposition of the sample due to a possible catalytic effect [8], which decreases the starting temperature of high-temperature decomposition of ammonium perchlorate. Using of Alex/B UFP in HEM does not lead to change the starting temperature and the rate of intensive decomposition.

### 3.2 Ignition parameters of HEM

The values of ignition and gasification times, recoil force of gasification products outflow for the HEM samples in atmospheric conditions were determined. Processing of signal recording from the recoil force transducer, the time delays of ignition and gasification, the recoil force outflow of gasification products from the burning surface of HEM samples have been got. The ignition time of HEMs dependences vs. the maximum value of the heat flux density (in the center of the laser beam) were determined (Fig. 4).

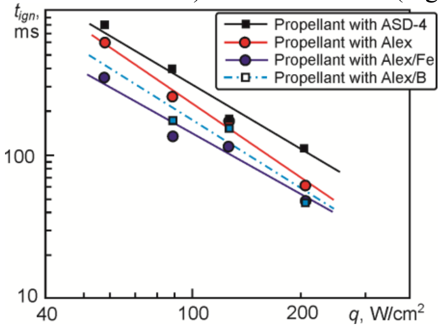


**Fig. 4.** The ignition time vs. the heat flux for tested HEM: ASD-4 – $t_{ign}=2.97\cdot10^5q^{-1.49}$; Alex – $t_{ign}=4.37\cdot10^5q^{-1.65}$; Alex/Fe – $t_{ign}=0.74\cdot10^5q^{-1.37}$; Alex/B – $t_{ign}=1.91\cdot10^5q^{-1.53}$.

The use of Alex/Fe powder in HEM decreases the ignition time by a factor of 1.3–1.9 in the heat flux range of 55–220 W/cm$^2$ in comparison with the base HEM sample with Alex and increases the recoil force of the gasification product outflow from the burning surface by 27 % at stationary combustion of HEM with the increase of the surface temperature on the HEM reaction layer (Table 1). The use of Alex/B powder in HEM causes 1.2–1.4 fold decrease in the ignition time. The recoil force of gasification product outflow from the burning surface slightly increases by 9 %.

**Table 1.** The ignition surface temperature for HEM samples in the flame appearance moment.

| ***q*, W/cm²** | ***$T_{ign}$* of HEM sample, °C** | | |
|---|---|---|---|
| | with Alex | with Alex/Fe | with Alex/B |
| 35 | 590 ± 50 | 720 ± 70 | 790 ± 80 |
| 80 | 720 ± 80 | 950 ± 110 | 770 ± 90 |

## 4 Conclusions

The effect of aluminum/iron and aluminum/amorphous boron fuels on ignition characteristics was studied in the HEM samples on the basis of AP and butadiene rubber. It was found that the use of Alex/Fe powder in the HEM sample decreases the ignition time by 1.3–1.9 times under initiation by $CO_2$ laser in air at the range of heat flux density of 55–220 W/cm$^2$ and increases of the recoil force of gasification products outflow from burning surface by 27 % during combustion of propellant due to possible of the catalytic effect, which reduces the beginning temperature of AP high-temperature decomposition by ~20 °C, and interaction of thermite mixture of aluminum and iron particles in condensed phase with the increase of temperature on the reaction layer surface of HEM.

The use of Alex/B powder in the HEM sample causes 1.2–1.4 fold decrease in the ignition time, the recoil force of gasification products outflow from burning surface is slightly increased by 9 % while the beginning temperature of high-temperature decomposition of HEM does not change and equals to ~310 °C.

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