Optics and Laser Technology 100 (2018) 21–26

Contents lists available at ScienceDirect

Optics and Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

Full length article

Comparative study of the expansion dynamics of laser-driven plasma and shock wave in in-air and underwater ablation regimes

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ARTICLE INFO

Article history:
Received 8 March 2017
Received in revised form 20 July 2017
Accepted 11 September 2017

Keywords:
Laser-induced shock
Laser-supported absorption waves
Plasma confinement effect
Underwater laser ablation
Photoelastic imaging technique

ABSTRACT

We compared the expansion characteristics of the plasma plumes and shock waves generated in laser-induced shock process between the two ablation regimes: in air and under water. The observation was made from the initial moment when the laser pulse hit the target until 1.5 µs. The shock processes were driven by focusing a single laser pulse (1064 nm, FWHM = 13 ns) onto the surface of epoxy-resin blocks using a 40-mm focal length lens. The estimated laser intensity at the target plane is approximate to 9×10^9 W cm^{-2}. We used the fast-imaging technique to observe the expansion of the plasma plume and a custom-designed time-resolved photoelasticity imaging technique to observe the propagation of shock waves with the time resolution of nanoseconds. We found that at the same intensity of the laser beam, the plasma expansion during the laser pulse follows different mechanisms: the plasma plume that grows in air follows a radiation-wave model while a detonation-wave model can explain the expansion of the plasma plume induced in water. The ideal blast wave theory can be used to predict the decay of the shock wave in air but is not appropriate to describe the decay of the shock wave induced under water.

1. Introduction

When a laser pulse interacts with a rigid target, the material is gasified and ionized to form a plasma. This plasma expands at supersonic velocity and drives a shock wave into the atmosphere and a stress wave into the solid target. It is known that the breakdown of the target material in air occurs when the leading edge of the laser pulse strikes the target. This initial plasma continues to absorb energy from the rest of the laser pulse, expanding within the laser beam channel and emitting luminescence that is visible to the naked eye [1–3]. Compared to in-air ablation, the plasma induced in underwater ablation is confined by the liquid layer that further increases the shock pressure. The laser-induced shock process (LSP) in the underwater regime has been applied in laser micromachining, laser cleaning and laser peening [4–14]. The supposedly simple underwater LSP is characterized by complex, ultrafast physical processes [4,7,10].

The expansion of plasma during the laser pulse has a particular importance in deciding the initial shock pressure and the dynamics characteristic of the induced shock wave. The expansion of plasma during the laser pulse has been investigated for in-air ablation and was shown to have different features at different ablation conditions [15–19]. In contrast, most of the researchers related to laser ablation in underwater regime centered on investigating the dynamics of the induced shock wave and exploring the conditions that optimize the shock pressure. The expansion of plasma during the laser pulse in underwater ablation has not been studied in details. A comprehensive comparison of the dynamical characteristics of the plasma induced in air and underwater is, therefore, desirable to clarify the confining effect of the liquid phase on the laser-induced shock process.

This study examined the expansion dynamics of plasma and shock wave induced in air and underwater from the initial moment after the laser pulse hit the target until 1.5 µs after irradiation. We investigated the different mechanisms involved in the plasma expansion in the two ablation regimes and highlighted the consequences of such different mechanisms on the induced shock processes. We used a gated image intensifier, and a charged-coupled device camera to observe the expansion of the plasma. A custom-designed time-resolved photoelasticity imaging technique [5,6,11–13] was used to monitor the expansion of shock wave and to evaluate the strength of stress wave with a time resolution of nanoseconds.

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https://doi.org/10.1016/j.optlastec.2017.09.021
0030-3992/

2. Experimental method

The pulses from a Nd:YAG laser operating at the wavelength of 1064 nm (FWHM = 13 ns) were used to induce laser ablation. The targets were epoxy-resin blocks of $25 \times 5.8 \times (18-20)\ \mathrm{mm}^3$ dimensions with the $25 \times 5.8\ \mathrm{mm}^2$ surfaces were coated with a thin layer of black paint. The shock process was induced by focusing a single laser pulse on the coated surface using a 40-mm focal length lens (LMH-5X-1064). For underwater ablation, the targets were fully immersed in a glass cell filled with pure water with the target surface located 5 mm under the liquid-air interface. For in-air ablation, the experiments were performed in the normal atmospheric condition. The target was moved by an XY translational stage to provide a fresh surface for each laser shot. The water was also replaced after each shot to avoid absorption of the laser pulse energy by particles formed by the former shot. The laser pulse energy was 60 mJ. The subsequent shot-to-shot pulse energy fluctuations were maintained at less than 5% throughout the experiments. The estimated spot diameter at the target surface was 250 μm. This configuration gives an intensity approximate to $9 \times 10^9\ \mathrm{W\,cm^{-2}}$ at the target plane.

The shock process was observed by a custom-designed time-resolved photoelasticity imaging technique [5,6,11–13]. Fig. 1 shows the schematic of the imaging systems, which include a Nd:YAG laser (Powerlite 8000) to provide ablation pulses, an ICCD camera operated in gated mode, and a polariscope consisted of polarizers and quarter-wave plates to provide photoelasticity images. For delay times from 0 to 57 ns, the Powerlite 8000 was used with a second-harmonic generator unit to generate both the fundamental radiation (1064 nm) as the ablation pulse (pump pulse) and the second-harmonic radiation (532 nm) as the probe pulse. The delay time was controlled by passing the probe pulse through an optical delay system (Fig. 1a). For delay times longer than 57 ns, a second laser (NY 82) was used to provide probe pulse (532 nm, FWHM = 6 ns). The delay time was maintained using a digital delay circuit (Stanford Research system), as has been shown in Figure 1b. The delay time of each image was defined as the interval between the rise of the pump pulse and the peak of the probe pulse. The time-resolved observation of plasma expansion was made without using the probe laser and the polariscope. The delay time of each image was identified as the interval between the pump pulse and gated pulse of the camera.

The gate width of the ICCD camera was set at 3 ns for plasma observation and for getting photoelasticity images of shock process at delay times smaller than 57 ns. For images taken at delay times from 100 ns to 1.5 μs, the gate width was set at 40 ns.

3. Results

Fig. 2a presents a comparison of plasma generated in air and under water. 0 ns denotes the rising of ablating pulse and 20 ns denotes the end of energy deposition process. The 60-mJ laser pulse hit the target from above. The plasma plume appears in the images as bright areas against the black background. As soon as the begin of the laser pulse (2 ns), the initial plasma appeared as a tiny bright region on top of the target surface, which has the approximate size in in-air and underwater ablations. However, the plasma plume grew much faster in air than under water during the laser irradiation. The plasma plume induced in water appeared to be confined on the solid target during the laser pulse. In contrast, the plasma plume induced in air developed faster toward the laser source. After the end of energy deposition process (after 20 ns) the brightness of both the plasma plumes induced in air and underwater gradually reduced, denoting the plasma cooling process. The plume emission cannot be detected in water after some hundred of nanoseconds but still can be seen in air for a longer delay time.

Fig. 2b and c present photoelasticity observation of laser-induced ablation plumes in air and under water from 2 ns to 1500 ns. For underwater ablation, we observed a tiny black point on top of the target surface at 10 ns, when the laser pulse reached its peak. For longer delay times, this dark point expanded and had the shape of a semicircle. We postulate that this expanding semicircular area was the shadow of a hemispherical shock front followed by laser-induced plasma. From 57 ns, we found a detachment of the shock wave front from the contact boundary between ablation plasma and water. After this detachment, the shock wave front continued to expand with a supersonic velocity, while the plasma decelerated its motion. This high-pressure plasma originated a cavitation bubble which contains all the gaseous ablation product, ablated debris and vaporized liquid and appeared as a black semicircle located at the center of the images. From 100 ns, the photoelastic image of stress wave in the solid phase can be observed. The number of photoelasticity fringes in the image of stress wave denote semi-quantitatively the strength of induced stress [5].

For ablation in air, we observed a dark area in the half-ellipsoidal shape, expanding on top of the target surface. This area was optically thicker at 10 ns but getting thinner during its expansion. From 50 ns, a thin layer which represents the shock front can be distinguished. The dark area in half-ellipsoidal shape observed during some first dozens of nanoseconds was the shadow of plasma plume. Due to its supersonic expansion, the plasma plume density decreased and could not cast a shadow in the image after 50 ns. The supersonic expansion of the plasma plume produced a shock wave which had a half-ellipsoidal shape (the same shape of the induced plasma) but gradually approached a hemisphere shape at latter delay times. From 100 ns, we observed the ejection of ablated material and the photoelastic image of stress wave. Compared to the image of the stress wave induced under water, the image of the stress wave induced in air has no fringes, showing that a much weaker shock has been generated.

To explore more about the difference in expansion dynamics between the plasma and shock wave induced in air and under water, we created the position-time plots for plasma plume and shock wave. To investigate the plasma expansion, we measured the distance from the target surface to the front of the plasma plume at different delay times during the laser irradiation (0–20 ns). We did not investigate the plasma expansion after the laser pulse ended since the image of the plume was dim and its front could not be well identified. To investigate the propagation of the shock wave, we measured the distance traveled by the shock front from 20 ns to 1500 ns after irradiation. At the early delay times, since the image of shock wave was not distinguished from the image of plasma in the photoelastic images, we assumed that the shock wave front was expanding outward the plasma plume. The distance traveled by shock wave was, therefore, identified by measuring the height of the shadow of shock wave merged with plasma. After the image of the shock fronts could be identified (after 50 ns), we measured their vertical radii, i.e. the height of shock wave fronts from the target surface. The results are given in Fig. 3 in double logarithmic scale. The dashed lines represent fitting to the power regression model $R \sim t^{\alpha}$.

For ablation in air, the plasma grows rapidly during the irradiation. The least square fit obtained from the power law yields the exponent α approximates 1, suggesting that the plasma expanded linearly with time. We thus estimated its growing velocity by fitting the data with a linear regression model. The result showed that plasma plume expanded with the velocity approximates