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Shockwave energy generated in laser ablation of solid in atmospheric condition

Năng lượng của sóng xung kích sinh ra trong quá trình phá hủy bằng tia laser trong môi trường không khí

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Abstract

We observed the propagation of shockwave induced by focusing a nanosecond laser pulse on the surface of an epoxy-resin block. The evolution of shockwave was observed within the first 1000 ns from irradiation. The shockwave energy was calculated based on the point-explosion model. The result indicated that the ablation process converted 60% of laser pulse energy into shockwave energy. We suggest that this result can be used for a simple estimation of shockwave energy in applications that use laser ablation of solids in atmospheric condition.

Keywords: Laser ablation; point-explosion model; energy conversion ratio.

Tóm tắt

Chúng tôi quan sát sự lan truyền của sóng xung kích sinh ra khi hội tụ một xung laser nano giây lên bề mặt của một khối epoxy-resin. Quá trình phát triển của sóng xung kích được quan sát trong vòng 1000 nano giây tính từ thời điểm chiếu chùm tia. Năng lượng sóng xung kích được tính toán dựa theo mô hình vụ nổ chất điểm. Kết quả chỉ ra rằng 60% năng lượng xung laser đã được chuyển hóa thành năng lượng sóng xung kích trong quá trình phá hủy. Chúng tôi đề nghị rằng kết quả này có thể được sử dụng để ước lượng nhanh năng lượng sóng xung kích trong các ứng dụng có sử dụng quá trình phá hủy bằng tia laser trong môi trường khí.

Từ khóa: Phá hủy bằng tia laser; mô hình vụ nổ chất điểm; tỉ lệ chuyển đổi năng lượng.

1. Introduction

Laser ablation is a process of focusing a laser pulse onto a solid target. When the laser pulse reaches the target, it vaporizes and ionizes the material to form plasma. This plasma expands rapidly into the ambient environment and generates a shock wave.

The laser ablation in atmospheric condition has many applications, especially in industry. We can count here laser cleaning for art

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conservation [1], laser micro-machining [2], or laser propulsion [3]. In the laser ablation process, one important parameter is the energy conversion ratio, which is the percent of optical energy successfully converted to the mechanical energy stored in the shock wave. This parameter is important for optimizing the laser ablation process.

In this paper, we present the observation of laser induced shock wave in atmospheric condition using photoelasticity imaging technique. The dynamic of the shock wave was investigated and the shockwave energy was deduced from the experimental data.

2. Experimental set-up

We focused a laser pulse (1064nm, 13ns) by a 5x objective lens on a surface of epoxy-resin block to induce the ablation. The photoelasticity imaging technique was used to capture the shock wave image induced in the air. The pulse energy was 20 mJ.

The photoelasticity imaging technique used in this research has been described in our previous works [4,5], and only a brief description is mentioned here. The imagining system uses a pump-and-probe imaging method with a polariscope to see the stress distribution in a transparent material (Fig. 1). We regulated the delay time between the pump laser, which induced the ablation, and the probe laser using a delay generator. The image was captured using an ICCD camera. A two-lens system was used for magnification and the bandpass filter was used to eliminate the noise.

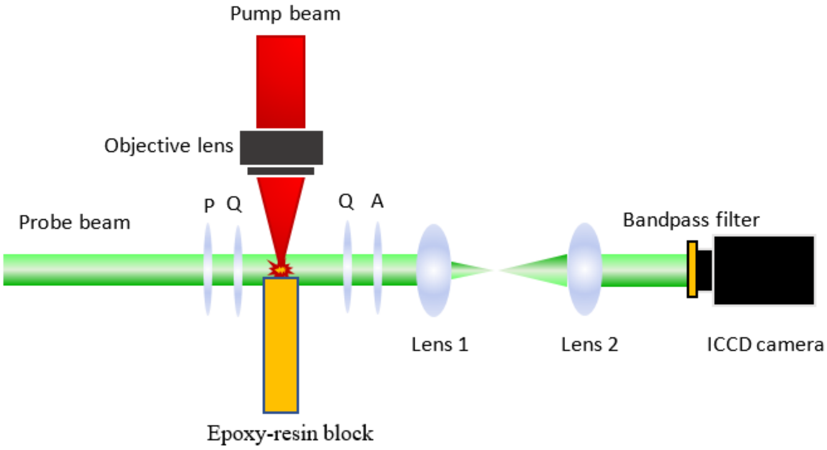

Figure 1. Diagram of the imaging system.

3. Results and discussion

Figure 2 presents images of the shock wave formed on the surface of epoxy-resin block. The shock wave was observed from 100ns to 1000ns.

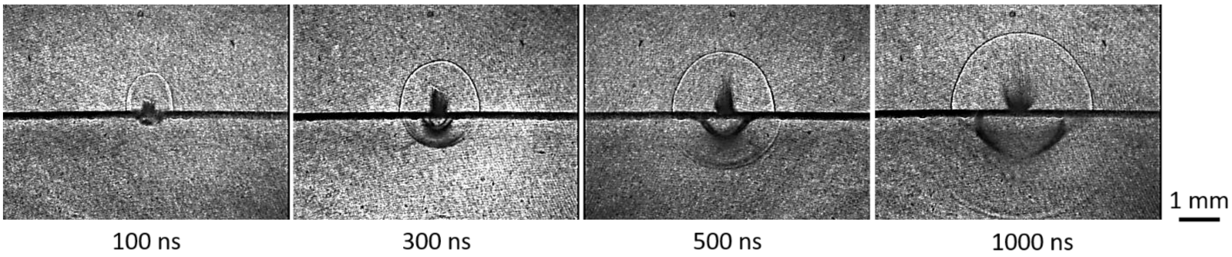

Figure 2. Evolution of laser-induced shockwave observed by photoelasticity imaging technique.

In the figure, the dark horizontal line at the middle of each image represents the target surface. The laser comes from above. The black curve in the upper part of the image is the shadow image of shockwave propagating in the air. In the lower part of the image, we can observe the photoelastic image of the laser-induced stress. Inside the shockwave front is the image of the ablated plume.

We measured the distance traveled by the shockwave with time. The distance was measured horizontally to eliminate the effect of plume elongated toward the laser source due to the growth of plasma during the laser pulse [1]. We presented the result in Fig.3.

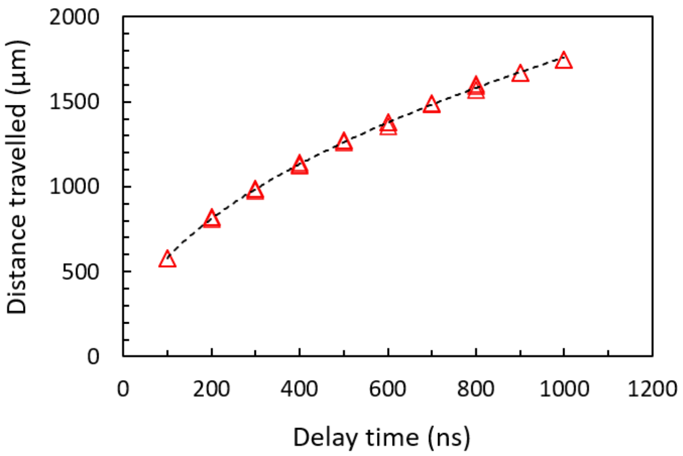

Figure 3. Distance travelled by shockwave as a function of time.

It has been showed that the propagation of laser-induced shock wave in air can be fit by point explosion model [6] and the relationship between shock radius and energy of the shockwave is given by [1]:

$$r = \frac{cE^{0.2}}{\rho_0^{0.2}} t^{0.4} \quad (1)$$

With E is the energy of shockwave, r is shockwave radius, t is delay time, ρ_0 is air density, ξ_0 is a constant close to unity that depends on the specific heat γ of the ambient air.

By fitting the experimental data with the model

$$r = at^{0.4} \quad (2)$$

We can find a, which is proportional to $\xi_0 \frac{E^{0.2}}{\rho_0^{0.2}}$.

Thus, the energy of shockwave can be deduced by:

$$E = \frac{a^5 \rho_0}{\xi_0{}^5} \quad (3)$$

For normal air, we can take $\xi_0 = 1.03$ [3].

By fitting the distance traveled by shockwave measured in our experiment with equation (2) we found that $a = 0.425$. From Eq. (3), we calculated that the shockwave energy was 12 mJ. Considering the laser pulse energy was 20mJ, we can conclude that about 60% of the laser energy was converted into shockwave energy during the process.

When the laser pulse reaches the target surface, not all its optical energy can be efficiently absorbed. Studies show that the plasma induced in air can only absorb about 60-70% of laser energy at the wavelength of 1064 nm [7]. The remaining energy is lost to the reflection at the target surface, reflection or scattering by the plasma, and most significantly: light energy lost due to the transmission through the plasma. The absorbed energy in the plasma plume is then converted to the shockwave energy during its expansion.

Our conversion ratio corresponds with the result reported by Mori et al. [3] and is lower than the result reported by Amer et al. [1] who reported a conversion ratio of approximately 80%. Compared to the laser-energy to shock-wave energy conversion ratio for underwater ablation, the conversion ratio of in-air ablation is larger. Vogel et al. [8] investigated the laser breakdown in water and showed that the conversion ratio is between 36-50% for nanosecond laser. A lower conversion ratio for in-water laser ablation can be explained by that a part of absorbed energy has been devoted to the energy of the cavitation bubble and as work done to the surrounding water.

Since the calculation of shockwave energy requires an observation of shockwave propagation with time resolution of nanoseconds, we suggest that energy conversion ratio can be used as a simple method to estimate the shockwave energy. From our result and results reported in literature, we propose that a ratio of 60% can be used in applications of laser ablation in atmospheric condition.

4. Conclusions

We observed the evolution of shockwave induced in laser ablation in the atmospheric condition. The distance traveled by the shockwave was measured and the shockwave energy was calculated. The result shows that about 60% of optical energy has been converted to the energy of shockwave during the ablation process. We suggest that this result can be used for a simple estimation of shockwave energy in applications that use laser ablation of solids in atmospheric condition.

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