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Fabrication of micro-texture channel on glass by laser-induced plasma-assisted ablation and chemical corrosion for microfluidic devices

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ABSTRACT

A process combined laser-induced plasma-assisted ablation (LIPAA) with chemical corrosion is proposed to fabricate micro-channels with micro-texture surface on glass. Micro-cracks form under the recast layer of glass due to the thermal expansion and contraction strain induced by the plasma during LIPAA. This "defect", micro-cracks, can be further developed into tree-like micro-textures as the recast layer is removed by chemical corrosion. The effects of chemical corrosion, including corrosive time and corrosive concentration, on the micromorphology of surface texture were investigated. Several representative textures on channel surface were obtained. In order to fabricate micro-channels with micro-texture surface, the effecting factors of LIPAA, including number of scanning cycles, scanning speed, pulse power density and gap distance between glass and sacrificial material, on the channel geometry and chemical corrosive rate were also investigated. The results show that the gap distance is the most significant influence factor on the channel width before chemical corrosion. The corrosive rate of channel width increases with power density and decreases with gap distance. The channel depth before corrosion and its corrosive rate increase with power density and decrease with scanning speed and gap distance. The corrosive rate of width and depth increases with number of scanning cycles till 150, and then reaches steady. The micro-channel with micro-texture surface fabricated by LIPAA and chemical corrosion can be potentially applied in some microfluidic devices.

1. Introduction

Nowadays, microfluidic device or lab-on-a-chip system has been widely applied in electronics, energy, chemistry, optical and biomedical fields, such as microelectronics cooling (Wang and Mamishev, 2011), micro fuel cell (Zhou et al., 2014), micro-reactor (Scialdone et al., 2014), measurement of fundamental biological components (Chang et al., 2015), biomedical diagnostic (Ghosh et al., 2014), fast drug detection (Kurbanoglu et al., 2015) and so on. Furthermore, micro channel with micro-texture surface plays an important role in bio-mineralization (Mills et al., 2007), scaffolds for growing animal cells (Textor et al., 2006), hydrophobic surfaces (Luo et al., 2010) and solar cell devices (Zhao et al., 1998). Glass material is widely employed to fabricate microfluidic devices due to its beneficial optical property, solvent compatibility, surface stability and high surface adsorption. Compared with polymer, glass material has the advantages of reusability, mechanical durability and low autofluorescence (Nieto et al., 2014).

A lot of methods have been reported to fabricate micro-channel, such as imprinting (Martynova et al., 1997), micromoulding (Fukuba et al., 2004), injection molding and embossing (Becker and Heim, 2000). However, the above mentioned methods are effective for polymer but not for glass. Lithography technique, including photolithography (Ko et al., 2014), deep plasma etching (Queste et al., 2010) and chemical etching (Zhang et al., 2015), is always proposed to fabricate micro-channel on glass. These traditional methods can fabricate complex micro-channel rigorously. However, it requires sophisticated and expensive equipment located in a clean room and its process is also complicated. Laser micromachining can also be used to fabricate micro-channel on glass. Kasaai et al. (2003) demonstrated that the pulse laser is much

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more efficient to fabricate micro-channel on glass than continuous-wave laser. Femtosecond laser can fabricate micro-channel on glass with excellent machined quality (smooth machined surface) due to its ultra-high power density. It is also able to fabricate 3D microstructure inside glass (Sugioka et al., 2014). However, facilities of femtosecond laser are outrageously expensive. Nanosecond near infrared radiation (NIR) laser, while providing good throughput and low cost facilities, gives poor machined quality such as rough surface and debris deposition as the work reported by (Nieto et al., 2014). Moreover, the laser fabrication of glass will fail if the power density of NIR laser pulse is insufficient (<10 GW/cm^2) (Hopp et al., 2007). Laser-induced plasma-assisted ablation (LIPAA) is a promising method to machine micro-channel on the transparent materials using nanosecond NIR laser with a low power density (Zhang et al., 1998b). The previous researches mainly focused on the forming mechanism of LIPAA (Hanada et al., 2005), the ablation rate of depth (Zhang et al., 1998a) and the crack-free process of glass substrate (Hong et al., 2002). The LIPAA method has not been employed to fabricate micro-channel on glass for microfluidic devices.

Many micro-fabrication methods have been reported on the formation of micro-texture structure on the micro-channel. Hu et al. (2003) utilized photolithography-based microfabrication techniques to produce symmetrically arranged prism elements for the enhancement of electroosmotic transport in channel. The photolithography technique is sophisticated but complicated as the above description. Hu et al. (2013) fabricated micro-textured structures on the inner surface of glass capillaries with zinc oxide nanorods by chemical deposition (chemical crystal). The nanorods can provide larger surface area and enhance the fluorescent signals. Abou Ziki et al. (2012) fabricated micro-texture on the micro-channel surface of glass by spark assisted chemical engraving. However, the channels were too shallow to apply them in microfluidic devices. The other methods, such as heat treatment (Ju et al., 2008), ion irradiation (Inomata et al., 1997) and chemical etching (Spierings, 1993), were also reported to fabricate surface micro-texture. The micro-texture is cumbersome to be modified on the surface of a micro-channel for microfluidic devices.

We present a composite process of LIPAA and chemical corrosion to fabricate micro-channel with micro-texture surface on glass for microfluidic devices. LIPAA utilizes plasma of sacrificial material and its shock wave to machine micro-channels on glass. During LIPAA, a lot of micro-cracks form under the recast layer of glass due to the thermal expansion and contraction strain induced by the plasma. This "defect", micro-cracks, can be developed into micro-textures after the removal of recast layer by a simple operation of chemical corrosion. This formation mechanism of micro-channel and its surface micro-texture are discussed. The effects of chemical corrosion, including corrosive time and corrosive concentration, on micromorphology of surface textures were investigated. The effect factors of LIPAA for fabrication of micro-channel, including number of scanning cycles, scanning speed (pulse overlap), pulse power density and gap distance between glass and sacrificial material, on the geometry of channel (depth and width) and the chemical corrosive rate were also investigated. A prototype microfluidic device and several functional patterns were fabricated to further demonstrate the feasibility of LIPAA in microfluidic devices.

2. Experimental

2.1. Experimental setup and materials

The experimental setup is composed of a pulse fiber laser machine (IPG, No: YLP-1-100-20-20-CN, Germany) and a Z axes positioner as shown in Fig. 1. The specific parameters of fiber laser are given in Table 1. The workpiece is the standard microscope soda lime glass slide (Sail Brand Inc.) fixed on the Z axes positioner over the sacrificial material. The aluminum silicon carbide (AlSiC) and aluminum alloy (Al) block were chosen as the sacrificial material. The properties and manufacturers are presented in Table S1 and Table S2. The gap distance between glass workpiece and sacrificial material can be adjusted by the Z axes positioner. The focus of laser was set on the upper surface of sacrificial material. The mixed solution of hydrofluoric acid (HF) and nitric acid (HNO_3) with the molar ratio of 1:1 was chosen as the corrosive solution.

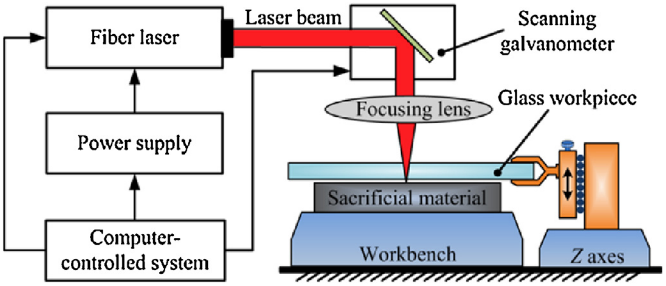

Fig. 1. Schematic of experimental setup.

Table 1
Specific parameters of fiber laser.

Parameters	Nomenclature	Value	Unit
Wavelength	λ	1064	nm
Pulse duration	Δt	100	ns
Focused diameter	ω_0	31.5	μm
Power density	P_0	0.128–1.28	GW/cm^2
Repetition rate	F	20	kHz
Beam quality(M^2)	M^2	1	N/A

2.2. Experimental procedures

The effect factors of laser on the channel geometry (width and depth) and chemical corrosive rate were investigated by single factor method experiments. Four controlled parameters varied: number of scanning cycles (300 cycles), scanning speed (630 mm/s), pulse power density (1.28 GW/cm^2) and gap distance between glass and sacrificial material ($\approx$0 μm). 0 μm gap distance is defined as the glass workpiece and sacrificial material is contacted with each other softly. The variation ranges of factors are shown in Section 4.3. In order to investigate the effect of chemical corrosion on the micromorphology of micro-texture surface, experiments with different corrosive time (1 min, 5 min, 10 min, and 20 min) and different corrosive concentration (0.1 mol/L, 0.5 mol/L, 1 mol/L, and 2 mol/L) were conducted.

The machining process was observed by an optical camera (EOS 600D, EFS 18–55 mm, Canon Inc.). The micromorphology and geometry of channel were observed by a scanning electron microscopy (SEM) (JEOL JSM-6380LA) and an optical microscopy (OLYMPUS BX51M). A high dynamic range digital microscope (KEYENCE VHA-2000) was employed to measure the channel depth and width.

3. Machining mechanism

3.1. Formation mechanism of micro-channel with micro-texture surface

According to the previous research of LIPAA by Prof. Sugioka' group (Zhang et al., 1998b), the laser beam penetrates through the glass workpiece and directly strikes onto the sacrificial material.