CO₂ Laser Microchanneling Process: Effects of Compound Parameters and Pulse Overlapping

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Abstract. PMMA (Polymethyl methacrylate) is commonly used in many microfluidic devices like Lab-on-a-chip devices, bioanalytical devices etc. CO₂ lasers provide easy and cost effective solution for micromachining needs on PMMA. Microchannels are an integral part of most of these microfluidic devices. CO₂ laser beams have been successfully applied by many authors to fabricate microchannels on PMMA substrates. Laser beam power and scanning speed are the most important laser input parameters affecting the output parameters like microchannel depth, width and heat affected zone (HAZ). The effect of these individual parameters on output parameters are well known and already elaborated by many authors. However, these output parameters can more significantly be described by some compound parameters (combination of direct input laser parameters) like laser fluence, specific point energy, interaction time and P/U (power/scanning speed) ratio. The explanation of effect of these compound parameters was not found in earlier researches. In this work, several experiments were carried out to determine the effects of these compound parameters on output parameters i.e. microchannel width, depth and heat affected zone. The effect of pulse overlapping was also determined by performing experiments at different pulse overlaps and with two different energy deposition settings. The concept of actual pulse overlapping has been introduced by considering actual beam spot diameter instead of using theoretical beam diameter. Minimum pulse overlapping was determined experimentally in order to ensure smooth microchannel edges.

1. Introduction

The applications of microfluidic devices are being increasingly diversified. Microchannels are an integral part of most of such microfluidic devices. Many chemical devices, biological devices as well as electronic devices are utilizing this technology to enhance their productivity and efficiency at the lowest possible cost [1].

In earlier days, materials like silicon, glass and quartz were the most favored materials to be used for such devices because of their high thermal stability, optical transparency and physical strength. However, in recent times, the application of polymer based microfluidic devices has increased manifold. Polydimethyl siloxane (PDMS) [2], polycarbonate (PC) [3], polyethylene (PET) and polymethyl methacrylate (PMMA) [4] are the most used polymers for such devices. In recent times, PMMA has emerged as one of the most prominent material to be used in polymeric microfluidic devices. The usual advantages of PMMA are its high optical transparency, strength, low cost and ease of fabrication using laser machining [5].

Fabrication of microchannels constitute the major part of any microfluidic device fabrication. There are a number of processes used for carving these microchannels on the substrate material. Lithography, chemical etching, mechanical micromilling, embossing and laser micromachining
are the most used processes for microchannel fabrication [1]. Majority of such processes inherently suffer from high initial cost, long processing time, multi-step processing, skilled labor requirements and supplementary processes along with clean room facilities [6].

Laser micromachining has evolved as one of the most efficient fabrication technique for microchannel fabrication on different substrate materials [1]. Selection of laser type for different substrate materials plays a key role in such cases. Wavelength of selected laser beam must have high absorptivity for that particular substrate material. PMMA behaves well with ultrashort lasers [5], ultraviolet (UV) lasers [7], excimer lasers [8] and CO\textsubscript{2} lasers [9] resulting in clean fabricated microstructures. UV lasers, excimer lasers and ultrashort lasers involve high input costs and complex optical and maintenance systems. CO\textsubscript{2} lasers, on the other hand, have emerged as a low cost solution for microchannel fabrication on polymers [10]. PMMA has been found to be most suitable to be cut with CO\textsubscript{2} laser beam as it produces clean cuts with very little amount of resolidified material and charring around the cutting zone. Although, the material removal process involves thermal ablation, the vaporized products are volatile in nature and do not produce significant heat related defects [4].

Any laser processing involves few fundamental input parameters such as laser power, scanning speed, pulse frequency etc. affecting the output microchannel dimensions, profiles and heat affected zone (HAZ). The effect of these input parameters are well documented [4]. However, the laser microchanneling process is also affected by some compound parameters like laser fluence, interaction time, specific point energy and F/U ratio. These parameters consist of two or more directly affecting parameters and therefore termed as compound parameters. The impact of these compound parameters on microchannels may prove more significant than direct parameters. To the best of author’s knowledge no previous studies have been performed to explain the effects of these compound parameters on resulting microchannel profiles. In this research work, the effect of these compound parameters on microchannel profiles and output parameters has been studied in details. Pulse overlapping also plays an important role in microchannel fabrication. Pulse overlapping was also not studied by authors in previous CO\textsubscript{2} laser microchanneling studies on PMMA. An insufficient pulse overlapping may produce irregular microchannels. The straightening of the microchannel edges can only be ensured by maintaining proper pulse overlapping. In order to understand properly the phenomenon of pulse overlapping, a concept of theoretical pulse overlapping factor (O\textsubscript{TH}) and actual pulse overlapping factor (O\textsubscript{ACT}) has been introduced and discussed.

2. Theoretical description
Transparent PMMA sheet was found to be absorbing 95 % of total CO\textsubscript{2} laser beam irradiation [11]. This makes the PMMA as a favorable material for CO\textsubscript{2} laser beam processing. CO\textsubscript{2} laser ablation generally removes the material by the process of thermal ablation or photoablation in which material is ablated by the process of heating, melting and vaporization. Further, the ablation results into vaporization of material without leaving significant melt zone. This makes the cut cleaner with negligible heat related defects. The end products are volatile in nature and do not get resolidified on the surface [9]. The laser beam intensity at the surface can be given as [12]:

\[ I(x, y) = I_0 e^{-\frac{2(x^2+y^2)}{w^2}} \]  

(1)

Where, \( I \) is the radiation intensity of laser beam at the surface at \((x, y)\) location, \( I_0 \) is original beam intensity at center i.e. \((0, 0)\) and \( w \) is laser beam radius. After impinging the surface, laser beam intensity reduces in z-direction according to Beer’s law given as [13]:
\[ I(z) = I_0 e^{-az} \]  \hspace{1cm} (2)

Where, ‘a’ denotes absorption coefficient of the material for CO\textsubscript{2} laser beam wavelength i.e. 10.6 \textmu m. CO\textsubscript{2} laser beam microchanneling process also depends upon some other parameters apart from direct parameters like laser power, scanning speed and pulse per inch (PPI). The theoretical descriptions of these other compound parameters are well defined and presented in many of the research works. For a quick recall, these are presented here in brief.

Interaction time \((T_i)\) is the actual amount of time for which each point is irradiated by laser beam. If \(D\) is the theoretical beam diameter and \(U\) is scanning speed, then interaction time is given as

\[ T_i = \frac{D}{U} \]  \hspace{1cm} (3)

The energy absorbed by the material during this interaction time can be given as,

\[ E_a = \alpha \times P \times T_i \]  \hspace{1cm} (4)

Where, \(\alpha\) represents absorptivity of laser beam for a particular material and \(P\) is laser beam power. Laser fluence can be defined as laser beam energy absorbed per unit area of the irradiated surface. Mathematically, it is written as

\[ F = \frac{E_a}{A} \]  \hspace{1cm} (5)

Where, \(A\) is area of laser beam diameter. Laser fluence is also termed as energy density. Suder et al. [14] introduced the concept of specific point energy \((S_{PE})\) and suggested that laser welding process can be fully characterized by power density \((P/A)\) and specific point energy. The same is also studied here to determine its effect on output parameters.

\[ S_{PE} = \frac{P \times D}{U} \]  \hspace{1cm} (6)

In most of the commercially available CO\textsubscript{2} lasers, pulse overlapping is governed by a factor termed as ‘PPI’ (pulse per inch). PPI defines the number of pulses falling per inch of the surface during laser beam movement. Pulse overlapping depends upon PPI, scanning speed and laser beam diameter. Pulse overlapping factor can be defined by using equation 7 [4]:

\[ O_{TH} = \left[ 1 - \frac{U}{f \times D} \right] \times 100\% \]  \hspace{1cm} (7)

Where, \(f\) is pulse frequency \((N\times U)\) and \(D\) is the theoretical beam diameter. \(N\) represents number of pulses per unit distance which is governed by PPI. Although, the theoretical beam diameter does not vary with laser power, the actual beam spot diameter on the irradiated material increases with energy deposition by the laser beam in actual experiments. Actual beam spot diameter increases with increase in beam power and decreases with increase in scanning speed.
In other way, a laser beam with larger P/U ratio will result in larger beam spot diameter due to larger energy deposition on the surface. The concept of change in actual beam spot diameter has been explained in figure 1. Threshold energy density represents the minimum intensity of energy density at which any change occurs at the surface resulting in formation of microchannel. Since, overlapping of the beam depends upon actual beam spot diameter rather than theoretical beam diameter, a concept of actual beam overlapping has been introduced here. Theoretical pulse overlapping factor depends upon theoretical beam diameter, which is fix for a particular laser beam. Actual beam overlapping is based on actual laser beam spot diameter, which may be either less or more than theoretical beam diameter. Schematic of beam overlapping during laser beam movement on the substrate has been depicted in figure 2.

For a particular PPI setting, pulse overlapping remains same throughout the microchannel. As the energy density or power density increases, the cutting kerf width also increases and vice versa. For microchanneling case on PMMA, the kerf width can be assumed to be equal to actual beam spot diameter. The increase or decrease in kerf width may be attributed to larger or reduced actual beam spot diameter. However, the basic reason for increase or decrease in actual
beam spot diameter lies in its Gaussian distribution and threshold ablation density (figure 1). Laser beams with top-hat energy distribution or rectangular shape energy distribution may not have significant difference in theoretical beam diameter and beam spot diameter. The theoretical beam overlapping factor \( O_{TH} \) is given by equation 7. The actual beam overlapping factor can be given as:

\[
O_{ACT} = \left[ 1 - \frac{U}{f \times \phi_{spot}} \right] \times 100\% \tag{8}
\]

Where, \( \phi_{spot} \) is beam spot diameter and is also taken as equivalent to channel width for microchanneling on PMMA case in this work.

3. Experimental

In this research work, commercial CO\(_2\) laser, (VLS 3.60, Universal Laser System Inc., USA), having maximum average power of 60 W was used. Microchannels were fabricated on 3 mm thick commercially available transparent PMMA. All the experiments have been performed at room temperature of about 27\(^\circ\) C. No external cooling procedures have been adopted in this experiment. Further details of CO\(_2\) laser system has been provided in table 1.

This CO\(_2\) laser system is a RF (radio frequency) excited pulse ON/OFF engraving machine. However, essentially it is a continuous wave laser system which can be turned “ON” or “OFF” on different timescales. The output power of the laser system remains constant over the time during “ON” period. The power variation with time for such lasers can be explained using figure 3. Details of carved microchannels have been provided in figure 4. Experiments were performed on a thin PMMA sheet having visual transparency greater than 99\%. Microchannel width, depth and heat affected zone were measured with the help of an optical microscope (Olympus STM-6).

4. Results and Discussion

All the fabricated microchannels were found to be clean and with small amount of redeposited/melt material on the channel walls. The thermal ablation results in localized storage of heat resulting in swelled heat affected zone (HAZ). The swelled HAZ poses problems for perfect bonding of devices and therefore should be minimized. The effects of relevant compound parameters are detailed in this section.

4.1. Microchannel width

Effects of laser fluence, P/U ratio, specific point energy and interaction time on microchannel width has been depicted in figure 5. Larger laser fluence results in larger microchannel width due to larger effective beam diameter and larger power deposition on the surface (figure 5 (a)). However, width is not the function of laser fluence solely instead, it depends upon P/U ratio for every particular laser beam diameter. P/U ratio originally signifies the amount of energy deposited on the surface per unit length. For the same P/U ratio, the width of the microchannel remains almost same. A small change in laser power or scanning speed, while maintaining the
same P/U ratio is undetectable in form of change in width (figure 5 (b)). The threshold limit allows only a part of such influence to get visible in form of ablated or removed material. In most of the experiments, a small increase in width was observed with lowering scanning speed or increasing beam power. This small increase in microchannel width may be attributed to relatively large interaction time (D/U ratio). Dependence of microchannel width on P/U ratio along with laser beam diameter can best be described using specific point energy (SPE). For particular specific point energy, microchannel width was found to be maximum with lowest power and lowest scanning speed setting (figure 5 (c)). This again may be attributed to larger interaction time. Finally, the variation of microchannel width with interaction time has been depicted in figure 5 (d). It was found that for the same power, microchannel width increases with increase in interaction time for each power setting.

4.2. Microchannel depth
The effects of laser fluence and P/U ratio on microchannel depth has been depicted in figure 6. The depth of microchannel is directly proportional to laser fluence. Higher the laser fluence, higher is the depth (figure 6 (a)). However, as similar to width, there is no particular trend in depth dimension observed when varying the power and scanning speed while keeping the P/U ratio same (figure 6 (b)). Microchannel depth was found to be least sensitive to changes in input parameters for constant energy deposition. The depth profile varies according to Gaussian distribution of laser beam with largest depth occurring at the center. The maximum depth variability is found to be around 10% when changing the power and scanning speeds while maintaining the constant P/U ratio. However, no particular trend of variation was observed. The threshold energy density also imposes the restriction for occurrence of any detectable change in microchannel depth with
change in power and scanning speed values similar to microchannel width. No significant changes were observed in depth with variation in power at different specific point energy and interaction time and therefore no trend has been provided here.

4.3. Heat affected zone

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°C) of PMMA. Figure 7 depicts the effects of laser fluence, P/U ratio, specific point energy and interaction time on HAZ. Due to low conduction heat transfer coefficient (0.19 Wm-1K-1), the heat accumulates into a local zone forming heat affected zone. Heat affected zone can be visually detected surrounding the microchannel. In an earlier experiment, HAZ was found to possess lower hardness value than parent material surface.
Figure 6. Microchannel depth variation with (a) laser fluence (b) different P/U ratio

Figure 7. HAZ variation with (a) laser fluence (b) different P/U ratio (c) specific point energy (d) interaction time
That is why the HAZ is also termed as softened zone in PMMA [4]. HAZ was measured on the top of the microchannel. HAZ was found to be increasing with increase in laser fluence (figure 7 (a)). HAZ was also found to be increasing with increasing P/U ratio due to larger energy deposition on the PMMA surface. The larger energy deposition manifests itself into larger heat accumulation on the surface. While, keeping the constant P/U ratio and varying P and U values, it was found to be decreasing with increasing P/U values (figure 7 (b)). For the same laser fluence, P/U ratio and specific point energy, HAZ was found to be lowest with highest scanning speed (figure 7 (c)). HAZ was also found to be affected by interaction time factor. Lower the interaction time, lower is the value of HAZ (figure 7 (d)). Therefore, it can be concluded that, HAZ is predominantly affected by interaction time similar to microchannel width.

4.4. Pulse overlapping
Pulse overlapping defines the shape of edge of the microchannel. A minimum acceptable limit of pulse overlapping factor ensures minimum HAZ and smooth microchannel edges. Due to difference in effective beam diameter at different beam powers, the actual pulse overlapping may differ from theoretical pulse overlapping. In order to determine effects of various pulse overlappings, several microchanneling experiments were carried out at two different power and speed settings (figure 8). Setting 1 (S1) corresponds to higher energy deposition (P = 2 W, U = 20 mm/s) and setting 2 (S2) with lower energy deposition (P = 1 W, U = 25 mm/s). Beam spot diameter was found to be 350 µm in higher energy deposition setting (S1) while, in lower energy deposition setting (S2), it was found to be 240 µm. In the case of -7% theoretical overlapping (O<sub>TH</sub> = -7%) (i.e. no theoretical overlapping) at 100 PPI, overlapping still takes place in setting S1 while no overlapping takes place in setting S2. Therefore, experimentally, it can be established that actual overlapping depends upon beam spot diameter rather than theoretical beam diameter. It can also be propounded that different values of PPI are required for different energy deposition setting for ensuring smooth microchannel edge. For example, microchannel with larger energy deposition setting (S1) starts smoothening at 220 PPI with theoretical overlapping factor of 51% while, microchannels with lower energy deposition (S2) starts smoothening at 340 PPI and O<sub>TH</sub> = 68% (figure 8). In both the energy deposition settings, microchannel starts smoothening at actual pulse overlapping of 70% approximately. This finding lays down the importance of introducing actual pulse overlapping factor. It can be concluded that microchannel with any energy deposition setting requires minimum of 70% actual pulse overlapping (O<sub>ACT</sub>) for smooth edges. Since, actual overlapping factor depends upon beam spot diameter which in turn depends upon microchannel width. By determining microchannel width, minimum PPI may be determined to ensure smooth edges using equation 8 by putting the value of overlapping factor equal to 70%.

5. Conclusions
In this work, the effect of compound parameters on the microchanneling process output parameters have been detailed. Microchannel width was found to be directly proportional to laser fluence and interaction time due to higher amount of energy deposition. Microchannel depth was found to be least sensitive to change in power and scanning speed values for same energy deposition. This is due to larger threshold limit in depth direction. HAZ was found to be most sensitive to change in power and scanning speed values for same energy deposition due to lower threshold value. HAZ was observed to be predominantly dependent on interaction time. After observing the parametric effects, it can be established that sensitivity of microchannel depth is less than microchannel width which is subsequently less sensitive than heat affected zone (HAZ) for laser parameter variation. The concept of theoretical and actual pulse overlapping was introduced. It was found experimentally that approximately minimum 70% actual overlapping factor should be ensured to achieve smooth microchannel edges.
Figure 8. Pulse overlapping at different PPI in two different energy deposition settings S1 and S2

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