CHARACTERISTICS OF ABLATION IMPULSE INDUCED BY REPETITIVE LASER PULSE IRRADIATIONS

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ABSTRACT

Experimental study is conducted to characterize an ablation impulse induced by repetitive laser pulse irradiations, which depends on laser operation and material conditions. A Nd:YLF laser with a 1047 nm wavelength and 5 – 15 ns pulse width is used for the experiment of small pulse energy and high pulse repetition frequency of up to 8 kHz. Nd: YAG laser with a 1064 nm wavelength and 7 ns pulsewidth is used for the experiment of relatively large pulse energy. An induced impulse by laser irradiation is measured with a torsion pendulum. Experimental results suggest promising applications of laser ablation to space propulsion including deorbiting and de-tumbling space debris.

1 INTRODUCTION

1.1 Problem in space activities

The amount of space debris is rapidly increasing due to swift expansion of space development activities. While space debris fragmentation is rapidly proceeding, the number of debris larger than 1 cm is also increasing, being estimated to exceed 600,000 and peaks at an orbital altitude of 800 km. While the relative collision velocity of the debris is at a level of 10 km/s, the satellites, space station, and so on can be seriously damaged because of collisions with even the small-sized debris. Moreover, according to “Kessler Syndrome” [1], the amount of debris will increase owing to fragmentation caused by mutual collisions. Debris below 1 cm in diameter are shielded by the debris shield mounted on the satellite, whereas debris larger than 10 cm are tracked by the debris tracking system, which sends an alert, so that the satellite can avoid a collision. Therefore, debris within the diameter range of 1 cm to 10 cm is the most dangerous. This is because the momentum of the impact exceeds the ability of the debris shield to withstand collisions. Moreover, this type of debris is large in quantity and difficult to find and track, using ground-based telescopes.

Future missions with geodetic or astronomic science goals require highly precise compensation of disturbing forces that prevent satellites from maintaining an ideal orbit or interfere with satellite formation fight [2]. Depending on the mission, disturbing forces are atmospheric drag in low earth orbit (1 mN), solar radiation pressure of the order of 10 to 100 μN (the dominating effect in deep space), torques due to Earth magnetic field and for the case of satellite formation fight balance of tidal forces. For future developments for example earth observation missions that provide higher resolution even space craft dynamics have to be considered.

1.2 Survey of space propulsion methods

The electric propulsion thrusters have already been developed, and demonstrating to be functional in their practical applications. The typical range of the specific impulse (I_{sp}) for electric propulsion is 10^2–10^4 s, which is considerably higher than the 300 s for chemical propulsion. While the maximum thrust density of electric propulsion is an order of magnitude smaller than chemical propulsion, the thrust range is as wide as of 1–10^4 N/m^2. For micropropulsion, the FEEP (Field Emission Electric Propulsion) thruster with a specified thrust of 0.1–100 μN has been developed [3-5]. The main feature of the electric thruster is the high specific impulse range of 4000–10000 s[6], which is achieved because of a high applied voltage of about 10 kV. The disadvantage of FEEP is a heavier weight of power supply caused by high voltage. Moreover, a neutralizer for the ion beam is also required.

An electrodynamic tether [7,8] can work as a thruster because a magnetic field exerts a force on a current carrying wire. This force is perpendicular to the wire and to the geomagnetic field vector. If the current flows downward through a tether connected to an eastward-moving spacecraft, the force exerted by the geomagnetic field on the system has a component that accelerates the satellite along the direction in which it is already moving. The propulsion method does not require any propellant on board. The thrust generated by a tether of a length of 10 km was estimated to be in the range of 0.3–1.2 N with an input power in the range of 0.3–1.5 kW. A smaller thrust can be obtained by shortening the tether length or by decreasing the input power. Although the use of electric propulsion is not necessary within a region such a low Earth orbit where

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the geomagnetic field is sufficiently strong, the deformation of the tether wire may cause a difficult in obtaining a stable thrust.

The typical I_{sp} of laser ablation propulsion (Fig. 1) is in the range of 200–3000 s. [9] The thrust density is on the order of 8×10^5 N/m^2 [10], because the thrust arises on a spot with an area equal to that of a focused laser beam. Remote thrust generation is a unique and clear advantage of this technique. It has the potential to achieve significant mass reduction and improved payload capability. The use of solid propellant alleviates problems in propellant storage. The thrust is roughly proportional to the laser power. Therefore, the system size can be scalable to a required thrust. However, regardless of such advantages, this propulsion technique has not been matured for practical applications.

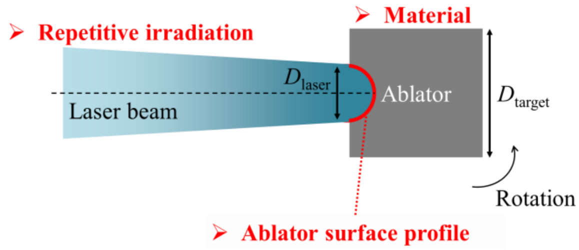

Figure 1. Impulse generation by laser ablation and influential parameters

1.3 Laser ablation propulsion

Laser ablation is the mass removal of target material by using laser energy. The material surface absorbs the laser energy, heats it up rapidly, and then ejects the materials basically in its gas phase. Laser ablation propulsion utilizes the recoil force of the ejection as a thrust. Its remote thrust generation is a unique and important advantage of this technique. Various materials can be ablated and imparted impulse by laser ablation. The impulse level can be controlled by laser irradiation conditions including a laser pulse energy, an energy density, the number of laser pulses etc.

The application of laser propulsion is a promising solution to the space debris problem. Laser ablation is capable of treating space debris at distances within 100 km. Thus, the operation can be conducted safely without the risk of collision with the debris. Moreover, multiple occurrences of the debris can be de-orbited by a single laser source. This feature is suitable for treating small type of debris, whose amount exceeds 600,000 and is spread over a large space.

Microthrusters [11,12] driven by the laser ablation are promising candidate for the future space mission which require small and highly precise thrust. Depending on the ablation threshold of the target material different approaches are possible: Diode lasers with relatively long pulses in the ms range have been used for ablation of polymer targets in transmission or T-mode, where the thin target is located on a transparent substrate [13]. The laser pulse transmit the substrate and then be absorbed by the target. The induced pressure acts on the substrate is in the direction of opposite of the laser direction. In this concept a fresh spot of coated material has to be provided for each shot. Microchip lasers that produce shorter pulses can be used for reflection or R-mode ablation of metal targets. The laser pulse is directly irradiated onto the metal target. This mode have a higher ablation threshold but are not subject to outgassing issues like polymer targets. Thrust levels between mN and µN have been demonstrated for laser ablative thrusters. Specific impulses of up to more than 3000 s have been demonstrated for R- mode metal ablation [14,15] and impulse coupling coefficients of up to 3000 µNs/J have been demonstrated in T-mode ablation of exothermic polymers [12]. A unique capability of laser ablative thrusters is the generation of very low minimum impulse bits down to < 1 nNs in a single shot operation [15,16].

1.4 Review of research and development for space debris mitigation

Active removal of debris is studied in many research institutes such as JAXA [17,18], ESA [19], and NASA [20-22]. Almost all the methods of debris removal have to approach and contact to the debris. However, the collision risk involved in and the fuel expenditure required for approaching the debris accompanies. These studies address single pieces of debris larger than 1 m. This is because large pieces of debris give rise to many smaller pieces of debris by collision with other debris. However, the spatial density of small debris has already a non-negligible level. For example, the International Space Station executes a collision avoidance maneuver about once a year. Therefore, development of active deorbiting method both for large and small debris is important to maintain safety on Earth's orbits.

The application of laser propulsion is one promising solution to this problem. Phipps et al. [23] advocated the concept of deorbiting space debris in low Earth orbit by using a 20 kW laser device located on the ground. Schall et al. [24] proposed space debris mitigation by space based deployment of the laser. A power higher than 1 kW with an about 40 % efficiency laser system named CAN (Coherent Amplifying Network) has been developed for space debris removal in orbit [25]. The system adopts a high operation repetition rate of more than 1 kHz with a constant fluence. It was reported that debris of 1 – 10 cm in size can be de-orbited with this laser system. Although a constant momentum coupling coefficient, C_m is used in their estimation, the actual C_m would change in repetitive laser pulse irradiations. The ablation phenomenon with repetitive irradiation is more complicated than single-pulse irradiation onto a planer ablator because the condition of a crater which is formed during the laser pulse irradiations influences the total impulse. Ebisuzaki et al. [26] embodied these concepts by utilizing the Extreme Universe Space Observatory (EUSO) and CAN fiber laser. De-tumbling of an artificial satellite model through the use of repetitive laser pulses was demonstrated in [27].

1.5 Impulse generation by laser ablation

Previous research on laser ablation propulsion was mostly focused on the impulse performance obtained with a single laser pulse irradiation using a target with a flat surface and dimensions that were much larger than the laser beam diameter. The impulse mainly depends on the incident laser fluence, ϕ_{p}, which is the energy density in the illuminated area. Phipps, et al. [9] proposed a model to relate C_{m}, and ϕ_{p} based on existing data and theory, and concluded that the fluence had an optimum value to maximize C_{m}, the value of which is strongly dependent on ablation materials and laser pulse specifications. In their proceeding paper [28], they obtained the same impulse performance with 130 fs laser pulse as that with a 100 ps laser pulse. In most practical applications except for the micropropulsion, a sufficient impulse cannot be obtained with a single laser pulse irradiation.

A previous study [29] showed that C_{m} was proportional to $(I\lambda\sqrt{\tau})^{-1/4}$ under plasma regime; C_{m} increases with decreasing λ. To support this tendency, metals ablated by 532-nm-wavelength laser pulses exhibited promising propulsion performance [30]. However, at the current technology level, a 1-μm-wavelength laser can reach higher output power and efficiency than those of its higher harmonics. Considering the 'overall' C_{m}, the ratio of a propulsive impulse to the input electrical energy to the whole system, the 1-μm-wavelength laser pulse still has an advantage over the higher harmonic waves. Souza [31] reported that with a femtosecond to picosecond level pulse duration laser, C_{m} is kept almost constant with the laser fluence, ϕ_{p} being varied in the range of 0.2 to1.6× J/cm^2. Impulse is not sensitive to f (5.0 – 6.5 kHz), N_{t} (100 – 3000 shots) and τ(100 – 940 ps). However, the main objective of work was to determine whether or not the pico-second pulse width offered a significant performance increase compared to nanosecond pulse width. A part of laser pulse width in his experiment is shorter than the plasma formation timescale, on the order of 1 – 10 ps. It is unknown if this pulse width range is useful for space propulsion applications or not.

1.6 Laser devices

There has been tremendous improvement in the recent performance of the diode laser. The commercial pulse laser by Quantel Co. generates up to 1 MW power with up to 65% efficiency and guarantees operation in space. The high efficiency helps in saving electric power, which is especially valuable in space, and in lowering heat generation. Moreover, because of the small volume, the cost of manufacturing, launching, and operation can be reduced. A laser system with efficiency of nearly 40 % and power more than 1 kW has been developed for the removal of space debris in the Earth's orbit [25]. The system adopts a high laser repetition rate of more than 1 kHz with a constant ϕ_{p}. It was reported that debris of 1 – 10 cm in size, at a distance of 100 km, was de-orbited with this laser system.

1.7 Specific research problems

1.7.1 Generation of required impulse

The minimum impulse induced by single pulse ablation is < 1 nNs and it satisfies most of the requirements for a small impulse. In the meantime, there is a limitation for the maximum impulse with single pulse ablation. Impulse, I_{m} generated on the object surface by laser ablation can be expressed as the multipullcation of laser energy, E by C_{m},

$$I_{\mathrm{m}} = EC_{\mathrm{m}} \tag{1}$$

The equation also gives the definition of C_{m}, which is the thrust effectiveness from laser energy to the impulse. In debris removal operation, there is a certain limitation on E mainly due to the limited debris surface area and the distance, so the C_{m} should be sufficiently high for obtaining enough impulse. Several authors have reported that C_{m} increased to the peak value and then decreased while increasing the fluence of the laser pulse, [9]. Therefore, the impulse generated with single pulse is insufficient for operation.

Repetitive irradiation of the laser pulse is useful for obtaining a sufficient impulse for practical use. Repetitive irradiation with a total number (N_t) of laser pulses and laser pulse repetition frequency f can affect the impulse. However, this has not yet been studied. Even due to ablation by a single pulse, the ablator surface undergoes slight deformation and the surface area changes. Moreover, the surface roughness and reflectivity also change. These elements continuously vary with increasing N_t. When f increases beyond a certain value, the second pulse is arrived before the ablator surface temperature once rose with the first pulse decreases to ordinary value. Under this condition, although the oscillations synchronize with f [32], the ablator temperature increases to the boiling point within several pulses and then remains constant. This may decrease the effective ablation threshold in the fluence, because the absorbed energy is not utilized for increasing the temperature. Double-laser-pulse impulse performance was reported by some authors: Colao, et al. [33] measured the emission spectrum of pulsed laser generated plasma. Using a Nd:YAG laser (wavelength 1064 nm, pulse width 8 ns) higher plasma density was obtained in ‘double pulse’ operation with 20 ms of pulse to pulse period than in single pulse operation even with an equal total energy. Mori et al. [34] reported the C_m enhancement effect by preheating the ablator before ablation. When f increases further, the plasma, gas, liquid, and solid particles exhausted by a previous pulse may remain near the ablated surface with non-negligible density and interfere with the next pulse resulting in a decrease in I_m.

For accomplishing constant impulse, even with repetitive irradiation, Phipps [12,28] developed a microthruster in which an ablator is fed as a roll of double layer tape, the layer on the irradiation side is transparent to the laser beam, the other side an ablator. The laser energy deposition is done on a virgin layer so that a single pulse performance is reproduced in every shot. However, this method is feasible only if an object to be propelled is a controllable one like a spacecraft, not applicable for an uncontrollable object such as space debris; even for a thruster in a spacecraft, the ablator utilization efficiency is degraded by the mass of the transparent layer and a dead area without irradiation.

The aerodynamic nozzle is another approach for enhancing impulse. The nozzle can be designed and attached to the thruster in advance. Sinko et al. [35] ablated carbon-doped polyoxymethylene POM in a set of conical aluminium (Al) mini-thrusters using a carbon dioxide (CO_2) laser. The laser had a pulse length of 300 ns, operating wavelength of 10.6 µm, and pulse energy in the range 1–4 J at standard temperature and pressure. I_m, C_m, and I_{sp} all increased with increasing expansion ratio, but the ablated mass per area appeared to remain approximately constant. These results imply that the addition of the thruster nozzle to the target does not change the ablation mechanism in the material, but does contribute additional thrust through the action of the exhaust pressure. The crater, which formed and deepened with repetitive ablation, could act as the nozzle. Suzuki, et al. [36] investigated the impulse performance of TEA (Transversely-Excited Atmospheric) CO_2 laser pulses onto polyoxymethylene (POM) with a repetition frequency of 50 Hz and up to 110 pulses. Under favorable conditions (ambient pressure; 10^{-2} Pa, single pulse fluence; 18.8× J/cm^2), C_m increased by 8 % after 100 pulses, due to the formation of a crater which acted as a nozzle. However, with an excessively high fluence, the C_m decreased when the depth to diameter ratio of the crater exceeded unity.

1.7.2 Ablator materials

In recent years, the impulse performance, which acts as a laser ablation propulsion propellant, of polymer ablation has been studied [39-42]. A variety of polymers are utilized in space applications such as thermal control components, electronics related components, composites for structural applications, and adhesives[43]. Generally, polymers have lower latent heats for melting and vaporization than metals, thereby ejecting a larger mass and generating larger impulses induced by laser ablation. Therefore, polymers are quite important for laser ablation applications in space propulsion such as space debris deorbiting[25,44,45], dead satellite de-tumbling to capture, and microthruster[2,11]. From the viewpoint of propellant, suitable machinability, low density, and reasonable price of polymers are advantage. In addition, functionalization by blending and lamination has been examined. Many reported that polyoxymethylene (POM) acted as a volume absorber [46] against a far-infrared 10.6 µm CO_2 laser pulse, obtaining favorable impulse characteristics[47-49]. At the state of the art, a CO_2 laser can output a relatively large laser pulse energy, E_p. However, this typical gas dynamic laser system is large, heavy, and has poor portability, thus is not suitable for the space applications. On the other hand, recent progresses in 1 µm high-repetition-rate solid-state lasers, including fiber lasers, are satisfactory in terms of energy conversion efficiency, weight, and cost. If a sufficient impulse performance is obtained with this type of laser device, the applicability of laser ablation in space propulsion is expected to be improved significantly.

Suzuki et al. [36] and Tsuruta et al. [50] examined the impulse characteristics by repetitively irradiating laser pulses on to a single spot. Colao et al. [33] measured the emission spectrum of a pulsed laser-generated plasma. Even with an equal amount of total energy, a higher plasma density was obtained using a Nd:YAG laser (wavelength, λ: 1064 nm, and a temporal pulse width, τ: 8 ns) in a double-pulse operation with a time interval of 20 ms than in a single-pulse operation. Mori et al.[34] preheated materials such as PVC, PMMA, and CFRP followed by laser ablation by CO_2 laser irradiation. As a result, the momentum coupling coefficient, C_m, which is the ratio of an impulse to a laser pulse energy irradiated on the ablator, of PMMA was increased by 20–40 µNs/J. Characteristics of I_m with high repetitive 1 µm laser irradiation have not yet been cleared, although they are essential for practical applications.

A summary of the principal parameters is shown in Fig. 1. Although magnitude relation of D_{laser} and D_{target} and rotation of the ablator should influence on impulse, these parameters are beyond the scope of this study.

The purpose of this study is to experimentally obtain characteristics of impulse with high repetitive 1 μm laser irradiation.

2 APRATUS AND METHODS

2.1 Experimental System

Figure 2 shows the schematic illustration of the experimental system. An ablator was mounted on one end of a torsion pendulum. The pendulum was placed in a vacuum chamber 0.7 m in diameter and 2.2 m in length. The vacuum chamber was evacuated to an ambient pressure of 2×10^{-2} Pa by a turbo molecular pump (2000 L/s, TMP-2003LM, Shimadzu co.) backed by a rotary pump (533 L/s, T2033SD, Alcatel). The output pulse from a laser was first sent into the vacuum chamber through a BK7 window and then focused by a 150 mm focal length achromatic lens onto the ablator. Laser ablation is occurred on the ablator surface, induce displacement of the torsion pendulum. The detail of the pendulum is explained in [51]. The 18-μm-thick cellophane film was placed just behind the beam condensing lens with an oblique angle of incidence of 30° to avoid contaminating the lens against the exhaust ablation plume. The transmittance of the film corresponding to the 1047 nm pulse was measured to be almost 99 %. The incident angle to the ablator surface was 90 degrees with less than 5 degrees of allowance.

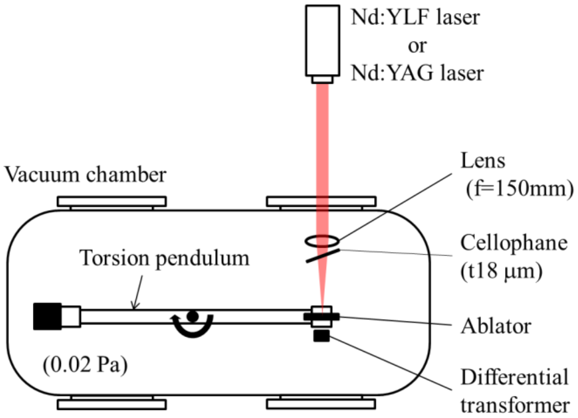

Figure 2. Setup of impulse measurement.

2.2 Laser Devices

The specifications of the lasers, which were used in this study, are summarized in Table 1. Wavelength and pulsewidth of each laser were the same order of magnitude. Nd:YLF laser can be used for investigating the performance under high pulse repetition frequency up to 10 kHz. While the pulse energy was small, fluence of 24 J/cm^2 is achieved by focusing. Nd:YAG laser can output relatively high energy pulse while the maximum repetition frequency was 1 Hz. Therefore, higher fluence and/or larger laser spot size were achieved. The larger spot size helps us to evaluate the profile of burnt surface.

Table 1. Laser specifications.

	Nd:YLF	Nd:YAG
Manufacturer	Edgewave	QUANTA system
Wavelength, nm	1047	1064
Max. Pulse Energy, mJ	13	450
Pulse width, ns	5–15	7
Beam Diameter, mm	4	9
Max. Repetition Rate, Hz	10000	1

3 IMPULSE CHARACTERISTICS OF ALUMINUM

3.1 Impulse characteristics with small energy pulses

The impulse characteristics of an aluminum ablator against repetitive 1 μm wavelength, Nd:YLF laser pulses were investigated[52]. fluence significantly influenced the impulse in the range from 6 – 24 J/cm^2. Impulse increased and reached saturation with increasing E_t. The saturation value of impulse increased with increasing fluence.

Figure 3 shows C_m increment with S. The increasing rate of C_m with the fluence of 5 – 8 J/cm^2 is larger than that with higher fluence. C_m is saturated with increasing S. This result indicates that the scaling effect is predominant when the ablation area is small.

3.2 Impulse characteristics with large energy pulses

Impulse characteristics against larger energy pulses of Nd:YAG laser (wavelength of 1064 nm, pulse duration of 7 ns) is investigated[53]. The larger range of fluence from 16 – 75 J/cm^2 is achieved. Larger crater formed on the ablator is helpful for investigating the relationship between impulse and the crater profile. The changes in surface area caused by crater deepening are measured with a laser microscope, and are then used for calculating the effective fluence. The fluence is compared to a corresponding variation in C_m with repetitive pulses. We conclude that the effective fluence is one of the dominant parameters for C_m.

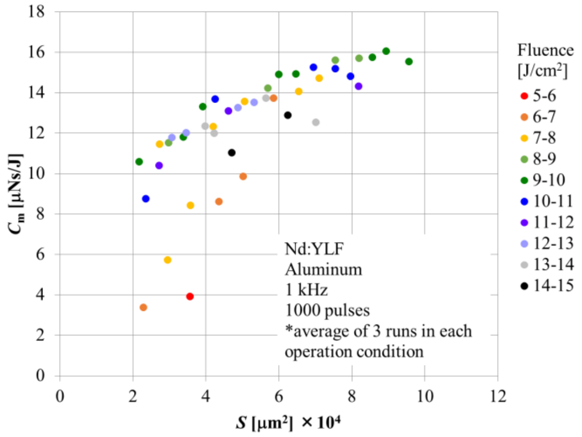

Figure 3. C_m dependence on S.

4 IMPULSE CHARACTERISTICS OF POLYMERS

The ablation spot area and impulse characteristics of various polymers are experimentally investigated against burst irradiation of Nd:YLF laser pulses with a pulse repetition frequency of 1 kHz and single-pulse fluence of 6.1 – 17.1 J/cm^2[54]. In order to characterize their impulse performance as a function of fluence, which should not depend on ablation material, an effective ablation spot area is defined as that obtained against aluminum, 1050A, as the reference material because its crater area variation indicated reasonable dependences on the number of laser pulse irradiations and laser pulse energy. An impulse that resulted from a single burst of 200 pulses is measured with the torsion-type impulse stand. Various impulse dependences on the fluence, which are not readily predicted from the optical properties of the material without ablation, are obtained. By fitting the experimentally measured impulse performance to Phipps and Sinko's model in the vapor regime, the effective absorption coefficient with laser ablation is evaluated, thereby resulting in three to six orders of magnitude larger than that without ablation. Among the polymers examined using polytetrafluoroethylene (PTFE) as the best volume absorbers, the highest momentum coupling coefficient of 66 μNs/J is obtained with an effective absorption coefficient more than six times smaller than that of the other polymers.

5 CONCLUSION

An ablation impulse induced by repetitive laser pulse irradiations depending on laser operation and material conditions is characterized. These results will be important when applying the laser ablation propulsion technique in future missions in space such as space debris deorbiting or de-tumbling, space transportation, and satellite attitude or orbital control using 1 μm laser pulses, which is obtained by diode and fiber lasers.

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