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Optimization of Micromilling Parameters using Taguchi Method for the Fabrication of PMMA Based Microchannels

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ABSTRACT

A method is proposed for rapid prototyping of Poly (methyl methacrylate) (PMMA) microfluidic devices utilizing a micromilling machine. The present study is to investigates the influence of micromilling machining parameters which include spindle speed, feed rate, and depth of cut on the surface roughness of the machined polymer microfluidic devices. The devices have been machined on a PMMA substrate using 200 μm diameter endmill tool (Titanium Aluminum Nitride (TiAIN) coated solid carbide material). Surface roughness is considered an important parameter for influencing fluid flow at the microscale. The surface roughness has been measured using Infinite Focus Microscopy (IFM) tool. Taguchi's method is used for designing the experiments and optimization of machining parameters. The results showed that a surface roughness of 67.3 nm has been achieved using machining parameters including spindle speed of 4000 rpm, feed rate of 10 mm/min and the depth of cut of 10 μm. Taguchi's factor analysis on the samples showed that the depth of cut has the largest impact on the average surface roughness

Keywords: Micromilling, Microfluidics, Microchannels, Surface Roughness.

1. INTRODUCTION

Microfluidics is a device technology which has great potential for portable low-cost sensors in the various field especially for biological analysis of nano to micro size particles detection[1][2]. Moreover, microfluidics can be fabricated using various techniques and processes such as etching[3], 3D printing[4], micro molding[5][6] and micromilling process[7]. The advantages of using micromilling process are that it allows devices to be fabricated much faster and the cost of fabrication is low as micromilling does not require the use of high-end facilities such cleanroom. Recent studies show that microfluidic device with a channel width of 200 μm and a depth of 50 μm are suitable for nano to micro size cell studies[1].The surface roughness of microchannel for microfluidic devices is vital as it can affect the fluid behaviour. Micromilling is one of the techniques of micromachining, which was widely used to manufacture microfluidic polymer devices. The benefits of using micromilling process for microfluidic polymer devices include fast fabrication process and cheaper. Polymethyl methacrylate (PMMA) is an widely been used in microfluidics research primarily due to its excellent optical properties, biocompatibility, sufficient strength and low cost[8]. Table 1 shows the comparison of fabrication techniques, materials of substrate used and average surface roughness of machined substrate, it shows the average surface roughness can be as low as 71 nm using a mold injection. However, by looking at the Table 2 shows comparisons of average surface roughness using micromilling on PMMA substrate which use different of tool's material, size of tools, spindle speed, feed rate, and different depth of cut. It is found that the low surface roughness (as low as 38 nm) can be achieved by using micromilling method when using tool (diamond coated) of diameter 0.45 mm, spindle speed 150,000 rpm, feed rate 5 μm/flute and depth of cut 50 μm. However, the tool with

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diamond coated is expensive and spindle speed of 150,000 require expensive CNC machine. Moreover, from the Table 2, it shows the correlation between 3 main parameters (spindle speed, depth of cut and feed rate) towards average surface roughness are not straightforward.

Table 1 Various microfabrication technique techniques and average surface roughness

Fabrication Technique	Materials	Average Surface Roughness	References	Year
Soft Lithography	PDMS	100 μm	[9]	2016
Hot Embossing	COC	1.17±0.19 μm	[10]	2011
Mold Injection	Polymer	71 nm	[11]	2011
Micromilling	Silicon	0.053 μm	[12]	2015
Micromilling	Aluminium	0.782 μm	[13]	2019

Table 2 Various microfabrication technique using micromilling and average surface roughness

Diameter of Tool	Materials	Spindle Speed	Feed Rate	Depth of cut	Average Surface Roughness	References	Year
0.8 mm	Carbide	2000 rpm	2 mm/min	1.5 μm	0.352 μm	[14]	2012
0.45 mm	Diamond Coated	150,000 rpm	5 μm/flute	50 μm	38 nm	[15]	2017
0.2 mm	N/A	20,000 rpm	300 mm/min	10 μm	0.13 μm	[16]	2015
0.1 mm to 0.5 mm	Carbide	10,000 rpm	20 mm/min	10-20 μm	70-85 nm	[17]	2013
0.8 mm	Carbide	30,000 rpm	2.65 mm/min	40 μm	128.24 nm	[18]	2015

Design of experiments (DOE) is a systematic method of determining the relationship between the factors that affect a process and its output. The DOE method can usually be divided into full factorial design and factorial fractional design also known as Taguchi experimental design. In full factorial design all parameter-level combinations are tested to analyze the results. On the other hand, only a selected sub-set of the levels is used in analysis in the Taguchi experiment design fractional factorial design[19]. As Taguchi method is a cost-effective and time-saving method of exploring relationships between parameters. The optimization of process parameters has been extensively applied[20]. In this study the cutting parameters include speed of the spindle, feed rate, depth of cut. The main objective of this study is to find the optimum cutting parameters to achieve a minimized roughness on a micromilled PMMA surface, followed by factor analysis using Taguchi method to determine the major cutting parameter in the fabrication process of micromilling.

2. MATERIAL AND METHODS

The cutting tool used in this study is a 200 μm diameter, two flute Titanium Aluminum Nitride (TiAIN) coated solid carbide endmill tool. The CNC micromilling machine used in this project is the Mini Mill GX 5-axis (Minitech) desktop CNC machine. The machining parameters that will be investigated are the depth of cut, feed rate and spindle speed. Table 3 and 4 are tool parameters and the milling process parameters respectively. Figure 1 shows the setup for the experiment. As shown in Figure 1, the endmill tool used is two flutes flat endmill tool with a diameter of 200 μm, attached to the CNC's machine spindle. The design parameters of the microchannel for the microfluidic device are 50 μm depth, 200 μm width and 1 cm in device length. Device characterization using surface analysis approach will involve the measurement of the average surface roughness using Alicona's Infinite Focus Microscopy (IFM) tool.

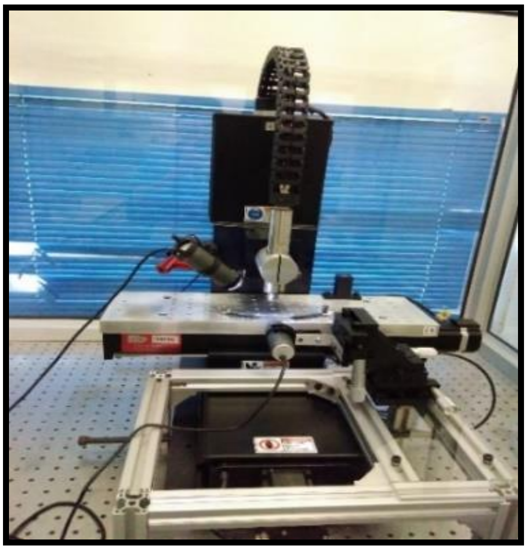

Figure 1. CNC Machine Mini Mill GX.

Table 3 Tool parameter

Parameters	Values
Tool Size	0.2 mm
Number of flutes	2
Material of tool	Carbide (*TiAIN* coated)

Table 4 Design of microchannel

Parameters	Values
Depth	50 μm
Width	200 μm
Long	1 cm

Taguchi method is an experimental design which seeks to obtain an optimum combination of factors and levels with the lowest cost result to meet the requirements of product quality [16]. Factor analysis is used to determine the main cutting parameter in machining the microchannel on the PMMA substrate. From Table 5 and Table 6 the three controlling factors which are spindle speed, depth of cut and feed rate with three level, resulting in 9 combination of cutting parameters. According to the Taguchi method, three parameters and 3 levels for each parameter, L9 orthogonal array should be selected for the experimentation. 3 level which resulting in 9 combination experiments in this work is sufficient to optimize the parameters, thus saving time and resources.

Table 5 Factor Analysis

Factors	Level 1	Level 2	Level 3
Spindle Speed (rpm)	4000	5000	6000
Depth Of Cut (μm)	0.01	0.025	0.05
Feed Rate (mm/min)	10	15	20

Table 6 Combination of factor analysis

Experiment Number	Spindle Speed (rpm)	Depth of Cut (mm)	Feed Rate (mm/min)
1	4000	0.010	10
2	4000	0.025	15
3	4000	0.050	20
4	5000	0.010	15
5	5000	0.025	20
6	5000	0.050	10
7	6000	0.010	20
8	6000	0.250	10
9	6000	0.050	15

3. RESULTS AND DISCUSSION

Selecting the ranges of cutting depth and feed rate below the minimum value reduces the machining time; however, selecting them above the maximum value reduces the tool wear, cutting force and the risk of breaking the tool [8]. Table 7 shows the experimental results based on the designed machining parameters for experiment 1 to 9 in Table 6. The results in Table 7 show values for the the optimal cutting parameters to achieve the minimal average surface roughness. The combination of machining parameters to achieve the smallest surface roughness as deduced from Table 7 are spindle speed of 4000 rpm, depth of cut of 0.01 μm and feed rate of 10 mm/min. The average surface roughness obtained for these parameters is 67 nm. After analyzing experimental data from Table 7, the lowest surface roughness can be obtained using the spindle speed of 4000 rpm, the feed rate of 10 mm/min and depth of cut 0.01 μm. However, based on a table of 7, it can be noted that during the spindle speed is 6000 rpm, the depth of cut and feed rate does not have a huge impact on the surface roughness, where the average surface roughness by using spindle speed of 6000 rpm recorded are from 100 nm up to 200 nm, in the same time, the increasing depth of cut and feed rate, is increasing the average of the resulting surface roughness. In addition, it can be noted all the average surface roughness resulting in less than 450 nm.

Table 7 Experimental results

Experiment Number	Spindle Speed (rpm)	Depth of Cut (mm)	Feed Rate (mm/min)	Average Surface Roughness (nm)
1	4000	0.010	10	67.3018
2	4000	0.025	15	267.2102
3	4000	0.050	20	406.8926
4	5000	0.010	15	170.2524
5	5000	0.025	20	350.468
6	5000	0.050	10	442.6494
7	6000	0.010	20	119.4901
8	6000	0.025	10	139.6821
9	6000	0.050	15	170.2192

To understand the impact on surface roughness of each factor with different levels, the average S/N ratio at each level was calculated and listed in Table 8. Table 8 shows the response table for signal-to-noise (S/N) ratio for the three machining parameter factors at three different level settings. As shows in Table 8, the larger the range, the larger influence of the corresponding factor to the surface roughness. The study show that the depth of cut has the largest range, meaning that depth of cut has the largest influence on the surface roughness. The feed rate, has the smallest range and has the smallest influence to the surface roughness.

Table 8 Response table for signal to noise ratios smaller is better

Level	Spindle Speed	Depth of Cut	Feed Rate
1	-45.76	-40.91	-44.13
2	-49.48	-47.44	-45.93
3	-43.02	-49.91	-48.21
Delta	6.46	9.00	4.08
Rank	2	1	3

Figure 2 shows the signal-to-noise (S/N) ratio for the surface roughness of the three different machining parameters. The results from Figure 2 show that the criteria of a smaller roughness with a larger S/N ratio can be used to determine the cutting parameters which can provide the minimal surface roughness. Similarly, the S/N ratio for surface roughness results also show that the combination to achieve the smallest surface roughness will include spindle speed of 5000 rpm, depth of cut of 0.01 μm and feed rate of 10 mm/min. From the Figure 2, show that increasing the spindle speed and decreasing the depth of cut and feed rate can reduce the micromilled average surface roughness. The results of the experiments are particularly difficult to conclude when the cutting depth is in micro sized, which may contribute the result of surface roughness for several reasons such as the properties of polymer materials and chips stuck on the micromilling tools[8].

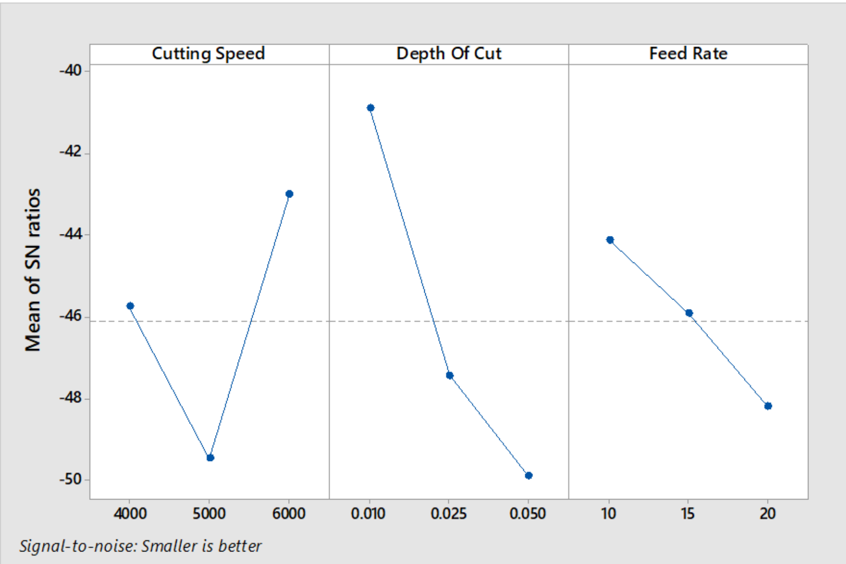

Figure 2. S/N ratio for surface roughness.

Table 7 previously also showed a trend that spindle speed with the speed of 6000 rpm would have a huge impact on the surface roughness than 4000 rpm and 5000 rpm. However, the speed of spindle 4000 rpm will be selected, given that higher spindle speed can lower the life of the tool [21]. To further validate the experiment, 10 microchannels were micro milled on the PMMA substrate with parameters of 4000 rpm for spindle speed, 0.01 μm for depth of cut and 10 mm/min for fee rate, and the results are presented in the Table 9. Furthermore, during the process, a drop of water added on the substrates to removes the debris. The average surface roughness in the Table 9 is 24.0824 nm with a standard deviation of 4.2509 nm. Drop of water can be used as chips removal during machining. During this experiment, there is no tool breakage. However, such parameters are likely not to refer explicitly to other micromilling devices. In addition, several factors that are generally ignored in macro-machining (substrate grain size and tool edge geometry) can actually play a dominant role in determining the surface quality of the micro-scale machining[22].

Table 9 Confirmation run

Experiment Number	**Surface Roughness (nm)**
1	21.3106
2	20.1148
3	26.7489
4	23.628
5	19.3741
6	23.5145
7	22.9668
8	27.5627
9	33.6486
10	21.9548
Average	24.08238
Standard Deviation	4.250855

4. CONCLUSION

In conclusion, the micromilling process is a useful method for rapid prototyping of polymer microfluidic device in particular during the product development process. Device fabrication using micromilling process can shorten the manufacturing process time and is useful for testing and validation of device performance. The objective of this study is to obtain the optimal machining parameters using Taguchi Method for minimum surface roughness on the polymer microfluidic device fabricated using the micromilling process. Three machining parameters are chosen in this study which are the spindle speed, feed rate and depth of cut. A total of nine experiments have been identified in this study and used in the experiment composing of three machining factors at three different levels. After analyzing the experimental data, the surface roughness of 67.3 nm can be achieved using the optimized machining parameters of spindle speed at 4000 rpm, feed rate at 10 mm/min and depth of cut at 0.01 mm. Moreover, from experiment of run confirmation, the average surface roughness can achieve as low as 19.3741 nm with standard deviation of 4.25 nm.

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