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Technical Notes

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Ambient Pressure Dependence of Laser-Induced Impulse onto Polyacetal

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Nomenclature

C_m = momentum coupling coefficient, ratio of impulse to laser energy
P_0 = ambient air pressure in test chamber
t = elapsed time from initiation of laser pulse irradiation
ϕ = effective laser fluence on ablator surface
ξ = ratio of ablated mass to laser energy

I. Introduction

LASER ablation can be usefully employed to generate a propulsive impulse on an object not only in the atmosphere but also in vacuum [1–3]. Larson et al. [4] proposed a launch vehicle propelled by repetitively pulsed laser ablation. Several authors [5–9] show that favorable propulsion performance in the atmosphere can be achieved with a polymer material, polyacetal, which is commercially named “Delrin” or is abbreviated as “POM.” The ablated gas from this material does not contain much air pollutant. Targeting space applications, the laser-ablative-propulsion performance of metals and polymers at low ambient pressures has been intensively investigated [10–17]. For many kinds of metals and polymers, C_m ranges from 10 to 100 μN-s/J, and depends strongly on the characteristics of the laser pulse. According to measurements by Gregg and Thomas [10], metallic materials have an optimum laser intensity that maximizes C_m. Phipps et al. [12] formulated experimental C_m characteristics of aluminum alloys and several polymers in terms of the intensity, width, and wavelength of the laser pulse. C_m can be further increased by utilizing the so-called “volume absorber” [13] or layered target [14]. Recent measurements by D’Souza and Ketsdever [17] of C_m for polyacetal at low ambient pressure using a frequency-doubled Nd:YAG pulsed laser showed peak of 110 μN-s/J at a laser intensity of the order of 10^9 W/cm^2.

Several authors investigated the influence of ambient pressure on C_m [18,19]. Pakhomov et al. [18] measured the impulse generated on an aluminum surface irradiated by a CO_2 laser pulse whose pulse width was 200 ns; C_m decreased monotonically with decreasing ambient pressure. In Dufresne et al.’s surface-pressure measurement [19], the ambient-pressure dependence of C_m for aluminum was quite sensitive to the laser pulse width. For polymer materials, Beverly and Walters [20] measured the CO_2-laser-induced shock pressure in cellulose acetate and polymethylmethacrylate. The peak shock pressures exhibited the complex dependence on the ambient pressure. The ablative impulse dependence of materials other than aluminum warrants further investigations.

To quantitatively evaluate the feasibility of laser-ablative-propulsion systems, the propulsive performance of polyacetal over a wide range of ambient pressure needs to be known. In the present paper, the influence of the ambient pressure on the impulse characteristics of polyacetal is investigated experimentally using a transversely excited atmospheric (TEA) CO_2 pulse laser.

II. Experimental Apparatus

A TEA CO_2 pulse laser (TC-300, General Physics Institute, Moscow, Russia) is used to ablate a surface of a polyacetal disk, with a 42 mm diameter and a 0.5 mm thickness, with a 0.5-mm-thick and 5-mm-long rim around its periphery and a mass of 1.4 ± 0.1 g [9]. The output laser beam has a 150×150 mm square cross section with an 80×80 mm square dark area that is the projection of a mirror for the unstable resonator in the laser discharge cavity. The laser power history consists of a leading edge spike of 50 ns FWHM containing 10% of the total laser pulse energy and a following slowly decaying tail, which lasts for 2.5 μs during which 90% of the total energy is irradiated. Figure 1 shows the schematic illustration of the experimental setup. The laser beam is introduced into a test chamber, 1 m in inner diameter and 3 m in length, through a ZnSe window after passing through a ZnSe lens whose focal length is 1.66 m. The beam cross-section on the disk surface is a 30×30 mm square with a 16×16 mm square dark area. The laser beam can be sent through Mylar sheets to adjust the effective laser energy; the transmitted laser energy is controlled by its thickness. The laser pulse energy that is sent onto the disk is measured using an energy meter (LREM1800, LAMET Ltd.) in the test chamber and it ranges from 23 to 290 J; its shot-to-shot uncertainty is maintained to better than ±5%. As a result, ϕ is varied from 3.6 to 45 J/cm^2. The disk is initially mounted in a through-hole of a holder plate, and is launched horizontally by the laser irradiation. The impulse is measured from the disk time-of-flight past two parallel diode-laser beams separated by a distance of 50 mm. The decrease in the momentum due to the aerodynamic drag is less than 4% [9], and is ignored in analyzing the impulse characteristics. The ablation jet and shock wave are visualized by the Schlieren method using a high-speed framing camera (ULTRA8, DRS Technologies) and a xenon flash lamp (energy; 200 J, duration; 350 μs).

III. Results and Discussions

Figure 2 shows framing Schlieren images at three ambient pressures. In all cases, ϕ is set to 44.5 ± 0.2 J/cm^2. In the case of

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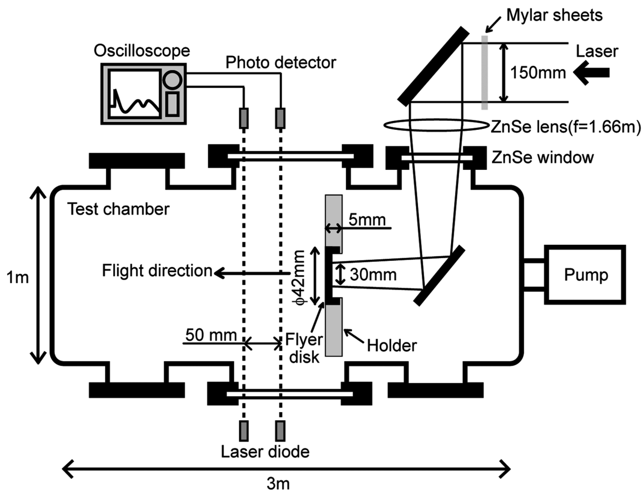

Fig. 1 Schematic of experimental setup.

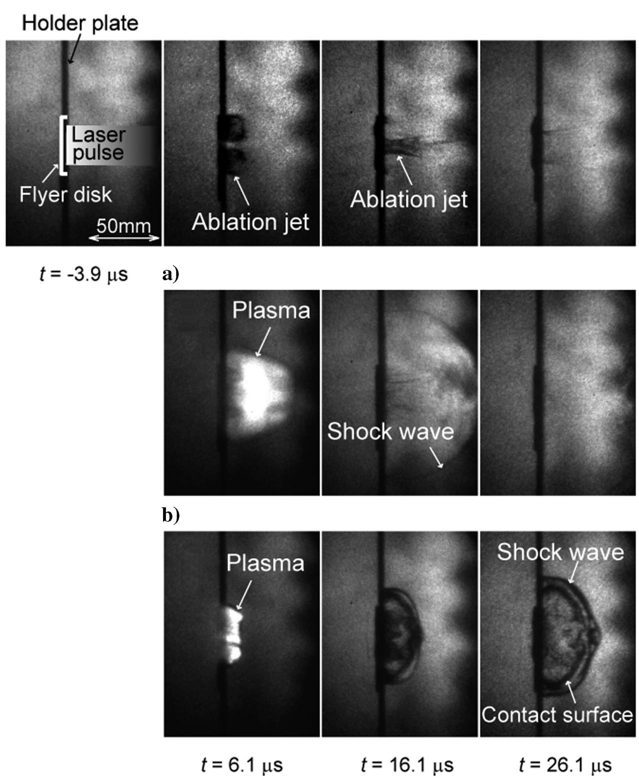

Fig. 2 Framing Schlieren images of laser-induced flow at P_0 = a) 10 Pa, b) 2 kPa, and c) 100 kPa, respectively. $\phi = 45\ \mathrm{J/cm^2}$, framing interval; 10 μs, exposure time; 20 ns.

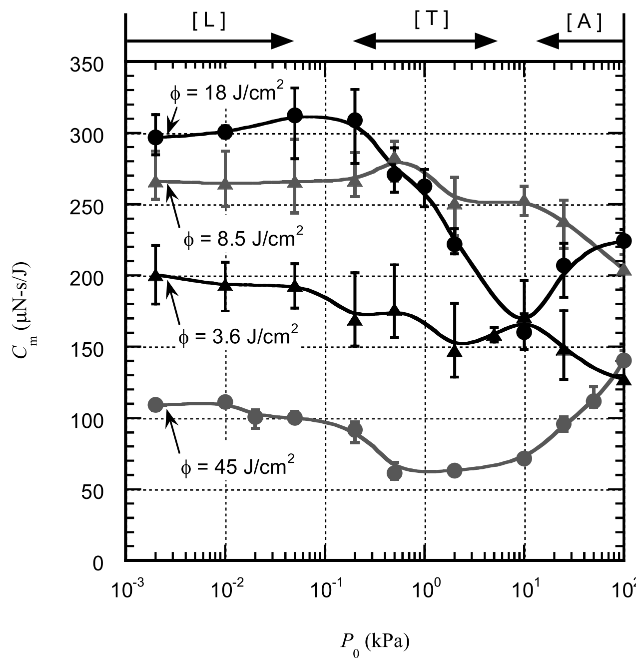

Fig. 3 C_m, vs P_0, ▲; $\phi = 3.6\ \mathrm{J/cm^2}$, ▲; 8.5 $\mathrm{J/cm^2}$, ●; 18 $\mathrm{J/cm^2}$, ●; 45 $\mathrm{J/cm^2}$.

Fig. 2a, $P_0 = 10$ Pa, the squared-toroidal jet is ejected from the surface. At $t = 16.1\ \mu$s, the lateral expansion of the ablation gas forms a focused jet along the axis of the laser beam. The jet continues to be observed even at $t = 26.1\ \mu$s while the laser irradiation is terminated at $t = 2.5\ \mu$s. In the higher-P_0 cases, b) $P_0 = 2$ kPa and c) $P_0 = 100$ kPa, the impulse generation processes are strongly influenced by the presence of the ambient air. The laser energy is absorbed through the breakdown in the air and/or in the ablation jet, which generates a luminous plasma observed over the target at $t = 6.1\ \mu$s. As will be discussed later, the impulse is caused both by the ejection of the ablation gas from the surface and by the plasma expansion confined by the ambient air. As observed at $t = 16.1\ \mu$s, the plasma expansion and the ablation gas ejection drive a propagating hemispherical shock wave. The propagation speed of the shock wave depends on the ambient pressure; it is higher in b) than in c). In case c), the contact surface between the plasma and the surrounding air is clearly visualized.

Figure 3 shows the relation between C_m and P_0 for different values of ϕ. Among the tested conditions, the largest C_m is achieved for $P_0 \leq 100$ Pa and $\phi = 18\ \mathrm{J/cm^2}$. Such an ambient-pressure dependence of C_m is unusual. First, let us discuss the most important impulse characteristics obtained at $\phi = 18\ \mathrm{J/cm^2}$. The P_0 dependence of C_m seems to comprise three regimes: the low-pressure regime (L); $P_0 \leq 100$ Pa, the transitional regime (T); $100\ \mathrm{Pa} < P_0 \leq 10$ kPa, and the air-confinement regime (A); $P_0 > 10$ kPa. In regime L, C_m exceeds 300 μNs/J and is almost independent of P_0. This value of C_m is more than 10 times as high as that obtained in previous work [12] using a CO_2 pulsed laser at low ambient pressures with aluminum alloys, Kevlar epoxy, carbon, graphite epoxy, and carbon phenolic, and it is of the same order of magnitude with celluloid, which is called a "volume absorber" in Phipps et al. [13]. Moreover, it is 3 times as high as the maximum C_m obtained with polyacetal using a frequency doubled Nd:YAG laser [17].

Figure 4 shows the relation between ξ and P_0. ξ exhibits a P_0 dependence similar to that of C_m. In the L regime, for $\phi = 18\ \mathrm{J/cm^2}$, ξ is 180 μg/J, which is one tenth of the value reported in Phipps et al. [13] for a volume absorber, celluloid.[§] Thus, polyacetal should be categorized as a surface absorber. In regimes T and A, both C_m and ξ are smaller than in regime L, and are more sensitive to P_0. The ambient air of nonnegligible pressure has two competing effects on the impulse performance: the first one is laser absorption in the plasma; once plasma is generated above the surface, it prevents the laser energy from being fully delivered to the surface, thereby decreasing the ablation pressure over the surface ("plasma-shielding" effect [19–21]; The so-called "plasma-clamping" [22] is closely related to this effect). The second one is that the ambient air acts as a confinement medium; the ambient air above the surface mechanically impedes the plasma and the ablation gas against expansion, resulting in the impulse enhancement ("air-confinement" effect). This effect is supposed to be dominant in the laser ablation of metallic materials in air atmosphere [18–21,23]. In regime T, the P_0 dependences of C_m and ξ should be dominated by the plasma-shielding effect: the fraction of the laser energy that is absorbed in the

§Note that in [13], the inverse of ξ is referred to as "ablation parameter" designated by Q^*.

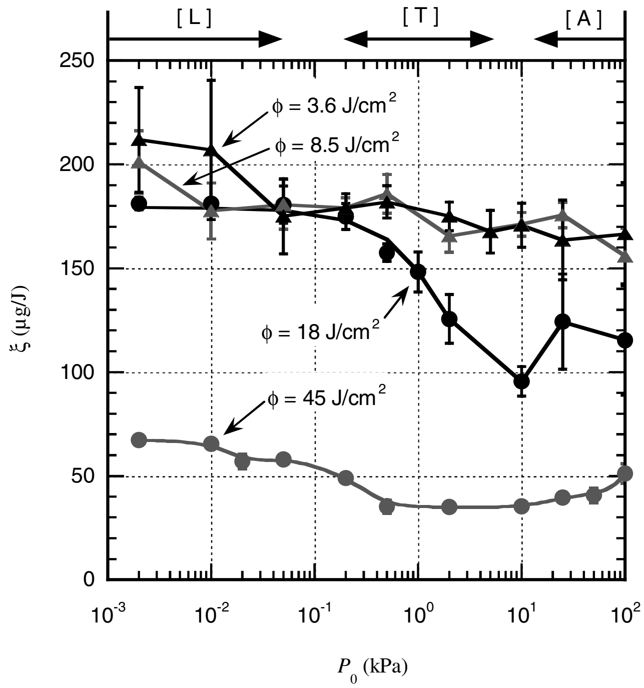

Fig. 4 ξ **vs** P_0**, ▲;** $\phi = 3.6\ \mathrm{J/cm^2}$**, ▲;** $8.5\ \mathrm{J/cm^2}$**, ●;** $18\ \mathrm{J/cm^2}$**, ●;** $45\ \mathrm{J/cm^2}$**. The error bars for** $\phi = 45\ \mathrm{J/cm^2}$ **are smaller than the symbol size.**

plasma increases with P_0, and hence both C_m and ξ decrease with increasing P_0. In regime A, C_m increases with increasing P_0 as the air-confinement effect becomes dominant.

The variations of C_m and ξ strongly depend on ϕ. For $\phi = 45\ \mathrm{J/cm^2}$, ξ is much smaller than for $\phi \leq 18\ \mathrm{J/cm^2}$ over the entire tested range of P_0. For this high fluence, the penetration depth of the ablating layer is reduced due to the so-called "self-regulation" effect [12]. Moreover, in regimes T and A, the plasma-shielding effect should be responsible for the decrease in ξ. Correspondingly, C_m for $\phi = 45\ \mathrm{J/cm^2}$ is much smaller than for $\phi \leq 18\ \mathrm{J/cm^2}$ as well. In regime L, C_m increases monotonically with ϕ up to $18\ \mathrm{J/cm^2}$, and then begins to decrease. This ϕ-dependence of C_m agrees qualitatively with the results reported in [10,12,17]. However, the mean intensity corresponding to the optimum fluence ($18\ \mathrm{J/cm^2}$) is of the order of $10^6\ \mathrm{W/cm^2}$, and is more than 2 orders of magnitude lower than the optimum intensity reported in previous literature. As discussed in Ref. [12], the optimum intensity strongly depends on the laser pulse duration and also on the material properties. For $\phi \leq 8.5\ \mathrm{J/cm^2}$ and $P_0 < 50$ Pa, ξ increases slightly with decreasing P_0. This may suggest that even at such a low-pressure level, the physicochemical processes of laser ablation could be interfered by the ambient air. At the same fluence level, in regimes T and A, both C_m and ξ decrease gradually with P_0 for a reason that is not clear at present.

IV. Conclusions

Favorable impulse performance is obtained with polyacetal even at low ambient pressures; for $P_0 \leq 100$ Pa and $\phi = 18\ \mathrm{J/cm^2}$, C_m reaches 300 μN–s/J, which is higher than the value obtained at atmospheric pressure. For $P_0 > 100$ Pa, under the influence of two competing effects, the impulse characteristics exhibit complicated behaviors. Moreover, the performance is quite sensitive to the laser fluence. For space applications, the above-mentioned favorable performance should be obtained with a variety of materials in vacuum, which requires further material examinations and associated diagnostics.

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