Title

Micromachining and Burr Formation for Precision Components

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Micromachining and Burr Formation for Precision Mechanical Components

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Abstract

An understanding of burr formation and edge defects is critical to efficient production of machined features in precision components. Analytical models of burr formation and edge effects including the tool/workpiece interaction and material influences are necessary for building databases describing cutting conditions for optimal edge quality, and design rules for burr and edge defect prevention. This paper reviews recent research work done on the fundamentals of burr formation in micro-milling of microfluidic devices using the Mori Seiki NV1500 DCG Vertical Milling Machine as part of the MTTRF machine loan program at the University of California at Berkeley. Specific applications of micromachining and burr formation test results for of micro-scale components are presented and discussed.

Keywords: Micromachining, burrs, experimental data bases

1 INTRODUCTION

Micro-machining as a manufacturing technique represents a continued trend towards miniaturization across all areas of manufacturing. However, there still remain many technical hurdles prior to widespread use of micro-machining, and specifically micro-milling, industry-wide. This is mainly due to the fact that as feature sizes continue to decrease, effects considered to have little or no influence at larger scales become dominant factors with strong influences on part accuracy, surface generation, and integrity of components [1]. These factors need to be addressed when developing process parameters to ensure machined parts meet desired form and tolerance specifications. It has been the goal of the Laboratory for Manufacturing and Sustainability over the years to conduct research on the fundamental aspects of burr characterization, minimization, prevention, and removal. It is a goal to continue to expand this research to machining at the micro-scale.

As these issues are addressed the applications where micro-milling can be utilized as a manufacturing technique will increase. It is increasingly common to see milling used for meso-scale electronics, plastic injection molds, and devices such as micro-turbines and pumps.

An interesting application for micro-milling is the area of micro-fluidic devices. These are miniaturized devices that are used to manipulate micro- and nano-liter volumes in an effort to understand cellular mechanisms. The devices are used for live cell experimentation to better understand inter- and intra-cellular interactions [2]. Typical applications of these devices are:

- Drug screening and testing
- Biological and chemical sensing
- Genetic analysis

Figure 1 displays a sample micro-fluidic device known as a micro-mixer. Efficient mixing of reagents is desirable for applications where fast diagnosis results are needed [3]. The size of the features makes micro-milling a viable option for manufacture of the device.

Micro-fluidic devices typically make use of more traditional microfabrication techniques used to pattern integrated circuits on silicon wafers [2]. The device illustrated in Figure 1 used a typical method of device fabrication where SU-8 and OmniCoat photoresist were spin coated on a nickel disk. The disks were then electroplated with nickel before removing the photoresist. Finally the nickel disks were used in a plastic injection molding process to make a polymer mold.

There are many advantages to traditional microfabrication techniques such as lithography, including being able to attain microscopic feature sizes, and high fidelity replication of desired features. However these traditional methods are limited in the complexity as they can only create features in 2.5-dimensions. Additionally they typically require longer lead times for manufacture. For example the electroplating process described above took in excess of 6 hours.

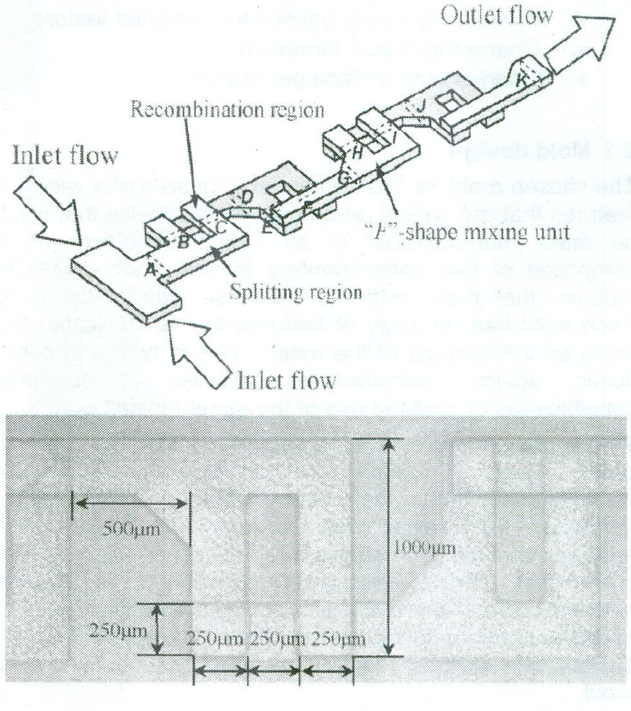


Figure 1: Micro-mixer micro-fluidic device [3].

Micro-milling may be a viable alternative to these processes due to the ability to manufacture true 3-dimensional parts. This provides a host of additional design options for micro-fluidic devices. For example the simple micro-mixer in Figure 1 could evolve to include more complex sweeps, curves, or helixes in all 3 dimensions. Micro-milling also has an advantage in that it is generally a speedier operation that other comparable manufacturing techniques. With a capable CAD/CAM system a designer could realize a mold for a micro-fluidic device in a very reasonable amount of time. In addition the speed of the cutting operation could be optimized to further reduce manufacturing times. Micro-milling also has the advantage of utilizing a wider range of materials. Finally, milling is generally a more environmentally benign process than traditional microfabrication techniques which tend to use large amounts of energy and water.

Milling has long been a desirable option for manufacture of conventional size injection molds. Therefore it is the goal of this work to extend the knowledge on conventional machining to the micro-scale. Experimental databases on cutting conditions for optimal surface and edge generation and design rules for burr and edge defect minimization and prevention must be expanded to the micro-scale if micro-milling is to be a mainstream option for manufacture of micro-fluidic devices.

2 EXPERIMENTAL DESIGN

The primary goal of this research is to evaluate the feasibility of manufacturing a micro-fluidic device, and compare this to results from current manufacturing methods. Additionally this research hopes to build on to current machining database knowledge in the area of micro-milling. Specifically:

- Determine optimum feed rate for micro-tools
- Examine tool path options for designed features
- Characterize burr formation
- Characterize surface generation

2.1 Mold design

The chosen mold for this experiment consists of a variety of features that are typical on a micro-fluidic device that would be mass manufactured in an industrial setting. It is comprised of two complimentary halves, each containing features that mate with the converse side of the mold. Each mold has an array of features that is duplicated four times on the surface of the mold. This is typical in micro-fluidic device manufacture because it facilitates simultaneous or multiple use of the same molded part.

The primary feature is a cross-shaped trench, 127µm in width, 10µm in depth. It is surrounded on the complimentary half of the mold by 178µm by 178µm square features. Each array also includes 100 127µm holes, arranged so that each adjacent hole is on an alternate side of the mold. These features were chosen because they are representative of the features that would be designed on an operational micro-fluidic device. Figure 2 displays the mold design, with shaded features residing on one half of the mold.

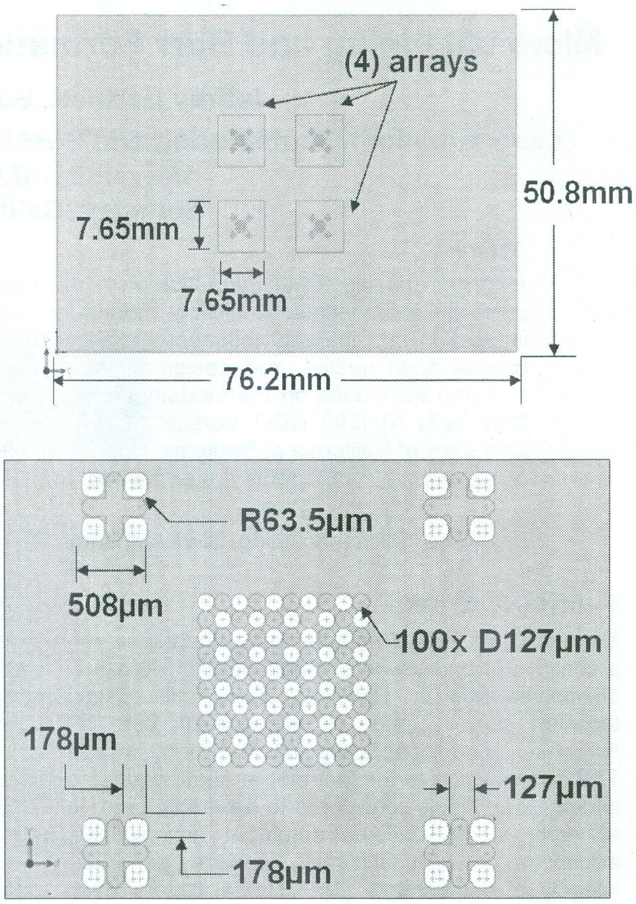


Figure 2: Mold design (shaded portions on top side of mold, clear portions on bottom side of mold).

2.2 Machining Plan

A 126.9µm diameter two-flute tungsten-carbide end-mill, with a nose radius of 0.770µm, shown in Figure 3, was used. The cutter was rotated at 24,000 rpm generating a cutting velocity of 10m/min on a Mori-Seiki NV1500 CNC milling center. The mold material was aluminum 6061.

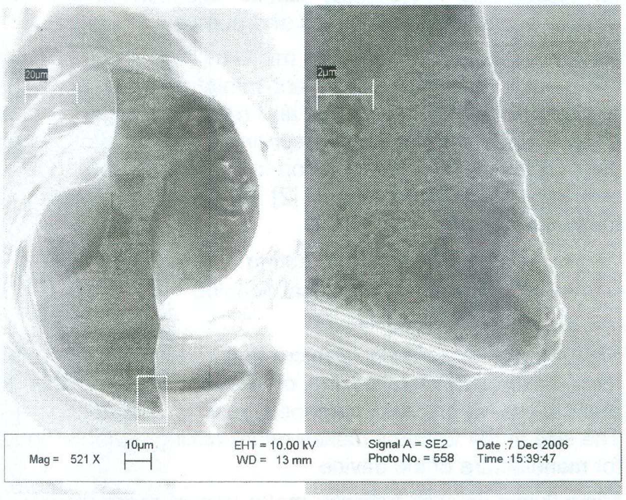


Figure 3: 126.9µm diameter WC-Co end-mill.

The workpiece was located relative to the micro-tool by means of a wireless acoustic emission (AE) sensor shown in Figure 4. The sensor mounts to the workpiece, and transmits an acoustic emission signal when the rotating micro-tool makes contact with the workpiece. As seen from Figure 5 the AE system detects end point detection prior to any cutting force development due to cutting edge engagement in the workpiece [4].

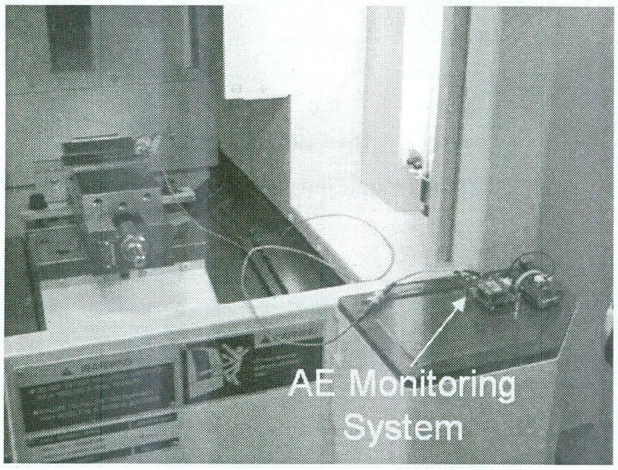


Figure 4: Acoustic emission end point detection system.

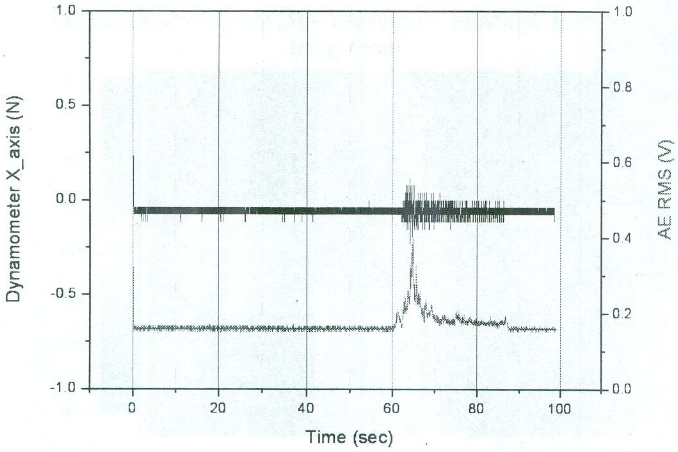


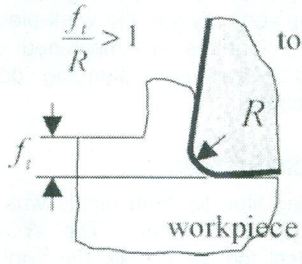
Figure 5: Comparison of acoustic emission signal and force measurement during end-point detection.

2.2.1 Feed

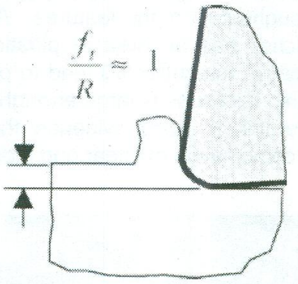
Feed per tooth plays an important role in determining chip thickness and the resulting cutting force. By applying Ernst-Merchant's shear plane model to the cutting process we see that increased feed increases the cutting force (F_s):

$$F_s = \frac{kf_t d}{2\sin\phi}$$

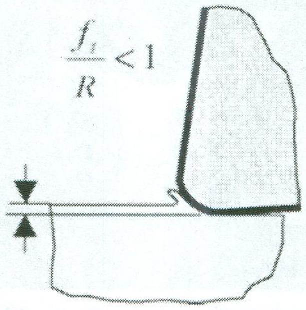
Where k is the shear strength of the material, d is the tool diameter, f_t is the feed, and Φ is the shear angle [5]. Assuming the tool geometry and material are constant, the cutting force is proportional to the feed per tooth. Therefore appropriate feed can be extrapolated from conventional machining handbooks [6]. However, at micro-scale the nose-radius of the cutting edge becomes important. As shown in Figure 6, if feed is decreased linearly below the nose-radius of the cutting edge, the rake angle becomes negative, affecting chip thickness and specific cutting energy. To more closely examine this problem a variety of feed rates are chosen, so that the relationship between feed per tooth divided by cutting edge nose-radius, are greater than, less than, and equal to one.



(a) $f_t/R > 1$



(b) $f_t/R \approx 1$



(b) $f_t/R < 1$

Figure 6: Influence of f_t/R [6].

2.2.2 Tool Path

The size of the features relative to the tool size greatly limits the variety of tool path options. Limiting the trenches to 127μm in width means that the tool is allowed only one pass over the feature, meaning the roughing and finishing passes are essentially the same. The axial depth-of-cut is 10μm, and the radial depth-of-cut is 127μm. Machining a 127μm trench means the cutter is up milling on one side of the trench and down milling on the opposite side.

The feature design eliminates the use of tool paths such as the window-framing technique, which limits the number of times the cutting edge exits the workpiece, thus minimizing areas where burrs are known to form in conventional cutting. However, having several locations of tool exit will allow us to confirm whether tool exits will also generate burrs at the micro-scale.

Additionally tool entry techniques are limited due to the small feature size relative to the tool diameter. Past research by CODEF (Consortium on Deburring and Edge Finishing) recommends avoiding tool entry and exit while the cutter moves to the specified depth-of-cut and width-of-cut [7]. The closest possible option given the designed features is to ramp vertically into the work-piece to avoid a tool-exit. Identical features are machined comparing a ramping pass to a traditional plunging pass used in conventional machining.

3 RESULTS & DISCUSSION

The total machining time for both molds was 13 minutes, with a feed length of 73.6mm. The WC-Co end-mill encountered modest tool wear, with the final nose-radius measuring 1.550µm. Figure 7 shows the results for a typical feature in the micro-mold. The trenches typically show a large top burr along the upper edge of the trench. This is seen throughout all of the features. Additionally the end of the trenches has an area of plastic deformation. This is likely because the cutter will tend to plough material until the uncut chip thickness is large enough to generate a chip. Therefore this is good evidence that the cutting mechanism is a combination of shear and ploughing.

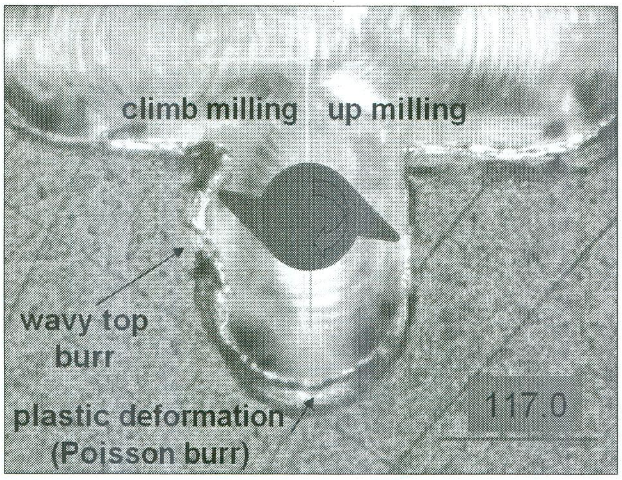


Figure 7: Burr formation when milling a 127µm trench.

3.1 Feed

As feed increases linearly, top burr size tends to decrease (Figure 8). This is likely due to the relationship between nose-radius and feed per tooth. At feeds per tooth below the nose-radius (f_t/r <1) the cutting edge does not necessarily create a chip with every cutting pass, thus there is some plowing of material that occurs, until the feed is large enough to create a chip. This leads to larger sized burrs, as well as increased tool wear due to uneven cutting forces. At higher feeds per tooth (f_t/r > 1) there is less plowing, and shear cutting is more dominant, thus creating smaller top burrs, and cutting more efficiently. The surface roughness was also measured along the bottom surface of the trenches. The average R_a over the entire surface was taken, and decreases modestly as feed per tooth increases likely for the same reasons as discussed prior (Figure 9).

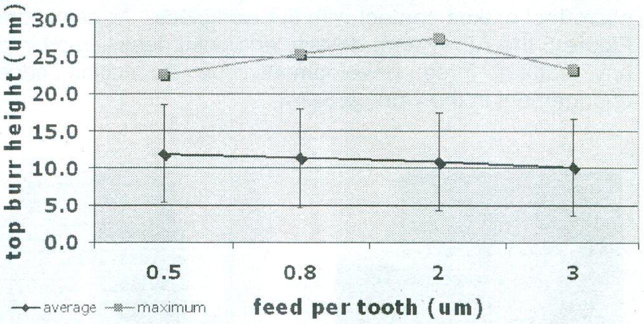


Figure 8: Top burr height (µm) versus feed per tooth (µm).

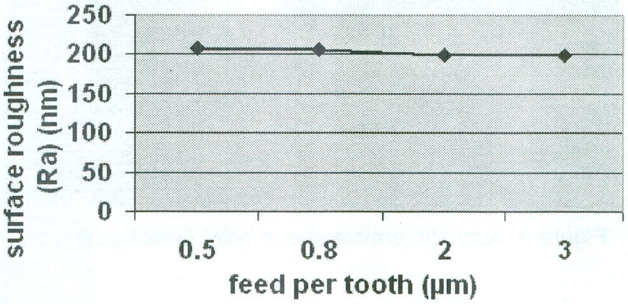
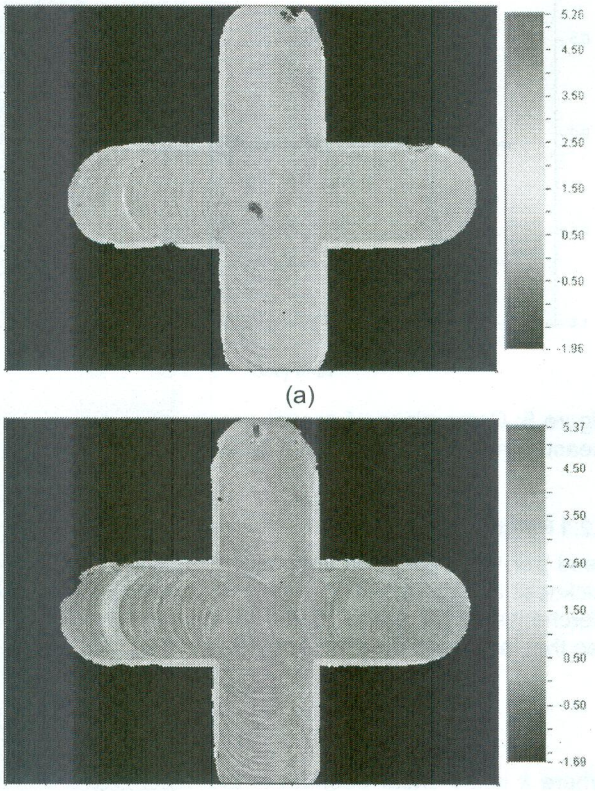


Figure 9: Surface roughness – R_a (nm) versus feed per tooth (µm).



(a)

(b)

Figure 10: Surface generation during a ramp tool entry (a) and plunge tool entry (b).

3.2 Tool Path

The difference between tool entry methods had a noticeable effect on top burr size, as well as surface generation in the area surrounding the tool entry path. A ramping pass produced smaller top burrs, and produced less plastic deformation along the top edge of the surface, as well as the bottom surface of the trenches (Figure 10-top). This is likely due to the fact that the tool is constantly engaged in the cutting process during the entire ramping entry, then immediately begins the full cut of the trench. Conversely the plunge tool entry enters and exits the workpiece several times along the side and bottom of the trenches before beginning the full cut of the trench (Figure 10-bottom).

3.3 Cutter Direction

The difference between up-milling and climb-milling on top burr generation is quite significant. The top burr generation is generally greater during climb-milling over all ranges of feed (Figure 11). This could be due to the fact that any chips created during up-milling are excavated away from the workpiece upper edge. Additionally, since the mill is simultaneously up- and down-milling, any chips or built-up edge created during up-milling could disrupt the down-milling which occurs on the opposite side of the trench after the up-milling is complete. However, this should be confirmed by attempting to create an edge using the up-milling technique only.

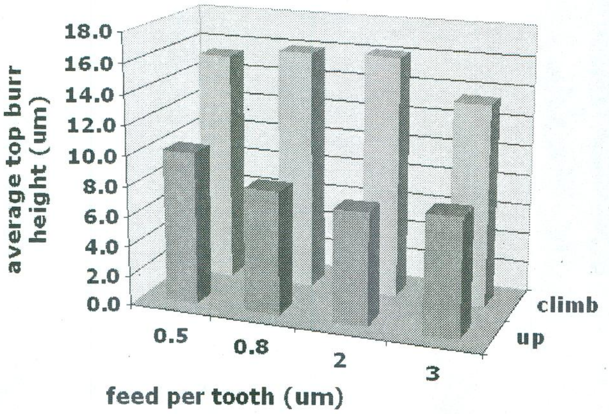


Figure 11: Average top burr height (µm) versus feed per tooth (µm) for up- and climb-milling.

3.4 Error Sources

An estimation of the combined run-out of the spindle, tool-holder, and tool was made by measuring the outer diameter or the 127µm holes at the center of each array.

$$R_{average} = \left(\frac{\Sigma d_{\max}}{n_{holes}} \right) - D_{tool}$$

Where $R_{average}$ is the run-out, d_{max} is the measure diameter of the hole, n_{holes} is the total number of holes, and D_{tool} is the measured diameter of the tool. The average run-out was calculated to be 6.1µm. Other significant sources of error include work-piece locating (±0.5µm), vise alignment (±3µm), parallelism of workpiece edges, and measurement (±0.050µm).

4 CONCLUSIONS

We have found that increased feed has a reductive impact on burr size and surface roughness. However it is important to consider the ratio of feed-per-tooth to tool nose-radius when selecting a tool, and aim for a ratio greater than 1. Experiments need to be completed to evaluate tool wear, which has been found to increase as feed increases. An optimal feed can thus be calculated.

It is best to avoid climb-milling where practicable, and may also be beneficial to avoid width-of-cut greater than half the tool diameter if possible. Additional work should be done to confirm this at smaller width-of-cut.

When constructing a tool path it is best to avoid tool entry close to any final edges to avoid formation of top burrs, and areas of plastic deformation. It is also best to employ a ramping tool entry method to achieve a more desirable surface finish. Additional work should be completed to evaluate features where roughing and finishing passes are needed, and width-of-cut is less than half the tool diameter.

Future machining operations should account for tool run-out calculated herein. Additional work must be done to reduce greatest sources of error, including alignment of workpiece and vise.

It can be concluded that micro-milling is a promising option for fabrication of micro-fluidic devices. There are however several issues that still need to be addressed. The practicability of micro-milling for micro-fluidic devices will increase as the tool size and error sources both decrease. Efforts need to be made on the part of tool manufacturers to explore methods of tool fabrication, and material advances that will generate tools one order of magnitude smaller than those used in this research in order to be truly advantageous in the widespread use of micro-milling. Despite not being able to achieve the minimum dimensions of traditional micro-fluidic device manufacturing methods, micro-milling still offers the ability to produce features in 3-dimensions. This capability makes micro-milling worthy of future research for device manufacture.

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