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Performance evaluation and thermography of solid-propellant microthrusters with laser-based throttling

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A B S T R A C T

Among propulsion devices, conventional solid-propellant thrusters require neither a tank nor a valve and therefore have relatively high reliability and simple structures. However, the interruption and restarting of thrust production in solid-propellant thrusters is difficult because combustion is autonomously sustained after ignition. Hence, we propose a new solid-propellant microthruster that can be throttled through laser heating. The proposed thruster uses a combustion-controllable hydroxyl-terminated poly butadiene/ammonium perchlorate-based solid propellant, wherein combustion is maintained only while the burning surface is heated using a semiconductor laser. In this study, thrust was measured at various laser-head traverse velocities to enhance the performance of the prototype. Moreover, propellant holders were fabricated from polycarbonate (PC) and polymethyl methacrylate (PMMA) because the melting point of PC is higher than that of PMMA, which could increase the local pressure in the interface between the propellant holder and the solid propellant and consequently reduce ignition delay. The prototype microthruster with the PMMA propellant holder yielded a thrust of 0.06 N and I_{sp} efficiency of 70% at a laser power density of 0.83 W/mm^2 and produced stable thrust at laser-head traverse velocities ranging from 0.85 to 0.95 mm/s, whereas that with the PC propellant holder exhibited unstable thrust in all tests. Firing tests showed an ignition delay of approximately 3 s and yielded a peak in P_c after ignition. Temperature profiles measured through thermography revealed that the burning-surface temperature was dependent on the laser-head traverse velocity and propellant-holder material. For stable combustion, the burning-surface temperature would be kept constant at 1040 K, an ignition temperature was 1250 K in vacuum, and one-half the ignition delay (1.5 s) is the time required for heating the burning surface to the ignition temperature.

1. Introduction

The relatively low development cost and short development period of microsatellites have rendered them attractive and feasible for, for example, universities and startup companies, who have developed microsatellites and have inserted them into Earth orbit [1–3]. For example, on December 3, 2014, three microsatellites were launched with the Asteroid Explorer Hayabusa2 by the H-IIA Launch Vehicle No. 26 [4]. PROCYON, one of the three piggyback satellites, was equipped with xenon cold gas jet thrusters for attitude control and an ion propulsion system for trajectory control [5]. There are some microsatellites using cold gas jet thrusters [6,7]. However, most microsatellites do not use thrusters but are instead equipped with momentum wheels (MWs) or magnetic torquers (MTQs) for attitude control. Although MWs and MTQs function appropriately in space, thrusters are still necessary to unload the MW and to execute complex missions such as formation flying and making high-precision observations. Thrusters for microsatellites should ideally be sufficiently reliable, compact, and throttleable. Hence, our research group has focused on a solid-propellant thruster that has a relatively simple and compact structure and thus high reliability. Conventional solid-propellant thrusters, however, have never been applied for attitude control or station keeping for spacecraft because of difficulties in throttling, including in the initiation and interruption of thrust production.

To develop a throttleable solid-propellant microthruster, we have previously proposed the application of a combustion-controllable solid propellant and compact, light-weight semiconductor lasers to thrusters, wherein thrust production is started and sustained by laser heating on the solid-propellant surface and

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Nomenclature

L^*	Characteristic length of combustion chamber	m	T	Temperature	K
v	Laser-head traverse velocity	mm/s	T_s	Burning-surface temperature	K
t	Time (time origin is the moment of initiation of laser heating)	s	T_o	Solid-propellant temperature at $x = \infty$	K
P_b	Backpressure	MPa	c_p	Specific heat of solid propellant	J/kg
P_c	Combustion chamber pressure	MPa	λ_p	Thermal conductivity of solid propellant	W/mK
I_{sp}	Specific impulse	s	ρ_p	Density of solid propellant	kg/m^3
r	Burning rate	mm/s	δ	Thermal-wave thickness	μm

interrupted by switching off the laser heating. In our previous study, strand burner tests showed that for hydroxyl-terminated poly butadiene (HTPB)/ammonium perchlorate (AP)/carbon black (C) = 30/70/0.5 wt%, combustion can be started and interrupted by switching the laser at a backpressure range of 0.01–0.58 MPa [8]. We found that burning rate is dependent on backpressure (Fig. 1): at backpressures of 0.18–0.3 MPa, the burning rate is low and the flame flickers, whereas the combustion is stable at backpressures less than 0.18 MPa. Hence, in our previous study, a 0.1-N class thruster with a target combustion chamber pressure P_c of 0.03 MPa was designed to realize stable combustion [9]. The prototype thruster, which had a polymethyl methacrylate (PMMA) propellant holder, yielded a P_c of 0.03 MPa, thrust of 0.02 N, specific impulse I_{sp} of 95.3 s, and I_{sp} efficiency (the ratio of experimental to theoretical I_{sp}) of 46% [9]. The ignition delay was approximately 3 s, and the P_c peaked after ignition.

In this study, thrust was measured at various laser-head traverse velocities to enhance I_{sp} and to reduce the ignition delay and P_c peak. In addition to the PMMA propellant holder, a polycarbonate (PC) propellant holder was used because the melting point of PC is higher than that of PMMA, which could increase the local pressures in the interface between the propellant holder and the solid propellant and consequently reduce the ignition delay. Subsequently, to clarify the dependence of the propellant-holder material and laser-head traverse velocity on ignition delay, thrust production stability, and peak combustion chamber pressure, the temperature profiles of the burning solid propellant were measured through thermography.

2. Prototype 0.1-N-class microthruster

Fig. 2 illustrates the 0.1-N prototype microthruster, which has a combustion chamber pressure of 0.03 MPa. Two propellant holders composed of PMMA and PC, which effectively transmit the laser beam, were fabricated and filled with a combustion-controllable solid propellant. The propellant was adhered to the inner wall of the propellant holder without any voids or gaps, because adhesion to the wall reduces ignition delay as laser heating through the propellant holder results in the development of local pressure in the interface of the propellant holder and the solid propellant. A laser head was connected to a fiber-coupled semiconductor laser via an optical fiber. During laser irradiation, the laser head was traversed using a linear traverser and a stepper motor at velocities of 0.7–0.95 mm/s, which were approximately equal to the burning rate and thus ensured that the laser beam followed the regressing burning surface. This design allowed the laser beam to continually and effectively heat the burning surface of the regressing solid propellant and reduced laser-power attenuation due to solid combustion products because propellant adhesion to the propellant holder prevented the combustion products from entering the laser-head area.

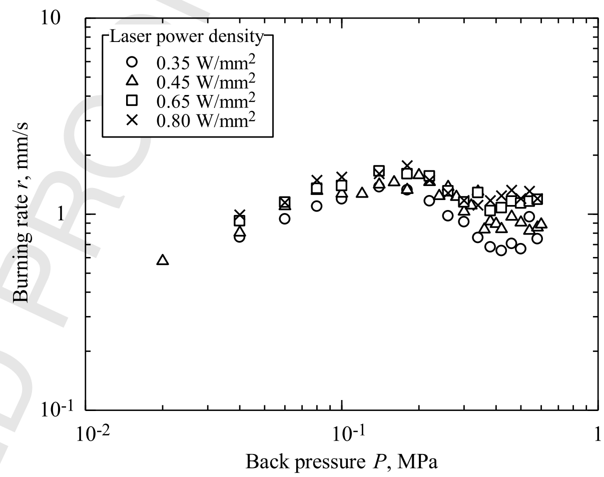

Fig. 1. Dependence of burning rate on backpressure at HTPB/AP/C = 30/70/0.5 wt%. (Reference [8]).

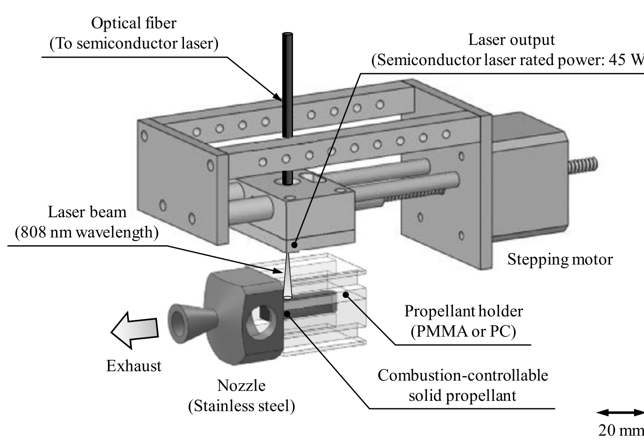

Fig. 2. Prototype 0.1-N-class microthruster.

2.1. Combustion-controllable solid propellant

An HTPB/AP-based composite solid propellant was used because of its relatively high I_{sp}. A fuel-rich propellant with HTPB/AP/C = 30/70/0.5 wt% was used in the prototype thruster because our previous study showed that when using this propellant, combustion can be started and interrupted by switching on and off the laser heating, respectively, at backpressures of 0.03–0.58 MPa [8]. Moreover, 0.5 wt% carbon black powders were added to effectively absorb the near-infrared laser beam. The diameters of the AP particles and carbon black powders were <100 and 50 μm, respectively. To prepare the solid propellant, propellant slurry was filled in a 20-mm-deep propellant-holder hole of cross-section 5 × 5 mm^2. To correspond with the laser beam diameter (5.18 mm), the width at the upper surface of the propellant was set to 5 mm. According