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Compare transient stress induced in in-air and in-water laser ablation using simulation method

So sánh ứng suất tức thời sinh ra trong quá trình phá hủy bằng tia laser trong không khí và trong nước bằng phương pháp mô phỏng

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Abstract

Photoelasticity images of pulsed laser ablation in water and in air were simulated by Finite Element Method. The Von Mises stress distribution in the target is deduced from the simulated images and is compared between the two-ablation regimes. The result confirms that pulse laser ablation in the water can induced a stress about 100 times higher than that induced in ablation in the air.

Keywords: Photoelasticity images; Finite Element Method; pulse laser ablation; plasma confining effect; stress enhancement.

Tóm tắt

Hình ảnh quang đàn hồi của quá trình phá hủy xung laser trong nước và trong không khí được mô phỏng bằng phương pháp phần tử hữu hạn. Phân bố ứng suất Von Mises trong mẫu được rút ra từ hình ảnh mô phỏng và được so sánh giữa hai trường hợp phá hủy. Kết quả xác nhận rằng phá hủy xung laser trong nước có thể tạo ra ứng suất lớn hơn khoảng 100 lần ứng suất sinh ra trong phá hủy xung laser trong môi trường không khí.

Từ khóa: Hình ảnh quang đàn hồi; phương pháp phần tử hữu hạn; quá trình phá hủy bằng tia laser; hiệu ứng nén plasma; tăng cường ứng suất.

1. Introduction

When focusing an intense laser pulse on a rigid surface, the material is gasified and ionized to form a plasma. The plasma expands at supersonic velocity and drives a shock wave and stress waves into the surrounding media. The breakdown of the target material in air occurs when the leading edge of the laser pulse strikes the target. This initial plasma absorbs energy from the rest of the laser pulse and

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expands. Compared to ablation in air, the plasma induced in underwater ablation is strongly confined by the water [1]. This confinement leads to a significant increase of the shock pressure, thus enhances the stress induced into the target [2, 3].

Due to the enhancement of shock pressure, the laser-induced ablation in the water regime has been extensively applied in laser cleaning, laser drilling, laser peening, nanoparticle synthesis etc. [4, 5]. Laser-matter interaction under liquid is accompanied by a number of notable phenomena, including ablation of the matter, dielectric breakdown of the liquid, plasma confinement, and bubble formation. Besides the purely physical interest, a deeper understanding of the behavior of laser-induced shock process in an under-liquid regime is required to evaluate and optimize its mechanical effect [6, 7].

Photoelasticity imaging technique has been proved as a unique tool to investigate the pulse laser-induced ablation in liquid (PLAL) that not only can give a whole field image of the transient stress wave but also can provide a semi-qualitative estimation of the strength of induced stress [2]. In the previous work [8], we introduced the simulation method to simulate the photoelasticity image of PLAL. By using simulation method, we can initially represent the photoelasticity image and can deduce the real value of laser-induced stress wave.

In this research, we simulate the laser-induced ablation in air and in water to compare the induced stress between the two ablation regimes First, the simulation is carried out to reconstruct the experimental images obtained by photoelasticity imaging technique for in-air and in-water ablation. Then, the Von Mises Stress is elucidated from simulation for each regime. The result confirms the stress enhancement effect of water layer and showed that the stress is increased by at least two orders of magnitude if the ablation is carried in water.

2. Material and methods

2.1. Photoelasticity Imaging technique

The technique and imaging system have been well described in our previous works [1, 2], thus only a brief is presented here. We focused a 1064 nm laser pulse, with full width at half maximum (FWHM) =13 ns, on to a surface of epoxy-resin (target). The target was either put in air or immersed in water. The pulse energy was 20 mJ. Photoelasticity images was obtained by using a pump-and-probe imaging system together with a polariscope. The images were captured at 2000 ns after irradiation.

2.2. Simulation

We used GID to create a three-dimensional model with the same size as the target used in the experiments ($25 \times 20 \times 6\ mm^3$). The model was mesh-partitioned by ADVENTURE_TriPatch. On the surface of the model, a cavity ($D = 0.005\ cm$) was created to represent the irradiated area. The laser-induced pressure was simulated by giving initial displacement to this cavity. Stress calculating was carried out using smoothing technique-based beta finite element method (β FEM). The retardation of light due to photoelasticity phenomenon was calculated based on the values of stresses obtained. After that, the photoelasticity image was reconstructed. Details of the simulation method can be found in our previous works [9, 8].

3. Results and discussion

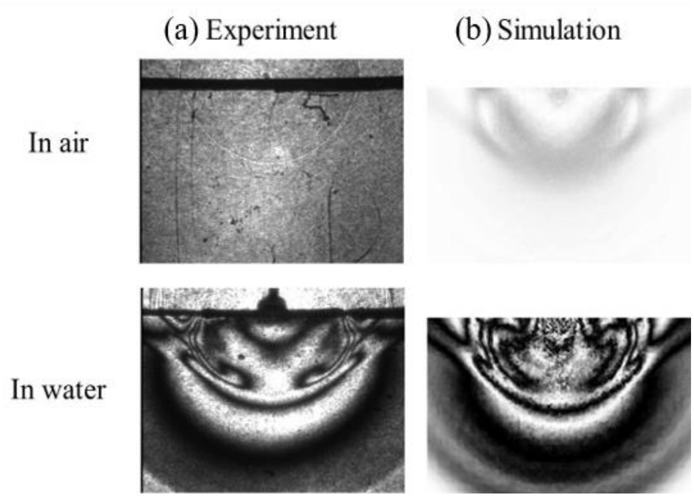

Figure 1. A comparison between simulation and experiment photoelasticity images at pulse energy of 20 mJ, for in-air and in-water ablation.

Figure 1(a) presents photoelasticity images in air and under liquid, respectively, observed at the same laser ablation conditions. The delay time was 2000 ns from irradiation. The image of in-air ablation does not have any fringes, whereas that of under-liquid ablation shows fringes with complicated patterns. Since the larger number of fringes indicates higher stress amplitude, these images qualitatively show that a stronger stress is generated in liquid, which is congruent with previous researches [10, 11].

To quantitatively investigate the increase of induced stress, we carried out the simulation for in air and in water. The results are shown in Figure 1(b). The simulation well represents the ablation in water and can reconstruct the ablation in air to a certain extend.

From the simulation result, we analyzed the Von Mises stress distribution inside the target at 2000 ns after irradiation. Figure 2 presents a comparison between the stress distribution in in-water and in-air ablation. In both cases, the induced stress is highest near the irradiated area and decrease as the distance increases. For in-air ablation, the maximum stress near the irradiated area is less than 10 MPa and decreases to approximate zero about 2.5 cm away. For in-water ablation, the maximum stress can reach 800 MPa near the irradiated area and still reach approximate 50 MPa at 2.5cm away the irradiated point. This result suggests that the ablation in water can increase the induced stress by about two orders of magnitude in comparison to ablation in air.

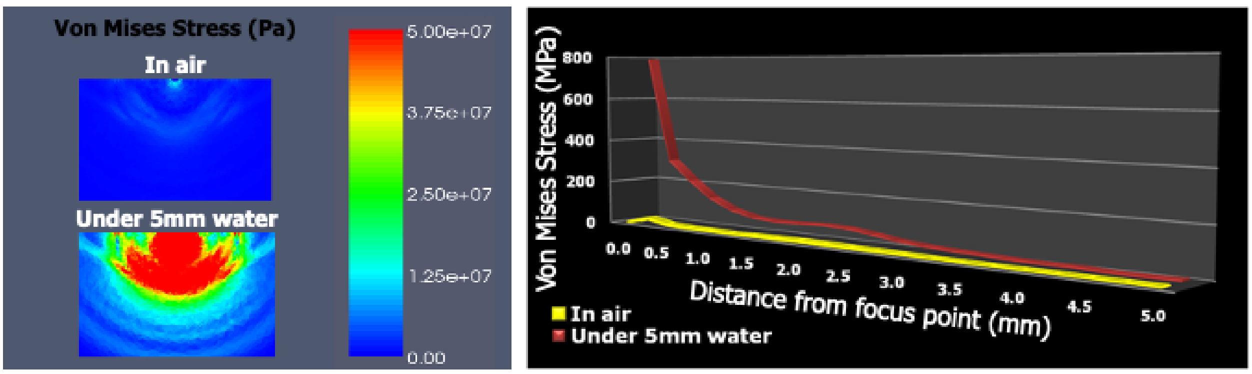

Figure 2. A comparison of stress distribution between in-air ablation and in-water ablation.

4. Conclusion

The simulation of photoelasticity images was carried out for in-air and in-water ablation, using finite element method. The simulation results can represent the photoelasticity images to a certain extent. The simulation result shows that for in-air ablation, a 20 mJ laser pulse induced a transient stress that is smaller than 10 MPa near the focal region. When the water was used as confining medium, the transient stress could be enhanced by two orders of magnitude.

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The photoelastic images were reconstructed from the stress distribution by using a program provided by Dr. Kenji Oguni and Dr. M.L.L Wijerathne from the University of Tokyo, Japan.

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