Dynamical Visualization of Laser-Induced Shock Phenomena in Liquid

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We observed dynamics of laser ablation in liquids through two high-speed imaging techniques, high-speed pump-and-probe photography and high-speed laser stroboscopic videography, and briefly described both imaging techniques. The target materials are epoxy-resin blocks immersed in a liquid environment, and the images were taken through circular polariscope optics in a bright-field mode. We simultaneously observed both phenomena in gas or liquid phases as well as inside a solid and visually demonstrated the confining effects of liquid on laser-induced shock processes. We also described the effects of liquid-layer thickness on the laser-induced shock process and studied the dynamical behavior of laser-induced cavitation bubbles through high-speed videography. The dynamics of a cavitation bubble was recorded successfully with 4-μs time resolution and its growth and shrinkage were analyzed. Secondary shocks are generated when the first bubble collapsed and the magnitude of the shock inside the solid was approximately one order smaller than that of the initial laser-induced shock.

Key Words: Laser ablation, Liquid, Epoxy-resin, Photoelasticity, High-speed imaging

1. Introduction

Laser-induced shock phenomena, which occur when an intense, short laser pulse is focused onto a solid surface, are significant in many engineering fields. High-temperature and high-pressure plasma are formed on the irradiated spot, which drives shock waves into the surrounding environment. When ablation is carried out in liquid, the liquid phase acts as a restricting medium to restrain the plasma expansion and induces a much stronger shock than ablation in normal atmospheric conditions.

To understand laser-induced shock processes, we must know what is actually happening during them. Their wide dynamical time scales range from several femto- or picoseconds to hundreds of microseconds, and their spatial scale is small, from some tens of nanometers to millimeters. Therefore, their direct and dynamic visualization is rather difficult task, and only a limited number of studies have been done so far. A visualization technique must be established that enables us to observe these phenomena that occur at high-speed and on a small scale.

We have been studying the laser ablation process in different conditions through several high-speed imaging techniques. Laser-induced plasma and shock were observed on metal surfaces by a pump-probe type photography technique. We monitored the intensity of laser-induced shock traveling through a solid target using a piezoelectric film as a transducer.

To dynamically visualize the stress distribution inside a solid and the shock wave propagation, we developed a dynamic photoelasticity method, where epoxy-resin was used to observe the stress distribution inside the material. To clarify the effects of the liquid phase on the plasma expansion, we observed laser ablation on the epoxy block in liquid. Laser ablation in liquid generates cavitation bubbles, which oscillate in micro- to millisecond time domains. The ablation phenomena inevitably suffer pulse-to-pulse fluctuations. Detailed studies on the dynamics of cavitation bubbles must be observed for single pulse excitation.

We employed a custom-designed high-speed laser stroboscopic videography technique, which was developed for a dynamical study on laser material processing and electric discharge machining processes, to study laser ablation in liquids. The dynamic behavior of cavitation bubbles formed by laser irradiation was imaged continuously at time resolution as high as 4-μs intervals. In this paper, we briefly describe our dynamical observation methods and dynamical studies on laser-induced shock processes in liquids.

2. Experimental techniques

2.1 Pump-and-probe, single-shot imaging systems

The imaging techniques that we employed are based on a kind of pump-and-probe system with some variations of optical elements and a combination of pump and probe lasers depending on specific delay time requirement. For photoelastic observation, the optical components were arranged to construct a circular polariscope in a bright-field mode in which one quarter-wave plate is inserted between a polarizer and a sample, and another such plate is inserted between the sample and an analyzer (Fig. 1). A laser source provides 532 nm laser pulses as illumination light (probe) to be recorded by a camera. To avoid the interference from plasma emission, we installed a band-pass filter at 532 nm that only passes the probe light to the camera. For images with less than 100-ns delay time, a Nd:YAG laser with 13-ns duration was used as both a pump and a probe laser. The output of the second harmonic generator was divided into 1064- and 532-nm radiations, and the former was used as a pump and the latter as a probe light. An optical delay line was installed in the pass of the probe light. To record the images up to some thousands of nanosec-
3. Dynamical observation

3.1 Observation by pump-and-probe system: Visualization of liquid-confining effect\(^{7-19}\)

Since ablation phenomena occur instantly after irradiation, pump-and-probe imaging is suitable to obtain images in a time scale less than microseconds.

Figure 2 shows the observed images of the laser-induced ablation of an epoxy block in water up to 300 ns. The black horizontal lines represent the target surface. The ablation laser pulse had a 13-ns duration. As quickly as 10 ns, a black area can be seen on top of the target surface and expands rapidly at some dozens of nanoseconds. After 48 ns, the edge of the black shadow changes into a double line that separates the shock wave and the dark area located inside, evident at a 100-ns delay time. After that, the shock wave and the dark area expanded separately. The dark area’s expansion slowed after it was separated from the shock wave. The dark area is probably a shadow image of the plasma in the first dozen nanoseconds and gas bubble shadows for the delay times after that. From 200 ns, three features became evident in the photoelasticity images: waves propagating into liquid, a cavitation bubble appearing as a tiny dark semi-circle on the target surface, and sharp black fringes that represent stress waves inside the solid. The photoelasticity images of an epoxy-resin observed in laser-irradiation in water can provide clear black-and-white patterns from which it is possible to deduce laser-induced stress distribution and to make relative and even semi-quantitative estimation of the magnitude of the laser-induced stress.

Figure 3 compares the images obtained for the ablation of epoxy blocks in water and air. The laser pulse energy is 60 mJ. Figures 3 (a) and (b) are photoelastic images in the bright-field mode in air and water, respectively, observed under the same irradiation conditions. The image of ablation in air does not have any fringes, but in liquid it shows fringes with complicated patterns. Since the appearance of fringes indicates larger stress amplitude, these images visually prove that much stronger stress is generated under liquid than in air, which was congruent with our expectations. Figures 3 (c) and (d) show the plasma observed at 50 ns after laser irradiation under the same conditions as the photoelastic images. The plasma that formed in the liquid is much smaller than that formed in air. This can be interpreted as the confining effects of the liquid phase; liquid, which is far denser than air, restricts the expansion of plasma and induces stronger pressure and intensifies the magnitude of stress-waves in solid.

As the pulse energy increases, the number of fringes in-
creases inside the epoxy-resin (Fig. 4). This increase also suggests a rise in the laser-induced stress in solids. Although it is not yet possible to deduce the actual stress distribution from the fringe pattern, the increasing number of fringes with pulse energy indicates that we can estimate the laser-induced transient stress, at least relatively and semi-quantitatively, by counting the number of fringes in the photoelasticity images.

### 3.2 Effects of liquid-layer thickness

Figure 5 shows the sequences of time-resolved photoelastic images taken for ablations with no liquid overlay (in air ablation) and with paraffin films from 0.1- to 1.0-mm thick and with bulk liquid paraffin. The pulse energy was 60 mJ. Instead of water, we used liquid paraffin because water did not form a thin layer on the epoxy block because of its poor wettablility. Before this experiment, we adjusted the distance between the lens and the target to find the position where the strongest stress was induced at a 1.0-mm-thick layer. For ablations at other liquid layer thicknesses, the working distance was adjusted to compensate the effect of refraction through different liquid layer thicknesses. For ablation under bulk liquid paraffin, the lens position was optimized to get the strongest stress in the bulk-liquid-confining regime.

Without liquid film, the shock waves that are induced in air, indicated by arrows in the images, have an initial half ellipse shape. They propagated twice as fast in the lateral direction as in the longitudinal direction and gradually approached the semispherical shape. The dark shadow on the target surface had an undefined shape and we consider it an ejected material plume. The image of the stress wave in the target did not have any fringes, suggesting that only a weak shock had been induced. In the full-immersed case, a semicircular cavitation bubble is induced that contains all the ablated material inside.

For ablation under a 0.1-0.2-mm liquid layer, a shadow of the shock wave can be observed on top of the liquid-air interface. This shock wave is smaller than that observed in the no-liquid ablation at the same delay time. Inside the shock front was a dark column whose shape became an inverted cone at later delay times. We describe them as the blown-off liquid from the surface layer. The shock wave front propagating in air had shapes that varied from shot to shot and their height shows poor reproducibility. The photoelastic image of the stress wave reveals that the induced stress was stronger than ablation in air but much weaker than ablation under bulk liquid. For ablations under thicker liquid layers (0.4 and 1.0 mm layers), no shock wave propagated outside the liquid layer. The liquid layers, however, were swollen differently due to the expansion of the cavitation bubbles.

Figure 6 (a) shows the threshold thicknesses required to induce the same stress as in the full-immersed cases for 5, 40 and 100 mJ laser pulses. Figure 6 (b) shows photoelastic images at corresponding energies for ablation under bulk-liquid, where a confining effect was fully realized. For pulse energies of 5 mJ, the image obtained under 0.6 mm liquid paraffin showed the same number of fringes as that observed in the ablation under bulk liquid. This suggests that a 0.6 mm thick liquid overlay is adequate to get the full confining effect of liquid overlays. From the images for ablation pulse energy of 40 and 100 mJ, 0.8 and 1.0 mm thick liquid layers were required to induce the same number of fringes as ablation under bulk liquid, suggesting that the threshold thickness depends on the ablation pulse energy. Since the pressure of the gasified material strengthens with higher pulse energy, the threshold thickness naturally increases with pulse energy, as was demonstrated by our result.

### 3.3 Observation by high-speed laser stroboscopic videography: Cavitation bubble dynamics

The dynamics of a cavitation bubble at 20 mJ in a microsecond time scale are shown in Fig. 7 through a selected set of
images taken by the high-speed laser stroboscopic videography technique in the photoelasticity mode. At 2 µs, the primary shock is signaled with the shock wave in water, and photoelastic fringes represent the stress wave inside the solid. The cavitation bubble is the black semi-circle on top of the target. The cavitation bubble expanded, reaching its first maximum at 142 µs, and then it shrank and collapsed. The bubble reached its minimum contraction near 302 µs, and emission of the secondary shock waves can be observed in consecutive frames. Secondary shock generation was revealed in our image as both shock waves traveling into the water and stress waves propagating into the solid with intensities roughly one order of magnitude smaller than the first one. We simultaneously observed several shock fronts in water with different radii that seem to start from different centers. Then another bubble, the secondary bubble, was generated that grew with an irregular shape boundary. The secondary bubble reached its maximum radius, which was smaller than that of the first bubble, then shrank, collapsed, and induced smaller bubbles.

The maximum bubble size depends on the laser pulse energy and the target materials: the higher the pulse energy, the larger the bubble. The bubble lifetimes vary by maximum size but do not depend on the pulse energy or the materials.

4. Conclusion

We introduced two kinds of imaging systems to study the high-speed phenomena occurring in laser ablation in liquid. One is a continuous imaging system with which we captured 100 images at 250,000 frames per second and the other is a pump-and-probe system. Both use a high-repetition rate, a short pulse laser as an illuminating light source, and a high-speed video camera or ICCD camera as a recording device. The visualization methods of the phenomena in laser ablation and our results obtained so far were summarized in this paper. We clearly observed the dynamics of shock waves both in liquid and in solid and cavitation bubbles using epoxy-resin blocks as transparent target. These images were recorded in the blight-field photoelasticity mode. Photoelastic fringes appeared in the solid reveal the relative intensity of laser-induced shock inside it.

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