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Development Study of 100μm-order Solid Rocket for Pico Satellite Application

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Abstract

A new 100μm-order solid rocket based on MEMS technology is proposed, built and tested in order to develop an attitude and position control system for pico-satellite. Pico satellite control requires a large number of fine impulses. Because the available number of shot of rocket array system is inversely proportional to the cross section of each rocket, the miniaturization of rocket is very important. So far great efforts have been made for 1mm-order micro rockets all over the world but their design is not applicable to 100μm-order due to the increased surface/volume ratio. Explosive propellant of high sensitivity can overcome the quenching there but the charging process becomes difficult and the possibility of unintentional firing increases. Our solution is to use spherically-synthesized DDNP (diazodinitrophenol) propellant in planar-type rocket and also to use PDMS (Poly-dimethylsiloxane) tank and membrane structure enabling its combustion even in vacuum condition, where the combustion pressure is hold by the membrane and burned gas bursts and go through it. The feasibility of this PDMS-based rocket is tested and confirmed and the obtained results of impulse and delay time are discussed with the ignition power and the propellant residue.

Keywords: MEMS rocket array, DDNP propellant, PDMS micro tank, Impulse measurement

1 - INTRODUCTION

Miniaturization of satellite brings many benefits to the total cost, development term, launch opportunity, etc. Recently many laboratories and universities all over the world are building small satellites of total mass of less than 50kg. The miniaturization of magnetic torquer and reaction wheel is straightforward from the current system but they can control only attitude but not position. In order to accomplish functional missions, high-performance-thruster onboard is desired. Especially for the control of the pico satellite of 1kg or less total mass, MEMS technology is expected to be able to build thruster but no satisfactory device has appeared yet [1-2].

So far, many kinds of MEMS-based thrusters have been designed, fabricated and tested. Considering all subsystems including valves, piping, tank, etc. the MEMS rocket array using solid propellant is the most promising system as the smallest thruster. This concept was proposed at the end of 1990s and a lot of improvement has been accomplished for the 1mm-order rocket [3-8]. On the other hand, further miniaturization of MEMS rocket up to 50μm-order was treated [9]. Because each rocket is used up shot by shot, the smaller rocket size leads to the increase of shot number and yields smaller amount of impulse, that is product of thrust force and firing duration, for more precise control of tiny satellite. However, such miniaturization causes quenching due to the increased surface/ volume ratio.

The authors [10-11] have been working on 100μm-order solid rocket in these years by using many kinds of propellant; nitrocellulose (NC), GAP (Glycidyl Azide Polymer), HMX, RDX, HTPB/AP/AL, PETN (Pentaerythritol Tetranitrate), lead styphnate, DDNP, etc. After such preliminary tests, it is concluded that the normal propellants other than explosives do not work in a 100μm-order tank as long as the ignition energy is limited. On the other hand, the explosive powder often causes unintentional ignition and difficult handling. It was already reported by the authors that the unique synthesis technique of spherical DDNP improves the handling issue. However, the DDNP combustion was also found to need high combustion pressure due to its pretty low sensitivity, which means that special techniques are required if it is used in vacuum environment.

This paper reports some breakthroughs for this DDNP propellant to use in 100μm-order rocket application in space. Membrane structure is applied for pressure keeping and PDMS is used for the tank material. The idea to use polymer for tank was already reported by the authors. The polymer's characteristics of low shock impedance and low thermal conductivity (0.17W/mK) are expected to work to prevent unintentional firing of array rocket. PDMS has another possible advantage that its good adhesion and flexibility

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prevent the gas leakage from tank. Here the detail of micro rocket structure is explained. The experimental results are discussed for the applicability of PDMS and directions of future improvement.

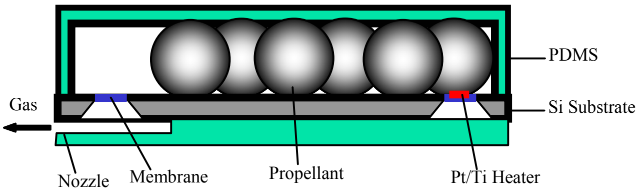
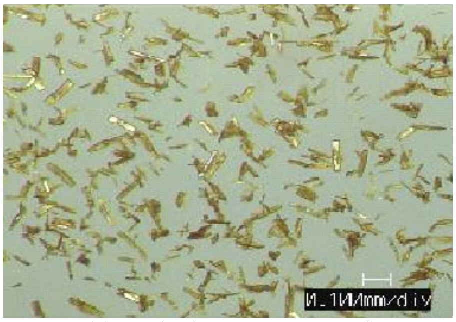
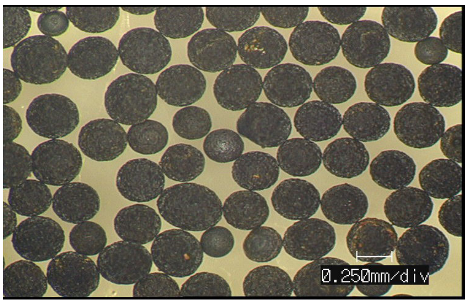


Figure 1 – Schematic of the proposed micro rocket using DDNP propellant and PDMS tank and nozzle. The height of tank is designed slightly shorter than the diameter of DDNP balls.



(a) Spicular DDNP crystal



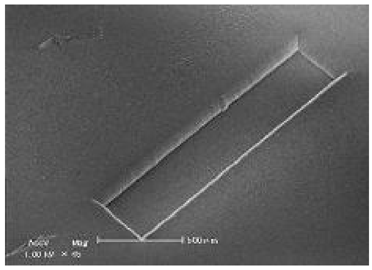
(b) Spherically-synthesized DDNP

Figure 2 – Microscopic image of the original DDNP crystal (a) and specially synthesized DDNP balls (b). The diameter of this DDNP can be set from 80 to 500µm.

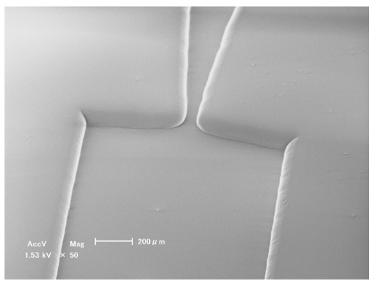
2 - DESIGN AND FABRICATIOM

A schematic of our micro rocket is shown in Fig. 1. Planar configuration is employed here mainly because the ignition and combustion can be observed. This configuration also enables tiny rockets of higher aspect ratio to be set in a very high number density, which is favorable for the demand that a huge number of shots are preferred to be available for satellite control. PDMS tank keeps the spherical DDNP propellant (Fig. 2) fastened due to its flexibility by making the tank height shorter than the propellant diameter. Its adhesion to the silicon substrate helps to prevent gas leakage during combustion. By using soft lithography technique, PDMS copies the micro structure of deep-reactive etched silicon substrates and tank and nozzle are formed on each side of a thin PDMS plate as seen in Fig. 3. The tank size is 400µm x 2000µm x 150µm for DDNP balls of 180µm diameter set in two rows, which turns to use constant propellant mass (70µg) resulting in uniform impulse at every shot. So far the nozzle configuration is not optimum because the burned gas condition is not fixed.

Two membranes made of silicon nitride of 300nm thickness are fabricated, one of which keeps the burned gas not to run away almost until the end of combustion and the other is for thermal insulation of ignition heater. The former membrane has area of 600µm x 600µm and confirmed to open perfectly in every operation. The latter one is set underneath the igniter to reduce the ignition power but was found to sometimes collapse at the propellant charging. So that crashed DDNP powder is applied only on the igniter membrane in the current study. Lead styphnate is also available just there. Pt/Ti heater for igniter is fabricated by lift-off method, whose size is 100µm x 400µm.



(a) PDMS tank



(b) PDMS nozzle

Figure 3 – SEM image of micro tank and nozzle made of PDMS using soft-lithography method. The nozzle is not optimum just for test. The tank is for DDNP of 180µm diameter charged in two lines.

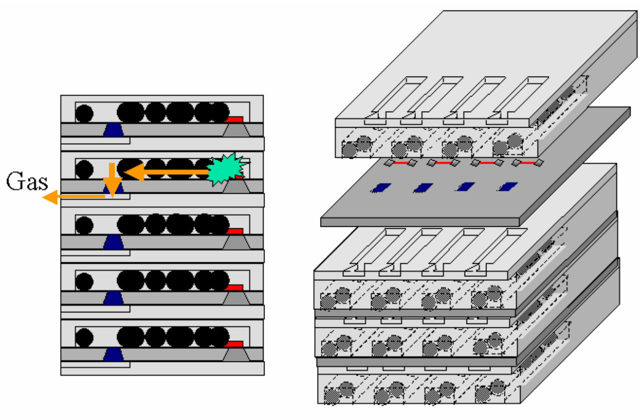


Figure 4 – 3D view of micro rocket array. The combustion starts at the igniter and propagates producing high-temperature gas which bursts the upstream membrane. The gas goes through the bulk-etched silicon substrate and PDMS nozzle and then thrust is yielded.

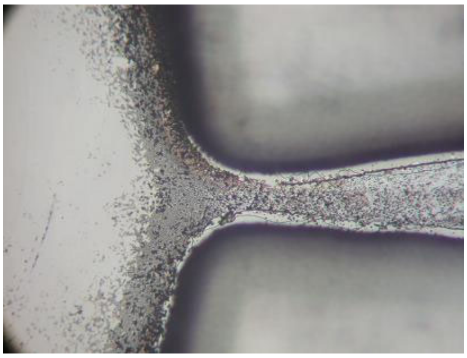


Figure 5 – Microscopic image of the nozzle after firing test. The throat is not clogged and also other part of PDMS structure is not damaged.

3 - EXPERIMENT

The sequence of rocket operation is also explained in the left picture in Fig. 4. The Pt/Ti heater ignites DDNP propellant and combustion propagates in the tank. The upstream membrane bursts due to the increased tank pressure and temperature. The burned gas goes through the broken membrane and nozzle. Two kinds of tests are conducted. One is for feasibility study on some concerned issues; membrane opening, effect on the other rocket, durability of PDMS. The other is to evaluate the rocket performance; ignition energy, delay time and obtained impulse.

3.1 - Feasibility test

By using a test chip of three-layered rockets, the feasibility of this rocket array design was tested. All three rocket tanks were charged with DDNP propellant and only the middle rocket was ignited. It was confirmed that the propellant in other two tanks are not affected. Both tank and nozzle of the ignited rocket were observed after firing but no damage was found and their original shape was hold as seen in Fig. 5. From these experiments, the feasibility of our design of micro rocket array is confirmed.

3.2 - Performance test

Impulse was measured by using a pendulum with high speed camera after a single rocket was set in acrylic plates as listed in Fig. 6. Obtained impulses and ignition delay time were 1.44μNs and 0.03s when applying 1.0W to the igniter and 0.82μNs and 1.1s delay when 0.5W. The lower ignition power yields lower impulse and longer delay. The post-firing observation of micro tank is shown in Fig. 7, which means the higher ignition power lefts smaller amount of propellant residues and produces more volume of gas jet. By the way, the effect of membrane for thermal insulation of igniter was also tested, where 11.3W and 0.61s of delay was found necessary for ignition without membrane structure.

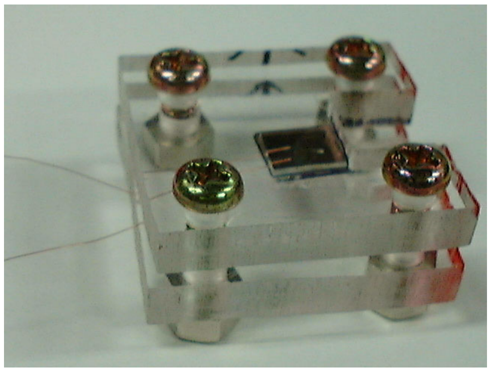
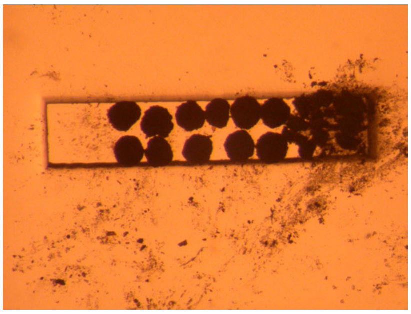


Figure 6 – Setup device for thrust measurement. The micro rocket is sandwiched by two acrylic places, which are pressed by screws to prevent burned gas leakage.

4 - DISCUSSION AND CONCLUDING REMARKS

For the feasibility of PDMS, the short duration of the explosive combustion helps a lot. However, such quick reaction causes shock-triggered ignition of other rocket. We suppose that the low shock impedance of PDMS prevents this problem. The extremely lower thermal conductivity of PDMS tank than glass and silicon also has advantage when the shot repeats in short period. The pretty low sensitivity of DDNP compared with lead styphnate is also favorable for the micro rocket array of high number density.

The obtained impulse data in dependent on the ignition power is reasonable and helps us to redesign this rocket according to the satellite mission. The rocket performance is planned to improve by changing the design of nozzle and membrane. For example, the residue in tank means that smaller area of membrane is better to keep the pressure in longer time. However, the degraded performance compared with the large solid rocket is not so concerned because this is the first success of practically-available 100μm-order rocket. As the next step, smaller rocket array using lower ignition power is under development.



(a) DDNP balls in PDMS tank before ignition

(b) PDMS tank after ignition of 0.5W power

(c) PDMS tank after ignition of 1.0W power

Figure 7 – Photographs of the tank before and after firing. The crashed propellant is used near the igniter (a). The amount of residuals in (b) and (c) is found dependent on the ignition power.

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