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Design, fabrication and test of a solid propellant microthruster array by conventional precision machining

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ABSTRACT

Prototypes of 10 × 10 and 100 × 100 scale solid propellant microthruster(SPM) array were fabricated with conventional precision machining, due to restriction on the manufacture of large-scale microthruster array with present MEMS manufacturing technique. The microthruster consists of ignition circuit layer, ignition powder layer, propellant layer, cavity layer and nozzle layer. Row–column driving control plan was applied in ignition circuit to realize simultaneous ignition and reduce the number of wires. The solid propellant was AP-HTPB pellet propellant with a diameter between 100 μm and 200 μm. A test to choose proper ignition powder was performed among black powder, modified back powder and self-made ignition powder, which demonstrated the reliability of self-made ignition powder and realize 100% ignition success rate. In the mean time, a measurement of ignition resistor's surface temperature was taken to determine ignition delay, together with numerical simulation and ignition resistor fusing test. Thrust was also measured for the 10 × 10 scale microthruster array, and the results show that the specific impulse is much lower than calculated result, so a more comprehensive numerical model is in need to depict the working process of a single SPM. The test also demonstrates the feasibility of large-scale solid propellant microthruster array's fabrication by conventional fabrication methods.

1. Introduction

Future space missions will rely on micro/nano spacecrafts to adjust attitude or orbits, so a propulsion system will be a necessary requisite [1–3]. Current propulsion systems are either too large, or need so much power that micro/nano spacecraft cannot afford. The micro/nano spacecrafts require a propulsion system to deliver low thrust values and impulse in short time [4]. Compared to other micro propulsion techniques, the solid propellant micorthruster has advantages of simple structure, high reliability, no frictional forces inherent to moving parts, no leakage of propellant and high propellant stability [5–7]. The major disadvantages are its low specific impulse and one-shot use, which can be mitigated by adopting an array of multiple microthrusters fabricated on a baseplate.

Relevant techniques of SPM arrays have been systematically studied in US, France, Singapore, Japan, South Korea and Canada [8–11]. Whereas, most of their research was aimed at the fabrication and the test on small scale SPM arrays with MEMS techniques, of which the thrusters on each array were no more than 100. MEMS fabrication method is suitable for mass fabrication, but the procedure of MEMS fabrication method is more complicated compared to conventional fabrication methods. Conventional fabrication methods such as laser drilling and mechanical drilling have advantages of fewer procedures and flexibility when re-design is in need. Another advantage of conventional fabrication is that the materials feasible for fabrication are varied, while only a few materials, like silicon, can be etched by applying MEMS techniques. Our work mainly focuses on the feasibility of large scale array fabrication, so we will use conventional methods to fabricate SPM arrays, which has been shown to be feasible in small scale SPM array fabrication [12]. Future space missions using micro/nano spacecrafts will need larger scale SPM arrays, so our work mainly focuses on fabrication, control system and the test of SPM arrays with 100 and 10,000 microthrusters to verify the performance of the SPM arrays and the feasibility of large scale SPM array fabrication with conventional methods.

2. Structure of the array

2.1. Structure of single thruster

A single SPM is composed of ignition circuit layer, ignition powder layer, propellant layer, cavity layer and nozzle layer, and the nozzle outlet is sealed with cover. Most SPM array proto-

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Nomenclature

φ_c	Pressure fluctuation coefficient
P_{max}	Maximum pressure in combustion chamber
D_{tc}	Diameter of the combustion chamber
$[\sigma_{tc}]$	Allowable stress
$[\epsilon_{tc}]$	Allowable strain
E_{tc}	Young's modulus
ϵ_r	Surface emitting rate
σ_0	Stefan Boltzmann constant
T_r	Radiation temperature
T_b	Real temperature
T_a	Atmospheric temperature
ρ	Density of the ignition resistor's materials
c	Specific heat of the ignition resistor's materials
λ	Thermal conductivity of the ignition resistor's materials
a_p	Pre-exponential factor of burning rate pressure exponent
n_p	Burning rate pressure exponent
T_f	Flame temperature of propellant combustion
r_p^0	Propellant powder's initial radius
ρ_p	Propellant density
r_p	Propellant powder's radius
ρ_c	Gas density in combustion chamber
p_c	Pressure in combustion chamber
r_b	Burning rate
k	Specific heat ratio
M_p	Propellant mass in the combustion chamber of each SPM
S	Burning surface area of solid propellant pellets in each SPM
Γ	A single valued function about specific heat ratio
R_0	Gas Constant
M	Molecular weight of gas
c^*	Characteristic velocity

types developed by researchers in the past are fabricated with MEMS processing techniques. Each layer is fabricated with conventional precision machining. The processing precision lies between 0.01 mm and 0.1 mm, which meets the demand for punching a micro hole with a diameter between 0.3 mm and 1.5 mm. At first laser drilling was selected as the drilling method, but the ablation effect will burn the edge of the wall, as is shown in Fig. 1, so mechanical drilling was actually applied then for fear that the ablation effect may reduce the wall strength of a single SPM and affect bonding of layers.

By applying high precision mechanical drilling methods with the help of CNC, fabrication of more than 1000 micro holes is feasible with high efficiency in one-time processing. The unpunched layer is fixed by a fixture assembly, then a reference position is set in the computer. According to the reference position, the first hole is punched. The punched hole is then used as the next reference for the next hole to be punched, so SPMs and alignment holes can be punched on all layers. Combining digital control technology to position each hole on the plate precisely, each layer of the SPM array can be fabricated.

The structure of a single SPM is shown in Fig. 2.

2.2. Material selection

Materials that have been applied to fabricate a SPM array mainly consist of silicon, machinable ceramic and photosensitive glass.

In our research, we chose epoxy resin as the material to fabricate the SPM array. Epoxy resin has perfect heat insulation property, of which the disadvantage is low strength. Therefore, strength checking is essential in the process of design.

2.3. Ignition powder and propellant

The ignition device of the SPM is a resistor. Due to the tiny scale of the heating surface, proper ignition powder with high sensitivity and high specific energy is requisite. The burning rate of the ignition powder should also be high enough to afford adequate energy releasing rate to efficiently ignite the propellant. AP-HTPB solid propellant was chosen as the tested propellant.

2.4. Structure design of the array

On the demand of fabricating large scale array and due to the restriction of fabricating methods, a multi-layer structure and a bottom ignition plan are applied. Our research mainly focuses on the feasibility of large scale array fabrication with conventional methods, so we chose a simple straight nozzle to substitute for a laval nozzle. On the premise that the heat loss and viscous loss are neglected, the thrust coefficient of the straight nozzle is 1.

According to existing research findings, no undesirable ignitions of neighboring thrusters are observed during the working process of a single thruster, when the wall material is MACOR® ceramic with a thickness of about 1 mm [6]. So it is believed that due to the better heat insulation property of epoxy resin compared with MACOR® ceramic, undesirable ignition will not happen to our SPM array with the same wall thickness. Whereas, a strength checking is essential to make sure that our SPM's wall thickness is enough to withstand high pressure in the combustion chamber.

Designed value of pressure in normal solid rocket motor's combustion chamber should lie between 7 MPa and 20 MPa to maintain the combustion of propellant, so we chose a value in this range, 12 MPa to decide the wall thickness. The minimum wall thickness was solved according to Eqs. (1) and (2).

$$\delta_{min} = \frac{\varphi_c P_{max} D_{tc}}{2.3\,[\sigma_{tc}] - \varphi_{tc} P_{max}} \quad (1)$$

$$[\sigma_{tc}] = E_{tc}[\epsilon_{tc}] \quad (2)$$

Epoxy resin is an isotropic material, so$E_{tc}$is considered equal to its Young's modulus, whose value is 34.138 GPa. The value of $[\sigma_{tc}]$ is 34.138 MPa, with $[\epsilon_{tc}]$'s value set to 0.001. The value of φ_c is set to 1.2. The value of D_{tc} is 1 mm. Accordingly, the value of δ_{min} is calculated to be 0.2246 mm. For safety and heat insulation reasons, the wall thickness was set to 1 mm, which means that the minimum distance between two neighboring SPMs is 1 mm.

3. Ignition system

The ignition system is used to control the thruster ignition and the ignition sequence, as is shown in Fig. 3.

3.1. Ignition circuit layer

Most relative research facilities have realized the ignition of a single SPM by separated ignition circuit. Whereas, it is difficult to apply the circuit layout to large scale situations. For instance, an array consisting 10,000 SPMs need 10,000 circuits, which is hard to fabricate. To achieve the ignition of a large scale SPM array and combine it with the row–column addressing control method, a circuit was designed. Ignition resistors with a resistance value of 2 Ω were used to heat ignition powders to ignition temperature, which were laid at the bottom of the ignition layer of an SPM array, so the