Investigation into the effect of ultra-short pulse laser parameters on machined surface integrity during laser milling

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ABSTRACT

Development in microfluidics community demands vast array of materials, methodologies and procedures. As research efforts increase and interest in this topic grows, various strategies and procedures are becoming increasingly accessible. Polycarbonate is the most commonly used material in microfluidics. They are amorphous, transparent and have good impact and heat resistance, making it ideal for medical and industrial uses. While numerous methods for polycarbonate micromachining have been documented, such as lithography, imprinting; there are certain limitations. Laser machining however has the potential to overcome the challenges. In the present work, micromilling on polycarbonate using ultrafast femtosecond lasers have been reported. Polycarbonate, micro-milled by femtosecond laser is first investigated for its surface roughness. Accordingly, influence of parameters like laser pulse-energy and pulse-overlap on surface roughness was also analysed. Based on the micro-milled polycarbonate sheet's minimal surface roughness, it was observed that lower values of pulse-overlap and pulse-energy results in high-quality surface finish.

1. Introduction

Microfluidics is a technique for manipulating and analysing fluids at the micrometre or nanometre scale. It is a pattern of microchannels and micro-reservoirs engraved on metals (Munaswamy & Samuel, 2019), glasses (Neito et al., 2014), polymers (Prakash & Kumar, 2017; Li & Xu, 2015; Sarma & Joshi, 2020), and other materials. The microchannels and micro-reservoir constituting a microfluidic device are connected in a systematic network to allow for proper fluid mixing and control; hence to meet the requirements of the desired application like lab-on-a-chip, electrophoresis, DNA analysis, etc.

Further, the materials used for microfluidic systems also play an important role. The materials used should have the appropriate properties like high transparency, high impact strength, high dimensional stability and high chemical stability. Silicon and glass were initially used for microfluidic applications; however, as years passed and technology developments occurred, new materials like polymeric substrates were developed. The wide range of polymers available allows great flexibility in selecting a suitable material with specific properties. They are easily available and are inexpensive compared to metals and hence are the most-commonly used microfluidic materials. PDMS is a valuable material for micro channels due to its unique properties. Additionally to being impermeable to water and organic solvents, it is optically transparent and insulating (Li & Xu, 2015). PMMA is a transparent, thermoplastic material that is frequently used in biomaterial applications like lenses, microfluidics and drug delivery systems (Day & Gu, 2005). The PC substrate, on the other hand, is a very transparent polymeric material that transmits over 90% of light. It is chemically resistant to alcohols, diluted acids, and organic solvents well. PCs have a high heat tolerance and are thermally stable up to 135°C. As a result, PC is preferable to the majority of transparent materials like glass, PMMA, and PDMS because it has such a distinctive set of chemical and physical properties.

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Numerous researchers from around the world have investigated and reported on the potential of different methods used for microfluidic fabrication on transparent materials. They are manufactured using both conventional and non-conventional methods, such as laser processing, lithography, injection moulding, micromilling and Laser Induced Plasma-Assisted Ablation (LIPAA) (Sarma et al., 2022; Samuel et al., 2022). Microchannels were fabricated on PDMS using the technique of micro-wire molding (Effati & Pourabbas, 2018). Also, microchannels were reported to be fabricated using the lithography process and was demonstrated for fluid delivery through the channel (Yao et al., 2005). The same technique of lithography has also been reported to produce an oriented array of microchannel (Laviano et al., 2010). The method of imprinting of microchannels on a variety of plastic substrates at room temperature was also discussed (Xu et al., 2000). It was demonstrated how this technique increased the yield of devices from about ten to over one hundred per template. However, there are certain difficulties faced in manufacturing microstructures using the above-mentioned techniques. Mould maintenance and material wastage is a severe problem in the micro-wire moulding process. Again, time consumption in the lithography process is quite high and may also lead to chemical contamination in the machined surface. On the other hand, laser micromachining has shown potential as a way of fabricating microchannels. The primary benefits of laser micromachining are its speed and accuracy. Since it is a contactless machining method, the material is not directly impacted. Additionally, complicated microstructures are precisely machined without the need of any chemicals or solvents (Sarma et al., 2022). It was discovered from the literature that the majority of studies on the processing of transparent materials are for the fabrication of microchannels. There hasn't been much research on fabrication of micro-reservoirs on polymeric substrates like polycarbonate using laser micro-milling technique. In this work, the micro-reservoir of a microfluidic system is highlighted. A micro-reservoir is used in a microfluidic system to enable controlled flow of fluids or reagents through the system as well as temporary storage of fluids.

In the present study, micro-reservoirs were micro-milled on PC using an ultrashort femtosecond pulsed laser. The roughness average (R_a) of surface of a micro-milled polycarbonate sheet is first examined using Mahr Surf M300 surface profilometer. Consequently, the impact of input variables like laser pulse energy and the overlapping percentage of laser pulses on surface roughness (R_a) is investigated. The experimental details of laser-induced micro-reservoir formation are provided in the following sections.

2. Experimental

2.1. Experimental details

In the present study, an ultrafast femtosecond laser (Model: Satsuma HP2, Air cooled version, Make: Amplitude Systems) having a wavelength of 1030 nm is used. The specification of the laser setup is shown in Table 1. The frequency was set at a fixed value of 5 kHz with varying laser pulse energy, scanning speed and correspondingly pulse overlap percentage. The laser beam is 20 µm in diameter and the pulse duration is kept constant at 300 fs. The laser setup consists of the laser head, lenses, adjusting mirrors, galvo scanner, X-Y tilt stage, f-theta lens and controller unit. Fig. 1. shows the experimental setup used for the study of the laser micro-milling process.

In the process, a polycarbonate sheet is placed on the X-Y tilt stage. The profile to be milled and its dimensions is given through the Kyla software.

2.2. Material

In the present research work, micro-reservoirs are generated on a transparent PC sheet. PC was chosen as the transparent sheet due to its high impact resistance, high optical clarity, high dimensional stability and non-polluting nature. Due to its ability to be sealed, to be filled with reagents, and to incorporate electrical and microelectronic components, PC is highly valuable for microfluidic devices (Temiz et al., 2015). They also have a glass transition temperature

Table 1
Specification of the ultrafast femtosecond laser.

Wavelength	1030 nm
Lasing medium	Ytterbium with Diode pump
Average power	20W
Pulse energy	40 µJ
Pulse duration	10 ps- 300 fs
Repetition rate	2 MHz
Beam quality, M^2	<1.2
Beam diameter	3 ± 0.5 mm

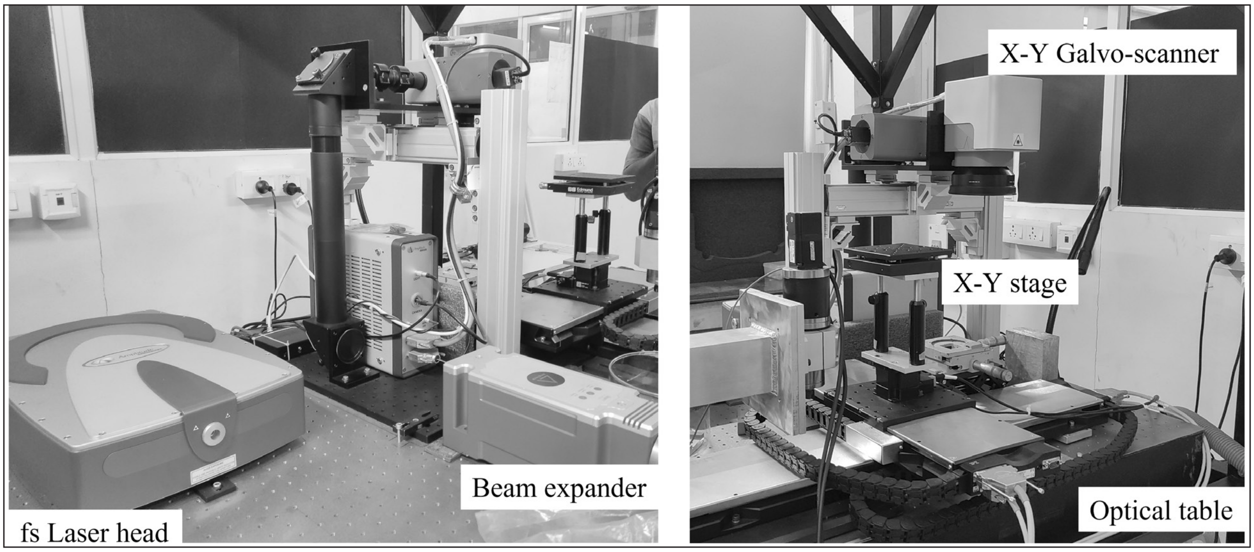

Fig. 1. Experimental setup of the ultrafast femtosecond laser.

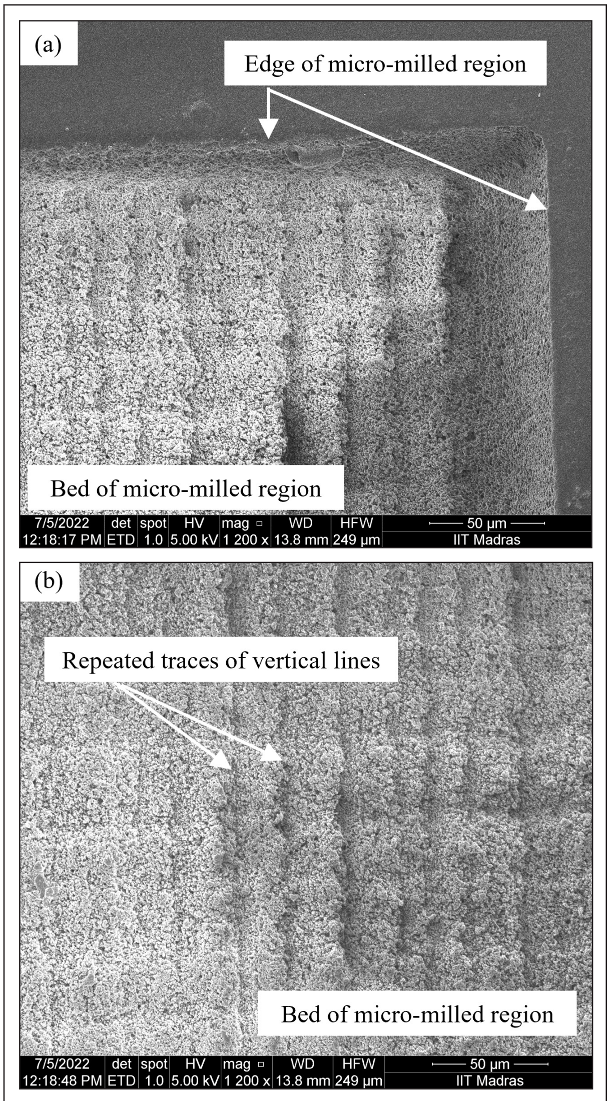

Fig. 2. FESEM images on (a) the edge and (b) the bed of the micro-milled region of the PC sheet.

of 154°C, which is higher than the majority of other comparable polymers like PMMA, polystyrene, or PDMS. The bio-medical and optical industries can therefore benefit greatly from PC as a material.

3. Results and Discussion

Using the high-power ultrafast fiber laser (Yb) system, micro-milling on the surface of PC has been carried out by the direct laser ablation method for the fabrication of micro-reservoirs. The experiments were carried out at fixed repetition rate and pulse duration of 5 kHz and 300 fs respectively. Repeated vertical lines were traced on the PC sheet by varying the laser pulse energy in the range of 23 µJ to 26 µJ and pulse overlap percentage from 75% to 50%.

The laser-material interaction time for the ultrashort-pulsed femtosecond laser is relatively short. Heat energy has no time to diffuse through the lattice. The femtosecond laser has an extremely high peak power. It has the ability to be focused into a very small dimension, much smaller than just the diameter of a human hair. Because of the high peak intensity, nonlinear interactions such as multiphoton absorption are possible, allowing for greater material versatility. The ablated particles evaporate from the surface as when the irradiated zone of the material rapidly reaches vaporisation temperature. Femtosecond laser ablation can thus remove materials with less residual thermal effect, and the device’s accuracy and quality are most often better than those of longer-pulse lasers. Fig. 2.

Table 2
Surface roughness (R_a) of the micro-milled PC sheet.

Sl. No.	Pulse overlap %	Laser pulse energy (μJ)	Surface roughness, R_a (μm)
1	50	23	0.923
2	50	24	1.010
3	50	26	1.067
4	75	23	1.101
5	75	24	1.117
6	75	26	1.133

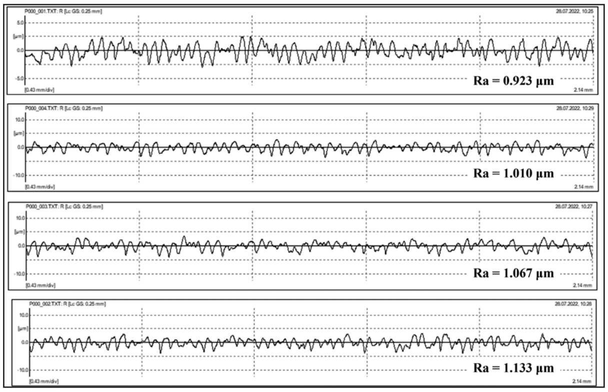

Fig. 3. Surface roughness profiles of the micro-milled region of the PC sheet.

shows the FESEM image of the micro-milled region on the PC sheet.

The surface roughness (R_a) of the micro-milled polycarbonate sheet is examined using Mahr Surf M300 surface profilometer with a least count of 0.250 μm and a traversing length of 3 mm. The complete set of experimental results and the roughness profiles of the micro-milled is shown in Table 2 and Fig.3 respectively.

Subsequently, it is examined in detail in the following sections how input variables like laser pulse energy and the percentage of overlapping laser pulses affect the surface roughness (R_a).

3.1. Effect of laser pulse energy on roughness

The variation of surface roughness (R_a) with increasing laser pulse energy is depicted in Fig. 4. With increasing laser pulse energy, the roughness value (R_a) of the micro-milled zone of the PC sheet is observed to increase. Furthermore, as the laser pulse energy increases at a higher value of laser pulse overlap percentage, the roughness values (R_a) become approximately constant.

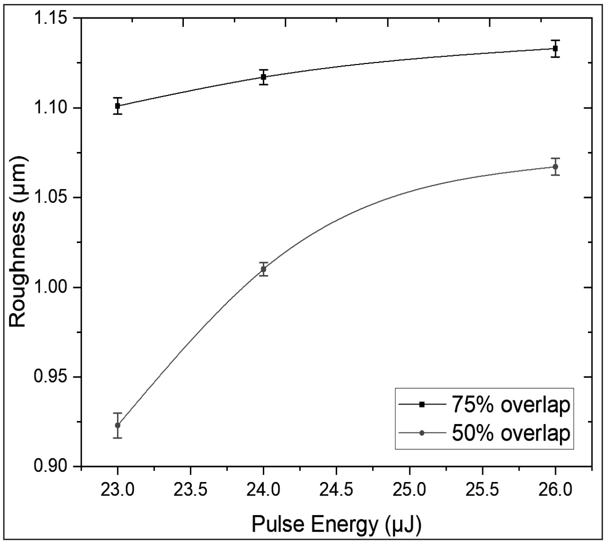

Fig. 4. Effect of pulse energy on surface roughness.

The cause of this variation can be explained by the fact that the irradiated zone will accumulate enough energy as the pulse energy increases. More PC material will melt as a result, some of which will resolidify in the material. Additionally, when more and more molten material is resolidified and deposited in the same irradiated zone with each successive scan (to achieve micro-milling effect on the PC sheet), the surface roughness (R_a) of the micro-milled PC sheet will increase.

Thus, it is clear that maintaining the laser pulse energy at a lower value of 23 μJ, while maintaining a lower overlap percentage of laser pulse will result in the least amount of surface roughness (R_a).

3.2. Effect of laser pulse overlap percentage on roughness

The variation of surface roughness (R_a) with increasing laser pulse overlap percentage is also being investigated and is shown in Fig. 5. Eqs. (1) and (2) can be used to calculate the overlap distance, D_L, and laser pulse overlap percentage, O between two laser pulses (Vora and Dahotre, 2015).

$$D_{\mathrm{L}} = \frac{v}{f} \qquad \text{................(1)}$$

$$O = \left(\frac{\omega - D_{\mathrm{L}}}{\omega} \right) \times 100\% \qquad \text{................(2)}$$

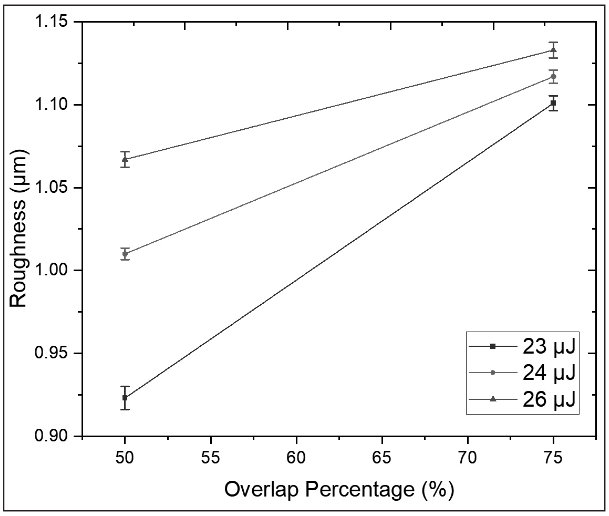

Fig. 5. Effect of pulse overlap percentage on surface roughness.

where, ω is the focused beam diameter, D_L is the overlap distance, *v* is the scanning speed and *f* the pulse repetition rate.

It can be noted from the figure that the roughness value (R_a) of the micro-milled zone of the PC sheet increases as the percentage of laser pulse overlap increases. The reason for this could be that as the percentage of laser pulse overlap increases, so does the concentration of laser energy on the overlapping region increases. As a result, the material's melting point temperature is exceeded, and more material is ablated. Furthermore, due to fluid thermodynamics, the molten material formed due to repeated pulses moves in an expanding direction. As it begins to resolidify, the mass distribution becomes non-uniform, thereby resulting in the increase in roughness value (R_a).

Thus, it is clear that maintaining the laser pulse overlap percentage at a lower value of 50%, while maintaining a low pulse energy will result in the least amount of surface roughness (R_a).

4. Conclusions

In our present work, laser micro-milling has been performed to fabricate micro reservoirs on polycarbonate sheet. The surface roughness (R_a) of the fabricated micro-reservoirs was methodically measured and analysed. The laser parameters such as laser pulse energy, scanning speed and correspondingly pulse overlap percentage were varied within an acceptable range and their influence on the surface roughness were studied (R_a). Repetition rate and pulse duration of 5 kHz and 300 fs were maintained constant throughout the experiments. Based on the experimental analysis, the important observations are as follows:

- The value of surface roughness (R_a) increases as the value of laser pulse energy increases. Additionally, the roughness values become constant as the laser pulse energy rises from 24 µJ to 26 µJ at a greater laser pulse overlap percentage.
- An increase in the percentage of pulse overlap results in an increase in the surface roughness value (R_a). Furthermore, at a constant percentage of pulse overlap of 50% or 75%, the change in roughness value is relatively consistent with increasing laser pulse intensity.
- The least value of surface roughness (R_a) will be achieved by keeping the laser pulse energy at a lower value of 23 µJ and at a lower laser pulse overlap percentage of 50%.

The surface roughness of the ablated areas of the micro-milled PC sheet is less than 1200 nm. Thus, it can be concluded that surface roughness obtained by laser micro-milling is comparable to the surface roughness achieved by a conventional mechanical method.

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