Impulse Transfer from Pulsed CO_2 Laser Irradiation at Reduced Ambient Pressures

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Abstract

EXPERIMENTAL and theoretical studies have been made of the impulse received by a target surface when irradiated by a high-power pulsed CO_2 laser at reduced ambient pressures. Correlation of experimental and theoretical results for aluminum targets indicates a maximum impulse-energy coupling coefficient $a_p \approx 2$ dyn s/J and an effective thermal coupling coefficient $a_t \approx 0.1$. Both theory and experiment show an increase in a_p with increasing ambient pressure. Structural deformation was experimentally demonstrated for an 1100 aluminum target.

Contents

Most of the previous work on impulse transfer from high-power laser pulses to surfaces, both experimental and theoretical, has been carried out for ambient air at or near 1 atm pressure, the measured impulse being dominated by the air environment.[1] The air above the target surface can become ionized, forming an absorptive plasma. At laser intensities above about 10^7 W/cm^2, this air plasma moves supersonically up the laser beam and away from the target, shielding the target surface from further direct radiation. This phenomenon is the well-known laser-supported detonation (LSD).[2,3] At low ambient pressures (densities), on the other hand, impulse data are more limited in quantity, and theoretical predictions and correlations are comparatively less well established. As the ambient pressure is lowered, the air plasma absorption length for laser energy increases, becoming comparable to or exceeding the width of the laser beam; the LSD wave in air becomes harder to maintain and eventually disappears.[3] In such cases, vaporization of the target material and the subsequent behavior of the vapor become the dominant factor in determining the impulse transfer. In the present work, both experimental measurements and theoretical calculations have been made of the impulse received by a target surface when irradiated by a high-power pulsed CO_2 laser at reduced ambient pressures.

The impulse experiments were carried out inside a 120-cm-diam × 160-cm-long vacuum tank. The pressure was varied from 10 to 0.01 Torr. The laser beam was admitted through a scintered NaCl window whose outside face was tilted to avoid reflecting energy back into the laser cavity. The 7.5-cm-diam beam was concentrated on the target by means of a copper mirror having a focal length of 114 cm located in the vacuum tank. By adjusting the distance between the mirror and the target, the laser spot diameter was varied from 0.38 to 2.3 cm. This was the only means used to adjust the flux density on the target.

A portion of the laser beam was monitored using a photon drag detector which was calibrated against a multithermocouple aluminum plate calorimeter. On the average, 80% of the pulse energy was contained in the first 8-14 μs, corresponding to a peak power of 14-26 MW. A weaker feature lasting 5-15 μs contained the remainder of the energy. The total beam energy varied from 110 to 270 J. The laser fluence on the target ranged from 60 to 2400 J/cm^2; the values being obtained from geometrical optics considerations.

Impulse was measured by a ballistic pendulum which had a 31-cm-diam face. The effective mass of the pendulum was $m = 62$ g, and its length was $L = 68$ cm, which checks against the measured period, $T = 1.66$ s. For small maximum lateral displacement of the pendulum from its equilibrium position, x_0, the impulse is given by $P = 2\pi \; mx_0/T$. Hence, the calibration factor is $P/x_0 = 235$ dyn-s/cm. In these experiments, the total swing $(2x_0)$ ranged from 0.6 to 6.4 cm.

Target materials chosen were 2024 aluminum alloy both painted and unpainted, carbon cloth, and carbon phenolic. Surface contamination on aluminum targets was removed by washing in Alconox and water. Calibration samples of this material exhibit absorption of 2-2.5% at 10.6 μm laser wavelength at low flux levels.

Evaporation of a solid into a vacuum due to laser irradiation has been studied theoretically by Anisimov,[4] who considered a one-dimensional case with a constant radiation flux. By treating the vapor as an ideal gas which expands into vacuum as a centered rarefaction wave, he solved the Boltzmann equation which governs the velocity distribution of vapor particles in a region within several mean free paths of the vaporizing surface (sometimes referred to as the "Knudsen layer"). The distribution outside of this layer is in local thermodynamic equilibrium and the gas motion is adequately described by equilibrium hydrodynamic equations. The results for $\gamma = 5/3$ are $T_1/T_e = 0.67$, $n_1/n_e = 0.31$, and $u_1 = c_1 = \sqrt{\gamma \mathcal{R} T_1}$, where T, n, and u represent temperature, number density, and velocity, respectively, the subscript e refers to the gas at the vaporizing surface, the subscript 1 refers to conditions just outside of the Knudsen layer, c is the sonic velocity, γ is the specific heat ratio, and $\mathcal{R}$ is the gas constant. The saturated vapor pressure p_e and number density n_e are related to T_e by the well-known Clausius-Claperon relations. These equations can then be solved together with the standard heat conduction equation, so that the impulse from evaporation can be calculated from

$$P_v = \int_0^\infty \int_{A_t} (p_1 + \dot{m} u_1) \, \mathrm{d}\sigma \mathrm{d}t \tag{1}$$

where $\dot{m}$ is the evaporation mass flux, dσ is a differential target surface area, A_t is the total target surface area, and t is the time. In general, numerical methods are necessary to evaluate the integrals.

Possible contributions to the total impulse from vapor expansion have also been considered. An approximate analysis[5] of the sudden expansion of a spherical gas cloud

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Index categories: Lasers; Ablation, Pyrolysis, Thermal Decomposition and Degradation (including Refractories).

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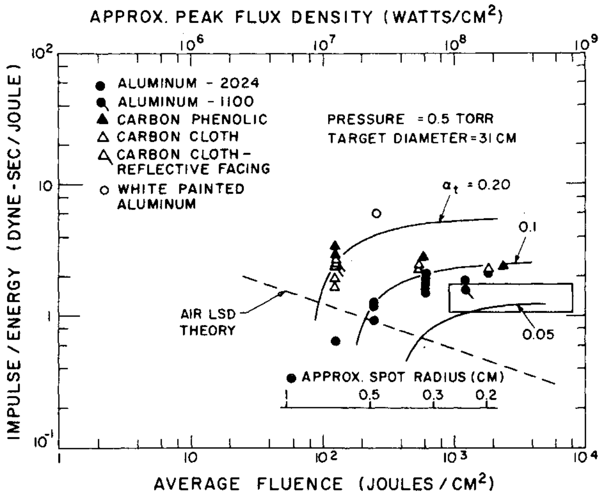

Fig. 1 Ratio of impulse imparted to various targets to incident laser energy (impulse/energy coupling coefficient) as a function of fluence incidence on target, at 0.5 Torr ambient pressure. Data of Apostol et al.[7] for bare aluminum are shown as the rectangular box. Solid curves represent present theoretical results for bare aluminum for several values of the thermal coupling coefficient a_t. Dashed line shows behavior of air LSD result.

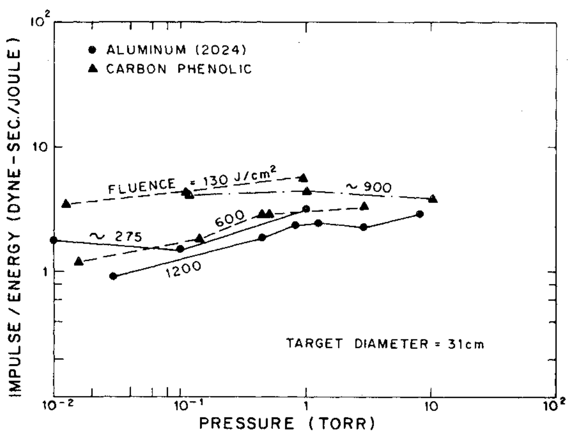

Fig. 2 Impulse per incident energy (impulse/energy coupling coefficient) as a function of ambient pressure.

into vacuum based on average, asymptotic values shows that the ratio between impulse from expansion into vacuum (P_x) and impulse from evaporation (P_v) is given by

$$\frac{P_x}{P_v} = \frac{\gamma}{2(\gamma+1)\sqrt{2\gamma(\gamma-1)}} \tag{2}$$

Thus, contribution to the total impulse from expansion into vacuum is small, being only 0.17, 0.22, and 0.33 of the total for $\gamma = 1.67$, 1.40, and 1.17, respectively.

At higher ambient densities, expansion into vacuum is no longer adequate for describing the expansion of the vapor cloud. Instead, a shock wave will be formed in the ambient gas; the expansion of the high-pressure vapor cloud behaves quite similarly to a strong explosion in an atmosphere. The idealized problem of a strong explosion in a homogeneous atmosphere is self-similar and has been studied by a number of people.[6] By using their results, we obtain the impulse delivered during this blast-wave expansion as

$$P_b = \frac{2Mc_I^2}{c_a\sqrt{2\gamma(\gamma+1)}} \tag{3}$$

where M is the total evaporated mass and c_a is the ambient sonic velocity. For typical conditions, expansion as blast wave contributes about 65% of the total impulse.

Impulse data obtained in the present work are shown in Figs. 1 and 2. Figure 1 shows the variation of impulse with fluence or flux density at a constant ambient pressure; for bare aluminum the agreement with data of Apostol et al.[7] is evident. Figure 2 illustrates the pressure dependence of the impulse. Our theoretical results for aluminum are also plotted in Fig. 1 for several values of the thermal coupling coefficient a_t (a_t was not measured in the present work).

Both experimental data and theoretical results indicate two regimes for the behavior of a_p vs laser flux. The low laser flux regime corresponds to unsteady heating of the target, such that target surface temperature and hence impulse from evaporation increase rapidly with laser flux and/or pulse time. For higher laser fluxes and/or longer pulses, a steady state is maintained where absorbed laser energy is nearly balanced by the energy of vaporization, resulting in an almost constant a_p. Correlation of experimental and theoretical results for aluminum indicates a maximum impulse/energy coupling coefficient $a_p \approx 2$ dyn-s/J and a thermal coupling coefficient $a_t \approx 0.1$. The impulse produced by LSD waves would show an $a_p \sim I_i^{-1/3}$ behavior, as shown in Fig. 1. This is in obvious disagreement with the data for aluminum at 0.5 Torr ambient pressure and supports the theoretical predictions of LSD maintenance thresholds.[3] The increase in a_p with ambient pressure exhibited by the experimental data plotted in Fig. 2 is consistent with the theoretical consideration that impulse from expansion increases with ambient pressure.

On an 1100 alloy aluminum target, the impulse imparted a dimple about 4 mm in diameter by 0.5 mm in maximum depth. This is the first demonstration, to the authors' knowledge, of thick target (>0.5 mm thickness) structural deformation by the mechanical loading of targets in vacuum by a pulsed laser.

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