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Analysis of Micromilling Process Parameters for Silicon-based Flow Cytometer Microfluidics Device

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ABSTRACT

Objective – This study investigates and analyses some of the micromilling process parameters that have been adopted for the micro channel device fabrication.
Methodology/Technique – The CNC micromilling process has been proposed due to its ability to produce micro structures directly from digital computer aided design (CAD). The microfluidics device has a channel width of 200 µm with a rectangular cross section whereas its channel depth is about 50 µm. The micromilling process study will involve the use of uncoated (carbide) and diamond coated micron-sized endmill using a high-speed CNC milling machine. The analysis of the micromilling process will involve the characterization of the fabricated silicon micro channels using both geometrical and surface integrity analyses.
Findings – The results show that the roughness for a diamond coated endmill tool provides the lowest roughness of about 99.3 nm compare to that of the uncoated endmill tool which gives a surface roughness of 397.5 nm.
Novelty – The surface integrity measurement involves the measurement of surface topography of the machined surface which shows the effect of the diamond coating endmill on the surface roughness. The lowest surface roughness as measured was 99.34 nm for diamond coated endmill with a feed rate and depth of cut of 5mm/min and 1 µm respectively.
Type of Paper: Empirical/ Review

Keywords: CNC, Cytometer, Hydrodynamic Focusing, Microfluidics, Micro Milling, Silicon

1. Introduction

Optofluidics refers to manipulation of light using fluids, or vice-verse, on the micro to nano meter scale. Recently, the potential of microfluidics for single particle analysis was also recognized by the flow cytometry community. Microbiology and marine biology are some of the applications of flow cytometry but it is mostly applied in laboratory medicine, in particular for differentiation and counting of blood cells(Frankowski et al. 2013)(Rahim et al. 2016)(Selamat et al. 2016). One of the phenomena involved in a substantial number of applications within the microfluidics field is hydrodynamic focusing mostly used in microflow cytometer tool.

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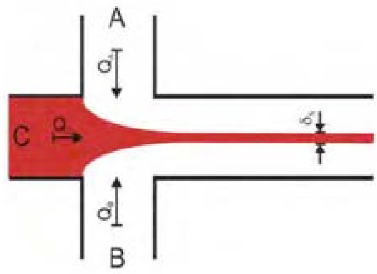


Figure 1. Schematic view of hydrodynamic focusing in a four channel intersection(Dziubinski 2012)

The concept of hydrodynamic focusing is based on the squeezing of one of the streams in a four-micro channel intersection by two side streams and reshaping it downstream into a thin center channel. This phenomena has been exploited for optofluidic-based microflow cytometer which allows sensing and cell manipulation capabilities(Lee et al. 2001). Figure 1 shows a schematic view of hydrodynamic focusing in a four channel intersection (Dziubinski 2012).

The conventional manufacturing process of microfluidic devices involves the use of semiconductor fabrication methods which can essentially be applied to a wide range of materials including silicon, glass and polymer. Silicon, being a material which allows light transmission beyond visible spectrum is a good candidate for the integration of microfluidic and optical devices. The absence of rapid prototyping method especially mechanical-based micromachining process for silicon device is due to the brittleness property of silicon. Silicon fails or breaks without significant deformation when subjected to tension or stress.

This study investigates and analyses some of the micromilling process parameters that have been adopted for the micro channel device fabrication. The CNC micromilling process has been proposed due to its ability to produce micro structures directly from digital computer aided design (CAD). The microfluidics device has a channel width of 200 μm with a rectangular cross section whereas its channel depth is about 50 μm. The micromilling process study will involve the use of uncoated (carbide) and diamond coated micron-sized endmill using a high-speed CNC milling machine. The analysis of the micromilling process will involve the characterization of the fabricated silicon micro channels using both geometrical and surface integrity analyses.

2. Research Methodology

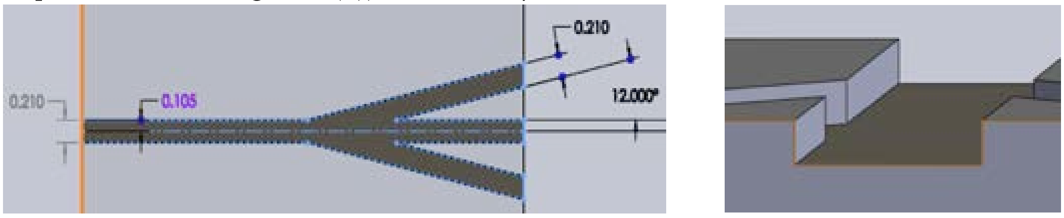
The project attempts to identify and analyse selected micromilling parameters that can be applied for machining micro channels on the silicon material. This project will involve four major stages: analysis of micromilling parameters, CAD/CAM of the design, micromilling of micro channels on silicon and characterization of micro channels.

2.1 Analysis of micromilling parameters

The tools used in this project composed of a 200 μm two flute carbide endmill (uncoated) and a 200 μm two flute diamond coated endmill tools. The tool edge or cutting radius for these 200 μm endmills are basically in the range of 9 μm, whereas the rake angle is approximately 4^{o} (Ko TJ, Rusnaldy, Kim JG 2005). The CNC milling machine used in this project is a Mini Mill GX 5-axis desktop CNC machine. Parameters that will be considered and utilized in the silicon micromilling process are the depth of cut, feed rate and the type of endmill tool, i.e uncoated or coated. The work material used for this project is a n-type (100) mono crystalline silicon wafer. It has a diameter of 75 mm and 400 μm in thickness.

2.2 CAD/CAM of Design

3D feature of the microfluidic device is created using CAD software. Figure 2 (i) shows the design of the microfluidic cytometer in CAD tool. The channel cross section is 0.21 mm which is slightly bigger than the actual diameter of the endmill of 0.2 mm machine. The branching angle use is about 12^o. The step height or the channel depth as shown in Figure 2 (ii)) is about 50 μm.



(i) (ii)

Figure 2. CAD design of the microfluidic channel (i) 2D profile (ii) step height of the design

2.3 Micromilling of micro channel on silicon

Brittle materials such as silicon will normally be machined under ductile-mode machining. Ductile mode machining removes material via plastic deformation of chips. If the silicon material is machined with incorrect machining parameters, brittle type machining occurs. One of the critical factor which determines the capability of the machining process to simulate ductile mode machining.(Rusnaldy, Ko, and Kim 2007). This factor is known as the chip load or also known as the feed per tooth. Chip load is a term used to describe the thickness of a chip removed by one cutting edge of the tool. The chip load or f_z (mm/tooth) is the radial depth of cut of the cutting tool in one revolution and calculated as follows ("Spindle RPM and Feed Rate Calculations | Chip Load Formula ", 2015):

$$f_z = \frac{V_f}{n \times Z_n} \quad (1)$$

where V_f is the feed rate (mm/min), n is the spindle speed (rev/min) and Z_n is the no of teeth of the tool (number of flute).

In order to obtain the required chip load, a suitable value for the feed rate, flute number and spindle speed must be obtained. However, it is anticipated that machining may not be directly done in ductile mode machining due to the limitation of the machine and tools being used in this project.

2.4 Characterization of micro channels

The characterization process is part of the analysis of the micromilling process parameters. This step will determine if the design values for the micro channel have been achieved. In the characterization process, two main characterization approaches are being proposed. As the device is mostly concerned with the geometrical features and also the surface properties, hence the characterization will involve the geometrical analysis and the surface integrity analysis. The geometrical analysis or visual inspection is done using a scanning electron microscope or SEM. Visual inspection allows the geometrical features on the machined surface to be precisely viewed and monitored. The surface integrity analysis in the form of surface topography measurement provided the surface condition of a work piece after being machined. This measurement will involve the measurement of the surface roughness and will be done using a 3D optical profiler tool.

3. Results and Discussions

The micro channels have been successfully fabricated on silicon wafer. The two machining parameters which are being investigated as in Table 1 are (i) the feed rate and (ii) the depth of cut (DOC). These two parameters are set prior to machining using the CAM software. The spindle speed however is set a fixed rate of 50,000 rpm. The milling strategy adopted in this research project is slot milling process, focusing specifically on method of machining brittle material and micron size features.

Table 1. Machining parameters.

Machine parameters	Value	Unit
Spindle speed (fix)	50,000	rev/min (rpm)
Feed rate (variable)	1-5	mm/min
Depth of cut (variable)	1-5	μm

Geometrical measurement is conducted in order to measure the geometrical features of the machined part. This measurement will involve the visual inspection of exact features machined on the silicon surface. The visual inspection process involves the use of high resolution scanning electron microscope (SEM). The SEM machine used in this section is the *JEOL SEM* (JSM-6510LV). The SEM allows direct analysis of the image which includes dimensional analysis. Figure 3 are the images taken from the imaging software of the SEM. The dimensional analysis done on one of the sample shows the step height is about 38 μm which is below the design step height about 50 μm.

(i) (ii) (iii)

Figure 3. SEM images of machined micro surfaces for the fabricated micro channels with different magnification: (i) 65x (ii) 350x: step height (iii) 300x

Visual inspection using SEM clearly show surface features of the fabricated micro channels. The magnified visual inspection shows that the surfaces of the machined work piece have been fractured in particular at the edges. As shown in Figure 3, the amount of fractures is visible throughout the edges of the micro channel. This indicates that the role of the cutting tool and the cutting dynamics have a significant effect on the generation of fractures. The results also confirmed that brittle type machining is dominant in this silicon micromilling process.

As for micron size milling, there is a lower limit for the depth of cut and feed rate that can be set in micromachining, and this is called the minimum chip thickness. It is reported that the minimum chip thickness is a small fraction of the tool edge radius (usually 5–43 % of the tool edge radius) (Arif 2011). One of the critical factor that determines the capability of the machining process to simulate ductile mode machining is known as the feed per tooth. Based on the defined parameter given earlier such as the feed rate, V_f , about 1 to 5 (mm/min), spindle speed, n of 50,000 (rev/min) and the tool flute number, Z_n of 2 flute the calculated feed per tooth for the micromilling is in the range of $f_z = 10$ to 50 nm/tooth. Rusnaldy et. al. who conducted micromilling of single crystal silicon using diamond coated endmill, showed that ductile cutting mode where plastic deformation is formed, can occur when the feed per tooth is at a critical value of 0.0012 μm/tooth or 1.2 nm/tooth(Rusnaldy, Ko, and Kim 2007). This value is much too small for the proposed and calculated feed per tooth which is 10 to 50 nm/tooth.

The surface topography measurement has been conducted using *InfiniteFocus* 3D micro coordinate measurement machine (CMM). The 3D micro CMM can measure complete surface features including forms, contours and surface roughness. The parameter that is used to quantify surface roughness in this project will be the arithmetic average surface roughness (center line average) or *Ra*. Figure 4 shows the images taken from the 3D profiler showing the surface topography of the machined surfaces of the micro channels. Table 2 shows the surface roughness measurement values for the selected fabricated samples.

Figure 4. Optical images from CMM of surface texture for the fabricated micro channels

Table 2. Surface roughness measurement.

Machined Silicon Wafer				
SAMPLE ID	MACHINING PARAMETERS		CUTTING TOOL (Carbide / Diamond coated)	AVERAGE SURFACE ROUGHNESS, Ra (nm)
	Feed rate (mm/min)	Depth of Cut (µm)		
1	5	1	uncoated	397.5675
2	5	5	uncoated	259.0516
3	5	1	diamond	99.3425

The results in Table 2 shows that diamond coated endmill provided significantly lower surface roughness compare to that of uncoated endmill. This indicates that the use of diamond coated endmill has a profound effect on the surface roughness of the silicon material as opposed to the uncoated carbide endmill. In addition, the effect of different machining parameters can be concluded where different machining parameters resulted in different values of surface roughness. It can be seen that the combined effect of depth of cut and the use of a diamond coated endmill tool on the surface roughness is much more significant. The use of uncoated endmill tool may not produce significant and repeatable improvement on the surface roughness. The effects of the depth of cut and the use of diamond coated endmill have be shown and reported, which a very low surface roughness was obtained when the depth of cut is set at 0.3 µm(Rusnaldy, Ko, and Kim 2007).

4. Conclusions

Micro channels on silicon have been fabricated using micromilling process. The fabrication involved several machining parameters including the feed rate, depth of cut and the use of a diamond coated endmill. Two characterization methods have been utilized which are the visual inspection using SEM and the surface topography measurement using 3D CMM. The visual inspection provided a visual inspection on the machined surfaces in particular indicating the location of fractured edges. The surface integrity measurement enables the surface roughness of the machined to be determined. The surface integrity measurement involves the measurement of surface topography of the machined surface which shows the effect of the diamond coating endmill on the surface roughness. The lowest surface roughness as measured was 99.34 nm for diamond coated endmill with a feed rate and depth of cut of 5mm/min and 1 µm respectively.

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