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Technical Paper

Pulse smearing and profile generation in CO_2 laser micromachining on PMMA via raster scanning

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ABSTRACT

CO_2 laser micromachining is an efficient and cost effective way for fabricating many polymeric microfluidic devices. Apart from direct laser writing also called vector cutting, raster scanning of CO_2 laser beam is an indispensable part of fabrication process. Raster scanning is commonly used to create different types of microstructures on the surface. Polymethyl methacrylate (PMMA) is an important polymeric substrate for various microfluidic devices. In this research work, CO_2 laser based raster scanning process has been explored for generation of microstructures of different widths and depths. The influence of high raster speeds on individual laser pulse shape has been discussed. Pulse smearing phenomenon was found to be detrimental to intensity of the laser beam. Reduction in energy intensity due to pulse smearing has been determined experimentally. Effects of process parameters on micromachined structure's output parameters have been detailed. An unique theoretical model has been developed for prediction of micromachined depth and profile on the basis of conservation of energy principal and superposition of Gaussian beams. The model takes into account the vertical pulse overlapping as well as pulse smearing effect. Evolution of surface in raster scanning has been discussed theoretically and experimentally. Developed model was found to be predicting the depth and evolved micro-structure profile close to actual depths and profile. The maximum prediction error for different power and scanning speed settings were less than 7.23%.

1. Introduction

Micromachining of polymers by laser is a current trending phenomenon. Lasers like femtosecond lasers [1], excimer lasers [2] and nanosecond lasers [3,4] can be utilized for microfabrication on polymer substrates. However, the fact that CO_2 lasers are approximately ten times cheaper than excimer and femtosecond lasers apart from being easy to operate and less maintenance requirement makes it a more popular choice among researchers and microfluidic industry. Further, most of the times, the whole microfluidic systems can be fabricated in a very small time with a CO_2 laser system [5]. CO_2 laser is commonly used for micromachining and cutting of PMMA [6–9]. The primary reason of CO_2 laser machining of PMMA lies in its high absorptivity and clean cutting edges [10].

Many polymeric microfluidic devices are fabricated utilizing CO_2 lasers [11,12]. Most of the commercial CO_2 lasers have two modes of operation i.e. direct writing (vector cutting) and raster scanning. In vector cutting mode, laser beam moves in a straight line or curved path producing the cutting widths depending upon beam spot diameter. The vector cutting is simple in nature and totally depends upon power and scanning speed settings to produce required cut features. However, due to limited capability of direct writing (vector cutting) features of CO_2 lasers, many microfluidic devices may not be fabricated by completely relying on this technique. On the other hand, by utilizing the raster scanning feature of a laser, many complex different features on the polymer surface can be generated which are tough to be generated by direct writing process efficiently. In fact, most of the microfluidic devices require the use of both features i.e. direct writing and raster scanning, to fabricate the complete microfluidic device in an efficient way. While the direct writing ensures minimum time consumption, raster scanning enables the system to produce diverse shapes or sizes required to be fabricated on the surface.

Few authors [13,14] have equated the raster scanning/patterning of the laser to mechanical micro-milling process with the only difference of milling tool replaced by a focused laser beam. Due to this reason, raster scanning has also been referred to laser milling by some authors. However, unlike a milling tool in its actual sense, lasers are contact-less machining tool which

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can be turned "ON" and "OFF" conveniently without creating mechanical stresses due to physical contact of milling tool. Due to the non-contact nature of lasers as a milling tool, there are no scope for tool breakage. Apart, extra accessories for holding the substrates are also not required. Laser as a cutting tool offers more flexibility in operation compared to mechanical micro-milling tools. The cutting speed of a laser cutting tool is not dependent on material and can be increased or decreased at will.

Pulsed laser milling was utilized for metal removal over a surface by many researchers. Wu et al. [15] used nanosecond pulsed laser for surface generation on poly crystalline diamond. Nanosecond pulsed laser milling was also used by Zhao et al. [16] for metal coating removal from a polymer substrate. Jensen et al. [17] were firstly investigated the raster scan phenomenon of CO_2 laser on a PMMA substrate. Experimentally they found that with the raster scan feature, a minimum of 200 μm of width and 50 μm of depth can be fabricated on a PMMA substrate. The quality of ablated surface was found to be dependent upon type and variant of PMMA used. A neural networks and fuzzy data based modeling of CO_2 laser micro-milling on PMMA was performed by D'Addona et al. [18]. Genna et al. [13] have experimentally investigated the CO_2 laser milling on PMMA and developed semi-empirical models for depth and volume removal.

Although, there are numerous advantages of raster scanning process, sufficient literature on this topic are not available due to complexity of the process. Earlier studies have totally ignored the pulse shape variations due to high scanning speed of the laser beam which plays a significant role in pulse intensity. Since most of the microfluidic devices require a specific width and depth of ablated structures, It is important to predict the ablation depth and profile of the ablated PMMA surface in order to have full control over the machining process and device fabrication. Jensen et al. [17] and Genna et al. [13] have developed a semi-empirical model for depth prediction while D'Addona et al. [18] developed mathematical models based on neural networks and fuzzy data. Most of the semi-empirical and statistical techniques are not fully dependent on the physics of the process and may not be validated beyond the set parameters. Also, these models have been developed for specific type of PMMA and may not be applicable to other types as PMMA is available with many different variants in market. In this work, an analytical model has been developed to predict ablation depth and profile of ablated surface. The model takes into account the pulse smearing effect due to high scanning speed and vertical pulse overlapping factor. Based on the developed model, the ablation depth and ablated surface profile can be predicted for different pulse overlapping factors. The developed model can be applied to different kind of PMMA and is independent of machine characteristics.

2. Raster scanning process

In direct writing feature, the laser moves in a straight or curved line depending upon the predefined path generated in the software of the machining system. In raster scanning process, laser moves over a surface much like inkjet or laser printer. In most usual cases they start from starting point at top and from left to right going downwards in successive steps while clicking laser ON and OFF at the places required or not required to be ablated. Fig. 1 shows the laser beam movement in raster scanning process. The difference between two successive horizontal lines determine the overlapping in downward direction. Since this form of overlapping takes place in vertical direction, it will be referred to vertical pulse overlapping hereafter. Vertical pulse overlapping ultimately controls the image density of the fabricating surface. Greater the number of horizontal lines per unit length, greater is the image density. A large image density leads to larger time consumption while a low image density produces irregular surface structures involving peaks and troughs due to insufficient overlapping of pulses.

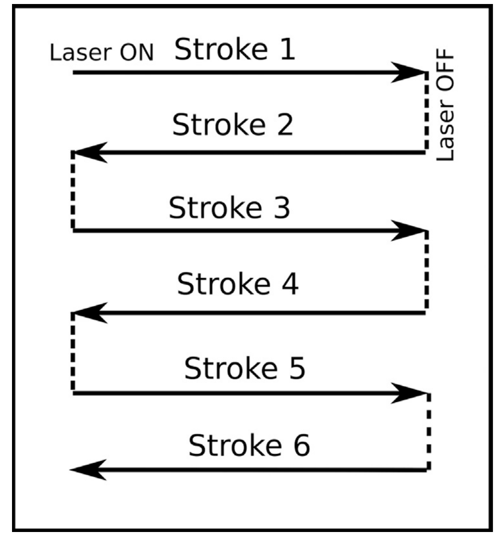

Fig. 1. Laser beam movement during raster scanning for six strokes.

Table 1
Vertical pulse overlaps at different image densities.

Image density	Horizontal lines per inch	Vertical pulse overlapping%
1	83	−29.12
3	250	57.13
5	500	78.56

Vertical pulse overlapping factor (PO_v) can be mathematically defined as:

$$PO_v = \left(1 - \frac{1}{N_L \times d}\right) \times 100\% \tag{1}$$

where N_L represents number of horizontal lines per unit vertical length and d represents beam diameter. Selection of appropriate image density is important for efficient and appropriate microstructure surface generation. Most of the low power (20–200 W) commercial CO_2 lasers come with selective options for image densities. Users are required to select the image density based on their experience. Experiments were conducted on a Universal CO_2 laser (VLS 3.60) at three different image density options (out of 7 settings). Fig. 2 shows the side cross-sectional optical microscopic images of microstructures in six different strokes at each of the three image density option. The microchannels were etched at three different image densities i.e. 1, 3 and 5. Image density values and corresponding vertical pulse overlap values can be calculated using Eq. (1). The percentage vertical pulse overlapping for each image density have been shown in Table 1. In this experiment, power was kept at 60 W and scanning speed was selected to be 250 mm/s in order to keep the maximum depth of microchannels in micron range. Fig. 2(a) shows the microstructures resulting from image density 1 from 1 to 5 strokes. Image density 1 corresponds to 83 horizontal lines per inch in downward directions. The corresponding vertical pulse overlapping is −29.12%. Negative pulse overlapping means that there is actually no vertical overlapping and two vertical pulses are separated by some distances. As evident in the figure, vertical pulses in each strokes are always separated by equal and fixed distances. The distance between two vertical pulses can be determined based on microchannel width. The distance between center of one stroke to center of another stroke is equal to approximately 29.12% of the width in addition to microstructure's width. At this image density, the microstructuring process remains very much similar to direct writing process at uni-