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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-. The hot roller embossing is a potential method to increase the productivity of polymer microfluidic devices fabrication through replication techniques.

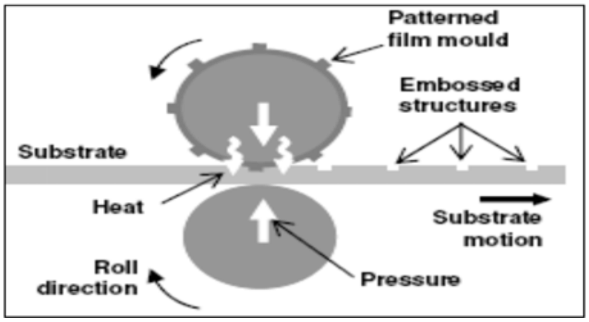

Figure-1. Hot roller embossing process [1].

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- 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).

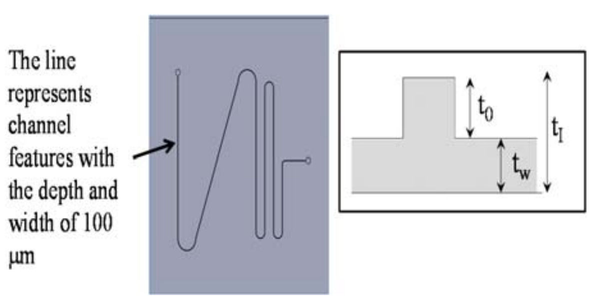

Figure-2. Embossing mould design (left) and mould cross section to illustrate mould thickness (t_I), channel height or depth of cut (t_0) and machined thickness (t_w) (right).

Workpiece and tool materials: 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-. 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-). 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

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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-). 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.

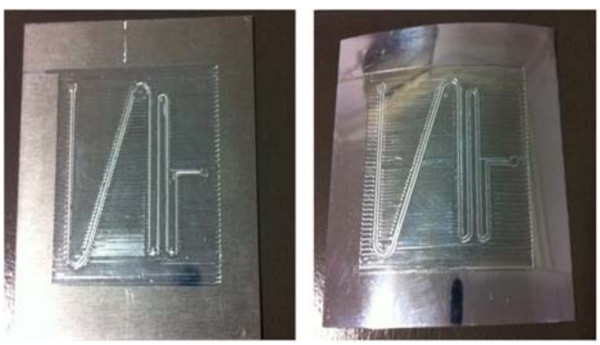

Figure-3. The 500 µm (left) and 260 µm (right) micro-milled mould.

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

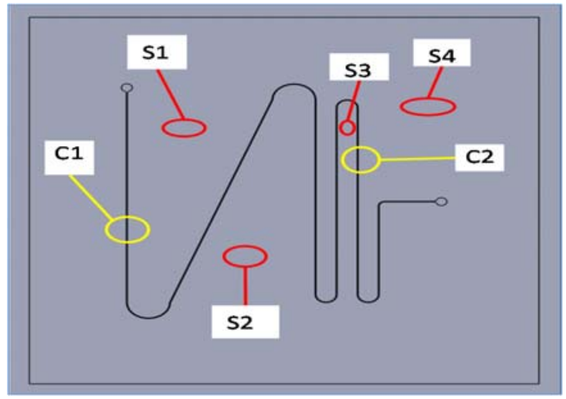

Figure-. The micrographs show that channels produced on the 500 µm thick mould has better surface and edge quality. In contrast the channel on the 260 µm thick mould show a little rough surface especially in the wall of the channel with no sign of burrs seen in the edges of viewed locations (Figure-). 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.

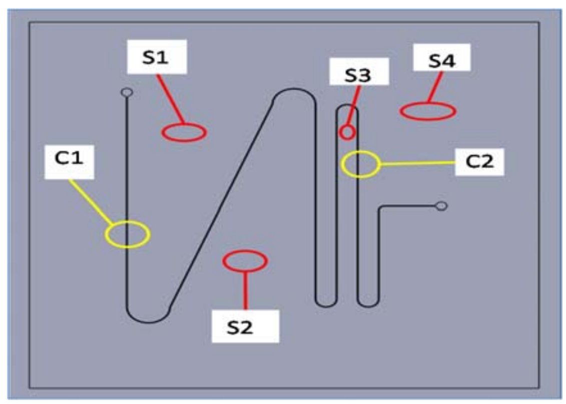

Figure-4. Location of the surface roughness measurement (S1, S2, S3 and S4) and surface profile (C1 and C2).

Surface roughness

The surface roughness measurements were conducted at four different locations chosen to represent different areas of the milled surface (

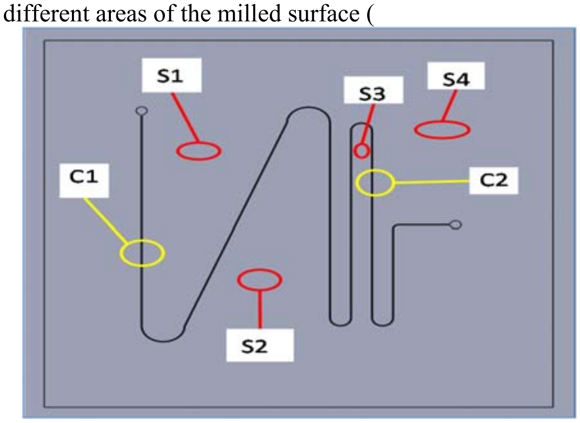

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Figure-). The three dimensional arithmetic average roughness (S_a) of the milled surfaces was measured using a Taylor Hobson Precision Talyscan 150 surface profiler. Surface roughness measurements of the milled surfaces revealed that the 260 µm thick mould has comparable values with the 500 µm thick one (Table-).

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-. 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.

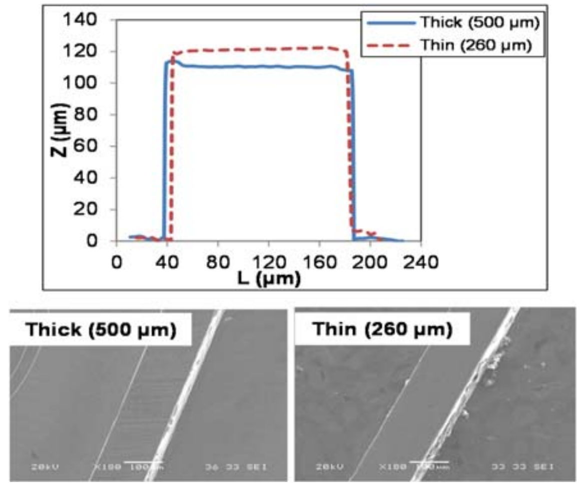

Figure-5. Channel C1 profile of the thick (500 µm) and thin (260 µm) and the SEM images.

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-). The embossing was conducted with the plate temperature of 110 ^oC, 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-). 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 ^oC 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.

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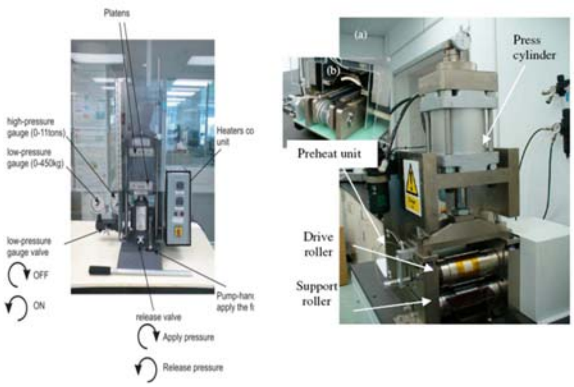

Figure-6. The conventional hot embossing carver manual press 4386 (left) and the lab-scale hot roller embossing machine [12] (right).

In general, the embossed PMMA reveal similar features resembling its embossing moulds. As seen in Figure-, 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.

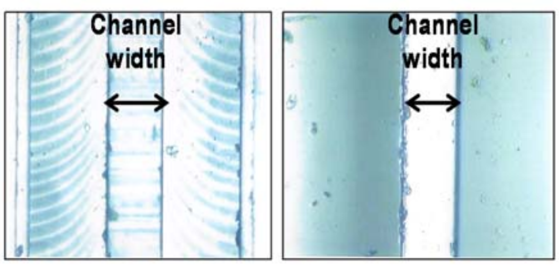

Figure-7. Optical Microscope images of the channel section on the embossed PMMA produced by 500 µm mould (left) and 260 µm mould thicknesses.

The channel depths are measured using a Confocal Imaging Profiler. As shown in Figure- 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.

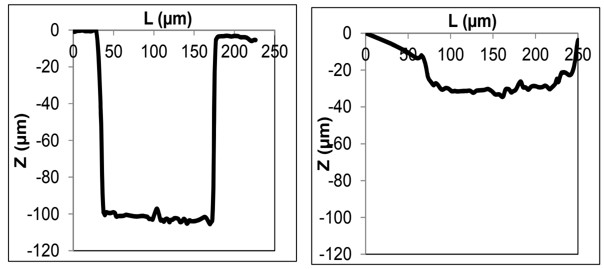

Figure-8. Channel C1 profile of the embossed PMMA produced by thick, 500 µm (left) and thin, 260 µm (right).

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.

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