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Simulating the photoelastic images of pulsed laser ablation in liquid by finite element method

Mô phỏng hình ảnh quang đàn hồi của quá trình phá hủy bằng tia laser trong môi trường chất lỏng bằng phương pháp phần tử hữu hạn

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Abstract

Photoelastic images of pulsed laser ablation in liquid were simulated by Finite Element Method. The real stress distribution in the target was deduced from the photoelastic images. The simulation result can represent to some extend the photoelastic images taken by the experiment. The result shows that a 20 mJ laser pulse could induce a transient stress that could reach at least hundreds of MPa near the focal region. When the pulse energy increased from 20 mJ to 60 mJ, the induced stress increased by a factor of 1.5.

Keywords: Photoelastic images; Finite Element Method; laser ablation in liquid.

Tóm tắt

Hình ảnh quang đàn hồi của quá trình phá hủy bởi tia laser trong môi trường chất lỏng được mô phỏng bằng phương pháp phần tử hữu hạn. Sự phân bố ứng suất thực tế trong mẫu được phân tích từ hình ảnh quang đàn hồi. Kết quả cho thấy hình ảnh mô phỏng có thể tái hiện gần đúng hình ảnh quang đàn hồi thu được từ thực nghiệm. Kết quả phân tích ứng suất cho thấy xung laser 20 mJ có thể tạo nên ứng suất lên đến hàng trăm MPa gần khu vực chùm tia hội tụ. Khi năng lượng xung tăng từ 20 mJ lên 60 mJ, ứng suất gây nên trong lòng vật mẫu tăng lên 1.5 lần.

Từ khóa: Hình ảnh quang đàn hồi; phương pháp phần tử hữu hạn; quá trình phá hủy bằng tia laser trong môi trường chất lỏng.

1. Introduction

Pulsed laser ablation is a process of removing materials from a solid surface by irradiating it with a focused laser beam. When the ablation is carried out in liquid, the process induces a strong shock that can cause residual stresses to the machined surface. Pulsed laser ablation in liquid (PLAL) has diverse

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applications, from laser cleaning, laser drilling, laser peening to nanoparticle synthesis.

In previous researches, we have introduced the photoelasticity imaging technique that provides us a unique tool to investigate the PLAL [1]. This technique could also provide a semi-qualitative estimation of the strength of laser induced stress. However, deducing the real value of induced stress field from these images is not straightforward.

Three dimensional photoelasticity provides one of the most common and widely used experimental methods for determination of three dimensional states of stress. Although the two dimensional photoelasticity is simple and straightforward, many difficulties arise in the evaluation of a tri-axial stress field, where the method of 3D photoelasticity is applied. This is mainly due to the variation of stress distribution along the light path that causes rotation of the principal-stress directions from layer to layer through a three-dimensional photoelastic model. Solution of the problem by conventional vectoral representation of polarized light is very difficult. Even if the stress distribution along the light path were known, a large amount of labor would be required to predict the polarization form of the emerging light. Solution of the inverse problem, that is, determination of the stress distribution along the light path from the observed optical patterns, is even more difficult and laborious [2].

The difficulties of interpretation of stress induced optical patterns in three dimensional (3D) photoelasticity led to the development of two separate techniques 3D stress state determination; namely the frozen stress and the scattered-light method. However, both the frozen stress and the scattered-light methods have serious limitation and disadvantages, which restrict their applicability. The frozen stress method need to cut the model into slices and thereby restricted to static loadings only. The scattered light method presents many difficulties in its application [2].

To date, no successful method is available to solve the inverse problem of 3D photoelastic without any special assumption on stress distribution or material birefringence. There were a few numbers of attempts have been made to solve this inverse problem of 3D photoelastic in general case, however, all of those are limited only to concept. Apart from these attempts for general cases, all other available methods are either based on 2D concepts or an approximate linear relation between output light vector and stress components [3].

To deduce the real stress distribution from a photoelastic image of PLAL, one has to deal with not only 3D but also super dynamic photoelastic phenomenon that makes any assumption of linear photoelasticity invaluable [4]. Therefore, we choose to approach the problem of quantitatively evaluating laser induced stress from photoelastic images by simulation method.

In this study, we use Finite Element Method (FEM) to simulate and reproduce photoelastic image. Quantitative evaluation of laser induced stress field is made by comparing simulated and experimental photoelastic images to evaluate the stress values.

2. Material and methods

2.1. Three-Dimensional Modeling

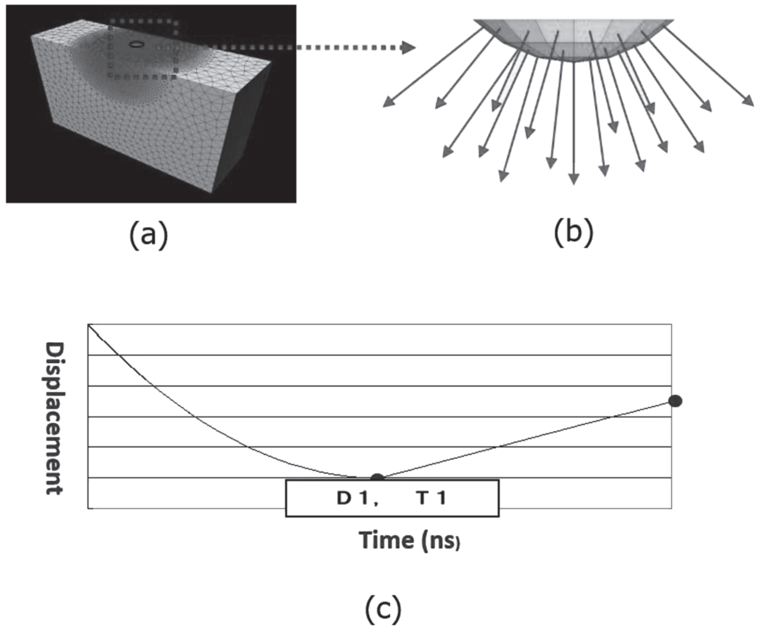


Figure 1. Three dimensional modelling and boundary condition setting

The 3D model was created using the GID software and being exported as IGES (Initial Graphics Exchange Specification) data format for mesh partitioning. The model was created as a three-dimensional block with the same size as that used in the experiments (25x20 x6 cm). On the surface of the model, a cavity ($D = 0.005cm$) was created to represent irradiated area (Fig. 1a). ADVENTURE_ TriPatch [5] was used to do mesh partitioning.

2.2. Set boundary condition

The laser-induced pressure was simulated by giving initial displacement to a small region representing the irradiated area. The displacement was spatial uniform but temporally varied. The temporal variation was calculated as a function of time step. Our simulations were carried out using 2000 time steps and the value of one time step was 1ns.

The irradiated area was designed as a hemisphere and the displacement was given in all directions (Fig. 1 b). The displacement D was increased from 0 to D1 after time T1 and then decreased to D2 after time T2 (Fig. 1 c), following the equations:

$$D = -\frac{D1 \times T^2}{T1^2} + 2\frac{D1 \times T}{T1} \qquad (0 \le T \le T1)$$

$$D = D1 - \frac{(T - T1)\,(D1 - D2)}{T2 - T1} \qquad (T1 \le T \le T2)$$

The value of D1, D2, T1, T2 were chosen so that the simulated image can best fit the experimental one.

In this study, the image obtained by photoelasticity imaging technique for non coated sample, taken at pulse energy of 20 mJ in underwater configuration was chosen to be the base image for carrying the simulation [6]. D1, D2, T1, T2 had been tried with different values until getting a simulated image that best represented the experimental image. The values chosen were: D1=180μm, D2=135μm, T1=800ns, T2=2000ns.

2.3. Calculating stress distribution and building photoelastic fringe patterns

Stress calculating was carried out using smoothing technique based beta finite element method (β FEM). The retardation of light due to photoelastic phenomenon was calculated based on the values of stresses obtained. After that, the photoelastic image was reconstructed [3].

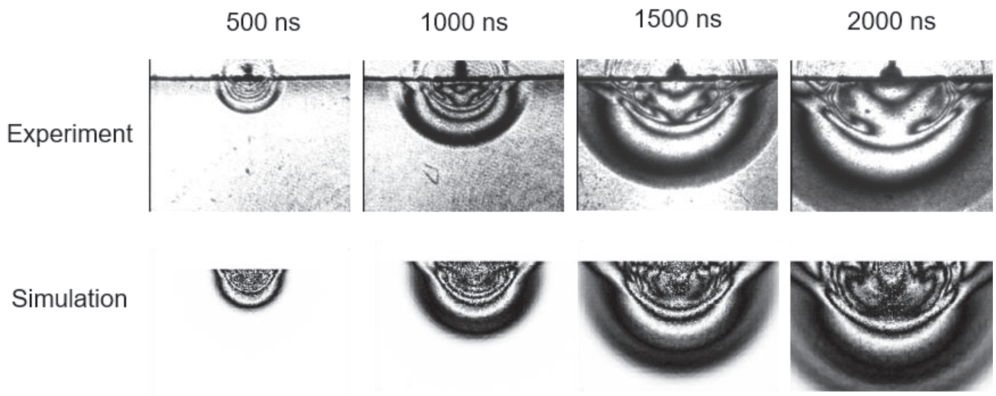


Figure 2. A comparison between simulation and experiment photoelastic images at pulse energy of 20 mJ.

To simulate the photoelastic images taken at larger pulse energies, the stress calculated at 20 mJ pulse energy was multiplied by a stress factor before calculating the light path. We can increase or decrease the simulated stress without changing the boundary condition by applying the factor for stress components. If no special mentions are provided, this stress factor equals 1.0.

2.4. Stress analysis

Stress analysis were carried out using Paraview [7].

3. Results and discussion

Figure 2 shows a comparison between the simulation and experimental results at pulse energy of 20 mJ, target was not coated. The results were compared from 500 ns to 2000 ns after irradiation. The results show that the simulation can reproduce the photoelastic images to a certain extent. The photoelastic patterns in the simulation images can represent the fringes obtained in the photoelasticity images. However, the simulation images seem to be broken near the focal point. A potential reason is that the stress is too high at this area that the program failed to calculate the correct displacement of light path.

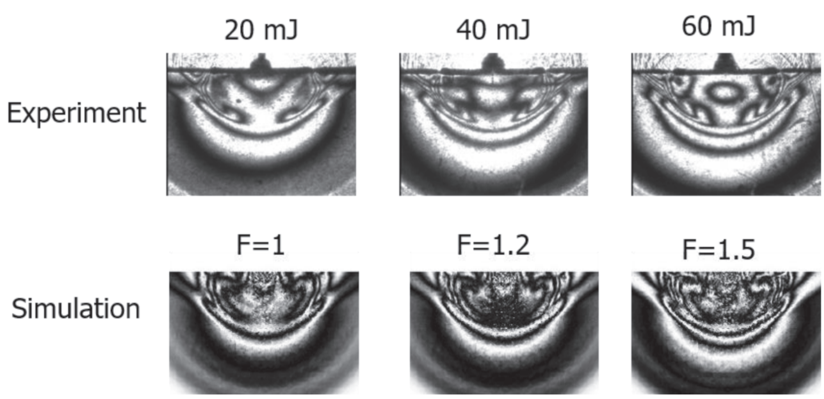
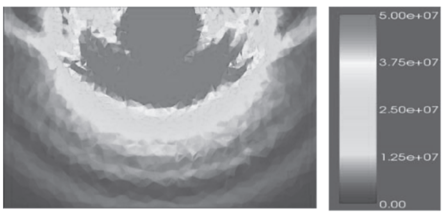
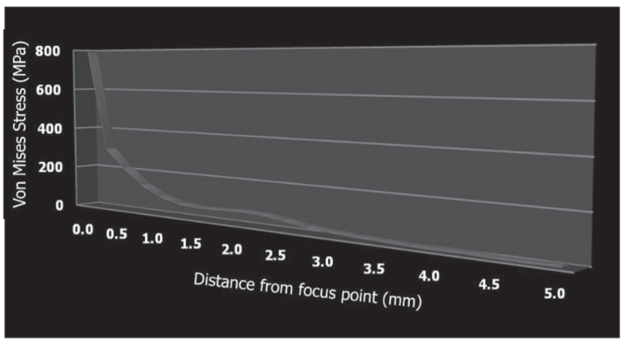


Figure 3. A comparison between simulation and experiment photoelastic images at different pulse energy. Delay time is 2000 ns.

Figure 3 shows a comparison between simulation and experimental results at the delay time of 2000ns. The experimental images were taken at pulse energies ranging from 20 to 60 mJ. The simulation images were produced with stress factor F increased from 1 to 1.5. The results show that as the pulse energy increased from 20 mJ to 40 mJ, the stress increased by a factor of 1.2. When the pulse energy increased to 60 mJ, the stress increased by a factor of 1.5.



(a) Von misses stress distribution (Pa)



(b) Von misses stress plotted against the radial distance from irradiated point

Figure 4. Von Misses stress in a solid target. Delay time: 2000 ns. Pulse energy: 20 mJ

To further investigate the stress distribution in the solid target, we calculated the Von misses stress for each element. Figure 4(a) presents the stress distribution within the affected area and Fig. 4(b) presents the stress distribution plotted against the radial distance from the focal point at 2000 ns after being ablated by a 20 mJ laser pulse. The result shows that a 20 mJ laser pulse can induced a transient stress that can reach at least hundreds of MPa near the focal region.

4. Conclusion

The simulation of photoelastic images was carried out using finite element method. The simulation results can represent the photoelastic images to some extent. The simulation result shows that a 20 mJ laser pulse can induced a transient stress that can reach at least hundreds of MPa near the focal region. When the pulse energy increased from 20 mJ to 60 mJ, the stress increased by a factor of 1.5. In the future, the simulation program needs to be improved to simulate the laser ablation process more satisfactorily.

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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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