

Application of aluminum-based micro-cell composite fuel in HTPB propellant

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Abstract: To study the combustion performance of aluminum-based micro-cell composite fuel aluminum@ammonium perchlorate (Al@AP), in hydroxyl-terminated polybutadiene (HTPB) solid propellant, the Al@AP was added to HTPB solid propellant instead of Al powder and part of AP. Firstly, the ignition and energy performance of Al@AP were investigated and the effects of Al@AP on the combustion, process and mechanical properties of HTPB solid propellant were studied by means of sphere explosion test system, adiabatic oxygen bomb calorimeter test, standard test engine test, residual active Al test, viscosity test, and tensile test. In addition, the combustion mechanism of Al@AP in HTPB solid propellant was analyzed. The results indicate that Al@AP composites offer faster ignition response than simple physical blends, and the heat of HTPB solid propellant increases from $7\,385\text{ J}\cdot\text{g}^{-1}$ to $7\,834\text{ J}\cdot\text{g}^{-1}$ when 21.3% Al@AP was used instead of aluminium powder. The amount of residue decreases from 3.88% to 2.10% in mass fraction, the content of active Al in residue decrease from 6.14% to 2.57%, and the particle size d_{50} of residue decrease from $298\text{ }\mu\text{m}$ to $62\text{ }\mu\text{m}$. The combustion efficiency of HTPB solid propellant improves from 94.0% to 94.6%. The mechanical and process properties of HTPB propellant containing Al@AP can satisfy the application.

Key words: Al@AP composite fuel; hydroxyl-terminated polybutadiene (HTPB) solid propellant; combustion performance

0 Introduction

Aluminum-based fuel is widely used in propellant due to its high enthalpy of combustion and low oxygen consumption. However, the ignition temperature (1 700—2 200 K) of aluminum (Al) powder is much higher than its melting temperature (800—1000 K) because of the dense aluminum oxide film attached to the surface of the Al powder^[1]. Some Al powder in solid propellant will agglomerate before combustion to form large Al agglomerates which cannot be completely burned. The large Al agglomerates trap unburned Al within their structure, resulting in insufficient combustion and reduced energy efficiency^[2]. The problem is particularly prominent in solid propellant with high Al powder content.

The traditional composite solid propellant is composed of micron-scale solid dispersed phase such as oxidizer and fuel, which is distributed in the continuous phase composed of binder through physical mixing^[3,4], and oxidizer and fuel in solid propellant are dispersed in micron scale. The energy release level of solid propellant is not only related to the

energy properties of formula components, but also restricted by the mass transfer process between components, especially between oxidizer and fuel. Therefore, the energy release efficiency of solid propellant is difficult to reach the ideal state in practical application^[5]. Micro-cell composite fuel refers to a new energetic material composed of two or more oxidizers-fuels in micro-nano scale^[6,7]. The oxidizer-fuel in micro-cell composite fuel is assembled in micro-nano scale, which greatly shortens the mass transfer distance between oxidizer and fuel during combustion. Reducing the influence of mass transfer and heat transfer on combustion performance makes the chemical reaction between oxidizer and fuel more complete^[8]. For example, Yan et al.^[9] prepared ammonium perchlorate/aluminum (AP/Al) composites with AP as the core and Al as the shell. It was found that the decomposition activation energy of the composites increased, and the content of active aluminum in the explosive residue decreased by more than 90% compared with the physical mixed samples. Hu et al.^[10] prepared ammonium perchlorate/nano-sized aluminum/polytetrafluoroethylene

(AP/nAl/PTFE) micro-cell composite fuel. Compared with the physical mixture, the combustion heat of micro-cell composite fuel increased from $18\,348.5\text{ J}\cdot\text{g}^{-1}$ to $20\,109.2\text{ J}\cdot\text{g}^{-1}$, and the combustion performance was greatly improved. Yang *et al.*^[11] prepared ammonium perchlorate@aluminum/nickel (AP@Al/Ni) composite fuel by acoustic resonance mixing technology. The peak decomposition temperature of AP at high temperature decreased by $76.9\text{ }^\circ\text{C}$, and the decomposition heat increased by 84.8% . Wang *et al.*^[12] employed AP-coated nAl in the study and found that the ignition temperature of AP-coated nAl was significantly lower than that of uncoated nAl. This was because the pressure rising after AP decomposition led to aluminum powder deflagration, which generated a lot of heat in a short time. According to the melting-dispersion mechanism, the volume expansion of active aluminum inside caused the surface oxide shell to break in the process of rapid temperature rise, and the oxygen-rich gas diffused to contact with the active aluminum and reacted. The reaction diagram of nAl@AP is shown in Fig.1.

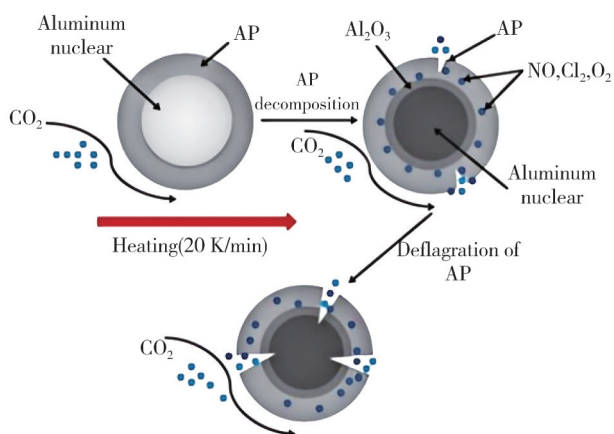


Fig. 1 Reaction diagram of nAl@AP^[10]

At present, the performance characterization of modified aluminum powder with high combustion efficiency is mainly studied in terms of density, heat of combustion, combustion efficiency and particle combustion rate, and progress has been made in the modification law of the combustion characteristics of aluminum powder under the influence of the combined factors^[13,14]. However, there is a lack of practical application research in the combustion performance enhancement of composite solid propellants containing modified aluminum powder^[15].

In our work, the combustion performance of hydroxyl-terminated polybutadiene (HTPB) propellant containing Al powder with w_{Al} of 16% was studied. 21.3% Al@AP composite fuel (the mass fraction of Al powder in propellant was 16%) was used to replace ordinary Al powder and part of AP. The influence of Al@AP composite on the

combustion performance of HTPB propellant was studied by adiabatic oxygen bomb calorimeter, engine experiment, and residual active aluminum content test, which provided technical support for improving the combustion performance of HTPB propellant.

1 Experiment

1.1 Reagents and instruments

1) Reagents

Ultra-fine spherical Al powder: particle size specification $(6\pm 1.5)\mu\text{m}$, active $\text{Al}\geq 98.0\%$, Angang Industrial Micro Al Powder Co., Ltd. Al-based micro-cell composite fuel (Al@AP): The particle size of Al powder was $(6\pm 1.5)\mu\text{m}$, with w_{Al} of 75% . Physical mixing of Al and AP (Al-AP): Al and AP were weighed according to the mass ratio of $3:1$ and fully stirred until evenly mixed. Hydroxyl-terminated polybutadiene, provided by Liming Chemical Research Institute; Dioctyl sebacate, provided by Shandong Haihua Tianji Chemical Co., Ltd.

2) Instruments

Acoustic resonance mixer was jointly developed by Huazhong University of Science and Technology and Shanghai Space Propulsion Technology Research Institute; propellant high pressure burning rate performance test system (DYR-07); YX-ZR/Q adiabatic oxygen bomb automatic calorimeter; microcomputer-controlled electronic universal test machine (WDW-10C\WDW-5J); and 20 L sphere explosion test system.

1.2 Experiment and performance test

The AP-coated Al was prepared by recrystallization method. 750 g of AP was accurately weighed according to the coating ratio, dissolved in deionized water at room temperature to form a saturated solution of AP, 250 g of Al was added and dispersed by ultrasonic dispersion for 30 min (200 W), and then stirred with a magnetic stirrer in a water bath at $60\text{ }^\circ\text{C}$ for 2 h to make a homogeneous dispersion. The solution was lowered to $25\text{ }^\circ\text{C}$ at a rate of $0.5\text{ }^\circ\text{C}\cdot\text{min}^{-1}$ and magnetically stirred (stirring rate: 500 revolutions per minute) for 12 h to allow the AP to crystallize directionally on the surface of the aluminum powder.

The formula composition of HTPB solid propellant is shown in Table 1. The components were weighed according to the design value and added to the acoustic resonance mixer for mixing. The temperature of mixing, pouring and curing was $(60\pm 2)\text{ }^\circ\text{C}$, and the curing time was $(168\pm 2)\text{ h}$. A sample of the prepared solid propellant was obtained after molding.

Table 1 Mass fraction of HTPB solid propellant

Sample	$w_{Al}/\%$		$w_{AP}/\%$	$w_{HTPB}/\%$	$w_{else}/\%$
	Al	Al@AP			
H ₀	16.0	0	71.5	8.6	3.9
H ₁	0	21.3	66.2	8.6	3.9

Combustion heat: The combustion heat of the sample was tested according to GJB5891.29—2006 constant temperature method. Test conditions: The dosage of composite powder was 2 g, the atmosphere was oxygen, and the pressure was 2.5 MPa.

Explosion heat of propellant: The explosion heat value of the sample was tested according to GJB5891.29—2006 constant temperature method. The dosage of HTPB solid propellant was 2 g, the atmosphere was argon, and the pressure was 2.5 MPa.

Ignition and explosion response test of composite powder: A 20 L spherical explosion test system was selected to test the ignition response of Al@AP samples with different mass fractions prepared by physically mixing Al-AP with the same mass ratio. Chemical igniter was selected in the experiment (energy was 10 kJ, zirconium powder accounts for 40% mass fraction, barium nitrate accounts for 30% mass fraction, and barium peroxide accounts for 30% mass fraction).

Residue amount: The residue amount was calculated by weighing the weight of the test sample before and after combustion. The combustion test method was target line method and the pressure was 7 MPa. **Active Al content of residue:** The active Al content was obtained according to GJB1738A—2015 test. **The particle size of residue:** The particle size of propellant residue was tested according to GB/T 29022—2021.

Dynamic burning rate and burning efficiency: According to GJB97A—2001 “*Technical Requirements and Data Processing of Standard Test Engine*”, the burning rate and specific impulse of propellant were obtained from the test run of standard test $\Phi 118$ engine, and the test pressure was 7 MPa. The ratio of measured specific impulse to theoretical specific impulse was the combustion efficiency.

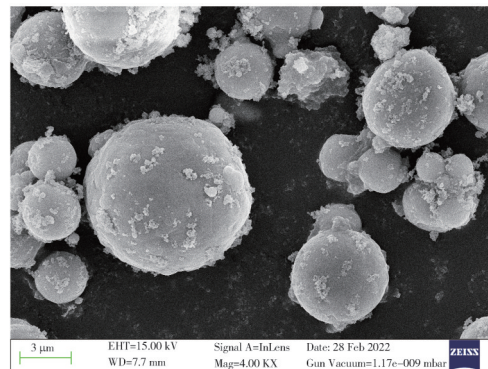
Mechanical property test: The test temperatures were 20, 70 and -40 °C respectively according to GJB770B—2005. The tensile rates at 20 and -40 °C were $100 \text{ mm}\cdot\text{min}^{-1}$, and the tensile rate at 70 °C was $2 \text{ mm}\cdot\text{min}^{-1}$.

Process performance test: The viscosity of solid propellant slurry was measured by rotary viscometer, and the test temperature was 60 °C according to GB/T 2794—2013.

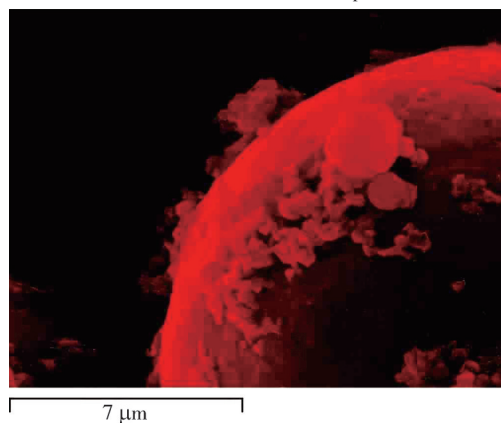
2 Results and discussion

2.1 Structural characterization of composite fuel

The surface morphology of Al@AP is observed by SEM, and the SEM results are shown in Fig.2.



(a) SEM of Al@AP composite



(b) Cl mapping of Al@AP composite

Fig. 2 SEM-mapping diagram of Al@AP composite fuel

It can be seen from the SEM diagram that the surface edge of Al@AP composite fuel was smooth, with clear outline and nearly spherical particles. It can be seen from the mapping diagram of the element Cl that the surface of composite particles was uniformly coated by AP, which indicated that AP and Al are successfully compounded.

2.2 Combustion performance

2.2.1 Explosion heat

The explosion heat of Al@AP Al-based microcell composite fuel and HTPB propellant prepared from it were tested. The test results are shown in Table 2.

As can be seen from Table 2, the combustion heat of physical mixing Al-AP is $17\,153 \text{ J}\cdot\text{g}^{-1}$, and that of Al@AP composite fuel is $19\,340 \text{ J}\cdot\text{g}^{-1}$, which is 12.75% higher than that of physical mixing. When 21.3% of Al and partial AP are replaced with Al@AP, the explosion heat of the HTPB solid propellant increases from $7\,385 \text{ J}\cdot\text{g}^{-1}$ to $7\,834 \text{ J}\cdot\text{g}^{-1}$, representing an enhancement of $449 \text{ J}\cdot\text{g}^{-1}$

(6.1% improvement). It shows that Al@AP has higher energy release efficiency.

Table 2 Combustion heat results for composite fuel and explosion heat results for propellant

Sample	$Q/(J \cdot g^{-1})$
Al@AP	19 340
Al-AP	17 153
H ₀	7 385
H ₁	7 834

2.2.2 Ignition performance of composite fuel

The pressure-time relationship of Al@AP and Al-AP with different mass fractions was tested by the explosion response of 20 L sphere. The test results of physically mixed Al-AP samples show that the higher the sample mass fraction, the higher the pressure of the system, and

the time to reach the highest pressure was 0.22–0.30 s. As can be seen from the pressure-time curves of Al@AP composite powder in Fig. 3(a), the time required to build pressure to the maximum pressure for Al@AP composite materials under different tested mass fractions is less than 0.20 s, and the ignition response becomes faster with increasing sample mass fraction during testing. Especially when the sample concentration is 1 000 g·cm⁻³, the ignition time to reach the highest pressure is only about 0.15 s. At the same time, the overall pressure-time of Al@AP composite is steeper, which shows that Al@AP composite has faster ignition response speed and more concentrated combustion or explosion reaction than simple physical mixing under the same mass ratio and test concentration.

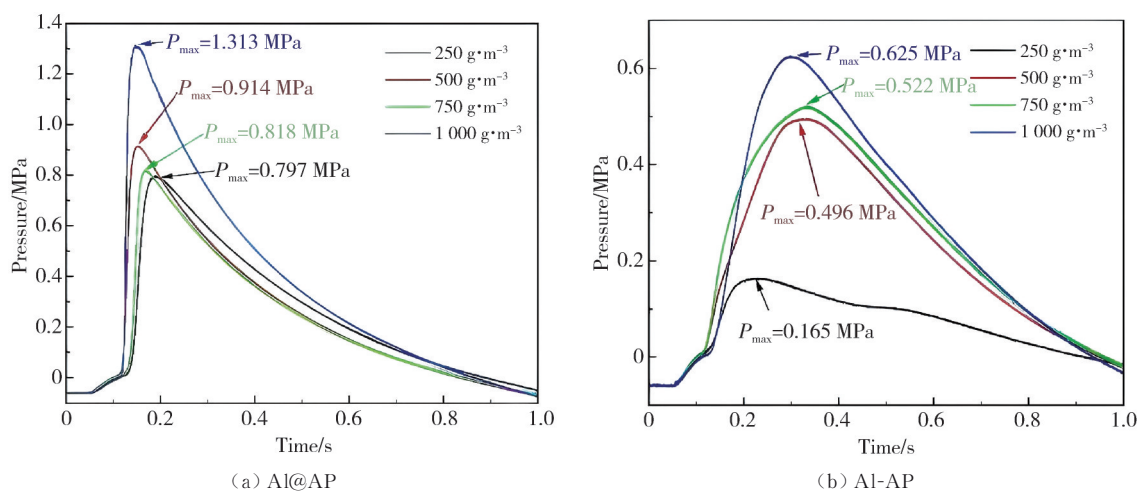


Fig. 3 Explosion pressure-time curves of powder tested by 20 L sphere

2.2.3 Combustion performance

The combustion performance of propellant containing Al@AP was tested by $\Phi 118$ standard engine. The combustion process of $\Phi 118$ engine was stable and the thrust-time curve is smooth, as shown in Fig. 4.

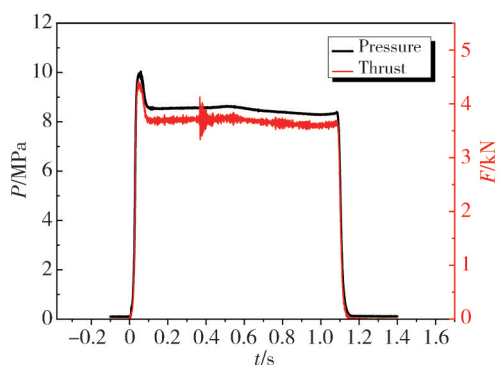


Fig. 4 Measured thrust-pressure curve of $\Phi 118$ engine with Al@AP propellant (H₁ propellant)

The test data of $\Phi 118$ engine are summarized in

Table 3. It can be seen that when the mass fraction of aluminum powder is 16%, the burning rates of propellants containing Al and Al@AP are 13.7 mm·s⁻¹ and 13.4 mm·s⁻¹, respectively. The difference of burning rates may be due to the change of particle size of Al after coating AP on its surface and alterations in oxidizer caused by its partial substitution of AP. The burning rate of Al@AP-contained propellant was lower than that of ordinary Al-contained propellant, and the measured specific impulse is increased from 2 441 N·s·kg⁻¹ to 2 459 N·s·kg⁻¹, an increase of about 1.8 s. After replacing Al with Al@AP, the combustion efficiency of HTPB solid propellant increases from 94.0% (H₀) to 94.6% (H₁), and the specific impulse efficiency of HTPB solid propellant exceeds 94.5% in the two tests. It was demonstrated that Al@AP could improve the problem of inadequate combustion of HTPB solid propellant and had the effect of improving the combustion efficiency of HTPB solid propellant.

Table 3 Test results of Φ118 engine

Sample	$r_{7MPa}/(mm \cdot s^{-1})$	Theoretical specific impulse/ $(N \cdot s \cdot kg^{-1})$	Measured specific impulse/ $(N \cdot s \cdot kg^{-1})$	$\eta/\%$	$\bar{\eta}/\%$
H ₀	13.7	2 598	2 440	93.9	94.0
			2 442	94.0	
H ₁	13.4		2 456	94.5	94.6
			2 461	94.7	

2.2.4 Residue and active aluminum content

The combustion products were further tested and analyzed, and the residue weight was obtained by collecting and weighing the residue after the combustion velocity test of the 7 MPa target line method. The residue of solid propellant Φ118 engine after testing was collected, and its particle size and active aluminum content were tested. The test results are shown in Table 4, and the physical diagram of the engine after commissioning was shown in Fig.5.

Table 4 Residue data of Φ118 engine after test

Sample	$m_{residue}/g$	$w_{residue}/\%$	$w_{Al}/\%$	$d_{50}/\mu m$
H ₀	0.70	3.88	6.14	298
H ₁	0.38	2.10	2.57	62

*Note: $m_{residue}$ is residue weight; w_{Al} is the active aluminum content; $w_{residue}\% = \text{residue weight}/\text{test sample weight} \times 100\%$, in which H₀ sample weight was 18.05 g and H₁ sample weight is 18.15 g.

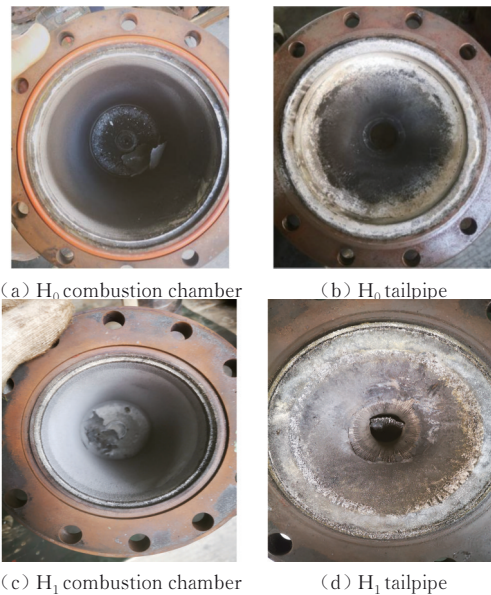
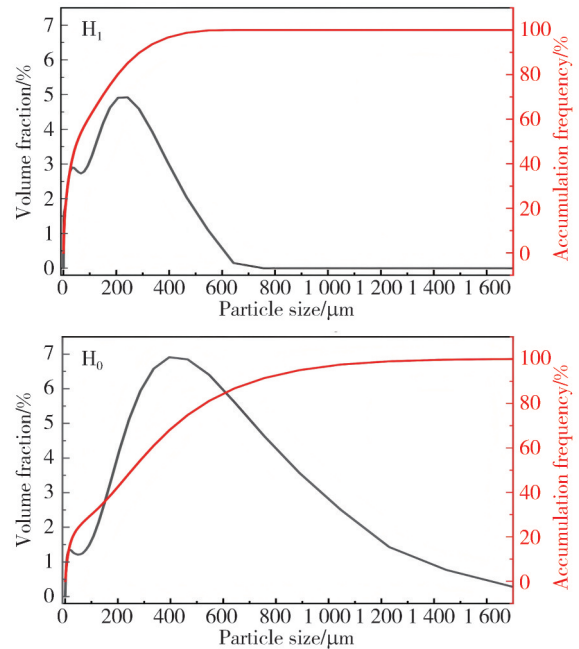


Fig. 5 Physical picture of Φ118 engine after test

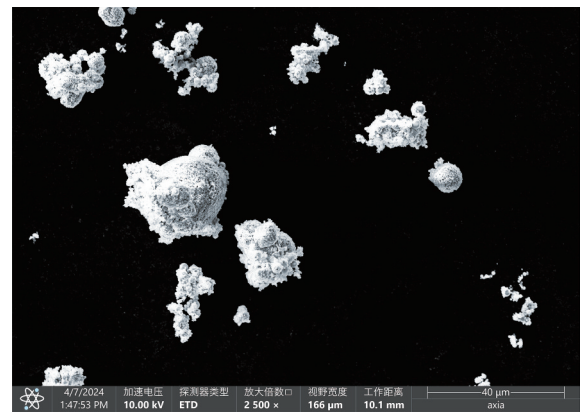
From the data in Table 4 and Fig.5, it can be seen that there are black granular residues in the combustion chamber of H₀ solid propellant containing ordinary aluminum powder, with a residue mass fraction of 3.88% and an active aluminum with a mass fraction of 6.14%. The mass, particle size and active aluminum content of the residues are relatively high, indicating that when the mass fraction of aluminum powder is 16%, the aluminum powder in the propellant is not completely burned. After adding HTPB solid propellant with Al@AP instead of Al, the whole combustion chamber is grayish white, and there are no large black granular substances left in the combustion chamber as

shown in Fig.5(c) and (d). The mass fraction of the residue is reduced from 3.88% to 2.10%, the mass loss rate is 45%, and the mass fraction of active aluminum in the residue is greatly reduced with only 2.57%.

By testing the particle size of the residue, it can be seen from the H₁ particle size distribution curve in Fig.6(a) that the particle size distribution of H₁ propellant residue is narrow and the particle size is mainly distributed in the range of 0.5–600 μm, and there is almost no residue with a particle size greater than 600 μm, and the d_{50} is 62 μm, d_{90} is 291 μm.



(a) H₀, H₁ Particle size distribution diagram of propellant residues



(b) SEM image of H₁ propellant residue

Fig. 6 Particle size distribution diagram and SEM image of propellant residues

It can be seen from Fig. 6(b) that the residue of H_1 propellant has no obvious large particle agglomeration phenomenon, and the particle size of the residue is concentrated in several tens of microns, which is consistent with the particle size tested. The particle size distribution of H_0 propellant residue is wide, showing a bimodal distribution, and the residue distribution range is wide, ranging from $0.8 \mu\text{m}$ to $1\ 600 \mu\text{m}$, and the d_{50} is $298 \mu\text{m}$, d_{90} is $643 \mu\text{m}$. where d_{50} refers to the size of the test sample when the cumulative percentage of the size distribution reaches 50%, and d_{90} refers to the particle size of the test sample when the cumulative particle size distribution reaches 90%. The results show that the particle size d_{50} of H_1 residue is significantly lower than that of H_0 , the particle size d_{50} of residue decreases from $298 \mu\text{m}$ to $62 \mu\text{m}$, and the particle size of H_1 residue is reduced by 80%.

The residue test results show that the addition of Al@AP could reduce the amount of HTPB propellant residue, reduce the active aluminum content in the residue, and significantly reduce the particle size of condensed phase products during propellant combustion. This may be because in the process of burning surface recession, the unique structure of the Al@AP composite enables uniform accumulation of gaseous decomposition products from AP around the molten aluminum, so as to effectively prevent aluminum powder from being entangled together after melting, and finally lead Al to fully combust to form oxide residues with smaller particle sizes, thereby improving the combustion efficiency of aluminum powder in the propellant and improving the phenomenon of incomplete combustion of HTPB solid propellant.

2.2.5 Technological and mechanical properties

The mechanical properties of HTPB solid propellant containing Al@AP composite fuel at 20, 70 and -40°C and the technological properties of HTPB solid propellant at 60°C were tested. The test results are shown in Tables 5–7. It can be seen from Table 5 that the 20, 70 and -40°C temperature tensile strength of HTPB solid propellant containing Al@AP composite fuel is high, and the maximum elongation (ϵ_m) is low. This is because the structural changes at the interfacial bonding zone in the Al@AP composite material and the existing design parameters cannot be directly applied to the propellant formulation system containing Al@AP composites. The mechanical properties of HTPB propellant could be subsequently optimized by adjusting formulation parameters. According to the process performance test data in Tables 6 and 7, the viscosity of HTPB solid propellant containing Al@AP composite fuel first decreases and then

slowly increases within 3 h, and the viscosity of 3 h is $219 \text{ Pa}\cdot\text{s}$. The leveling time of HTPB solid propellant slurry at 60°C is more than 30 min, and the dispersion coefficient is 1.53, which indicates that the addition of Al@AP composite fuel can meet the application requirements of HTPB solid propellant slurry in its applicable period.

Table 5 Mechanical properties of HTPB solid propellant

Sample	20 °C, 100 mm·min ⁻¹		70 °C, 2 mm·min ⁻¹		-40 °C, 100 mm·min ⁻¹	
	σ_m/kPa	$\epsilon_m/\%$	σ_m/kPa	$\epsilon_m/\%$	σ_m/kPa	$\epsilon_m/\%$
H_0	1 357	40.2	782	34.9	2 705	33.1
H_1	1 722	34.3	1 136	32.6	3 158	37.3

Table 6 Process properties of H_1

Sample	Time/h	Viscosity/(Pa·s)
H_1	0	204
	1	179
	2	203
	3	219

Table 7 Dispersion coefficient of H_1

Sample	Time/min	Radius/mm	Dispersion coefficient
H_1	5	29.5	1.53
	10	32.5	
	20	35.5	
	30	37.0	
	40	38.0	
	50	38.0	

2.3 Preliminary study on combustion mechanism

Based on the morphology characterization and combustion performance test of Al@AP composite fuel and its influence on the properties of HTPB solid propellant, such as explosion heat, combustion efficiency, and residue, the combustion mechanism of Al@AP in HTPB solid propellant was analyzed. As shown in Fig. 7, the Al@AP micro-unit composite fuel is formed by combining oxidizer and fuel, where each Al@AP unit can be regarded as an independent combustion cell. In the Al@AP composite structure, aluminum particles are encapsulated within AP crystals, achieving uniform distribution at the micro-mesoscopic scale. In the process of propellant burning surface retreat, the segregation of aluminum powder caused by “pocket” model distribution is avoided. At the same time, the micro-cell structure avoids the separation of Al and AP caused by the preparation process of propellant, so that the oxidant AP and fuel Al powder directly contact after ignition, which greatly increases the surface contact area between them and effectively shortens the diffusion path of oxygen atoms. Furthermore, it promotes the mutual diffusion efficiency of oxygen-rich and fuel-rich areas in the propellant combustion flame, so that the oxygen-rich and fuel-rich areas in the combustion system can be

homogenized faster, and the combustion efficiency of metal fuel can be improved, thus improving the combustion efficiency of solid propellant^[16].

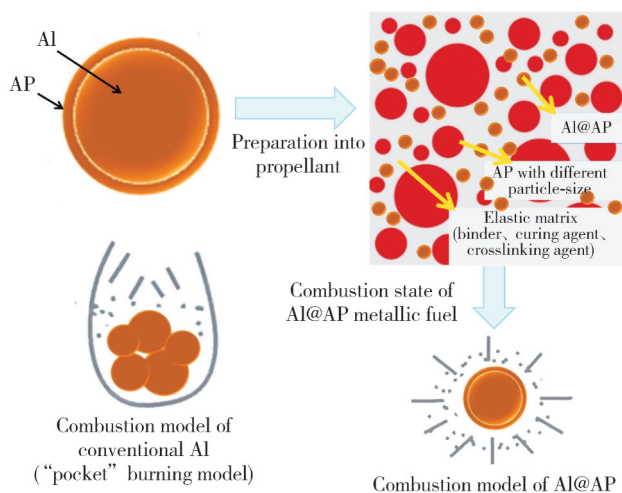


Fig. 7 Schematic diagram of combustion mechanism

3 Conclusions

The Al@AP micro-cellular composite fuel has higher energy release efficiency, increasing the heat of combustion by 12.75% from $17,153 \text{ J} \cdot \text{g}^{-1}$ to $19,340 \text{ J} \cdot \text{g}^{-1}$ compared to the physically blended specimen.

After replacing Al and part of AP with the Al@AP with mass fraction of 21.3%, the heat of explosion of HTPB solid propellant increased from $7,385 \text{ J} \cdot \text{g}^{-1}$ to $7,834 \text{ J} \cdot \text{g}^{-1}$, which is 6.1% increase; the amount of residue decreases by 1.78% in mass, and the content of activated aluminum in the residue decreases from 6.14% to 2.57%, and the HTPB propellant is stably combusted at 7 MPa, with an increase in combustion efficiency from 94.0% to 94.6%.

The special composite structure of Al@AP makes the oxygen-rich and fuel-rich areas of the flame in the combustion system reach homogenization faster, and alleviates the phenomenon of molten aluminum powder in the fuel-rich area via the “pocket” combustion model. Compared with the HTPB propellant with ordinary aluminum powder, a reduction of 80% in residual particle size d_{50} and a reduction of 3.57% in active aluminum residue are achieved.

The mechanical and technological properties of HTPB propellant containing Al@AP meet the application requirements.

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Declaration of conflicting interests

The authors have no conflict of interests related to this

publication.

References

- [1] MAGGI F, DOSSI S, DELUCA L T. Combustion of metal agglomerates in a solid rocket core flow. *Acta Astronautica*, 2013, 92(2): 163-171.
- [2] LIU M Y, XU C E, HUANG H X, et al. Characterization of final condensed phase products in solid rocket motors. *Rocket Propulsion*, 2024, 50(3): 90-101.
- [3] PANG A M, Ma X G, Tang C Z. Theory and engineering of solid rocket propellant. Beijing: China Astronautic Publishing House, 2014.
- [4] BABUK V A, Vassiliev V A. Propellant formulation factors and metal agglomeration in combustion of aluminized solid rocket propellant. Beijing: China Astronautic Publishing House, 2014. BABUK V A, VASSILIEV V A, SVIRIDOV V V. Propellant formulation factors and metal agglomeration in combustion of aluminized solid rocket propellant. *Combustion Science and Technology*, 2001, 163(1): 261-289.
- [5] SON S F, YETTER R, YANG V. Introduction: nanoscale composite energetic materials. *Journal of Propulsion and Power*, 2007, 23(4): 643-644.
- [6] WANG H Y. Electrospray formation of nano energetic materials and characterization of the combustion properties. Nanjing: Nanjing University of Science and Technology, 2015.
- [7] ZHANG T T, JIANG Y Q, HUO W L, et al. Preparation and combustion performance of AP@Al composites. *Solid Rocket Technology*, 2024, 47(6): 803-814.
- [8] LEVITS V I, MCCOLLIM J, PANTOYA M, et al. Pre-stressing micron-scale aluminum core-shell particles to improve reactivity. *Scientific Reports*, 2015, 5(1): 7879.
- [9] YAN J W, QU W C, DU F, et al. Preparation and properties of aluminum based core-shell material AP/Al. *Chinese Journal of Explosives & Propellants*, 2024, 47(3): 271-278.
- [10] HU Y H, TAO B W, HAO D Y, et al. Fabrication and mechanistic study of AP/nAl/PTFE spherical encapsulated energetic materials with enhanced combustion performance. *Chemical Engineering Science*, 2020, 222: 115701.
- [11] YANG S L, NIE H Q, YAN Q L. Preparation and thermal reactivity of AP@Al/Ni composite fuel. *Chinese Journal of Energetic Materials*, 2022, 30(7): 648-658.
- [12] WANG Q C, ZHU B Z, SUN Y L, et al. Thermal reaction characteristics and ignition combustion characteristics of nano-aluminum powder coated with ammonium perchlorate in carbon dioxide. *The Chinese Journal of Process Engineering*, 2017, 17(2): 271-277.
- [13] XIE P N, LIAO X Q, ZHANG W K, et al. Effect of aluminum content on the ignition and combustion characteristic of HTPB propellants. *Journal of Fire Explosives*, 2025, 48(3): 238-245.

- [14] LI D L, ZHANG W Q, XU S Y, *et al.* Research on laser ignition performance of AP/HTPB/Al composite propellant under low-pressure. *Journal of Propulsion Technology*. <http://kns.cnki.net/kcms/detail/11.1813.V.20241119.2333.006.html>.
- [15] AO W. Analysis of the current status of solid propellant condensed-phase combustion products and recommendations. *Journal of Fire Explosives*, 2023, 46(7): 553-556.
- [16] WANG H S, ZHANG X, WANG Y W, *et al.* Application of aluminum-based composite fuel in NEPE solid propellant. *Chinese Journal of Energetic Materials*, 2022, 30(8): 819-825.

铝基微单元复合燃料在HTPB推进剂中的应用

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摘要: 为研究铝基微单元复合燃料(Aluminum@ammonium perchlorate, Al@AP)在端羟基聚丁二烯(Hydroxyl-terminated polybutadiene, HTPB)固体推进剂中的燃烧性能,以Al@AP代替铝粉和部分AP加入HTPB固体推进剂,采用爆炸测试系统、绝热式氧弹量热仪测试、标准试验发动机试验、残渣活性铝测试、粘度测试、单向拉伸试验等手段研究了Al@AP的点火响应、能量性能以及其对HTPB固体推进剂燃烧、工艺、力学性能的影响,并对Al@AP在HTPB固体推进剂中的燃烧机理进行了分析。结果表明:Al@AP复合材料比简单物理混合具有更快的点火响应速度。以21.3%的Al@AP代替铝粉后,HTPB固体推进剂的爆热由 $7\,385\text{ J}\cdot\text{g}^{-1}$ 升至 $7\,834\text{ J}\cdot\text{g}^{-1}$,残渣的质量分数由3.88%降至2.10%,残渣中活性铝含量由6.14%降至2.57%,残渣粒径 d_{50} 由 $298\text{ }\mu\text{m}$ 降至 $62\text{ }\mu\text{m}$,HTPB固体推进剂燃烧效率提升,由94.0%升至94.6%,且含Al@AP的HTPB推进剂力学、工艺等性能满足应用。

关键词: Al@AP复合燃料; HTPB固体推进剂; 燃烧性能

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