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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.

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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 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 1 (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 1 (a2 and b2)).

The micro-milled micro-features designs in the experiments are shown in Figure 2. 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.

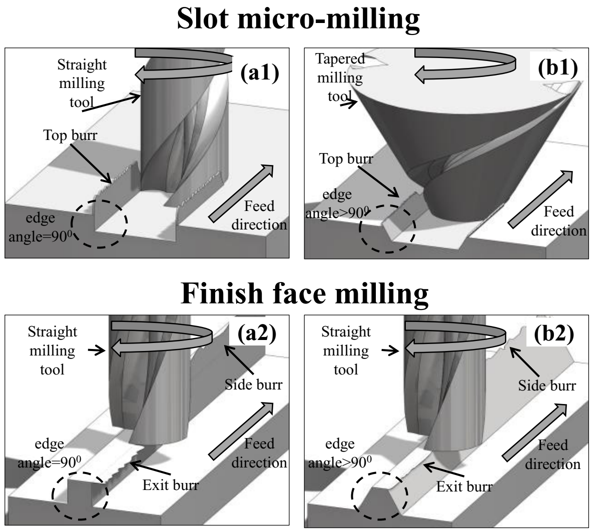

Figure 1. A tapered tool (b1 and b2) is expected to reduce top burrs formed and help in reducing the exit burrs formed in the subsequent finish face milling compared to a non-tapered tool (a1 and a2).

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 3). 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.

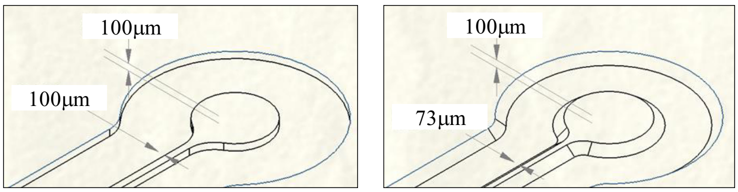

Figure 2. Mold designs with straight wall (left) and tapered walls (right).

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

Table 1. 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 15º, 30º, 40º and 50º 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 4). 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 2 shows the channel cross-sectional areas and the differences for various taper angles compared with a non-tapered channel design.

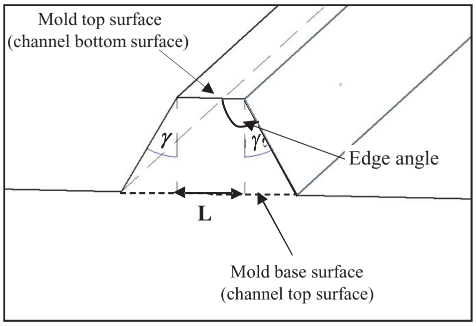

Figure 4. Cross-section of the channel.

Table 2. Cross-section area of the channel.

Taper angle γ **(°)**	***Edge angle***	***L*** **(μm)**	**Channel Cross-section area (μm²)**	**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 5). 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.

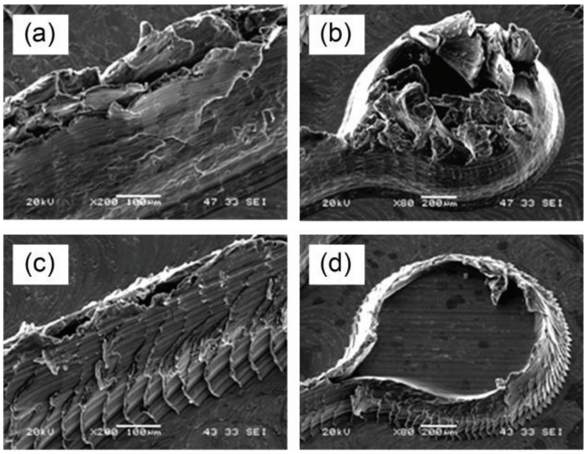

Figure 5. Effect of milling direction (15^0 tapered tool, before finish face milling pass) (a), (b) Down milling (c), (d) Up milling. Down milling is seen to produce more severe top/side burrs.

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 6. The burrs are seen to be very severe with dimensions comparable to the wall height (Figure 6(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 6(c) (d)). The edges also appear broken and the top burrs are seen to be fairly severe enough to interfere with the embossing process.

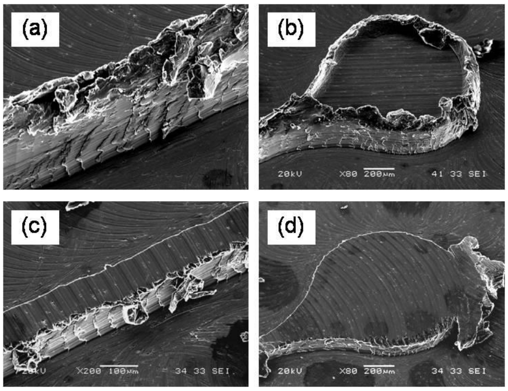

Figure 6. Burrs in straight wall feature mold. (a), (b) Before finish face milling pass; top burrs generated from the slot milling are comparable to the channel itself. (c), (d) After finish face milling pass; exit burrs generated from the finish face milling pass can be seen clearly.

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 7 and Figure 8 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 7 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 8). 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.

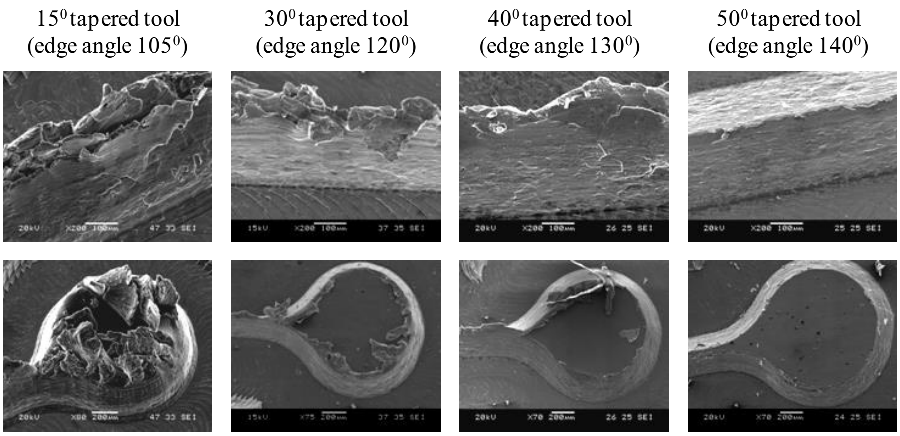

Figure 7. Effect of taper angle on top/side burr formation on the micro-features. The top row shows the channel section of the mould and bottom row shows the conical frustum protrusion section of the mould. The reduction in top burr formation with increasing taper angle is evident.

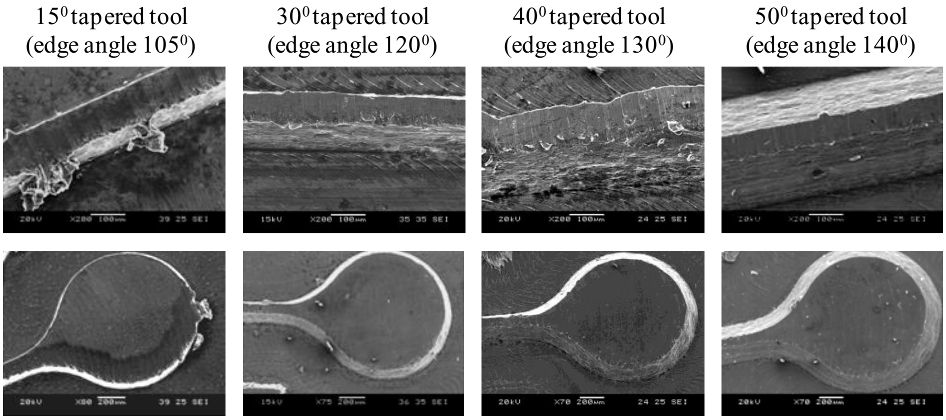

Figure 8. Effect of taper angle on exit burr formation on the micro-features followed by finish face milling pass. The top row shows the channel section of the mould and bottom row shows the conical frustum protrusion section of the mould. The reduction in exit burr formation with increasing taper angle 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 2) while the burrs are the lowest when milling the channel of this geometry (Figure 7). 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 ^oC, top plate temperature 115 ^oC and pressure 10 MPa. The embossing results for straight tool and 50^o taper angle tool are shown in Figure 9. The embossed PMMA revealed similar geometry features with its embossing mould.

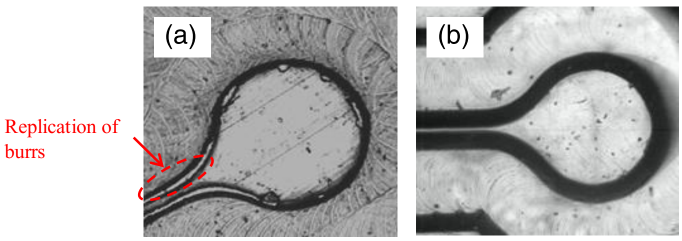

Figure 9. Embossed features on PMMA (a) Embossing mould produced using straight tool, (b) Embossing mould using 50^o taper angle tool, with down milling and without finish face milling pass.

As seen in Figure 9, 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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