MICRO-CUTTING OF BIOCOMPLATIBLE MATERIALS USED FOR MEDICAL APPLICATIONS

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2017

ACKNOWLEDGEMENTS

In the name of Allah, Most Gracious, Most Merciful.

I am grateful and would like to express my sincere gratitude to all the project members for their support in this research. My sincere thanks go to all my colleagues and technical staff in Faculty of Manufacturing Engineering Universiti Malaysia Pahang who helped me in many ways during the completion of this project.

I acknowledge my sincere indebtedness and gratitude to my family, my wife and my daughter and my son for their support and love throughout this project.

ABSTRACT

Micro-end milling is one of the promising methods for rapid fabrication of features with 3D complex shapes. However, controlling the micro-end milling process to obtain the desired results is more challenging compared to that of macro-end milling due to the size effect and uncontrollable factors such as vibrations, burrs and tool breakage. The problem is much pronounced when workpiece material is a difficult-to-process material such as titanium-based alloys which are widely used as material of choice for medical implants. The objective of this research is to study the micro milling of selected bio-compatible materials which in this case is titanium alloys. The study is focused mainly on the experimental work on the effect of machining parameters especially feed rate and depth of cut with constant spindle speed in wet and dry condition on Ti-6Al-4V's surface roughness using micro-milling process. This experiment was design using Design of Experiment (DOE) method and few numbers of experiments were constructed. The result from this research can be applied in the production of the biomedical implants especially those consist of micro-scale features. The implants are being used in many different parts of the body for various applications such as orthopedics, pacemakers, cardiovascular stents, neural prosthetics or drug delivery system. The results show that feed rate is the most critical parameter which effect on surface roughness during machining process followed by depth of cut. Dry condition shows better surface quality compared to wet condition.

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ABSTRAK

"Micro-end milling" adalah salah satu kaedah yang menjanjikan untuk fabrikasi yang pantas dengan ciri-ciri bentuk 3D yang komplek. Walau bagaimanapun, pengawalan proses "micro-end milling" untuk mendapatkan keputusan yang dikehendaki jauh lebih sukar berbanding dengan „macro-end milling" disebabkan oleh kesan saiz dan faktor-faktor yang tidak terkawal. Masalah ini lebih ketara apabila bahan bahan kerja adalah bahan yang sukar untuk proses seperti aloi berasaskan titanium yang digunakan secara meluas sebagai bahan pilihan untuk implan dalam bidang perubatan. Kajian ini adalah mengenai kesan parameter pemesinan iaitu „feed rate" dan kedalaman permotongan dengan menggunakan kelajuan spindle tang sama dalam keadaan basah dan kering ke atas kekasaran permukaan Ti-6AL-4V menggunakan prosess micro-milling. Eksperimen ini menggunakan kaedah "Design of Experiment (DOE)" dan beberapa percubaan eksperimen telah dihasilkan. Keputusan menunjukkan bahawa „feed rate" adalah parameter yang paling kiritkal ke atas kekasaran permukaan semasa proses diikuti dengan kedalaman pemotongan. Pemesinan dalam keadaan kering menunjukkan kualiti permukaan yang baik berbanding dalam keaadaan basah.

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CHAPTER 1
INTRODUCTION

1.1 Introduction

The need for miniaturized in medical devices and systems, with the features and components range from a few micro-meters to a few hundred micro-meter sizes, is rapidly growing in order to improve the quality of human life. The applications of biomedical devices and systems are mainly in microfluidic devices used for analysis in medical industry and bio-mimicry of natural and artificial biomaterials used for body components. One example of the miniaturized in medical systems is disposable polymer microfluidic devices. Polymer microfluidic devices are integration tools use for analysis of chemical samples performed in one platform. These devices have been used widely in genetic analysis, drug discovery, clinical diagnostics, biomedical and biochemical industries, and also in the field of chemistry [1]–[3]. Different fabrication processes have been developed to produce such polymer microfluidic devices, such as injection molding and hot embossing [2], [4]. These processes employ a mold insert (also referred to as a replication tool, master mold or embossing mold) that replicates a positive relief pattern onto the polymer surface at a temperature above its glass transition temperature. Simpler and cost effective manufacturing methods and materials selection of these micro-size ranges components are necessary in order to anticipate the increase in healthcare costs. The present research related with the fabrication methods and materials for the applications of micro-size features especially mold and other implants used in medical applications are described briefly below as a background for the proposed research.

1. *Manufacturing methods*

Many fabrication methods have been developed to produce micro-size features products such as mold insert with most of them are reported using Micro Electro Mechanical System (MEMS) based process such as dry etching, lithography, electroplating, *Lithographie Galvanoformung Abformung* (LiGA). However, the MEMS based processes are expensive, require clean room facilities, involve hazardous chemicals and have a long series of stages that require tight tolerance control. Non-conventional based micro-machining such as laser ablation technology have also been reported but this process can change the properties of surfaces. One of the potential methods to produce micro-features for medical applications is mechanical micro-machining (micro-cutting). Fabrication of micro-features and micro-components using micro-cutting such as micro-milling has some advantages over MEMS based processes such as capability to manufacture 2D, 2 ½D and 3D features with high aspect ratio, have flexibility and simplify the production of micro-parts and micro-components, ability to process a wide range of materials [5]. In addition, micro-cutting can avoid the use of hazardous chemicals, reducing operational and investment costs. One of the applications of mechanical micro-machining in medical devices reported in the literature is in the fabrication of micro-mold to produce bio-degradable polymer membranes. Lima *et al.* [6] used micro-milling and micro-drilling to produce micro-embossing mold consists of micro-pillars and micro-cavities on stainless steel block and additional electrochemical polishing was applied to make the features smoother (Figure 1). Therefore, micro-cutting is a potential method to produce micro-size ranges components used in microfluidic systems. However several challenges related with the process such as surface quality, size effect and microstructural effect of materials have to be solved.

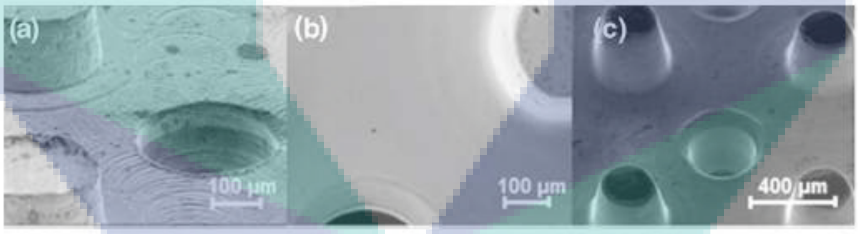


Figure 1. **Scanning Electron Microscope (SEM) images of the micro-milled stainless steel master mold surface, (a) before and (b), (c) after electrochemical polishing treatment [6].**

2. *Selections of Material*

The mold insert and implants materials generally must have good corrosion resistance, appropriate surface properties, biocompatibility, high mechanical strength, high hardness, good wear resistance, high thermal strength, and high fatigue strength [7], [8]. In this case, some candidate materials such as: stainless steel, titanium alloys, magnesium alloys, aluminium, hardened steel, silicon, and amorphous alloys (Bulk Metallic Glass) are the most preferable materials. Stainless steel, hardened steel and silicon are widely used for the mold. Titanium alloys are potential candidates for the application of implants micro-features due to their biocompatibility properties. The study of the micro-machining of these alloys has been reported widely in aspects of tool path optimization [9], surface qualities and tool analysis [10] and also effect of microstructures [11]. Bulk Metallic Glass (BMG) can be used as a mold insert as well as bio-implants due to its excellent properties. Bakkal and Nakşiler [12] reported their work on micro-meso milling of BMG materials with main problem in surface quality (Figure 2).

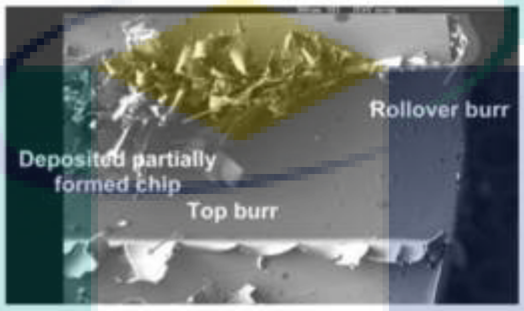


Figure 2. Burr formations at the edge of the slots in micro-end milling of BMG [12].

Currently, the study of micro-machining BMG materials reported in the literature is still rare. Another material that can also be used is Metal matrix Composite (MMC). The study of micro-machining this material is also still rare in literature as reported by Jian Liu *et al.* [13].

1.2 Problem Statement

There still a gap in the understanding of micro-machining of the bio-compatible materials especially titanium alloys, bulk metallic glass and metal matrix composites. It is thus important to fill the gap in order to understand the mechanical micro-machining of biocompatible materials especially improvement in surface and sub-surface qualities using controlled and cost effective method in order to avoid the use of additional finishing process.

1.3 Objectives

The intentions of the proposed research are:

1. To study the mechanism and some issues related with micro-cutting of the biocompatible materials candidates such as surface quality, machinability and machining behaviour of biomaterials in the micro-cutting process. These need to be

considered because of the anisotropic behaviour of materials, size effect and microstructural effect.

2. To determine the tool geometry and tool materials suitable for micro-cutting of biocompatible materials based on tool wear analysis and surface quality on the machined workpieces.

CHAPTER 2
RESULTS OF PROJECT

This project consists of two phases which are experimental and analyze phase. The first phase is experimental phase. During this phase, the physical micro-milling experiments will be conducted in order to collect all necessary data in measured surface roughness and observed burr formation. The main method in this phase is a design of experiment using Minitab software. In the second phase which is analyze phase, all data obtained in the experimental phase were used to analyses the data. It is also analyze using Design of Experiment (DOE) method.

2.1 Material Preparation

The project will be start by choosing and select the best material for the project. After selection, the material will be order. The raw material that will be used for this project is thin Ti-6Al-4V plate which is 100 mm x 50 mm x 10mm in size. The sizes of material need to be decide carefully to avoid waste because the price of the material is quite expensive.

2.2 Design of Experiment

To determine the optimal cutting condition which produces good surface roughness and minimum formation or burr in Ti-6Al-4V material, design of experiment based on full factorial design will be applied with two-factor three-level design. The parameters that will be tested are feed per tooth (f_z in millimeter per minute) and depth of cut (DOC, in millimeter) by constant spindle feed (Ω in revolutions per minute). This experiment will use full factorial design for two process parameters with three levels. Table 2.1 shows the parameters and level assign for the experiment.

Table 2.1: Set of parameters and levels for the experiments

Factors	Micro-milling parameters	Levels		
		−1	0	1
fz	Feed Rate (mm/min)	25	58	100
DOC	Depth of cut (mm)	10	20	40
Ω	Spindle Speed(RPM)	4000		

Table 2.2: Design of Experiment using Full Factorial Design

StdOrder	RunOrder	PtType	Blocks	*Fz* (mm/min)	DOC (mm)	*Ra* (µm)	
						without coolant	with coolant
9	1	1	1	58	20		
7	2	1	1	100	40		
3	3	1	1	58	40		
4	4	1	1	100	20		
6	5	1	1	58	10		
1	6	1	1	100	10		
8	7	1	1	25	10		
2	8	1	1	25	20		
3	9	1	1	25	40		

2.3 Experimental Process

Rectangular plate of Ti-6Al-4V material will be machined using Makino KE55 CNC milling machine by using carbide type of 1.0 mm diameter end-mill tool. The experiment will follow the parameters of DOE in Table 2.2. First experiment is without using coolant. It will then repeat by using coolant. The length of cutting slot is 10 mm. Diagram of micro-milling operation is shown in Figure 2.1.

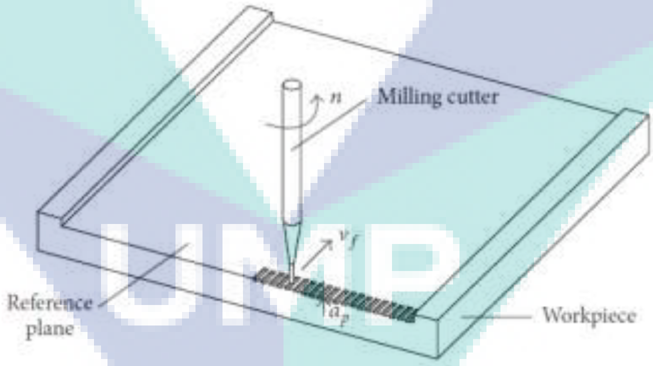


Figure 2.1: Diagram of micro-milling process.

To ensure that the experiment was running smoothly, the experiment must follow working procedure. Figure 2.2 shows overall experimental set up procedure for slot milling operation using CNC Milling Machine.

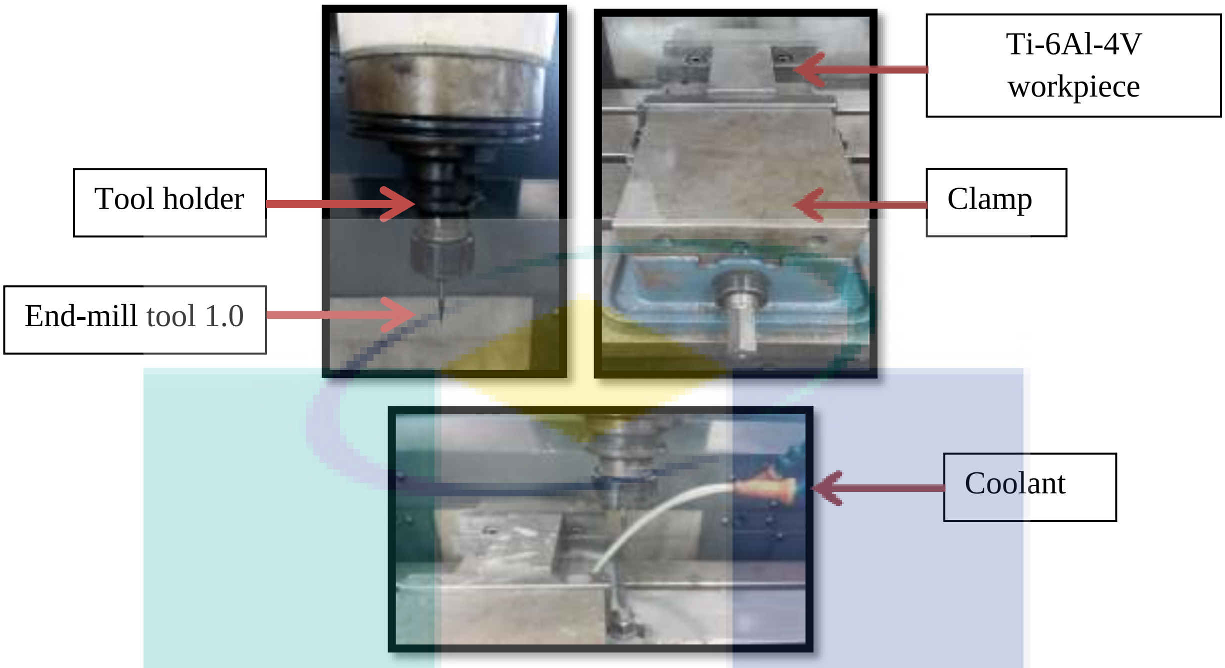


Figure 2.2: Experimental Set up

In each experimental run, the response will be measured in term of average surface roughness (*Ra*) and total top burr width. Surface roughness will be measure using Surface Roughness Tester SURFCOM 130A model. Burr formation and milling marks will be observed using Video Measurement System. In milling operation, there are few types of burr will be formed during machining operation. However, in this project, the measurement of burr only focuses on top burr formation.

2.4 Perform Analysis Using Minitab Software

Design of Experiment (DOE) by Factorial method is used as the method of analysis. The analysis has been performed after the all the surface roughness measurement, burr formation and milling marks are recorded. Main Effect Plot and Interaction Plot graph will be create using Factorial Plots. It were plotted to visualize the effects of both factor to the response.

2.5 Results and Discussion

2.5.1 Tool Wear Analysis

During the experiments conducted, there must be some wear to the end-mill tool. The wear obtain is results from the force occur during slot milling operation. It also may cause due to the vibration during machining. Tool wear were observed using Video Measurement Optical Microscope. Table 2.3 and Table 2.4 show the observation of tool wear from side and bottom view of four flute 1.0 mm carbide end-mill tool before and after machined. It shows that the tool is in good condition and there is no tool wear before machining operation. However, after machine there is some tool wear observed for both tool with and without coolant. When making comparison between end-mill tool during conducting experiment with coolant and without coolant, there is some difference in tool wear. Amount of tool wear using coolant is higher than without using coolant. Those situations maybe occur because of the quantity of coolant used will give effect to the rotating of tool during machining.

Table 2.3: End-mill tool observed before and after slot milling operation without coolant

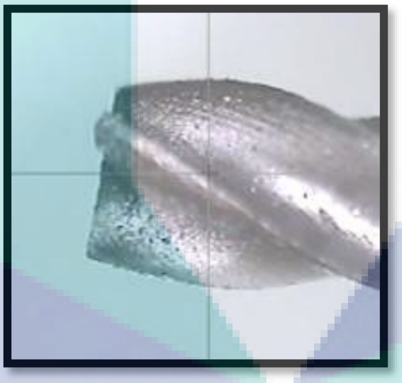
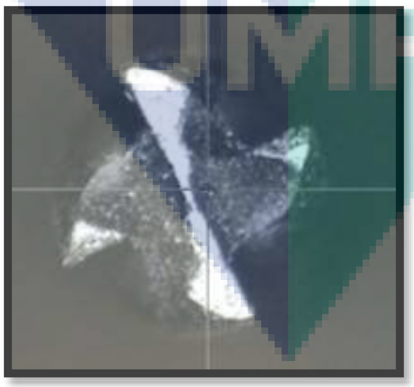
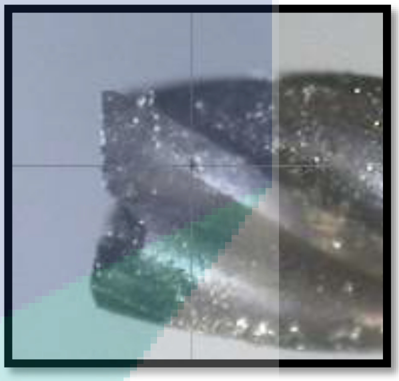
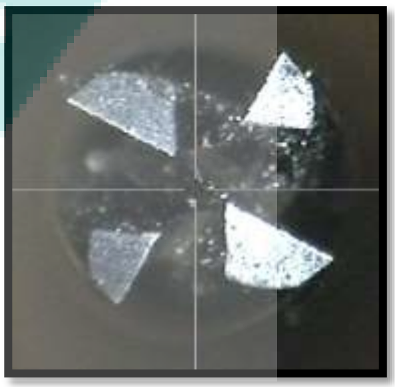
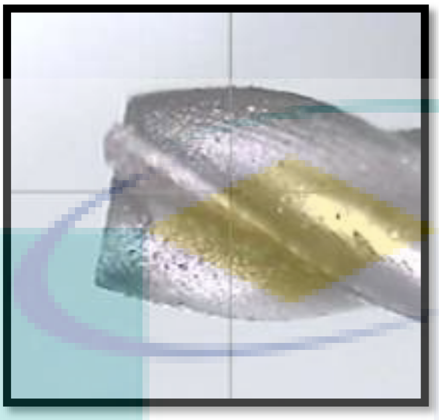
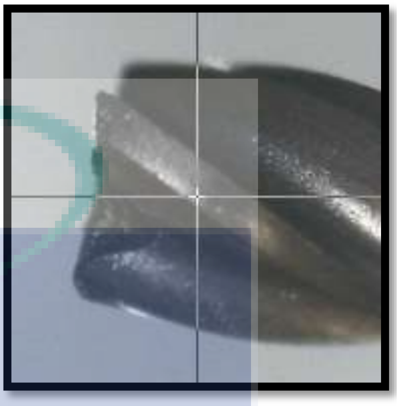
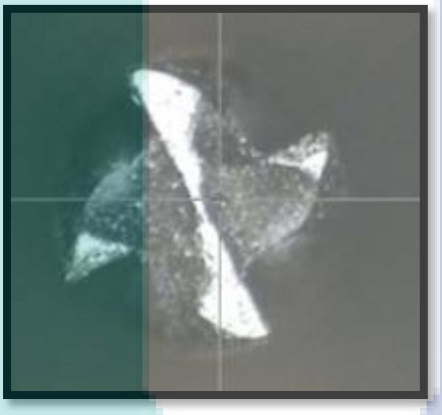
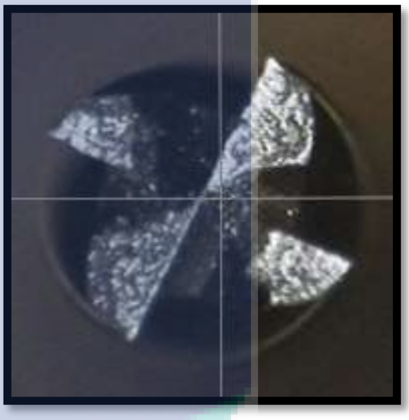
Tool	Before	After
Without Coolant	 	 

Table 2.4: End-mill tool observed before and after slot milling operation with coolant

Tool	Before	After
With Coolant		
		

2.5.2 Surface Roughness

In order to verify the effect of feed rate and depth of cut to the surface roughness of Ti-6Al-4V material, nine experiment were conducted using coolant and without coolant. The experiment was design in such way to identify the relation of surface roughness between feed rate and depth of cut by constant spindle speed. The slot milling experiment were carried out on Ti-6Al-4V material under different cutting condition that given graphically in Figure 2.3 and the corresponding experimental value of surface roughness when machined using and without coolant are shown in Table 2.5. Surface roughness was measured using Surface Roughness Tester.

Figure 2.3: Slot milling Experiment under different cutting condition

Table 2.5: Experimental values of *Ra* when machined with and without coolant

StdOrder	RunOrder	PtType	Blocks	*fz* (mm/min)	DOC (mm)	*Ra* (µm)	
						without coolant	with coolant
9	1	1	1	58	20	0.161	0.250
7	2	1	1	100	40	0.195	0.425
3	3	1	1	58	40	0.162	0.260
4	4	1	1	100	20	0.191	0.290
6	5	1	1	58	10	0.131	0.153
1	6	1	1	100	10	0.146	0.195
8	7	1	1	25	10	0.109	0.135
2	8	1	1	25	20	0.116	0.155
3	9	1	1	25	40	0.126	0.170

2.5.3 Effect of Feed Rate and Depth of Cut on Surface Roughness

Interaction plot can be used when the effect of one factor depends on the level of the other factor. In this study, an interaction plot is used to visualize possible interactions between feed rate, *fz* and depth of cut, DOC. There is no interaction when the interaction plot shows parallel lines. The degree of interaction will be higher if the difference in slope between lines is greater.

Figure 2.4 shows interaction plot for Mean Surface Roughness, *Ra* without coolant. There are three level of Feed Rate, *fz* and Depth of Cut, DOC. The plot indicates an interaction between as the plot not parallel lines. Based on the interaction plots, *fz* 100 mm/min shows the greater mean of surface roughness followed by 58 mm/min and 25 mm/min. For *fz* 100 mm/min, the highest mean of surface roughness is when DOC 40 mm. The trends are similar with *fz* 58 mm/min and 25mm/min which are when the level of DOC increase, the mean of surface roughness also increases. For *fz* 25mm/min, there is only slightly increase in the mean *Ra* along DOC 10 mm, 20 mm and 40 mm.

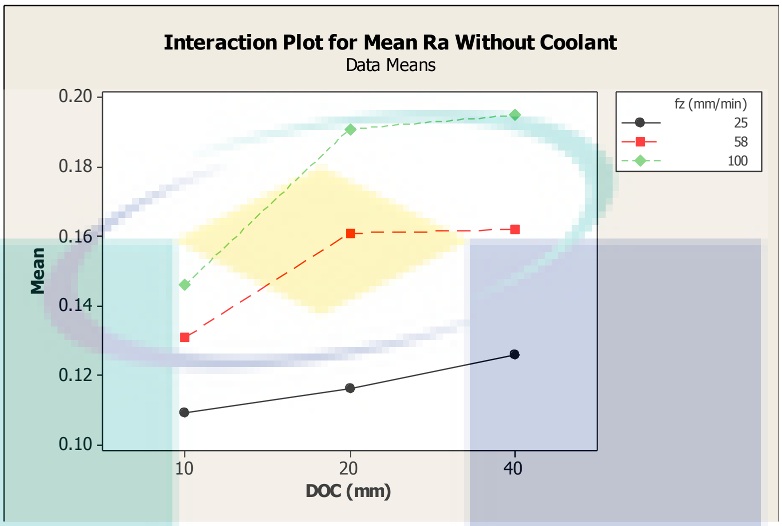


Figure 2.4: Interaction plot for Mean Surface Roughness, *Ra* without coolant

An interaction plot for Mean *Ra* with coolant is shown in Figure 2.5. The plot also indicates that there is interaction between *fz* and DOC. The trends are almost same with the interaction without coolant. The highest mean for surface roughness is goes to *fz* 100 mm/min when DOC 40mm followed by *fz* 58 mm/min and 25 mm/min. However, there is sharply increase in mean of surface roughness for *fz* 100 mm/min from DOC 20 mm to 40 mm.

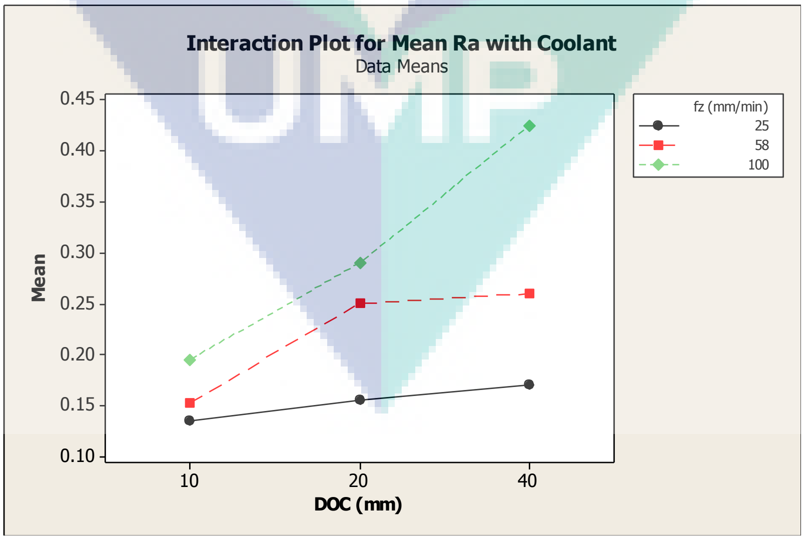


Figure 2.5: An interaction plot for Mean *Ra* with coolant

Main effects plot were used to examine the differences between level means for one or more factor. There is main effect when different levels of a factor affect the response differently. A main effects plot graphs the response mean for each factor level connected by a line. In this study, the main effects plot graphs mean of surface roughness, *Ra* for each level of feed rate, *fz* and depth of cut, DOC. Based on Figure 2.6, the plot for mean *Ra* without coolant shows there are main effect for both factors because the line for both factors are not horizontal. It shows that mean *Ra* for *fz* is greater than mean *Ra* for DOC. Other than that, the slope of *fz* line is steeper than DOC line. It is meaning that *fz* is the most influence factor to the surface roughness when not using coolant. *fz* 100 mm/min shows the highest mean of *Ra* followed by *fz* 58 mm/min and 25 mm/min. For DOC, the highest mean of *Ra* lies on 40 mm followed by 20 mm and 10 mm.

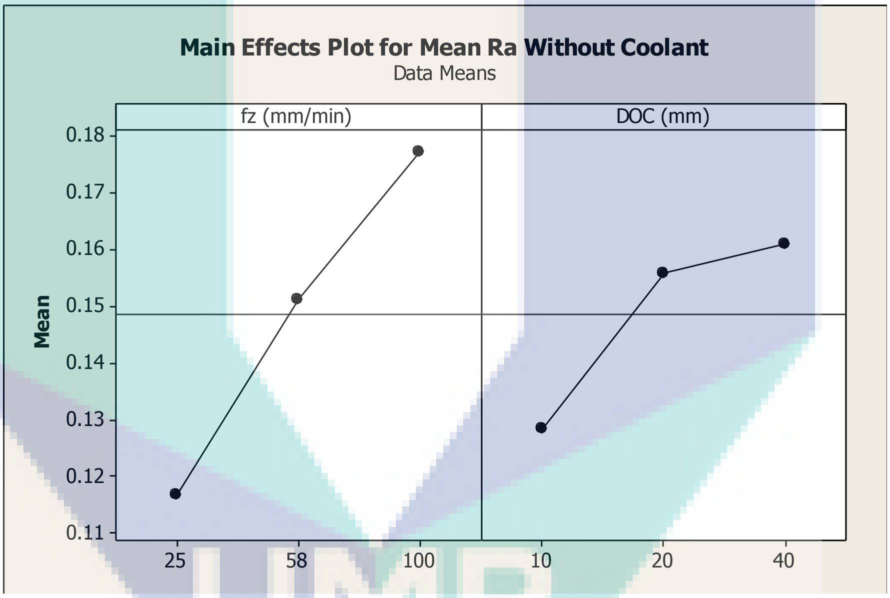


Figure 2.6: Main effect plot for mean *Ra* without coolant

Main effect plot for mean Ra with coolant are shown Figure 2.7. It shows that both factors give main effect to the mean *Ra* because the line is not horizontal. However, the slope of *fz* line is steeper than DOC line. It is meaning that *fz* is the most influence factor to the surface roughness. The mean of *Ra* for *fz* show the highest compared to DOC. Both factors shows that the mean of surface roughness increasing when increase their level.

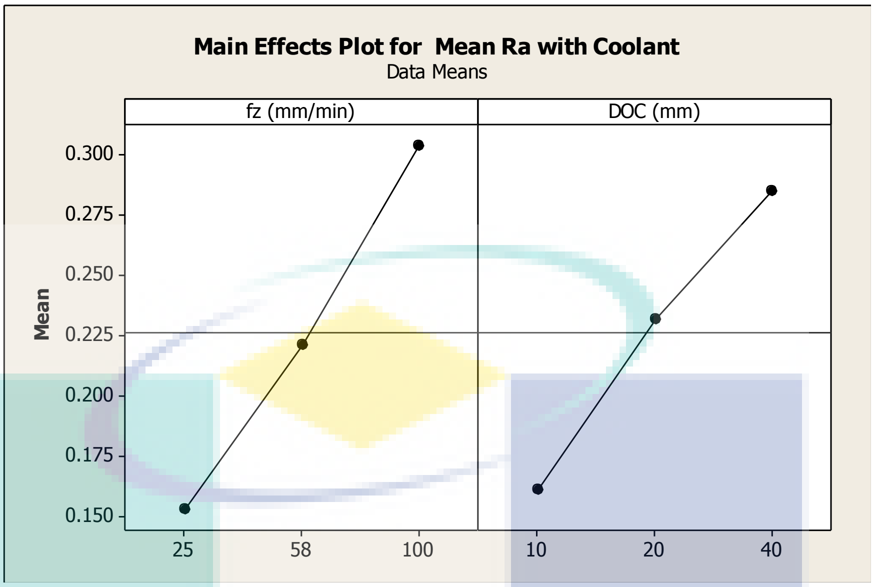


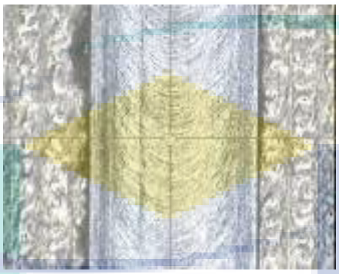
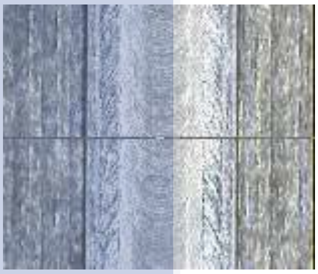
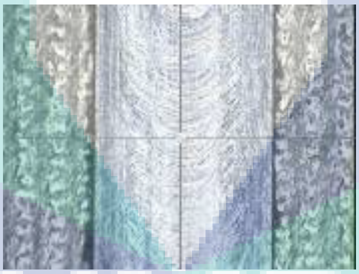
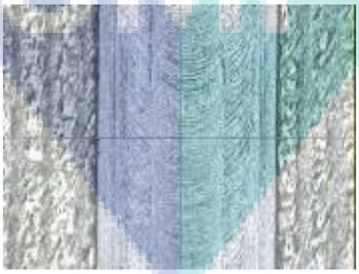
Figure 2.7: Main effect plot for mean *Ra* with coolant

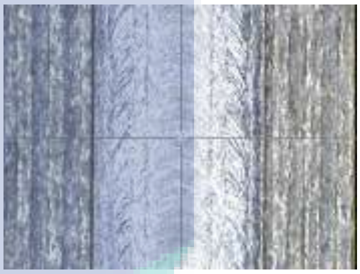
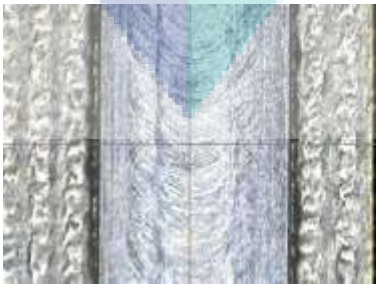
When making comparison between mean of *Ra* with coolant and without coolant, it shows that the mean of *Ra* for *fz* with coolant is higher than without coolant. It is same goes to the DOC. This is maybe happens due to some vibration occurs because of high volume of coolant used.

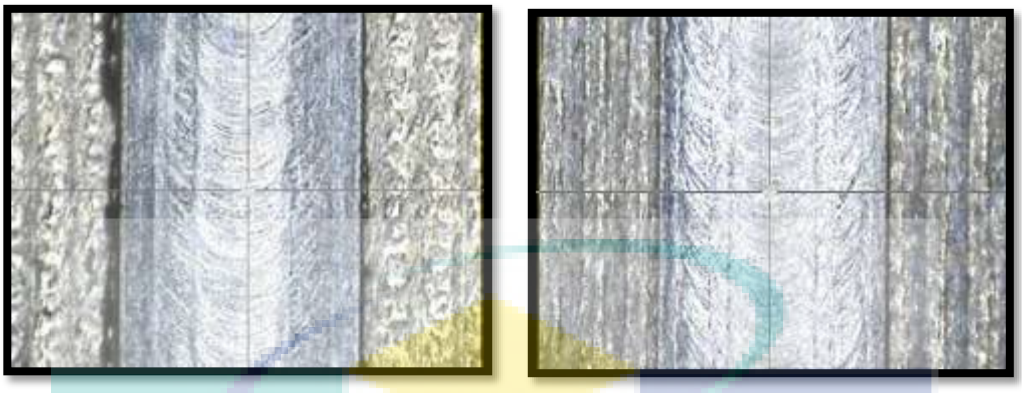
2.5.4 Effect of Coolant on Surface Quality of Ti-6Al-4V

Milling operations will leave some milling marks to surface of workpiece. Due to occurrence of milling marks, surface quality of workpiece is not good. In this study, the comparism of surface quality was making between machining using coolant and without coolant. Table 2.6 below shows the result obtain from the observation of surface quality respect to the feed rate and depth of cut by constant spindle speed for nine run of experiment. It compares the surface quality of experiment conducted without using coolant and with coolant.

Table 2.6: Results of surface quality observations

Slot no.	Feed rate (mm/min)	Depth of cut(mm)	Without coolant	With coolant
9	58	20	 *Ra*=0.161 μm	 *Ra*=0.250 μm
7	100	40	 *Ra*=0.195 μm	 *Ra*=0.425 μm
3	58	40	 *Ra*=0.162 μm	 *Ra*=0.260 μm
4	100	20	 *Ra*=0.191 μm	 *Ra*=0.290 μm

6	58	10	 *Ra*=0.131 µm	 *Ra*=0.153 µm
1	100	10	 *Ra*=0.146 µm	 *Ra*=0.195 µm
8	25	10	 *Ra*=0.109 µm	 *Ra*=0.135 µm
2	25	20	 *Ra*=0.116 µm	 *Ra*=0.155 µm
5	25	40	 *Ra*=0.126 µm	 *Ra*=0.170 µm



(a) (b)

Figure 2.8: Comparism of milling marks, (a) Without coolant (b) With coolant

When comparing surface texture of Ti-6Al-4V using coolant and without coolant as shown in figure 2.8, machining without coolant shows better surface quality compared to using coolant because it shows less milling marks on the surface of Ti-6Al-4V. Other than that, there is no burr formation observed on the surface of Ti-6Al-4V because the tool used is very small tool which is 1 mm diameter. Burr formation will only exist if the diameter of tool used is larger.

CHAPTER 3

(This result presented in International Conference on Production, Energy & Reliability 2016 and published in ARPN Journal of Engineering and Applied Sciences 2016)

MICRO-MILLING OF THIN MOULD FOR CONTINUOUS PRODUCTIONS OF POLYMER MICROFLUIDIC DEVICES

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ABSTRACT

This paper reports an attempt to produce thin embossing mould by using micro-milling process and subsequently tested in fabricating polymer microfluidic devices using hot roller embossing process. Two embossing moulds with thicknesses of 260 µm (thin) and 500 µm (thick) made of Al6061-T6 are fabricated using micro-milling process. The thin and thick moulds subsequently will be used for hot roller embossing process and conventional hot embossing process respectively to produce PMMA microfluidic devices. The performance of the micro-milled thin embossing mould in the hot roller embossing process will be compared with the thick mould used in hot embossing process. The diamond end-mill tool is used for finishing the profile in order to reduce burr formations. The adhesive will be used to hold the thin and thick workpiece in the fabrication of moulds. The experimental results show that the micro-milling is capable to create the features necessary for a microfluidic in thin embossing mould. The thin embossing mould with thickness of about 160 µm with feature height of about 100 µm has been produced successfully using the micro-milling process. The surface quality of the thin embossing mould produced by micro-milling and held using adhesive is comparable with the thick mould.

Keywords: micro-milling, hot roller embossing, and thin mould

INTRODUCTION

Polymer microfluidic devices are micro analyser tools used in monitoring and analysis of chemicals, such as sample collection, pre-treatment, amplification and detection, all to be performed in one easy to handle as if in a standard laboratory. In the current trend, most of the polymer microfluidic devices are disposable to avoid any contamination due to reuse and inadequate cleaning during sterilization; therefore they require materials and fabrication methods that are low cost and are of high precision and high volume.

A continuous manufacturing process is thus necessary in order to reduce cost, increase the productivity while providing flexibility to make different types of microfluidic devices. One example of such a continuous process is the hot roller embossing process Figure-1. The hot roller embossing is a potential method to increase the productivity of polymer microfluidic devices fabrication through replication techniques.

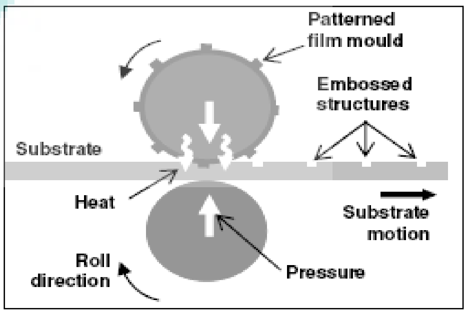

Figure-1. Hot roller embossing process [1]

The positive features patterns that transferred onto the polymer sheet material as channels features can be made directly on cylindrical roller surface or made on thin sheet (thin embossing mould). In the case of the thin mould, it is wrapped and mounted around onto the cylinder roller and as the polymer sheet is passing through; it will transfer the micro-features patterns onto the polymer material. In this kind of method, the embossing mould should be flexible enough to wrap onto a roller and in addition should be durable for continuous imprinting and have sufficient modulus and strength to transfer the features to the substrate [2].

Whereas the conventional hot embossing process is a batch process which has long thermal cycle of heating, holding, and cooling, hence it is inefficient for mass production. Roller embossing process offers some advantages compared to the conventional hot embossing such as better uniformity, less force and ability to repeat a mould continuously on a large substrate [3].

Several manufacturing processes to produce thin embossing mould have been proposed in the literature such as dry etching [4], lithography [5], electroplating [1], and *UV-LiGA* (*Ultraviolet - **Li**thographie **G**alvanoformung **A**bformung*) [6]. These processes have successfully fabricated moulds with thicknesses down to 50 µm. However, these processes are expensive, involve hazardous chemicals and have a long series of stages including creating custom masks that require tight tolerance control [7]. Alternatively, the thin embossing mould can be manufactured by the mechanical micro-machining process such as micro-milling. Application of micro-milling with uniform fixturing on the surface area of the sheet is a new method to produce features on a thin mould to be used for roller embossing. The micro-milling process has the capability of producing the necessary micro-features in the embossing mould, with a possibility of producing thin embossing mould for roller hot embossing process.

However several challenges of the micro-milling especially for thin workpieces have to be studied such as reducing burrs, fixturing method and its effects. The micro-milling process is such a complex process in which the quality of micro-milled workpiece depends on the effects of machining parameters, tool geometry and workpiece materials. It is thus important to investigate these aspects in order to produce flexible continuous roller embossing mould. Producing thin features at the micro size is not only important in the embossing mould applications but can also be applied to other micro engineering applications such as housings for mechanical micro-devices and surgical instruments [8]. Hence, the objective of this work is to understand the thin mould fabrication using micro-milling, hot roller embossing and measurement methods related to the fabrication of embossing moulds. The observations in this study will be focusing on the mould quality and the surface finish of the milled parts and feature edges.

EXPERIMENTAL SETUP

The micro-features to be created in the mould were selected in order to represent common shapes found in the microfluidic devices and also to challenge the capability of the micro-milling process. Figure-2 shows the mould design used in this experiment, where the lines representing the micro-features consist of channel and circular region. The channel height (t_0) is 100 µm and width is 100 µm. The overall embossing mould size is 50 mm x 50 mm. Two moulds are produced with two thicknesses (t_I) of 500 µm and 260 µm in order to represent the thick and thin moulds used for conventional hot embossing and roller embossing processes respectively. The 260 µm thick workpiece is produced by reducing the thickness of a 500 µm thick workpiece using single point diamond turning (SPDT) process. The 260 µm thick workpiece is selected to give higher ratio of feature height (t_0) to the machined thickness (t_w). In addition, this thickness is considered not to be too thin to avoid damage and to get stronger moulds but also not to be too thick which is difficult to bend onto the cylinder roller. Fabrications of the thick and thin embossing moulds consisting of micro-features were conducted using a 3-axis machining centre (Mikrotools multiprocessing machine DT110).

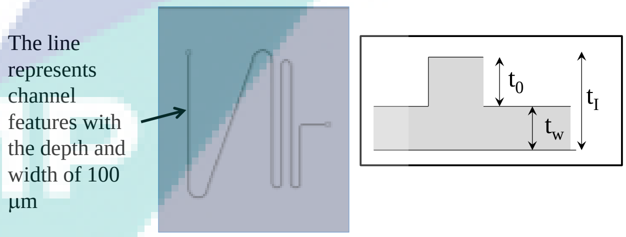

Figure-2. Embossing mould design (left) and mould cross section to illustrate mould thickness (t_I), channel height or depth of cut (t_0) and machined thickness (t_w) (right).

<u>*Workpiece and tool materials*</u>. The mould material is aluminium Al6061-T6, two types of cutting tools were used: a two-flute end mill made of tungsten super micro grain carbide tool and a diamond end-mill tool. Most of the material was removed by pocketing methods using micro-milling tungsten super micro grain carbide tools except for the generation of the channel and the circular feature which was created by diamond end-mill tool. The pocketing method is the preferred method used in machining thin workpiece [8]. The burrs occurring in the

micro-features are detrimental and can be comparable with the size of the features itself. One of the solutions to avoid and reduce the burrs is by using the sharp tool, i.e. diamond tool. The diamond tool has sharp and small edge radii compared to carbide milling tool.

Cutting Parameters. Cutting parameters used in the experiment are shown in Table-1. The cutting is conducted in four passes with each pass having an axial depth of cut of 25 µm to give total axial depth of cut (t_0) of 100 µm. These resulted in t_0/t_w of about 0.625 for the case of 260 µm mould thickness (t_I) (Figure-2). The ratio is considered as being high because the depth of cut (t_0) is comparable to the final machined thickness (t_w). The machining time for one embossing mould is less than 30 minutes which is considered as being fast when compared to other fabrication processes, while the time to enter the input parameters and code to the machine was about 2 hours. The comparison study between micro-machining (micro-milling) compared to other methods such as MEMS (DRIE and electroplating) have been conducted by Kang and Ahn [9]. Their results show that micro-machining process is faster and produces cheaper mould when compared to MEMS based processes. The workpiece was held using 30 µm thick adhesive on workpiece holder at the bottom, in order to avoid slip-off. The adhesive is subsequently removed by dipping in to the *acetone*. Subsequently, the hot embossing and hot roller embossing process are conducted to study the performance of the different mould thicknesses.

Table-1. Milling Parameters.

Workpiece	Al6061-T6
Pocketing parameters	
Tool	Tungsten super micro grain carbide tool diameter 1 mm
Feed rate	100 mm/min
Axial depth per cut	25 µm
Spindle speed	40,000 rpm
Total depth of cut (t_0)	100 µm
Milling direction	down milling
Cutting condition	dry cutting
Finish profiling parameters	
Tools	Diamond end-mill diameter 0.5 mm
Feed rate	50 mm/min
Axial depth per cut	25 µm
Spindle speed	20,000 rpm
Total depth of cut (t_0)	100 µm
Cutting condition	dry cutting

The machined embossing moulds produced by micro-milling were visually analysed using a Scanning Electron Microscope (SEM) JEOL 5600 to observe the quality of the micro-features. Surface roughness is also measured on the machined embossing moulds using a Taylor Hobson Talyscan 150 surface profiler whereas the height and profile measurements of the moulds and embossed polymer are conducted using Confocal Image Profiler.

RESULTS AND DISCUSSIONS

Visual Observations

The thick and thin moulds were successfully produced using micro-milling. In the macroscopic view, the thin mould shows relatively little warping compared to the thick mould (Figure-3). The surface conditions and the micro-feature shapes are relatively similar. During the milling process, large amounts of material are removed and leaving the remaining channel features around the centre region. This removal and the stress induced by the milling process disturb the equilibrium state and furthermore induce warping or deflection if the workpiece is too thin especially when the depth of cut is comparable to the workpiece thickness. In addition, if the stresses are high enough this can cause damage or slip off during the milling process [10]. However, the application of the uniform adhesive to hold the workpiece was seen to avoid the occurrence of any slipping during the milling process.

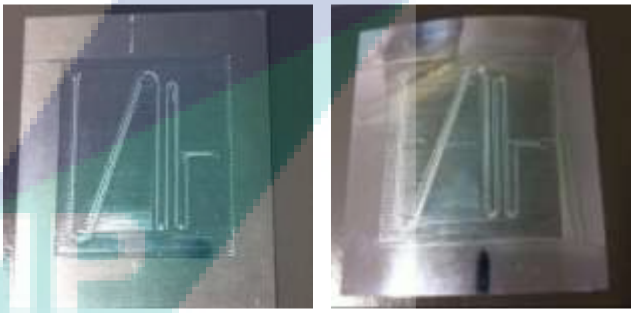

Figure-3. The 500 µm (left) and 260 µm (right) micro-milled mould.

The locations chosen for measurements of the surface roughness, observation of the milled mould micro-features and the SEM micrographs for different mould thicknesses are shown in Figure-4. The micrographs show that channels produced on the 500 µm thick mould has better surface and edge quality. In contrast the channel on the 260 µm thick mould show a little rough surface especially in the wall of the channel with no sign of burrs seen in the edges of viewed locations (Figure-5). These results show that the use of a diamond milling tool improved significantly the results as compared to the use of straight carbide milling tool.

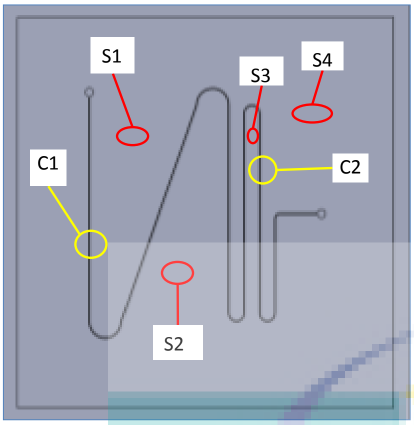

Figure-4. Location of the surface roughness measurement (S1, S2, S3 and S4) and surface profile (C1 and C2).

Surface Roughness

The surface roughness measurements were conducted at four different locations chosen to represent different areas of the milled surface (Figure-4). The three dimensional arithmetic average roughness (S_a) of the milled surfaces was measured using a Taylor Hobson Precision Talyscan 150 surface profiler. Surface roughness measurements of the milled surfaces revealed that the 260 µm thick mould has comparable values with the 500 µm thick one (Table-2).

In most of the measured areas, the S_a value of the thin workpiece is higher than the thick workpiece, except in region S3 where the S_a value was lower. In the thick mould, region S3 has the highest surface roughness compared to other region. In contrast, region S3 has the lowest surface roughness value in the thin mould. The differences of surface roughness value of region S3 can be occurred due to the different milling strategy used in that region [8]. In the smaller area such as region S3, milling tool moves in the path parallel with the length of the channel and has smaller step in between each line of the tool path. This strategy may give different surface roughness values. The surface roughness values of four different locations selected to be measured show no major variations for thick and thin moulds.

Table-2. Surface roughness measurements (S_a) of the moulds in µm

Region	Thick (500 µm)	Thin (260 µm)
S1	0.039	0.059
S2	0.047	0.072
S3	0.101	0.033
S4	0.044	0.049
Average	**0.058**	**0.053**

The results show the use of carbide milling tool with a diameter of 1 mm is sufficient to remove large areas of the part in the pocketing process with correct machining parameters. The adhesive as the fixture method is sufficiently strong to hold the thin workpiece. In addition, embossing moulds do not require very fine surface roughness [11] especially on the floor in order to provide good bonding between the flat polymer plate and the embossed polymer plate to obtain a good polymer microfluidic devices set.

Profile Measurements

In addition, the surface profile measurements were conducted using a Confocal Imaging Profiler at two different locations selected on the channel features, one of the results is shown in Figure-5. From the 2-D views, the height of the channel feature for the thick mould is seen to be about 110 µm whereas the height of the thin mould is relatively higher at about 120 µm.

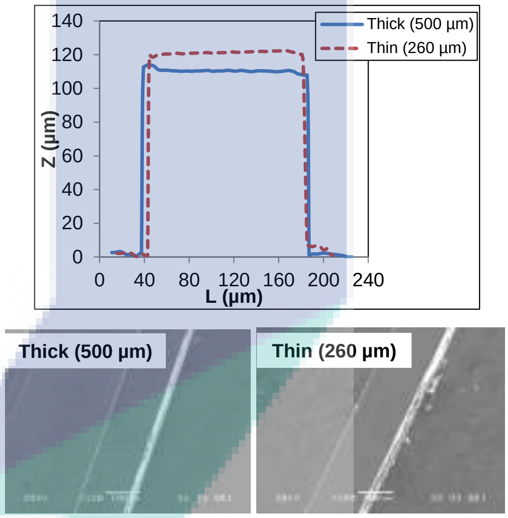

Figure-5. Channel C1 profile of the thick (500 µm) and thin (260 µm) and the SEM images.

The higher profile of the channel might occur because of the high axial force experienced by thin workpiece during milling process. The adhesive is not rigid enough at certain locations to withstand the axial forces exerted by the milling tool resulting in the thin workpiece getting pushed down by the tool. However, the results indicate that the machining of the thin workpiece is very sensitive to the uniformity of the fixturing forces and strength of the fixture.

Conventional Hot Embossing and Hot Roller Embossing

Conventional hot embossing and hot roller embossing experiments were performed to emboss the moulds on to a 1 mm thick *Polymethylmethacrylate*

(PMMA) sheet. The conventional hot embossing Carver Manual Press 4386 is used for embossing of polymer microfluidic devices using the thicker mould (Figure-6). The embossing was conducted with the plate temperature of 110 ^{o}C, with the applied pressure 2 tons for about 10 minutes. The hot roller embossing using the thin mould was conducted using lab scale hot roller embossing machine (Figure-6). The thin mould (260 µm) is wrapped and attached to the roller. The hot roller embossing process was conducted with the following parameters: pre-heat PMMA to a temperature of 125 ^{o}C for about 60 seconds, the pressure applied is 0.6 MPa, the roller speed is 9.31 mm/s and the mould is at room temperature.

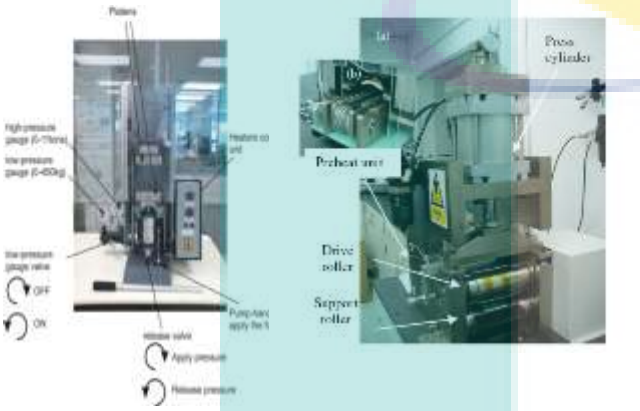

Figure-6. The conventional hot embossing Carver Manual Press 4386 (left) and the lab-scale hot roller embossing machine [12] (right).

In general, the embossed PMMA reveal similar features resembling its embossing moulds. As seen in Figure-7, the PMMA embossed using the 500 µm thick mould exhibits replication of milling marks on the floor of the channel side. In contrast, PMMA embossed using the 260 µm thick mould exhibits no sign of milling mark.

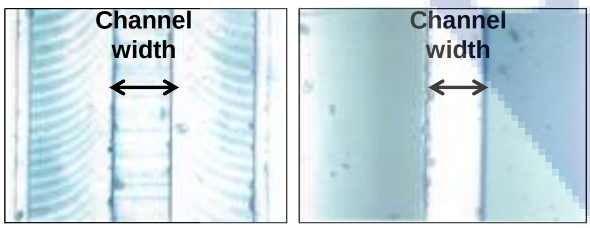

Figure-7. Optical Microscope images of the channel section on the embossed PMMA produced by 500 µm mould (left) and 260 µm mould thicknesses.

The channel depths are measured using a Confocal Imaging Profiler. As shown in Figure-8 the channels on the PMMA produced using the 500 µm thick mould visually have a better shape than the channels on the PMMA produced using the 260 µm thick mould and replicate similarly with the features in the mould. In addition, the depth of the channel on the PMMA formed using the thick mould is about 100 µm whereas the depth of the channel formed using the thin mould is only about 20 µm depth. The shallow channel depths on the embossed PMMA produced using hot roller embossing might occur because of the parameters used for the process are not optimized. This also explains the optical microscope images show in Figure-6 where milling mark can be seen clearly on the embossed PMMA produced by hot plate embossing and no sign of milling mark on the embossed PMMA produced by hot roller embossing due to the shallow depth of the channel. The channel depth in the hot roller embossing process can be increased by optimizing the embossing process and reducing the roller speed [12]. Accordingly, further roll embossing studies are needed in order to find these optimum conditions to increase and improve the replication results on the embossed PMMA.

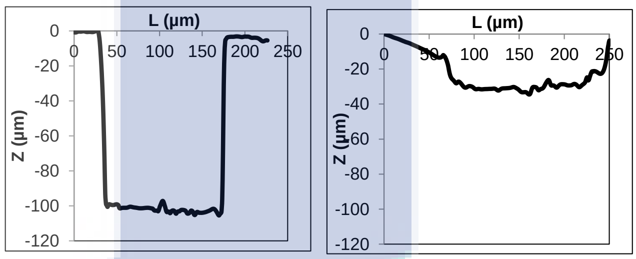

Figure-8. Channel C1 profile of the embossed PMMA produced by thick, 500 µm (left) and thin, 260 µm (right).

CONCLUSIONS

The fabrication of thin embossing mould produced by micro-milling and followed by hot roller embossing has been conducted to understand the mould performance. Some of the main findings are stated below:

- A thin mould with the machined thickness of about 160 µm with feature height of about 100 µm has been produced successfully using the micro-milling process.
- Visual observations, surface roughness measurements and profile measurements on the thick and thin moulds show that the surface quality of the thin embossing mould produced by micro-milling and held using adhesive is comparable with the thick mould.
- The embossed PMMA shows that the thin mould produced by micro-milling is capable to be used in the hot roller embossing applications. Although, the features are not perfectly transferred to the embossed PMMA due to the non-optimized roller process parameters the results prove the capability of the micro-milling process to create the features necessary for a microfluidic in thin embossing mould.

- The importance of the workpiece holder to produce good quality thin embossing moulds by micro-milling is also pointed out in this work. The application of the adhesive as the fixture method is necessary to avoid the vibration problems and to obtain the uniformity of the surface and features quality of the thin machined moulds.

ACKNOWLEDGEMENT

The author would like to thank to Assoc. Prof. Sathyan Subbiah from Department of Mechanical Engineering Indian Institute of Technology Madras India and Dr. Liu Kui from Singapore Institute of Manufacturing Technology for their supports.

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CHAPTER 4

(This result presented in: Advances in Material & Processing Technologies Conference 2017, published in Procedia Engineering)

Burr Reduction of Micro-milled Microfluidic Channels Mould Using a Tapered Tool

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Abstract

Moulds with micro-sizes features needed for many applications, such as for hot embossing, can be manufactured using micro-milling process. However, the burrs formed in the micro-milling process are a challenge that needs to be addressed. The burr sizes are comparable to the micro-milled feature sizes and the common types of burr seen being the top/side and exit burrs. The use of a tapered geometry micro-milling tool is investigated in this paper that enables reduction in both the top and exit burrs. The straight and tapered micro-milling tools of various angles are used and the burrs formed are observed. Micro-milling experiments are conducted on an aluminium alloy by producing common positive features seen in the mould for the production of polymer microfluidic devices. The results show that the burr reduction can be attributed due to the increase of the taper angle. It is seen that the tapered tool not only substantially reduces the top burrs, but also leaves behind inclined walls which further help in reducing exit burrs formed during the subsequent finish face milling. Furthermore, embossing trials performed with the micro-milled tapered geometry moulds show improved performance not only because burrs are reduced and also because the taper eases mould release.

Peer-review under responsibility of the organizing committee of the Advances in Material & Processing Technologies Conference.

Keywords: burrs; micro-milling; tapered; mould; microfluidic devices

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1. Introduction

Burr formation is a common problem that occurs in micro-milling. In the micro-milling process, the burr size can become comparable to the features being created. The two main types of burrs occurred in micro-milling are: (a) the burr attached to the surface machined by the minor edge of the tool which is exit burr and (b) the burr attached to the top surface of the workpiece which is called a top/side burr [1]. In general, there are two approaches reported in the literature to overcome the burrs. One way is to remove the burr (deburring [2]) after the machining and the other is to reduce the tendency for burr formation during the machining process.

Removing the burr on the micro-scale features produced by micro-milling is challenging; it must be performed carefully to avoid damage to the features themselves. Incorrect selection of deburring techniques or parameters also may introduce dimensional errors, damage, surface finish, and residual stresses. Many researchers have explored and reported burr reduction through different

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machining strategies. Formation of burrs in ductile materials can also be reduced using sharp single crystal diamond cutting tools with very small edge radii; diamond micro-milling tools are commercially available in the market but are expensive and require good vibration control and precision on the machine tool for effective usage.

It has been reported that by strengthening the edge of the machined wall using tapered milling tools can reduce the burrs formation [3]. In this paper, the application of tapered shape geometry micro-milling tool in fabricating the common micro-channel features exist in the microfluidic devices is studied. The micro-channel features are selected to represent a typical feature seen on an embossing mould used in the hot embossing process in the production of polymer microfluidic devices. Polymer microfluidic devices are micro analyzer tools used for integration of monitoring and analysis of chemicals, such as sample collection, pretreatment, amplification and detection, all to be performed in one easy to handle as if in a standard laboratory. The integration offered by the polymer microfluidic devices is advantageous in that it can reduce the consumption of the chemical samples that may be rare and expensive, provide faster and more accurate analysis, offer simplicity of use, provide higher sensitivity, and offer lower cost compared to conventional devices [4]. The embossing mould for the production of polymer microfluidic devices can be fabricated using micro-milling process. The micro-milling process can produce faster and cheaper moulds when compared to lithography and MEMS based processes [5].

In addition, the effect of the subsequent finish face milling pass on the top burrs and surface quality of the positive features produced by tapered tools is also studied. Lastly, hot embossing trials using moulds made of tapered micro-milling tools are also performed to study the efficacy of the burr reduction technique. Therefore, this work is needed to be conducted especially for ductile materials using carbide tools, to confirm that use of tapered tool can solve the burr problems during fabrication of embossing mould using micro-milling.

2. Experimental Setup

The micro-channel feature is adopted as the experimental features to be produced by slot micro-milling followed by a finish face milling pass. By increasing the edge angle between the wall of the slot and the top surface, the top burrs are expected to decrease (Figure 9 (a1 and b1)). The formation of the higher edge angle also strengthens the edge, which can lead to the reduction of exit burrs on the top surface of channel by the subsequent finish face milling pass (Figure 9 (a2 and b2)). The micro-milled micro-features designs in the experiments are shown in Figure 10. The designs were selected to represent a typical feature seen in microfluidic devices. The proposed design for the straight wall mould consists of a protruded straight wall with a rectangular cross-section (100 µm width and 100 µm depth) connected to a cylindrical protrusion with a 1 mm diameter and 100 µm depth. Meanwhile the tapered mould consists of a trapezoidal cross section straight protruded wall with a top width of 73 µm and depth of 100 µm. This is connected to a conical frustum protrusion with the same depth.

The channels were manufactured by slot micro-milling process using a straight end-mill (0.8 mm diameter) and various tapered end-mill (with a bottom diameter of 0.5 mm) of carbide milling tool (Figure 11). The wall angle is varied by varying the taper angle of the micro-milling tool from 15^0 to 50^0. In order to observe the effect of the additional finish face milling, the channel is micro-milled with excess depth (50 µm), and this was subsequently removed using a straight 2.5 mm diameter milling tool. Two channel features were made using each tool in order to observe the effects of taper angle and additional finish face milling pass on the burr formation and surface quality. Subsequently, the hot embossing process is conducted to study the performance of the mould consisting of micro-features produced by various taper angle and additional finish face milling.

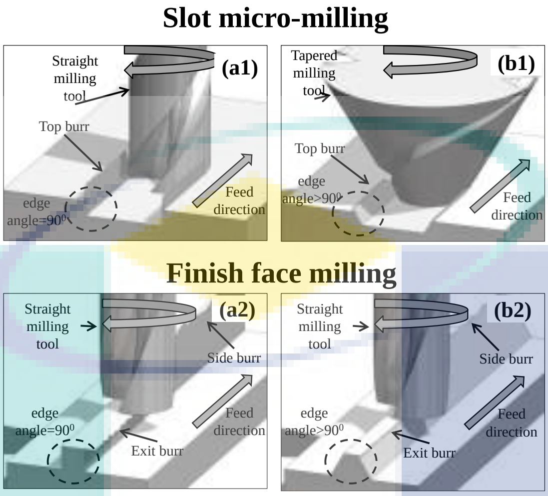

Figure 9. A tapered tool (b1 and b2) is expected to reduce top burrs formed and help in reducing the exit burrs formed in the subsequent finish face milling compared to a non-tapered tool (a1 and a2).

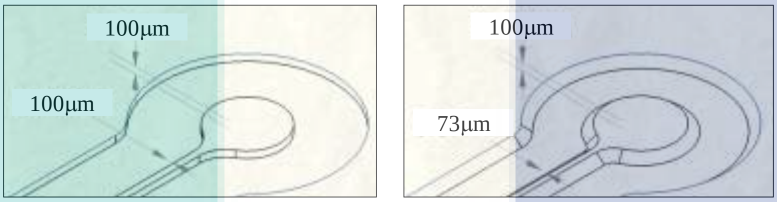

Figure 10. Mold designs with straight wall (left) and tapered walls (right).

Experiments were conducted to produce the micro-channel features by micro-milling process using a Mazak FJV-250 3-axis conventional CNC machine. The Al6061-T6 block workpiece was milled flat using 4 mm diameter milling tool. Preliminary experiments are conducted to determine the optimum parameters for the micro-channel milling and finish face milling process. Based on these results the micro-milling slot parameters for micro-channel and finish face milling parameters to be used are listed in Table 3. Micro-milling of channels under dry conditions is undertaken at a spindle speed of 10,000 rpm and a feed rate of 25 µm/rev. All experiments were conducted in dry cutting condition. The micro-channels and burrs were observed using a scanning electron microscope (SEM) JEOL 5600L.

Figure 11. Micro-milling tools, from left to right: straight tool, 15^0, 30^0, 40^0 and 50^0 tapered tools.

Table 3. Experimental conditions.

Workpiece	Al6061-T6
Milling tools	Two flute end mills super micro grain carbide tool 0.8 mm diameter (straight) 0.5 mm bottom diameter tapered tool with 15°, 30°, 40° and 50° taper angle 2.5 mm diameter (straight) for finish face milling
Slot micro-milling of micro-channels	
Feed rate	250 mm/min
Axial depth per cut	25 µm
Spindle speed	10,000 rpm
Total depth of cut	100 µm (without finishing pass) 150 µm (with finishing pass)
Cutting condition	Dry cutting
Finishing face milling	
Feed rate	500 mm/min
Axial depth per cut	25 µm
Spindle speed	10,000 rpm
Total depth of cut	50 µm
Cutting condition	Dry cutting

3. Results and Discussions

3.1. The influence of tapered channels design on a mould

The proposed tapered design when implemented in an embossing mould has some design implications such as in the final microfluidic device, since the taper geometry changes the channel width and/or the cross sectional area. In order to maintain the same flow rate of the fluids through the channels, it is expected that the channel cross-section size produced by the tapered micro-milling tool should be in the same range as that in a non-tapered channel design. However, by keeping the width at the top of the channel to be the same, the width of the bottom channel can now be increased because of the taper tool angle (Figure 12). The width of the channel (L) with a value of 73 µm is selected for tapered tool in order to maintain slenderness of the channel by proportionately maintaining the ratio of the channel height to the width. High aspect ratio can weaken the mould resulting in mould damage during embossing mould and shorten its useful life. Microfluidic channels with angled walls are reported in the literature [6], where the embossing moulds were made in Silicon by wet-etching. The etched plane preference causes sloped walls in the Silicon channels. It is reported that such sloped walls result in better mould release and hence leads to better embossed features; also the edges are now stronger resulting in less edge breakage. Table 4 shows the channel cross-sectional areas and the differences for various taper angles compared with a non-tapered channel design.

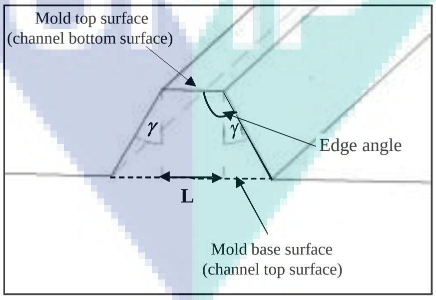

Figure 12. Cross-section of the channel.

Table 4. Cross-section area of the channel.

Taper angle □ (°)	*Edge angle*	*L* (µm)	Channel Cross-section area (µm^2)	Cross-section Difference (%)
0	90	100	10,000	0
15	105	73	9,979	-0.21
30	120	73	13,074	30.74

40	130	73	15,691	56.91
50	140	73	19,218	92.18

3.2. Micro-channels Features

3.2.1. *Effect of milling direction:* Experiments conducted with slot milling in the up milling direction and down milling direction showed severe differences in top/side burr formation. Top burrs are seen to be much more severe when slot milling in the down milling direction. This was seen to be the case for both straight milling tool and the tapered milling tool (Figure 13). However, the opposite was true for the side wall surface finish appearance. The side wall finish was visibly better in SEM micrographs with down milling than with up milling; again this was true regardless of whether the tool was straight or tapered. The side wall produced using up milling reveals regular jagged like shape associated with the milling mark pattern [7]. Hence, in the subsequent parts, the discussions are focused mainly for the results when using down milling process.

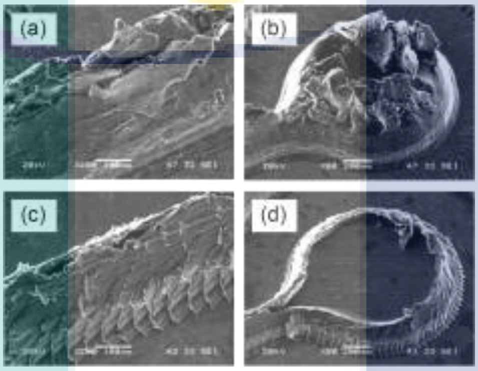

Figure 13. Effect of milling direction (15^0 tapered tool, before finish face milling pass) (a), (b) Down milling (c), (d) Up milling. Down milling is seen to produce more severe top/side burrs.

3.2.2. *Burr formation using straight milling tool:* The burrs on the edges of the milled features when using a straight micro end mill can be seen in Figure 14. The burrs are seen to be very severe with dimensions comparable to the wall height (Figure 14(a) (b)). Burrs are seen to be severe both in the straight wall and in the cylindrical protrusions. After undergoing the finish face milling pass, the top burrs generated earlier are replaced with exit burrs (Figure 14(c) (d)). The edges also appear broken and the top burrs are seen to be fairly severe enough to interfere with the embossing process.

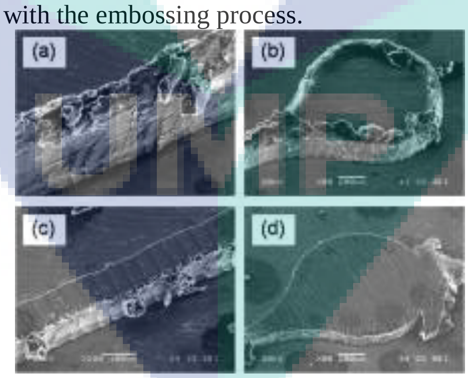

Figure 14. Burrs in straight wall feature mold. (a), (b) Before finish face milling pass; top burrs generated from the slot milling are comparable to the channel itself. (c), (d) After finish face milling pass; exit burrs generated from the finish face milling pass can be seen clearly.

3.2.3. *Effect of taper angle:* The effect of the taper angle in reducing the top burr formation during slot micro-milling and exit burrs during the subsequent finish face milling pass can be observed in Figure 15 and Figure 16 respectively. As the tool taper angle is increased from 15^0 to 50^0, the top burrs formed both in the channel section and in the cylindrical protrusion section of the moulds decreased substantially. From the micrographs of Figure 15 it is not very evident that the top burrs have decreased in the channel sections because of the viewing angle and the proximity of the burrs from both edges. The results are more easily evident in the conical frustum protrusion portion of the mould. Higher the taper angle, lesser are the top burrs formed during the slot micro-milling process. In addition, after the finish face milling pass, the exit burrs generated are minimized as the taper angle is increased (Figure 16). Again, as the taper angle increases the burr condition at the edges is less. It may very well be possible that a finish face milling pass may not be necessary if the process parameters is optimized further.

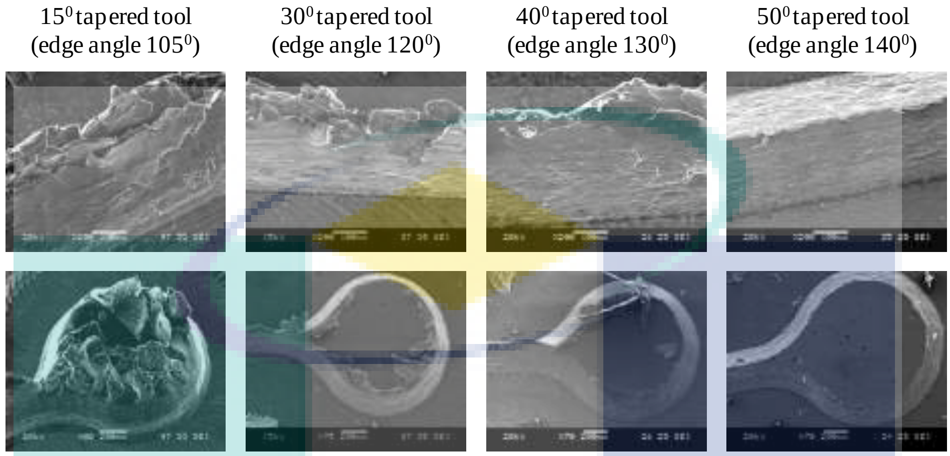

Figure 15. Effect of taper angle on top/side burr formation on the micro-features. The top row shows the channel section of the mould and bottom row shows the conical frustum protrusion section of the mould. The reduction in top burr formation with increasing taper angle is evident.

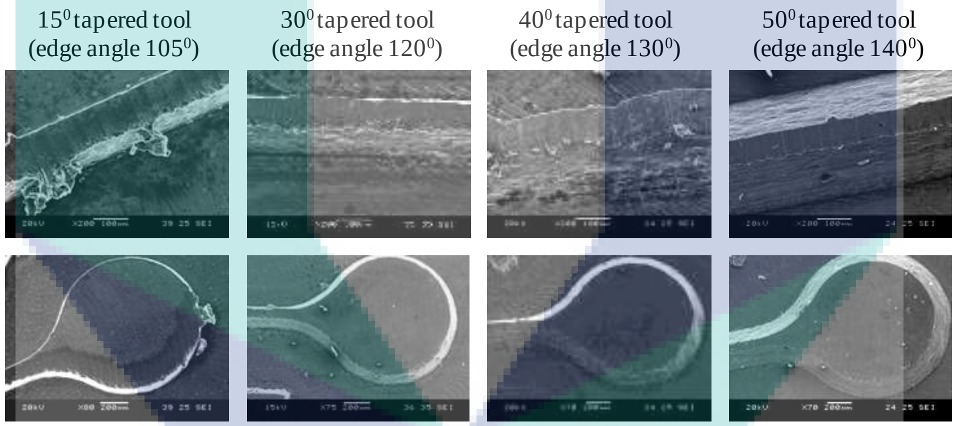

Figure 16. Effect of taper angle on exit burr formation on the micro-features followed by finish face milling pass. The top row shows the channel section of the mould and bottom row shows the conical frustum protrusion section of the mould. The reduction in exit burr formation with increasing taper angle is evident.

The results obtained above with higher taper angle and minimal burrs are surprising given that the milling was performed without any coolant. Hence, if there is flexibility in designing the microfluidic channels with tapered walls, then it is possible to economically make these micro-channels for moulds such as for embossing using conventional carbide cutting tools on conventional CNC machining centres. It is noted that the 50^o taper channel has resulted in an increase in cross sectional area by 92.18% (Table 4) while the burrs are the lowest when milling the channel of this geometry (Figure 15). Increasing the width of the channel affects the final size of the complete microfluidic device, especially in the case of a complex design with parallel multiple flow channels. This impact needs to be considered when designing the microfluidic device embossing mould using tapered micro-milling tool since there may be a limitation in the size of microfluidic devices required for certain applications.

3.3. Hot plate embossing

In order to observe the performance and quality of the different features produced with and without taper shape, embossing trials were performed. The machined mould consists of micro-features was subsequently transferred onto a polymer substrate such as PMMA (*Polymethylmethacrylate*) by hot embossing. PMMA is the most commonly used polymer for moulding applications because of its biological compatibility, its optical properties and ease of moulding [8]. It is noted that the hot plate embossing is sensitive to temperature, time, and pressure [9]. The embossing process is performed using the hot plate embossing system Carver Manual Press 4386. The PMMA was embossed with the following hot plate embossing parameters: 10 minutes time, base plate temperature 93 ^{o}C, top plate temperature 115 ^{o}C and pressure 10 MPa. The embossing results for straight tool and 50^{o} taper angle tool are shown in Figure 17. The embossed PMMA revealed similar geometry features with its embossing mould.

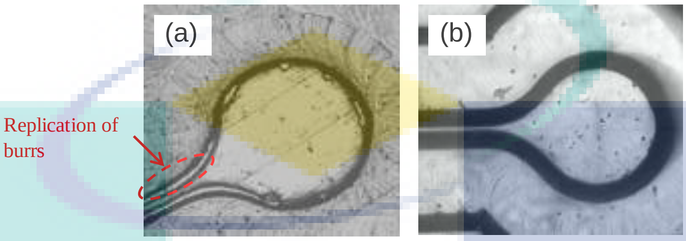

Figure 17. Embossed features on PMMA (a) Embossing mould produced using straight tool, (b) Embossing mould using 50^{o} taper angle tool, with down milling and without finish face milling pass.

As seen in Figure 17, the embossed PMMA with straight wall exhibits replication of burrs especially at the edges of the micro-features. In contrast, the micro-features of the embossed PMMA with 50^{0} taper angle exhibits good results with no sign of burrs. The tapered channel shape also improved the de-embossing process of hot plate embossing. The taper angle provides easy mould release and avoids sticking between the embossing mould and PMMA. Hence, the tapered mould design may have potential advantages in mass manufacturing the polymer microfluidic devices.

4. Conclusions

The main conclusions of this work are:

- Down milling results in a smoother side wall surface however it produces larger top burrs compared to up milling.
- The burr reduction observed as the taper angle of the micro-milling tools increases with a taper angle of 50^{o} angle shows no burr formation at the top side and has smooth surface on the side wall of the mould.
- The larger machined edge angle created by higher tapered tool angle can help in further reducing the exit burrs formed in the following finishing face milling process.
- Moulds with burr-free micro-features for embossing moulds can be satisfactorily made using tapered micro-milling tools on conventional machining centres. Hot embossing trials using the tapered mould design showed good process performance especially during de-embossing process.

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CHAPTER 5

CONCLUSIONS AND RECOMMENDATION

The purpose of this research is to study micro-milling characteristic on biocompatible materials especially selected material which is titanium alloys material, to optimize the cutting parameters in micro-milling Ti-6Al-4V and to observe surface quality of Ti-6Al-4V material when machining in dry and wet condition.

5.1 CONCLUSION

The study presents the micro-milling characteristic on titanium alloy materials. Ti-6Al-4V is very hard material for machining operation. The machining parameters need to be decided carefully to avoid loss effect from broken tool. The factor that gives the effect most to the surface roughness of Ti-6Al-4V was determined from the experiment. Based on two parameters used in milling operation, feed rate is the most significant machining parameter affecting surface roughness compared to depth of cut. At higher feed rate, surface roughness is higher and tool will easily break.

The optimum parameter for good surface finish based on this study was determined which is when using feed rate is 22 mm/min and Depth of Cut is 10 µm. The use of lower feed rate and depth of cut will result better surface finish.

While, machining in dry condition or without using coolant shows better surface finish compared to in wet condition. It is affected by the quantity of coolant used during machining operation. Other than that, micro-milling tool for machining in dry condition shows less wear compared to machining in wet condition. Machining in dry condition also shows less milling marks compared to wet condition.

Overall of this project can be concluded as below:

1. The optimum parameter for lower surface roughness based on this experiment is when using lower feed rate and depth of cut.
2. Surface roughness when using coolant is higher compared to without using coolant.
3. Machining without coolant shows better surface quality on the surface of Ti-6Al-4V material compared to using coolant.

5.2 RECOMMENDATION FOR THE FUTURE RESEARCH

Based on the Final Year Project that was done, a lot of experiences were gained throughout conducting this project. From the selection of parameter, the recommendation is to test parameter to the Ti-6Al-4V before proceed for the real experiment to avoid any unexpected things happen such as tool break because the tool is very limited.

Besides, to ensure that depth of cut is accurate to all experiment, it is recommended that to do facing to the workpiece before run the experiment. Inaccurate depth of cut will give effects to the surface roughness.

Other than that, it would be recommended that the used of coolant or lubricant must be consistent in term of volume. It is because the quantity of lubricant gives effect to the machining operation. So, the quantity of lubricant in milling operation is needed to be study further for next research.

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