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Microchannel fabrication on cyclic olefin polymer substrates via 1064 nm Nd:YAG laser ablation

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ABSTRACT

This paper presents a method for fabrication of microchannels on cyclic olefin polymer films that have application in the field of microfluidics and chemical sensing. Continuous microchannels were fabricated on 188-μm-thick cyclic olefin polymer substrates using a picosecond pulsed 1064 nm Nd:YAG laser. The effect of laser fluence on the microchannel morphology and dimensions was analysed via scanning electron microscopy and optical profilometry. Single laser passes were found to produce v-shaped microchannels with depths ranging from 12 μm to 47 μm and widths from 44 μm to 154 μm. The ablation rate during processing was lower than predicted theoretically. Multiple laser passes were applied to examine the ability for finer control over microchannel morphology with channel depths ranging from 22 μm to 77 μm and channel widths from 59 μm to 155 μm. For up to five repeat passes, acceptable reproducibility was found in the produced microchannel morphology. Infrared spectroscopy revealed oxidation and dehydrogenation of the polymer surface following laser ablation. These results were compared to other work conducted on cyclic olefin polymers.

1. Introduction

Until recently, the typical materials of choice for microfluidic devices and micro-total analysis systems have been glass or polymers such as polymethyl methacrylate (PMMA), polycarbonate (PC), and polydimethylsiloxane (PDMS). These materials have good mechanical properties allowing for easy processing, but often lack good optical transparency in the mid-ultraviolet spectrum (200–300 nm). Optical transparency in this range is crucial for the optical analysis of many organic compounds such as aromatics, proteins and nucleic acids. Cyclic-olefin polymer (COP) and co-polymer (COC) are an emerging new classes of polymers which have been noted for their low cost, high chemical resistance, biocompatibility and high optical transparency from NIR to mid-UV wavelengths [1]. COPs are also recognized for their low water absorption and high mechanical and dimensional stability when in contact with liquids, and as such make extremely suitable platforms for microfluidic devices when compared with previously used alternatives. Owing to these exceptional properties, COP-based devices have been utilised for various applications such as substrates for chromatographic stationary phases [2] and microfluidic devices for the analysis of drugs [3], IR waveguide coatings [4] and as substrates for laser deposited nanomaterials [5].

For microfluidic device fabrication, techniques such as xurography [6], micromilling [7], UV-polymerisation [8] and, more recently, 3D printing [9,10] allow for fast and flexible prototyping of devices leading to shorter periods to device optimisation. For large-scale fabrication of devices, techniques such as hot embossing [11] or injection moulding [12] tend to be used due to their cost-effectiveness. However, these lack the ability for rapid prototyping due to the requirement of moulds or negatives to be fabricated. Contrastingly, laser processing provides a fast, repeatable, clean and cost efficient method of microfluidic device manufacturing. The use of laser processing [13–15] and pulsed laser ablation [16] has been demonstrated to be capable of both surface modification and creation of micro- and nanoscale structures on polymer surfaces,

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along with the incorporation of nanoparticles onto the substrate surface for functionalisation and nanotexturing [17].

Neodymium-doped yttrium aluminium garnet (Nd:YAG) lasers are widely used in industry for materials processing [18], however, very few studies have examined the feasibility of using Nd:YAG lasers for the processing of cyclic olefin polymers [6]. Various alternative laser systems, such as ultra-violet and extreme ultra violet laser systems and femtosecond lasers, have been utilised for polymer processing in the past. UV excimer lasers have been used for the processing of optically transparent polymers [19], and specifically COC [20]. The low ablation depth per pulse for COC, which was found to be smaller when compared to PMMA, would allow for the creation of small features although the extent of ablation was seen to be dependent on the norbornene content of the copolymer [21]. However, UV excimer lasers tend to have higher operating cost and lower beam quality when compared to solid-state laser systems. Extreme ultraviolet (EUV) lasers, typically used in microelectronics manufacturing, have also been shown to be capable of nanoscale changes in depth and surface roughness of polymer surfaces due to low penetration depth of EUV radiation [22,23]. Despite these advantages, EUV lasers require a vacuum and highly specialised optics for operation and therefore are not well suited for the fabrication of low-cost microfluidic systems.

Femtosecond lasers, which interact with materials through non-linear photon absorption, have been demonstrated for the efficient processing of materials transparent to the wavelength of the laser used [16]. For COP processed using a femtosecond titanium sapphire (800 nm) laser, low surface roughness of the processed area was reported [24]. However, some degradation in optical transmission was seen due to a combination of oxidation and dehydrogenation when compared with PMMA or polystyrene (PS) processed under the same conditions. While fast delivery of power by femtosecond lasers allows for efficient processing of materials transparent to the wavelength of the laser, these systems tend to be both more expensive and complicated to maintain than laser processing systems typically used in industry.

In this work, we examine the use of an infrared picosecond pulsed Nd:YAG laser for direct-write fabrication of continuous microchannels on the surface of thin COP substrates. The use of multiple laser passes for fine control of dimensions and dimensional uniformity was also examined. Optical profilometry was used for dimensional analysis of the microchannels and scanning electron microscopy was performed to analyse changes in surface morphology. Raman and infrared spectroscopy were performed to examine the effect of laser processing on the surface chemistry.

2. Materials and methods

2.1. Materials

The substrate material used was ZeonorFilm ZF14-188 (Zeon) cyclic olefin polymer purchased from Ibidi, Germany, with a thickness of 188 μm. The polymer sheet was cut, cleaned with isopropanol, rinsed with deionised water and dried using compressed clean dry air to ensure the substrate was pristine prior to laser processing.

2.2. Laser processing and substrate fabrication

The direct-write laser system used consisted of a 1064 nm Q-switched, diode-pumped solid-state neodymium-yttrium aluminium garnet laser (BrightSolutions 1064 WEDGE HF), specifications of which are listed in Table 1. A 2D scanning galvanometer (Raylase SS-12) was used to raster the beam in the xy-plane, and a movable z-stage (PI M-404 4PD) was used to control the position of the sample. The laser beam was focussed to a spot size of 140 μm and scanned unidirectionally across the sample at a speed of 1.2 mm/s to form parallel channels separated by 200 μm. The COP films were mechanically fastened to the sample stage for the duration of processing. Further details of the processing parameters are listed in Table 2.

Table 1
Specifications of the 1064 nm laser processing system.

Wavelength	1064 nm
Maximum Average Output Power	4.5 W
Maximum Pulse Energy	45 mJ
Repetition Rate	7.5–100 kHz
Pulse width	0.7–5.2 ns
Beam diameter	140 μm

Table 2
Process parameters used during laser processing of COP substrates.

Process Parameter	Single Pass	Multiple Passes
Fluence	0.15–0.78 J/cm^2	0.51 J/cm^2
Scan Rate (mm/s)	1.2	1.2
Beam diameter (μm)	140	140
Pulse Width (ps)	750	750
Pulse Repetition Frequency (kHz)	7.5	7.5
No. of passes	1	2–10

2.3. Characterisation

Scanning electron microscopy was conducted using an EVO LS15 (Zeiss) with LaB_6 filament, accelerating voltage of 10 kV, and a beam current intensity of 25 pA. Samples were gold coated using a Scan-Coat Six (Edwards) sputter coater set at a deposition current of 25 mA for 80 s, resulting in a coating thickness of 34 nm.

The profile of the microchannels was examined using a VHX-2000 (Keyence) 3D Optical Microscope. Samples were previously coated with a 68-nm-thick film of gold using the ScanCoat Six sputter coater, which was sufficient to reduce the transmission in the visible range by approximately 90% [25] and allow the sample surface to be imaged optically. Images were taken at 0.43 μm increments from the base of the channel upwards at 1000× magnification. For the figures presented hereafter, the error bars relate to a 90% confidence interval of the measured microchannels width and depth.

The optical absorbance of the polymer film at the laser wavelength was examined using a Cary 50 (Varian) UV–vis spectrometer. Infrared spectroscopy was performed to examine changes to the substrate surface chemistry as a result of laser processing. Micro-Raman spectroscopy was conducted using a LabRam HR800 (Jobin-Yvon Horiba) system with an Ar^+ 488 nm air-cooled laser and an accumulation time of 20 s. The HR800 was operated in a backscattering configuration with a resolution of 1.1 cm^{-1}. FTIR spectroscopy was performed using a Perkin 100 spectrometer (PerkinElmer) in attenuated total reflectance (ATR) mode. Spectra were collected with 4 scans at a resolution of 1 cm^{-1} over the range of 4000–650 cm^{-1}. A baseline correction was applied to the FTIR spectra using Origin Pro 9, to allow accurate comparison of relative peak intensities.

2.4. Calculation of ablation rate

The number of laser pulses, N, incident per unit area in a scanning beam can be estimated from the laser pulse repetition frequency, f, the beam waist, w_0, and scan rate, v, as follows [26]:

$$N = (w_0 f)/v \quad (1)$$