Dimensions and cost prediction modelling of $Nd:YVO_4$ laser internal micro-channel fabrication in PMMA

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ABSTRACT

This paper presents the employment of Design of Experiments (DoE) as the prediction tool for the laser micro-machining process. Laser internal micro-channels machined using pulsed $Nd:YVO_4$ laser in PMMA were studied. The experiments were carried out according to 3^3 factorial Design of Experiment (DoE). In this paper the input process control parameters were laser power, P; pulse repetition frequency, PRF; and sample translation speed, U. The channel width and the micro-machining operating cost per metre of produced micro-channels were the measured responses. The responses were adequately predicted within the considered micro-machining parameters limits. For both responses, quadratic polynomial regression equations were constructed. The developed regression equations can be utilised to find optimal micro-machining process parameters within the studied process limits under experimental and operational conditions.

Keywords: response surface methodology (RSM), design of experiments (DoE), $Nd:YVO_4$ laser, mathematical models, PMMA.

1 INTRODUCTION

Laser micro-machining is a materials-processing technique that utilise lasers to cause managed thermal alterations to provide required micro-scale geometrical shape and dimensional ablations. In spite of the fact that laser micro-machining is a technically complex manufacturing process, research work has made the production of accurate, regular, and defect-free parts possible at high rate [1-3]. Laser micro-machining is employed in many micro-machining applications in the domains of telecommunications, glass cutting, micro-sensors [4-6]; micro-via, ink jet printer nozzles, biomedical catheter drilling, thin-film scribing [7]; micro-fluidic channels for blood/protein analysis [8]; optical vibration sensors [9]; three-dimensional binary data storage [10]; and novelty fabrications [11].

To get a set of laser operating parameters that provides the favoured micro-channel dimensions for a specific application under certain processing restrictions, predictive structures can be used. Various statistical and numerical methodologies have been implemented to predict and optimise several laser manufacturing processes including design of experiments, genetic algorithms, finite elements analysis, Artificial Neural Networks (ANN), ant colony optimisation, and fuzzy logic [3, 12-13].

Design of Experiments (DoE) models were constructed, utilised and analysed for significance in this work. These models describe the relationship between the input laser processing parameters and the output responses of dimensions and process cost. These models may be utilised to select the input parameters for required output dimensions and to estimate process cost in advance of contracted work commencement.

2 EXPERIMENTAL SET-UP

2.1 Experimental work

The $Nd:YVO_4$ laser system was used for micro-machining in this work. This laser has a 2 W maximum power and 1064 nm wavelength. Polymethyl methacrylate (PMMA) sheets of 10 mm thickness were used as sample material to create the micro-channels in. The distance between each two micro-channels was set to be 2 mm to facilitate the measurement of the micro-channels' widths which done using a Leica optical microscope. OMNIMET image analysis software was used for dimensional measurements. The PMMA sample was positioned at the beginning of each experiment such that the laser micro-machining process to be started with the laser spot on the back surface of the PMMA sheet. The PMMA sheet work piece was set on the 3D positioning stage and then moved away from the laser source, thus creating the micro-channel from the back to the front of the sample.

2.2 Experimental design

In order to determine the relationship between the main laser process parameters of the $Nd:YVO_4$ laser and the machining process cost and the width of corresponding developed micro-channel, a series of experiments using DoE were designed. After initial screening experiments, a factorial design of experiments was carried out using Design-Expert, V7, software. The three process parameters analysed in this work were P, PRF and U. Each of these were analysed at three levels in the form of a 3^3 factorial design of experiments. The low, middle and high levels were chosen for P, PRF and U. The high level is represented by 1, the middle by 0 and the low level by -1.

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Table 1shows laser input parameters and the actual and coded experimental design levels used.

Variables	Actual			Coded		
	Low	Mid	High	Low	Mid	High
P (W)	0.5	1.0	1.5	-1	0	1
PRF (kHz)	13	23	33	-1	0	1
U (mm/sec)	0.50	1.74	2.98	-1	0	1

Table 1: Control parameters design levels.

There are 27 possible combinations of the three process parameters at the three levels. For variability analysis, five additional experiments were duplicated at the middle point of the considered ranges, such that the conducted experiments' total number of was 32 (=3^3+5). Table 2 shows a list of these 32 combinations of the laser control parameters that were used in the conducted experiments.

Exp. No.	Run No.	P	PRF	U	Exp. No.	Run No.	P	PRF	U
1	**23**	0.5	13	0.5	**17**	**1**	1	33	1.74
2	**15**	1	13	0.5	**18**	**16**	1.5	33	1.74
3	**11**	1.5	13	0.5	**19**	**4**	0.5	13	2.98
4	**20**	0.5	23	0.5	**20**	**9**	1	13	2.98
5	**14**	1	23	0.5	**21**	**8**	1.5	13	2.98
6	**32**	1.5	23	0.5	**22**	**7**	0.5	23	2.98
7	**2**	0.5	33	0.5	**23**	**21**	1	23	2.98
8	**17**	1	33	0.5	**24**	**12**	1.5	23	2.98
9	**28**	1.5	33	0.5	**25**	**27**	0.5	33	2.98
10	**24**	0.5	13	1.74	**26**	**10**	1	33	2.98
11	**22**	1	13	1.74	**27**	**26**	1.5	33	2.98
12	**30**	1.5	13	1.74	**28**	**6**	1	23	1.74
13	**3**	0.5	23	1.74	**29**	**31**	1	23	1.74
14	**18**	1	23	1.74	**30**	**13**	1	23	1.74
15	**5**	1.5	23	1.74	**31**	**25**	1	23	1.74
16	**29**	0.5	33	1.74	**32**	**19**	1	23	1.74

Table 2: List of the performed experiments.

2.3 Micro-machining cost calculation

Laser of micro-machining processing cost can be approximately estimated as micro-machining per time for a specific laser micro-machining operation or cost per length. Unplanned maintenance and breakdown have not been taken into consideration while calculating the processing cost. The labour cost was not considered since the Nd:YVO_4 laser was for experimental purposes however, it should be considered when dealing with operational system.

Assuming that electrical consumption of the laser power supply is linearly proportional to the laser power emitted by the laser head, the total approximated operating cost per hour as a function of the output power can be expressed by 1.4723 + 0.064×P. Table 3 shows a breakdown of estimated micro-machining cost per hour. The total approximated operating cost per unit length (in €/m) is given by the following Equation (1), assuming 85% utilisation.

Micro-machining cost [€/m] =

$$\frac{1.4723+0.064\times \mathrm{P}\ \frac{€}{\mathrm{hr}}}{(0.85)\times U\left[\frac{mm}{sec}\right]\left[3600\,\frac{sec}{\mathrm{hr}}\right]\left[\frac{m}{1000\,mm}\right]} = \frac{(0.481+0.021\ \mathrm{P})}{\mathrm{U}} \qquad (1)$$

Element of cost	Calculations	Cost €/hr
Laser power supply	(800 W) (€0.16/kW hr) (P/2) / 1000	0.064×P
DELL PC Optiplex 170L & monitor	(140 W)(€0.16/kW hr) / 1000	0.0224
CompactRIO - control power	(8.2 W) (€0.16/kW hr) / 1000	0.0013
D-link network switch	(4.5 W) (€0.16/kW hr) / 1000	0.0007
BWD MiniLab - motion power	(43 W) (€0.16/kW hr) / 1000	0.0069
Diode replacement	(€ 11,410 / 10000 hr)	1.141
Maintenance labour	(12 hr/2000 hr operation) (€ 50/hr)	0.3
	Total estimated micro-machining cost per hour	1.4723 + 0.064×P

Table 3: Breakdown of estimated micro-machining cost per hour.

3 RESULTS AND DISCUSSION

3.1 Experimental results

The width values of the all the developed micro-channels were measured. An optical microscope with a high numerical aperture was used to get the measurement data with a high level of accuracy. This method was repeated for three different locations along the micro-channel and the average value was calculated for each micro-channel. Table 4 shows the actual versus predicted value of the performed experiments.

3.2 Analysis of variance (ANOVA)

Analysis of variance (ANOVA) for the two models was carried out using Design-Expert software in order to test the significance of the regression models.

Exp. No.	Width (μm)		Cost (€/m)	
	Actual	Predicted	Actual	Predicted
1	60.3	69.1	0.991	0.993
2	79.8	77.5	1.012	1.012
3	62.8	85.9	1.033	1.031
4	103.4	106.2	0.991	0.993
5	125.9	114.6	1.012	1.012
6	142.2	123.0	1.033	1.031
7	135.5	143.3	0.991	0.993
8	155.1	151.7	1.012	1.012
9	166.5	160.1	1.033	1.031
10	74.0	65.8	0.283	0.279
11	92.6	74.2	0.289	0.289
12	99.5	82.6	0.295	0.299
13	86.5	71.7	0.283	0.279
14	73.9	80.1	0.289	0.289
15	67.7	88.5	0.295	0.299
16	65.8	77.5	0.283	0.279
17	80.2	85.9	0.289	0.289
18	92.1	94.3	0.295	0.299
19	75.8	86.2	0.165	0.167
20	87.9	94.6	0.169	0.169
21	109.7	103.0	0.172	0.170
22	57.7	60.8	0.165	0.167
23	71.5	69.2	0.169	0.169
24	67.7	77.6	0.172	0.170
25	45.1	35.3	0.165	0.167
26	60.2	43.7	0.169	0.169
27	47.0	52.2	0.172	0.170
28	87.1	80.1	0.289	0.289
29	68.9	80.1	0.289	0.289
30	89.0	80.1	0.289	0.289
31	69.6	80.1	0.289	0.289
32	74.2	80.1	0.289	0.289

Table 4: Experimental measured and calculated responses vs predicted from the width and cost models.

The step-wise regression method was chosen for eliminating the insignificant model terms automatically. The ANOVA for the two models summarises the analysis of each response in terms of sequential F-test, lack of fit test and show the significant model terms. The results of ANOVA for the width and cost models showed that quadratic regression models adequately described and modelled the laser micro-machining process in PMMA. Other adequacy tests including R^2, adjusted R^2 and predicted R^2 were all quite close to 1 and indicate significant relationships. The adequate precision ratios, being above four, in both models indicate adequate models discrimination. Table 5 lists the adequacy tests for width and cost models

Model	R^2	Adjusted R^2	Predicted R^2	Adeq. precision
width	0.861	0.834	0.782	23.584
cost	0.999	0.999	0.999	904.922

Table 5: Adequacy measures for the two developed models.

3.3 Development of experiential and mathematical models

Developing an experiential model is crucial for understanding the laser micro-machining process performance and its behaviour and for optimising the process itself. The mathematical models for micro-channels' width and micro-machining cost in terms of actual factors as established by the Design-Expert software are shown below:

$$\text{Width} = 4.023 + 16.811 \times P + 4.973 \times PRF + 12.947 \times U - 2.522 \times PRF \times U + 7.685 \times U^2 \quad (2)$$

$$\text{Cost} = 1.429 + 0.045 \times P - 1.008 \times U - 0.0142 \times P \times U + 0.196 \times U^2 \quad (3)$$

While the following final mathematical models are in terms of coded factors:

$$\text{Width} = 80.07 + 8.41 \times P + 5.85 \times PRF - 22.72 \times U - 31.27 \times PRF \times U + 11.82 \times U^2 \quad (4)$$

$$\text{Cost} = 0.29 + 0.010 \times P - 0.42 \times U - 0.008 \times P \times U + 0.30 \times U^2 \quad (5)$$

3.4 Interaction effects of control parameters on the responses

Figure 1 (a) shows the interactive effect on the micro-channels' width between translation speed, U, and pulse repetition frequency, PRF with P = 1 W. This graph shows that increased pulse repetition frequency at high level of speed decreased the width, whereas the opposite trend is noticed at the low level of sample translation speed. Moreover it shows that increased speed at high level of pulse repetition frequency decreased the width, whereas the opposite trend, to a lesser degree, was noted at the low level of pulse repetition frequency. Figure 1 (b) shows the interactive effect on the micro-machining cost between laser power, P, and translation speed, U where PRF was 23 kHz. This graph demonstrates that the micro-machining cost was significantly decreased by increasing the sample translation speed and insignificantly increased by increasing the laser power. PFR also had no significant effect on micro-channel production cost.

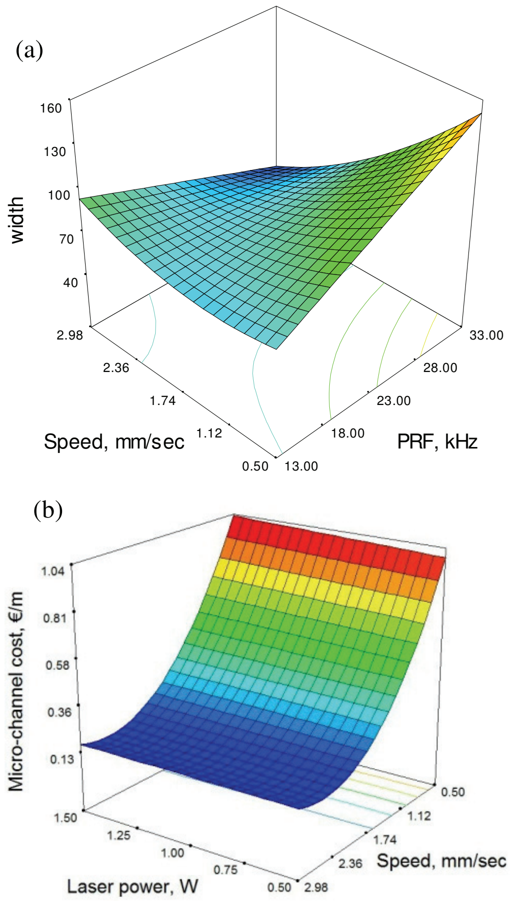

Figure 1: Interactive effect (a) on width value for U and PRF with P = 1 W and (b) on micro-machining cost for P and U with PRF = 23 kHz.

4 CONCLUSION

From this work several deductions can be made about the micro-channel production process with the limit of the process parameters investigated.

1. A 3^3 factorial Design of Experiments (DoE) can be employed as a prediction tool for the laser micro-machining process by creating mathematical and experiential models that can be utilised for optimisation. The developed models using Response Surface Methodology (RSM) are effective estimation tools for the selection of laser micro-machining parameters
2. Micro-channels of preset diameter and minimum cost can be processed by using the constructed models to predict the micro-machining input process parameters.
3. With a power of 1 W, interesting interactive effects between pulse repetition frequency and speed were noticed. The effect of the PRF parameter on the width is significantly different when the speed parameter is changed from the lower level to the higher level and vice versa.
4. Micro-machining cost is inversely proportional to the sample translation speed which has a key role in determining the operating cost. Laser power and pulse repetition frequency on the other hand have insignificant effect on the process cost.

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