# Micro-hole drilling with femtosecond fiber laser

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### ABSTRACT

In this paper, micro-hole drilling in ambient air is presented using fs fiber laser (750 fs & 1030 nm). Micro holes were fabricated in both transparent (glasses) and non-transparent materials (metals and tissues). Hole shape and morphology was characterized and evaluated with optical microscope and scanning electron microscopy (SEM). Debris-free micro holes with good roundness and no thermal damage were demonstrated for both glass and metal. Micro-hole drilling in hard and soft tissues with no crack or collateral thermal damage is also demonstrated.

Keywords: Femtosecond laser, fiber laser, drilling, micro-hole, tissue, glass.

### 1. INTRODUCTION

Fabrication of micro-holes has received much attention due to applications across nearly all manufacturing sectors, such as aircraft engine turbine blades, automotive fuel filters, combustion chambers, surgical needles and microfluidic devices. Meanwhile, the demand for high aspect ratio micro-holes in different materials (both transparent and non-transparent) is increasing in micro-pumps, micro-sensors, micro-chemical-reactors and micro-heat-exchangers to obtain higher efficiency and performance. Current fabrication method still heavily relies on photolithography techniques, which require advanced facilities and numerous process steps and it is often limited in both material type and geometry.

As one of the major applications of laser machining processes, laser hole drilling is widely used in electronic and semiconductor industries. Drilling with ns or longer pulsed laser is always accompanied with the formation of melting and recast layer, although the geometrical precision could be improved by using drilling technique such as helical drilling, the quality and precision achievable with ns laser pulses is still limited due to the uncontrolled redeposition of melt. Drilling with ps pulse duration laser still has detrimental effects such as cracks and heataffected zone in the surrounding area due to the high energy input and thermally induced stress. This affects not only the accuracy but also the reliability of the process. Recently, the development of femtosecond (fs) laser sources has given a precise and versatile method for micro-scale and even nano-scale fabrication technique, owning to its unique nonlinear absorption that is different from conventional lasers. The main advantages of fs laser drilling lies in the low heat input and the reduction of melt component of material removal. Many researchers have paid much attention to the micro-holes fabrication using fs lasers, including transparent materials [1-8] and non-transparent materials [9-13]. Especially for transparent materials, different methods have been used to generate high aspect ratio micro-holes such as combination with chemical etching [4-5], beam shaping [1, 6], and liquid-assisted drilling from rear surface [2-3, 7]. However, the fs laser sources generally used is traditional solid state laser, which is expensive and bulky and needs regular maintenance. This disadvantage can be overcome by fs fiber laser which is much cheaper and more compact and it is also reliable and maintenance-free.

In this paper, micro-holes drilling using a fs fiber laser (1030 nm wavelength & 750 fs pulse duration) radiation was investigated. The drilling was performed with different materials, including glasses, metals and tissues. Examples of drilled micro-hole patterns and fabricated micro-features are included with discussions on their potential applications. Debris-free micro holes with good roundness and no thermal damage were demonstrated for both glass and metal. Furthermore, no crack or collateral thermal damage is observed for both hard and soft tissue material drilling.

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### 2. METHODS & MATERIALS

#### 2.1 Experimental setup

Figure 1 shows the sketch of the work station used in this study for laser micro-hole drilling. The fs laser system is a commercial mode-locked seed fiber laser (PolarOnyx Laser. - Uranus Series, www.polaronyxlaser.com), generating 750 fs pulses (FWHM) at 1030 nm wavelength with pulse repetition rate tunable between 1 Hz and 1 MHz with an acousto-optic modulator (AOM). The output collimated beam is a nearly symmetric Gaussian with  $M^2$ <1.3 and the maximum output pulse energy is 10  $\mu$ J. The laser beam is linear polarized and focused by a long working distance microscope objective lens (N.A.=0.55). The focal spot size (D) for the laser beam can be calculated by the diffraction limit, as shown by Eq. (1):



Figure 1. Experimental set up for fs laser welding and sealing of transparent materials

where  $\lambda$  is the laser wavelength and N.A. is the numerical aperture of the objective lens. The focal spot diameter is less than 5 µm. The total loss of the beam delivery system is less than 50%. Such a loss has been accounted for in the irradiation pulse energy values stated hereafter. An attenuator is used to control the laser pulse energy for fabrication and a mechanical shutter is used to switch the laser beam. A CCD camera is placed along the optical axis and used to align the sample and obtain a live view for the laser processing.

Simple percussion drilling cannot fulfill the requirements of high precision and quality. Trepanning drilling was used in this study and the samples were moved while the laser beam was fixed irradiating from top. Initially the beam is located away from the sample surface, and the sample is moving closer at slow speed in a direction perpendicular to the beam. The surface of the sample is then brought into the beam focal region and material ablation begins. All the experiments were performed in ambient air and without shielding gas, except for a transverse air flow to remove the ablation debris and shielding particles. The linear motion stage and the delay generator for AOM are controlled by computer to achieve different sample moving speeds and different pulse repetition rates.

#### 2.2 Materials

In this study, different materials were used, including metal (stainless steel), glass (soda lime glass) and tissues (bovine bone and tendon). The bulk targets of these materials were cleaned before the experiments by isopropanol. Both metal and glass samples were used in the form of rectangular plates. The tissue samples were cut and prepared from fresh bovine bone and tendon from local supermarket.

#### 2.3 Microscopy & measurements

After laser drilling, the micro topography of the drilled holes was characterized with an upright digital microscope (ME520T) at first. Then the drilled holes quality were checked and measured by a scanning electron microscopy (SEM, FEI QUANTA FEG 600).

## 3. RESULTS & DISCUSSION

#### **3.1** Transparent material

Unlike traditional thermal processing using ns or CW lasers, where a laser wavelength is chosen such that the material naturally absorbs the laser beam, glass materials are transparent at the laser wavelength of 1030 nm. The high intensity inside the focal volume will induce multi-photon or tunneling ionization and subsequent avalanche ionization occurs. This gives the unique capability of transparent material processing using fs laser.

At first, successive drilling is performed in glass materials. Here trepanning drilling technique was used since it can generate large holes with good consistency and holes taper compared with percussion drilling. The trepanning drilling was realized using the XY translational stages and the glass substrate was moving in a defined spiral movement while the beam was maintained stationary. A number of passes were required for the complete drilling of the glass material and acceptable quality of micro-hole array pattern was obtained.



Figure 2. SEM view of drilled hole in soda lime glass using fs fiber laser. (a) overview; and (b) detail view of the hole edge and side wall.

Figure 2 shows the SEM view of drilled hole in soda lime glass drilled using fs fiber laser. The laser parameters used include 5.1  $\mu$ J pulse energy, 105 kHz repetition rate and 1 mm/s trepanning speed. The hole drilled has the entrance and exit diameters of 400 and 270  $\mu$ m, respectively and the total thickness of the glass is 200  $\mu$ m. A higher magnification SEM view of the drilled hole showing the side walls of the hole is illustrated in Fig. 2(b). The inner wall surface is irregular due to the brittle structure of glass. The drilled holes have good circular geometry for both entrance and exit sides and no micro-cracks or thermal damage is observed around the edges, which is different with the results using long pulsed lasers.

Figure 3 shows the SEM images of drilled holes using ns and ps lasers by other researchers. Figure 3(a) and 3(b) shows the 50  $\mu$ m holes in Pyrex glass drilled with ns laser (10 ns & 500 Hz) [14], ands Figure 3(c) shows the 20  $\mu$ m hole drilled in silicon with ps laser (10 ps & 355 nm) [15].Cracks is clearly seen around the exit side of the ns laser drilled hole and thermal damage is visible for both ns and ps laser drilled holes. The difference is mainly due to the fact that the fs laser pulse length is ultra short compared to the time scale for thermal diffusion into the material and

the buildup of thermal and mechanical stresses in the material is suppressed. The ability to fabricate such holes and even holes arrays with consistent regular shape due to the deterministic nature of fs laser drilling is promising and remarkable. Even more exciting is the fact that no post-processing is required. Further improvement of the taper angle and aspect ratio can be achieved by using scanner with F-Theta lens or liquid-assisted rear side drilling [2-3, 7]. It should be pointed out that thermal damage and cracking can be pronounced even for fs laser when the laser fluence and the repetition rate is set too high to increase the drilling efficiency [16-17].



Figure 3. SEM images of drilling results using ns laser: (a) Pyrex glass - front side; (b) Pyrex glass-back side from reference [14] and ps laser: (c) silicon from reference [15].

### 3.2 Metals

Figure 4 shows the SEM view of drilled hole in stainless steel using fs fiber laser. The laser parameters used include  $3.0 \,\mu$ J pulse energy, 225 kHz repetition rate and 1 mm/s trepanning speed. The hole drilled has the entrance and exit diameters of 400 and 300  $\mu$ m, respectively and the total thickness of the glass is 200  $\mu$ m. Figure 4(b) shows the higher magnification SEM view of the side walls of the drilled hole. The drilled holes have good circular geometry for both entrance and exit sides. It can be seen that the machined hole-walls have good surface roughness of micron size and no visible micro-cracks are present around the edges.



Figure 4. SEM view of drilled hole in stain-less steel using fs fiber laser. (a) overview; and (b) detail view of hole side wall.



Figure 5. SEM view of drilled hole through steel plate with ns laser (a) from reference [18] and ps laser (b) from reference [19].

Figure 5 shows the SEM view of a drilled hole through steel using ns and ps laser from references [18-19]. There is a large amount of melt droplet was redeposited on the hole edge drilled using ns laser (10-30 ns & 0.9 mJ), as shown in Figure 5(a). For the drilled hole using ps laser (Figure 5(b), 5 ps & 0.6 mJ), heat-affected zone is observed around the hole edge affecting the sharpness and quality of the hole. The comparison with ns and ps laser drilling results shows the advantage of fs laser drilling.

Furthermore, deeper hole drilling was also investigated using fs fiber laser. Figures 6 shows the top and side view of a deeper through hole drilled on a stainless steel sample plate. The stainless steel sample has a thickness of 813  $\mu$ m. The roundness of the hole on the entrance side and exit side was quite good. The diameter of the hole entrance is 290  $\mu$ m, and that of the exit is 150  $\mu$ m. The taper angle is less than 5 degrees.



Figure 6. SEM view of drilled hole in stain-less steel using fs fiber laser. (a) top view; and (b) side view of hole side wall.

Figure 7 shows the bottom surface of another partially drilled hole in stainless steel. Interestingly, fine subwavelength ripple structure is found with about 170 nm width and 5 to 10  $\mu$ m length. The ripple spacing is generally less than 100 nm and some of the ripples structures are close to each without spacing. The orientations of the ripples structure are parallel to each other. It is not clear whether or not these ripples are due to interference effects and the orientation depends on laser polarization as further investigation is needed. Similar ripple structure has been observed in various materials for fs laser drilling [12-13]. Smooth surfaces are generally preferred for precision machining and micro-fluidics whereas rippled structures can find applications in grating fabrication and adhesion of deposited materials.



Figure 7. SEM view of ripple structure on bottom of drilled hole in stainless steel using fs fiber laser.

### 3.3 Tissue materials

Since the first use of lasers in the medical field, medical applications comprising diagnosis and tissue processing using laser light have been in the focus of interest to replace conventional surgical tools. Conventional long pulsed lasers have not succeeded in replacing the dental drill in many hard tissue applications mainly due to the unacceptable collateral damage.

In this study, tissue hole drilling was also demonstrated using fs fiber laser, as shown in Fig. 8 and 8. Figure 8(a) shows the microscopic view of the hole drilling results in bovine bone using fs fiber laser. Fig. 8(b) shows the SEM view of the side walls of the hole illustrated in Fig. 8(a). The laser parameters used include 2.7  $\mu$ J pulse energy, 56 kHz repetition rate and 1 mm/s trepanning speed. The drilled hole has diameter of 400  $\mu$ m and depth of about 200  $\mu$ m. Spiral pattern can be seen on the bottom of the sample. Compared with glass and metal, the drilling efficiency is relatively low and the surface roughness is large. This is due to the higher ablation threshold and non-flat sample surface.

Figure 9 shows the microscope view of the hole drilling results in soft tissue (bovine tendon) using fs fiber laser. It was processed using 5.1  $\mu$ J pulse energy, 105 kHz repetition rate and 1 mm/s trepanning speed. The drilled hole has diameter of 400  $\mu$ m and depth of around 500  $\mu$ m.

As shown in Fig.8 and Fig.9, remarkableness is the complete absence of visible cracks or thermal damage around the edges of the drilled holes. This is totally different with the results using CW or long pulsed lasers. Typically, treatment by a conventional pulsed laser (ns to ms pulse width) leads to cracking, melting, charring of the surrounding materials from a few tens of microns to a few hundreds of microns range [20-21]. The use of fs fiber

laser would allow the implementation of cheaper, compact and reliable laser systems for life science and medical applications.



Figure 8. Micro-hole drilling in bovine bone using fs fiber laser: (a) Microscope top view, (b) SEM detail view of drilled hole edge.



Figure 9. Microscope view of micro-hole drilling in bovine tendon using fs fiber laser

# 4. SUMMARY

In this paper, the micro-hole drilling of both transparent and non-transparent materials using a fs fiber laser was investigated. The drilled holes quality was characterized using optical microscope and SEM. It is found that debrisfree micro holes with sharp edge and no thermal damage were achieved for both glass and metal. Furthermore, complete absence of visible cracks or thermal damage was observed around the edges of the drilled in both hard and soft tissues. This technique can be applied in fabrication of microfluidic device combined with optical waveguide for detection and medical device, and in microsurgery applications.

#### ACKNOWLEDGE

This work was funded by NSF, Army, NIST, and AFOSR.

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