Chapter

Micro Milling Process for the Rapid Prototyping of Microfluidic Devices

Muhammad Syafiq Rahim and Abang Annuar Ehsan

Abstract

Micro milling process has become an attractive method for the rapid prototyping of micro devices. The process is based on subtractive manufacturing method in which materials from a sample are removed selectively. A comprehensive review on the fabrication of circular and rectangular cross-section channels of microfluidic devices using micro milling process is provided this review work. Process and machining parameters such as micro-tools selection, spindle speed, depth of cut, feed rate and strategy for process optimization will be reviewed. A case study on the rapid fabrication of a rectangular cross section channel of a microflow cytometer device with 200 um channel width and 50 um channel depth using CNC micro milling process is provided. The experimental work has produced a low surface roughness micro channel of 20 nm in roughness and demonstrated a microflow cytometer device that can produce hydrodynamic focusing with a focusing width of about 60 um.

Keywords: rapid prototyping, micro milling, microflow cytometer, surface roughness, subtractive manufacturing

1. Introduction

The field of microfluidics refers to systems that use millimeter to nanometer-sized fluids for analysis purposes [1]. The system analyzes small samples from micro to nano. Microfluidics is a combination of several fields, such as molecular analysis, molecular biology, biological defense and electronic electronics [2]. Each of these areas contributes to the advancement of microfluidic technology and increased interest in microfluidics [1]. Microflow cytometer are used in the microfluidic flow system, which is a system consisting of a combination of microfluidic and optical, where optical systems are required for analysis purposes [3]. The latest technology for micro flow cytometers focuses on particle focusing to be tested in microfluidics, fluid-controlled shrinkage, optical shrinkage and application integration and integration [3, 4]. Microfluidics are very relevant as they have several advantages, such as requiring only small-sized fluids, and indirectly allowing microfluidics to be tested using micro-to-nano samples [5]. Also, the advantage of microfluidics is that it can be used on small chips. This allows the chip to be used as a portable tool, especially for point of care diagnostic devices (Point of care) (POC). These advantages allow microfluidics to be able to analyze the sample information quickly.

One of the rapidly evolving phenomena in microfluidic studies is hydrodynamic focusing [6]. Hydrodynamic focusing is a technique that concentrates the flow in the center of the device by manipulating the flow rate of the side [7, 8]. During hydrodynamic focusing the middle path is concentrated by being narrowed by the side path flow. This method of hydrodynamic focusing is important in increasing microfluidic sensitivity [9]. Hydrodynamic focusing can be used to accurately position positions of cells, particles and sensor targets [9]. This hydrodynamic focusing method can be used for the purpose of manipulating cells found in blood composition such as white blood cells and red blood cells [10].

Microfluidic devices can initially be designed using Micro-Electro-Mechanical (MEMS) method [11], the manufacture of silicon-based microfluidic devices usually using this method of Micro-Electro-Mechanical System (MEMS) [3], where its progress is in line with the advancement of semiconductor technology [11]. The processes in this MEMS method involve processes such as oxidation, ion application, low pressure chemical vapor deposition (LPCVD), diffusion, splash, etc. [11].

In addition, for the manufacture of microfluidic rapid prototypes, microfluidic devices can be made using PDMS materials using soft lithographic manufacturing methods or PMMA materials using micro milling.

However, micro milling for microfluidics using PMMA material although a simple and inexpensive method, however, the manufacturing period is longer and not suitable for manufacturing devices in large quantities [12]. This micro milling method for microfluidics is an automated process suitable for the rapid manufacture of prototype devices [12]. Micro milling is a subtractive fermentation process, in which cutting tools are used to remove bulk material from the workpiece. The micro-milling system basically has a work table for XY positions for workpieces, cutting [12].

2. Theory

2.1 Microchannel geometrical shape

The advancement of microfabrication enables the construction of micro channels with micrometer dimensions. Since microfluidic are usually integrated into microsystems, it is important to determine the characteristics of fluid flow in microfluidic for better microfluidic design and operation. From **Figures 1** and **2**, microfluidics can be designed using circular or rectangular shapes. Theoretically, the best form of fluid flow mechanism is a circular channel. But, it is not so noticeable when the device has reached the level of micro or nano scale. First of all, a circular duct has a minimum surface area exposed to fluid that can reduce friction between the wall surface and the liquid. So, the energy required is less to pump water for a given flow

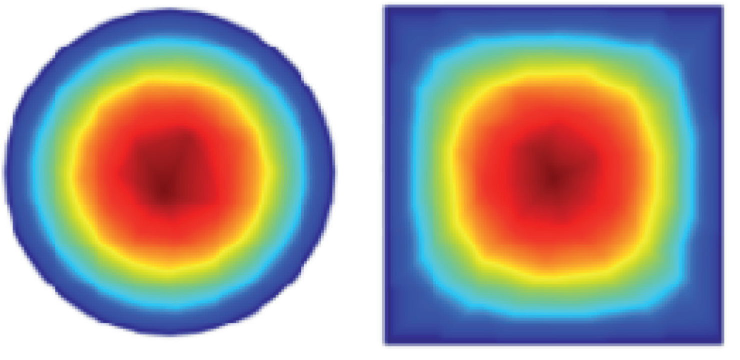

Figure 1.
Microchannel with rectangular and circular geometrical shape [13].

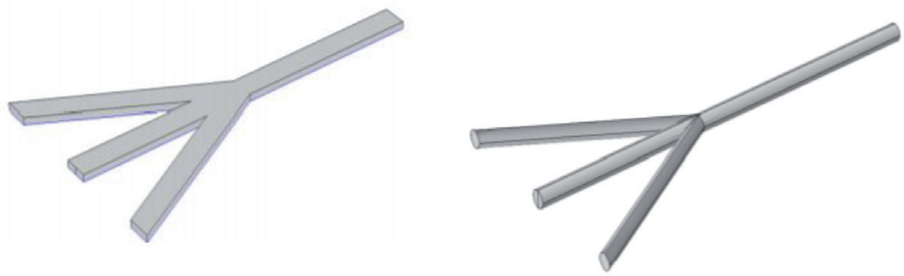

Figure 2.
Microfluidic with rectangular and circular geometrical shape.

rate. Second, the shape of the circle is efficient for handling internal stress. Using a circular channel, the pressure power distribution is uniform across the channel circumference. The presence of sharp corners in the rectangular duct will focus on the edges and sometimes this area needs to be strengthened to resist pressure.

Cell traps with hydrodynamic methods also show the advantage of a round shape to isolate a cell by reducing the applied pressure. By doing this, cells will have a higher percentage to survive in extreme flow conditions [14]. The purpose of this study was to simulate the flow of fluid in the micro-channel using COMSOL Microfluidic. The rectangle was chosen because it is widely used during the fabrication process of PDMS devices with soft lithography.

2.2 Surface roughnes of microchannel

The terms surface roughness and surface finish are widely used in the manufacturing sector to measure surface after machining. Average roughness is the arithmetic mean of the surface roughness profile measure of the mean line, and is the most widely used and universally recognized surface roughness parameter. The surface roughness of the machine in the final micro milling process depends on commonly used process parameters such as tool geometry, spindle speed, feed rate and depth of cut [15]. There are other factors of the micro milling process that affect the surface roughness such as the tip of the micro milling, the breakdown of the tool, the breakdown of the tool (and the nature of the workpiece which has a high quality surface).

Therefore, factors such as vibration and chip removal where these factors are not critical in the macro scale, can have a significant impact on the surface produced on the micro scale. The surface produced after micro milling is found to be affected by the end radius of the micro-tool and the feed rate. It is reported that when the 2 μm of the end radius, and in the state of the feed rate is reduced, the surface roughness increases, indicating that, the optimal feed rate can produce the lowest surface roughness. Cutting speed d an cutting depth affects the surface roughness on the PMMA material [16]. Further, it is found from previous studies as well, depth cutting has the greatest impact while, cutting speed has the lowest effect [16]. Surface roughness also depends on machining parameters and workpiece conditions, tool and heat conditions were also found to affect surface roughness [16]. In addition, the resulting surface quality after machining can be improved by increasing the rigidity and accuracy of the equipment. Because there are various manufacturing methods for polymer-based microfluidics, changes in the surface of the polymer after the manufacture of microfluids attract the interest of many researchers. Many researchers have tried various methods to reduce surface roughness for microfluidics to improve optical quality and improve biological capabilities.

Table 1 shows the surface roughness produced using the micro milling technique. Based on previous studies, it was found that the surface roughness produced by the micro milling can reach up to as little as 38 nm. However, surface

Diameter	Material	Spindle speed	Feed rate	Depth of cut	Surface roughness	Reference
0.8 mm	Carbide	2000 rpm	2 mm/min	1.5 μm	0.352 μm	[17]
0.45 mm	Diamond Coated	150,000 rpm	5 μm/flute	50 μm	38 nm	[18]
0.2 mm	N/A	20,000 rpm	300 mm/min	10 μm	0.13 μm	[19]
0.1 mm to 0.5 mm	Carbide	10,000 rpm	20 mm/min	10–20 μm	70–85 nm	[20]
0.8 mm	Carbide	30,000 rpm	2.65 mm/min	40 μm	128.24 nm	[21]

Table 1.
Surface roughness using different of material, spindle speed, feed rate and depth of cut.

roughness can be achieved up to 38 nm if the micro tool used is coated with the diamond. Micro–tool coated with high-cost diamond are not an option for micro-manufacturing.

3. Case study

3.1 Design of microfluidic

Since this study uses a micro milling a microfluidic design with a rectangular geometry will be used. From **Figure 3**, the designed depth is 50 um, 200 um wide, and the circle on the inlet and outlet has a diameter of 0.6 um. **Figure 3** shows microfluidics with 2 layer PMMA to be fabricated. From **Figure 3**, the top layer has 4 holes with a diameter of 0.8 mm, the design of the hole is based on the need to place a tube with an outer diameter of 0.7 mm. While the design for the bottom layer of microfluidics, there is a circular inlet and outlet with a diameter of 0.6 mm which is smaller than the outer diameter of the tube, to allow the tube to be above the microfluidic layer and the entire fluid can enter the micro flow.

The tool used in this research is a 0.2 mm diameter tool made of carbide material, has 2 flutes and Aluminum coated. While the workpiece that will be used in this research is Poly (methyl methacrylate) or referred to as acrylic which has a thickness of 2 mm.

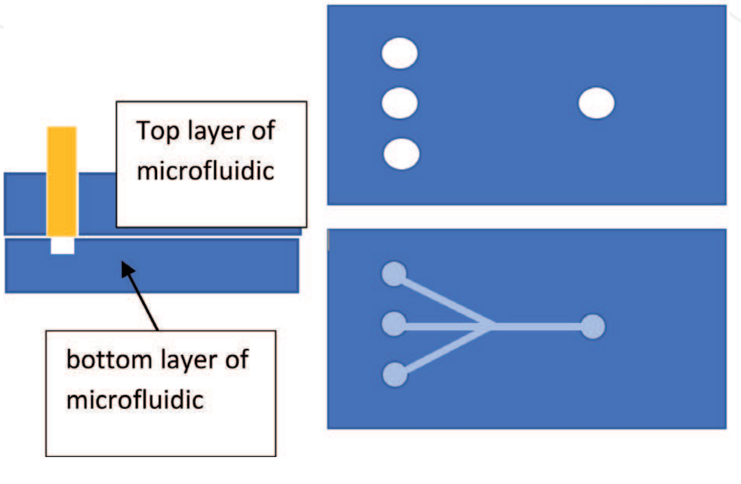

Figure 3.
Top and bottom layer of microfluidic.

3.2 Fabrication of microfluidic using micromilling

The Taguchi method as shown in **Table 2** is used taking into account 3 main parameters, namely, spindle speed, cutting depth, and feed rate to obtain the lowest surface roughness. The Taguchi method which uses 3 parameters along with 3 stages is used as **Table 2**. Spindle speeds consisting of 4000 rpm, 5000 rpm, and 6000 rpm, and spindle speeds lower than 10,000 rpm are used because PMMA material will burn when high speeds are used, as high speeds can increase the temperature on the tool can cause micro flow size the result is greater than desired. The cutting depths used for each cut are 0.01 μm, 0.025 μm, and 0.05. This is to ensure that the discarded chip is smaller than the tip of the tool. While the feed rate used is 10 mm/min, 15 mm/min, and 20 mm/min. Due to the high feed rate it can cause the tool to break. The total number of experiments produced is 9 experiments as shown in **Table 3**, each surface roughness average will be recorded, based on the smallerer the better method, and the smallest surface roughness average parameter will be taken. Then the optimal parameters will be repeated 10 times to ensure that the parameters produce consistent and stable results.

After analyzing the experimental data from **Table 4**, the lowest surface roughness can be obtained by using a spindle speed of 4000 rpm, a feed rate of 10 mm/min and a depth cut of 0.01 mm. However, based on **Table 4**, it can be seen that while the spindle speed is 6000 rpm, cutting depth and feed rate do not have a significant impact on surface roughness, where the average surface roughness is recorded around 100 nm to 200 nm, at the same time, increasing cutting depth and feed rate, increasing average surface roughness resulting. Moreover, it can be observed that all the resulting surface roughness is less than 450 nm. Next, to validate the experiment, 10 microcontrollers were built on PMMA with spindle speed parameters of 4000 rpm, feed rate of 10 mm/min and depth depth of 0.01.

Factors	Level 1	Level 2	Aras 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 2.
Machining parameter (Taguchi method).

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

Table 3.
Experiment number (Taguchi method).

Number	Spindle speed (rpm)	Depth of cut (mm)	Feed rate (mm/min)	Surface roughness (nm)
1	4000	0.01	10	67.3018
2	4000	0.025	15	267.2102
3	4000	0.05	20	406.8926
4	5000	0.01	15	170.2524
5	5000	0.025	20	350.468
6	5000	0.05	10	442.6494
7	6000	0.01	20	119.4901
8	6000	0.025	10	139.6821
9	6000	0.05	15	170.2192

Table 4.
Surface roughness by using different machining parameters.

During the machining process, a drop of water is placed on the substrate to remove debris during machining. The average surface roughness obtained from 10 validation experiments is shown in **Table 5**, where the average roughness is 24.0824 nm with a standard deviation of 4.2509 nm.

Selecting the cutting depth range and the feed rate with less than the minimum value will result in an increase in machining time, however, the cutting depth value, spindle speed and high feed rate, can increase the risk of damaged tool as reported [22]. From **Table 4** a total of 9 microchannel with a depth of 50 μm and a width of 200 μm were tested using the Alicona Infinite Focus Microscopy (IFM) 3D Optical Profiler used to measure the roughness of the surface on the cut of microchannels. The area of surface roughness shown at **Figure 4**. Analytical factors can be used to determine the main cutting parameters in the micro milling of the PMMA substrate. Based on **Table 4**, the larger the resulting range, the greater the influence of these factors on surface roughness, in this research, the depth of cutting indicates the largest range. This shows that the depth of cutting has a great influence on surface roughness. Whereas, the feed rate indicates a low range, this means that the feed rate has the least influence on surface roughness.

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

Table 5.
Surface roughness by using optimal machining parameters.

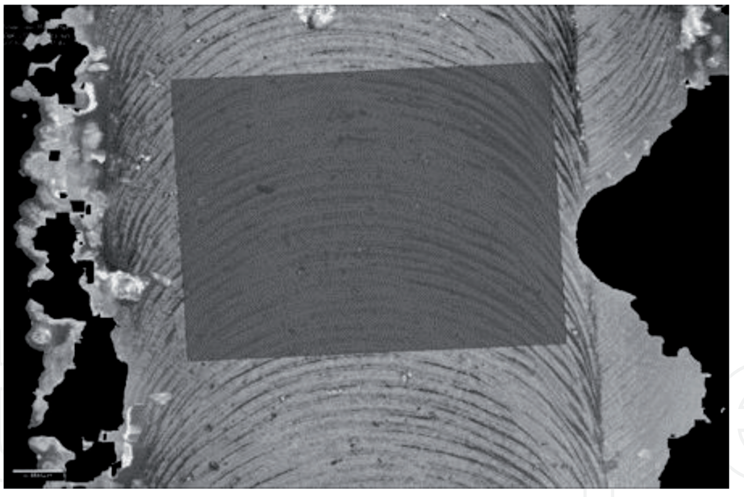

Figure 4.
Area for surface roughness measurement using infinite focus microscopy.

Table 4 also shows the optimal cutting parameters for obtaining minimal surface roughness. **Table 4** shows the combination of machining parameters to obtain the smallest surface roughness is the spindle speed 4000 rpm, cutting depth 0.01 μm and feed rate 10 mm/min. Based on **Table 4**, the average surface roughness average achieved for this parameter is 67.3018 nm. Moreover, from this study, based on **Figure 5**, if the study is compared by looking at the same parameter readings, shows that the spindle speed of 6000 rpm can produce the lowest surface roughness compared to the spindle speed of 4000 rpm and 5000 rpm. It shows that the cutting depth of 0.01 μm produces the lowest surface roughness followed by 0.025 mm and 0.05 mm. Furthemore, the feed rate of 15 mm/min produces the lowest surface roughness followed by 10 mm/min and 20 mm/min. Based on **Table 4**, it shows that the cutting depth most influences the roughness of the resulting surface followed by spindle speed and feed rate. This is in line with the theory that low cutting depths can result in low chip loads, this allows lower surface roughness to be achieved. As previously discussed, low depth of cut can result in low surface roughness.

3.3 Hydrodynamic focusing experiment

After successful microfluidic installation, the experiment was continued by testing the hydrodynamic focus. This feature is important to ensure that the designed microfluidics can operate, there are several factors that can cause the microfluidics to be unable to operate, firstly due to clogged microwaves, secondly because the bond between the 2 wafers is not strong causing small holes that cause leakage. Based on **Table 6**, the resulting focusing width is related to the sheath and sample flow rate ratio. The resulting focusing width can be adjusted according to the desired application. However, the sample flow width must be adjusted according to the specific cell size for detection, at the same time, allowing cells to pass through them one by one on the sample flow, this is to increase the sensitivity of the constructed device. Reynold numbers are kept in low condition, this is to avoid uninterrupted flow of microfluidics [23].

Based on this hydrodynamic focusing experiment shown at **Figure 6**, the side path with a flow rate of 3000 μl/min and the flow rate for the sample path of 10 μl/min can produce a focusing width as low as 39 μm. However, with an sheath flow rate of 3000 μl/min and a sample path flow rate of 100 μl/min, the resulting focusing width is 60 μm. Both of these results answer for the objective of the study, namely the production of hydrodynamic focusing around 60 μm. Based on **Table 6** it can also be observed, that if a flow rate ratio of 10 and 100 is used, a

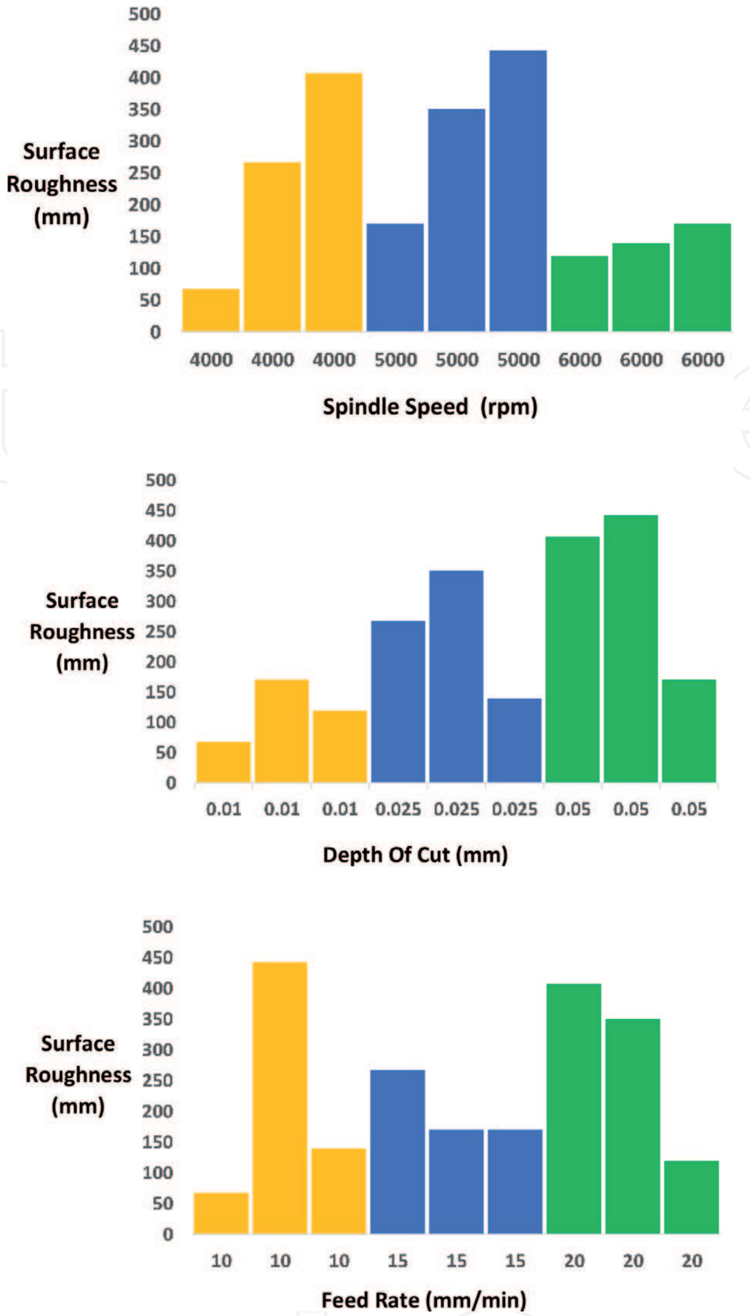

Figure 5.
Result of surface roughness by comparing same machining parameter.

Ratio	Sheath flow rate	Sample flow rate	Width of hydrodynamic focusing
10	1000 μl/min	100 μl/min	89 μm
100	1000 μl/min	10 μl/min	67 μm
30	3000 μl/min	100 μl/min	60 μm
300	3000 μl/min	10 μl/min	39 μm

Table 6.
Width of hydrodynamic focusing.

focusing width of 67 μm and 89 μm can be produced. From the simulation results show that effective hydrodynamic focusing occurs only when the sheath flow rate is higher than the center flow rate.

Furthermore, from the simulation results of nonlinear behavior will occur when too high a ratio is used. Increasing the ratio of sheath flow rate to large central

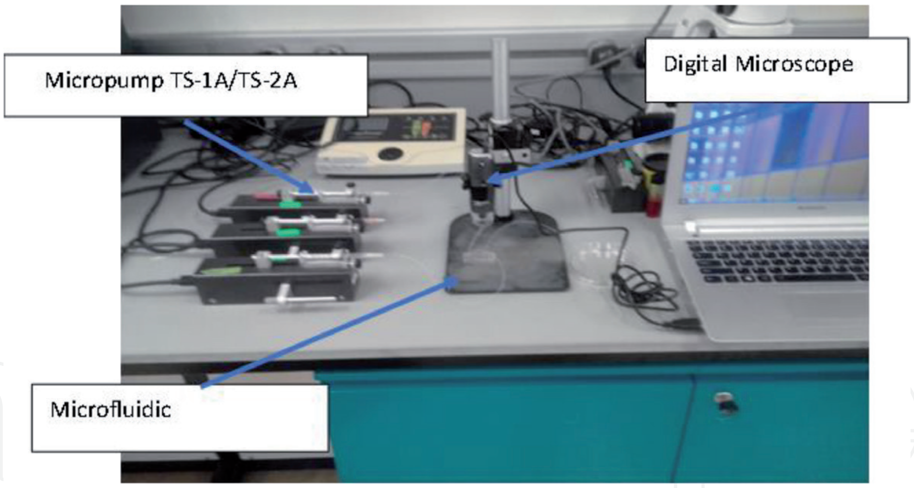

Figure 6.
Setup for hydrodynamic focusing experiment.

flow will only have a small effect on hydrodynamic focusing and may even cause hydrodynamic focusing not to occur if too high a flow rate is used. As shown in **Figure 7**, the hydrodynamic focusing that occurs is in the state of laminate and fully developed. This experiment can also give the impression that the bonding technique between 2 PMMA wafers using ethanol material was successfully performed, since hydrodynamic focusing can be formed. However, it should be noted that the hydrodynamic focus that occurs is not only due to the inflow rate by the fluid only, but the microfluidic geometry constructed also has a significant impact on the characteristics of hydrodynamic focusing. Especially when taking into account the rectangular geometry is easier to do by a micro milling than a round design. The forces formed to control hydrodynamic focusing are more complex than hydrodynamic focusing calculated only on the flow rate ratio [24].

An important aspect of designing and operating for the purpose of hydrodynamic focusing is to identify the position of the focus flow formed. Both lateral flows should have the same flow rate to ensure that the focusing flow flows in the middle of the micro flow. If the asymmetric focusing flow, the focusing flow will be deducted from the flow axis. Based on **Figure 7**, it can be observed that the

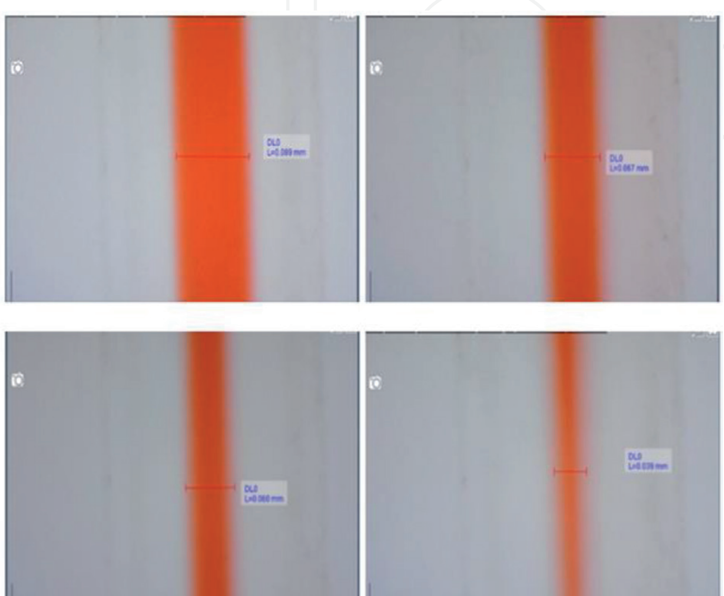

Figure 7.
Hydrodynamic focusing.

hydrodynamic focusing width will decrease if the ratio (sheath flow rate to the main flow rate) increases. It can also be observed from the experiment, it shows that the results of focusing will shrink if a larger ratio is used.

4. Conclusion

In this study, simple, low-cost and real-time methods have been used to detect touch between tools and workpieces. The objective of this study is to find the optimal parameters to achieve low surface roughness using a micro milling, from the data trends obtained, the parameters to obtain the lowest surface roughness are 4000 rpm spindle speed, 10 mm/min billing rate and 0.01 μm cutting depth. However, from the data obtained as well, it shows that water droplets placed on the tool during cutting also contribute to the reduction of surface roughness. In addition, there are several other parameters that can be studied in the future, namely the tool material (e.g. diamond), the smaller tool size, and the type of coolant used.

Since microfluidics manufacturing studies designed using micro milling are still limited, its function can be tested by looking at the hydrodynamic focusing that occurs. This study uses 2 PMMA-based wafers and is bonded using thermal-assisted ethanol. Based on the experiments conducted, the resulting hydrodynamic focusing has a width as small as 39 μm if the sheath flow rate and the center flow rate used are 3000 μl/min and 100 μl/min. Apart from using fluids such as water and dyes, fluids that have properties such as blood can also be used so that more accurate results can be produced.

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Author details

Muhammad Syafiq Rahim and Abang Annuar Ehsan*
Institute of Microengineering and Nanoelectronics (IMEN), Universiti Kebangsaan Malaysia (UKM), Bangi, Malaysia

*Address all correspondence to: aaehsan@ukm.edu.my

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