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Taguchi method modelling of Nd:YAG laser ablation of microchannels on cyclic olefin polymer film

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ABSTRACT

This paper presents the development of a model for Nd:YAG laser ablation of cyclic olefin polymer (COP) films. Two Taguchi orthogonal array experimental designs were implemented to produce a model for the prediction of microchannel depth and width produced on ZeonorFilm® ZF14 and ZF16 polymer films via laser ablation. The width and depth of the produced microchannels were measured using 3D optical profilometry. Microchannels produced were seen to range in depth of up to 50 μm, and widths of 112 μm via single-pass laser depending on the grade of COP, with feature size increasing as the number of laser passes increased. The models are discussed in terms of adjusted coefficient of determination, signal to noise ratio and model significance. The effect of the process parameters used such as fluence and scan speed on three different grades of COP was examined with an aim to produce a simple model suitable for predictive control of surface microstructuring of COP.

1. Introduction

Cyclic olefin polymer (COP) and cyclic olefin copolymer (COC) are increasingly popular substrate materials replacing traditional polymers such as polymethyl methacrylate (PMMA), polycarbonate (PC) and polydimethylsiloxane (PDMS) in analytical applications [1]. COC and COP have been reported for use in a wide variety of applications ranging from diffractive optic elements [2], waveguide coatings [3] and as substrates for the deposition of nanomaterial films [4] which exploit the polymer's high transparency in the UV-Visible-NIR range. Furthermore, COPs and COCs have also exhibit excellent biocompatibility which allows them to find application in high-adhesion biomimetic surfaces [5] and cell culturing platforms [6]. As COP and COC are also noted for low water absorption and resistance to acids, bases and most non-hydrocarbon solvents, they offer an excellent alternative for liquid analysis platforms which have been typically fabricated using PDMS and PMMA to-date.

With increasing applications, the need to develop new processing techniques for the manufacture of devices utilising COP and COC becomes critically important. Techniques such as injection moulding [7], embossing [8], xurography [9], 3D-printing [10] and micromilling [11] have all been successful in the creation of micro- and nanoscale features on COC and COP substrates. Laser processing offers the ability for rapid, single-step prototyping of devices. To date, laser processing of COC and COP has been examined using excimer [12,13], femtosecond titanium sapphire [14] and carbon dioxide lasers [15,16]. Recently, the use of solid-state neodymium-doped yttrium aluminium garnet (Nd:YAG) lasers has also been examined for microchannel fabrication on COP [17].

In this paper, we present an investigation into laser ablation of ZeonorFilm® ZF14 and ZF16 COP using an industrial picosecond pulsed Nd:YAG laser. The effect of parameters such as laser fluence, beam scan speed and number of passes on the depth and width of the produced microchannels was examined. A Taguchi orthogonal Design of Experiments (DoE) was then used to develop a model for the ablation of two grades and three thicknesses of COP with an aim to develop a simple protocol suitable for model predictive control of machining of COP.

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2. Methods and materials

2.1. Experimental Setup

The experimental setup is shown in Fig. 1. The laser used was a WEDGE HF 1064 (BrightSolutions, Italy) 1064 nm diode-pumped solid-state Nd:YAG. The laser had a pulse width of 700 ps, a maximum power output of 1.2 W at a pulse repetition frequency of 10 kHz, and a maximum pulse energy of 160 μJ. The beam was rastered in the xy-plane unidirectionally using an SS-12 2D-scanning galvanometer (Raylase, Germany) to form microchannels separated by 200 μm. The sample was positioned in the laser beam waist using a 404-4PD single-axis nanoposition stage (PI, Germany) at a laser spot size of 140 μm.

Microchannel morphology was examined using a VHX-2000 3-dimensional optical profilometer (Keyence, Japan) scanning upwards from the base of the channel in 1 μm increments. The average measurement of 16 channel profiles (four profiles across four channels) per sample at a 500x magnification were recorded where the channels were examined for two parameters: depth (defined as the length from the base of the channel to the mean height of the channel crests) and full-width half-max (FWHM, defined as the width of the channel measured at half the depth of the channel).

2.2. Materials

The substrates used in this experiment were ZeonorFilm® ZF14-188, ZF16-100 and ZF16-250 cyclic olefin polymer (Zeon Chemical LP, Japan) with film thicknesses of 188 μm, 100 μm and 250 μm respectively. Material properties of note are listed in Table 1.

2.3. Taguchi orthogonal array

The experimental design chosen for the study of laser ablation of ZF14 was a Taguchi orthogonal array L_{16} (with three factors at four levels, outlined in Table 2) and was produced and analysed using the Design-Expert 7 (Stat-Ease Inc., USA) and Minitab 17 (Minitab Inc., USA) software packages. The minimum fluence level of the design was chosen to be above the threshold fluence for ablation. Previous work by our group determined a threshold fluence for ZF14-188 of 0.32 J/cm^2 for a single laser pass and a beam scan speed of 1.2 mm/s [17]. A reduced quadratic model was developed using a backwards elimination to remove insignificant terms and increase model simplicity while maximising the adjusted coefficient of determination.

Table 1
Material properties of ZeonorFilm® ZF14 and ZF16 grades of cyclic olefin polymer [17,18].

Property	ZF14	ZF16
Water absorbency (%)	<0.01	
Glass transition temperature (°C)	136	163
Refractive index	1.53	
Birefringence (nm)	3	
Effective optical penetration depth at 1064 nm (nm)	140	

Similarly, for the ZF16 ablation study, an L_{32} matrix ($2^1 + 4^9$) was used by coupling two L_{16} matrices using the same levels as before with a fourth factor, film thickness, added to the experimental design with two levels. A reduced quadratic model was developed for the ZF16 ablations with a backwards elimination applied as before. The full orthogonal arrays for the ZF14 and ZF16 models are listed in Tables 1S and 2S respectively in the ESI.

3. Results and discussion

3.1. Microchannel morphology

Fig. 2 shows the typical microchannel morphologies produced via laser ablation as measured via 3D optical profilometry. Across all samples, the microchannels produced had a v-shaped morphology, which is consistent with previous work on infrared laser ablation of COP, with deeper microchannels having a more pronounced V-shape. Along the base of the microchannels were isolated wells, which became less pronounced as the microchannels became deeper. This was attributed to the pulsed nature of the applied scanning beam of radiation. Outside the ablation site, condensed melt and debris was seen, being more evident with deeper channels. For deeper microchannels, the debris was seen to be more smoother, suggesting that melting occurred within the channel.

3.2. Signal-to-noise analysis

To determine which factors had the greatest effect in the model, the signal-to-noise (S/N) ratio was calculated for the depth and FWHM profilometry measurements. Many analytical devices require microchannels with high surface area-to-volume ratios, for enhanced surface-chemical interaction or increased mass transfer for example [19,20]. As analytical applications are of particular interest in this study, a target for high aspect ratio channels (i.e. large depth and small width) was decided. Two different S/N ratios were decided upon based on these experimental goals. Eqs. (1) and

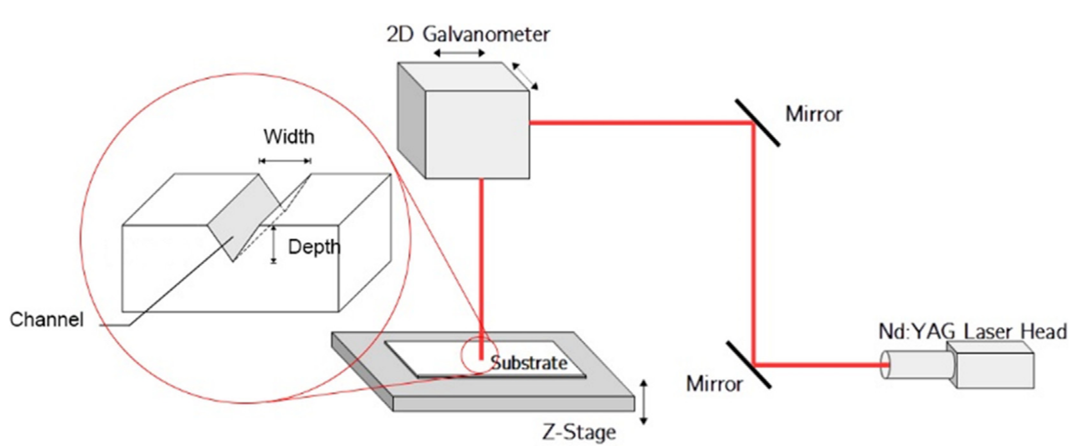

Fig. 1. Schematic of the 1064 nm laser ablation setup and responses measured.