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A study of energy conversion during Nd:YAG laser ablation of metal surfaces in air by means of a laser beam deflection probe

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Abstract: We measure shock wavefront transition times of optoacoustic (OA) transients generated in air during laser ablation and employ the solution of the point explosion model to determine blast energy of the OA transients. We examine the dependence of OA energy conversion efficiency on laser energy and pulse duration.

1. INTRODUCTION

Recent experimental evidence ⁽¹⁻³⁾ indicates that strong OA waves generated in the surrounding air during laser ablation of a solid surface bear much resemblance to the so called blast waves produced by explosions. Several features of spherical OA transients have been explained ⁽³⁾ by using the point explosion model ⁽⁴⁾, where an instant deposition of blast energy E in a small volume of a perfect gas is assumed.

In this contribution we make use of the fact, known in the physics of explosions ⁽⁴⁾, that the shock front trajectory of a blast wave is primarily determined by the blast energy E coupled into the wave and that it is possible to determine E by measurement of the shock trajectory. Employing a laser beam deflection probe we detect OA transients generated in air during Nd:YAG laser ablation of metallic surfaces. We measure their shock wavefront transit time t_s across the distance r_s between the probe beam axis and the irradiated surface, the acoustic wave transit time t_a for the same distance, pressure p_0 and temperature T_0 of the ambient air. Using this data and the theoretical shock trajectory based on a numerical solution ⁽⁵⁾ of the point explosion model we determine the blast energy. We examine the dependence of blast energy and energy conversion efficiency (the ratio of blast energy to incident laser energy) on laser energy and pulse duration. We analyze measurement uncertainty of this method and compare it with the uncertainty of a similar method ⁽⁶⁾ which is based on measurement of duration t_+ of the compressive phase of blast wave instead of the shock transit time t_s .

2. EXPERIMENT

We ablated the samples by two Nd:YAG lasers of 1.06 μm wavelength with pulses of 12 ns and 60 ns duration and beams focused to a spot of 0.5 mm in diameter on the ablated surface (FIG. 1). The sample assembly and the focusing lens were mounted together on a mechanical translator allowing precise setting of the distance r_s while maintaining constant focustion of the ablation beam. We detected deflection of the probe beam due to the passage of a OA wave by means of a quadrant photodetector with a 2.5 MHz bandwidth. By changing the incident laser energy E_l and pulse duration we acquired a set of OA signals for each sample. We started with the highest available energy and irradiated a spot on the sample surface with laser pulses of decreasing energy until the OA signal would disappear in noise. All signals were acquired in the single shot mode. Before the ablation experiment we calibrated the monitoring energy meter by means of another (traceable) calibrated energymeter with the probe in place of the sample.

FIG. 1 Experimental set-up

Most OA transients were detected in the weak shock range (far from the OA source). In this case, the transfer function of the laser probe can be adequately modeled⁽¹⁾ and its effect on the measured signal can be eliminated by means of deconvolution. The signal waveforms obtained after this processing agree very well with the theoretical density waveforms calculated by using a numerical solution^(4,5) of the point explosion model. Even with the signals detected in the intermediate shock range (e.g. FIG. 2), which exhibit substantial nonlinearities, the deconvolution procedure gives remarkably good results (FIG. 3).

FIG. 2 A typical measured signal (steel sample)

FIG. 3 Signal of FIG. 2 deconvolved with the transfer function of the laser probe (solid line) and the corresponding theoretical density waveform (dashed line)

3. THEORY

In the intermediate and weak shock range, only a numerical solution of the point explosion model exists which is commonly expressed in terms of dimensionless space $\xi = r/r_c$ and time $\tau = t/t_c$ coordinates with characteristic scaling parameters^(4,5):

$$r_c = (\alpha E/p_0)^{1/3} \quad \text{and} \quad t_c = r_c/c_0, \quad (\text{for air: } \gamma = 1.4 \text{ and } \alpha = 1.175)^{(5)} \quad (1)$$

where $c_0 = \sqrt{\gamma RT_0}$ is the sound velocity of the undisturbed gas while p_0 and T_0 are the ambient pressure and temperature respectively.

In principle, any theoretical function f of the form $\tau = f(\xi_s)$, giving some characteristic time τ of the dimensionless waveform at the dimensionless distance ξ_s from the source, can be used to determine blast energy E from the measured data. We employ ⁽⁶⁾ two such functions (FIG. 4): the shock trajectory $\tau_s = f_1(\xi_s)$, and the dependence of the compression duration $\tau_+ = f_2(\xi_s)$ on ξ_s ⁽⁵⁾. In both cases, the functions are constructed from the numerical solution by means of spline interpolation. In order to save space, we shall consider here only the shock trajectory. The formulae pertinent to the other function can be obtained from the stated ones by merely exchanging τ_s with τ_+ , f_1 with f_2 , and t_s with t_+ .

By replacing the function argument ξ_s with $\xi_s = r_s/r_c = c_0 t_a/r_c$ and the function value with $\tau_s = t_s/t_c = c_0 t_s/r_c$ we get the equation:

$$c_0 t_s/r_c = f_1(c_0 t_a/r_c), \quad (2)$$

which we solve numerically for r_c and then use eq. (1) to determine blast energy E . The energy E_h contained in a hemispherical wave is assumed to be a half of the blast energy that would produce the same mechanical effect in the spherical case: $E_h = E/2$.

FIG. 4 Theoretical functions employed to determine blast energy E_h

FIG. 5 Theoretical functions employed to determine measurement uncertainty of E_h

In order to assess how the uncertainties ("errors") of the measured variables (p_0 , t_a , t_s , T_0) affect the uncertainty of blast energy we differentiate the equations employed:

$$E_h = p_0 r_c^3 / 2\alpha \Rightarrow dE_h/E_h = dp_0/p_0 + 3 dr_c/r_c, \quad (3)$$

$$c_0 = \sqrt{\gamma R T_0} \Rightarrow dc_0/c_0 = dT_0/2T_0, \quad (4)$$

$$\tau_s = f_1(\xi_s) \Rightarrow d\tau_s/\tau_s = [\xi_s f_1'(\xi_s)/f_1(\xi_s)] d\xi_s/\xi_s, \quad (5)$$

$$\tau_s = c_0 t_s/r_c \Rightarrow d\tau_s/\tau_s = dc_0/c_0 + dt_s/t_s - dr_c/r_c, \quad (6)$$

$$\xi_s = c_0 t_a/r_c \Rightarrow d\xi_s/\xi_s = dc_0/c_0 + dt_a/t_a - dr_c/r_c, \quad (7)$$

and eliminate the auxiliary variables. Analysis of the resulting form:

$$\frac{dE_h}{E_h} = \frac{dp_0}{p_0} + 3(\sigma_1 + 1) \frac{dt_a}{t_a} - 3\sigma_1 \frac{dt_s}{t_s} - \frac{3}{2} \frac{dT_0}{T_0}, \quad (8)$$

$$\text{where: } \sigma_1 = \frac{1}{\xi_s f_1'(\xi_s)/f_1(\xi_s) - 1}, \quad (9)$$

shows (FIG. 5) that the use of shock trajectory f_1 promises good results (small uncertainties) only in the strong and intermediate shock region (where $\sigma_1 \approx 1$). In the weak shock region, however, σ_1 can be quite large implying that small uncertainties of t_a and t_s give rise to large uncertainties of E_h . In this region, function f_2 (compression duration) with σ_2 asymptotically decaying to 1 offers a much better performance. This potential of f_2 in the weak shock range, however, might be difficult to exploit fully as it might require higher fidelity of the measurement system and much more sophisticated signal processing.

4. RESULTS

In FIG. 6 we illustrate some characteristic observations on OA energy conversion efficiency. The efficiency increases monotonically with the increase of incident laser energy E_I . The steepness of the efficiency rise with E_I decreases above some threshold energy. The efficiency curves thus exhibit two characteristic regions: intense efficiency increase at low energies E_I and gradual increase (saturation) at high E_I . With the longer (60 ns) ablation pulses the region of the efficiency rise is steeper and starts at higher energy. The highest efficiencies observed in this experiments were around 20% and did not depend much on the irradiated material or pulse duration. In the saturation region, we observed generally only minor pulse to pulse efficiency variations. Below that these variations were relatively more intense and depended very much on the state of the surface. No systematic dependence of blast energy on r_s was observed and we take this as an evidence that the model applies well.

Fig. 6 Energy conversion efficiency vs. incident laser energy

In conclusion, most recent optoacoustic studies of the ablation process use the OA signal amplitude as the relevant OA parameter. Comparison of the ablation data in terms of OA amplitude could be a problem because it depends on several experimental factors. In such a case, the use of blast energy would be the solution.

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