

Laser-induced plasma and glass type effects on the process of micro-channel fabrication using CO₂ Laser

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1 INTRODUCTION

Laser energy absorption of materials depends highly on the wavelength. Glass materials absorb strongly at or near 10 μm making the CO₂ laser very efficient for machining these materials [1, 2]. The fabrication of micro-channels on the surface of transparent materials can be used for various applications in telecommunication, energy or biomedical engineering [3].

The surface breakdown mechanisms of laser ablation are dependent on many characteristics of both the laser and the material. In the infrared spectral region, the light absorption by glasses is increased due to the oscillating modes of the glass structure. The energy of the light heats, softens, melts and eventually evaporates the surface [4]. Plasma is formed at the target's surface and temperature can exceed 10⁴ K during the ablation [5].

In previous work pulse energy and scanning speed were considered as the main factors affecting the process [6]. Relatively few studies have been conducted using industrial CO₂ 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 [7].

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 17 mm in length were fabricated on the surface of the samples using a 1.5 kW pulsed mode CO₂ laser. The laser beam was focused co-incident with an air jet at 1 bar parallel onto the sample surface with a 90 μm spot size for channel processing. The results of previous design of experiment models were used to set the range of the laser

parameters [6]. From transverse sections of the samples, width and depth of the channels, were measured using an optical microscope (Beuhler Omnimet Enterprise).

2.2 Design of experiments

The experiments were designed based on a three level Box–Behnken design with full replication [8]. Laser power P, pulse repetition frequency PRF and scanning speed U, were set as the laser independent input variables. Response Surface Methodology was applied to the experimental data using statistical software, Design-Expert V8, for statistical analysis. First and second order polynomials were fitted to the data to obtain the regression equations. A step-wise regression method was used to fit a second order polynomial equation to the data and to identify the relevant model terms [7, 9]. The same processing parameters were applied to soda lime, borosilicate, quartz and fused silica glass samples [10].

| Variables | -1 | 0 | +1 |
|------------|-----|-----|-----|
| P [W] | 9 | 12 | 15 |
| PRF [Hz] | 160 | 194 | 228 |
| U [mm/min] | 300 | 400 | 500 |

Table 1: Experiment input variables

2.3 Optical transmission measurement

Optical transmission properties were measured by illuminating channels with light from a tungsten halogen calibrated light source, Ocean Optics LS-1-CAL. Transmitted light was collected by a 100 μm optical fibre and measured using Ocean Optics MayaPRO 2000 spectrometer. Sample channels from each glass type were used to measure the transmittance.

3 RESULTS AND DISCUSSION

3.1 Statistical analysis of the channel topology results

The step-wise regression method with two factors interaction (2FI) modelling method was used to develop mathematical model of the channel dimensions [8]. Equations 1 and 2 describe the process model mathematically within the investigated ranges of parameters that were generated from the above results for the channel width and depth in quartz, respectively.

$$\text{Width} = 274.23 - 8.22 \times P + 1.58 \times PRF - 1.26 \times U + 0.06 \times P \times PRF - 5.95 \times 10^{-3} \times PRF^2 + 1.56 \times 10^{-3} \times U^2 \quad (1)$$

$$\text{Depth} = 524.30 + 141.88 \times P - 5.94 \times PRF - 2.32 \times U - 0.15 \times P \times PRF - 0.08 \times P \times U - 1.63 \times P^2 + 0.02 \times PRF^2 \quad (2)$$

3.2 Channel topology

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

1. The mathematical models adequately described the responses within the limits of the factors investigated.

2. Quartz and fused silica samples had the smallest and most predictable channel size.
3. P had the largest effect on the channel size, width and depth, for the four types of glasses.
4. Channel widths decreased slightly with increased PRF or U.
5. Channel depths decreased significantly with increased PRF or U.
6. Channels made on soda lime and borosilicate presented a heat affected region where material melted but did not evaporate, (Fig. 1 c, d). This was attributed to the differences in thermal expansion coefficients, summarised in Table 2, for which lower values would result in a shorter distance over which the shockwave would travel in these substrates.

Table 2 Thermal expansion coefficients for the four glass types [11]

| | Quartz | Fused silica | Borosilicate | Soda lime |
|--|--------|--------------|--------------|-----------|
| Coefficient thermal expansion [$\mu\text{m}/\text{m } ^\circ\text{C}$] | 0.7 | 0.54 | 4.00 | 9.50 |

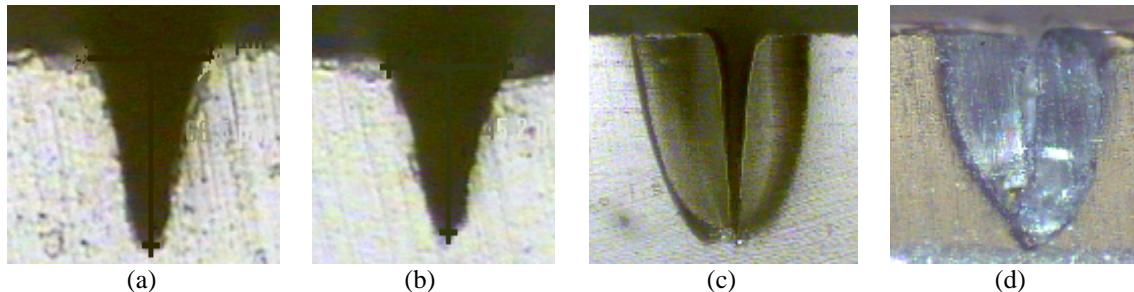


Fig. 1: Transverse images of the ablated channels in (a) quartz, (b) fused silica, (c) borosilicate, (d) soda lime.

3.3 Transmission experiments

Fig. 2 shows the results of transmittance through fabricated channel compared to non-processed glass substrate in the range of 380 to 1050 nm. Borosilicate samples transmittance dropped to 9%, fused silica and quartz to 5.5% and soda lime to almost 0%. The triangular shape of all channels (with slopes of $\sim 26^\circ$) promotes the divergence of incident lights from collecting fibre. Many channels, especially in fused silica and quartz, presented dark patches created by adhering burnt material to the glass surface [12]. Application of argon during laser processing should help eliminate this cause of reduction in transmittance values.

4 CONCLUSION

The developed mathematical models fitted well to the experimental data within the investigated range of parameters allowing widths and depths of processed channels to be predicted. Quartz and fused-silica samples presented more uniform channel topologies. Their lower thermal expansion coefficients limited deformation and formation of cracks during laser

processing in these materials. The light transmission measurements showed that the topology of channels resulting from the laser processing conditions had a great effect on the transmittance capabilities of processed channels. The possibilities of creating rectangular or circular shape channels will be investigated which should improve the transmittance of the channels.

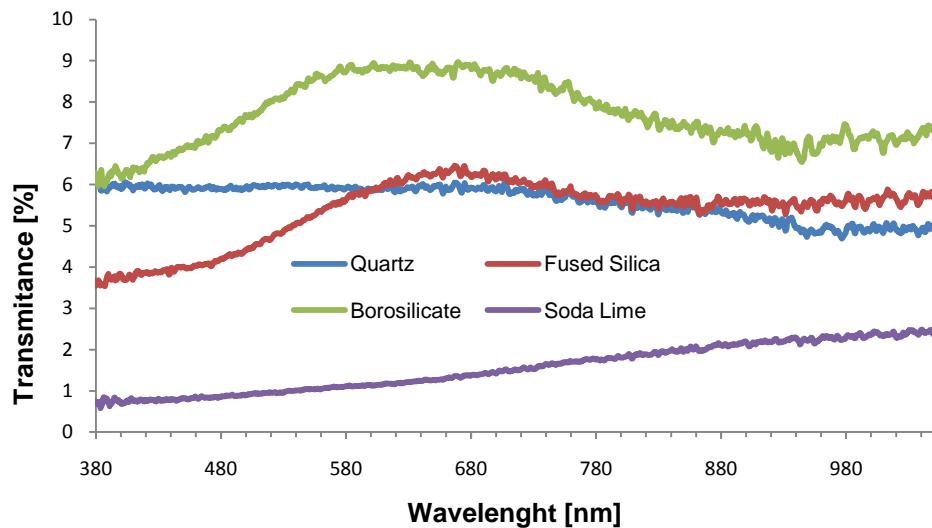


Fig. 2: Optical transmission results from glass micro-channel

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