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Influence of plasma shielding in optoacoustic measurements

R. Hrovatin, J. Mozina and J. Diaci

University of Ljubljana, Faculty of Mechanical Engineering, Askerceva 6, P.O. Box 394, 61000 Ljubljana, Slovenia

Abstract: Simultaneous measurements of laser excited ultrasonic waves in a solid sample and in the surrounding air were used for characterizing the plasma shielding effect and for the evaluation of its influence in optoacoustic measurements. Typical modifications of ultrasonic waves are discussed and the acoustic energy distribution between the solid and the atmosphere is assessed by a comparative analysis of optoacoustic responses received from both probes.

1. INTRODUCTION

Two mechanisms of ultrasonic wave generation with short laser pulses have been frequently discussed: thermoelastic and ablative [1-6]. Typical wave parameters and wave evolution were described and modeled for both of them [2-4]. The prevalence of each mechanism defines the final ultrasonic wave shapes in two media: in the irradiated solid and in the surrounding air. For a given material the ablative mechanism prevails as the intensity is increased.

For higher pump beam intensities the dielectric breakdown is achieved and high-temperature plasma formation can be observed above the sample surface. Only a small fraction of the incoming laser pulse is exploited for its formation. The rest of the pulse is absorbed mostly through the inverse bremsstrahlung mechanism by a thin layer in the plasma plume where the plasma frequency is close to the frequency of the incoming laser light [7,8]. In this way the underlying material is effectively shielded from the rest of the pulse. The main mechanism of energy transport to the underlying target is now heat conduction by electrons which is accompanied by high pressure gradients [9,10].

The described changes in the ablation kinetics are also reflected in the laser induced ultrasonic waves. The plasma expansion caused by pressure gradients is accelerated by the absorption of the laser radiation, causing the formation of a blast wave as a shock compression front in the air followed by a long rarefaction [3]. Evaporation and expansion of the surface material lasts even after the laser pulse shutoff, because of heat conduction from the plasma to the target. The mechanical impulse in the target is thus extended, demonstrated as a step-like normal displacement [4].

In this paper we are presenting an optoacoustic study of the plasma influence on ultrasonic waves in solid and in the surrounding atmosphere. A different approach has been used to confirm that the plasma shield formation is the actual source of the changes in ultrasonic waves. For this purpose two plasma formation regimes are considered: breakdown of the evaporated target material and breakdown in the air without any influence of the ablated material.
2. EXPERIMENTAL

The experimental arrangement is shown in Fig. 1, the detailed description is given elsewhere [11]. A Nd:YAG laser, nominal pulse energy of 85 mJ and pulse duration of 10 ns, was used for excitation. The beam was focused \((f = 75 \text{ mm})\) normally to the sample surface; 5 mm thick aluminum samples were used. The experiments were performed in several series with constant pulse energies in each of them. Different power densities were achieved by different focusing. In the case of an attenuated beam, the plasma was only observed on the sample surface near focal positions close to \(x = 0\). Breakdown in the air for distances \(x < 0\) (the focus was in front of the sample) was introduced by exploiting the whole pump beam energy. Power densities of \(I \approx 10^{11} \text{ W/cm}^2\) are assessed to be reached in this case.

The effects on ultrasonic waves in the sample and in the surrounding atmosphere were observed simultaneously using two detection techniques. Simultaneous measurements were provided to assure the same generation conditions for both waves. The waves propagating in the air were detected by a microphone [12]. It detected the blast wave coming directly from the plasma source and the wave generated on the sample surface. The microphone response in the far field of ultrasonic wave propagation was verified closer to the surface by the probe beam deflection (PBD) [13,14]. The 5 mW He-Ne beam passed the sample parallel to the surface and probed the density gradient 17 mm above the surface. Simultaneously the normal ultrasonic displacements propagating through the material were detected on the other side of the sample. The stabilized Michelson interferometer [15], which was compensated for low frequency noise, was used.

3. RESULTS AND DISCUSSION

Different optoacoustic responses were observed with respect to the different generation mechanisms established. Using the beam deflection probe we observed a characteristic transition from typical thermoelastic bipolar response to ablative, in consistence with other authors' results [3]. Acoustic wave transients measured by the microphone were longer, which is partially a consequence of the microphone bandwidth limitation (144 kHz) and an increase of the total waveform width with propagation distance. In the plasma formation region, several wavefronts were obtained, the first being always the strongest. In experiments with breakdown in the air, two of the optoacoustic sources were present: breakdown in the air and the optoacoustic effect on the sample surface as it is shown in fig. 2.
The shape of the ultrasonic wave propagating in a thin plate varies with excitation radiation intensity. In the thermoelastic regime the normal displacement takes the form of a negative step, becoming of pulse-like in the ablative regime, and in the presence of plasma at the sample surface it is a positive step. With breakdown in the air it takes one of the first two forms described, depending on the intensity of radiation which passes the plasma plume. In the plasma regime, the time step function is a good model for the force, confirming extended plasma effect as mentioned in the introduction.

For further analysis a relatively simple evaluation of recorded signals was introduced. PBD and microphone responses were evaluated by the first amplitude, corresponding to the first arriving compression. Bulk waves were evaluated by the first longitudinal wave amplitude, which conveys the information about the primar absorption, neglecting later plasma effects. Amplitude curves for the beam deflection probe and for the interferometer are shown in Fig. 3. A minimal bulk wave amplitudes are observed for focal positions near $x = 0$ at all pulse energies. For all energies a minimal amplitude of $2 \pm 1$ nm, which is caused by the ablation before the plasma shield formation, was measured at $x \approx 0$.

The bulk wave amplitude versus the incoming radiation power was calculated for each measurement. For longitudinal wave amplitudes were shown to be proportional to the radiation energy \[4\], so the measured amplitudes were normalized and plotted versus power density (Fig. 4). Using this procedure, the results are dependent only on the radiation power density. A reasonable spread of the values measured was obtained in the region of pure ablation (from 20 MW/cm$^2$ to $\approx 100$ MW/cm$^2$) as well as for the regime with plasma shielding. This leads to the assumption that for constant incident power density the linear relation between the displacement $u_0$ and the pulse energy can be extended in the region of plasma shielding. For all energies, the threshold for a plasma shielding effect of 130 MW/cm$^2$ was determined as the power density where the amplitude decrease starts.

The major difference between the amplitude curves for air breakdown and the mean value of other measurements is caused by the absorption in the plume which causes the attenuation of transmitted light. The reduction of the incoming energy because of the shield can be calculated. Transmittance of 56\% (32.5 mJ) of the laser pulse energy was determined by scaling the air breakdown amplitude curve and fitting it to the mean value curve with respect to the power density (fig. 4). The same value of power density at the plasma shielding threshold is determined for this curve as for the other measurements.
Fig. 4: Bulk amplitudes, normalized by the corresponding pulse energy versus the incoming pump beam power density. The mean values of the measured data are connected with a solid line. The power density at the sample surface is calculated for each x position without taking into account any possible loss of energy, i.e., the average pulse power is divided by illumination area. Therefore the “air breakdown” curve, where breakdown was induced in the air in front of the sample, differs from the rest of the data, since the energy loss due to the air breakdown is not calculated. This curve was corrected by fitting it on the “mean value” curve, where pulse energy was the fitting parameter, and both normalized amplitudes and power densities were corrected. Best fit was obtained for 56% of pulse energy. Therefore we assume that air breakdown consumes 44% of the pulse energy. The “air breakdown” data and its calculated correction are shown with solid and dashed line, respectively.

4. CONCLUSION

To summarize, it is demonstrated that optoacoustic measurements are influenced by plasma shield in the case of its formation. Pure ablative regime experiments were extended to the prevailing plasma shielded regime and to breakdown in the air. The latter actually confirms the shielding during the laser pulse. For aluminum 130 MW/cm² is determined to be the threshold power density for plasma shield influence. The amount of energy transmitted through the plasma plume in the air is assessed to be approximately half of the incident energy for a pulse of 58.5 mJ. Finally we demonstrated that proportionality between the ultrasonic amplitude and the incident pulse energy at constant intensity is valid for a pure ablative regime as well as for an ablative regime with strong shielding.

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