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Design, fabrication and characterization of electrically controlled solid microthruster

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Abstract
In the current research, the formula of the electrically controlled solid propellant (ECSP) composed of oxidizer, adhesive, crosslinking agent, and other functional additives was determined, and the laboratory preparation process of the propellant was proposed. The electrically controlled solid microthruster was designed and assembled, and the combustion test system of the microthruster was built. The ignition delay time, energy required for ignition, mass loss, extinguishment delay time and thrust were taken as the performance indicators of the microthruster, and the influences of Al content on the microthruster under different loading voltages were studied. The results show that when the content of Al is too low, the ignition cannot be ignited at 150V, and the combustion performance is unstable.

1. Introduction

Micro-nano satellite has the characteristics of functional specificity, small size, and short research cycle and has been widely used in aerospace fields. Its attitude control and orbit transfer require precise thrust and impulse provided by the micro propulsion system [1-2]. By applying/removing voltage and changing the voltage, the electrically controlled solid propellant (ECSP) can realize multiple ignition and extinguishment and thrust adjustment of the microthruster, providing an intelligent power source for micro/nano satellites [3-4]. Compared to traditional solid rocket propellants, ECSPs are not throttleable, toggleable, or insensitive to external ignition sources and expands the potential applications for solid propellants that were previously infeasible [5]. Recently, a series of electrically controlled solid propellants have been developed and extensive research has been conducted on their combustion and decomposition performance[7-11]. Raytheon has developed and tested true on/off/restart solid propellant thrusters which are controlled only by electrical current. This new class of energetic rocket propellant is safe, controllable and simple [5,12]. In the current research, an electrically controlled solid microthruster was designed and its performance under different aluminum contents was tested. The results may throw some light on its application in the field of small satellites.

2. Experiment

2.1 Composition of propellants and preparation of microthrusters

Aluminum powder (Al) has the advantages of large specific surface area, high combustion enthalpy, and low oxygen consumption. It is widely used in solid propellants to increase burning rate, combustion temperature, and specific impulse, which can further enhance the stability of solid propellant combustion. Therefore, a certain amount of aluminum powder particles (5 μm) is added to the formula in order to explore the effect of aluminum content on the performance of electrically controlled solid micro thrusters, with aluminum powder mass fractions of 7%, 8%, 9%, and 10%. The detailed formulations used in this study are shown in Table 1.

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Table 1: Propellant formulations with different Al contents

No.	HAN（%）	AN（%）	Al（%）	PVA（%）	HB（%）
1	73.15	3.85	7	15	1
2	72.2	3.8	8	15	1
3	71.25	3.75	9	15	1
4	70.3	3.7	10	15	1

The preparation process of electrically controlled solid microthrusters is shown in Figure 1. The device used is a vacuum mixer (ZKJ-3 type) with a 250 mL stirring cup, with a vacuum degree of less than 5 kPa during stirring and a stirring speed of 270 rpm · min-1. Due to the fact that the entire propellant preparation process is carried out in an approximate vacuum, there are fewer bubbles in the propellant, which can effectively improve the performance of the propellant grain.

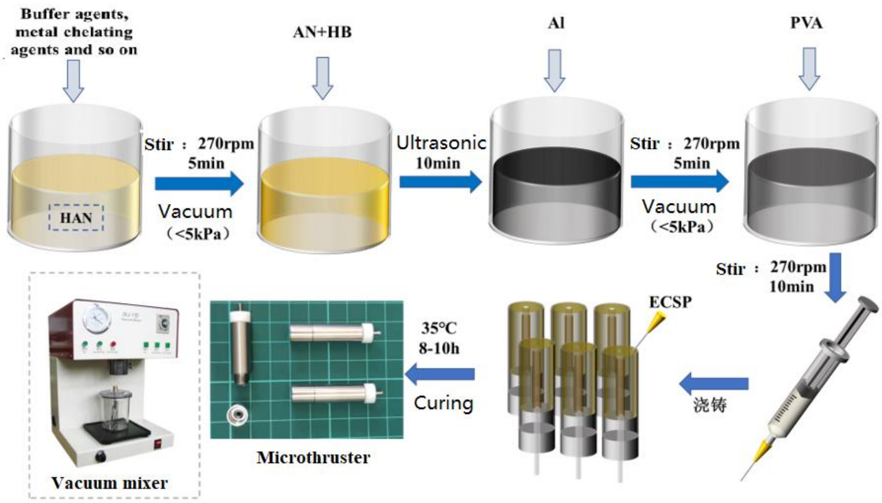

Figure 1: Preparation procedure of the microthrusters

2.2 Morphological characterization of the propellant

In order to understand the internal morphology of the propellant grain prepared by the above process, the propellant grain was prepared using the PTFE mold with the same structure. Field emission scanning electron microscope (FESEM, Quanta 400 FEG) was used to characterize the internal cross-section morphology of the propellant, and X-ray micro computer tomography was used (μ-CT, nanoVoxel-2700) to characterize the three-dimensional microstructure inside the propellant. The SEM morphology of the internal cross-section of the solidified electrically controlled solid propellant is shown in Figure 2 (a). The mixed solution is fully swelled in adhesive PVA, and there is no agglomeration of other large particles except Al particles. Figure 2 (b) shows the μ-CT images of the microthruster, the components of the propellant inside the micro thruster are tightly combined, and there are almost no bubbles inside. The propellant prepared by this process can meet the requirements.

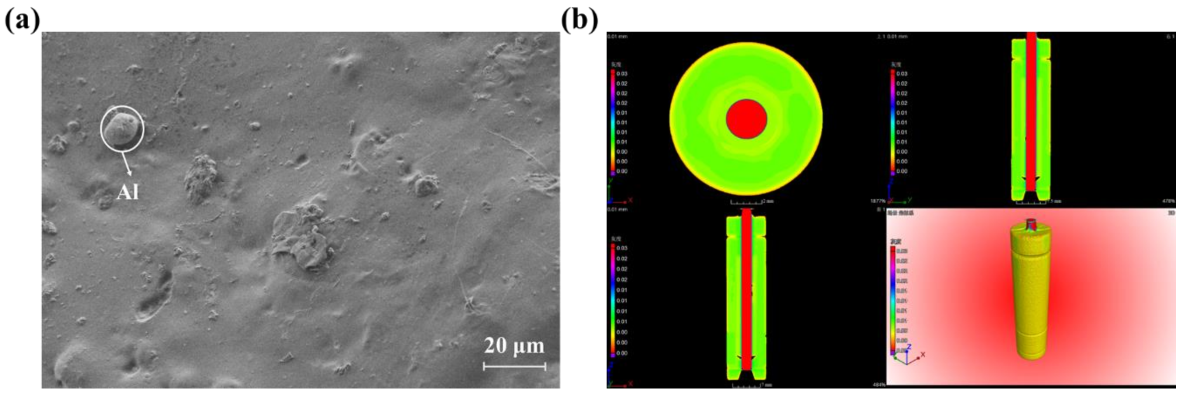

Figure 2: SEM image of internal propellant (a) and overall μ- CT image (b) of the microthruster

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3. Result and Discussion

Figure 3 shows the ignition delay time and ignition energy required for the microthruster with different Al contents. It can be observed that under low loading voltage, the ignition delay time of the electrically controlled micro thruster is higher, and the energy required for ignition is also higher. As the voltage increases, the ignition delay time and energy required for ignition rapidly decrease. When the addition amount is 7%, the microthruster cannot be ignited, so there are no relevant data points. Taking 150 V and 250 V as examples, when the loading voltage is 150 V and the Al content increases from 8% to 10%, the ignition delay time and ignition energy required decrease from 212 ms and 25.9 J to 174.4 ms and 20.3 J, respectively. When the loading voltage is 250 V and the Al content increases from 7% to 10%, it decreases from 17.4 ms and 13.4 J to 5.4 ms and 6.9 J. The higher the Al content, the faster the propellant releases a large amount of heat after being ignited at low voltage, shortening the ignition time and reducing the required ignition energy. High voltage can increase enough energy, so the Al content has little effect on ignition.

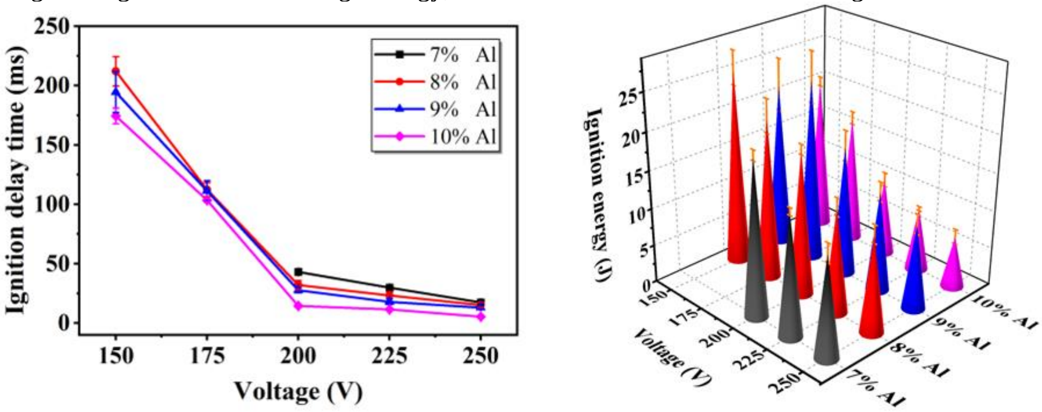

Figure 3: Ignition delay time and ignition energy required for the microthruster with different Al contents

Figure 4 shows the mass loss and extinguishment delay time of the microthrusters under different Al contents. The combustion performance of the microthrusters is greatly affected by the Al content, as shown in Figure 4, where there is a significant difference in mass loss. When the Al content is between 7% and 9%, the propellant is difficult to ignite, resulting in a significant reduction in mass loss. However, when the addition amount is 10%, it can ignite smoothly at 150 V to 250 V, resulting in significant mass loss. From previous research, it can be seen that the ignition delay time of the microthrusters that are easy to ignite will correspondingly decrease. This is because the accumulation of heat decreases, making it easier to extinguish. Taking the loading voltage of 250 V as an example, when the addition amount increases from 7% to 10%, the mass loss increases from 166.6 μg/J increased to 213.3 μg/J, while the extinguishment delay time decreased from 18.3 ms to 7.8 ms. In addition, as the voltage increases, the mass loss and extinguishment delay time both decrease. This is because high voltage provides higher external energy, and the single working process of the microthruster is shorter, resulting in relatively less propellant ablation. Figure 5 shows the combustion process diagram under different Al contents. It can also be seen that as the Al content increases, the flame brightness, length, and flame area also become larger.

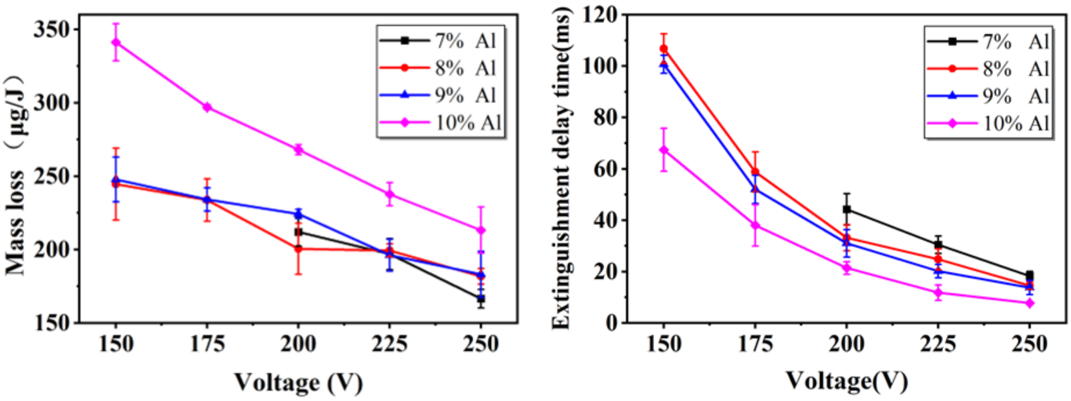

Figure 4: Mass loss and extinguishment delay time of the microthruster under different Al contents

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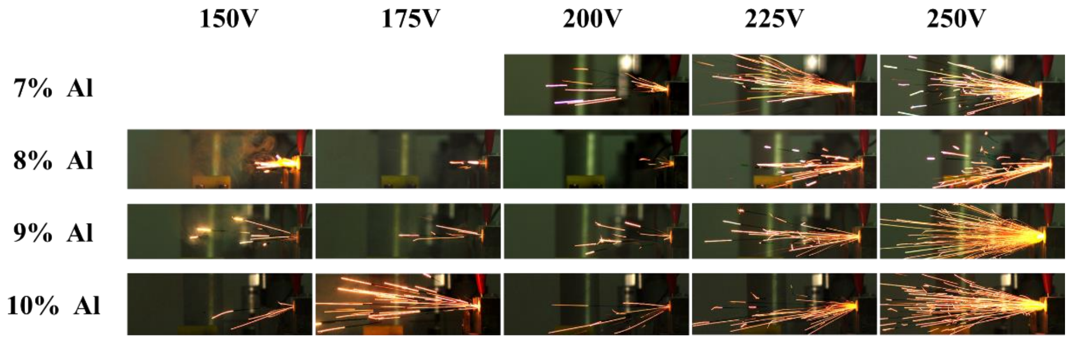

Figure 5: Combustion process the of microthrusters under different Al contents

The thrust variation of the microthrusters under different Al contents was studied using a microthrust testing platform, as shown in Figure 6. The thrust of the electrically controlled microthrusters increases with the increase of Al content and voltage. When the addition amount is 7%, the thrust is relatively small. This is because the Al content is too low, and the microthrusters cannot burn normally, resulting in less gas produced during combustion. When the addition amount is 10%, the thrust shows a certain pattern with voltage. At a loading voltage of 250 V, as the addition amount increases from 8% to 10%, the thrust increases from 172.5 mN to 203.9 mN. When the amount of Al added is too low, the propellant cannot be ignited at the corresponding voltage, and the electrically controlled microthrusters cannot work. Even if ignited at high voltage, the generated thrust will be very small, and the amount of Al powder added will also affect the performance of the microthruster. As Al is a high-energy component, when the amount of Al added is too high, it will make the propellant unable to ignite repeatedly. Therefore, based on previous experiments, it can be seen that when the amount of Al added is 10%, the comprehensive performance of microthrusters is good.

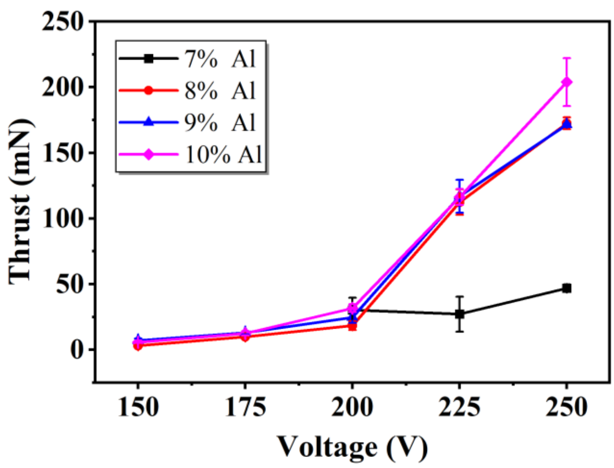

Figure 6: Thrust of the microthrusters with different Al content

4. Conclusion

The effect of Al content on the electrically controlled solid microthrusters was studied in detail. The results indicate that as the voltage increases, the ignition delay time and energy required for ignition rapidly decrease. Taking the loading voltage of 250 V as an example, when the Al content increases from 7% to 10%, the ignition delay time and ignition energy required decrease from 17.4 ms and 13.4 J to 5.4 ms and 6.9 J. The combustion performance of the microthrusters is greatly affected by the Al content. When the Al content is between 7% and 9%, the propellant is difficult to ignite, resulting in a severe reduction in mass loss. When the addition amount ranges from 7% to 10%, the mass loss ranges from 166.6 µg/J increases to 213.3 µg/J, while the extinguishment delay time decreased from 18.3 ms to 7.8 ms. As the addition amount increased from 8% to 10%, the thrust increased from 172.5 mN to 203.9 mN.

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