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# Secondary shock emitted during the collapse and rebound of a laser-excited cavitation bubble

## Sóng shock thứ cấp phát ra trong quá trình xẹp và phục hồi của bóng khí sinh ra bởi tia laser

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### Abstract

The secondary shock emitted at the collapse and rebound of a laser-induced cavitation bubble was studied directly and visually by the photoelasticity imaging technique. The result shows the image of the pressure wave transmitted into the solid target due to the impact of the secondary shock. From the observation, we recommend that the secondary shock is quite strong and homogeneous, thus can be utilized to provide additional machining effect to the laser ablation process.

*Keywords:* Photoelastic images; secondary shock; laser-induced cavitation bubble.

### Tóm tắt

Sóng shock thứ cấp phát ra tại thời điểm xẹp và phục hồi của bóng khí sinh ra bởi tia laser được nghiên cứu trực tiếp và trực quan bằng kĩ thuật chụp ảnh quang đàn hồi. Kết quả cho thấy hình ảnh của các sóng ứng suất lan truyền trong mẫu chất rắn dưới tác dụng của sóng shock thứ cấp. Từ quan sát này, chúng tôi thấy rằng sóng shock thứ cấp khá mạnh và đồng nhất, và do vậy có thể được sử dụng để tạo nên các hiệu ứng gia công thêm vào cho quá trình phá hủy bằng tia laser.

*Từ khóa:* Hình ảnh quang đàn hồi; sóng shock thứ cấp; bóng khi sinh ra bởi tia laser.

### 1. Introduction

When focusing a laser pulse on a solid target immersed in a liquid, the laser beam gasifies and ionizes the solid materials and develops a high-pressure plasma. The expansion of this plasma drives a shock wave into the liquid and a tress wave into the solid medium [1], [2]. When the radiation finishes, a water vapor developed around the plasma initiates a cavitation bubble. The high initial pressure inside the bubble drives it to grow until its pressure equals the saturation pressure. At that point, the bubble attains the maximum radius. Subsequently, the bubble collapses until the

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vapor pressure within the bubble is high enough to reverse the motion [3], [4]. At the collapse and rebound, the bubble emits a secondary shock [1], [5], [6]. In laser ablation of a solid in liquid, this secondary shock can provide an extra impulse to the target.

In this work, we experimentally demonstrated the expansion and collapse of a laser-induced cavitation bubble from a few hundred nanoseconds after irradiation until hundreds of microseconds. The evolution of the bubble was recorded using the photoelasticity imaging technique. This system allows us to look at the evolution of the cavitation bubble and the emission of secondary shock in the liquid while simultaneously monitoring the stress wave induced in the solid target [7].

We report here a direct observation of the secondary shock wave and the impulse induced in the target at the collapse and rebound of the cavitation bubble.

## 2. Material and methods

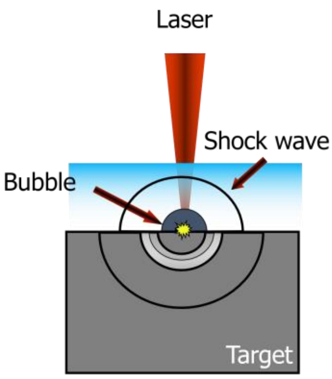


**Figure 1:** Schematic of laser-induced cavitation bubble.

The cavitation bubble was induced by focusing a single laser pulse (1064 nm, FWHM 13ns) by a 40-mm focal length lens onto an epoxy-resin block (25 x 5.8 x 20 mm$^3$). The surface of the target was located 5 mm under the water-air interface, as shown in Figure 1. The upper 25 × 5.8 mm$^2$ surface of the epoxy-resin block was ground by sandpaper to obtain the roughness of 1.0 µm before being coated by a thin layer of black paint to enhance the absorptivity. The pulse energy was 50 mJ. The time-resolved photoelasticity imaging technique was applied with a pump-and-probe system to record the dynamics of the cavitation bubble. The detailed experiment setup for imaging systems is the same as our previous reports [7] and is not described here. With this system, only one image was taken per shot. The time-resolved observation was produced by taking many pictures at different delay times.

## 3. Results and discussions

Figure 2 presents the dynamics of a cavitation bubble through a selected set of images. A time history was built up by single exposures taken at different samples with different time delays. The observation was carried out from 2 µs when the bubble was initiated until ~ 500 µs when the bubble was already collapsed and rebounded.

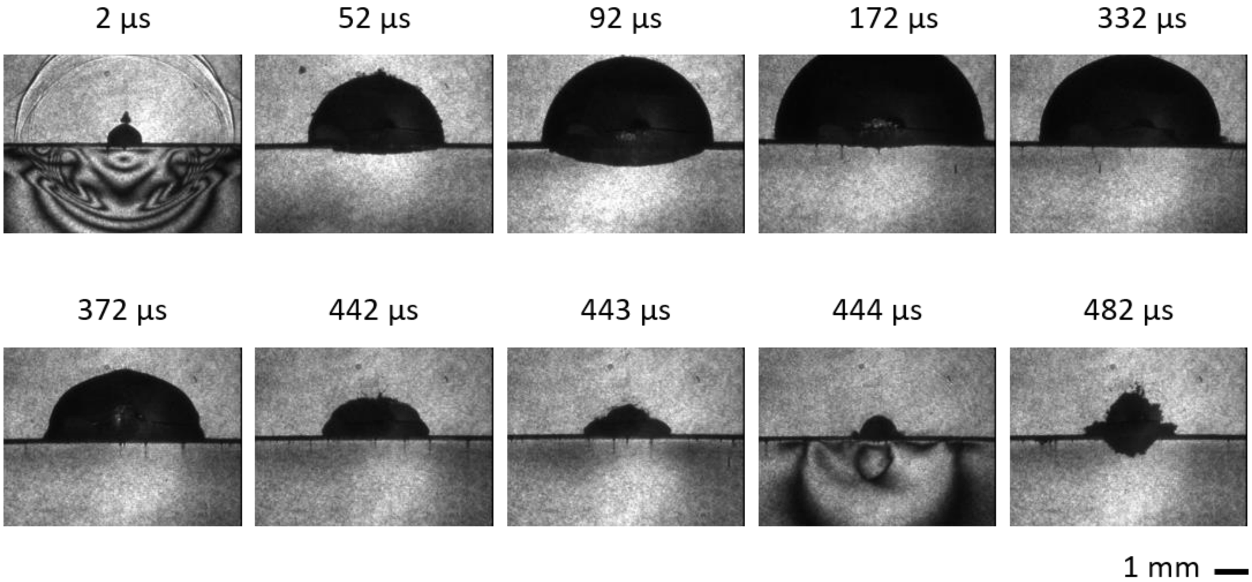


**Figure 2:** Time history of a laser-induced cavitation bubble. The pulse energy was 50 mJ. The liquid was water. The laser beam hits the target from above.

At 2 μs, the image shows the typical appearance of underwater laser ablation of a solid in a liquid. In the figure, we can see three simultaneously features: primary shock wave in the liquid, stress wave in the solid, appearing as photoelastic fringes, and a cavitation bubble, as discussed in our previous work [7]. At 52 μs, the shock wave and stress waves propagated outside the observation frame. Thus, in the image, we can only see the cavitation bubble had a semi-circular shape sticking onto the target surface during the expansion phase. The cavitation bubble reached its maximum radius and then collapsed. At minimum contraction, the bubble emitted a secondary shock and then rebounded. The secondary shock can be observed at 444 microseconds, revealed via the photoelastic fringes in the solid target. After the emission of the secondary shock, the cavitation bubble broke up into smaller bubbles, which rebounded and then collapsed several times before disappearing. By comparing the photoelastic images of the primary and secondary shocks, we propose that the bubble-collapse-induced shock did exert a considerably strong mechanical to the solid target.

Because only one image was taken per shot, there was an inevitable fluctuation between the images. However, the images well represented the evolution of the cavitation bubble. The photoelasticity images provided clear and observable evidence of the secondary shock. Conventionally, the bubble-emitted secondary shock is considered harmful since it can destroy the machined surface. However, from our observation, the secondary shock was quite homogeneous and strong. It is reported that about 10-30% of laser energy is contained in the cavitation bubble [8]. The impulse induced by the bubble collapse would be strong enough to provide a significant impulse to the target. We therethrough recommend that further studies should be carried out to utilize this secondary shock energy for applications in laser ablation of a solid in a liquid.

## 4. Conclusions

By using a custom-designed photoelasticity imaging technique, we have provided a direct image of the secondary shock that was induced at the collapse and rebound of a laser-induced cavitation bubble. The image was able to show clearly the photoelastic fringes which represents the stress wave induced in the solid target under the impact of the secondary shock. From the observation, we recommend that the secondary shock is strong and homogeneous and would be able to provide an additional machining effect to the laser ablation process. We recommend that further studies should be carried out to utilized this secondary shock energy.

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