Investigation on Depth of the Micro-Channels generated by Underwater Laser Transmission Micro-Machining

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Abstract

Laser beam micro-machining is a widely used non-contact type of advanced machining process which has an immense potential to fabricate micro-fluidic devices like lab on a chip, micro-electro mechanical system (MEMS), ink jet printer, instruments for various biomedical applications, electrophoresis, blood protein analysis, chromatography, DNA analysis etc. In the present study, an attempt has been made to fabricate micro-channels on a thick Poly methyl methacrylate (PMMA) plate having 11.328 mm thickness and partially submerged in water by utilizing laser transmission micro-machining technology. Pulsed Nd: YAG laser has been employed here to carry out the experiments. The effects of various process parameters, such as laser power, pulse frequency, pulse width, cutting speed on the micro-channel depth has been studied and discussed subsequently. Finally, optimization of the aforesaid process parameters has been performed in order to achieve maximum dimension of the micro-channel depth for utilizing in various micro-fluidic applications.

Keywords: Micro-channel, Nd: YAG laser, underwater laser transmission, micro-channel depth.

1. INTRODUCTION

Laser beam micro machining is one of the most widely used thermal energy process which employed in the micro-machining applications owing to its clean machining nature along with the ability to machine different complex shapes in a wide variety of engineering materials, i.e., polymers, metals, ceramics, semiconductors etc. [1]. In various polymers, Polymethyl methacrylate (PMMA) has been vastly used for micro-fluidic applications in biological and chemical synthesis due to its excellent optical properties, high chemical resistance and good mechanical strength. Micro-channels on PMMA for micro-fluidic devices are emerged as a suitable alternative to glass, silica etc., due to its biocompatibility, light in weight, low cost and ease of availability [2]. Micro-channels on PMMA generally produce by laser beam micro-machining due to its high transmitting coefficient at the large spectrum of wavelengths from near-infrared to ultraviolet region. Nd:YAG laser with 1064nm wavelength in NIR region have some adverse effect during micro-channeling of PMMA, such as large heat affected (HAZ) zone, sub surface micro crack formation, bulging along the kerf and debris redeposition, due to photo thermal ablation [3]. These aforesaid undesired machining characteristics may be reduced by laser transmission cutting at fully/partially submerged condition [4]. During laser transmission cutting operation an absorbent is added at the bottom surface of the thick PMMA plate where laser beam is focused and that absorbs the laser energy. The absorbed thermal energy heated up the bottom surface of the thick plate by conduction and transmission of this thermal energy. This way the laser transmission cutting has performed. Whereas a very few literature have been documented on laser beam micro-channeling of thick PMMA plate.

The main aim of this study is to perform NIR Nd:YAG laser transmission micro-channeling on thick transparent PMMA plate at partially submerged condition. Laser working power, pulse frequency, pulse width and cutting speed are taken as process variables whereas depth has been chosen as machining response. Here central composite design technique of response surface methodology has been used to perform the micro-channeling operation. Developed regression model is further used to carry out ANOVA analysis and single objective optimization procedure to get desired machining characteristics.

2. EXPERIMENTAL DETAILS

To perform the laser micro-channeling operation, the CNC controlled pulsed Nd: YAG laser machine (model no. SLT-SP-2000) manufactured by M/s Sahajanand Laser Technology, India has been used. Transparent Polymethyl methacrylate (PMMA) plate with the dimension of 55 mm × 65 mm ×11.328 mm has been selected as workpiece material. The thickness of the PMMA plate has measured at different sections throughout the workpiece using a digital vernier calliper, having a resolution of 0.001 mm. The properties of work material are given in Table 1.

Table 1
Mechanical and Thermal Properties of PMMA [1]

Work material	Strength (MPa)		Density (g/cm^3)	T_{mp}(°C)
	Yield	Ultimate		
PMMA	53.8–73.1	48.3–72.4	1.19	160

Here black cellotape of 0.04 mm has chosen as an absorbent material which is affixed at the bottom surface of the PMMA plate. A hand press is used here for proper affixation of the cellotape. This cellotape coated sample is kept in a specially designed workpiece holding unit to carry out laser transmission micro-channeling at partially submerged condition. Schematic diagram of workpiece holding unit is given in Figure1.

Workpiece is partially submerged in 6 mm height of water column. Height of the water column is measured from the height of the sleeve gauge and kept constant throughout the experiments by pouring the water externally. The parametric ranges have chosen based on the extensive trial experiments one factor at a time approach which is listed in Table2. Numbers of pass have kept constant at one during the present set of experimentations. Schematic diagram of laser transmission machining is given in Figure 2.

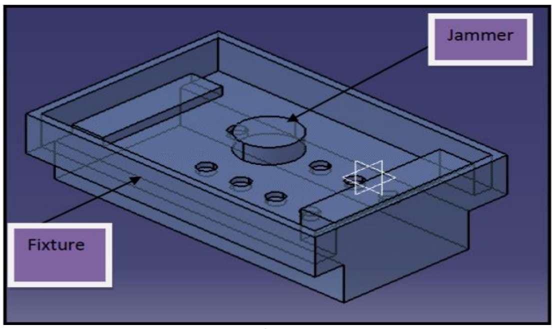

Fig 1: Workpiece holding unit for underwater laser transmission machining [7]

Table 2: Range for Input Parameters of Laser Beam Transmission Micro-Channeling

Process Parameters & Symbol	Working Ranges				
Working Power (watt) (A)	9	9.5	10	10.5	11
Pulse frequency (kHz) (B)	25	30	35	40	45
Pulse width (%) (C)	90	92	94	96	98
Cutting speed (mm/sec) (D)	1	1.25	1.5	1.75	2

Images of the machining response have been taken by Olympus-STM-6, optical microscope at 20X magnification. Depth for all the experiments has been measured at three different locations along the micro-channel.

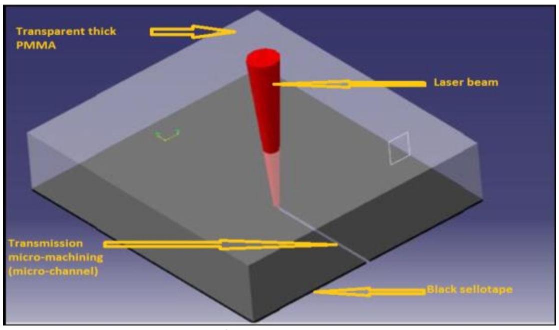

Fig 2: Schematic diagram of laser transmission micro-machining of transparent PMMA coated with black sellotape

3. EXPERIMENTAL RESULT AND DISCUSSION

A response optimizer tool of MINITAB software version 17 is used for optimization. Experimental results in terms of depth of kerf are listed in Table 3.

3.1 Analysis of variance for Depth

The developed second-order polynomial model is presented below

$$\mathbf{Y_{CD}} = -3438 + 748.8\ A + 43.62\ B - 38.0\ C + 1218\ D - 46.80\ A*A - 0.5370\ B*B + 0.136\ C*C - 13.16\ D*D - 0.147\ A*B + 2.548\ A*C - 28.45\ A*D - 0.0398\ B*C - 0.354\ B*D - 9.70\ C*D \ldots\ldots\ldots\ldots\ldots\text{(i)}$$

From the Table 4, it is observed that, the p-values of the different process parameters, square effect of parameters and interaction between parameters are much less than 0.05 whereas for the lack-of-fit, it is 0.655 which is desirable and indicates at the statistical significance of the developed polynomial model..

Table 3: Process Parameters and their Response

S. No.	Process Parameters				Response
	Working power (watt)	Pulse frequency (kHz)	Pulse width (%)	Cutting Speed (mm/sec)	DEPTH (μm)
1	9.5	30	92	1.25	45.37
2	10.5	30	92	1.25	53.20
3	9.5	40	92	1.25	54.73
4	10.5	40	92	1.25	58.80
5	9.5	30	96	1.25	41.57
6	10.5	30	96	1.25	60.60
7	9.5	40	96	1.25	46.73
8	10.5	40	96	1.25	59.17
9	9.5	30	92	1.75	51.50
10	10.5	30	92	1.75	40.53
11	9.5	40	92	1.75	50.90
12	10.5	40	92	1.75	44.50
13	9.5	30	96	1.75	23.40
14	10.5	30	96	1.75	25.37
15	9.5	40	96	1.75	27.57
16	10.5	40	96	1.75	29.43
17	9.0	35	94	1.50	19.70
18	11.0	35	94	1.50	31.40
19	10.0	25	94	1.50	17.93
20	10.0	45	94	1.50	19.37
21	10.0	35	90	1.50	86.80
22	10.0	35	98	1.50	62.27
23	10.0	35	94	1.00	83.90
24	10.0	35	94	2.00	54.23
25	10.0	35	94	1.50	66.13
26	10.0	35	94	1.50	69.03
27	10.0	35	94	1.50	68.35
28	10.0	35	94	1.50	70.10
29	10.0	35	94	1.50	74.80
30	10.0	35	94	1.50	75.07
31	10.0	35	94	1.50	71.97

It has been also observed that the S-value (3.10068) of the responses are smaller and R-Sq (98.69%), R-Sq (adj) (97.54%) and R-Sq (pred) (94.96%) values of the responses are moderately high, from which it can be concluded that the data for each response are well fitted in the developed models and working power on depth of cut when the pulse frequency and cutting speed are kept constant at 35 kHz and 1.5 mm/sec respectively. It is observed that the depth of cut increases with the increase in working power upto mid value. Above that, the depth of cut decreases with any further increase in working power. On the other hand, the depth of cut decreases with the increase in pulse width in a linear manner. The reason behind this anomalous behaviour can be attributed to the fact that at lower pulse widths, the peak power is comparatively more that higher pulse widths for which depth of penetration is more. Hence, depth of cut is more at lower pulse width. On the other hand, energy density on the irradiate spot is comparatively less at high working power with higher value of pulse width at partially submerged condition, results in decrease value of cutting depth.

Table 4: ANOVA for Depth

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	14	11573.0	826.64	85.98	0.000
Linear	4	2366.8	591.69	61.54	0.000
A	1	118.1	118.06	12.28	0.003
B	1	45.8	45.84	4.77	0.044
C	1	756.6	756.57	78.69	0.000
D	1	1446.3	1446.31	150.43	0.000
Square	4	8515.4	2128.85	221.43	0.000
2-Way Interaction	6	690.8	115.13	11.98	0.000
Error	16	153.8	9.61		
Lack-of-Fit	10	86.8	8.68	0.78	0.655
Pure Error	6	67.0	11.17		
Total	30	11726.8			
S	R-sq	R-sq(adj)		R-sq(pred)	
3.10068	98.69%	97.54%		94.96%	

3.2Effect of Process Parameters on Depth

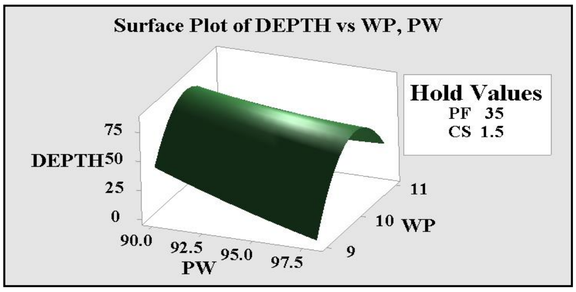

Fig 3: Surface plot of depth vs pulse width (PW) and working power (WP)

Figure 3 shows the combined effects of pulse width

Figure 4 shows the combine effects of the cutting speed and working power on depth of cut when the pulse frequency and pulse width are kept constant at 35 kHz and 94% respectively. It is observed that depth of cut is decreases with increase in cutting speed whereas increases with working power upto certain value then decreases. The reason behind this anomalous behaviour can be attributed to the fact that pulse energy concentration at the machining zone is comparatively more at lower cutting speed with low to moderate working power due to more interaction time. This results in more transfer of energy to the PMMA from absorbent and material removal is more. Lesser amount of laser energy is added in case of higher cutting speed due to decrease in interaction time though the working power is more. For that reason the amount of thermal energy conducted to the PMMA is less. Thus decrease in depth is observed. Figure 5 shows the combined effects of cutting speed and pulse width on depth of cut when the working power and pulse frequency are kept constant at 10 watt and 35 kHz respectively. It is observed from the surface plot that depth is comparatively more at higher value of pulse width and lower value of cutting speed from vice versa. Reason behind the observed phenomenon may be that more interaction time plays a vital role here, over the low peak power at higher value of pulse width and accumulate more energy by the absorbent. That thermal energy transfer to the bottom surface is more which helps to melt the material to create a channel, results in increase in depth.

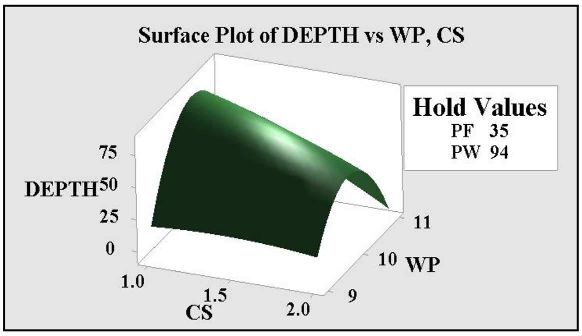

Fig 4: surface plot of depth vs cutting speed (CS) and working power (WP)

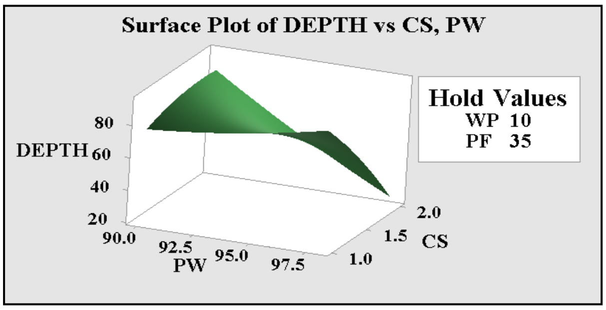

Fig. 5: Surface plot of depth vs pulse width (PW) and cutting speed (CS)

4. SINGLE OBJECTIVE OPTIMIZATION

In order to find the optimum values of the micro-channel characteristic, i.e. depth has been optimized by single objective optimization technique. It can be observed from the Figure 6 that the optimal conditions for maximum depth (97.3036µm) may be achieved at working power of 10.20 watt, pulse frequency of 35.0 kHz, pulse width of 98% and cutting speed of 1 mm/s.

5. CONFORMITY OF THE EXPERIMENT

In order to validate the results at optimum condition, five confirmation experiments have been conducted and took the average result. It is observed that the experimental result is fairly close to the predicted result. Microscopic view of micro-channel is given in Figure7. The absolute prediction error (APE) in percentage has been calculated using the following formula,

Table 5 shows the comparison of experimental results with predicted results and APE for single pass

$$APE = [1 - \frac{\Pr edicted}{\exp erimental}] \times 100\% \cdots\cdots\cdots\cdots\cdots\cdots \text{[ii]}$$

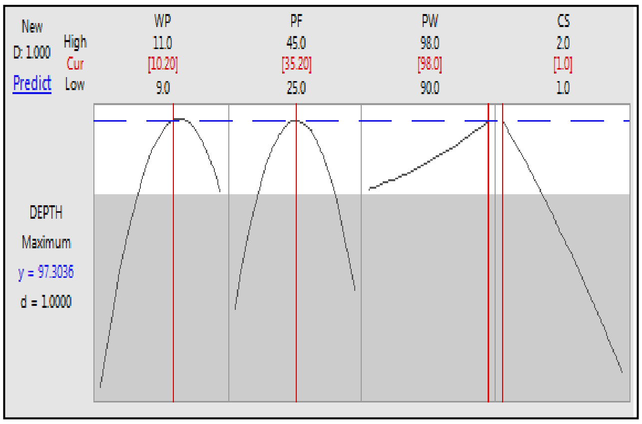

Fig 6: Parametric optimization results for depth.

Table 5
Confirmation Test Result

Response	Experimental (µm)	Predicted (µm)	APE (%)
HAZ width	94.80	97.30	2.637

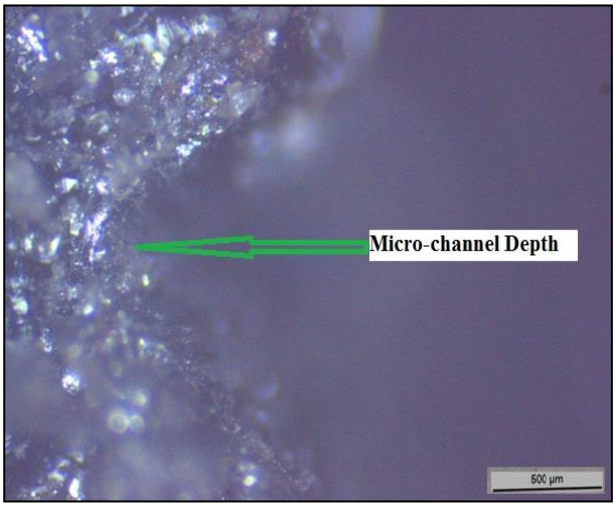

Fig 7: Microscopic view of the micro-channel depth (side view taken)

6. **CONCLUSIONS**

In this work, micro-channeling operation on a thick transparent PMMA plate, partially submerged under water has been successfully carried out and the subsequent machining results have been studied in detail. It can be concluded from ANOVA results that all the process variables are statistically significant, out of which cutting speed is the most significant and pulse frequency is the least affecting parameter. The parametric study carried out to explain the complex relationships between the interacting machining parameters (i.e. pulse width, working power and cutting speed) and predefined machining characteristic i.e. depth of cut. From the surface plots it is observed that depth of cut varies linearly with pulse width and cutting speed whereas the measured value of depth of cut is highest at the mid value of working power within the chosen design space. Single objective optimization technique is applied to obtain the combination of best parameter settings which yields highest depth of cut of 97.30 µm. The results of the confirmatory tests give an absolute prediction error (APE) of 2.64% which indicates at the feasibility of proposed micromachining technique.

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