NANOSECOND PULSED LASER PROCESSING OF TRANSPARENT POLYMER (PMMA).

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RESUMEN.

Se investigó el micro-maquinado de Polimetilmetacrilato (PMMA) utilizando un láser de estado sólido Nd:YAG nano pulsado con un tercer armónico el cual genera una longitud de onda UV (355 nm). El material PMMA fue seleccionado por ser bio-compatible y por su transparencia. Este trabajo se enfocó principalmente en dos parámetros de proceso: la intensidad de energía (energía/área) y la superposición de los pulsos. La intensidad fue modificada al incrementar el voltaje de la lámpara que excita el medio láser, la superposición de los pulsos fue modificada al cambiar la velocidad de avance de la mesa de trabajo. En este trabajo se obtuvieron los parámetros de proceso que produjeron un mejor acabado; el impacto de los parámetros mencionados sobre el producto final también fue investigado.

ABSTRACT.

PMMA processing using a nano-second pulsed solid state Nd:YAG laser using a third harmonic generator which achieves a UV wavelength (355 nm) was studied. PMMA polymer was selected due to its bio-compatibility and transparent properties of the material. The study was focused on two main process parameters: fluence and overlapping. Fluence was changed by raising the flash lamp drive voltage of the laser source and overlapping of the beam was changed by modifying the traverse speed. Best quality process parameters were obtained and the impact of the parameters upon the final product was also investigated.

INTRODUCTION

Laser processing has many applications in micro-manufacturing such as stents, MEMS and microfluidic systems, just to mention a few. Some of the advantages of laser processing are its high precision and its ability to focus high energies on a small area. Being a contact-free process, it avoids the possibility of contamination due to tool contact, coolant or lubricant fluids. This is very important when manufacturing components for medical devices.

Although nano-second laser interaction with transparent polymers is not the most adequate due to peripheral thermal damage and associated debris, IR nanosecond lasers remain more commonly available. Nd:YAG lasers are more commonly available and have the ability to process polymers more adequately when using their harmonics to obtain UV wavelengths. Therefore, it is important to investigate the different effects of UV wavelength nanosecond laser processing in transparent polymers.

Among the different applications that can take
advantage of laser processing, the fabrication of microfluidic devices is of particular interest. Microfluidics describes the use of analytical systems that are able to manipulate, process and control small quantities of fluids. These devices use components such as channels, electrodes, columns, reactors that handle volumes in the order of Pico-liters and Nano-liters. Its applications include: Lab-on-a-chip [1], DNA analysis [2], neration [4-8], bio-detection [3], spectrometry, fluorometry, among many others. The basic components of many microfluidic systems are micro-channels.

This work studies the effect of UV nanosecond laser processing parameters on the width and depth of micro-channels fabricated on PMMA.

EXPERIMENTAL SETUP AND METHODOLOGY

The experimental set up used in this work comprises:
- Vibration-free board
- Nd:YAG laser
  - Third harmonic
- Optical system
  - Beam expander
  - Mirror
  - Objective lens
- Workpiece
- CNC table (XYZ)

This experimental set up presented in figure 1

![Experimental setup diagram](image)

Figure 1 Experimental setup.

The laser source used is a Continuum Surelite I-10. It is a nanosecond Q-switched high energy solid-state Nd:YAG laser with a fundamental wavelength (λ) of 1064 nm, average power (P) of 4.85W at a pulse frequency (f) of 10 Hz, pulse duration (τ) of 5 – 7 ns and a laser beam diameter (Ø) of ≈ 6mm. Harmonic generating units were used to obtain a UV wavelength of 355 nm (third harmonic). The focusing objective used for this experiment provides a spot size diameter of 0.075 mm for this UV wavelength.

From previous experimental work, in which the laser power was measured with changing Q-switch delay time, it was found that a Q-switch delay of 180 µs provides the highest laser average power for this system. Thus, this delay time was used for the experiment.

Two main process parameters were investigated: Fluence and Overlapping. Fluence \( \Phi \) [J/cm\(^2\)] is calculated as:

\[
\Phi = \frac{\text{Pulse Energy}}{\text{Spot Size Area}}
\]

Fluence is affected by:
- Drive Voltage [kV]
- Q-switch delay [µs]
- Spot size diameter [mm]
  - Focusing objective
  - Z-level

In this experiment, the fluence was varied by modifying the flash lamp drive voltage of the laser.

The concept of overlapping [%] is shown in figure 2. It is a relation between the traverse speed, pulse frequency and spot size diameter. It is basically the percentage of the spot size distance between two pulses. It is calculated as:

\[
Ov = 100 \times \left(1 - \frac{\text{TrSpeed} / \text{PulseFreq}}{\text{Spot Size Diameter}}\right)
\]

![Overlapping diagram](image)

Figure 2 Schematic sketch which illustrates the concept of overlapping with a 190 µm spot size.

Overlapping is affected by:
- Traverse speed [mm/s]
- Pulse frequency [Hz]
- Spot size diameter [mm]
  - Focusing objective
  - Z-level

In this experiment, the overlapping was varied by modifying the traverse speed. Most of the variables affect fluence or overlapping as mentioned above. This is the main reason why
this work mentions these process parameters only.

From previous experimental work, Z-level was found optimum locating the focal point 50 micrometers above the surface. This value was used for the experiments of this work.

A screening experiment was performed in order to roughly find the process window. Then a more detailed experiment was executed. The variable process parameters for this experiment are shown in table 1.

Table 1 Variable Process Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluence [J/cm²]</td>
<td>475 (0.97)</td>
</tr>
<tr>
<td>(Drive Voltage [kV])</td>
<td>1131 (1.05)</td>
</tr>
<tr>
<td></td>
<td>1629 (1.10)</td>
</tr>
<tr>
<td>Overlapping %</td>
<td>87 (101)</td>
</tr>
<tr>
<td>(Scanning rate [pulses/mm])</td>
<td>91 (146)</td>
</tr>
<tr>
<td></td>
<td>95 (263)</td>
</tr>
</tbody>
</table>

Fixed parameters:
- Pulse frequency = 10 Hz
- Q-switch delay time = 180 µs
- Wavelength = 355 nm

An array of 9 channels was made, each channel had a change in one of the parameters; these variable parameters are mentioned above.

All channels were measured using a Gamma Scientific Inc. 700 – 10 measuring microscope with a 40x magnification and a numerical aperture of 0.30. Channel images were taken by using a Celestron LCD/Digital camera in that microscope. To obtain the channel profile image processing software (Image Pro Insight 8.0) was used; in order to calibrate the device a scale of one millimeter was utilized.

In order to access and measure the cross-section of the channels, they were sliced using face milling process. An incremental step of =100 µm was cut off the material; then, a photograph was taken and processed.

The measurement methodology is:
1. Images are taken from top of the sample
2. Samples are milled to obtain cross-section profile
3. Cross-section images are taken
4. Image of the scale is taken
5. Software is calibrated
6. Images of top and cross-section are processed
7. Channel features are measured

Material removal rates were calculated using the following equation

\[ MRR = \frac{A \times l}{t} \]

Where:
- \( A \) is the cross section area of the channel [mm²]
- \( l \) is the length of the channel [mm]
- \( t \) is the time needed to machine the length [min]

RESULTS AND DISCUSSION

As previously mentioned, a screening experiment was executed in order to perform an initial analysis of the influence of the parameters and to find the process window.

Figure 3 shows part of the screening for overlapping (top view). For a small overlapping the pulses are not close enough, and it causes the channels to have a very rough edge as seen in the image of the channel with 75% of overlap. As the overlapping is increased channels show a more straight edge, being 95% the best result. If the overlapping is excessive, the channel walls become rough as seen in the image of the channel machined with 98%.
Regarding the fluence, figure 4 shows the results of drive voltage (and thus, fluence) variation on the channel geometry, with a constant overlapping of 95%. It can be appreciated in the images how the channel dimensions increase as the fluence is raised. As the energy is increased, more material is removed.

Fluence impacts directly in the dimensions of the machined channels, which also reflects on MRR. As the fluence gets higher there is an increment in MRR.

As seen on Table 2, fluence is important: when raised, the channel width and depth also increase.

Table 2 Fluence vs. Overlapping vs. Width and Depth.

<table>
<thead>
<tr>
<th>Fluence Φ [J/cm²]</th>
<th>Overlapping Ω [%]</th>
<th>Width W [mm]</th>
<th>Depth D [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>419</td>
<td>87%</td>
<td>0.097</td>
<td>0.035</td>
</tr>
<tr>
<td>1146</td>
<td>87%</td>
<td>0.122</td>
<td>0.053</td>
</tr>
<tr>
<td>1543</td>
<td>87%</td>
<td>0.096</td>
<td>0.055</td>
</tr>
<tr>
<td>419</td>
<td>91%</td>
<td>0.094</td>
<td>0.042</td>
</tr>
<tr>
<td>1146</td>
<td>91%</td>
<td>0.129</td>
<td>0.051</td>
</tr>
<tr>
<td>1543</td>
<td>91%</td>
<td>0.148</td>
<td>0.063</td>
</tr>
<tr>
<td>419</td>
<td>95%</td>
<td>0.090</td>
<td>0.060</td>
</tr>
<tr>
<td>1146</td>
<td>95%</td>
<td>0.120</td>
<td>0.071</td>
</tr>
<tr>
<td>1543</td>
<td>95%</td>
<td>0.152</td>
<td>0.077</td>
</tr>
</tbody>
</table>

Overlapping is also important, when the value of overlapping is at 91% and 95% the process becomes a quasi linear relation between dimensions and overlapping. As it would be expected the Cross Section Area behaves similarly to the influence of these parameters: when overlapping and/or fluence increase, the area of the channels is affected.

Table 3 shows the analysis of only one channel and how the process varies due to the beam energy which is not constant, it shows how one pulse has larger energy thus the channel becomes wider and deeper. This ultimately affects the homogeneity of the channels.

Table 3 Channel measurements. (Red numbers are below the average and green numbers are above average).

<table>
<thead>
<tr>
<th>Measurement #</th>
<th>Width W [mm]</th>
<th>Depth D [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0931</td>
<td>0.063</td>
</tr>
<tr>
<td>2</td>
<td>0.0903</td>
<td>0.056</td>
</tr>
<tr>
<td>3</td>
<td>0.0903</td>
<td>0.045</td>
</tr>
<tr>
<td>4</td>
<td>0.0932</td>
<td>0.059</td>
</tr>
<tr>
<td>5</td>
<td>0.0924</td>
<td>0.066</td>
</tr>
<tr>
<td>6</td>
<td>0.0938</td>
<td>0.05</td>
</tr>
<tr>
<td>7</td>
<td>0.1007</td>
<td>0.054</td>
</tr>
</tbody>
</table>
Using MINITAB (Release 14.1) a statistical approach was taken. Figure 8 and figure 9 show a surface plot which has the standard deviation from the measurements taken and it is compared against the fluence and overlapping to see where the channel had less variation. A total of 10 measurements per channel were taken to obtain this data.

<table>
<thead>
<tr>
<th></th>
<th>Width</th>
<th>Overlapping</th>
<th>Fluence</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>0.0993</td>
<td>0.041</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>0.098</td>
<td>0.054</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0.1181</td>
<td>0.064</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>0.09692</td>
<td>0.0552</td>
<td></td>
</tr>
</tbody>
</table>

Also using MINITAB a main effects plot was obtained and can be appreciated in figure 10.

This figure shows how as fluence is set higher the width also rises. To some extent, when overlapping is increased, width also increases. However, between 91% and 95% of overlapping there is a very small variation (reduction) in width. This small change had no statistical significance. This is due to the variability of the process, since inside this range it has reached a value were, if the overlapping is varied, it will have no effect on the channel width.

A main effect plot for depth was also obtained and it is shown in figure 11.

In this case depth behaves differently and the lowest process variability value is found at 91% of overlap and a low value of 475 J/cm² fluence value.

In both cases the best values can be seen at a low fluence value; when more energy is applied the channel it tends to have a rougher finish.

Other researchers like Krüger et al. [12] investigated the effect of nanosecond pulsed laser with a 1064nm wavelength on bare and
doped PMMA. The result showed that bare PMMA machined with the nano-second pulsed laser had disruptions rather than an ablated surface.

It is noted that nano-second pulsed laser is not the most adequate to machine micro-channels in PMMA. Many researchers have instead opted for the use of femto-second pulsed laser to machine this polymer [10,12,14,15]. Other authors have used deep UV wavelength which have higher photon energy and chemical breakdown of the bonds increase [9,11,13,16].

CONCLUSIONS

Nanosecond pulsed laser micro-machining of PMMA polymer was achieved with an Nd:YAG laser using a third harmonic to obtain a UV (355 nm) wavelength.

The following conclusions can be made:

- Important machining parameters were found and can now be used for further channel fabrication.
- Process window was obtained.
- Best quality process values for machining micro-channels in PMMA polymer using a nano-second pulsed UV wavelength (355 nm) laser were obtained.
- Overlapping should be kept around 95% to reduce variability.
- Low fluence showed to be the best quality value.
- The process produces some thermal damage to the work-piece and debris on the surrounding area of the machined path.
- The variability of the process is high due to the difference of energy in the pulses and the re-solidification of the material.
- For industrial purposes a laser with higher frequency would be needed.

ACKNOWLEDGEMENTS

The authors would like to thank the Mexican Council of Science and Technology (CONACYT).

REFERENCES


