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Damage morphology and mechanism in ablation cutting of thin glass sheets with picosecond pulsed lasers

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ABSTRACT

We experimentally investigated the morphology and mechanism of laser-induced damage in the ablation cutting of thin glass sheets with picosecond pulsed lasers and we compared the experimental results to our models. After several passes of laser ablation, we observed two different kinds of damage morphologies on the cross-section of the cut channel. They are distinguished to be the damage region caused by high-density free-electrons and the heat-affected zone due to the heat accumulation, respectively. Furthermore, micro-cracks can be observed on the top surface of the workpiece near the cut edge. The nano-cracks could be generated by high energy free-electrons but opened and developed to be visible micro-cracks by thermal stress generated in the heat-affected zone. The crack length was proportional to the volume of heat-affected zone. Heat-affected-zone and visible-cracks free conditions of glass cutting were achieved by controlling the repetition rate and spatial overlap of laser pulses.

1. Introduction

Ultrashort pulsed laser ablation has become a powerful technology in micromachining of transparent dielectrics, such as waveguide writing [1,2], drilling [3–5] and cutting [6,7]. Nonlinear absorption of laser energy by multi-photon ionization and avalanche ionization allows localized material removal with high accuracy in micro/nanometer scale. As the time of laser energy deposition into the material is much shorter than that of material removal, the destructive thermal and thermo-mechanical effects are minimized. Because of these advantages, laser ablation with ultrashort laser pulses is an attractive solution for precise and controllable cutting of thin glass sheets (typical thickness < 1 mm), which are of great interest in widespread applications but mostly the mechanical properties are delicate.

Superior edge and surface qualities and an absence of cracks are the critical requirements for cutting brittle, transparent dielectrics. Ablation characteristics, such as ablation rate and crater shape and size, have attracted most of the attentions in the reported studies of micromachining transparent dielectrics [3,5]. Laser-induced damage in the surrounding volume of the ablated crater, however, is another crucial issue in glass cutting with ultrashort laser pulses. On one hand, laser-induced high-density free-electrons could result in damage tracks, so called electronic damage, because of refractive index modifications [8–12]. The electronic damages are possible sources of crack formation in the application of glass pieces. On the other hand, high repetition rate of laser pulses provides adequate processing speeds but suffers from the inherent risk of localized heat accumulation [13], which will lead to a heat-affected zone (HAZ) due to softening and melting [12–14]. Thermal stress in the HAZs can initialize crack formation [15] in the glass volume. These incidental damages near the cut edges will reduce the quality of the glass product, e.g. the break strength. Prevention of HAZ and cracking is one of the most important tasks in laser cutting of brittle materials. Therefore in order to optimize the glass-cutting process with picosecond laser pulses, it is very important to thoroughly investigate the damage morphologies and the underlying physical mechanism as well as the impact of experimental parameters on the damage formation.

In this paper, we experimentally study the damage mechanisms and morphologies in glass cutting with picosecond lasers and compare those results with the models for electronic and thermal damages. The thermal model is presented here while the plasma model was presented in [10]. After several passes of laser ablation, several kinds of laser-induced damages are observed and studied in different regions of the glass sample, i.e. the top surface near the

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cut edge and the cross section of the ablated channel. First, the influences of spatial overlap, repetition rate and number of passes on the electronic and thermal damage of the ablated channel in cross sections are investigated and discussed. Second, the characteristics and formation mechanism of micro-cracks on the top surface are analyzed in detail. Finally, the optimized experimental conditions free of HAZs and micro-cracks are concluded based on the experimental and analytical results.

2. Experimental setup and cutting strategy

The experiments of glass cutting with picosecond lasers were carried out on the setup shown in Fig. 1(a). A frequency-doubled mode-locked laser system (Hyper Rapid, Coherent) was used to deliver laser pulses of 10 ps duration at 532 nm. The maximum pulse energy is 50 μJ and the repetition rate f_{rep} of laser pulses is varied from10 kHz to 400 kHz. Laser pulses were focused on the top surface of the glass sample with an f-Θ objective of 63 mm focal length and the spatial distribution of laser intensity at the focus is determined to be a Gaussian profile. The radius w_0 of the focal spot is 6.5 μm, where w_0 is the radius at which the intensity drops to $1/e^2$ of its axial values. The glass sample is Corning Eagle XG® (an alkaline earth boro-aluminosilicate glass) with a thickness of 0.3 mm. Its band-gap was measured to be 3.45 eV by the Tauc plot method [16]. The refractive index n_0 of the glass sample is 1.51 at the wavelength of 532 nm [17].

In the experiments, a cutting strategy shown in Fig. 1(b) was implemented. Several passes of laser ablation with a time interval of several milliseconds on a single line were carried out by scanning of laser pulses. However, for cutting through of glass samples ablating several lines in parallel and then several passes of scan on top of each other were required to overcome the saturation effect [5]. Therefore the cutting process discussed in this paper is a reduced condition suitable to study the damage mechanisms. Certain spatial overlap of adjacent laser pulses is necessary for efficiently cutting the glass sheet. As shown in Fig. 1(b), the displacement between adjacent pulses along the scanning direction is calculated to be $s = v/f_{rep}$, where v is the scanning velocity of laser beam along the single line. We define the spatial overlap r of adjacent pulses by

$$r = \begin{cases} (1 - \frac{s}{2w_0}) \times 100\% = (1 - \frac{v}{2w_0 f_{rep}}) \times 100\%, & \text{when } 0 < s \le 2w_0. \\ 0\%, & \text{when } s > 2w_0. \end{cases}$$

Note that it is different from the overlap of the ablated craters. Since the pulse energy applied in the experiments is 40 or 50 μJ, the diameter of the ablated carter is larger than that of laser spot on the sample. The repetition rate f_{rep} and the scanning velocity v can be chosen to control the spatial overlap r. When the repetition rate is set up, the spatial overlap can be adjusted from 0% to 90% by changing the scanning velocity v of laser beam. In our experiments, four spatial overlaps, i.e. 0%, 54%, 85% and 90%, were used and their corresponding displacements s between adjacent pulses were 18 μm, 6 μm, 2 μm and 1.25 μm, respectively. The scanning velocity v of laser beam on the sample surface is in the range of 0–7.2 m/s. The repetition rates of 10 kHz, 100 kHz and 400 kHz were studied. The spatial overlap and repetition rate are two key parameters in the experiments. Their influences on the damage formation will be discussed in detail in Section 3.1.3.

After ablation cutting at the designed conditions, the glass samples are cut with laser into small pieces roughly 8 mm × 8 mm for cross sectioning. Several pieces are glued together with resin. To make sure that no influence comes from the edges of the block, at each end an additional glass plate is positioned. After that at least 1 mm thickness is grinded away to make sure that no influence of the laser cutting of these samples is seen on the cross-section of the ablated channel. The grinding process consists of lapping and then polishing. The lapping/polishing is done with a Lapping machine PM5 from Logitech. In detail, lapping is done with an iron plate and lapping suspension (PWA 12 Al_2O_3 from Fujimi). An iron plate is used in lapping for conditioning to make sure that no inhomogeneities in roughness are in the plate due to the last lapped sample. After lapping the lapping plate is changed to a polishing plate which is conditioned with a diamond tool. For polishing a polishing suspension type SF1 from Logitech is used. The grinding is done with minimal weight to prevent additional cracking of the samples. The samples are not removed from the clapping device during these processes to prevent a different lapping/polishing direction/angle due to new clamping. When investigating the samples after grinding with microscope we focus into the sample and make sure that no additional cracks are introduced during grinding process. Finally, microscope images of the cross sections and top surfaces of the cutting channel are obtained with a microscope.

The focus height of laser pulses plays a key role in laser ablation cutting of thin glass sheets, especially in damage formation. Therefore here we introduce the determination and controlling of the focus height in detail. In the experiments, laser pulses were focused on the top surface of the glass sample. The focus position is defined by scribing several lines in different focus positions and the focus position is at the thinnest line. The behaviors around the focus spot are symmetrical and are checked during this procedure. The sample is positioned by a camera (also aligned parallel to the focus plane). During the above mentioned procedure the distance (Δx, Δy and Δz) between camera and scanner is measured. All samples are positioned under the scanner afterwards. With the camera an accuracy of the focal position of less than 20 μm is achieved, which is much smaller than the Rayleigh length (about 250 μm) of the laser beam. Therefore the focal position of laser

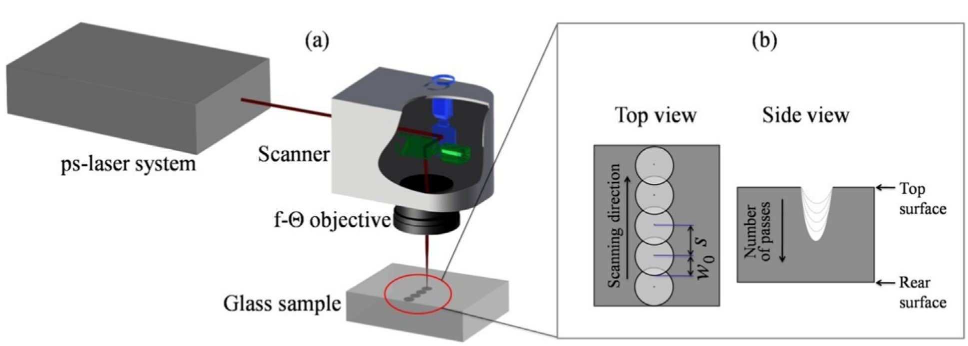

Fig. 1. Schematic diagram of the experimental setup (a) and the cutting strategy and the spatial overlap between adjacent pulses in one pass of laser ablation cutting (b). Note that in the left part of (b) it is not the overlap of the ablated craters but that of the laser spots.