Effect of hydroborate iron additives (BH-Fe) on the properties of composite solid rocket propellants

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Abstract: Several industrial - and research - types of hydroxy-terminated polybutadiene (HTPB) - based composite solid propellants with and without hydroborate iron additives (BH-Fe) were experimentally prepared. In general, they feature the same nominal composition, but different mass fraction of BH-Fe particles are investigated as burning catalysts and contrasted to a conventional formulation without BH-Fe particles, which are taken as reference. Strand burning rates and the associated combustion flame structures of propellants were analyzed. The mechanical sensitivity and microstructure surface of the formulations were compared to that of a referenced propellant already certified as steady. The results show that the BH-Fe powders are of irregular shapes, which tend to disperse or not stick together easily into cold clots. The BH-Fe powder are insensitive for friction and impact stimuli (0%, >125.0 cm) and all the propellant formulations containing different mass fraction of BH-Fe particles were sensitive to impact and friction (96 %, 10.0 cm), which is a bit sensitive to the referenced formulation without BH-Fe particles (92 %, 30.2 cm). The hydroborate iron additives (BH-Fe) can affect the combustion behavior and change the burning rate effectively. The burning rate can be increased more than 12.1 % for 3 % of BH-Fe particles replaced common Al powder in the formulations. The burning rate and pressure exponent values depend little on the formulation of the mass fraction of BH-Fe powder. A change of part mass fraction of BH-Fe particles may boost the burning rate a bit higher than that of the common Al powder, and the pressure exponent was increased little from 0.30 to 0.31 at the experimental pressure range.

1. Introduction
Improving the performance of the solid propellants is always an important aspect for researchers, especially the combustion performance of propellants [1-3]. Nano - sized particles, due to small particle size, large surface area, many surface atoms complex microstructures and defects of grain, have high catalytic activity, therefore, replacing the conventional catalysts in solid propellant by nano-sized catalysts becomes a key researching hot point to improve the combustion performance of propellants [4-6]. Whereas, the addition of nano-sized particles to the propellant formulation may worsen the processibility of solid propellant slurry for its large specific surface area. The highly energetic combustion agent, tetraethylammonium decahydridecaborate (BHN), a new energetic
material with a high heat of combustion (49.5 MJ kg\(^{-1}\)) and low mechanical sensitivity (\(H_{50} > 128\) cm, \(P = 0\%\)), can be used as a main ingredient in cast explosives and propellants [7-9]. There are a few reports on the synthesis and evolution of combustion catalysts in propellants and explosives. The most commonly used, in a large range of applications, are obtained by co-precipitation, of decahydrodecaborate salts, together with some oxidizers, such as \(K_2B_{10}H_{16}\), \(Cs_2B_{10}H_{16}\), \((NH_2)_{2}B_{10}H_{16}\), \(Cs_2B_{10}H_{16}\)CsNO\(_3\)and \(Cs_2B_{10}H_{16}/\)KNO\(_3\), etc. [10-13]. Pang W.Q. et al [14] have ever studied the effect of tetraethylammonium decahydro-decaborate (BHN) on the properties of fuel rich solid propellant, it was found that the addition of BHN to the fuel rich propellant can increase the mass and volume combustion heat of propellant, and the pressure exponent of fuel rich solid propellants decrease with increase in the mass content of HBN in propellant formulation. The use of new type of burning rate catalyst with high catalytic activity, is one of the important ways to improve the combustion properties of solid propellant. Moreover, Chen F.T. et al.[15] reported the effects of \([N(C2H5)]_4\)B\(_{12}\)H\(_{12}\) on the combustion properties of nitrate ester plasticized polyether (NEPE) propellants. Their results showed that it is not an effective catalyst for the decomposition of AP, whereas it can increase the decomposition of nitramines, the burning rate of NEPE propellants can be increased by the addition of this compound, and also that a “platform” appears over the high pressure range 7-11 MPa. Thus, from the point of view of the high performance mentioned above, it has potential for possible use as an energetic ingredient in solid propellants and explosives [16, 17]. However, there are few reports on the combustion properties of composite solid propellants containing hydroborate iron salt (BH-Fe) additives. In the present work, the characteristics of the BH-Fe particles were analyzed by using the diagnostic techniques of scanning electron microscopy (SEM), and grain size distribution. Different mass fractions of BH-Fe particles were added to the formulations and three different propellant compositions with and without BH-Fe were produced. The focus of this paper is on how BH-Fe affects the combustion properties (burning rate and pressure exponent) of composite solid rocket propellants, placing the emphasis on the combustion flame structure and thermal decomposition performances of the solid propellants, which could be used for solid rocket motor applications.

2. Experimental

2.1. Raw materials

The binder system consists of hydroxyl - terminated polybutadiene (HTPB, \(E_{OH} = 7.8 \times 10^{-4}\) mol/g) plasticized with Di-2-ethylhexyl sebacate (DES) to increase the processibility, which is cured by 2,4-toluene diisocyanate (TDI). The additive isophthaloyl-bis-(2-methylaziridine) (HX-752) and bi-(2-methy-1-aziridinyl) phosphine oxide (MAPO) were used as a cross - linker and a bonding agent, respectively. Aluminum powders with an average particle size of 5 \(\mu\)m was used in the formulations (Purchased from Nanjing Chemical Industry Co., Ltd.), and parts of AP were replaced by hydroborate iron additives (BH-Fe) additive. The involved propellant formulations also contain catocene (GFP) and chromite copper (CC) as burning rate modifier. Ammonium perchlorate (AP), as oxidizer was always used, and kept tri-modal. The first and the second modal of AP consisted of pure research grade AP (> 99 % pure) with an average particle size of 0.178 - 0.250 mm and 0.105 - 0.150 mm, respectively. The third modal of AP was made by grinding AP (> 99 % pure) in a fluid energy mill to an average particle size of around 1-3\(\mu\)m.
2.2. Tested Ingredients and Formulations
The composite solid propellant used as the baseline, is an HTPB/AP/Al/Catalysts formulation in the mass ratios 11.5/65/18/5.5 for all involved samples. Modified BH-Fe additive was used as catalyst additive by replacing aluminum powders. Except where otherwise stated, all propellants were manufactured, processed, and tested at Xi’an Modern Chemistry Research Institute under identical conditions and using identical procedures. Table 1 shows the mass fraction of these chemicals in different propellant samples.

Table 1. The main ingredients of composite solid propellant with and without BH-Fe particles.

| Samples           | HTPB/% | AP/% | AI/% | GFP/% | CC/% | BH-Fe/% | Additives/% |
|-------------------|--------|------|------|-------|------|---------|-------------|
| CSP-1 (Reference Formulation) | 9.5    | 65   | 18   | 4     | 1.5  | 0       | 2           |
| CSP-2             | 9.5    | 65   | 17   | 4     | 1.5  | 1       | 2           |
| CSP-3             | 9.5    | 65   | 15   | 4     | 1.5  | 3       | 2           |

2.3. Processing
Propellant formulations were mixed in 500 g batches using a vertical planetary mixer of 2 L capacity. All batches were mixed and cast under a vacuum by a slurry cast technique [21]. The propellant was cured at 50 °C for 3 days in a water jacketed oven to solidify the propellant samples.

2.4. Characterization methods
2.4.1. BET and SEM tests. The specific surface area measurement was computed from the nitrogen adsorption isotherm, obtained by static volumetric measurement at a liquid nitrogen boiling temperature (77 K). Samples were out-gassed at 100 °C for at least 4 h at an absolute pressure of less than 10⁻³ Torr. All measurements were carried out on a completely automated instrument (ASAP 2010 from Microm - meters, USA), leading to the final value of the specific surface areas expressed in m²·g⁻¹. Electron microscopy was used to study the shape, size, morphology, and defects of powders. The morphologies of solid particles were examined by a scanning electron microscope (SEM) technology.

2.4.2. Particle size distribution experiments. Particle size and size distribution of samples were performed through laser scattering (Malvern Mastersizer 2000) using a dry dispersion unit (Scirocco). Tests were performed with the same feed rate (45 %) and varying feeding pressure in order to achieve sensitivity on this parameter. The quantity of material per test was about 0.07 to 0.09 grams, fed through the “Micro Volume” tray. Obscuration filtering was switched on and set to values within the range of 0.5 % - 10 %.

2.4.3. Density test. The density measurement of solid propellants were carried out on a Model AG 104 METTLER TOLEDO balance with samples of 30 mm × 30 mm × 10 mm rectangular stick s in steeping medium of liquid paraffin at the temperature of (20 ± 2) °C.

2.4.4. Hazardous properties test. The impact instrument made in Xi’an Modern Chemistry Research Institute was used to test the impact sensitivity of the propellant with different metric metal particle
samples. Each sample (35 mg) was tested 25 times to obtain $H_{50}$ values (The $H_{50}$ value represents the height from which dropping a 5 kg weight results in an explosive event in 50 percent of the trials.). With 5 peering tests, an average value of $H_{50}$ was calculated. Friction instrument (90°, 3.92 MPa) also made in Xi’an Modern Chemistry Research Institute was employed to test the friction sensitivity of samples. Each sample (20 mg) was tested 25 times and an explosive probability $P$ (%) was obtained. An average value of $P$ was estimated with 5 peering tests \cite{22-24}.

2.4.5. TG-DTG analysis. The thermal decomposition processes of the propellants were measured by differential thermal analysis (DTA) and thermo-gravimetry (TG). The equipment was operated under the condition of the flowing nitrogen at atmospheric pressure. TG and DTA tests were carried out with a heating rate of 10 K·min$^{-1}$, while 3.0 mg samples were heated in Al$_2$O$_3$ pans without cover.

2.4.6. Burning rate test method. Strand burning rate of the propellants were determined in the pressure range of 1-12 MPa by means of fuse-wire technique \cite{25,26}. The methodology involved the combustion of strands (ignited by means of a nichrome wire) with the dimensions of $150 \text{ mm} \times 5 \text{ mm} \times 5 \text{ mm}$ in a nitrogen pressurized steel bomb. For the trial conducted, the burning rates were computed from the time that was recorded at each pressure level for each sample.

2.4.7. Combustion flame structure tests. The combustion flame structure tests were carried out in a transparent combustion bomb with four sides. The combustion behavior of the composite propellant, containing different aluminum samples with the dimensions of $1.5 \text{ mm} \times 5 \text{ mm} \times 15 \text{ mm}$, were performed at the scheduled pressure under $N_2$ atmosphere, and ignited by chromium-nickel wires from top to down.

3. Results and Discussion

3.1. SEM and grain size distribution analysis

Detailed information of particles, concerning morphology, and particle size distribution were collected by running a series of advanced diagnostic techniques, including SEM, BET, and grain size distribution. The morphology is one of the most important parameters for characterizing the quality of particles. Specific material properties such as ability to flow, reactivity as well as compressibility, and its hardening potentials are determined by the size distribution. The solid particle size distribution is a key factor in its atomization processes and other chemical processes such as combustion. The BH-Fe particles with and without modification with different particle sizes were tested “as received”. The visual inspections of the collected SEM morphologies and particle size distribution of tested BH-Fe powder were investigated and the results are show in figure 1. Table 2 summarizes the characteristic data of hydroborate iron additives obtained by Malvern laser granulometer and report the calculated average diameters.
Figure 1. SEM images and grain size distribution of tested BH-Fe powder (High Magnification: x500).

Table 2. The characteristics of BH-Fe powder.

| Sample | D[3,2]/μm | D[4,3]/μm | D(0.1)/μm | D(0.5)/μm | D(0.9)/μm |
|--------|-----------|-----------|-----------|-----------|-----------|
| BH-Fe  | 72.12     | 101.54    | 40.77     | 93.51     | 186.88    |

| Sample | Span | SSA\(^a\)/(m\(^2\) g\(^{-1}\)) | SSA\(^b\)/(m\(^2\) g\(^{-1}\)) | Density/g cm\(^{-3}\) |
|--------|------|---------------------------------|---------------------------------|---------------------|
| BH-Fe  | 1.562 | 0.083                           | 0.088                           | 0.981±0.002         |

\(^a\) - determined by Malvern Mastersizer; \(^b\) - measured by BET method.

It can be seen from figure 1 and table 2 that the microstructure of the tested BH-Fe particles presents an irregular shape, and tend to disperse or not stick together into cold clots. The \(d_{50}\) of BH-Fe particles is 93.51 μm, and the particle size distribution curve is a bit coarse. Corresponding to the high values of \(d_{50}\), the width of BH-Fe particles is 1.562, and the specific surface area of BH-Fe is 0.083 m\(^2\) g\(^{-1}\) (Malvern) and 0.088 m\(^2\) g\(^{-1}\) (BET). In the micro-sized sample, particles show no cold cohesion, a phenomenon occurring at room temperature during storage, handling, and manufacture, which is responsible for micro-sized clusters reducing the specific surface.

One point we must emphasize is that dry laser granulometry may be affected by errors if the material creates clots. The accuracy of these measurements is also affected by the fact that well fluid particles are not found freely but sometimes are available as an agglomerate/aggregation powder, thus making it difficult to measure the definition of a particle mean diameter.

3.2. Density

Table 3 summarizes the tested density of composite solid propellants containing different mass fraction of BH-Fe powder, as measured at our Institute.

Table 3. Comparing densities of the tested composite solid rocket propellants with and without BH-Fe.

| Samples | Measured density/(g cm\(^{-3}\)) | Porosity/% |
|---------|---------------------------------|------------|
| CSP-1   | 1.754±0.004                     | Negligible to Modest |
| CSP-2   | 1.750±0.006                     | Negligible  |
| CSP-3   | 1.742±0.002                     | Modest     |
From the results in table 3, one can see that the density of composite solid propellant formulations, with common aluminum particles, is larger than those of BH-Fe additive based propellants, which can be attributes to the modest porosity of BH-Fe powders during the manufacture of propellant formulation. It can be concluded that increasing the BH-Fe powder percentages leads to a decrease in propellant density, which may be because the density of surmise (0.981 g·cm\(^{-3}\)) is lower than that of Al (2.70 g·cm\(^{-3}\)), and the poor shape of BH-Fe and powder packing during the manufacturing process is more worse than that of Al composition.

3.3. Hazardous properties

The impact sensitivity of an energetic material to unintended initiation is an important safety factor in their use. There are many uses for knowing the hazardous properties of a material’s impact and friction. These can purpose the evaluation of material sensitivity over time as determination of one material replaces another one in a particular process which compares sensitivity of two materials. The sensitivity of the different aluminum particles and propellants with aluminum powder can be confirmed this way.

**Table 4.** The hazardous properties of BH-Fe powder and composite solid propellant with different mass fraction of BH-Fe particles.

| Samples | Friction sensitivity(\(P\))/% | Confidence level of 95 % believe level | Impact sensitivity \((H_{50})/\text{cm}\) | Standard deviation S (logarithmic value) |
|---------|------------------------------|---------------------------------------|---------------------------------|----------------------------------|
| BH-Fe   | 0                            | (0 %, 14 %)                           | >125                            | -                                |
| CSP-1   | 92                           | (74 %, 99 %)                          | 30.2                            | 0.09                             |
| CSP-2   | 92                           | (74 %, 99 %)                          | 17.0                            | 0.08                             |
| CSP-3   | 96                           | (80 %, 100 %)                         | 10.0                            | 0.07                             |

From the results in table 4, the following conclusions can be made that the tested BH-Fe powders is insensitive for friction and impact sensitivity (0 %, and > 125 cm). The designed and prepared propellants containing different mass fraction of BH-Fe particles were sensitive to impact and friction, and the impact sensitivity and friction sensitivity are increase with increasing in mass fraction of BH-Fe powder in the formulation. The reference propellant without BH-Fe powder is 92 % and 30.2 cm, respectively. The effects of BH-Fe powder on the impact and friction sensitivity of solid propellants is not significant, when comparing formulations without BH-Fe powder. The sensitivity depends on a lot of factors (such as molecular structure, active group, interaction, superfine particles and the aggregation state, et al). The interaction maybe is possible for C C and BH-Fe additives, which increases the interfacial contacts resulting in higher activity, the activity is responsible for hot spot generation. Also, the large specific surface area of CC powder with high surface activity may be one the reasons for increasing the mechanical sensitivity [20]. In case of particle size of BH-Fe influence on the mechanical sensitivity, it should be investigated detailed in the future. Thus, researches must be done to decrease the mechanical sensitivity of the designing composite solid rocket propellant with hydroborate iron additives.
3.4. Combustion characterization

3.4.1. Burning rate and pressure exponent. Propellant burning rates can influence the rate of gas generation, which determines the pressure inside the motor and the overall thrust. Also, it can be affected by changes in composition (ingredients, mass fraction, and particle-size distributions) and conditions (pressure and initial temperature). The focus of this paper is on the different types of metal additives, and how they interact with the RDX and binder under high pressure and temperature, thus affecting the burning rates and the data are shown in table 5 and figure 2.

Table 5. Burning rate of composite solid rocket propellant with and without BH-Fe additives.

| Samples | Content of BH-Fe/% | Burning rate (r)/mm·s⁻¹ |
|---------|--------------------|-------------------------|
|         | 1MPa               | 4MPa | 7MPa | 10MPa | 12MPa |
| CSP-1   | 0                  | 19.63| 27.29| 33.07| 37.64| 42.74|
| CSP-2   | 1                  | 20.22| 27.55| 33.52| 37.85| 43.18|
| CSP-3   | 3                  | 20.68| 30.49| 37.08| 39.34| 44.08|

| Samples | Content of BH-Fe/% | Pressure exponent (n) |
|---------|--------------------|-----------------------|
|         | 1-4MPa | 4-7MPa | 7-10MPa | 10-12MPa | 1-12MPa |
| CSP-1   | 0      | 0.24   | 0.34    | 0.36     | 0.70    | 0.30    |
| CSP-2   | 1      | 0.22   | 0.35    | 0.24     | 0.61    | 0.35    |
| CSP-3   | 3      | 0.32   | 0.35    | 0.17     | 0.37    | 0.31    |

Figure 2 Effect of different mass fraction of BH-Fe additives on the burning rate of composite solid rocket propellant at the different pressures (pressure range: 1-12 MPa; initial temperature: $T_0 = 293$ K).

It can be seen in figure 2 and table 5 that when the oxidizers can catalysts are the same, the BH-Fe additives can affect the homogeneous combustion behavior and change the burning rate effectively. A change to the content of BH-Fe additives may boost the burning rate of composite propellant even though the referenced HTPB/AP/Al composite formulation exhibits a high burning rate here. The burning rate can be increased more than 12.1 % for 3 % mass fraction of BH-Fe replaced common Al powder in the formulations, however, the pressure exponent can’t be changed much from 0.30 to 0.31 (1-12 MPa). Thus, it can be concluded that the increasing mass fraction of BH-Fe powder not only can increase the specific impulse but can also increase the burning rate for a composite propellant. An
interesting feature is that the burning rate values depend on the mass fraction of BH-Fe powder, however the pressure exponent did not change much. Moreover, the influence of the particle size of BH-Fe powder for a composite propellant could be investigated further.

The addition of BH-Fe additives to the formulation can increase the burning rate of propellant, which may be attributed to the heat release and heat feedback to the combustion surface. From the energetic viewpoint [18-20], the heat release and heat feedback to the combustion surface for BH-Fe particles are higher than those of Al ones, and its promoting effect on the propellant combustion process is the main function in the experimental pressure range. From the heat transfer viewpoint, the addition of BH-Fe powder to the propellant formulation can increase the heat adsorption effectively during the combustion process. The enhanced heat transfer to the propellant surface, due to large energy releases and reduced flame standoff distance in the gas phase at elevated pressure, overrides the influence of preconditioned temperature in determining the energy balance at the surface, and consequently decreases the temperature sensitivity of burning rate. As shown in the results, the basic assumptions in the following description of the burning rate model are as follows: (1) one-dimensional burning; (2) steady-state burning at a fixed pressure; (3) radiative energy from the gas phase is absorbed at the burning surface [27].

Lastly, one point we must emphasize is that the decomposition at a lower temperature indicates that the gaseous products formed during decomposition exert higher feedback to the deflagrating propellant surface. Hence, more energy is released in the combustion process (at the surface), which supports the augment of the burning rate [28].

3.4.2 Combustion flame structure. Typical combustion flame structures of composite solid rocket propellants containing different mass fraction of BH-Fe particles at 1 and 3 MPa are shown in figure 3.
It can be seen from the photos mentioned in figure 3 that the combustion flame structures of composite solid propellants, with and without BH-Fe particles at various pressure ranges, present multi-flame structures, and the brightness of the flame structures is increased with an increase in pressure. During the propellant combustion, there are many sparks on/near the propellant burning surface, which can be attributed to the aluminum particles addition to the composite propellant formulations. Although the metal oxidation process follows a common set of events, aggregation/agglomeration phenomena near the burning surface may be noticeably different depending on the enforced operating conditions and details of the solid propellant formulation.

3.5. TG-DTG analysis
Additives, such as BH-Fe have important effects on the combustion properties of HTPB-based composite solid propellant. For example, the influence mechanism can be related with the thermal decomposition of propellants [18]. Figure 4 shows the TG-DTG curves of composite solid propellants with different mass fraction of BH-Fe particles at the heating rate of 10 K·min⁻¹.
Figure 4. The thermal decomposition curves of composite propellant containing with and without BH-Fe particles.

It is found from the TG-DTG patterns that the HTPB-based composite solid propellants with and without BH-Fe particles show three main mass loss stages (stages I -III). The first stage begins at about 150.05 °C and ends at 199.8 °C, accompanied with about 4.5 % mass loss, corresponding to the mass of burning rate catalyst GFP that evaporates and decomposes. The second stage (CSP-1 sample) begins at 224.7 °C and ends at 297.2 °C, accompanied with 16.8 % mass loss. This is mainly attributed to the partial decomposition of the polymer binder HTPB and AP, which is in agreement with the mass fraction amounts of AP in the formulation. The third stage begins at 301.5 °C and ends at 347.8 °C, and is accompanied with a 35.3 % mass loss, which is in agreement with the decomposition of part of the AP binder [12,25]. In the temperature range of 348.1 °C - 450.0 °C, the mass loss is more than 40.0 %, which indicates that there are a few remains at the end of the decomposition. In essence there is no visible difference on the excess stage for the three types of propellant. Also, the decomposition process of the propellant containing BH-Fe particles indicates that the gaseous products formed during decomposition exert higher feedback to the deflagrating propellant surface, which can increase the burning rate. Consequently, it is in agreement with the burning rate results.

3.6. Mechanical properties tests
In order to analyze the behavior of different BH-Fe particles in composite solid propellants, the mechanical properties and the surface microstructures of composite propellants with and without BH-Fe particles are shown in table 6 and figure 5, respectively.

Table 6. Mechanical properties of fuel rich propellants with different mass fraction of BH-Fe particles.

| Samples  | Mechanical properties \(\sigma/\varepsilon/E\) (+20 °C) |
|----------|--------------------------------------------------|
|          | \(\sigma_{m}/\text{MPa}\) | \(\varepsilon_{m}/\%\) | \(E/\text{MPa}\) |
| CSP-1    | 1.78 | 56.6 | 8.18 |
| CSP-2    | 1.69 | 60.1 | 7.98 |
| CSP-3    | 1.65 | 55.8 | 7.89 |
\( \sigma_m \) as a maximum tensile strength, \( \varepsilon_m \) as an elongation at maximum tensile strength, \( E \) as an elastic modulus.

![Figure 5. SEM surface image of solidified propellant with and without BH-Fe additive.](image)

It can be seen that the elastic moduli (\( E \)) at +20 °C of fuel rich propellants prepared above are high (>7.80 MPa), and the elastic moduli (\( E \)) and maximum tensile strengths (\( \sigma_m \)) of propellant samples CSP-1 are larger than those of the other propellants. Contrary to the referenced propellant samples CSP-1, the elongation at maximum tensile strength (\( \varepsilon_m \)) of the other propellant samples did not change very much at 20 °C (table 6). It can be also found that there are obviously many spherical particles on the surface of cured composite solid rocket propellants, which may be attribute to the addition of AP particles to the formulation, and the particles with smaller diameters can fill into the spaces between the bigger grains effectively (figure 5).

References

[1] Zheng Yuan-yang and Wang Min-wen 1989 Chinese Journal of Explosives & Propellants (3) 32-7
[2] Wang Wei-qiang, Xue Yun-na and Yang Jian-ming et al 2012 Chinese Journal of Energetic Materials 20(1) 132-6
[3] Spielvogel B and Cook K 2005 Method of production of B10H10 ammoniumsalts and methods of production B18H22: US 2005/0169828A1 08
[4] Price E W 1984 Combustion of Metallized Propellants In: Kuo K K, Summerfield M, eds. Fundamentals of Solid Propellants Combustion AIAA Progess in Aeronautics and Astronautics 90 Chapter 9
[5] Babuk V A, Vasilyev V A and Sviridov V V 2000 Formation of Condensed Combustion Products at the Burning Surface of Solid Rocket Propellant. In: Yang V, Brill T B, Ren W Z, eds. Solid Propellant Chemistry, Combustion, and Motor Interior Ballistics, Progress in Aeronautics and Astronautics AIAA. Reston, va, pp 749-76
[6] Ivanov S V and Casas B 2010 Process for producing boranes : US 771815482, 05
[7] Prajacta R Patil, V N Krishnamurthy and Satyawati S Joshi 2006 Propellants, Explosives, Pyrotechnics 31 pp 442-6
[8] Tang Song-qing and Ding Hong-xun 1983 Journal of Propulsion Technology 2 35-51
[9] S Yuasa, Y Zhu and S Sog 1997 Combustion and Flame 108 pp 387
[10] Shan Wen-gang, Sun Tie-gang and Zhang Guo-dong 1995 *Journal of Solid Rocket Technology* **18**(3) 24-6

[11] Peryshkov D V, Popov A A, Strauss S H 2009 *J. Am. Chem. Soc.* **131** 18393-403

[12] Drozdova V V, Zhizhin K Y and Malinina E A et al 2007 *Russian Journal of Inorganic Chemistry* **52**(7) 996-1001

[13] X G Wu, Q L Yan and X Guo et al 2011 *Acta Astronautica* **68**(7-8) 1098-112

[14] Pang Wei-qiang, Fan Xue-zhong and Zhao Feng-qi et al 2013 *Journal of Solid Rocket Technology* **36**(5) 647-53

[15] Chen Fu-tai, Tan Hui-min and Luo Yun-jun 2000 *Chinese Journal of Explosives &Propellants* **27**(3) 19-21

[16] Luigi T DeLUCA, Luciano Galfetti and Filippo MAGGI et al 2012 *Chinese Journal of Energetic Material* **20**(4) pp 465-74

[17] Glotov O G, Zarko V E and Karasev V V et al 1997 Effect of binder on the formation and evolution of condensed combustion product of metallized solid propellants *28th International Annual Conference of ICT, Karlsruhe, Federal Republic of Germany, June*

[18] Chuiko S V and Sokolovskii F S 2009 *Russian Journal of Physical Chemistry B* **3**(6) 926-35

[19] Gulinsa Guoyiqibai, Zhang Rui and Yan Hong 2010 *Chinese Journal of Inorganic Chemistry* **26**(5) 733-43

[20] Nie Yong, Chen Hai-yan and Miao Jin-ling 2009 *Chinese Journal of Organic Chemistry* **29**(6) 822-34

[21] Vuga S M 1991 *Propellants, Explosives, Pyrotechnics* **16** 293-8

[22] 1960 Development of Sensitivity Tests at the Explosive Research Laboratory (Ed.: D. H. Mallory) *Bruceton Pennsylvania, NAVORD* Report No. 4236

[23] J K G Peters 1921 Production Program of Julius Peter Company for Members of M. B. B. Course-81 Berlin pp 14

[24] Jakub ŠELEŠOVSKÝ and Jiri Pachman 2010 *Central European Journal of Energetic Materials* **7**(3) 269-78

[25] Maggi F, Bandera A and DeLuca L T et al 2011 *Prog. Prop. Phys.* **2** pp 81-98

[26] Sivaev I B and Bregadze V I 2000 *Journal of Organometallic Chemistry* **614-615** 27-36

[27] Zhang Ren, Li Jia-hua and Weng Wu-jun 1994 *Journal of Propulsion Technology* **3** 62-5

[28] Lin Rui-bin and Li Zhan-xiong 2010 *Chinese Journal of Synthetic Chemistry* **18**(2) 229-31