Influence of Illuminating Angle on Impulse Characteristics with Pulsed Laser Ablation

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The relationship between impulse and incident angle of Nd:YAG laser pulses (wavelength of 1064 nm, pulse duration of 7 ns) on an Al target is investigated. Effective fluence is varied with a variation of incident angle because an effective laser spot area is changed. The μNs level impulse is measured in vacuum by a torsion type impulse balance. The incident angle has an optimum value for the maximization of the momentum coupling coefficient. The optimum incident angle decreases with the increase of single pulse energy.

Key Words: Laser Ablation Propulsion, Incident angle, Aluminum

Nomenclature

C_m	:	momentum coupling coefficient
E	:	laser energy
S	:	laser spot area on surface of target
ϕ	:	fluence
θ	:	incident angle of laser
Subscripts		
e	:	effective
p	:	per single pulse
0	:	normal

1. Introduction

Laser ablation is a mass removal by coupling laser energy to a target material. Matter irradiated with a laser pulse can be extremely heated then ejected in the state of solid particles, liquid, gas, and even plasma. The recoil force of expansion provides momentum to the ablated object.

Laser ablation is a promising method for the application of space debris removal because of its unique property that momentum generation to a remote place.[1-3] Several techniques for space debris removal need to approach and contact with the space debris for attaching a device or grasp.[4-6] So, the amount of propellant for approaching and possibility that unexpected collision increases. Laser ablation can avoid these negative factors because of laser irradiation from a remote place. Compared with continuous wave laser, pulsed laser is more advantageous in such mission because it is much easier to reach higher intensity needed for initiating ablation on the target, and the plasma shielding effect[7] with pulse laser shooting will be not so serious.

Previous research on laser ablation propulsion was mainly focused on the impulse performance obtained with single laser pulse irradiation. Here, a momentum coupling coefficient, C_m, is defined as the ratio of the laser ablation impulse to irradiated laser energy. C_m depends strongly on the incident laser fluence, ϕ_p, which is the ratio of the laser pulse energy to the focal spot area. Phipps et al.[8] proposed a model to relate C_m and ϕ_p based on the existing data and theory, and concluded that the ϕ_p has an optimum value for the maximization of C_m. The optimized ϕ_p for C_m depends strongly on the ablated material and laser specifications.

Actual space debris has not only translational motion, but also rotational motion. Moreover, debris has a variety of shapes. So, it is necessary to research the relationship between illuminating angel and impulse characteristics with laser ablation. In the case of irradiation with oblique incident angle, the illuminated area of the target surface is varied with $1/\cos\theta$. So, the effective fluence, ϕ_e, is expressed as;

$$\phi_e = \frac{E}{S_e} = \frac{E}{S_0}\cos\theta \tag{1}$$

where, S_e denotes the effective laser spot area on the target with oblique angle of incidence and S_0 is a laser spot area with a normal angle of incidence. So, C_m is changed with θ even constant E and distance to the target. Directionality of ablation plume is perpendicular to the target surface regardless of the incident angle of the laser pulse.[9] So, illumination with oblique incident angle can avoid the plasma shielding effect caused by interference with ablation plume.

In previous study, the influence of the illuminating angle on impulse characteristics is investigated through impulse measurement.

2. Apparatus and equipment

2.1. Apparatus

Fig. 1 shows the schematic illustration of the experimental system. The target (a pure aluminum plate) is equipped on a torsion pendulum. The pendulum is installed in a vacuum chamber with 0.7 m diameter and 2.2 m in length. The output Nd:YAG laser pulse (wavelength of 1064nm, 7 ns pulse width) passes through BK7 chamber window, reflected by two

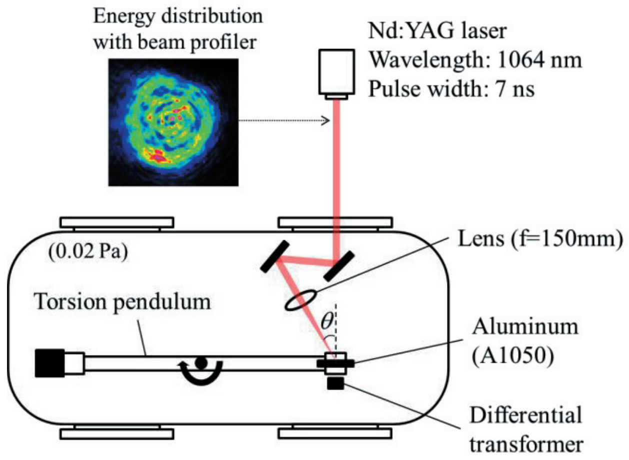

Fig. 1 Experimental system.

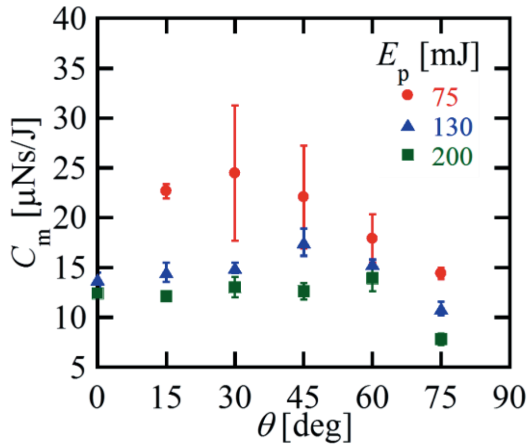

Fig. 2 Relation of C_m and θ.

mirrors, then focused by an achromatic lens with focal length of 150 mm onto the target. The incident angle was varied as a control parameter, keeping distance of a focusing lens to a target surface constant. In this case, S_e was varied with $1/\cos\theta$. S_0 is constant, 7.6×10^5 μm^2 which was determined based on the laser microscope numerical data. When the target is ablated, the laser generated plasma ejects to the direction perpendicular to the target surface and the torsion pendulum begins to oscillate. The displacement of the torsion pendulum is converted to a varying voltage signal by a differential transformer (1591ST, sensitivity; 0.29 V/mm) which is displayed on an oscilloscope. The vacuum chamber was vacuumed to a pressure less than 3×10^{-2} Pa by a combination of a rotary pump (T2033SD, exhaust velocity; 533 l/min) and a turbo molecule pomp (TMP-2003LM, exhaust velocity; 2000 l/min).

2.2. Method of impulse measurement

The torsion pendulum which was developed by Suzuki et al[10] is used to measure the ablation impulse. However, it is different in our case that the mass of the pendulum balance weight was changed from 9 kg to 1 kg, because of the necessity of measuring a μNs-level impulse. With this arrangement, the natural vibration period of the torsion pendulum was changed from about 27 seconds to 10 seconds, which is extremely longer than the typical ablation duration period of 50 ns.[11] In this case, the error in the impulse measurement due to deflection of the pendulum arm is negligible.

Calibration of the torsion pendulum was done by hitting the pendulum with an impact hammer (086E80, sensitivity; 22.5 mV/N). The impulse was obtained by an ICP® (Integrated circuit piezoelectric) pressure sensor which was equipped at the tip of the hammer. After the hitting, the displacement signal of the torsion pendulum was obtained by a differential transformer and displayed on an oscilloscope.

3. Results and discussions

The illuminating angle is varied, keeping distance between focusing lens and the target surface. So, S_e is varied with $1/\cos\theta$, similar condition as debris removal operation. Fig. 2 shows the relation of C_m and θ. Each plot is obtained as the averages of 3 tests under each operating condition, the error bar represents the standard deviation for each group of data sets. Firstly, C_m at θ=0 degrees increases with the decrease of E_p, while a part of the data is not obtained. This relation is same as a past result.[12] C_m increases to a maximum then turn to decrease with the increase of θ. This is because S_e is increased proportional to $1/\cos\theta$, which means ϕ_e decreases. C_m has a peak value with changing of ϕ as mentioned in Introduction part. Moreover, θ which C_m reaches to maximum increases from 30 degrees to 60 degrees with the increase of E_p. Cause of this tendency still under discussion. Maximum C_m varied from 14 μNs/J to 25 μNs/J with the decrease of θ. This is maybe because smaller laser spot area enhances C_m. Solana et al. reported that the deepening rate of the drilling increases with the decrease of laser spot area with constant ϕ_p,[13] while the exhaust velocity of ablation plume is not clear.

4. Conclusions

The relationship between impulse and incident angle of Nd:YAG laser pulses (wavelength of 1064 nm, pulse duration of 7 ns) on an Al target is investigated. Effective fluence is varied with a variation of incident angle because an effective laser spot area is changed. θ has an optimum value for the maximization of C_m. This is because ϕ_e decreases with the increase of θ. The optimum θ decreases with the increase of E_p. This is maybe because smaller laser spot area enhances C_m.

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