TẠP CHÍ KHOA HỌC & CÔNG NGHỆ ĐẠI HỌC DUY TÂN
DTU Journal of Science and Technology 02(39) (2020) 58-62

TRƯỜNG ĐẠI HỌC DUY TÂN
DUYTAN UNIVERSITY

Simulation of pulsed laser ablation in transparent materials by finite element method

Mô phỏng quá trình phá hủy bằng tia laser trong vật liệu trong suốt bằng phương pháp phần tử hữu hạn

Thao Thi Phuong Nguyen[a,b*]
Nguyễn Thị Phương Thảo[a,b*]

[a]Institute of Research and Development, Duy Tan University, Da Nang, 550000, Vietnam
[a]Viện Nghiên cứu và Phát triển Công nghệ cao, Đại học Duy Tân, Đà Nẵng, Việt Nam
[b]Faculty of Natural Sciences, Duy Tan University, Da Nang, 550000, Vietnam
[b]Khoa Khoa học Tự nhiên, Đại học Duy Tân, Đà Nẵng, Việt Nam

(Ngày nhận bài: 16/11/2019, ngày phản biện xong: 04/12/2019, ngày chấp nhận đăng: 4/5/2020)

Abstract

Photoelastic images of pulsed laser ablation in glass and epoxy-resin were simulated by Finite Element Method. A comparison between simulation and experimental results obtained at 10 mJ laser ablation showed that the simulation program was able to reconstruct the laser ablation process inside transparent materials. The fringes that represent the stress wavefronts were successfully reproduced. However, a close view showed that the simulated images were broken near the focal area. In the future, we will attempt to improve the quality of simulated images.

Keywords: Photoleasticity image; laser ablation; Finite Element Method; stress wave.

Tóm tắt

Hình ảnh quang đàn hồi của quá trình phá hủy bởi tia laser trong vật liệu kính và epoxy-resin được mô phỏng bằng phương pháp phần tử hữu hạn. Kết quả so sánh giữa hình ảnh thực nghiệm và hình ảnh mô phỏng cho thấy chương trình mô phỏng có thể tái hiện quá trình phá hủy bằng tia laser trong vật liệu trong suốt. Các vân đàn hồi thể hiện mặt sóng ứng suất được tái hiện thành công. Tuy nhiên, hình ảnh mô phỏng bị rạn gần khu vực chùm tia hội tụ. Trong tương lai, chúng tôi sẽ khắc phục vấn đề này để cải thiện chất lượng hình ảnh mô phỏng.

Từ khóa: Hình ảnh quang đàn hồi; phá hủy bằng tia laser; phương pháp phần tử hữu hạn; sóng ứng suất.

1. Introduction

Laser ablation in transparent materials is induced by the non-linear absorption of photon energy at the beam focal area [1]. When high-power laser pulses are focused into transparent media, the medium suddenly becomes opaque to the laser irradiation as soon as a certain irradiance threshold is surpassed. The sudden

[*]*Corresponding Author: Nguyen Thi Phuong Thao; Institute of Research and Development, Duy Tan University, Da Nang, 550000, Vietnam; Faculty of Natural Sciences, Duy Tan University, Da Nang, 550000, Vietnam.*
Email: thaonguyen@duytan.edu.vn

rise in the absorption coefficient is due to the formation of a dense, optically absorbing plasma. It leads to rapid heating of the material in the focal volume, followed by its explosive expansion and the emission of shock wave [2]. During this process, extremely high temperature and stress can be created and may result in the structure changes. Recent studies demonstrated that a single short laser pulse tightly focused inside the bulk of a transparent solid could produce a cavity confined in a pristine dielectric or a crystal; and a multi pulses can form three-dimensional structures with a controlled size less than half of a micrometer [3]. This laser ablation inside transparent materials is considered as an inner modification of materials and has many promising applications, such as 3D data storage, direct writing of waveguide, optical grating, etc.

In the previous research, we observed the laser-induced ablation inside glass and epoxy-resin [4]. The custom-designed time-resolved photoelasticity imaging technique was used to observe the propagation of induced stress waves. The laser absorption did not happen at the focus point but along the laser beam axis in both cases. In epoxy-resin, the laser absorption happened at the same or very near instance and the induced wavefronts had approximate the same size. In the glass, the laser absorption started at the focal point and propagated toward the laser source during the irradiation. The wavefronts induced near the surface was smaller than that induced at the focal point.

In this paper, we aim to simulate the photoelasticity images of laser ablation inside glass and epoxy resin by finite element methods and evaluating the potential of this method in studying the process.

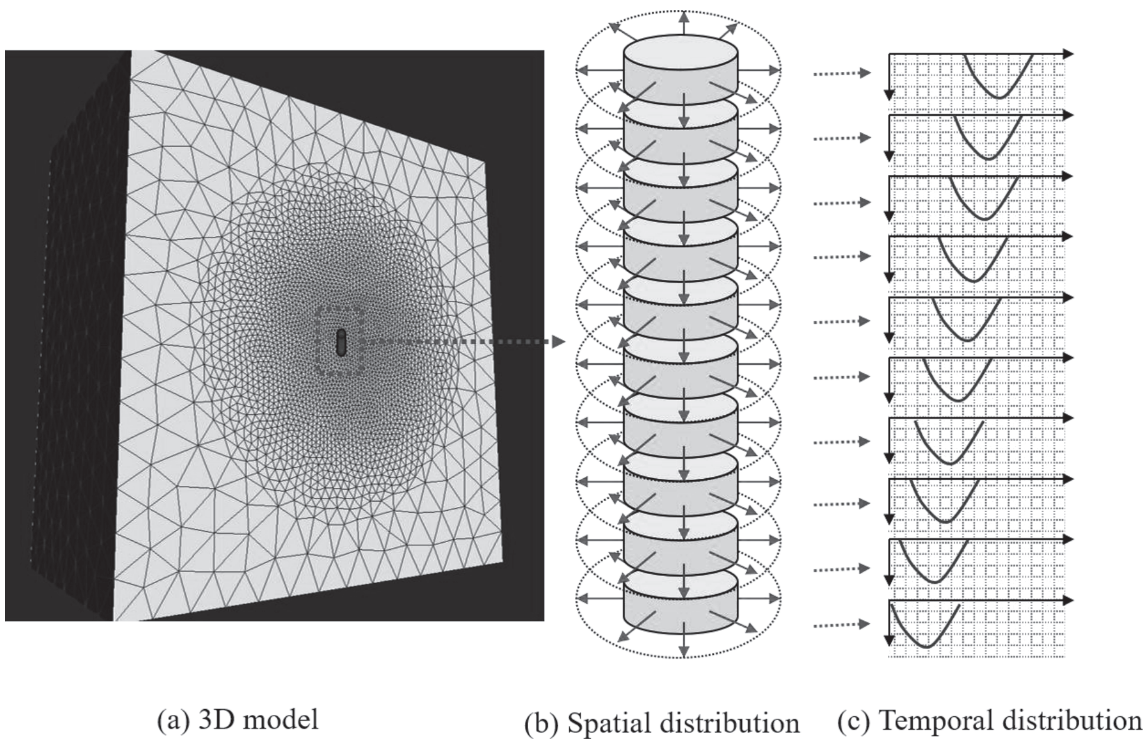

Figure 1: Three dimensional modelling and boundary condition setting

2. Material and methods

2.1. Three-Dimensional Modeling

The model was created as a three-dimensional block with the same size as that used in the experiments (30 x 30 x 6 mm). At the center of the model, a cylinder was created to simulate the ablated area (Figure 1a). The cylinder has a diameter of 100 μm. The length equals to 810 μm if the model is built for glass, 1440 μm if the model is built for epoxy resin. ADVENTURE_TriPatch [5] was used to do mesh partitioning.

2.2. Set boundary condition

Our previous experiment showed that the non-linear absorption inside glass and epoxy resin doesn't occur at once but the absorbing point moves from the inside to outward along the laser beam axis. Therefore, we built a boundary condition in which the irradiated area is divided into discrete portions which undergo independent initial movement. The irradiated area is divided into 10 portions with each portion has the form of a small cylinder with a radius of 100 mm. Each portion is given an initial centrifugal displacement which is spatially uniform but temporally varied (Fig. 1b). The temporal displacement form is the same for all portions but being delayed from the first portion to the tenth one (Fig. 1c). The delay time is calculated basing on the damage growing velocity at 10 mJ pulse energy obtained from experiment result, i.e. 27mm/ns for glass and 60mm/ns for epoxy resin.

For each portion, the displacement increases from 0 to D1 after time T1 and decreases to D2 after time T2. The values of D1, D2, T1, T2 were chosen so that we can reproduce photoelastic images that best match the experiment result. For simulating photoelastic images obtained inside glass: D1= 4 μm, D2= 0, T1=20 ns, T2 = 500 ns. For simulating photoelastic images obtained inside epoxy resin: D1= 10μm, D2= 0, T1=20 ns, T2 = 500 ns.

The displacement D is a function of time T following the equations:

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

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

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 [6].

3. Results and discussion

Figure 2 shows a comparison between the simulation and experimental results when focusing a 10 mJ laser pulse inside the glass. The results were compared from 100 ns to 200 ns after irradiation, with the increment of 50 ns. In these pictures, the center area shows laser-induced damage at the irradiated region. Surrounding rings show photoelastic fringes that represent laser-induced stress wave. The rings become bigger as the laser-induced stress wave propagates far from the irradiated area.

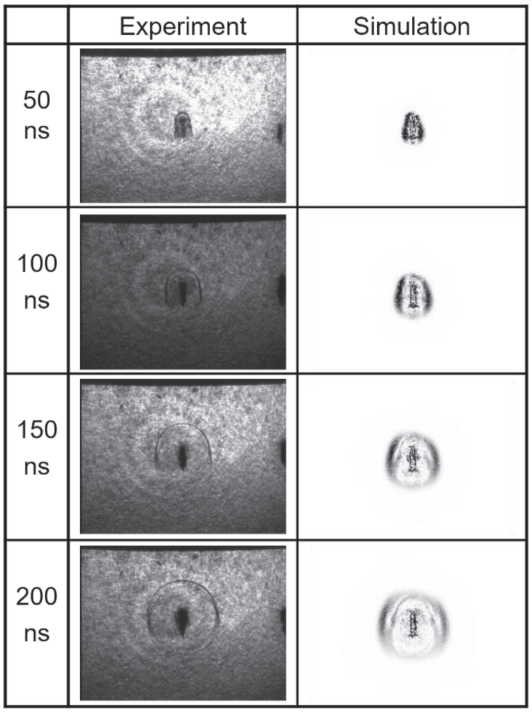

Figure 2: A comparison between simulation and experiment photoelastic images for pulse laser ablation in glass. Pulse energy was 10 mJ.

From the results, we can say that the simulation did reconstruct experimental photoelastic images. The simulation images show a collection of many wavefronts, the same as in the experimental ones [4]. The tilted form of wavefronts is also successfully simulated, which convince our success in simulating ablation process inside the glass. However, the simulated images are still broken near the irradiated area

Figure 3 shows a comparison between simulation and experimental when focusing a 10 mJ laser pulse inside epoxy-resin. The center area shows laser-induced damage and the surrounding rings represent stress wavefronts propagating from the irradiated area. Similar to the ablation in glass, several wavefronts are created in this case. The diameters of created wavefronts inside epoxy resin are quite homogeneous, i.e. all wavefronts appear to have the same diameter. This is because the absorption occurs at very near instance along the beam axis [4]. As can be seen from Fig. 3, the form of laser-induced stress wave has been reconstructed. Although the photoelastic images weren't satisfactorily reproduced, we can say that our simulation did reconstruct the phenomenon to some extent.

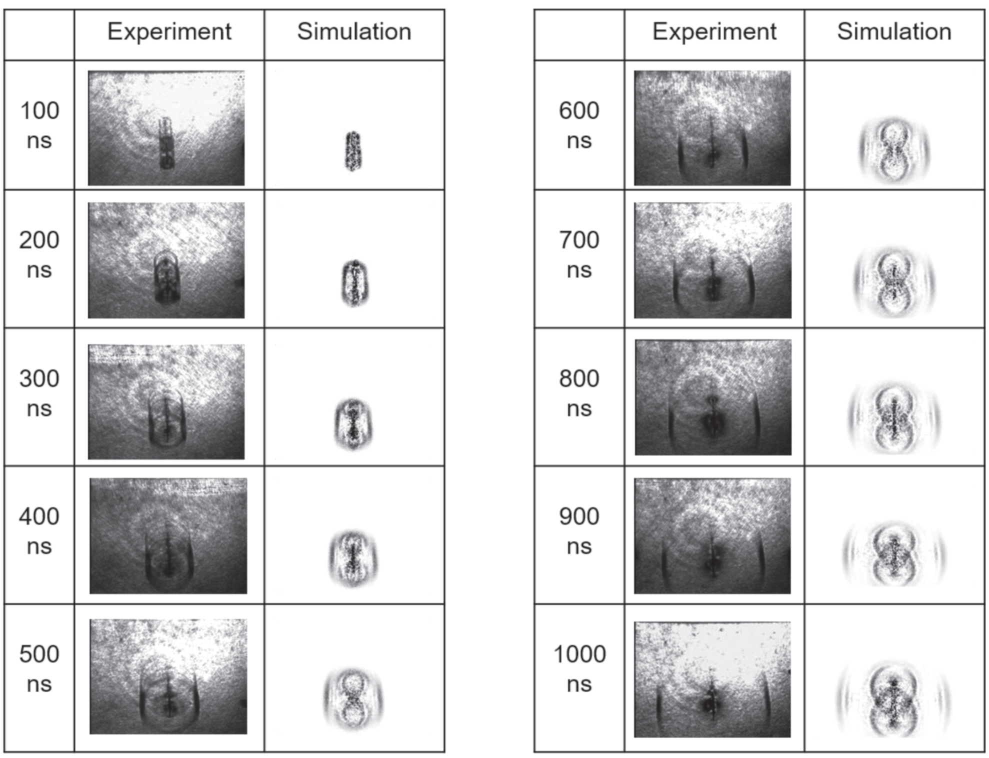

Figure 3: A comparison between simulation and experiment photoelastic images for pulse laser ablation in epoxy-resin. Pulse energy was 10 mJ.

4. Conclusions

The simulation for laser-induced ablation inside transparent has been carried out using the finite element method. Our simulation program was able to reconstruct the laser ablation process inside transparent materials. However, a close view of a simulated image showed that there existed many scratch-liked patterns in the image. The reason for these scratched patterns hasn't been known at present. In the future, we will attempt to solve this problem to improve the quality of simulated images.

Acknowledgment

The experiment results presented in this paper were based on the experiments performed at Department of Mechanical Engineering, Nagaoka University of Technology, Japan. I would like to express the great appreciation to Prof. Yoshiro Ito and Dr. Tanabe-Yamagishi Rie for their valuable support and advice.

The photoelasticity 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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