Applied Mechanics and Materials Vols. 799-800 (2015) pp 407-412
© (2015) Trans Tech Publications, Switzerland
doi:10.4028/www.scientific.net/AMM.799-800.407

Submitted: 2015-06-22
Accepted: 2015-07-06

Elimination of Clogging in PMMA Microchannels using Water assisted CO_2 Laser Micromachining

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Keywords: PMMA, Clogging, heat affected zone, CO_2 laser ablation, thin water layer

Abstract. The accuracy and clogging of microchannels are important for assessing the quality of lab on chip (L-O-C) devices. The clogging affects the fluid mixing efficiency and influences the bonding of substrate. In this paper, inexpensive and quick method for microchannel fabrication in polymethyl methacrylate (PMMA) while reducing the thermal damage is introduced. Accordingly, the substrate was covered with a thin layer of water during CO_2 laser ablation. The effect of water cooling on the clogging formation, heat affected zone and the microchannel geometry in terms of depth and width is investigated. Clogging formation mechanism in the intersection of Y-channel is studied to improve its quality for microfluidics applications. During the experimental work, the CO_2 laser power was varied from 2.4 to 6 W at scanning speed from 5 to 12.5 mm/s. The results showed that covering the PMMA substrate with a thin layer of water prevented clogging formation and reduced the heat affected zone.

Introduction

Over the last few years fast growing interest and use of microfluidics devices in bio-chemical analysis and medical applications had been noticed [1-3]. Direct laser ablation is used for fabrication of microfluidics chips since it is fast and flexible method used for that purpose as a compared to replication methods. To overcome contamination problems in some critical microfluidics applications, the chip should be fabricated for one time use. CO_2 laser is preferable for that purpose due to its low capital and operational cost compared to ultraviolet laser. Because CO_2 laser ablation is based on photothermal process it leaves thermal damage on the laser projected area such as bulges, clogging, and heat affected zone.

Polymethyl methacrylate (PMMA) is a common thermoplastic material, used for the fabrication of Polymer- based microfluidics chips which is easily distorted by direct laser ablation due to the high temperature gradient [4]. Several research studies have investigated the process of CO_2 laser ablation for PMMA substrates with the aim of avoiding thermal damages. Yiing C. Yap et al [5] demonstrated the effect of using stainless steel pinhole of 50 μm diameter during direct laser ablation. Their results showed that channel width was reduced from 300 μm to around 60 μm and the bulges height were reduced to 0.8 μm. C.K. Chung et al [6] demonstrated the effect of using 0.03 mm of stainless steel metal-film on the PMMA substrate as a protection during CO_2 laser ablation process. Their results showed that the bulges, resolidification, heat affected zone and clogging phenomena were reduced. Additionally C K Chung et al [7] reported an approach to ablate microchannels of PMMA without bulges by adding a cover of unexposed and exposed JSR photoresist and polydimethylsiloxane (PDMS) on the PMMA substrate. These attempts partially succeeded to reduce the bulge formation in the top of microchannel rims. However, thermal damages inside the microchannels still exist, which badly affect the fluid mixing. In a further work C.K. Chung et al [8] fabricated microchannel in Pyrex 7740 glass without cracks and the bulges were reduced by covering the substrate with different thicknesses of water layer during laser ablation. Yinzhou Yan et al [9] presented experimental and modelling studies for underwater laser machining of deep cavities in alumina. It was accordingly found that underwater machining enhanced the product quality by reducing the thermal damage and preventing the crack initiation.

This paper presents an experimental investigation of the effect of using water assisted laser machining for microchannels fabrication in PMMA substrate. In this work a thin water layer of 300 µm thickness is added on the substrate during CO_2 laser ablation. Measured parameters include channel depth and width, clogging, and heat affected zone. Tests are conducted in air and water at a set of process control variables including laser power and scanning speed.

Experimental Procedures

The water assisted laser machining is schematically shown in figure 1. Microchannels were fabricated using commercial 30W CO_2 laser (Universal Laser System, VLS 3.5, USA). Such a system has a vector cutting mode for lines width of less than 200 µm and raster engraving mode for line widths more than 200 µm. The vector cutting mode was used in present experiments to cut lines with a width of less than 200 µm. The resolution of laser system was set at its maximum value of 1000 PPi. The laser power was varied from 2.4 W to 6 W while the scanning speed was varied from 5mm/s to 12.5 mm/s. CorelDRAW software was used as computer aided design program (CAD) for drawing the desired channels.

In water assisted machining, PMMA substrate with dimension of 40x20x3 mm was submerged in an aluminum fixture that contains distilled water. All experiments were performed at a temperature of 15° C. Tween 20 was used as a surfactant agent that was added to the distilled water with concentration of 7% to increase the wettability of PMMA substrate and make it easier to control water level above the PMMA substrate. The contact angle between the PMMA and water droplet was measured before and after adding the Tween 20 as shown in figure 2 using Rame-Hart 500-F1 advanced goniometer (Rame-Hart Instrument Co., USA). At the end of experiment, the substrate was washed in ethanol for 15 minutes using ultrasonic bath for removing any stuck particles. 3D and profile measurements laser microscope (KEYENCE VK-x100) was used for measuring the channel geometry and clogging while the heat affected zone (HAZ) was measured using MarVision MM320 Microscope.

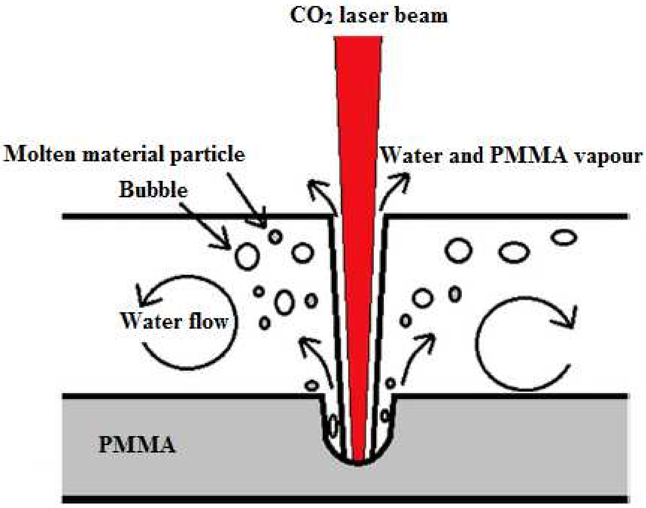

Fig.1: Water assisted laser machining schematic [9]

Fig.2: Effect of adding 7% Tweet 20 on the contact angle, (a) Water droplet(70°) (b)Water droplet and 7% tween 20 (17°)

Results and Discussion

Figure 3(a) shows 3D profile of Y-channel fabricated by CO_2 laser in air. At Y-channel intersection, clear bulges are formed in both rims of the channel. CO_2 laser ablation is based on photothermal process due to large wave length 10.6 µm, which means that the projected area to laser beam instantly melts and evaporates when the accumulated energy is high enough for that purpose. PMMA remains in glassy state below 115 °C and reaches a rubbery state beyond 115 °C. Long range deformations of chains of molecules occur at temperatures between 170 and 210 °C. Then the decomposition occurs at temperatures around 360 °C [10]. The high pressure of hot evaporated gases pushes out the molten particles from the ablation zone into all directions at different kinetic energies. The ejected molten particles with high kinetic energy spatter away from the channel while ejected particles with medium kinetic energy accumulate on both rims of channel to build-up bulges. Additionally, the ejected molten particles which have lower kinetic energy are accumulated on both channel walls and cause clogging. These defects directly reduce the bonding quality of microfluidic device components.

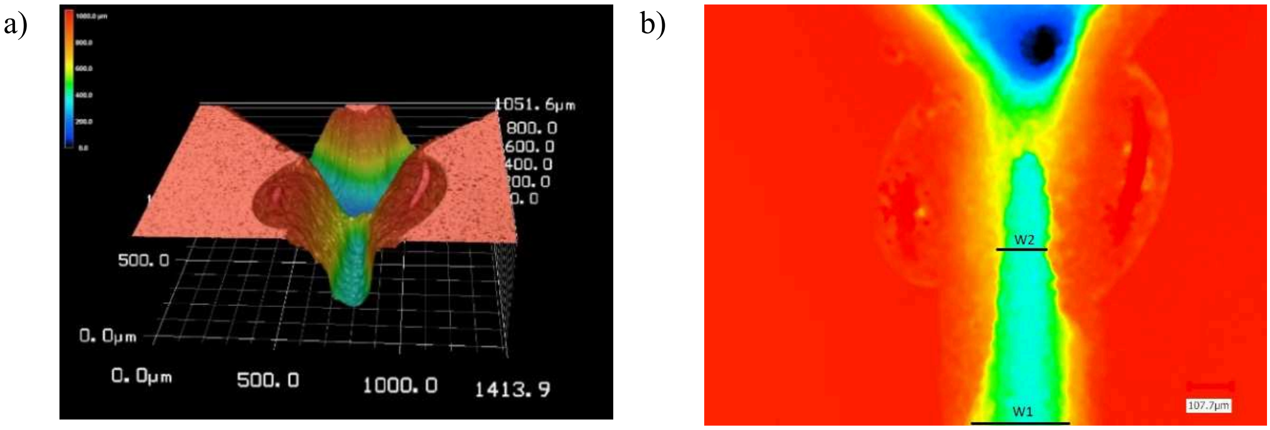

Fig.3: Y-channel fabricated in air at power of 3.6 W and scanning speed of 5 mm/s (a) 3D profile (b) Heights image

Channel clogging was calculated as percentage of reduction of measured channel width at top of channel walls using Equation (1):

$$P_{clogging} = \frac{w_1 - w_2}{w_1}\ \% \tag{1}$$

Where w_1 is the width of straight channel and w_2 is a width of clogged channel, figure 3(b). At a laser power of 3.6 W and scanning speed of 5 mm/s, the percentage of clogging reaches 44% while the percentage of clogging was reduced to 37% at scanning speed of 12.5 mm/s. On the basis of clogging formation in air, PMMA substrate was covered by 300 µm of water layer to rapidly cool the substrate and prevent the ejected molten particles from resolidification on the ablation zone which improves the channel quality. When the laser beam impacted the water layer surface, water absorbs a portion of energy for rapid heating and evaporation due to the high water absorption of wavelength of 10.6 µm. Laser beam forms a keyhole in water and the other portion of energy was used for laser machining as shown in figure 1.

Figure 4(a) shows the 3D profile of Y-channel fabricated by CO_2 laser in water with laser power of 3.6 W and scanning speed of 5 mm/s. Obviously a clear channel is free of bulges compared to that in air, figure 3 (a). Figure 4(b) shows heights image for the Y channel machined at the same condition. The absence of clogging is evident if compared to that machined in air, figure 3(b).

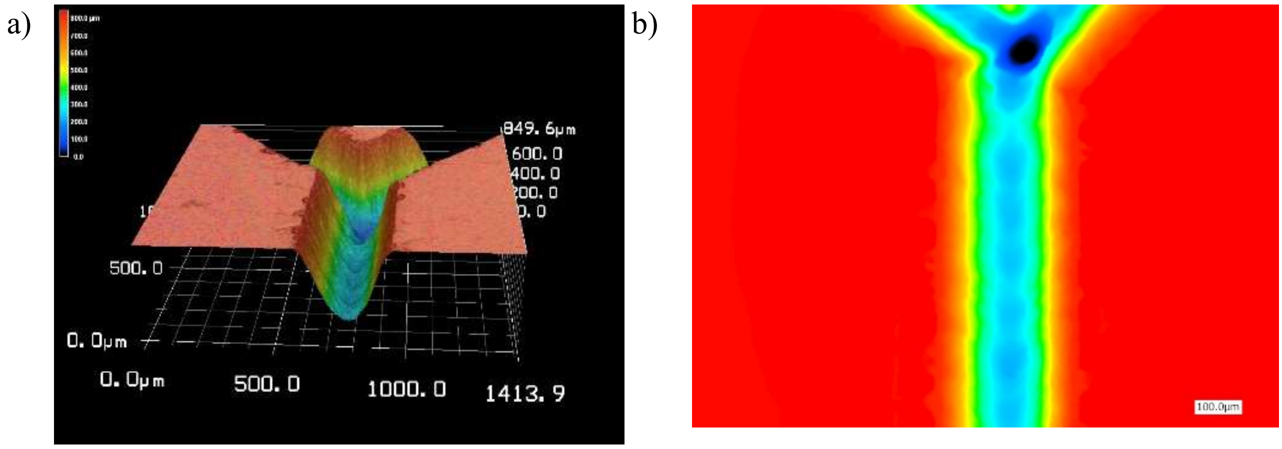

Fig.4: Y-channel fabricated in water at power of 3.6 W and scanning speed of 5 mm/s (a) 3D profile (b) Heights image

During laser ablation water cools the ejected molten particles rapidly before resolidification on the channel rims which forms bulges or inside the channel leading to channel clogging. Additionally water works as insulator between molten particles and the substrate. During water assisted machining the temperature gradient and thermal stress are reduced due to heat convection coefficient of water that ranges from 500 to 10000 W/m^2 K while for air it ranges from 10 to 100 W/m^2 K, which means that the heat convection in water is 2-3 times higher than that in air [8]. The HAZ formed around the channel in air and water at laser power of 3.6 W and scanning speed of 5, 7.5, 10 and 12.5 mm/s are shown in figure 5. PMMA has low heat capacity, low heat conductance and high absorptance (α) of about 0.92 in the infrared region, which lead to high temperature gradient for the substrate during direct laser ablation [11]. Generally, HAZ decreases as scanning speed increases due to the reduction of local heating time. Propagation of HAZ in PMMA substrate fabricated in air reached 493 μm at scanning speed of 5 mm/s and power of 3.6W. Obviously high values of HAZ in air due to high temperature gradient are noticed while lower temperature gradient of PMMA substrate in water reduced the HAZ to 142 μm.

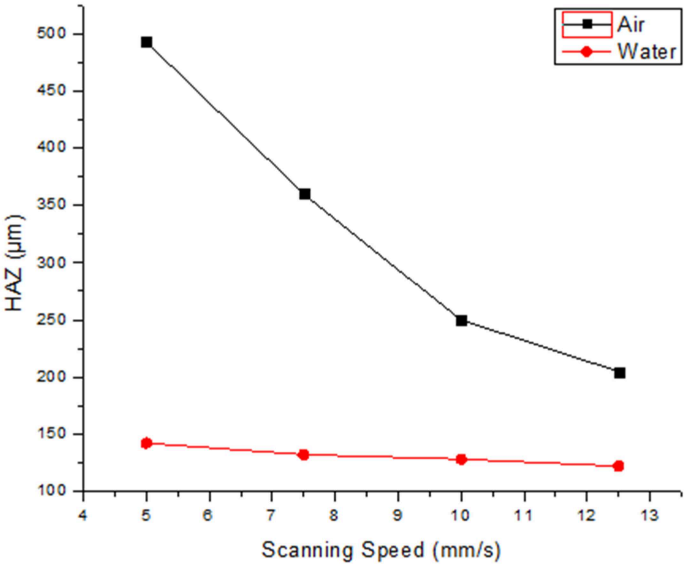

Fig.5: Relation between HAZ and scanning speed in air and water at 3.6 W

Figure 6 (a) and (b) shows the channel depth and width respectively as a function of scanning speed at laser power of 2.4 W and 6 W. It is accordingly clear that both channel depth and width decrease at higher scanning speed as well as small laser power. Moreover water assisted CO$_2$ laser machining reduced the channel depth and width due to water absorption of portion of laser energy.

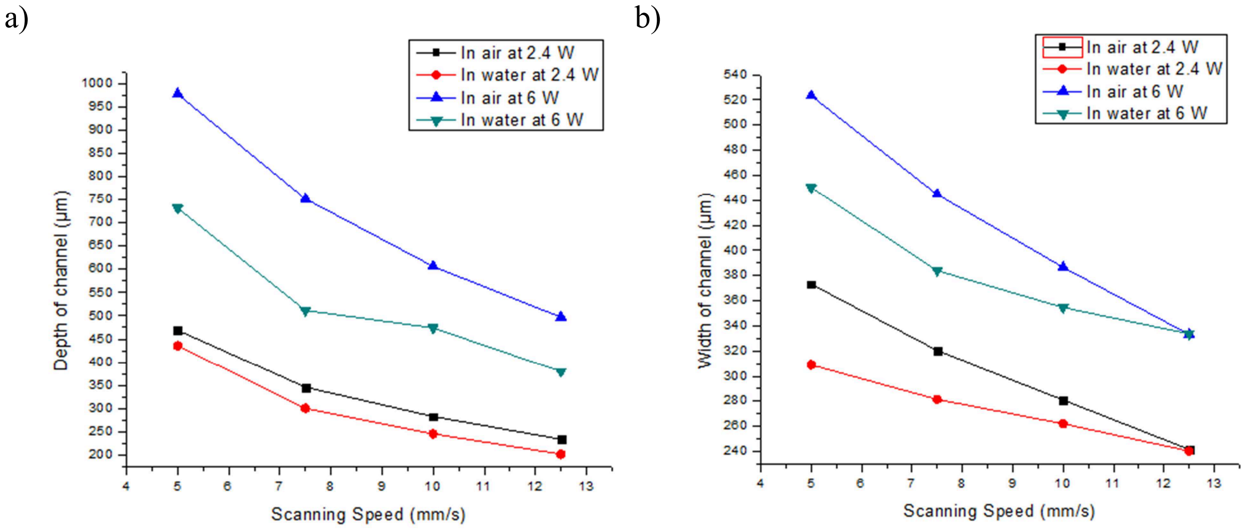

Fig.6: Relation between scanning speed and channel geometry (a) Depth (b) Width

Conclusion

This work has presented a low cost method for fabrication of microchannels in PMMA substrate with low thermal damages by adding a thin water layer of 300 µm thickness on the top of the substrate during laser ablation. Clogging formation mechanism in the intersection of Y-Channel was studied during ablation in air. Adding thin layer of water during ablation improved the channel quality in terms of reducing bulging and eliminating channel clogging. Water has two functions: The first is to work as medium that carry away the ejected molten particles and prevent them from resolidification in the ablation zone. The second is to cool the ablation zone and reduce the high temperature gradient of the PMMA. HAZ is reduced from 493µm in case of air to 142 µm in case of water. HAZ is significantly affected by the scanning speed in air and less affected in case of water. Smaller channel geometry is possible in case of water due to the absorption of a portion of laser energy by water.

Acknowledgment

This work was supported by the Mission Department of the Ministry of Higher Education in Egypt and Egypt-Japan University of Science and Technology (E-JUST).

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