Study on impulse and ablation of aluminum irradiated by millimeter spot of short pulse laser

Mingyu Li\textsuperscript{1a}, Jifei Ye\textsuperscript{*1b}, Chentao Mao\textsuperscript{1c}, Sibo Wang\textsuperscript{1d}, Chenghao Yu\textsuperscript{1e}

\textsuperscript{1}State Key Laboratory of Laser Propulsion & Application, Department of Aerospace Science and Technology, Aerospace Engineering University, Beijing 101416, China
\textsuperscript{a}merle_lee@outlook.com, \textsuperscript{b}yjf1981@163.com, \textsuperscript{c}794449157@qq.com, \textsuperscript{d}bosiwang1@163.com, \textsuperscript{e}yuchenghao0536@163.com

Abstract—Aluminum is a high performance working medium for laser ablation micro propulsion. In order to study the propulsion performance and ablation of aluminum under millimeter light spot irradiation, a short pulse Nd: YAG laser with wavelength of 1064nm and pulse width of 8NS was used to irradiate aluminum target in atmosphere. The impulse, the impulse coupling coefficient and the ablation morphology of the aluminum target produced by 6 kinds of millimeter-level light spots are measured. The experimental results show that when the spot diameter reaches 6-7mm, the increasing trend of impulse and impulse coupling coefficient of aluminum target with the increase of laser energy slows down; A large number of ablation products began to accumulate on the surface of the target pit.

1. Introduction
The rapid development of micro-nano satellite has put forward the technical requirements of lightweight and micro-element for space micro-propulsion technology. Laser ablation micropropulsion, as a space micropropulsion technology, uses solar energy as the main energy source and has the advantages of small impulse element, high specific impulse and high control precision, which can provide more accurate attitude and orbit control for micro/nano satellites\cite{1}\cite{2}. In addition to laser, the main optimization direction of laser ablative micro-thruster is the iteration of more efficient working medium and the improvement of working medium supply mode. At home and abroad in recent years have been a variety of laser ablation thruster principle prototype test engineering prototype and some have space, Phipps\cite{3}\cite{4} has been developed, such as ms - mu LPT I and ms - mu LPT II laser ablation principle prototype micro thruster, domestic Yanji Hong\cite{5} disc type is developed, such as laser ablation principle prototype micro thruster, above the operation mode of the prototype are transmission type; Akira Kakami et al.\cite{6} designed a reflective laser micropropulsion prototype, and the LDU-7 laser ablative microthruster engineering machine launched by the Russian Federal Space Agency (ROSCosmos)\cite{7} also works in reflective mode\cite{8}. All of the above laser ablation microthruster types contain complex working medium supply systems, and all of them generate microthrust for laser focused ablation working medium. Although the micron spot after focusing can bring larger single-pulse impulse, it also brings some difficulties for accurate supply of working medium. In this paper, surface ablation is realized by increasing the diameter of laser spot, forming a one-dimensional working medium supply, increasing the space of laser system and working medium in the prototype, so as to improve the performance of thruster. Using nanosecond pulse width laser, the aluminum target is irradiated with different spot diameters. The impulse of aluminum target under different laser energy.
energy, impulse coupling coefficient, target pit morphology and target pit depth are measured. Combined with the physical process of laser irradiating metal aluminum, the propulsion performance and ablation morphology of aluminum target irradiated by millimeter spot are analyzed. The obtained propulsive performance and ablation morphology provide reference for laser surface ablation of solid targets.

2. Experimental device and measurement method

2.1. Experimental device
The experimental device for laser ablation of aluminum metal is shown in Figure 1, which is mainly composed of laser, impulse measurement torsion pendulum, isolation cover and laser rangefinder.

![Fig.1 Schematic diagram of experimental equipment](image)

As the increase of spot area will lead to the decrease of laser power density and energy density, in order to ensure the experimental effect, the Nd:YAG laser with the maximum single pulse energy of 900 mJ, wavelength of 1064nm and pulse width of 8 ns is used as the energy source in the experiment. The experimental material was a cylindrical 1060 aluminum alloy target with a diameter of 15mm and a thickness of 5mm, and its purity was greater than 99.6%.

2.2. Measurement method

2.2.1 Impulse measurement
Microthrust of the order $\mu N \cdot s$ was usually measured using a torsional pendulum. Figure 2 shows the impulse measurement torsion pendulum customized according to the size of the experimental material, mainly composed of precision flexible pivot, measuring beam, high-precision displacement sensor and stop rod (used to measure the fast balance of beam). The dynamic model of impulse measurement torsion pendulum is a second-order mass-spring-damping system. The maximum linear displacement of torsion pendulum can be measured by displacement sensor after the pulse laser beam is applied to the target, and the formula of impulse $I$ can be obtained:\[1\]

$$I = \frac{k}{l_1 l_2 \omega_n} \cdot \delta$$

Type:
- $k$: Torsional stiffness coefficient of torsional pendulum;
- $\omega_n$: Angular frequency of torsion beam;
- $l_1$: The distance between displacement sensor and flexible pivot (measuring arm);
- $l_2$: The distance between pulse laser ablation point and flexible pivot (moment arm);
$s$: The maximum linear displacement of the first swing after pulsed laser loading;

The relationship between impulse coupling coefficient $C_m$ and impulse $I$ and incident laser energy $E$:

$$C_m = \frac{\Delta mv}{E} = \frac{I}{E}$$

Type: $\Delta m$: Ablative mass; $v$: Plume jet velocity; $E$: Incident laser energy

2.2.2 Target pit depth measurement

Laser rangefinder (as shown in Figure 3) was used to measure the ablation depth of the target pit, and different sections of the ablation plane of the same target pit were measured at the distance of 100 $\mu m$.

3. Experimental process and results

3.1. The experimental process

1) Experimental study on the propulsion performance of aluminum ablated by millimeter light spot ablation by short pulse laser. The aluminum target fixed on the torsional pendulum measuring beam was irradiated independently for several times by 18 kinds of Nd:YAG laser with the output energy range of 100-1000MJ and six kinds of millimeter light spots with diameters of 9.6mm, 8.6mm, 7.7mm, 6.6mm, 5.5mm and 3.5mm. The experimental data were recorded by displacement sensor.

2) Experimental study on the morphology of aluminum target pits ablated by millimeter light spot ablation by repeated pulsed laser. A Nd:YAG laser with the output energy of 1000mJ laser beam, repeated frequency of 4Hz, and six millimeter light spots with diameters of 9.6mm, 8.6mm, 7.7mm, 6.6mm, 5.5mm and 3.5mm were used to irradiate the aluminum target on the fixed beam 7200 times, and the ablation depth was measured by laser rangefinders.

3.2. The experimental results

1) Experimental study on the propulsion performance of aluminum ablated by millimeter light spot ablation by short pulse laser.

Figure 4(a) shows the impulse of pulsed laser ablation of aluminum target with different energy and spot diameter. It can be seen from the figure that the impulse of aluminum target increases with the change of monopulse laser energy in an inverse and non-linear relationship with spot diameter. When spot diameter increases to 7.7mm, the impulse increases with the increase of monopulse energy gradually decreases.

Figure 4(b) shows the impulse coupling coefficient of aluminum target ablated by pulsed laser with different energy and spot diameter. It can be seen from the figure that the impulse coupling coefficient
of aluminum target ablated by laser with millimeter light spot also increases with the change of laser energy and is inversely proportional to spot diameter and non-linear. When spot diameter increases to 6.6-7.7 mm, the increase of single pulse energy decreases the increase of impulse coupling coefficient.

![Fig.4 The relationship of impulse and impulse coupling coefficient with single pulse energy and spot diameter](image)

By the above experimental results it can be seen that the laser energy within the 1000 mj, as large as possible while assuring ablation area, under the condition of the laser spot diameter is 6.6-7.7 mm, mm level spot of laser ablation of aluminum impulse and impulse coupling coefficient can be considered to be the optimal solution, for subsequent repeat impulse millimeter level spot ablation experiments, The selection of spot size provides reference.

2) Experimental study on the morphology of aluminum target pits ablated by millimeter light spot ablation by repeated pulsed laser.

A laser with a single pulse energy of 1.02 J and a repetition frequency of 4 Hz is used to ablate the aluminum target loaded on a fixed beam with a number of 7200 pulses. The ablations of different spot sizes are shown in Figure. 5. Spot diameter D=9.6 mm, low energy density 1.41 J/cm², incomplete ablation, ablation product residues, target pit surface smooth and black; The spot diameter D= 8.6 mm, the energy density was 21.76 J/cm², the ablation was incomplete, there were ablative product residues, and the target pit surface was smooth and black, compared with the target pit surface of D=9.6 mm, the black residue was reduced. The spot diameter D=7.7 mm, the energy density was 22.19 J/cm², the ablation is complete, the more clear Gaussian energy distribution ablation ring can be seen, the ablation plane is flat. The spot diameter D=6.6 mm, the energy density was 22.98 J/cm², the ablation is relatively complete, also has a clear Gaussian energy distribution ablation ring, the ablation plane is flat. The spot diameter D= 5.5 mm, the energy density was 24.29 J/cm² the ablation was complete, and the ablation plane began to concave. Spot diameter D=3.5 mm, energy density was 10.6 J/cm², ablation complete, ablation plane obviously concave.
Figure 5 Target pit morphology of aluminum ablated by millimeter-grade laser spot ablation by repeated pulse laser with fixed energy.

Figure 6 shows the measurement results of target pit depth after repeated pulse ablation experiments when spot diameters are 9.6 and 8.6mm. As can be seen from the figure, due to the low energy density and incomplete ablation, the cross section height is higher than the target surface due to the serious accumulation of ablation products. "O" refers to the area where the black ablative products are more densely packed, so that the laser can not be ranging, and the bad point appears. In the figure, there are more bad spots in the 9.6mm spot than in the 8.6mm spot, which indicates that the larger the spot area, the more incomplete ablation and more bad spots.

Figure 7 shows the measurement results of target pit depth after repeated pulse ablation experiment when spot diameters are 7.7mm, 6.6mm, 5.5mm and 3.5mm. As can be seen from the figure, when the spot diameter decreases gradually, a clear target pit boundary formed by ablation melting begins to appear, and the depth of the target pit is also significantly lower than the target surface, indicating that the laser irradiation of aluminum target at this time produces effective ablation. In addition, when the...
spot diameter is 3.5mm, the inner surface of the target pit is smooth and concave obviously. The inner surface of target pits with spot diameters of 6.6mm and 5.5mm is smooth, but the aluminum target with spot diameters of 5.5mm is ablated more fully, so the inner surface of target pits is smoother, which is roughly consistent with the results obtained by direct observation.

4. Analysis and discussion

The laser irradiates the target material to make the surface structure material absorb the laser energy and convert it into the internal heat energy of the target material, and then through the internal diffusion, it affects the physical and mechanical properties of the target material.

Generally, there is no body heat source when the infrared wavelength laser irradiates the metal target. The laser irradiation is a surface heating process, so the body heat source can be changed to surface heat source on the surface boundary conditions according to certain boundary conditions.

Therefore, the temperature field distribution of millimeter spot ablation of aluminum by fixed energy repeated pulse laser can be regarded as surface absorption, and the temperature field distribution of incident laser power density — $q_{inc}(r, t)$ is gaussian distribution. Then its axisymmetric temperature distribution$^{[10]}$ is:

$$
T(r, z, t) = \frac{Aq_{inc,0max}\omega^2}{\kappa} \sqrt{\pi} \int_0^\infty \frac{B(t-t_1)}{t_1(4\kappa t_1 + \omega^2)} \ dt_1 \cdot \exp\left(\frac{z^2}{4\kappa t} \ - \ \frac{r^2}{4\kappa t_1 + \omega^2}\right)
$$

Type:

$q_{inc,0max}$ : Maximum power density of spot center; $B(t)$ : The time distribution function;

$\kappa$ : Thermal conductivity of materials; $\omega$ : Gaussian beam radius.

As the target continuously absorbs laser energy and converts it into its own internal energy, the surface temperature of the target continues to rise to the boiling point and gasification occurs. The gasification products will continue to absorb laser energy and further ionize to form plasma. The expansion movement of plasma generates impulse.
Clausius-clapeyron equation is used to calculate the saturated vapor pressure and density of the target surface through the target surface temperature[11]:

\[ N_s(T_s) = N_a \exp\left[\frac{\Delta H_{av}}{Q} \left( \frac{1}{T_b} - \frac{1}{T_s} \right) \right] \]

\[ \rho_s = \frac{N_s}{k_B T_s} \times \frac{m_v}{s} \]  

(4)

Type:
- \( N_s \): Saturated vapor pressure on the surface of the target;
- \( T_s \): Surface temperature of target;
- \( T_b \): Boiling point temperature of target material when \( N_a = 1 \) atm;
- \( \Delta H_{av} \): Gasification enthalpy;
- \( Q \): Gas constant;
- \( k_B \): Boltzmann constant;
- \( m_v \): Atomic mass of vapor.

Because the pulse width of laser is nanosecond, the duration of ablation pressure on target surface is very short, so impulse can be used to characterize its macroscopic mechanical effect. For a pulsed laser, the impulse coupling coefficient can be expressed as the ratio of the cumulative ablation pressure on the target surface to the power density of the incident laser:

\[ C_m = \frac{N}{q_{inc}} = \frac{4Nt}{E \pi D^2} \]

(5)

It can be known from equations (3), (4) and (5):

- \( T_s \propto q_{inc} \), \( N \propto T_s \), \( I \propto N \), \( C_m \propto N \)
- \( I \propto \frac{1}{D^2} \), \( C_m \propto \frac{1}{D^2} \)

(6)

It can be known from Equation (6), the coupling coefficient of impulse and impulse increases with the increase of single pulse energy, while the increase of spot diameter accelerates the attenuation of the coupling coefficient.

The spatial distribution of laser energy is Gaussian distribution, so under the same laser energy, the larger the spot diameter, the more uniform the spatial distribution of laser energy. And the decrease of energy density will cause the ablation effect to decrease. Therefore, the plane of the target pits with spot diameters of 9.6mm and 8.6mm is relatively flat, and at the same time, black ablation products with a relatively uniform distribution appear on the surface of the target pit. However, target pits with smaller spots of 3.5mm have smooth surface and obvious concave phenomenon.

5. Conclusion

Based on the results and discussions presented above, the conclusions are obtained as below:

In the experiment of nanosecond pulse width laser irradiating metal aluminum, the 5~7mm diameter spot can take into account the propulsion performance, spot size and target pit plane flatness; Due to the low energy density of 7~10mm light spot, the target ablation is incomplete and the propulsion performance is poor; 3~5mm light spot has high energy density. Under repeated pulse ablation, the target pit plane will be obviously concave.

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