Proceedings of 10th International Conference on Precision, Meso, Micro and Nano Engineering (COPEN 10)
December 07 – 09, 2017, Indian Institute of Technology Madras, Chennai – 600 036 INDIA

Dimensional Control Through Process Parameters in Microchannel Fabrication on PMMA with a CO_2 Laser

Shashi Prakash*[1] and Subrata Kumar[2]

[1]School of Engineering and Applied Science, Ahmedabad University, Gujarat -380 009, INDIA

[2]Department of Mechanical Engineering, Indian Institute of Technology Patna – 801 106, INDIA

Abstract

Polymethyl methacrylate (PMMA) is commonly used as a substrate material in many polymer based microfluidic devices for biological, chemical and analytical applications. Microfabrication on PMMA using a CO_2 laser has been proved as a cost as well as time effective method. However, precise dimensional control in a CO_2 laser fabrication process on PMMA is difficult due to variations in the values of various thermo-physical properties of PMMA. Therefore, in order to have control over precise output microchannel dimensions, a series of experiments were performed on PMMA. Experiments were performed on two different variants of PMMA i.e. CAST PMMA and EXTRUDE PMMA having different values of thermo-physical parameters. Also, two different types of focusing lens were chosen with focal lengths of 50 mm and 38 mm. Efforts were made to identify critical set of input parameters which can effectively control the output dimensions i.e. width and depth irrespective of type of PMMA and CO_2 laser systems. Specific point energy was found to be an effective parameter.

Keywords: CO_2 Lasers, Microchannel Fabrication, PMMA.

1. INTRODUCTION

Development of micromachining processes is essential for the development of MEMS and microfluidic applications and devices. Micromachining processes consist of several different types of methods in order to create miniaturized structures on different substrate material by utilizing different types of energy including thermal, mechanical, chemical, electrical types of energies. Although, microfabrication process is mostly performed with different micromachining tool which essentially refers to a subtractive process, additive processes are also not uncommon. Various microfabrication processes include lithography, etching, injection molding, embossing, micromilling, and laser based micromachining processes [1, 2]. Beside these, there are many specially developed processes limited to specific applications and have not been used widely. Many of such microfabrication processes require clean-room facilities and multi-step processing by a trained person and any modification in design consumes a lot of time and money. Most of these processes are material specific with low reproducibility.

Lasers are capable of machining almost all types of materials (with suitable wavelengths) without the need of clean-room facilities. Further, they are a type of contact-less machining, thereby producing no mechanical stress. The time consumption is often too small to be compared with any other process and it also does not require any type of specially designed fixtures. Overall, it is the most versatile machining tool for micro-fabricating over a range of materials with utmost simplicity and dependable repeatability. Continuously increasing demand for Microchannel based microfluidic devices have put the microchannel fabrication processes in hot spot. Laser processing is a cost effective and time saving solution for fabricating microchannels on a variety of substrate materials. Many of these laser processed microchannels do not require after-finishing processes. Unlike many other processes, they do not require masks or clean room facilities. Lasers can also perform several operations like drilling, engraving, joining, microstructuring etc. which makes it an ideal tool for fabricating the whole microfluidic device in entirety [3]. Selection of lasers for fabricating microchannels depend upon the type of substrate material. Nd:YAG lasers [4], diode lasers [5], excimer lasers [6] and CO_2 lasers [7, 8] are the most commonly used lasers for microchannel fabrication. CO_2 laser is about ten times cheaper than excimer laser, femtosecond laser and wet etching equipment [9]. It takes only few minutes to fabricate whole microfluidic chip. PMMA ablation by a CO_2 laser is the widely studied phenomenon and many authors have used this method to produce microchannels for various microfluidic devices. With the further advancement of low cost commercial CO_2 lasers, the microchannel fabrication process has become lot more easier, faster and cheaper.

In a typical microchanneling process, width and depth of the microchannels vary with laser power and scanning speed. However, in market, various variants of PMMA are available with different thermo-physical properties. Hence, similar laser parameters may give different output results if employed on different PMMA variants. Also, laser systems may have different beam diameters which again make it difficult to predict output Microchannel dimensions using laser power and scanning speed as only input parameters.

Hence, it was observed that laser power and scanning speed alone are unable to precisely predict the output Microchannel dimensions. Deploying analytical models for predicting output dimensions require determination of thermo-physical properties which involves time and resources. In this regard, it was thought that if the output dimensions can be predicted using a combination of input parameters, a lot of time can be saved in form of not performing pilot experiments or determining different thermo-physical properties. In this study, it was attempted to control the microchannel dimensions through some compound parameters instead of laser power and scanning speed only. The effect of specific point energy and some compound parameters were investigated in order to have precise control over microchannel dimensions.

*Shashi Prakash, Email: spasthana@gmail.com

ISBN: 978-93-80689-28-9

2. LASER MICROCHANNELING PROCESS AND COMPOUND PARAMETERS

In a simple direct writing/vector cutting process, laser beam moves in a predefined direction as assigned by the user in desired direction. In this way microchannels are formed on the surface by unidirectional laser beam movement (figure 1).

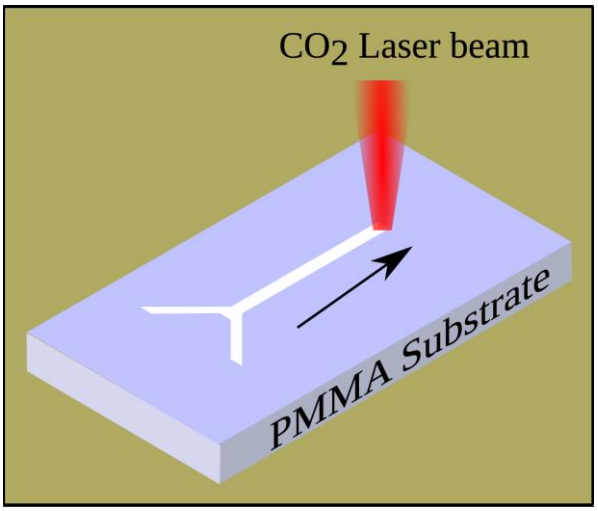

Fig. 1. Schematic of microchannel formation using direct writing/vector cutting process

On this CO_2 laser system (universal laser 3.60), the basic controllable input parameters are average power (P) and scanning speed (U). These two parameters can be altered conveniently using software control of the CO_2 laser system. The laser power stability was found to be within ±3% even after commanding the same input power. The average power is the output beam power coming from focusing lens. The output power can be measured anywhere below the focusing lens using a power meter. This power was calibrated using a 200 W Mahoney laser power meter probe. The speed with which laser head moves is termed as scanning speed/cutting speed. Scanning speed of the laser head was calibrated using a time-distance test. Any fabricated microchannel has three direct basic output dimensional characteristics i.e. top width of the microchannel, maximum depth of the microchannel and heat affected zone at the top surface. Figure 2 shows the output parameters for a microchannel. The HAZ can be easily identified under the optical microscope having a distinct differentiating line and color difference from pristine part as shown in figure 2 (a) and (b).

In any typical CO_2 laser based microchanneling process, all of the output parameters i.e. width, depth and heat affected zone (HAZ) increases with increase in power and decreases with increase in scanning speed.

In other words these output parameters are directly proportional to ratio of power and scanning speed (P/U). The unit of P/U ratio is equivalent to amount of energy deposited per unit length (J/mm). This energy deposition term was investigated in this work for its effect on output parameters. Also, some more parameters were studied here for their effects on output parameters as interaction time and specific point energy. Since, these parameters consist of two or more directly affecting basic parameters hence termed as compound parameters.

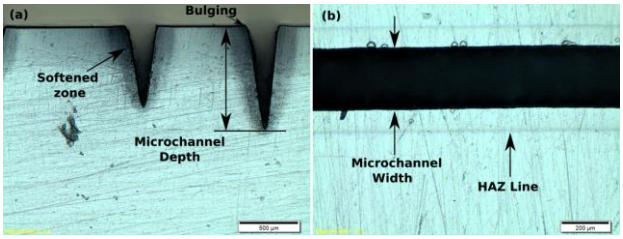

Fig. 2. (a) Cross-sectional and (b) top view of typical CO_2 laser fabricated microchannels

The impact of these compound parameters on laser microchanneling process may prove more significant than direct parameters. These compound parameters can be defined as follows:

Energy deposition per unit length also called deposited energy or energy deposition is defined as ratio of power to scanning speed (P/U).

Interaction time (T_i) is the actual amount of time for which each point is irradiated by laser beam. Interaction time is given as:

$$T_i = d/U \quad (1)$$

Suder et al. [10] introduced the concept of specific point energy (SPE) for laser welding process and suggested that melting width can be fully characterized by power density (P/A) and specific point energy terms. Here, effect of specific point energy was also studied to determine its effect on output parameters especially on microchannel widths and heat affected zones. Specific point energy is defined as:

$$SPE = P.d/U \quad (2)$$

3. EXPERIMENTS

Different experiments were conducted to determine the effects of these compound parameters on output values (i.e. Microchannel width, depth and heat affected zone (HAZ). In these experiments, deposited energy was varied at five levels i.e. 0.1 J/mm, 0.15 J/mm, 0.2 J/mm, 0.25 J/mm and 0.3 J/mm. Power was varied at five levels i.e. 1W, 1.5W, 2W, 2.5W and 3 W. Scanning speed was adjusted to maintain constant P/U ratio and typically varied between 3.33 mm/s to 30 mm/s at different levels. During different experiments, approximately 5% variation was observed in output dimensions using similar input parameters. In order to determine the effect of beam diameter on output dimensions, two different kinds of focusing lens were used. Lens 1 having 50 mm of focal length and 237 µm of beam spot diameter while 190 µm of beam spot diameter belong to another focusing lens (Lens 2) is having 38 mm of focal length. Total sixteen combination of specific point energy factor were emerged from these experiments. For each lens type and each PMMA variant, four different specific point energy value were identified as evident in figure 3 (d), 4 (d) and 5 (d).

4 RESULT AND DISCUSSION

4.1 Microchannel Width

Effects of deposited energy i.e. P/U ratio, interaction time, beam diameter effect and specific point energy on microchannel width has been depicted in figure 1.

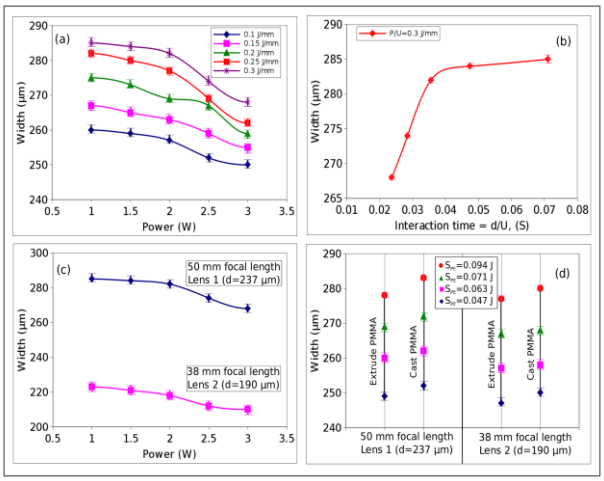

Fig. 3.Microchannel width variation with (a) power at different P/U ratio (b) interaction time, (c) power at two different beam diameters, and (d) specific point energy

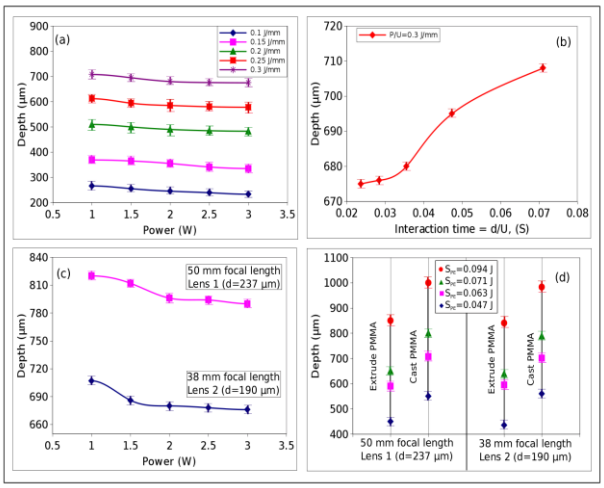

Fig. 4.Microchannel depth variation with (a) power at different P/U ratio (b) interaction time, (c) power at two different beam diameters, and (d) specific point energy

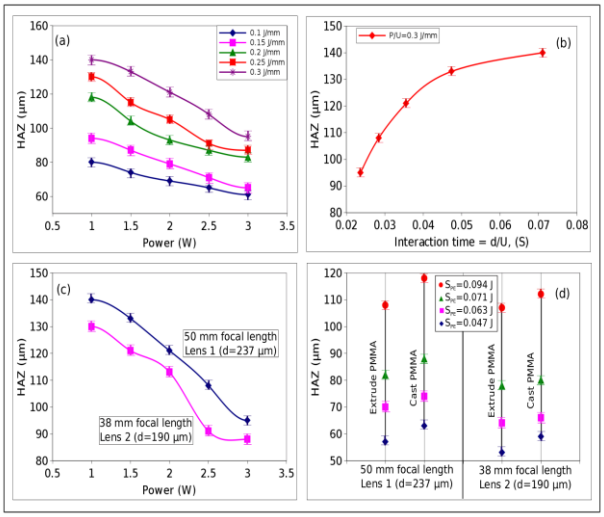

Fig. 5. Heat affected zone (HAZ) variation with (a) power at different P/U ratio (b) interaction time, (c) power at two different beam diameters, and (d) specific point energy

It can be observed that Microchannel width decreases with increase in power and scanning speed together even when the P/U ratio was kept constant. With the larger values of P and U, lower microchannel widths can be obtained compared to smaller values of P and U. The rate of decrease is higher at higher power levels compared to lower power levels (figure 3 (a)). Scanning speed is inversely proportional to interaction time. For the same energy deposition, microchanneling process with lower interaction time produces lower microchannel width. Typical variation of beam width with interaction time has been given in figure 3 (b). At 0.3 J/mm, microchannel width increases with increase in interaction time. However, the width increases at higher rate initially but do not increase much beyond a certain level (0.04 s here). Microchannel width variation cannot be specified by deposited energy and interaction time alone. Width of a CO_2 laser machined microchannel also varies with beam diameter. In order to determine the effect of beam diameter on microchannel widths, two different kinds of focusing lens were used. As such, the width of a microchannel fabricated with beam diameter of 237 μm was found to be much larger than microchannel widths fabricated with beam diameter of 190 μm even at equal energy deposition (figure 3 (c)). Hence, in order to completely specify the beam width for all practical purposes, another factor termed as specific point energy was studied. Specific point energy incorporates the beam diameter values alongside power and scanning speed. In order to study the effects of specific point energy, experiments were conducted with two different types of lenses on two variants of transparent PMMA. These two different types of PMMA were extrude PMMA and cast PMMA. These two variants possess different values of thermo-physical properties and resulted in different microchannel width and depth values at same energy deposition. Experiments were conducted at four different values of specific point energies i.e. 0.047 J, 0.063 J, 0.071 J and 0.094 J. It was observed that at equal amount of specific point energies, width values do not change much and remain approximately similar irrespective of material type and beam diameter. For example, at 0.047 J, microchannel width dwells around 250 mm for both types of PMMA at 237 μm of beam diameter as well as 190 mm of beam diameter (figure 3 (d)).

4.2 Microchannel Depth

Effects of deposited energy i.e. P/U ratio, interaction time, beam diameter effect and specific point energy on microchannel depth has been depicted in figure 4. Microchannel depth also decreases with increase in power and scanning speed together while keeping the fixed energy deposition. However, decrease in depth values were not found to be as significant as width values and remain almost same for all the P/U ratio settings (figure 4 (a)). The largest depth variation with interaction time was observed to be less than 5% within the considered experimental range (figure 4 (b)).

Microchannel depth was found to be least sensitive to changes in input parameters for constant energy deposition. Also, microchannel depth values also change with different beam diameters as 190 μm beam diameter produces higher beam intensity compared to 237 μm beam diameter (figure 4 (c)).

Although, specific point energy was an apt parameter to determine and specify microchannel width, it is not an effective parameter to define microchannel depth. At equal specific point energy, microchannel depth varies considerably (figure 4 (d)). However, for the similar material variant, equal specific point energy gives almost equal depth values irrespective of beam diameter.

4.3 Heat Affected Zone (HAZ)

Heat affected zone (HAZ) was found to be most sensitive to changes in input parameters. This is probably due to lower threshold limit for detection of any change due to changes in input parameters. Also, the heat affected zone appears even before any sign of microchannel due to low glass transition temperature (about 105^{o} C) of PMMA. Figure 5 depicts the effects of P/U ratio, interaction time, beam diameter and specific point energy on HAZ. Similar to width and depth, HAZ also decreases with increase in power and scanning speed at fixed energy deposition (figure 5 (a)). However, the difference was observed to be more effective than width and depth. HAZ is predominantly dependent upon interaction time. Larger the interaction time, larger is the HAZ value. Similar to width, HAZ also becomes less variable at higher interaction time values compared to lower interaction time values (figure 5 (b)). HAZ also depends upon beam diameter values as lower beam diameter produces lower HAZ compared to higher beam diameter. However, the difference in HAZ was not as significant as difference in width and depth values due to beam diameter (figure 5 (c)). At equal amount of specific point energies, HAZ behaves very similar to width. It was observed that at equal specific point energy values, HAZ was also found to be approximately equal irrespective of material variant and beam diameter (figure 5 (d)).

Apart from microchannel width, depth and HAZ, some authors [11] have also discussed the ratio of microchannel cross-sectional area over the rectangular area formed by the microchannel called as uniformity index (UI) as one of the quality parameters. However, in this study all the microchannels were formed in nearly Gaussian shape as shown in figure 1 (a). It was found that uniformity index remains nearly half in all the experiments with very little variation as all the microchannels remain in V-shape. Increasing or decreasing the input parameters does not cause any major change in the value of uniformity index for all the microchannels considered in these experiments.

5. CONCLUSIONS

At equal amount of specific point energies, width values do not change much and remain approximately similar irrespective of material type and beam diameter. Although, specific point energy was an apt parameter to determine and specify microchannel width, it is not an effective parameter to define microchannel depth. However, for the similar material variant, equal specific point energy gives almost equal depth values irrespective of beam diameter. Energy deposition has a profound effect on microchannel width and HAZ while depth does not vary much within considered zone of parameters. Specific point energy is most suitable parameter to describe microchannel width and HAZ. For the same specific point energy, width and HAZ remain almost same irrespective of PMMA type and beam diameter.

References

[1] Becker H. and Locascio L. E., "Polymer microfluidic devices", *Talanta*, **56** (2002) 267 – 287

[2] Prakash S. and Kumar S., "Microchannel fabrication via direct laser writing" *In Microfabrication and precision engineering: Research and Development*, Woodhead publishing (Elsevier), (2017), ISBN:978-0-85709-485-8, p 163.

[3] Malek G. K., "Laser processing for bio-microfluidics applications (part II) ", *Analytical and Bioanalytical Chemistry*, **385** (2006) 1362–1369

[4] Prakash S., Acherjee B., Kuar A.S., and Mitra S., "An experimental investigation on Nd:YAG laser microchanneling on polymethylmethacrylate submerged in water", *Proc. of the Inst. of Mech. Eng., Part B: J. of Engineering Manufacture*, **227 (4)** (2013) 508–519

[5] Oh K. H., Lee M. K., and Jeong S. H., "Laser micromachining of high-aspectratio metallic grooves for application to microthermal devices", *Journal of Micromechanics and Microengineering*, **16(10)** (2006) 1958, 2006.

[6] Heng Q., Tao C., and Tie-chuan Z., "Surface roughness analysis and improvement of micro-fluidic channel with excimer laser", *Microfluidics and Nanofluidics*, **2(4)** (2006) 357–360.

[7] Qi H., Tao C., Yao L., and Tiechuan Z., "Micromachining of microchannel on the polycarbonate substrate with CO2 laser direct-writing ablation", *Optics and Lasers in Engineering*, **47 (5)** (2009) 594 – 598

[8] Yuan D. and Das S., "Experimental and theoretical analysis of direct write laser micromachining of polymethyl methacrylate by CO_2 laser ablation", *Journal of Applied Physics*, **101(2)** (2007),

[9] Husain A. and Kim K.-Y., "Thermal Optimization of a Microchannel Heat Sink With Trapezoidal Cross Section", *Journal of Electronic Packaging*, **131** (2009) 021005–021005

[10] Suder W. J. and Williams S. W., "Investigation of the effects of basic laser material interaction parameters in laser welding", *Journal of Laser Applications*, **24(3)**, (2012).

[11] Madhukar Y. K., Mullick S., Nath A. K., "A study on co-axial water jet assisted fiber laser grooving of silicon" Journal of Material Processing Technology, 227 (2016) 200-215