Research and Development of Compact Laser Ablative Thrusters for Small Satellites

IEPC-2007-339

Presented at the 30th International Electric Propulsion Conference, Florence, Italy
September 17-20, 2007

Hirokazu Tahara*
Osaka Institute of Technology
Asahi, Osaka 535-8585, Japan

Abstract: In this study, effects of propellant species on performance of laser ablative thrusters were examined. Metals with high specific weight and high melting point are expected to generate high impulse bit. Because polymer-gels have characteristics between solid and liquid, it is considered that they have smaller melting latent heat than solid. Since materials with small melting latent heat, that is, polymer-gels, will be ablated easily and efficiently, it will result in higher impulse bit. Furthermore, a special propellant of polymer-gel, on the surface of which small carbon particles were deposited, was also prepared. Carbon particles are used in order to make transparent gel absorb laser energy. Metal propellants generated lower impulse bit than polymer propellants due to their high reflection rate. However, the impulse bit of metals was independent of laser shot number. A gel propellant generated as high impulse bit as a conventional polymer propellant PTFE although its specific weight and melting point were lower than those of PTFE. The polymer gel with carbon particles generated a high momentum coupling coefficient of 102μNs/J, and this value exceeded that of PTFE. Moreover, this propellant could generate the maximum impulse bit at the 1st shot.

I. Introduction

A laser ablative thruster generates thrust by simply utilizing ablation of solid propellants, and its construction is very simple and small. Therefore, this thruster satisfies the demand for downsizing the thruster for small satellites.[1,2] However, because the laser thruster doesn't satisfy the demanded thrust for position control of satellites, improvement of performance is needed for practical use. Furthermore, the detailed physics and performance characteristics are unclear.[3] For example, influences of propellants on thrust performance are not understood.[4]

In the ablative thruster, pulsed laser is irradiated onto the surface of propellant, and just after irradiation ablation of propellant intensively occurs, resulting in generation of reaction force, i.e., thrust. Repetitive-pulse operational mode is conducted for practical use. Generally, polymer propellants with high specific weight and high melting point generate higher momentum coupling coefficient than those with low specific weight and low melting point, and polymer propellants with carbon improve the thrust performance.[5,6] A momentum coupling coefficient shows a rate of momentum for input laser energy. In previous studies, PTFE generated the highest momentum coupling coefficient because PTFE has the highest specific weight and the highest melting point in the conventional polymer propellants. Furthermore, polymer propellants generate the maximum momentum coupling coefficient at the 2nd or 3rd shot, but the maximum momentum coupling coefficient at the 1st shot is practically desirable.[4]

In this study, a laser ablative thruster is operated with many kinds of propellant in order to enhance the momentum coupling coefficient, that is, impulse bit. Metals with high specific weight and high melting point are

* Professor, Department of Mechanical Engineering, tahara@med.oit.ac.jp

expected to generate high impulse bit. Because polymer-gels have characteristics between solid and liquid, it is considered that they have smaller melting latent heat than solid. Since materials with small melting latent heat, that is, polymer-gels, will be ablated easily and efficiently, it will result in higher impulse bit. Furthermore, a special propellant of polymer-gel, on the surface of which small carbon particles were deposited, is also prepared. Carbon particles are used in order to transparent gel absorb laser energy.

II. Experimental Apparatus

The experimental facilities are shown in Fig. 1. A thrust stand of pendulum type is placed in a vacuum chamber. The thruster is fixed at the bottom of the pendulum. In front of the thruster, a focus-lens with 200 mm in focal length is placed. A displacement meter and an electromagnetic damper are settled in the back of the thruster. By a counter weight at the top of the pendulum and the electromagnetic damper, vibration from external port can be controlled. A laser is placed outside the vacuum chamber and irradiated to the thruster immediately after the electromagnetic damper is off. The irradiated laser beam is simply focused on the surface of a propellant fixed to the thruster by the focal lens. The amplitude of the pendulum is measured by the displacement meter. The generated impulse bit is calibrated by known impulse bit with small lead-ball impacts.

Table 1 shows laser module. The laser is Nd:YAG laser, its wavelength is 1064 nm, output energy is 0.3J, its pulse width is 6nsec, and its beam diameter is 7mm. All experiments were performed at a vacuum chamber pressure of 5×10^{-3} Pa during operation.

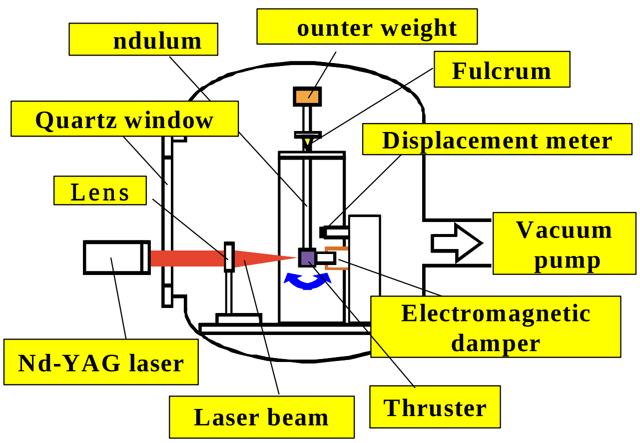


Figure 1. Experimental facility.

Table 1. Module of Nd:YAG laser.

Wavelength	1.06 μm
Energy/shot	0.3J/shot
Pulse width	6 nsec
Beam diameter	7 mm

In this study, effects of propellant species, such as metal, polymer-gel, and carbon were examined. Metals with high specific weight and high melting point are expected to generate high impulse bit. Aluminum and copper were prepared as metal propellants. The properties of PTFE and the metal propellants are shown in tables 2 and 3. The metal propellants have much higher specific weight and higher melting point than those of PTFE.

Because polymer-gels have characteristics between solid and liquid, it is considered that they have smaller melting latent heat than solid. Since materials with small melting latent heat, that is, polymer-gels, will be ablated easily and efficiently, it will result in higher impulse bit. Two kinds of gel propellant were prepared in this experiment. One is low-hardness urethane elastomer gel. This has properties near solid relatively. The other is segmental polyurethane gel. This has properties near liquid relatively, and this is transparent. Therefore, the segmental polyurethane gel is difficult to be ablated. Thus, a special propellant of polymer-gel, on the surface of which carbon particles are deposited, was prepared as shown in Fig.2. Carbon particles with very high efficiency of laser absorption are used in order to make transparent gel absorb laser energy. Furthermore, a carbon block was prepared in order to examine effects of carbon itself on thrust performance.

Table 2. Properties of PTFE.

Specific Weight	**2.1**
Specific Heat [J/(gK)]	**1**
Melting Point [K]	**550**

Table 3. Properties of aluminum and copper.

	Aluminum	Copper
Atomic weight	**26.98**	**63.5**
Specific Weight	**2.7**	**8.96**
Specific Heat [J/(gK)]	**0.9**	**0.38**
Melting Point [K]	**933**	**1537**
Heat of fusion [kJ/mol]	**10.79**	**13.05**
Boiling Point[K]	**2792**	**2840**
Heat of vaporization [kJ/mol]	**293.4**	**300.3**
Steam pressure [Pa]	**2.42 E-06**	**5.05 E-02**
Thermal Conductivity [W/mK]	**180**	**360**

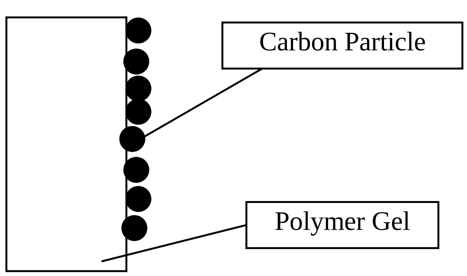


Figure 2. Schematic of special propellant of polymer-gel with carbon particles on surface.

III. Experimental Results and Discussion

A. Metal Propellants

Figure 3 shows the momentum coupling coefficient depending on shot number with metal propellants and PTFE. Figure 4 shows SEM images of the surface of metal propellants and PTFE after 30 shots of laser irradiation. The metal propellants of aluminum and copper generate lower momentum coupling coefficient than PTFE, although the momentum coupling coefficient is independent of laser shot number. Two reasons are considered for the result that these metal propellants generated lower momentum coupling coefficient than PTFE. First, because metals have large melting latent heat as shown in Table 2, metals need much energy until reaching its melting point and boiling point. Consequently, metals were difficult to be ablated resulting in low momentum coupling coefficient. Actually, as shown in Figs.4 (b) and (c), the surfaces of metal propellants are hardly ablated and are clearer than that of PTFE as shown in Fig.4 (a). Moreover, because metals have high thermal conductivity, metals are ablated not locally but uniformly over the surface. Secondly, as shown in Table 4, metals have very high reflection rate. As a result, because most of laser energy was reflected, the metal propellants were hardly ablated. This energy loss effects due to reflection can be predicted from thrust efficiency as shown in Fig.5. Since the thrust efficiency which is a rate of thrust energy on input energy is very low, it is considered that most of laser energy irradiated becomes loss. As a result, the momentum coupling coefficient with metal propellants declined as compared with PTFE.

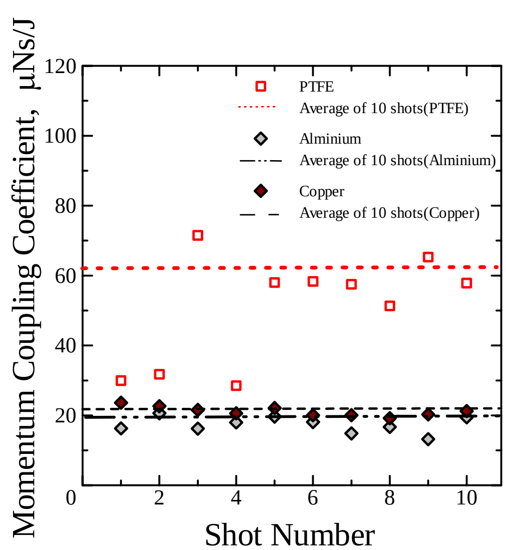
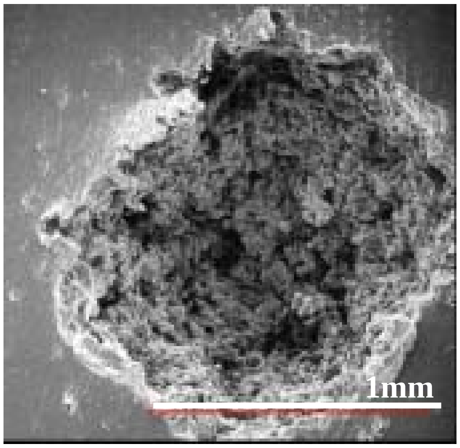
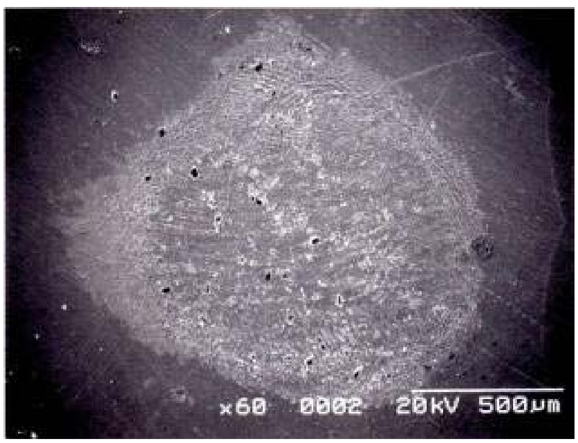


Figure 3. Coupling momentum coefficient vs shot number with metal propellants.



(a) PTFE.



(b) Aluminum.

(c) Copper.

Figure 4. SEM images of surface of aluminum, copper and PTFE after 30 shots laser irradiation.

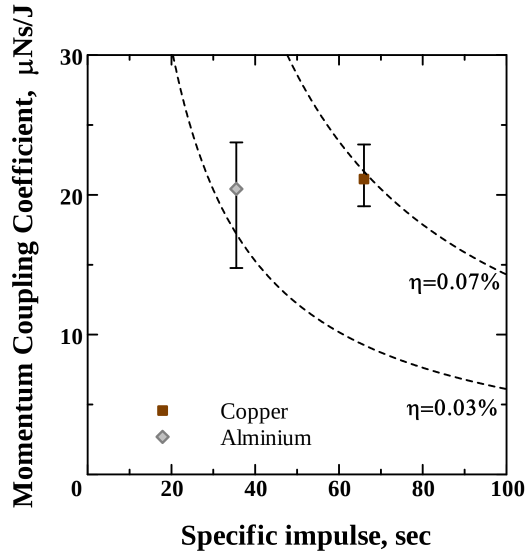


Figure 5. Thrust performance characteristics with metal propellants.

However, it is noted that the momentum coupling coefficient with metal propellants was independent of laser shot number. Because the surface of metal propellants after laser irradiation is relatively clear as shown in Figs.4 (b) and (c), momentum coupling coefficient is not expected to depend on laser shot number. From this fact, it is considered that metal propellants are suitable for the mission which demands a stable operation of laser thruster.

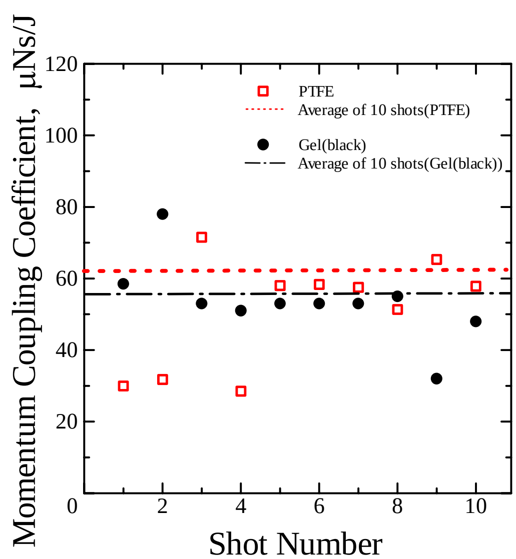


Figure 6. Coupling momentum coefficient vs shot number with low-hardness urethane elastomer gel and PTFE.

B. Polymer-gel Propellants

Figure 6 shows the momentum coupling coefficient depending on shot number with low-hardness urethane elastomer gel and PTFE. Although the low-hardness urethane elastomer gel has half as high specific weight as PTFE, it generates as high momentum coupling coefficient as PTFE. This is considered because the low-hardness urethane elastomer gel was ablated easily due to its small melting latent heat although it had low specific weight. Since the melting latent heat is small, liquid region would exist around the spot at which laser was irradiated.

The gel propellant vaporized would be released from the center of the spot, and then the liquid region would be also released together. As a result, the total mass released was as much as that of PTFE. Accordingly, the gel propellant could generate as high momentum coupling coefficient as PTFE. Figure 7 shows the SEM image of the surface of low-hardness urethane elastomer gel after 30 shots of laser irradiation. It is observed from this image that its ablation trace is rougher than those of metal propellants. The result shows that not only specific weight but also melting latent heat influences thrust performance.

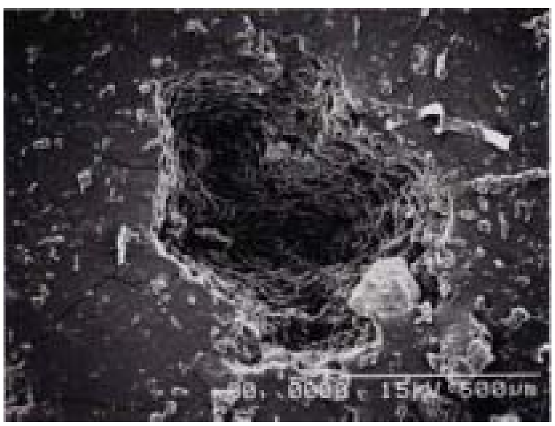


Figure 7. SEM image of surface of low-hardness urethane elastomer gel after 30 shots laser irradiation.

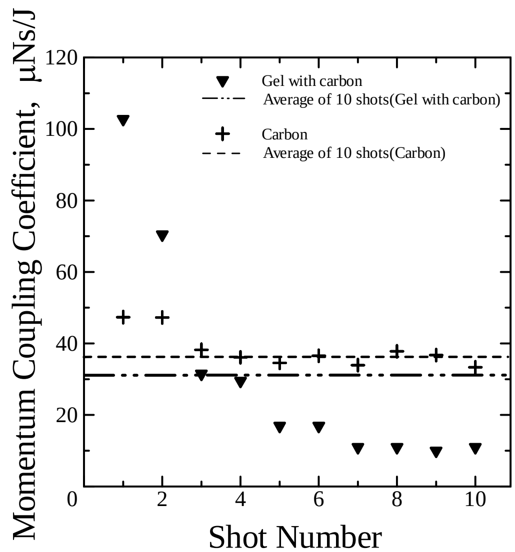


Figure 8. Coupling momentum coefficient vs shot number with segmental polyurethane gel with carbon particles and carbon block.

The segmental polyurethane gel could not be ablated because laser irradiated had gone through it, but segmental polyurethane gel with small carbon particles on the surface could be ablated. Figure 8 shows the momentum coupling coefficient vs shot number characteristics with segmental polyurethane gel with carbon particles and with carbon block. The segmental polyurethane gel with carbon particles generates a high momentum coupling coefficient of 102μNs/J, and this value exceeds that of PTFE which generated the highest one in previous studies.[5] Furthermore, although with PTFE there is the problem that the highest momentum coupling coefficient is generated at the 2nd or 3rd shot, the segmental polyurethane gel with carbon particles generated the highest momentum coupling coefficient at the 1st shot. On the other hand, carbon itself generates a low momentum coupling coefficient. This is because carbon is difficult to be ablated, although it has characteristic to intensively absorb laser energy, since carbon has very high melting point and boiling point. In the case of segmental polyurethane gel with small carbon particles, carbon particles on the surface of segmental polyurethane gel absorb laser energy, and become high temperature. The segmental polyurethane gel receives large thermal energy from the carbon layer with high temperature, and is ablated intensively. Then, since carbon is particle, the particles are released with the gel ablated. These released carbon particles contribute to improvement of thrust performance because carbon has a large specific weight of 2.7.

Consequently, as propellants for laser ablative thruster high specific weight, small melting latent heat, and high absorption efficiency of laser energy are required. Moreover, combining some materials with these properties will be effective to enhance the thrust performance.

IV. Conclusions

In this study, effects of propellant species, such as metal, polymer-gel, and carbon, were examined in order to enhance thrust performance for laser ablative thruster. Metals with high specific weight and high melting point were expected to generate high impulse bit, but generated lower impulse bit than that of PTFE. However, the impulse bit was independent of laser shot number. Since polymer-gels are ablated easily and efficiently, it was expected to enhance thrust performance. Although low-hardness urethane elastomer gel which has characteristics near solid has low specific weight, it generated as high impulse bit as PTFE. Therefore, it is considered that not only specific weight and melting point but also melting latent heat affects thrust performance. Segmental polyurethane gel with carbon particles generated a high momentum coupling coefficient of 102μNs/J, and this value exceeded that of PTFE which generated the highest one. Moreover, segmental polyurethane gel with carbon particles generated the highest momentum coupling coefficient at 1^{st} shot. On the other hand, carbon itself generated low momentum coupling coefficient.

References

[1]Phipps, C. R.,“ Impulse Coupling to Targets in Vacuum by KrF, HF, and CO_2 Single-Pulse Lasers,” *J. Appl. Phys*, Vol. 64, 1988, pp. 1083-1096.

[2]Larson, C. W., and Franklin B. M,“ Laser Propulsion and the Constant Momentum Mission,” *Proc. International Symposium on Beamed Energy Propulsion*, 2004, pp. 216-222.

[3]Srinivasan, R., and Braren, B.,“ Mechanism of the Ultraviolet Laser Ablation of Polymethyl Methacrylate at 193 and 248 nm: Laser-Induced Fluorescence Analysis, Chemical Analysis, and Doping Studies,” *J. Opt. Soc. Am. B*, Vol.3, No.5, 1986, pp. 785-791.

[4]Koizumi, E.,“ Effects Of Nozzle Geometry On Performance Characteristics of Laser Ablative Thrusters,” *International Symposium on Space Technology and Science*, ISTS 2004-b-39, 2004.

[5]Maesato, H., Koizumi, E., and Tahara, H.,“ Performance Characteristics of Low-Power Laser Ablative Thrusters for Small Satellites,” *Proc. International Symposium on Beamed Energy Propulsion*, 2005.

[6]Koizumi, H., Inoue, T., Kojima, K., Mori, K., Komurasaki, K., and Arakawa, Y.,“ Study on Microthruster Using a Diode Laser,” *Applied Plasma Science*, Vol. 10, 2002, pp. 44-51.