TẠP CHÍ KHOA HỌC & CÔNG NGHỆ ĐẠI HỌC DUY TÂN
DTU Journal of Science and Technology 01(56) (2023) 69-72

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Damage formation in glass under the ablation of a nanosecond laser pulse observed by shadowgraph imaging technique

Sự hình thành của khuyết tật trong vật liệu kính dưới tác dụng phá huỷ của xung laser nano giây quan sát bằng phương pháp chụp bóng

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(Ngày nhận bài: 17/10/2022, ngày phản biện xong: 22/10/2022, ngày chấp nhận đăng: 12/12/2022)

Abstract

We observed the formation of damage induced by focusing a nanosecond laser beam inside a glass block using the shadowgraph imaging technique. The damage growth was observed during some first dozens of nanoseconds of the process. The result shows that the damage growth is divided into two periods. During the laser pulse, the damage grows quickly, following the formation of laser-induced plasma. When the laser is switched off, the damage grows at a much slower rate. We propose that the growth of damage during the second period is due to the propagation of the shear wave inside the material.

Keywords: Laser ablation; shadowgraph imaging technique; non-linear photon absorption.

Tóm tắt

Chúng tôi quan sát sự hình thành của khuyết tật sinh ra khi hội tụ một chùm tia laser nano giây trong lòng vật liệu kính sử dụng phương pháp chụp bóng. Sự phát triển khuyết tật được quan sát trong khoảng thời gian một vài chục nano giây đầu tiên của quá trình. Kết quả cho thấy sự phát triển của khuyết tật được chia làm hai giai đoạn. Trong thời gian tác dụng của xung laser, khuyết tật phát triển nhanh chóng theo sau sự hình thành của plasma. Khi xung laser đã tắt, khuyết tật tiếp tục phát triển nhưng với tốc độ thấp hơn nhiều lần. Chúng tôi đề xuất rằng sự phát triển của khuyết tât trọng giai đoạn thứ hai của quá trình là do ảnh hưởng của sự lan truyền sóng ứng suất trong lòng vật liệu.

Từ khóa: Phá hủy bằng tia laser; phương pháp chụp bóng; hiện tượng hấp thụ photon phi tuyến tính.

1. Introduction

In general, a single photon does not have enough energy to excite an electron from the valance band to the conduction band. However, at high energy intensity, non-linear absorption where an atom can absorb many photons at the same time happens [1]. When high-power laser pulses are focused into transparent media, the medium suddenly becomes opaque to the laser when a certain irradiance threshold is

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surpassed. The sudden 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. During this process, extremely high temperatures and stress can be created and cause structural changes inside the transparent materials [2].

Laser ablation of transparent material is usually conducted using a femtosecond laser. Recent studies demonstrated that a single short laser pulse tightly focused inside the bulk of a transparent solid can produce a cavity confined in a pristine dielectric or in a crystal. Thus, multi-pulses can form three-dimensional structures with a controlled size of less than half of a micrometer [3]. This laser ablation inside transparent materials is considered an inner modification of materials and has many promising applications, such as 3D data storage, direct writing of waveguides, optical grating, etc. [3-5].

Although has been rarely used in inner modification applications, nanosecond laser can also induce structure changes inside transparent material via a multi-photon absorption [6]. Due to the longer pulse duration and larger energy, a nanosecond laser pulse usually induce larger damage in comparison to a femtosecond laser [2]. The formation of damages in nanosecond laser ablation of transparent material, especially at the early stage of the process has been rarely investigated.

In this research, we aim to observe the formation and evolution of damage when a nanosecond pulse is focused inside a glass bock. The damage formation was observed during some first dozens of nanoseconds of the process with a time resolution of nanoseconds. The image of the damage is captured using the shadowgraph imaging technique.

2. Experimental method

We focused a laser pulse (1064nm, 13ns) by a 5x objective lens into a glass block ($30x30x5mm^3$) to induce the damage. The pulse energy was 10mJ. The shadowgraph imaging technique was used to observe the formation of the damage inside the glass.

The shadowgraph imaging technique is an optical method that can reveal the non-uniformities in transparent media. This method is similar to the Schlieren method but is much simpler. In principle, we cannot observe a temperature, pressure, or density change in the air. However, all these non-uniformities diffract light, thus casting a shadow on a screen.

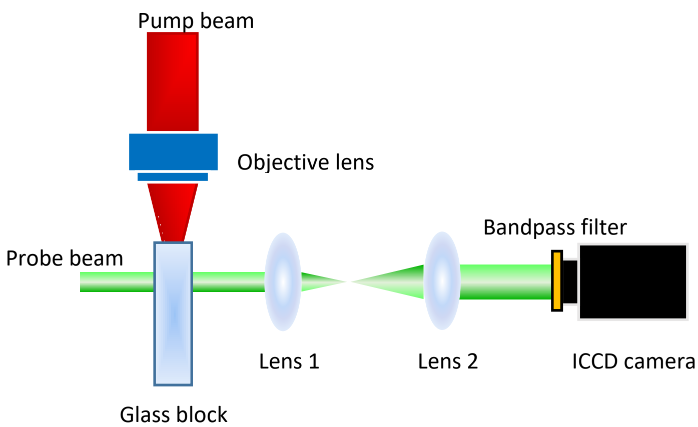

Figure 1. Diagram of the experimental system.

In this research, we used a typical pump-and-probe imaging system and an ICCD camera to capture the image of laser-induced damage. A 1064-nm laser pulse (pump pulse) was used to induce the breakdown in the air. A probe pulse with a wavelength of 532nm was directed through the breakdown area before going through a lens system for magnification. The image was then captured by the camera. A bandpass filter was installed in front of the camera to eliminate all the noise. The time delay between the pump and the probe pulses was regulated by an optical delay system.

3. Results and discussion

Figure 2 presents images of the damage formed inside the glass block. The damage was observed as early as when the laser beam interacting with the target (0ns) until 16ns. Also, final damage was also included in the figure to compare the size between the initial damage and the final one.

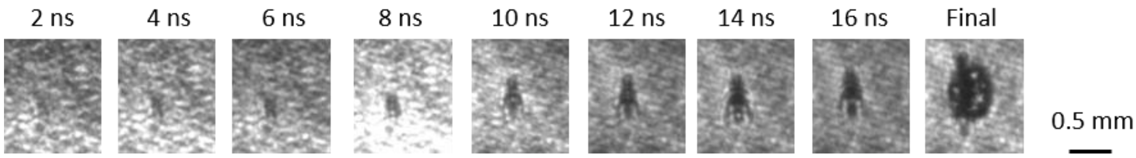

Figure 2. Evolution of damage induced by laser in the glass block, observed by the shadowgraph imaging technique.

In the figure, the dark region at the center of each image represents the laser-induced damage. The laser comes from above. The increase in length of this region indicates that laser-induced damage grows with time in the glass. From these results, we can when a laser pulse is focused inside the materials, the nonlinear absorption begins inside the sample and then propagate toward the laser source along the laser axis.

In order to investigate the damage growing velocity, we measured damage length at each time delay. Measured values were plotted versus delay time in Fig. 3. The fit values were calculated by using the least square method applying the mean values of damage length at each delay time. The final damage size was measured to approximately 800µm.

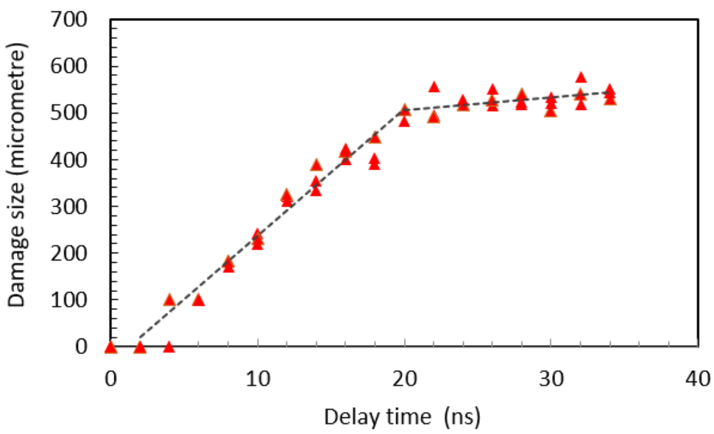

Figure 3. Evolution of damage size during the first 30 ns.

It can be seen that the damage-growing process includes two periods. The damage grew fast during the first period and slower during the second period. The first period ends after about 20ns. Our calculation showed that the growing velocity of the first period in glass is

27μm/ns with an uncertainty of 4.8%. During the second period, the damage grew at a rate of 2.6μm/ns with an uncertainty of 24%. The final length of the damage was approximately 800micrometers. Thus, after the first period, the damage reached 65% of its final length. Until the limit of our observation, the damage did not reach its final size.

The first period of the damage growth corresponds to the laser-matter interaction period. Thus, the rapid growth of the damage during this time can be explained by the growth of plasma during the laser pulse. When a laser pulse is focused in a transparent material, the first part of the pulse ionizes the material to form plasma. Once initiated, the plasma absorbs the rest of the laser pulse energy and expands toward the laser source. This phenomenon is the same as being reported in laser-induced plasma on a solid target [7]. Because most of the laser energy was observed at the plasma's top layer, the plasma grows toward the laser source. The plasma causes rapid heating of the material, resulting in the rapid growth of damage.

During the second period, the laser is already switched off. The growing speed of damage at this stage was in the order of shear speed in the glass (approximate 3500m/s) [8]. We thus suggest the shear wave induced during the laser-matter irradiation contributes to the growth of damage during the second period.

4. Conclusions

We observed directly and visually the formation of damage inside a glass block due to the non-linear absorption of laser energy. The damage is formed a few nanoseconds after the laser pulse reaches the target and develops during the laser pulse at the rate of 27μm/ns. When the laser is switched off, the damage continues to grow but at a much slower rate. From the observation, we suggest that the damage induced in glass reaches 65% of its final size during the laser irradiation, then continues to grow after the laser is switched off under the effect of a shear wave. The result contributes to the understanding of damage formation in glass under the ablation of a laser pulse.

Acknowledgment

The results presented in this paper are based on the experiments conducted at the Laser Laboratory, Nagaoka University of Technology, Japan. We appreciate the support from Emeritus Prof. Yoshiro Ito from the Nagaoka University of Technology, and Associate Prof. Tanabe-Yamagishi from the Fukuoka Institute of Technology.

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