Performance Evaluation of Combustion-controllable 0.1-N-Class Solid Propellant Microthrusters Using Laser Heating*  
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Conventional solid-propellant thrusters do not require tanks or valves and, accordingly, have high reliability and simple structures. Nevertheless, thrusters have not been applied to the attitude or station control of satellites because of problems with throttling. We therefore propose a new combustion-controllable, solid propellant microthruster using laser heating. The proposed thruster uses combustion-controllable, hydroxyl-terminated polybutadiene/ammonium perchlorate solid propellant where combustion is maintained only while the burning surface is heated with a laser. Therefore, combustion is started and stopped by switching the laser heating. In a previous study, laser-switching was used to start and stop thrust production. Stable thrusts and combustion chamber pressures with a thrust and specific impulse $I_{sp}$ of 0.02 N and 95 s, respectively, were obtained. However, firing tests showed an ignition delay of approximately 3 s. In this study, to shorten the ignition delay, the diameter of carbon black (C) used to absorb the laser beam was reduced from 50 to 20 µm. Thrust measurements showed that a $\phi$20-µm C produces a shorter ignition delay and 120-s-class $I_{sp}$ by adjusting the laser-head traverse velocity.

Key Words:  Microthruster, Solid Propellant, Combustion Control, Laser Heating

1. Introduction  
The Japanese space industry has seen significant developments over the years, from the 23-cm-long Pencil Rocket to the H-IIB rocket, which has a launch capability of 16.5 t and is approximately 110 times larger than the 150-kg L-2 rocket.1) While many massive spacecraft have been launched, microsatellites have also attracted considerable attention because of their lower cost and shorter development period. Since 2013, the number of commercial microsatellites has increased considerably, and their development has shifted from the research stage to the application stage.2)  
Microthrusters are lightweight and low cost and have high reliability. To realize more complex microsatellite missions, microthrusters are necessary for orbit transfer and attitude control. However, most microsatellites do not have thrusters because conventional thrusters are not preferable for the following reasons.  
Conventionally, liquid-propellant thrusters have been used for orbit transfer and attitude control because they can be readily throttled by adjusting the propellant flow rate or pulsing duration. However, they are not appropriate for some microthrusters because they require both a tank and a valve. In contrast, solid-propellant thrusters are more compact and lightweight because they do not require either a tank or a valve. Moreover, these thrusters are relatively reliable because they never induce propellant leakage. However, combustion is autonomously sustained once they are ignited, leading to difficulty in the starting and interruption of combustion. Hence, solid-propellant thrusters have rarely been used for orbit transfer and attitude control.3)  

We developed a combustion-controllable solid propellant, in which the combustion is sustained only when energy is supplied to the burning surface by adjusting the mixture ratio. Then, we proposed a 0.1-N-class thruster using the developed solid propellant and a semiconductor laser as the heat source. In a previous study, we showed that combustion can be controlled using a laser,4) and a prototype thruster can produce a stable thrust of 0.02 N and specific impulse $I_{sp}$ of 95 s. Moreover, the prototype showed restart capability: the combustion was interrupted by switching off the first laser heating, and afterward, the second laser heating restarted combustion.5)  
However, the prototype yielded an ignition delay of 3–5 s.6)  
Accordingly, to reduce the ignition delay, the carbon black (C) diameter was reduced from 50 to 20 µm so that the laser beam could be absorbed effectively. Moreover, thermography was conducted on the solid-propellant surface under laser irradiation to clarify the reason that the ignition delay depended on the C diameter.

2. Prototype 0.1-N-Class Thruster  
2.1. Thruster design  
Figure 1 shows a schematic of the prototype microthrus-
The prototype has a relatively simple structure consisting of a nozzle, propellant holder, and semiconductor laser. The top surface of the solid propellant is irradiated by the laser through a laser-introducing window made of polymethyl methacrylate (PMMA).

The linear traverser moves the laser head such that the regressing burning surface is kept heated. The laser head is initially placed above the nozzle end of the solid propellant. During irradiation, the laser head is moved at a constant speed by the linear traverser so that the laser head follows the regressing burning surface, and the laser-head traverse velocity \( v \) ranges from 0.7 to 1.5 mm/s.

### 2.2. Solid propellant

Hydroxyl-terminated polybutadiene (HTPB)/ammonium perchlorate (AP, less than 100 µm in diameter) composite solid propellant was used. The mixture ratio was HTPB/AP = 30/70 wt%, with which combustion can be controlled at back pressures lower than 0.58 MPa by switching the laser on and off.\(^7\) C was added to absorb laser beams effectively by 0.5 wt%. The carbon black ratio was not optimum, while the previous study showed that 0.5 wt%– and 5 wt%– C propellants were combustion controllable when using a laser.\(^4\)

Since theoretical specific impulse increases when reducing the carbon black ratio, the carbon black mixture ratio was set at 0.5 wt%. In preparation, HTPB/AP/C slurry was filled in a propellant holder made of PMMA and cured for seven days in a thermostat. As a result, the propellant adhered to the PMMA window without a gap. In this study, the C diameter was varied from 50 to 20 µm to reduce the ignition delay. The theoretical \( I_{sp} \), calculated using Chemical Equilibrium with Applications\(^8\) was 204.5 s at a target combustion chamber pressure of 0.03 MPa and nozzle area ratio of 50 for the frozen flow.

### 2.3. Semiconductor laser

A 45-W-rated semiconductor laser with a wavelength of 808 nm (JOLD-45-CPXF-1L) was used as the heat source to both initiate and sustain combustion. Figure 2 illustrates a typical laser power profile at a distance of 13 mm from the laser head. This figure shows that the laser provided a total power of 30 W, an average laser power density of 0.93 W/mm\(^2\), and a beam diameter of 6.6 mm (1/e\(^2\)). Based on these results, the solid-propellant width was set at 5 mm to ensure that the top surface of the propellant was entirely heated. Therefore, the propellant shape was a 5 × 5 × 20 mm\(^3\) rectangular parallelepiped.

### 2.4. Nozzle and combustion chamber

The nozzle was a stainless-steel de Laval nozzle, which had a cross-section of 0.79 mm\(^2\), an expansion ratio of 50, and a characteristic length \( L^* \) of 3.0 m. The target combustion chamber pressure and target thrust were determined to be 0.03 MPa and 0.1 N, respectively, because the solid propellant yielded stable combustion below 0.18 MPa.\(^7\)

The intermittent combustion was attributable to laser attenuation caused by the combustion products. The measurement showed that laser transmissivity decreases as the combustion chamber pressure increases; 68.3% at 0.1 MPa and 47% at 0.4 MPa.

### 3. Experimental Evaluation

#### 3.1. Vacuum chamber

The prototype was examined in a stainless-steel vacuum chamber with dimensions of 320 × 320 × 320 mm\(^3\), as shown in Fig. 3. The ambient back pressure was maintained below 1.0 kPa during firing owing to the rotary-pump evacuation.

#### 3.2. Thrust stand

The thrust was evaluated using a pendulum-type thrust stand set in the vacuum chamber. The thrust was determined based on the pendulum displacement, which was measured using a laser-displacement sensor with a 1.5-µm spatial resolution. The thrust stand was calibrated by pushing the pendulum using a load cell and then measuring the reference force applied.

The specific impulse was evaluated using the propellant consumption for a single firing and thrust impulse that was calculated by integrating thrust with time. The propellant consumption was calculated using the combustion period and the weight difference of the propellant holder through the firing.
3.3. Pressure sensor

The combustion chamber pressure was evaluated using a pressure sensor (SICK, PBT Pressure Transmitter). The pressure measurement port was located on one side of the combustion chamber surface, and the pressure was measured using a 50-mm-long tube with a 1-mm inner diameter. This approach was utilized so that the sensing element of the pressure sensor was not directly exposed to the flame, because the pressure sensor would be thermally damaged by combustion gas without the tube. The pressure histories were used to determine the ignition delay, which is generally defined as the period from ignition (i.e., the start of laser irradiation) to the moment when the combustion chamber pressure increases to 10% of the peak value. Both the signals from the pressure sensor and the laser displacement sensor of the thrust stand were recorded using a desktop computer at a sampling rate of 25 Hz.

3.4. Experimental setup for thermography

To investigate the influence of the C diameter on the ignition delay, thermography was conducted on the solid-propellant surface with laser irradiation using a far-infrared ray thermography camera (FLIR Systems, T620) set to a spatial resolution of 25 µm. The solid propellant was fixed on a strand burner and a collimated laser beam was aimed at the propellant end, as shown in Fig. 4. The back pressure was varied by adjusting the nitrogen flow rate. To simulate the combustion chamber before ignition, the back pressure was maintained below 1.0 kPa.

Thermography measurements were conducted through a germanium window with a transmittance of approximately 42% in the far-infrared region, implying that the thermography camera indicated temperatures that were lower than the actual values. Therefore, the camera was calibrated using a thermocouple heated with a nickel-chromium coil heater.

4. Experimental Results

4.1. Thrust history and stability

Figure 5 shows the time histories of the thrust and combustion chamber pressure for φ50-µm C at a laser head traverse velocity \( v = 1.1 \text{ mm/s} \). The time origin \( t = 0 \) was defined as the moment when laser irradiation started. The solid propellant was ignited at \( t = 3.5 \text{ s} \), and the combustion chamber pressure quickly reached a maximum of 0.28 MPa. Then, the combustion was stabilized. After \( t = 7 \text{ s} \), the thrust and combustion chamber pressure were maintained at 0.07 N and 0.1 MPa, respectively. Interrupting the laser heating at \( t = 15.4 \text{ s} \) immediately extinguished the flame. The PMMA window neighboring the burnt propellant changed shape but maintained its transparency, and that next to the unburnt propellant maintained both transparency and shape. In the test, the prototype yielded an ignition delay, \( I_{\text{sp}} \), and \( I_{\text{sp}} \) efficiency of 3.5 s, 109.6 s, and 53.6%, respectively.

In contrast, combustion became unstable under some conditions. Figure 6, which was obtained at \( v = 0.7 \text{ mm/s} \), is an example. The combustion was started by laser irradiation but was autonomously interrupted despite continuous laser irradiation. Then, the combustion was reignited and quenched repeatedly. The interruption of laser heating interrupted combustion.

For φ20-µm C and \( v = 1.35 \text{ mm/s} \), the thrust and combustion chamber pressure were also stable, as shown in Fig. 7. A flame appeared immediately after laser irradiation and was stably maintained after \( t = 5 \text{ s} \). Interrupting the laser at \( t = 13.2 \text{ s} \) immediately stopped the combustion. The prototype provided an ignition delay, \( I_{\text{sp}} \), and \( I_{\text{sp}} \) efficiency of 3.5 s, 109.6 s, and 53.6%, respectively.
The stability of thrust production was affected by \( v \) and the C diameter, as shown in Table 1. For \( \phi 50 \)-\( \mu \)m C, flames appeared and disappeared repeatedly at \( 0.7 \leq v \leq 0.95 \text{ mm/s} \), and the thruster yielded stable combustion for \( v = 1.0 \text{–} 1.15 \text{ mm/s} \). However, combustion was not induced for \( v \geq 1.2 \text{ mm/s} \). In contrast, the \( \phi 20 \)-\( \mu \)m C propellant showed intermittent combustion for \( v \leq 1.0 \text{ mm/s} \), whereas the combustion was stable for \( v \geq 1.05 \text{ mm/s} \), except for \( v = 1.15 \text{ and } 1.2 \text{ mm/s} \). From these results, it can be seen that the \( v \) range for stable combustion is dependent on the C diameter.

### 4.2. Specific impulse

Figure 8 shows the dependence of \( I_{sp} \) on \( v \). For \( \phi 50 \)-\( \mu \)m C, an increase in \( v \) increases \( I_{sp} \); the maximum \( I_{sp} \) and \( I_{sp} \) efficiency were 125 s and 61.3%, respectively, at \( v = 1.0 \text{ mm/s} \), where stable combustion was obtained. For \( \phi 20 \)-\( \mu \)m C, stable combustion with the maximum \( I_{sp} \) of 119 s and \( I_{sp} \) efficiency of 58.4% was produced at \( v = 1.25 \text{ mm/s} \). Hence, \( \phi 20 \)-\( \mu \)m C is comparable to \( \phi 50 \)-\( \mu \)m C in terms of the maximum \( I_{sp} \).

### 4.3. Ignition delay

Figure 9 shows the dependence of the ignition delay on \( v \). For a given \( v \), the thruster with \( \phi 20 \)-\( \mu \)m C produced shorter ignition delays than that with \( \phi 50 \)-\( \mu \)m C.

For the \( \phi 50 \)-\( \mu \)m C propellant, the ignition delay shows a convex-downward curve with respect to \( v \), except when \( v = 0.7 \text{ mm/s} \). For the stable combustion cases, the ignition delay ranged from 2.1 to 5 s for \( v = 1.0 \text{–} 1.15 \text{ mm/s} \), whereas the shortest ignition delay (1.6 s) was obtained at \( v = 0.9 \text{ mm/s} \), at which time unstable combustion was induced. In contrast, the highest \( I_{sp} \) of 125 s was obtained with an ignition delay of 2.1 s at \( v = 1.0 \text{ mm/s} \), at which time combustion stabilized. Accordingly, there was no optimum \( v \) that simultaneously enabled a relatively high \( I_{sp} \) and low ignition delay with stable combustion.

In the case of \( \phi 20 \)-\( \mu \)m C, the ignition delay exhibited almost the same value for \( v < 0.9 \text{ mm/s} \), a monotonic increase for \( 0.9 < v < 1.1 \text{ mm/s} \), and fluctuation in the vicinity of 2 s for \( v \geq 1.2 \text{ mm/s} \). The lowest ignition delay (0.75 s) was ob-
Experimentally obtained in Section 4.3, for a given \( v \), the thruster with a \( \phi20-\mu m \) C produced shorter ignition delays than that with a \( \phi50-\mu m \) C. According to the thermography results, \( \phi20-\mu m \) C had a faster temperature rise rate. Therefore, laser heating using smaller C diameters increased \( T_c \) more rapidly to the ignition temperature of the solid propellant.

The faster temperature rise rate for \( \phi20-\mu m \) C is attributable to a thinner laser-beam penetration depth. In general, beams are attenuated in materials in an exponential manner because of the absorption and scattering that occur. When the particles in the material attenuate the laser beam, the laser penetration depth is inversely proportional to the particle diameter. Therefore, the finer C diameter reduced the laser penetration path, and accordingly, increased the temperature rise rate under laser heating. As a result, C with a smaller diameter is more effective in further reducing the ignition delay.

5.3. Reducing ignition delay and enhancing \( I_{\text{sp}} \)

Based on the results in Section 4, decreasing the C diameter from 50 to 20 \( \mu m \) did not seem to produce a clear effect on the maximum \( I_{\text{sp}} \) (126 to 119 s) or ignition delay (2.1 to 2.4 s). However, using \( \phi20-\mu m \) C can produce stable combustion with a shorter ignition delay and 120-s-class \( I_{\text{sp}} \) by adjusting the traverse velocity. That is, initially, \( v \) was set to 0.85 mm/s to obtain an ignition delay of 0.75 s, and then,
it was increased to 1.25 mm/s to produce stable combustion with $I_{sp} = 119$ s. Changing $v$ for φ50-µm C would be effective as well, but the ignition delay would be no less than 1.6 s (with the lowest value obtained at $v = 0.9$ mm/s). Accordingly, using φ20-µm C while adjusting $v$ is more effective for increasing $I_{sp}$ and reducing ignition delay. Moreover, according to Section 5.2, a finer C diameter reduces the ignition delay further without detrimentally affecting $I_{sp}$.

6. Conclusion

In this study, a combustion-controllable 0.1-N-class solid-propellant microthruster with laser heating was tested in a vacuum chamber. The main points of this research can be summarized as follows:

1. The C diameter was reduced from 50 to 20 µm, and 0.5 wt% C powder was added to HTPB/AP solid propellant to shorten the ignition delay.
2. Decreasing the C diameter from 50 to 20 µm reduced the ignition delay for a given $v$. However, there was no optimum $v$ that simultaneously enabled relatively high $I_{sp}$ and low ignition delay with stable combustion.
3. Varying the laser head traverse velocity after ignition was effective in reducing the ignition delay and producing higher $I_{sp}$ while maintaining stable combustion. With φ20-µm C, $v$ was initially set to 0.85 mm/s to obtain an ignition delay of 0.75 s, and then increased to 1.25 mm/s to produce stable combustion with $I_{sp} = 119$ s.
4. Changing $v$ for φ50-µm C provides better results; however, the ignition delay can only be reduced up to 1.6 s. Therefore, φ20-µm C is more effective than φ50-µm C.
5. The solid-propellant temperature was obtained under laser heating through thermography. The φ20-µm C propellant yielded a higher laser-heated surface temperature than the φ50-µm C propellant. Therefore, the difference in ignition delay is attributable to the discrepancy in the temperature increase rate of the laser-heated surface.

6. In future work, a finer C diameter will be used to reduce ignition delay, and the laser-head traverse velocity will be adjusted before and after ignition to increase $I_{sp}$ and reduce ignition delay.

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