Effect of laser processing parameters and glass type on topology of micro-channels

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ABSTRACT

Traditional processes to manufacture micro-fluidic devices include standard lithography, electron beam writing and photo-patterning. These techniques are well established but most are limited to surface micro-fabrication. Laser micro-machining provides an alternative for micro-fabrication of devices. This paper presents Design of Experiment models for the fabrication of micro-channel structures with four different types of glass, soda-lime, fused-silica, borosilicate and quartz. A 1.5kW CO_2 laser with 90 µm spot size was used to fabricate micro-channels on the surface of glass sheets. Power, P, pulse repetition frequency, PRF, and translation speed, U, were set as control parameters. The resulting geometry of the channel (depth and width) and transmission capabilities were measured and analyzed. A comparison of the results of this experimental testing with the four glass types showed that quartz and fused-silica glasses would have better channel topologies for chemical sensing applications.

Keywords: Pulsed CO_2 laser; micro-fluidics; micro-channel; glass; optical transmission

1 INTRODUCTION

Laser energy absorption of materials depends highly on the wavelength [1, 2]. Transparent glass materials allow incident visible spectrum to be transmitted but absorb strongly at or near 10 µm. This makes the CO_2 laser very efficient for machining these materials [1]. The fabrication of micro-channels on the surface of transparent materials can be used for various application such as telecommunication, energy and biomedical engineering. Using laser processing to fabricate micro-fluidic channel is a faster alternative to traditional techniques such as lithography, electron beam writing and photo-patterning [3]. Several studies investigated the breakdown thresholds of various transparent materials using lasers of various wavelength [4, 5]. Micro-channels in these studies were reported to be made on or beneath the material's surface. However, such systems require tight laser focusing and precise sample translation [6, 7]. This does not only make the process more expensive, it also imposes limits on the dimensions of the channels that can be achieved. In previous work, the pulse energy and scanning speed were considered as the main factors affecting the process. Relatively few studies have been conducted using industrial CO_2 lasers to experimentally relate the process control parameters to the resulting micro-channels' characteristics. A systematic and well designed study of the process is possible by experimental methods that give real measurements of responses and allow a mathematical model to be developed, which can then be used as a channel manufacturing guide [8].

2 EXPERIMENTAL SETUP

2.1 Topology characterisation

Glass samples of 20 mm by 40 mm and 2 mm thick of soda lime, borosilicate, quartz and fused silica were used in this study. Channels length of 15 mm were fabricated on the surface of the samples using a 1.5 kW CO_2 laser operated in pulsed mode. The laser beam was delivered coaxially with an air jet at 1 bar. Laser beam, spot size 90 µm, was focused on the surface of the glass samples for channel processing. The laser's angle of incidence to the sample surface was set at 90° to minimise reflections. The results of previous design of experiment models were used to set the range of the laser parameters [5].

From transverse sections of the samples, topology of the channels, width, and depth, were measured using a Zeiss Evo LS15 Scanning Electron Microscope (SEM) at 15 keV.

2.2 Design of experiments

The experiments were designed based on a three level Box–Behnken design with full replication [10]. Laser powers, P, (18, 21 and 24 W), pulse repetition frequencies, PRF, (160, 194 and 228 Hz) and scanning speeds, U, (300, 400 and 500 mm/min) were set as the laser independent input variables.

Response Surface Methodology was applied to the experimental data using statistical software, Design-expert V6. Linear and second order polynomials were fitted to the experimental data to obtain the regression equations. Adequacy measures of sequential *F*-test and lack-of-fit test and other adequacy measures were used . A step-wise regression method was used to fit a second order polynomial equation to the experimental data and to identify the relevant model terms [8,11]. The same statistical software was used to generate the statistical and response plots. The same processing parameters were

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applied to soda lime, borosilicate, quartz and fused silica glass samples.

Exp No	Run	P	PRF	U
1	1	18	160	400
2	2	24	160	400
3	9	18	228	400
4	14	24	228	400
5	12	18	194	300
6	7	24	194	300
7	4	18	194	500
8	15	24	194	500
9	13	21	160	300
10	3	21	228	300
11	11	21	160	500
12	16	21	228	500
13*	8	21	194	400
14*	6	21	194	400
15*	17	21	194	400
16*	10	21	194	400
17*	5	21	194	400

Table 1: Laser control parameters of the experiments; *repeated experiments

2.3 Optical transmission measurement

Optical transmission capability of fabricated channel was also measured by exposing channels to white light from a high power tungsten halogen light source. Transmitted light was collected by a 50 µm optical fibre and measured using Ocean optics Maya 2000 PRO spectrometer. Figure 1 explains the experimental set up. Sample channels from each glass type have been used to measure the transmission and compare it to non processed glass samples.

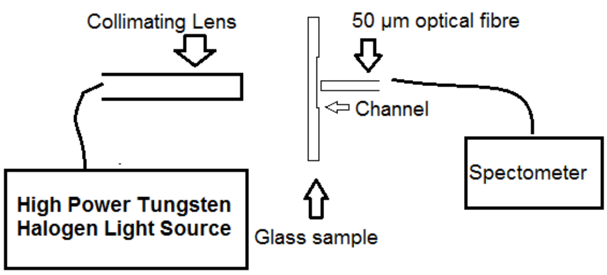

Figure 1: Transmission experimental set up

3 EXPERIMENTAL RESULTS

3.1 Channel topology results

The width and depth values of all fabricated channels were measured with Scanning Electron Microscope (SEM). Prior to imaging, samples were coated with 5 nm gold film to improve imaging. Table 2 shows the width the measurements with four types of glasses.

Exp No	Soda lime	Borosilicate	Quartz	Fused silica
1	307	243	229	199
2	323	258	301	276
3	250	205	214	239
4	261	201	288	181
5	278	223	198	161
6	280	221	291	173
7	295	240	179	239
8	281	239	267	181
9	228	216	307	142
10	276	233	250	182
11	312	235	281	250
12	270	209	224	189
13	313	250	250	301
14	270	238	275	191
15	293	233	250	219
16	245	202	261	197
17	278	227	247	174

Table 2: Channel width produced on four glasses

3.2 Statistical Analysis and Modelling

Choosing the step-wise regression method with two factors interaction (2FI) modelling method led to eliminating the insignificant model terms [9]. Equations 1 and 2 describe the process model mathematically within the investigated ranges of parameters that were generated from the above results for quartz width and depth, respectively.

$$\text{Width} = 116.30 + 13.62 \times \text{P} - 0.52 \times \text{PRF} - 0.11 \times \text{U} \quad (1)$$

$$\text{Depth} = 1061.75 + 21.17 \times \text{P} - 2.65 \times \text{PRF} - 1.030 \times \text{U} \quad (2)$$

Table 3 lists the adequacy tests for width and depth. It shows the calculated Analysis of Variance (ANOVA) results with the variance for the model and each of the parametric terms in the model. The table also shows the adequacy measures R^2, adjusted R^2 and predicted R^2. All the adequacy measures are close to 1, and in reasonable agreement indicating an adequate model [9].

Model	R^2	adjusted R^2	predicted R^2	Adeq. precision
Width	0.8136	0.7706	0.6367	13.962
Depth	0.7904	0.7420	0.7118	13.071

Table 3: ANOVA analysis of the mathematical model.

3.3 Transmission results

Figure 2 shows the results of spectral transmission substrate in the range of 350 to 1100 nm for a micro-channel fabricated on quartz.

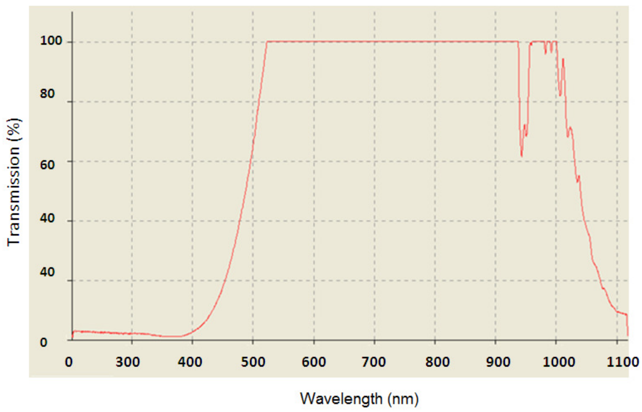

Figure 2: Optical transmission of quartz micro-channel

4 DISCUSSION OF RESULTS

4.1 Channel topology

Figure 3 (a) shows the actual response versus predicted response for the channel width, on quartz substrate. The relation between the actual and predicted responses is close to a 45º line on this equiaxed plot. Therefore, the model can adequately describe the response within the limits of the factors being investigated in this study. Figure 3 (b) shows the interaction effect among the parameters within the investigated range, where it can be seen that the power P has the strongest effect on the response, as it controls the laser beam intensity. Changing P from the minimum to maximum values increased the response by 47%. Changing PRF and U decreased the channel width by around 5%.

Figure 4 (a) as in figure 3 (a) shows that the model can adequately describe the response within the limits of the factors being investigated in this study. Figure 4 (b) shows the interaction effect among the parameters within the investigated range, where it can be seen that the P has the strongest effect on the depth of the channel, The effect of the laser parameters on the depth of the channel is similar to the effect of the same parameters on the width.

The results of the response surface methodology applied to the same experiments with soda lime, borosilicate and fused-silica glasses showed:

1. Quartz and fused silica samples have the smallest and most predictable channel size.
2. P has the strongest effect on the channel size, width and depth, for the four types of glasses. This effect is even stronger with soda lime and borosilicate glass.
3. With quartz and fused silica, the effect of PRF and U on the width of channel is very week. Channel width decreases slightly with the increase of PRF and U. While, the effect of PRF and U on the depth of channel is more considerable, around 30%. Channel depth decreases considerably with the increase of PRF and U.
4. Channels made on the quartz and fused silica substrates showed much smoother surface than the channels fabricated on soda lime and borosilicate.

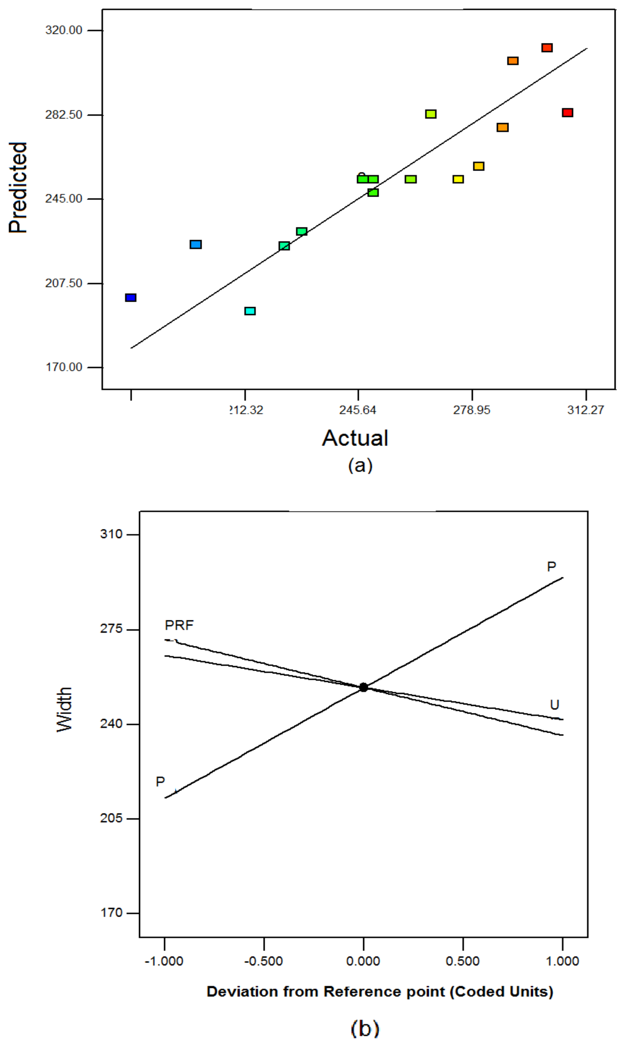

Figure 3: Quartz samples: (a) Data fit of the model, actual vs. predicted, (b) Interaction effect of the parameters.

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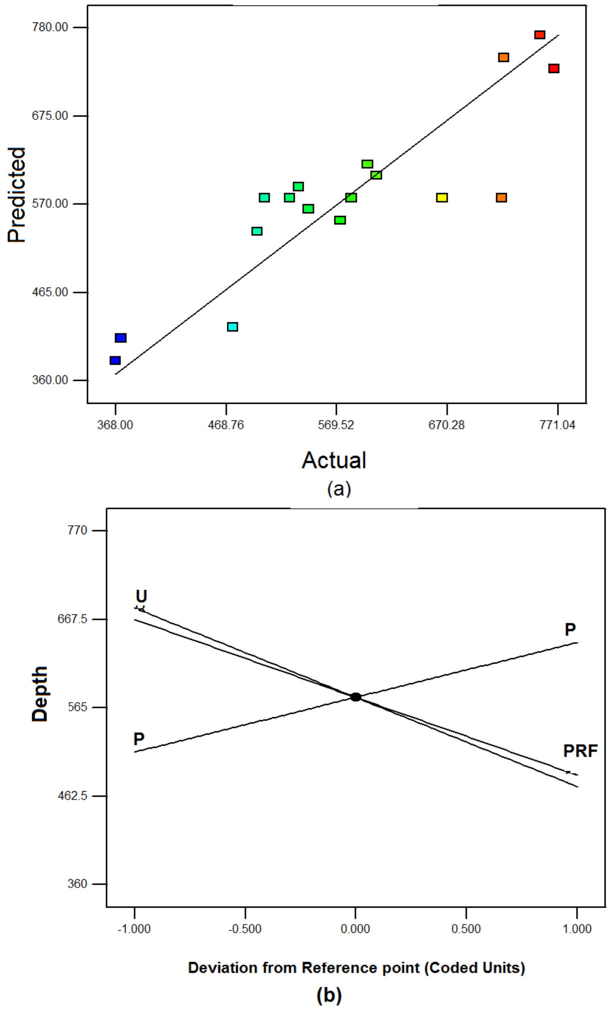

Figure 4: Quartz samples: (a) Data fit of the model, actual vs. predicted (b) parameter interaction effects.

4.2 Transmission experiments

. Spectral transmission graphs showed that all types of glasses presented 100% transmission from 520 to 950 nm. Around 950 nm, the transmission capabilities decreased below 65% for quartz and fused silica, bellow 60% for soda lime and around 85 % for borosilicate. The transmission increased again to 100% within a range of 950 nm to 1020 nm, at which the transmission decreased to 0%.

5 CONCLUSION

The average values R^2 of about 0.85 for quartz and fused silica combined with the satisfactory residual analysis indicate that the model is a good fit of the data and that the channel width and depth, within the investigated range of parameters, can be predicted.

Quartz and fused-silica samples presented more uniform channel topologies. This can be explained by a lower thermal expansion, which limits deformation and thermal cracks during laser processing [11]. Furthermore, light transmission measurements showed that these glasses preserve their optical capabilities within most of the UV and IR region after laser processing.

For future work, inspection of the channel surface roughness will be performed and modelled using the same procedure. Furthermore, a mathematical thermal model developed earlier for soda-lime laser processing [12] will be modified to calculate the theoretical temperature distribution in borosilicate, quartz and fused silica glass samples. Hence, estimations of the channel width, depth and surface roughness will be readily available. This data will be used to compare the experimental model to the theoretical thermal model.

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