CO₂ Laser Micro-Engraving of PMMA Complemented By Taguchi and ANOVA Methods

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Abstract. Laser micromachining is used in the microfluidic application, especially in biomedical technology, the point of care diagnostics, and chemical analysis. In this research work, a micro-engraving was done on PMMA (Polymethylmethacrylate) using a CO₂ laser. Based on the Taguchi design of the experiment; 25 experiments were done to study the effect of laser parameters on the micro-engraving process. The effect of input parameters, laser power, engraving speed, and overlapping space has discussed on the micro-engraving characteristic, surface roughness, engraving depth, and overall time of the process. The results show different surface roughness ranged between 7 – 1.72 µm. Also, the depth results ranged between 20.4 – 5800 µm which could be used in many various applications. The ANOVA results showed that the engraving speed has a significant effect on surface roughness and engraving depth, but in engraving time, the laser power has a substantial impact at 94.06%.

1. Introduction

Laser machining was one of the most critical technology in recent years [1]. Also, the development of laser sources can be conducted through variable pulse duration, which reaches nanosecond and femtosecond [2]. These sources have been used in different applications like welding, drilling, cutting, marking, scribing, engraving, and other industrial, medical, and military uses [3]. Furthermore, there are numerous blessings of this method, no contact with the machined, high reliability, a less heat-affected area, high-velocity, flexibility, versatility, and easily automated and controlled with the computer, also the compact processing time and little price[4,5]. One of the most vital motives for laser machining technology development is its amazing machining accuracy, production of complicated forms, as well as, the machining of different materials like metallic, wood, polymeric, ceramic [6-10].

The laser engraving technique used in many fields and application such as marking industry, milling different material, mold making, deep engraving, marking on jewelry as well as, the microfluidic field gained considerable interest for their entry into many applications such as making Microchannel, micromixer, micropumps, microvalves and many other fields [11-13]. There are many kind of laser which used in industry for marking and engraving like Q-switched Nd: YAG laser, CO₂ laser, Excimer laser, semiconductor laser, and fiber laser [14]. The CO₂ is the most efficient and reasonable for
engraving on polymer. Polymer are not conduct for temperature and electricity. As well, the organic material has high absorption for 10µm wavelength [15].

Furthermore, the CO$_2$ laser was a useful technique for machining the Polymethylmethacrylate (PMMA) due to the proper absorption of PMMA to the laser beam [16]. Polymethylmethacrylate (PMMA) have been attracted significant attention over the past decade due to its wide range of applications which replaces the metal and wood by PMMA for its satisfactory properties and is produced at a lower cost [17]. This material was suitable for laser micro-engraving for its many applications and in addition to its features like absorption for CO$_2$ laser radiation about 92%, lower heat capacity, bad conductance to heat, and lower temperature degradation (350-380°C) [10,18].

Nowadays, the design and manufacture of micro parts are one of the significant challenges in the manufacturing sector because of a prominent demand for microproducts. Micro parts have gained its presence in various fields such as in optics, electronics, medicine, biomedical devices, communications, and avionics [19,20]. The micro-engraving on PMMA acquired a significant importance in the past decade for its broad application in microchannel based microfluidic devices used for biomedical and chemical analyses [19]. On account of carving or engraving polymer materials, particularly polymer-based life science items, for example, single-utilize medical gadgets or diagnostic consumables, controlling on depth, endpoint identification, and material kind are basic properties. When the laser beam is focused on a workpiece surface, interaction with thermal reaction occurs, and an amount of energy is sent to the workpiece from the laser beam. During this interaction, laser energy transforms into heat energy. The intensity of this heat energy increases with every pulse of the beam. Hence, the surface temperature is raised rapidly up to the melting and vaporization temperatures causing the material removed from the target area as a vapor. The heating and vaporization process occurs locally, and the absorbed energy does not affect the entire parts. The removal mechanism occurs layer-by-layer in the laser beam application area [21].

The surface roughness of micro-engraving is a critical rule for some microfluidics applications. Many earlier works were done in this field, S. Genna and et al. studied the influence of CO$_2$ laser parameter of the milling process parameters, surface roughness, depth and removed volume, for PMMA material. Their results show a suitable surface roughness in micron with depth in micron, which is used as a micro-mold for many medical and chemistry applications [18]. Shashi Prakash and Subrata Kumar investigated the effect of the multi-pass CO$_2$ laser beam on the PMMA sample for micro-channel production. Their methodology produces a low heat affected zone, high aspect ratio, micro-channel with smoother wells, and less tapering in micro-channel [8]. Ting-Fu Hong and et al. used a CO$_2$ laser for Rapid prototyping of PMMA microfluidic chips. This technique shows a smooth channel for the fabrication of two types of microfluidic chips a cytometer and an integrating microfluidic chip for methanol detection [22]. Much researches have been conducted to enhance the surface roughness and obtain depth in microns, such as the consideration made by Q. Wu and J. Wang [16]. The level of accuracy for the engraved shape depends on the ability of the laser to remove the layers from the material. In the laser engraving process, the material removal rate and the surface quality essentially depend on the material properties, laser source characteristics, and the process parameters [2]. Therefore, it has become essential to optimize the choice of process parameters like wavelength, scanning speed, power, and overlapping of the parallel line or step [1].

In this paper, the Taguchi methodology used for the design of the experiment and analysis of variance (ANOVA) was performed to find out the significant process parameters for PMMA micro-engraving. The laser parameter power, scanning speed, and line overlapping was used to investigate their effect on surface roughness and engraving depth.

2. Experimental set-up

The laser micromachining was performed using a CO$_2$ CNC machine (UK-SCIENTIFIC LTD) working in fundamental wavelength 10.6 µm in CW mode operation, the other detail of the device listed in the table 1. All machining was conducted at room temperature (25 oC). The highest power of this laser was 100 Watts and working in continuous mode. The device is controlled using a CAD
package (laser cut53) which derives stepper motors from moving the working stage according to the predefined laser machining path. The working stage was moving in x-y directions only for engraving (raster) and deep cutting (vector) modes. Figure 1 shows the schematic representation of the laser machine set up. The commercial PMMA utilized as workpiece material in sheet form with dimensions 6 mm ×180 mm×180 mm. This material was suitable for deep laser engraving for its many applications and in addition to its features like absorption for CO₂ laser radiation about 92%, lower heat capacity, bad conductance to heat, and lower temperature degradation (350-380 oC) [18]. When the laser beam hits the sheet surface, the PMMA sheet absorbs the entire beam, and the temperature of the material surface increases rapidly. In this temperature, vaporization occurs due to random breaking in the chain of material [18].

Table 1. The detailed characteristics of the laser system.

| Characteristics             | Value     | Unit  |
|-----------------------------|-----------|-------|
| Source type                 | Electrical discharge excitation | -     |
| Wavelength                  | 10.6      | µm    |
| Output power                | 1 – 100   | W     |
| Scanning speed              | 0 – 60    | m min⁻¹|
| Mine Power supply           | 110 – 240 | V     |
| Reposition accuracy         | ± 0.1     | mm    |
| Working delicacy            | 0.0254    | mm    |
| Maximum engraving range     | 900 * 600 | mm    |
| The focal length of the lens| 55        | mm    |

Figure 1. Schematic diagram of CO₂ laser micromachining process [23].

3. Input laser parameter and micromachining characteristic

The various process parameters were selected before designing the experiments depending on the literature review of laser engraving and cutting. Also, a lot of experimental trials for reducing any unwanted phenomena like the burning of the material surface, vaporization, carbonization. The various engraving parameters used in this work shown in table 2 and the response parameters are the surface roughness and depth of the engraving. The optical microscope shown in figure 2 has been used to measure the engraving depth and a portable roughness measurement instrument of type pocket surf® III Gage has been conducted to measure the surface roughness (Ra).
Table 2. Engraving factor and their value

| Engraving factor                  | Value                        |
|-----------------------------------|------------------------------|
| Laser power (W)                   | 20 – 30 – 40 – 50 – 60       |
| Scanning speed (mm min\(^{-1}\)) | 100 – 300 – 500 – 700 – 1000 |
| Line overlapping (mm)             | 0.01 – 0.03 – 0.05 – 0.1 – 0.2 |
| Spot size (µm)                    | 148                          |

Figure 2. A sample for measuring the engraving depth under an optical microscope with 5.5 µm power zoom.

4. Design of experiment

To investigate the effect of each parameter on the output properties, the Taguchi design of the experiment method has been applied using the L25 orthogonal array. For all the L25 orthogonal array experiment, a rectangle with 30*15 mm\(^2\) in size engraved, as shown in figure 3. The experimental design was created using Minitab Software. Details of L25 experiments and the values corresponding to the responses listed in table 3.

For estimating the effect of each factor on the surface roughness and engraving depth the means and signal to noise (S/N) plotted for all controlled parameters. The signal to noise ratio for surface roughness using the smaller is the better which calculated from the following equation [21,24-26]:

\[
\frac{S}{N} = -10 \log_{10} \left[ \frac{1}{n} \sum_{i=1}^{n} y_i^2 \right]
\]

where \(n\) is the number of experiments and \(y\) is the experiment value. As well as the signal to noise ratio of engraving depth was calculated using the larger is the better categories from the following equation [21,24-26]:

\[
\frac{S}{N} = -10 \log_{10} \left[ \frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i^2} \right]
\]

Table 3. Taguchi design of the experiment and the measured surface roughness, engraving depth, and time with the calculated S/N ratio.

| Exp. No. | Power (W) | Speed (mm min\(^{-1}\)) | Overlap (mm) | Surface roughness (µm) | Depth of engraving (µm) | Time (min) | Surface roughness (dB) | Depth of engraving (dB) | Time (dB) |
|----------|-----------|--------------------------|--------------|-------------------------|-------------------------|------------|------------------------|-------------------------|-----------|
| 1        | 20        | 100                      | 0.01         | 2.70                    | 3800                    | 199.82     | -8.63                  | -11.60                  | -41.01    |
| 2        | 20        | 300                      | 0.03         | 6.00                    | 1480                    | 22.72      | -13.36                 | -9.20                   | -43.05    |
| 3        | 20        | 500                      | 0.05         | 6.38                    | 317                     | 8.53       | -14.47                 | -7.46                   | -41.31    |
| 4        | 20        | 700                      | 0.1          | 2.99                    | 48.4                    | 3.65       | -13.66                 | -6.22                   | -40.06    |
| 5        | 20        | 1000                     | 0.2          | 3.37                    | 20.4                    | 1.52       | -13.20                 | -5.25                   | -39.09    |
|   | 30 | 100 | 0.03 | 2.84 | 5800 | 66.82 | -12.72 | -9.24 | -38.75 |
|---|----|-----|------|------|------|-------|--------|-------|--------|
| 7 | 30 | 300 | 0.05 | 5.73 | 1700 | 13.75 | -13.17 | -8.81 | -38.10 |
| 8 | 30 | 500 | 0.1  | 3.06 | 208  | 4.43  | -12.86 | -8.24 | -37.52 |
| 9 | 30 | 700 | 0.2  | 3.95 | 30.2 | 1.92  | -12.76 | -7.73 | -37.01 |
| 10| 30 | 1000| 0.01 | 1.96 | 85.6 | 26.78 | -12.40 | -7.27 | -36.62 |
| 11| 40 | 100 | 0.05 | 1.72 | 4600 | 40.22 | -12.01 | -8.31 | -36.36 |
| 12| 40 | 300 | 0.1  | 4.20 | 827  | 7.03  | -12.10 | -7.97 | -35.98 |
| 13| 40 | 500 | 0.2  | 4.41 | 193  | 2.38  | -12.16 | -7.62 | -35.64 |
| 14| 40 | 700 | 0.01 | 6.25 | 1232 | 35    | -12.57 | -7.39 | -35.43 |
| 15| 40 | 1000| 0.03 | 5.32 | 224  | 9.03  | -12.73 | -7.09 | -35.13 |
| 16| 50 | 100 | 0.1  | 4.50 | 3800 | 20.26 | -12.75 | -7.56 | -34.89 |
| 17| 50 | 300 | 0.2  | 4.81 | 185  | 3.70  | -12.81 | -7.30 | -34.63 |
| 18| 50 | 500 | 0.01 | 5.84 | 2950 | 41.45 | -12.99 | -7.44 | -34.53 |
| 19| 50 | 700 | 0.03 | 5.58 | 779  | 11.76 | -13.12 | -7.24 | -34.30 |
| 20| 50 | 1000| 0.05 | 3.26 | 0.119| 5.48  | -13.01 | -7.01 | -34.08 |
| 21| 60 | 100 | 0.2  | 7.00 | 1900 | 10.28 | -13.30 | -6.96 | -33.88 |
| 22| 60 | 300 | 0.01 | 4.22 | 4200 | 67.52 | -13.27 | -7.43 | -34.05 |
| 23| 60 | 500 | 0.03 | 5.84 | 1600 | 14.03 | -13.38 | -7.33 | -33.87 |
| 24| 60 | 700 | 0.05 | 4.96 | 479  | 7.13  | -13.41 | -7.15 | -33.69 |
| 25| 60 | 1000| 0.1  | 4.10 | 119  | 2.82  | -13.37 | -6.98 | -33.51 |
5. Results and discussion

5.1. The effect of process parameters on surface roughness

The measured value of surface roughness ranged between $7 - 1.72 \mu m$. Depending on the L25 design of the experiment, the S/N ratio effect plot of process parameters on the surface roughness shown in figures 4, 5, 6. From figure 4 it can be seen that the optimum parameters combination are (30 W, 100 mm/min and 0.1 mm), whereas, from figure 5 the speed is 1000 mm/min. This difference in speed levels in both figures leads to thought that the two levels can produce good surface finish. The smaller is the better equation has been used to calculate the S/N ratio value for surface roughness which listed in table 3. From the S/N ratio figure, it is clear that the surface roughness decreases with increasing the laser power more than 30W due to increase in the ablation process with increasing the laser power. Also, it noted that at low engraving speed, the surface roughness was high (100 – 500
mm/min) because of the melting process leading to bulges formation which increases the roughness. However, at high speed from 600-1000 mm/min, the surface roughness was decreased due to decreasing in laser-matter interaction time, and the ablation process was dominant. Also, at high scanning speed, the material surface does not have time for cooling and bulges formation. The overlapping space effect on surface roughness is fluctuating because of its dependence on laser power and engraving speed.

Figure 4. the effect plot between the S/N ratio of surface roughness and laser power.

Figure 5. the effect plot between the S/N ratio of surface roughness and engraving speed.

Figure 6. the effect plot between the S/N ratio of surface roughness and overlapping space.

5.2. The effect of process parameter on the micro-engraving depth

The measured value of engraving depth ranged between 20.4 – 5800 µm. Depending on the L25 design of the experiment, the S/N ratio effect plot of process parameter on the engraving depth shown in figures 7,8,9. From the two figures, the optimum micro-engraving depth produced by the parameters combination (60W, 100 mm/min and 0.01 mm). The smaller is the better equation has been used to calculate the S/N ratio values for surface roughness which listed in table 3. From the S/N ratio figures, it is clear that the engraving depth increase with increasing the laser power due to increases in material ablation. Also, the engraving speed and overlapping space show the same relationship where the engraving depth decreases with increasing the engraving speed because of the rapid decrease in the ablated material from the material surface. As well as, the increase the overlapping space between the scanning beam reduce the ablated material from the surface which reduces the engraving depth.
5.3. The process parameter and time consumption

Depending on the L25 design of the experiment, the S/N ratio effect plot of process parameters on the time consumption shown in figures 10, 11, 12. From the S/N ratio figure, it is shown that the power, the engraving speed and the overlapping that gives less machining time are \(60\, \text{W}, 100\, \text{mm/min}\) and \(0.01\, \text{mm}\), respectively. Whereas, the main effect shows the optimum power level is \(50\, \text{W}\). It should be mentioned; the higher power can be applied with faster speed to produce the same engraving depth that generated using the lower power. This will reduce the lesser time required to generate this engraving depth as shown in figure 8, i.e. the time decreases with increasing the speed. Also, the overlapping space increasing, reduces the time needed for engraving due to diminishing the traveling length of the machine and it depends on the power and engraving speed settings to have the necessary depth. So that for obtaining the best micro-engraving and in lower time a higher power with fast speed and suitable overlapping space for good surface roughness must be chosen.
6. Analysis of variance (ANOVA)

The ANOVA is used to investigate the effect of each parameter on the quality characteristic and to explain which machining parameters have a statistically significant effect on the surface roughness, engraving depth, and engraving time. This effect is evaluated with percentage contribution and calculated from the total sum of the squared deviation of S/N ratios. The parameter which has a higher percentage contribution is recognized in the analysis. Besides, the F-test was conducted to estimate the critical parameter affecting the response. The higher F-value has a considerable effect on performance characteristics [27]. The ANOVA analysis consists of the degree of freedom (DOF), the sequential sum of squares (SS), the adjusted sum of squares, and the adjusted mean squares (MS), F value, and P-value. The last column of the table shows the percentage value of each parameter contribution which indicates the degree of influence on the process performance [21].

Tables 4, 5, and 6 show the results of the ANOVA for S/N ratios of the surface roughness, engraving depth, and engraving time, respectively. Also, the percentage contributions of process parameters on response criteria plotted, as shown in figure 10. Based on the results of ANOVA for Ra, the parameters, surface roughness, engraving depth and engraving time all are significant, but the engraving speed has the most potent effect on the Ra. The same effect appeared for engraving depth. The result of engraving time shows that the power has the most substantial impact and the other parameter has so much little effect.

Table 4. Analysis of variance (ANOVA) test for surface roughness, Ra.
Table 5. Analysis of variance (ANOVA) test for micro depth.

| Factor               | DOF | SS   | MS   | F    | P    | Contribution effect % |
|----------------------|-----|------|------|------|------|-----------------------|
| Laser power          | 4   | 4.00 | 1.00 | 0.68 | 0.611| 18.4                  |
| Engraving speed      | 4   | 12.67| 3.17 | 3.08 | 0.039| 58.39                 |
| Overlapping space    | 4   | 5.03 | 1.26 | 0.89 | 0.486| 23.18                 |
| Total                | 24  | 21.7 |      |      |      | 99.97                 |
| Error                | 20  | 25.98|      |      |      |                       |

Table 6. Analysis of variance (ANOVA) test for engraving time.

| Factor               | DOF | SS   | MS   | F    | P    | Contribution effect % |
|----------------------|-----|------|------|------|------|-----------------------|
| Laser power          | 4   | 162.9| 40.725| 61.83| 0.00 | 94.06                 |
| Engraving speed      | 4   | 7.48 | 1.48 | 0.22 | 0.923| 4.32                  |
| Overlapping space    | 4   | 2.81 | 0.70 | 0.08 | 0.987| 1.6                   |
| Total                | 24  | 173.19|      |      |      | 99.98                 |
| Error                | 20  | 118.3|      |      |      |                       |

Figure 13: Percentage contributions of process parameters on response criteria.

7. Conclusion

This work showed an experimental investigation for laser engraving of PMMA material using a CO2 laser CNC machine to estimate the effect of the process parameters, such as laser power, engraving speed, and overlapping space. Besides, an optimization of the best combination of those parameters has been conducted. The main determination of this work are:

- The applied Taguchi optimization method succeeded to achieve a smooth surface for microfluidic applications with less time.
The optimum process parameters that produce the minimum surface roughness are (30W, 100 or 1000 mm/min and 0.1 mm) for the laser power, the engraving speed, and overlap space. The optimum parameters that provide optimum micro-engraving are (60W, 100 mm/min and 0.01 mm) for the power, speed, and the overlap. The less time can be achieved from the process factor combinations (50 or 60 W, 100 mm/min and 0.01 mm) for the laser power, laser speed, and the overlap. It was found that the minimum micro depth and less surface roughness were on experiment number 10 which have 1.955 µm roughness and 85.6 µm depth using 30 W laser power, 1000 mm/min engraving speed, and 0.01 overlapping spaces. Experiment number 5 has the smallest depth of 20.4 µm at the lowest time 1.52 min with 3.37 µm roughness.

The current research optimizing of the laser engraving process is expected to open up recommendations that may be advised to carry on this work. The first, investigating more parameters, such as the laser type effects and the engrave complex geometry. The second recommendation is applying other methods of optimization, such as neural network, Fuzzy logic, and genetic algorithm. The multi-objective optimization can be applied to estimate the optimum machining conditions for all the responses.

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