Study on the optimum parameters for laser-solid interaction

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The optimum parameters for laser propulsion are discussed, such as laser induced pressure on targets, interaction parameters (C_m, $I_{\rm sp}$) and optimum laser intensity I_s, etc. It is verified that the larger laser power density will induce higher thrusting force. It is also found that, to drive a 1.010-kg target during confined laser ablation in vacuum and a 17.45-g one during direct laser ablation in air at the standard pressure, the needed minimum power intensities are on the same order of magnitude.

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The concept of laser propulsion (LP) is not very new. Kantrowitz introduced the idea in 1972[1−3]. He suggested using remotely generated laser power to heat a propellant sufficiently to produce a vapor or plasma jet for thrust, which is the principle of laser ablation space propulsion. Through a decade of active research in the mid-1970s and mid-1980s, it culminated in the first field demonstrations led by Mead and Myrabo in the mid-1990s, which describing an air-breathing, laser-driven aero spike flyer or "lightcraft", this flyer has a very specific design featuring light concentration near the rim of a Frisbee-like shape that provides thrust from laser-supported detonations in air. Myrabo and Bohn have actually flown small "lightcraft" devices to altitudes of 10 − 30 m using tens-of-kW lasers[1,2]. It is also discussed that a laser space propulsion concept dubbed orbital debris removal using ground-based sensors and lasers (ORION) capable of clearing near-earth space of 1 − 10-cm debris using a ground-based laser in two years. Phipps *et al.* showed that there is an optimum set of parameters for laser space propulsion that can reduce the cost of lifting mass to low earth orbit (LEO) 100-fold[2].

The classic analysis of high-intensity laser interaction with materials divides into two regimes: laser supported combustion (LSC) and laser supported detonation (LSD)[3]. Although the analysis originally developed from the aerodynamicists for interactions in air, the concepts can also apply to a solid target in vacuum. With the energy density $U = 1500\ \mathrm{J/cm^3}$, combination of laser intensity I ($\mathrm{W/cm^2}$), pulsewidth τ (s) and wavelength λ (cm), for our purposes, it is sufficiently accurate to describe shock formation by the relationship[4]

$$P_{AB} = 5.83\frac{\Psi^{9/16}}{A^{1/8}}\frac{I^{3/4}}{(\lambda\sqrt{\tau})^{1/4}}, \qquad (1)$$

where Ψ equals to the coefficient $(A/2)[Z^2(Z+1)]^{1/3}$, A is the plasma average atomic mass number, P_{AB} is the laser-initiated plasma-mediated pressure on a plane surface, and Z is the plasma average ionization state number. Table 1 uses these values to illustrate the order of magnitude of pressure predicted by Eq. (1) during a 970-nm laser pulse front-illuminating a standard-material target in vacuum.

Table 1. Laser-Induced Pressure Versus Laser Parameters[3]

Pulse Duration τ	4 ms	10 ns
Conditions	Laser Welding	Laser Fusion
Intensity I	13 $\mathrm{kW/cm^2}$	5.9 $\mathrm{GW/cm^2}$
Pulse Energy	4 mJ	1800 J
Pressure ($\times10^5$ Pa)	0.43	10k

For coupling coefficient, Eq. 1 gives

$$C_m = 5.83\frac{\Psi^{9/16}}{A^{1/8}(I\lambda\sqrt{\tau})^{1/4}}. \qquad (2)$$

Note that Eq. (2) predicts C_m will become very large in the limit $I\lambda\sqrt{\tau} \to 0$. This may seem counterintuitive, but one has to remember that C_m is just the ratio of a momentum to energy and so varies $\sim 1/v$, becoming very large as $v \to 0$. That is to say, there is an optimum C_m for all missions, related to the Δv which is to be supplied[3]. It requires laser fusion conditions in an unconfined target to create a shock in the target. In a confined target, on the other hand, it takes far less laser intensity. Fabbro *et al.* have shown pressure amplification up to a factor of 70 by confining the plasma between an anvil and a glass plate through which the laser light is introduced to the target[5]. We have also demonstrated the different effects with different confined materials. And good results have been obtained by using a water film to provide ablation confinement for industrial applications[6].

The laser momentum-coupling coefficient C_m is defined as the ratio of momentum flux delivered to a target system to the incident laser pulse fluence W. Momentum transferred is mainly due to formation of an ablation jet on the surface of the target, and only very slightly due to light pressure.

$$C_m = \frac{J}{W} = \frac{m\Delta v}{W}\ \ (0.1\ \mathrm{N/MW}). \qquad (3)$$

For opaque materials in vacuum irradiated by pulsed lasers at or above plasma threshold intensity, with Mach number M_A, C_m is given within a factor of 2 by[7]

$$C_m = 3.95M_A^{0.44}/[Z^{0.38}(Z+1)^{0.19}(I\lambda\sqrt{\tau})^{0.25}]. \qquad (4)$$

In the ablation process, Q^* joules of laser light is consumed to ablate each gram of target material: $Q^* = \frac{W}{\Delta m}$, the two elements of the pairs (C_m, Q^*) and (C_m, $I_{\rm sp}$) are not independent, but increasing one decreases the other. And C_m, $I_{\rm sp}$ are materials depended (see Fig. 1).

$$C_m Q^* = V_E = g I_{\rm sp} \ \ {\rm cm/s}, \tag{5}$$

and

$$g C_m I_{\rm sp} = C_m^2 Q^* = 2\eta_{AB}, \tag{6}$$

where V_E is the exhaust velocity of the ablation jet, $g = 980$ cm/s^2 is the acceleration of gravity at the earth surface, and η_{AB} is the efficiency with which laser energy is converted to exhaust kinetic energy. The impact of $\eta_{AB} \leq 1$ is that the C_m value deduced from a given V_E may be less than the maximum permitted by conservation of energy. But the specific impulse $I_{\rm sp}$ up to 8000 s has been measured with pulsed lasers[7].

Experimental data shows that the optimum target surface intensity $I_{\rm s}$ for achieving the best coupling is just above that plasma formation, and is given approximately for all opaque materials by $I_{\rm s} = F\sqrt{\tau}$ W/cm^2, where $F \approx 4 \times 10^4$ is constant[2].

Based on analysis of data reported in Ref. [8], a formula that looks approximately thermal (fluence $\Phi \alpha \tau^{0.5}$) will describe the fluence required to achieve the pressure given by Eq. (5) as a function of pulse duration, and wavelength does not matter very much[6].

While in ion collimation, when a short light pulse is focused on the surface, supersonic ejection of matter is directional process. Maximum in energy and mass flow occur normal to the surface and can be described with a simple cosine function $E(\theta) = E_0 \cos^n(\theta)$[9], where θ is the angle of ejection with respect to the surface normal, E stands for energy or density of ejected atoms, and n depends on ablation conditions and varies from 1.0 to 4.0 – 8.0.

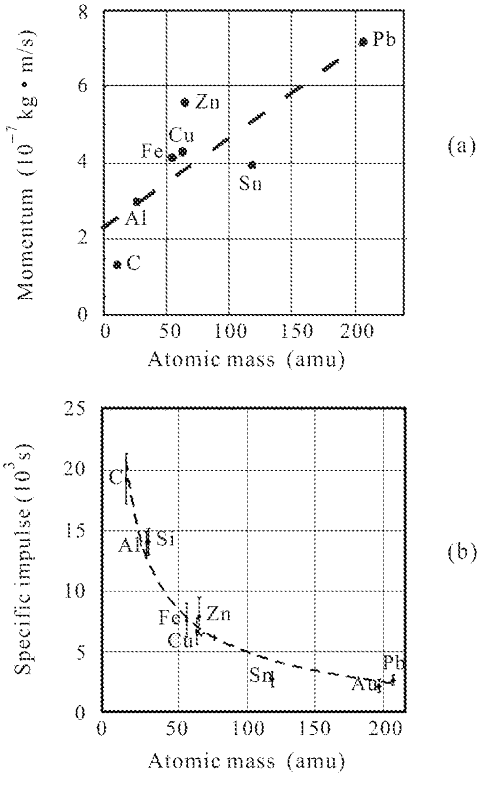

Fig. 1. (a) Laser momentum coupling coefficient versus atomic mass of propellant; (b) specific impulse versus atomic mass of propellant.

The condition of total reflection of light by a plasma frequency exceeds a critical value $\omega_{\rm pc} = \omega$, where ω is the frequency of incident light. This critical electron density $N_{\rm ec}$, corresponding to $\omega_{\rm pc}$, can be derived from

$$N_{\rm ec} = \frac{m\varepsilon_0 \omega_{\rm pc}^2}{e^2} = \frac{m\varepsilon_0 \omega^2}{e^2}, \tag{7}$$

where m and e are electron mass and charge, and ε_0 denotes the permittivity of free space. Assuming that impact ionization is the dominant mechanism in electron density growth (i.e. neglecting multiphoton ionization) and that the time scales are short enough so that all major loss mechanisms can be neglected, it can be resulted that

$$\frac{{\rm d}N_{\rm e}}{{\rm d}t} = vN_{\rm e}, \tag{8}$$

where v is the ionization rate. Solving Eq. (8) for t yields $t = \frac{\ln(N_{\rm ec})}{v}$, the strictest limit for critical pulse length $t_{\rm c}$ is of the order of 100 ps, and it can actually be longer if two-photon absorption and electron losses are taken into account[10].

In the experiments, the diffraction limited laser beam from a pulsed $\rm Cr^{4+}$:YAG/Nd:YAG laser is capable of emitting 87.5-mJ pulses at 1.064 μm, which are focused to a peak power density at the target surface using a plano-convex lens (f = 230 mm). The pulse width is approximately 35 ns (FWHM). The pulsed energy was monitored with a PT-IC laser energy meter, and the energy-time history of the pulses was detected by a photodiode PIN in conjunction with an oscilloscope.

With the spot diameter of 0.315 mm, which is observed with a 10× microscope, we can conclude that during confined laser ablation in vacuum, the minimum power intensity necessary to drive the target (1.010 kg) is 7.1986×10^{10} W/cm^2, and double-layered target is found to be the better propellant[11]. From Table 2, we can also derive that the larger laser energy density is, the higher thrusting force will be. And we find that during direct laser ablation in air at the standard pressure with black coatings on the targets, the minimum power intensity necessary to drive the target (17.45 g) is 5.042×10^{10} W/cm^2. Fabbro *et al.* have discussed that the shock created in the confined target is at least 70 times of that created in an unconfined target, and to yield the same laser-induced pressure, the laser energy is at least two orders of magnitude more than that needed in the confined target. From the datum reached above, we can get that to drive a 1.010-kg target during confined laser ablation in vacuum and a 17.45-g one during direct laser ablation in air at the standard pressure, the needed minimum power intensities are on the same order of magnitude. And the error bars associated with the measurement technique do not account for scatter in the datum.

Table 2. Summarized Datum Acquired in the Direct Laser Ablation of Various Material Targets in the Range of Measurement Errors

Torsion Balance	I (GW/cm^2)	m (g)	R (cm)	A (mm)	Torsion Angle θ (rad)
1	43.36	16.55	1.841	41	0.1380
2	305.78	17.00	1.841	63	0.2140
3	1.196×10^5	12.80	1.838	117	0.3970
4 (Double Layer)	2.1663×10^4	7.50	1.349	178.44	0.6043
Pendulum	I (GW/cm^2)	m (g)	L (cm)	A (mm)	Tilt Angle α (rad)
1	573.20	7.50	94.775	6.85	0.0230
2	129.94	9.39	95.885	6.05	0.0206
3	71.29	17.45	98.950	3.50	0.0120
4	50.42	17.45	96.525	0	0

We have proposed a new rocket model combining air breath propulsion with ablative laser propulsion, and demonstrated the feasibility of it in the experiments. And it is successful in launching a simulate bullet (with the mass of 5.87 g) up to 1.48-m height with a single laser pulse[12]. Having demonstrated the feasibility of the laser driven micro-lightcraft, we are continuing to plan experiments to research on the coupling of pulsed laser to various targets. Several applications of laser ablation may benefit from this ablation geometry.

In conclusion, from the historically first application of laser cutting, machining, welding, and laser shock processing, it has delivered to laser fabrication, rapid prototyping and laser micro engineering. The properties of laser light, which are most beneficial for material processing, are high brightness and high energetic efficiency[4]. Depending on the application, narrow (or broad) bandwidth, a specific or unusual wavelength, ultrashort pulse duration, and high peak or high average power may also be important features. Laser advanced material processing has such a wide range of current applications, microscopic applications and exotic and futuristic applications, including a diode-laser-driven micro-Newton thruster for micro- and nano-satellites, and proposals to use lasers to clean hundreds of thousands of small but hazardous space debris from near-earth space and to launch 5-kg payloads into near-earth orbit.

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References

1. A. V. Pakhomov and D. A. Gregory, AIAA Journal **38,** 725 (2000).
2. C. R. Phipps, J. P. Reilly, and J. W. Campbell, http://members.aol.com/orionweb3/launch1.pdf (Feb. 10, 2001).
3. C. R. Phipps, J. R. Luke, G. G. McDuff, and T. Lippert, Proc. SPIE **4760,** 833 (2002).
4. C. Phipps, Riken Rev. **50,** 11 (2003).
5. R. Fabbro, J. Fournier, P. Ballard, D. Devaux, and J. Virmont, J. Appl. Phys. **68,** 775 (1990).
6. Y. Takashi, P. Claude, A. Keiichi, Y. Masashi, N. Ryu, M. Hitoshi, O. Youichi, B. Choijil, N. Masamichi, F. Etsuo, Y. Kunio, and K. Itsuro, Appl. Phy. Lett. **80,** 23 (2001).
7. C. R. Phipps, http://www.llnl.gov/planetary/pdfs/Interdiction/04-Phipps.pdf (2002).
8. C. Phipps and J. Luke, http://members.aol.com/orionweb2/AIAApart1.pdf (2001).
9. A. V. Pakhomov, A. J. Roybal, and M. S. Duran, Applied Spectroscopy **53,** 979 (1999).
10. A. V. Pakhomov and D. A. Gregory, in *Young Faculty Research Proceedings* (the University of Alabama in Huntsville, 2000).
11. L. Y. Lin, S. B. Wang, D. H. Guo, and H. X. Wu, Chin. Phys. Lett. **20,** 1498 (2003).
12. D. H. Guo, H. X. Wu, S. B. Wang, X. J. Hu, and Z. P. Tan, Chin. J. Lasers (in Chinese) **29**(Suppl.), 549 (2002).