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Technical paper

Nanosecond pulsed laser micromachining of PMMA-based microfluidic channels

Daniel Teixidor[a], Thanongsak Thepsonthi[b], Joaquim Ciurana[a], Tugrul Özel[b,*]

[a] Department of Mechanical Engineering and Industrial Construction, University of Girona, Girona, Spain
[b] Manufacturing and Automation Research Laboratory, Department of Industrial and Systems Engineering, Rutgers University, Piscataway, NJ, USA

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ABSTRACT

This paper reports an investigation into the effects of nanosecond laser processing parameters on the geometry of microchannels fabricated from polymethylmethacrylate (PMMA). The Nd:YAG solid-state pulsed laser has a wavelength of 1064 nm and a measured maximum power of 4.15 W. The laser processing parameters are varied in a scanning speed range of 400–800 pulses/mm, a pulse frequency range of 5–11 Hz, a Q-switch delay time range of 170–180 μs. Main effects plots and microchannel images are utilized to identify the effects of the process parameters for improving material removal rate and surface quality simultaneously for laser micromachining of microchannels in PMMA polymer. It is observed that channel width and depth decreased linearly with increasing Q-switch delay time (hence average power) and increased non-linearly with higher scanning rates and not much affected by the increase in pulse frequency.

1. Introduction

Microfluidics is an emerging technology for advanced analytical chemistry, biology, diagnostics and biomedical research. The microfluidic devices are used in manipulating liquids and gases in channels having cross-sectional dimensions in the order of 10–500 μm [1,2] and can undergo chemical and physical changes, mix or separate each other when covering predetermined paths. For microfluidic device fabrication, transparent polymers such as polymethylmethacrylate (PMMA) have become more and more important compared with conventional materials such as silicon and glass due to a number of advantages. Polymers are less expensive and easier to work with than silica-based or glass substrates. A wide selection of low-cost polymer materials is made possible due to their favorable thermal and chemical resistance, molding temperature and surface derivation properties.

On the other hand, laser micromachining is a highly precise, fast and force-free technology and it has been demonstrated as a promising method for fabrication of polymer-based medical devices. The speed of the fabrication process and high flexibility in changing the design for making more complex microchannel systems provide this technique an advantage over other micromachining techniques in microfluidics field.

In literature, there are several research work reported the use of laser micromachining of microfluidic channels on polymeric materials. Most of them utilized either expensive ultra-short pulsed lasers in which the pulse duration is about $\tau = 10$–500 fs with visible light wavelengths ($\lambda = 700$–900 nm) or ultraviolet (UV) wavelength ($\lambda < 400$ nm) pulsed lasers. However, little or no attention was paid for utilizing low-cost nanosecond pulsed IR Nd:YAG lasers.

Gomez et al. [3] used a Ti:sapphire femtosecond pulsed laser system to directly fabricate passive microfluidic components in PMMA. They ablated channels by using different fluence and feed rate levels. These channels had well-defined edges with neither heat affected zone (HAZ) nor burr formation. They concluded that the surface finish is no longer acceptable for laser fluence level above $\Phi = 1$ J/cm^2. Microchannel width dimension presented a difference of 22% from the fastest to the slowest feed rate whereas depth achieved a logarithmic behavior of the inverse of feed rate for all the fluence levels. Suriano et al. [4] analyzed the effect of femtosecond laser pulses on the morphological features and changes in chemical structure of thermoplastic polymers commonly used in microfluidics, e.g. PMMA, polystyrene (PS) and cyclic olefin polymer (COP). The average surface roughness of ablated areas was lower than 400 nm, comparable to that achieved by a standard mechanical micromachining method. Among thermoplastic polymers, PMMA was found to have the most stable polymer structure for laser processing. Day and Gu [5] also used femtosecond laser pulses with pulse energy of $E = 0.9$ nJ at pulse repetition rate of $PF = 80$ MHz and a wavelength of $\lambda = 750$ nm to fabricate straight microchannels (with diameters of 8–20 μm) on a PMMA polymer substrate. The size and shape of the microchannels were controlled by changing the process parameters of scanning speed, number of fabrication repeats and the time delay in between fabrication repeats.

* Corresponding author.
E-mail address: ozel@rutgers.edu (T. Özel).

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Some other researchers used CO_2 infrared (IR) lasers to ablate PMMA polymer material. Romoli et al. [2] investigated the influence of process parameters such as laser incident power, scanning speed and spot diameter on microchannel profile. Channel depths ranging between 50 and 600 μm and widths between 150 and 400 μm were achieved by using IR laser irradiation. Nayak et al. [6] investigated effects of laser power and processing speed on the depth, width and surface profiles of microchannels manufactured. They observed that channel depth varies linearly with an increase in laser power at a particular speed. For a prescribed laser power, channel depth decreased with an increase in laser scanning speed. However, channel width increased with an increase in laser power but decreased with an increase in scanning speed. Snakenborg et al. [7] ablated several microchannels and developed a simple model to relate laser-cut channel depth to velocity, power and number of passes of the laser system. Additionally they explored the effects of processing sequences and number of passes, in particular the effects of cooling time, channel width change and profile. Yuan and Das [1] fabricated microchannels using low laser powers and low scanning speeds. Heat transfer models for channel depth and profile based on given laser power and scanning speed were developed and applied with a maximum deviation of 5% for the range of experimental parameters, i.e. laser power and scanning speed tested.

Finally, several groups utilized ultraviolet (UV) pulsed lasers to ablate microchannels on polymeric surface. Waddell et al. [8] used a KrF laser (λ = 248 nm) to create microchannels in PMMA, polyvinylchloride (PVC), polyethylene terephtalate glycol-modified (PETG), and polycarbonate (PC). They studied the effect of laser fluence and the laser repetition rate, as well as the local ablation atmosphere to control the topography and surface state of the channel. Smoother channels were obtained by using slower velocities, lower fluence, and higher pulse repetition rates. The physical morphology of the channels was also found to be a function of local atmosphere at the ablation site. Pfleging et al. [9] used various UV lasers to directly ablate and locally modify PMMA polymer substrates. They ablated grooves to determine the best parameters selection to fabricate small grooves with well-defined depth and surface quality for microfluidics or micro-optical applications. The best surface quality was obtained for the KrF laser at λ = 193 nm wavelength. It was also found that increasing laser fluence increases ablation rates and resultant surface roughness. The literature on laser micromachining of PMMA is summarized in Table 1.

Consequently, little or no research studies were reported on use of nanosecond pulsed laser micromachining with near-infrared (NIR) wavelength of λ = 1064 nm. Therefore, the main objective of this study is to investigate the feasibility of utilizing an NIR nanosecond laser to ablate microchannels in a transparent PMMA polymer substrate for microfluidic applications. The paper also aims to develop experimental models to optimize laser process parameters such as Q-switch delay, pulse frequency, scanning rate and focused beam distance from the surface with objectives in obtaining high material removal rate (MRR) and consistent microchannel shapes with high quality.

2. Experimental work

The main purpose of the experimental work is to analyze the influence of laser process parameters on final quality micro-geometries in polymeric substrates and material removal rate per pulse. Furthermore, effectiveness of laser micromachining technique for direct fabrication of microfluidic channels in transparent PMMA polymer is also investigated. The experiments were performed using a nanosecond Q-switched Nd:YAG solid-state laser with an average measured laser power (P) of 4.15 W, wavelength (λ) of 1064 nm, pulse duration (τ) of 5–7 ns and a laser beam spot diameter of 6 mm which is reduced with optics into a focal spot diameter (D) size of $\O$ = 0.190 mm. The experimental setup of the laser ablation system at Rutgers Manufacturing and Automation Research Laboratory is presented in Fig. 1.

The system has a central computer control, which controls the movement of XYZ stages for translating the work under the focused laser spot. The video microscope system is used for proper location and in situ monitoring of the laser ablation operation. The power monitor is also used to adjust optical attenuation to reduce or increase the power in conditioned optical beam. The average power at the exit port was measured by using a Molectron EPM1000 with a thermopile type Molectron PM150 power sensor. Average power at the laser at PF = 10 Hz was measured for varying Q-switch delay times as shown in Fig. 2. Maximum average power was obtained at a Q-switch delay of 180 μs which corresponds to the maximum stable pulse intensity of E = 0.415 J and P = 4.15 W at PF = 10 Hz pulse frequency.

Polymethylmethacrylate (PMMA) was used as a workpiece material for microfluidic channels. This substrate was chosen as a benchmark polymer material with potential applications in the microfluidics field because of its biocompatibility, low cost, thermal stability and mechanical properties which offer the capability of obtaining a high quality on the machined surfaces. The experiments were carried out on laser machining microchannels of 2 mm in length by approaching to the material from outside in order to avoid the effects of forming cracks during the early firing of pulses.

Table 1
Summary of literature on laser micromachining of PMMA.

Reference	Laser type	Wavelength [nm]	Pulse duration	Fluence [J/mm^2]	Scan speed [mm/s]	Microchannel geometry	Mechanism
Yuan and Das [1]	CO_2	10,600 (IR)	CW	–	2.0–14	Width (44–240 μm) Depth (22–13 μm)	Photothermal
Romoli et al. [2]	CO_2	10,600 (IR)	CW	–	25–125	Depth (75–165 μm)	Photothermal
Gomez et al. [3]	Ti: sapphire	800 (visible IR)	90 fs	0.03	0.5	Width (31–6 μm) Depth (22–12 μm)	Photothermal/ photochemical
Suriano et al. [4]	Ti: sapphire	800 (visible IR)	40 fs	0.088–0.884	0.8	Width (30–15 μm) Depth (60–15 μm)	Photothermal/ photochemical
Day and Gu [5]		750 (visible IR)	80 fs	–		Width (8–2 μm)	Photothermal/ photochemical
Nayak et al. [6]	CO_2	10,600 (IR)	CW	–	7.04	Width (220–40 μm) Depth (50–65 μm)	Photothermal
Snakenborg et al. [7]	CO_2	10,600 (IR)	CW	–	50–1000	Width (223–305 μm) Depth (150–65 μm)	Photothermal
Waddell et al. [8]	KrF	248 (UV)	7 ns	0.00555–0.02	0.625–10	–	Photochemical
Pfleging et al. [9]	Nd:YAG	355 (UV)	4 ns	0.004–0.1	–	Width (30 μm) Depth (20 μm)	Photochemical