COMBUSTION CHARACTERISTICS OF A MICRO-SOLID PROPELLANT ROCKET ARRAY THRUSTER

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Abstract

We are developing a micro-solid propellant rocket array thruster for simple attitude control of a 10 kg class micro-spacecraft. The prototype has ϕ 0.8 mm solid propellant micro-rockets arrayed at a pitch of 1.2 mm on a 22 × 22 mm substrate. In previous studies, an impulse thrust of 4.6×10^{-4} Ns was obtained in vacuum, but we found the problems of unacceptably low ignition success rate and incomplete combustion. This paper describes experiments to improve the ignition rate. In order to achieve this goal, we tried to solidify paste-like ignition aid (RK) on the ignition heaters with strong adhesion. To make the paste-like RK, isoamyl acetate was added to RK powder. We tested 9 rockets, but only 2 rockets were ignited with huge ignition energy. This is because the heat conduction between the ignition heater and the RK was too low to ignite the RK, since dried RK had a lot of pores. Also, a large cavity was sometimes found just above the ignition heater.

1. Introduction

The weight of spacecrafts has increased approximately 5-10 times in the past 20 years, and has reached over 1 ton. The launch of heavy spacecrafts is performed using massive rockets, and costs colossally. Therefore, miniaturization of spacecrafts has distinguished advantages in 1) decreasing launch costs, 2) shortening development time, 3) increasing mission reliability by the redundancy of spacecrafts, and 4) networking the spacecrafts for cooperation working. In order to miniaturize spacecrafts and open up a new area in space technology, micro-electromechanical system (MEMS) technology plays a key role. In 1995, the National Astronautics and Space Administration (NASA) of the U.S.A. implemented "New Millennium Program" to dramatically miniaturize spacecrafts. The goals of this program include the development of a micro-spacecraft with weight of about 10 kg or less. This can be achieved by the miniaturization of its components, especially using MEMS technology.

Recently, several micro-solid propellant rocket array thrusters composed of many one-shot solid propellant micro-rockets arrayed on a substrate are developed for the attitude control of micro-spacecrafts[1-7]. These micro-solid propellant rocket array thrusters have following advantages: 1) The system is completed on a substrate and compact. 2) Solid propellant has no anxiousness of leakage, unlike gas or liquid propellants. 3) The thruster has no moving parts. 4) The system is highly redundant. 5) The thrust is controlled digitally by adjusting the numbers of micro-rockets ignited.

We are developing the micro-solid propellant rocket array thruster for simple attitude control of a 10 kg class micro-spacecraft. In this paper, we first describe our recent achievements and problems found in a series of experiments. After that, some trials to solve the problems are reported.

2. Structure

The micro-thruster has ϕ 0.8 mm solid propellant micro-rockets arrayed at a pitch of 1.2 mm on a 22 × 22 mm substrate. Figures 1 and 2 show the micro-solid propellant rocket array thruster and its cross-sectional structure, respectively. It consists of three layers. The first silicon layer has nozzles (Fig. 3) and ignition heaters (Fig. 4) on diaphragms. The diaphragm, which bursts away after ignition, thermally insulates the ignition heater, and also seals a solid propellant. The second glass layer contains the solid propellants, and the third one covers them. The first and second layers are anodically bonded, and then, the solid propellants are inserted from the second layer. Finally, the second and third layers are bonded using adhesive.

In this study, we selected boron/potassium nitrate propellant (NAB), because NAB has low ignition temperature, and can burn in vacuum. ϕ 0.7 × 1 mm NAB pellets shaped using a punch and dice are inserted to the propellant cylinders. Lead rhodanide/potassium chlorate/nitrocellulose (RK) is used to facilitate ignition.

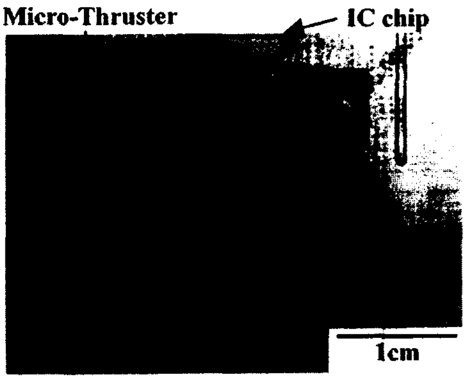

Fig. 1 Micro-solid propellant rocket array thruster

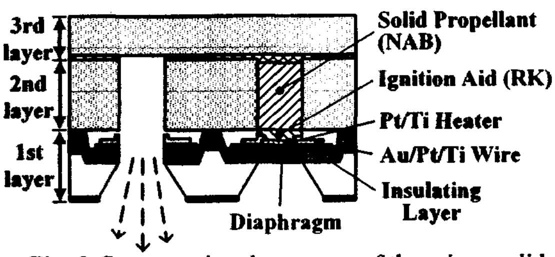

Fig. 2 Cross-sectional structure of the micro-solid propellant rocket array thruster

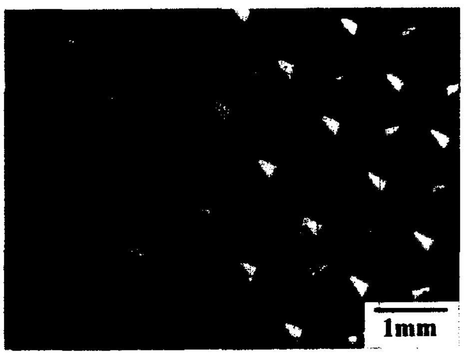

Fig. 3 Fabricated nozzles

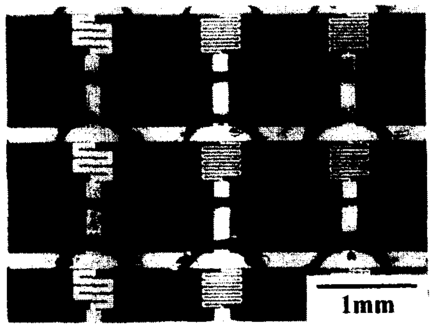

Fig. 4 Ignition heaters

3. Achievements and Problems in Previous Studies

We have performed the vacuum tests of the micro-solid propellant rocket array thruster in the previous studies[7]. We used an IC chip for ignition control, and the whole system worked successfully. The maximum obtained impulse was 4.6 x 10^{-4} Ns, which is approximately a half of our target (Fig. 5).

On the other hand, we have faced two problems. The first one is unacceptably low success rate of ignition, which was approximately 20 % with NAB, and 30 % with NAB + RK. Although high success rate of ignition has been reported in air[5], it is more difficult to ignite propellant in vacuum.

The difficulties are summarized as follows. 1) Only selected propellant can be ignited and combusted in vacuum. HTPB/AP and GAP are normally used as propellant, but a combustion chamber should be pressurized by the combustion of an ignition aid to ignite them. NAB can be ignited in vacuum, but its combustion characteristics in a submillimeter cylinder are not clear. 2) Heating a propellant through air is not expected in vacuum, thus good thermal contact between the propellant and heater is important.

The second problem we have found is incomplete combustion. Solid propellant still remained inside the propellant cylinder after combustion. This could be due to fast depressurization in the propellant cylinder after the diaphragm is burst away. This is more serious in vacuum than in air.

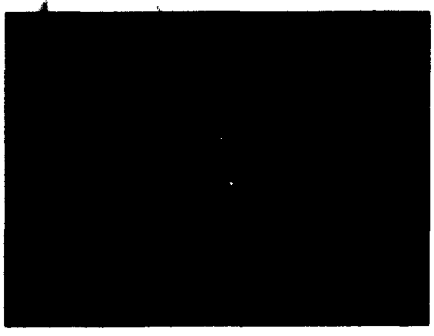
Fig. 5 Combustion scene in vacuum

As mentioned, there are several problems found in vacuum. In this study, we focused on improving the success rate of ignition, because we think this is the critical problem that we first need to overcome.

We think that the problem of low success rate of ignition is mainly due to unstable contact between the ignition heater and ignition aid, RK. In the previous study, we covered the ignition heater with powdered RK, and then inserted a NAB pellet on the RK. After that, we pushed the NAB pellet to make close contact between the ignition heater and RK. We think that this propellant loading method needs to be improved as shown in Fig. 6. In the new method, paste-like RK is solidified on the ignition heater with strong adhesion, and the NAB pellet is inserted in the propellant cylinder, touching softly on the RK. In this method, the heat conduction from the ignition heater to the RK improves, and also low power ignition would be realized because the heat capacity is dominated by the amount of the RK, not by the total amount of the propellant (RK + NAB).

In order to demonstrate the validity of this method, we tried to make paste-like RK and loaded it in cylinders drilled on a transparent plastic plate for observation using a microscope. Next, combustion test using the micro-thruster was performed in vacuum.

4. Combustion Test

Isoamyl acetate was added to RK powder to make the paste-like RK. The RK powder is dispersed in isoamyl acetate, and it looks like slurry. The slurry-like RK was inserted in cylinders of 0.8 mm in diameter and 1 mm in depth drilled on the transparent plastic plate. Observation was performed from the backside of the plate using an optical microscope. Figure 7 shows a representative example of the loaded RK. The slurry-like RK was dried in contact with the bottom of the cylinder, but a lot of pores were found in the RK. The RK loaded in this method was served for the combustion test.

Figure 8 shows an experimental setup for the combustion test. The micro-thruster is in a vacuum chamber, and a high-speed camera (MEMRECAMfx K3, NAC) records combustion scene.

We tested 9 rockets by applying ignition power of 3-6 W, and 2 rockets were ignited. For ignition, one thruster needed 5 W for 13 s (65 J), and the other needed 6 W for 1.4 s (8.4 J). These ignition energies were too large compared to those in the previous tests (several to several tens mJ).

Because the loaded RK was highly porous and was not bonded with the ignition heater, heat conduction between the ignition heater and the RK was too low to ignite the RK. Also, a large cavity was sometimes found just above the ignition heater as shown in Fig. 9. In order to insert the propellant as shown in Fig. 6, further study is needed. A kind of propellant, the diameter of propellant powder, a kind and amount of binder and dispersion medium, and the propellant loading method should be systematically reconsidered.

In the series of experiments, we have met another problem that the micro-thruster was broken as shown in Fig. 10. From calculation, we found that the maximum tolerable transmembrane pressure of the diaphragm can reach anodic bonding strength, if anodic bonding is not strong. In such a situation, the first and second layers separate from each other. This can sometimes trigger sympathetic detonation, resulting in the destruction of micro-thruster as shown in Fig. 10. The area of nozzle throat, the thickness of diaphragm, the area of bonding between the first and second layers, and the amount of RK should be tuned in order to avoid the destruction of the micro-thruster.

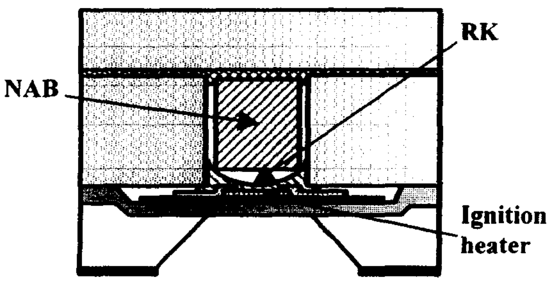

Fig. 6 New propellant loading method

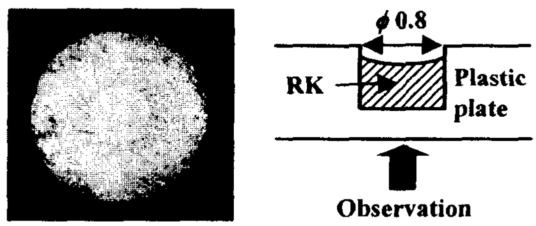

Fig. 7 RK inserted in ϕ 0.8 mm cylinders drilled on a transparent plastic plate

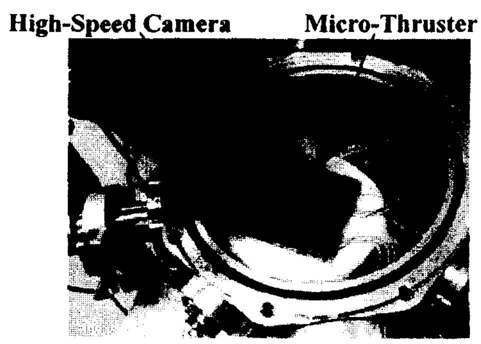

Fig. 8 Experimental setup for combustion test

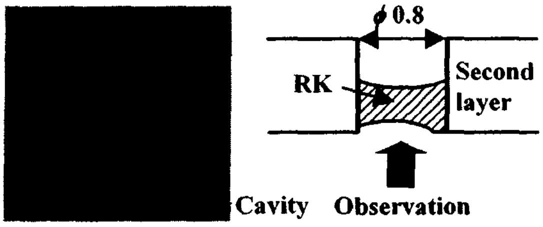

Fig. 9 RK observed from the backside of the second layer separated from the first layer

Fig. 10 Destruction of the micro-thruster

5. Conclusion

We are developing a micro-solid propellant rocket array thruster for simple attitude control of a 10 kg class micro-spacecraft. The prototype has ϕ 0.8 mm solid propellant micro-rockets arrayed at a pitch of 1.2 mm on a 22 × 22 mm substrate.

In previous studies, an impulse thrust of 4.6×10^{-4} Ns was obtained in vacuum, but we found the problems of unacceptably low ignition success rate and incomplete combustion. This paper describes experiments to improve the ignition rate. In order to achieve this goal, we tried to solidify paste-like ignition aid (RK) on the ignition heaters with strong adhesion. To make the paste-like RK, isoamyl acetate was added to RK powder.

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The micro-thruster was sometimes broken in combustion tests. We found that the maximum tolerable transmembrane pressure of the diaphragm could reach anodic bonding strength, if anodic bonding is not strong. This could result in the destruction of the micro-thruster.

Acknowledgements

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