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Curved drilling via inner hole laser reflection

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ABSTRACT

In this paper, we describe curved hole drilling via the reflection of a laser beam off the sidewall of the drilled hole. A slightly offset laser beam forms a tilted surface at the bottom of the hole, controlling the angle of curvature. An ultraviolet laser beam operating at a wavelength of 266 nm was used. To visualize the hole formation process, borosilicate glass was used as the laser workpiece. This method was able to drill a curved hole with an average angle of ~3° with curvature beginning at a depth of 400–600 μm. A curved hole with a diameter of <50 μm was achieved. A branched hole was also demonstrated by using the reflection of the tilted sidewall. The curved hole formation process was recorded with a high speed camera. Once the ablated sidewall reached a certain depth, drilling ceased as the laser energy fell below the ablation threshold. Ultimately, judicious selection of an appropriate laser fluence and sidewall angle allow the formation of curved holes.

1. Introduction

Curved hole drilling has been the focus of much investigation because it increases flexibility in mechanical design. For example, electrical discharge machining has been used to drill curved holes by attaching an electrode to the tip of a universal joint or self-moving electrode (Ishida and Takeuchi, 1999). An electrochemical machining technique was tested by placing an electrode on the tip of a flexible tube (Sasahara et al., 2007). Laser drilling has been performed by emitting a laser beam and liquid jet from the tip of a thin curved tube (Hidai et al., 2013). Optical fiber has also been used to transmit laser light to the bottom of a curved hole (Hosono et al., 2012; Yamashita et al., 2008). When drilling into a transparent material, a laser beam can be focused within the material. Many investigations have reported curved hole formation in glass with ultra-short pulsed lasers by direct ablation (Hwang et al., 2004) or modification and successive chemical etching (Gattass and Mazur, 2008).

To date there have been various reports on deep laser drilling. Forsman et al. (2005) reported that a double laser pulse with a delay of 30–150 ns was an effective means of deep drilling. Tokarev et al. (2000, 2003) calculated final hole profile and depth vs. incident fluence and achieved high aspect ratio holes. Ancona et al. (2008) demonstrated that a heat accumulation effect enhanced ablation rate. Döring et al. (2013) demonstrated that a reduced ambient pressure lead to an increased ablation rate and therefore drilling efficiency. Unwanted hole bending during laser drilling has also been previously investigated. Kononenko et al. (2001) showed that bending was caused by the structural anisotropy and Fresnel reflection coefficient on polarization orientation. Döring et al. (2012) drilled a silicon wafer with a femtosecond laser and attributed the curved hole formation to the intensity distribution at the bottom of the hole. Xia et al. (2015) concluded that the disturbance of the laser beam by the ablated aerosol caused bending.

We have previously investigated deep micro drilling in glass using ultraviolet lasers (Hidai et al., 2010a,b, 2015). In these experiments, the inner surface reflection of the hole enables deep drilling. Additionally, it was shown that the laser energy emitted through the hole was larger than the calculated energy without including the effect of surface reflection (Hidai et al., 2010a). In the work described herein, we demonstrate curved hole drilling by using the reflection of a laser beam at the bottom of the hole with an ultraviolet laser. The tilted side wall at the hole bottom was formed by the slight offset of the laser beam, thereby controlling curve direction. Borosilicate glass was used to visualize the hole formation process.

2. Experimental

The experimental apparatus used for the present work was same as that described in our previous reports (Hidai et al., 2016). Briefly, a circularly polarized ultraviolet laser beam (DS20H-266, Photonics Industries International, Inc., NY, USA) was focused on the sample through a convex lens with a focal length of 30 mm. The laser was operated with a wavelength of 266 nm, 100 μJ of energy, a

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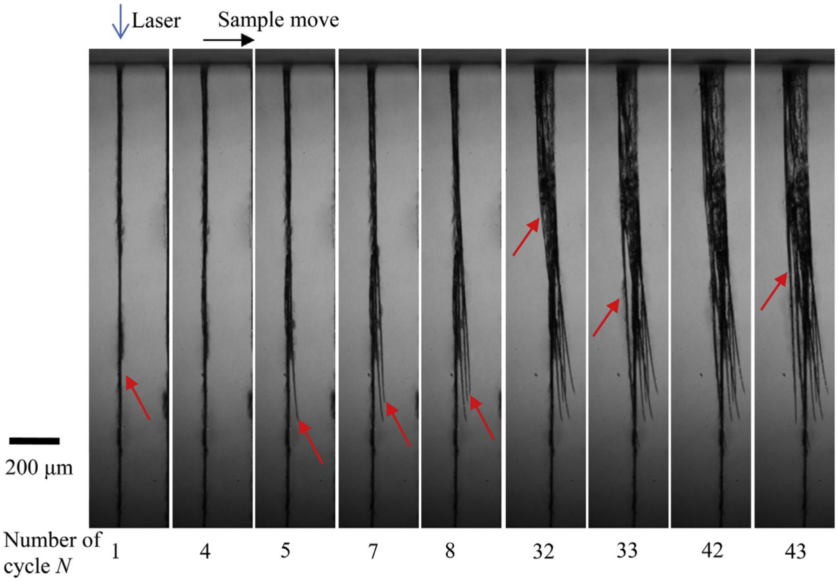

Fig. 1. Transverse section of the drilled hole. P_N: 5000 pulses, Δx_N: 2 μm.

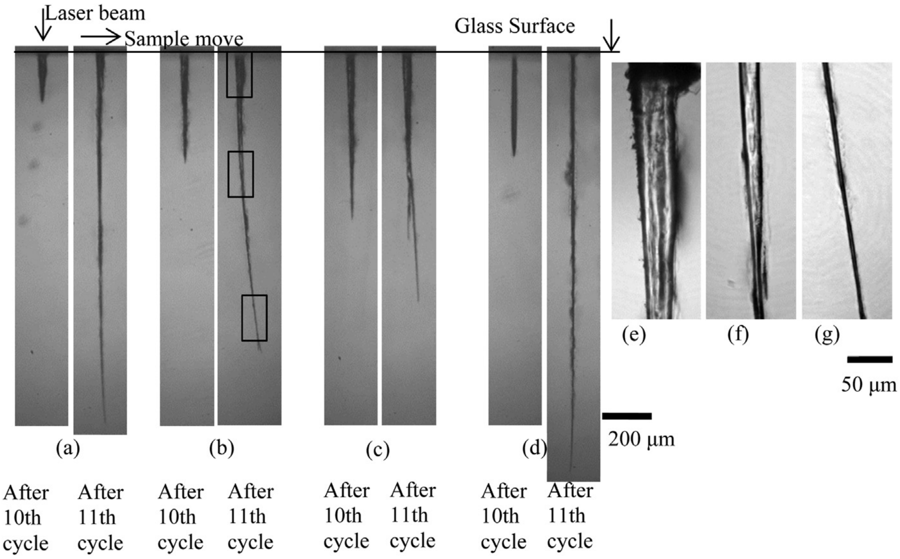

Fig. 2. Transverse section of the drilled hole. (a) $N = 11$, $P_N = 40$ ($N = 1$–10), $P_{11} = 4600$, $\Delta x_N = 2$ μm (b) $N = 11$, $P_N = 100$ ($N = 1$–10), $P_{11} = 4000$, $\Delta x_N = 2$ μm (c) $N = 11$, $P_N = 160$ ($N = 1$–10), $P_{11} = 3400$, $\Delta x_N = 2$ μm (d) $N = 11$, $P_N = 100$ ($N = 1$–10), $P_{11} = 4000$, $\Delta x_N = 0$ μm (e)–(g) magnified image of (b) indicated by rectangular.

repetition rate of 10 kHz and pulse width of 8 ns. The calculated beam spot diameter was 14.5 μm. The laser beam was TEM_{00} mode and beam quality factor M^2 was <1.3. The beam divergence was <1 mrad. Borosilicate glass (Pyrex®, Corning 7440, Corning Inc., NY, USA) with a thickness of 10 mm was used as the workpiece. The laser was focused on the top surface of the glass. A high-speed camera (phantom v7.3, Vison Research Inc., NJ, USA) was set orthogonal to the optical axis of the laser beam to observe the drilled hole. The shutter of the high-speed camera and the timing of the laser pulse were synchronized using a delay generator. The camera exposure time was set to 30 μs. A transmitted image was obtained by placing a light source on the back face of the sample.

The possibility of curved hole formation was first confirmed by drilling a deep hole. The deep hole was formed by using 5000 laser pulse illuminations without sample movement. After 5000 laser pulse illuminations, the drilled hole was observed by the camera and the sample was moved 2 μm in the orthogonal direction of the laser optical axis. Then, another 5000 laser pulses were illuminated. In this study, a cycle comprises the following processes: laser illumination, observation by the camera, and sample movement. Thus, the laser was illuminated for 5000 pulses, the hole image was obtained, and the sample was moved, followed by the next cycle. In this paper, the number of cycles is expressed as N, the number of laser pulses in the N-th cycle is P_N, the sample movement in the N-th cycle is Δx_N, and the position of the laser illuminated during the N-th cycle is X_N. The position where the image is obtained during the N-th cycle is indicated by

$$X_N = \sum_{n=1}^{N-1} \Delta x_n.$$

Curved hole drilling was then attempted after pilot hole drilling by changing laser illumination conditions: total number of cycles, N; number of pulses in the N-th cycle, P_N; and sample shift in the N-th cycle, Δx_N. The number of laser pulses in the last cycle, adjusted

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