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Precision glass machining, drilling and profile cutting by short pulse lasers

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Abstract

Demands for producing micro-crack free, high quality and high-aspect ratio microholes and microfeatures in glass substrates have been increasing for a number of applications such as in MEMS device packaging, optical fibre alignment, mini-vision systems and microelectronic packaging. However, due to the poor thermal properties of most glasses the fabrication of finely machined features, e.g. grooves, microholes etc. has been a challenging task. In this study, short pulse solid-state lasers with pulse duration in the ns to fs range were used to process different types of glass materials. The effect of the pulse duration and other process parameters on the machined features was analyzed to reveal the underlying thermal effects and nonlinear processes. Edge quality, circularity, aspect ratio, formation of the redeposit material and machining rate were also studied with respect to the process variables such as focusing optics, laser power, wavelength and repetition rate. Arrays of drilled micro-hole patterns and fabricated microfeatures are demonstrated with discussions on their potential applications.

Keywords: Laser materials processing; Glass drilling and micromachining; Microfabrication in glass; Microchannels in glass

1. Introduction

Small components free of micro-cracks, good edge and surface quality as well as with a high aspect ratio, made of hard materials such as ceramics and glass, are difficult to fabricate and often require complex, multi-step processing. On the other hand, demands for microholes and microfeatures in these materials have been increasing for a number of miniature product applications such as in MEMS device packaging, optical fiber alignment, mini-vision systems and microelectronic packaging. Direct write laser processing, in which the material removal occurs at high power densities during the laser ablation process, has been demonstrated as a powerful technique. Compared to other conventional techniques of machining glass, laser machining offers a number of advantages such as single-step processing, high flexibility, direct writing of features by integrating CAD/CAM software, high speeds, no contamination and sterility. Precise focusing of the laser beam allows material removal with high accuracy, high repeatability and localized material removal with micron size tolerances [1]. However, due to the presence of thermal effects, the spatial resolution available from conventional, wider pulse lasers operating at visible and infrared wavelengths of the spectrum is limited. At present, there are mainly two ways to overcome this limitation. One way is to use UV laser wavelengths that can be focused down to smaller spot size and thereby reduces the extent of thermal damage around the machined edges [2,3]. During processing, materials having a higher absorption coefficient in the UV region, tend to concentrate the absorbed energy in relatively smaller volume resulting in controllable material removal. The other approach is to use ultra-fast lasers with much shorter pulse durations, e.g., in the picosecond (ps) or femtosecond (fs) regimes [4–6]. It is clear from the literature that the energy coupling into the materials at ultra-fast time scale significantly reduces the thermal effects during processing [7,8]. Additionally, the ultrafast laser pulses can induce multiphoton absorption and other non-linear optical effects, which can be of significant advantage to fabricate precise microfeatures in a controlled fashion [9,10].

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Glass is one of the most important materials in optoelectronic devices and other industrial applications with a high transmission from the UV to IR wavelength region, excellent thermal and electrical properties, and high chemical resistivity [11,12]. Furthermore, the glass properties are controllable by adjusting the composition during development and fabrication. However, these very properties make the glass a challenging material to machine [1,13]. Due to poor thermal properties, fabrication of finely machined features using laser-based processes e.g. grooves, channels, microholes, stand-alone levers, etc., in glass materials has been quite a difficult task. Although a significant amount of efforts were expended in using the simulation methods, analytical techniques and the experimental observation of morphologies of micro-structures/features [14–23], comparative discussions are lacking primarily due to the fact that the individual results have been obtained under different laser conditions and specific experimental arrangements. In this study, short pulse solid-state lasers with pulse duration from ns to fs regime and laser-induced plasma machining technique have been used to process different types of glass materials under comparable experimental conditions. The effect of the pulse duration and other process parameters on the feature qualities and its formation is analyzed to reveal underlying thermal effects and nonlinear processes. Edge quality, circularity, aspect ratio, burrs formation, re-deposition of materials and machining rate were also studied with respect to the process variables such as focusing optics, laser power, wavelength and repetition rate. Examples of arrays of drilled micro-hole patterns and fabricated microfeatures are included with discussions on their potential applications.

2. Experimental details

Fig. 1 illustrates a schematic diagram of the workstation used in this study for the laser micro-machining of glass samples. The laser beam was focused onto the sample surface through a beam expander and a fused silica lens or a microscope objective, mounted on the *Z*-axis translation stage. The lasers used in this work, include a Q-switched Nd:YVO_4 laser operating at 532 nm wavelength with pulse width 3 ns and a repetition rate of 1 kHz. A frequency-tripled Nd:YAG laser, operating at 355 nm wavelength with pulse duration ranging from 10 to 30 ns, and an ultrafast Ti:sapphire laser (Clark MXR 2000) at operating at its fundamental 775 nm wavelength having a fixed pulse duration of 150 fs and a repetition rate of 1000 Hz was also used. Depending on the experimental arrangement, different optical configuration was chosen and the optical beam path was modified to meet the process requirements. For femtosecond laser machining experiments, a 1/4 wave plate was introduced into the beam path to convert the original *p*-polarized beam in to a circularly polarized beam and the beam was focused on to the glass surface using a 50-mm focal length lens.

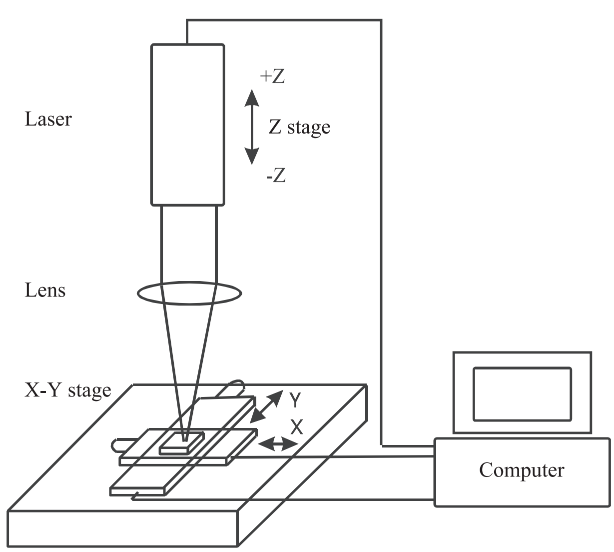

Fig. 1. Schematic diagram of the laser micro-machining system.

The samples were held on to a mount fitted to the computer-controlled *X*–*Y* translational stage. The resolution of the translation stages was ±1 μm. Corning microscope slide, commercial Vitrocom S-105, doped silica and fused silica capillary fibers were used as sample glass materials. The morphology of the sample specimens was observed using optical microscopes, scanning electron microscope, and the WYKO interferometric profiler (NT-2000).

3. Results and discussion

3.1. Laser micro-machining of grooves in glass using nanosecond lasers

The frequency-tripled Nd:YAG laser beam at 355 nm wavelength was focused on to a sample surface in ambient with an 8× beam expander and a plano-convex lens having a focal length of 50 mm. The minimum spot diameter available was approximately 7 μm at beam waist. The sample was machined at a scan rate of 2.5 mm/s during the machining process. Fig. 2 illustrates the laser micro-machined grooves on the glass surface under a number of focused and defocused conditions. The central grooves in Fig. 2(a) and (b), marked by arrows, represent the optimum machining with the best focusing conditions. The grooves from left to right represent conditions when the focusing lens moved away from the sample surface consistently in steps of 25 μm in the upward *Z*-direction for each neighboring groove. Machined surface grooves with noticeable cracks can be found in Fig. 2(a). The large cracks in the glass were produced when the high intensity laser beam was directly focused on to the surface. Using careful selection of experimental parameters such as wavelength, intensity, repetition rate, sample surface conditions, scanning rate, etc., to control the thermal process interactions, high quality, crack-free laser machined micro-features can be produced in