XFab MicroMachining: Uses & Limitations

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Executive Summary:

During the duration of this quarter -- the last 10 weeks, we characterized a tool within the fab with a nonexistent user base. Exploration of the tools abilities towards two applications were done -- microfluidics, the primary advertisement for the tool commercially, and shadow mask production. Further we determined, by means of trial and error, best practices when using the tool (e.g. recommended end mill diameter and probability of breaking).

Figure E1 below is a general summary of our best practices, detailing the three different materials used (aluminum [Al] & stainless steel [SS] for shadow mask production, polycarbonate [PC] for direct microfluidic patterning), recommended speed, corresponding tool fidelity, and the feature size possible, based on our empirical evidence. Further, employment of developed fixtures was done. In the case of shadow mask production, to hold down a thin metal sheet and ensure no motion during machining, blue tape was employed. This was a cost effective solution to quickly enabling the machining of thin metal sheets, vital to reaching the goals of our class project. Moreover, development of a protocol for effective cooling of the end mill was employed. 'Tufoil' a polytetrafluoroethylene (PTFE) based oligomer, liquid at room temperature, provided a splash free means of effective cooling of end mills, greatly reducing the breaking probability, as compared to the air cooler used otherwise.

Development of GCode to create custom patterns was also done, the details and instructions thereof can be found the corresponding section below. Unfortunately, as a new tool with an extremely small user base, it was prone to many glitches that, at the point of this course, were not yet 'ironed' out. A compilation of such notes can be found below in the corresponding section, and the effective work arounds and repercussions of employing them can also be found below.

Lastly, we demonstrate and show, via 3D confocal scanning, our results on direct microfluidic patterning on a polycarbonate substrate. We show the ability to create dynamic structures, having various steps. We further show the resolution limits, and document the primary issues we saw. As for shadow mask production, we explain our materials choice, and need for switching to a more compliant material as we explored pushing the patterning limits of the tool. Comparative edge qualities are shown between laser cutting and micromill, showing a vastly superior cut for the micromill. This correspondingly created significantly between line qualities post evaporation. Documentation of our findings regarding limit resolution can be found below, in the associated section. End mill fidelity, in general was significantly worse when working with these thin metals. Employment of an effective coolant, proper fixturing, and proper end mill speed significantly increased end mill fidelity.

End Mill Diameter

Material	2 mm	400 um	100 um	50 um	20 um
Al (65 um)	1000 RPM	5150 RPM	20600 RPM	41250 RPM	103100 RPM
PC (N/A)	600 RPM	3000 RPM	11900 RPM	23800 RPM	59500 RPM**
SS (60 um)	400 RPM	2000 RPM	8000 RPM	15900 RPM	39700 RPM

	Operation OK	Careful Use	Must Employ Best Practices	No Proof of Concept
Breaking Probability	5%	40%	80%	100%

Figure E1. Summary table comparing end mill diameter to the three materials explored with associated thicknesses. End mill speed employed shown, with associated box color detailing the fidelity of the tool bit employed. 'No proof of concept' refers to the fact that the tool bits always broke prior to making an impactful or discernable feature. 'Must employ best practices' showed low tool fidelity but proof of concept. 'Careful use' had higher fidelity, but recommend not pushing the speed or otherwise feed rate of the tool. 'Opeiation OK' signified almost no damage to the end mill, recommended starting end mill diameter for day to day use.

Tool Introduction:

The microfill is a very powerful tool that can create intricate patterns to depths with aspect ratios up to 3:1 (depth:width). Figure 1 above is a schematic of the micromill (albeit a slightly older model) and associated end mills, shown via SEM with various portions of ant anatomy as a size comparison. The micromill is a CNC based mill capable of making small parts with intricate detail. As advertised, the tool is primarily used for making small medical device parts and doing direct microfluidic patterning. Otherwise, it can be used for conventional milling, and if desired, in tandem with the mills provided in the varian physics machining shop.

Herein we additionally explore the use of the micromill for shadow mask production and compare it to conventional laser cutting. With regards to microfluidic applications, the micromill provides end mill sizes down to 5 um, with the potential of creating wells as deep at 15 um. As a means of direct microfluidic writing, the tool provides the ability to use other materials for microfluidic applications such as acrylics or polycarbonates (or any machinable material). This vastly improves the material selection space from the current PDMS based process established in the XFab. As PDMS tends to leach materials out over time, it's not an ideal microfluidic foundation material for biological applications. Such issues have driven the field to costly methodologies of directly patterning glass.

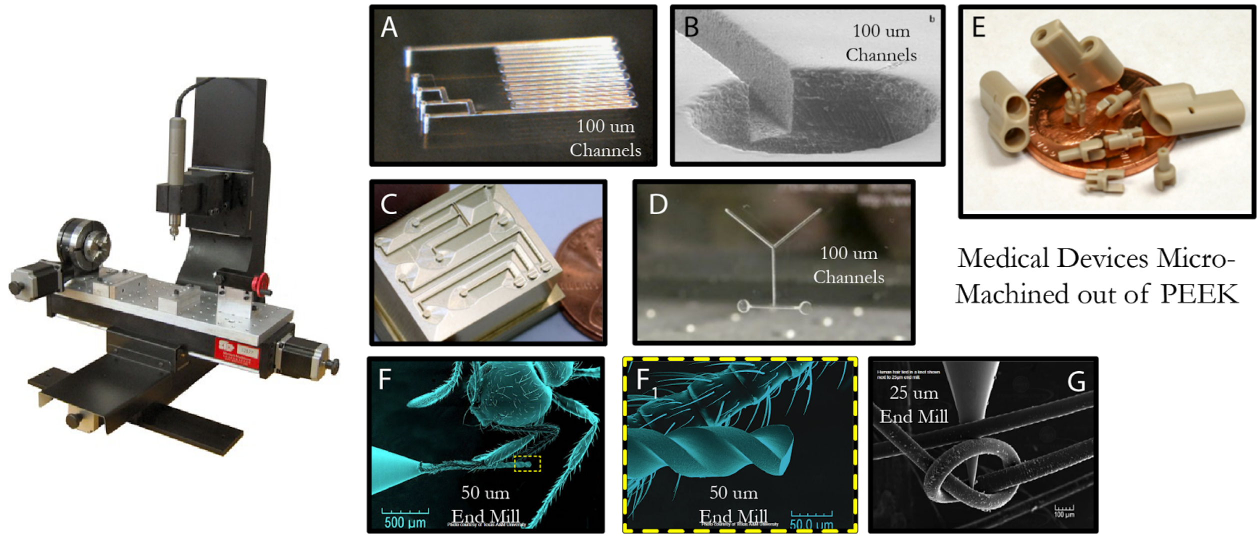

Figure 1. (Left) Micromill. (Right) Various microfluidic demonstrations, medical devices micromachined out of peek, and sub 100 um end mills. (A-D) Microfluidic applications, showing 100 um channels, (C) depicts a microfluidic mold. (E) Medical devices micromachined out of PEEK. (F-F1) 50 um end mill, (F1) is the accompanying zoom, next to ant anatomy. (G) 25 um end mill, next to a human hair. *All images taken from the manufacturer's website, Performance Micro Tools (http://www.pmtnow.com/).*

Our motivation to develop an XFab process for shadow mask production began following discussing with a colleague and coming to the realization that no current methodology exists, despite having the equipment needed for it. Shadow mask production is very costly industrially, as typically photochemical machining is employed to create such masks, but given that it's a roll-to-roll lithographic based process, it's very costly to do a few shadow masks, but to produce the same one many times at scale becomes more economical. As such we wanted to bring this capability in house so that, if a user desired, they could make a series of shadow masks and deposit the metal layers within the same day. Below we detail the best tool practices, our findings with regards to fixturing, coolant, uses & limitations, end mill fidelity & speed, and gcode production. We follow this by detailing our updated run sheet, discussing the various issues and methods of addressions (as well the repercussions of doing so). We follow by discussing our progress with regard to microfluidic patterning and shadow mask production, and end with future recommendations to the next ENGR 241 class.

Best Tool Practices:

Below best tool practices are documented in the following sections. Fixturing primarily focuses on the methodologies created to best hold down a thin metal film for proper machining. The coolant section explains the coolant we selected, which ones we tested, and the impact on end mill fidelity as it compared to the compressed air currently available on the tool. Uses & limitations goes into detail regarding end mill diameter recommended for the materials we explored. Further, in this section we discuss the speed recommended as it relates to the materials tested, and end mill fidelity. Lastly, our findings regarding GCode for custom patterning are discussed below.

Fixturing:

Fixturing within the micromill follows standard practices when using any traditional based CNC based mill. For those not well acquainted with mills, or have not taken the machining course offered by Mehmet in the machine shop (Varian Building, below physics store), the first part of this section will briefly discuss how to quickly mount a sample to be machined. The latter portion of this section will discuss our findings and best practices when machining thin metal films for shadow mask production.

Here in Figure 2 we show an image of the micromaching stage.

1. Please ensure that the end mill is out of range, by pressing the **'Reset'** button followed by **'home all'** button.
2. Post home all, the stage should be in the position as shown in Figure 2. Please note the various components in Figure 2, the two metallic plates (2B, C) are positioned to elevate your sample. These leveling plates can have their height altered to better fit the material being machined in question (2C, simply by loosening the screw, and sliding the top potion to change the overall height).
3. As shown in 2D, the sample you wish to machine should be placed as shown, on top of the two leveling plates. An indicator is traditionally used to ensure the surface is flat, otherwise using one of the larger end mills (2 mm or greater) you can, via machining, level your sample.

The finish from the end mill is ok, but for microfluidic applications I would highly recommend buying the substrate with a polished finish (recommended vendor: McMaster-Carr), as it will be crucial depending on the methodology used to close the microfluidic channels. Please note that the sides of your sample should be level, with one another, otherwise a tilt will be evident in the surface you aim to machine. Our recommendation is to purchase pre machined and polished substrates from Mcmaster-Carr to save yourself the tedious work of creating one yourself. This is especially important if you do not have access to a mill elsewhere on campus, as the micromill, though functional in theory, supplies end mills too small to practically shape any large substrate.

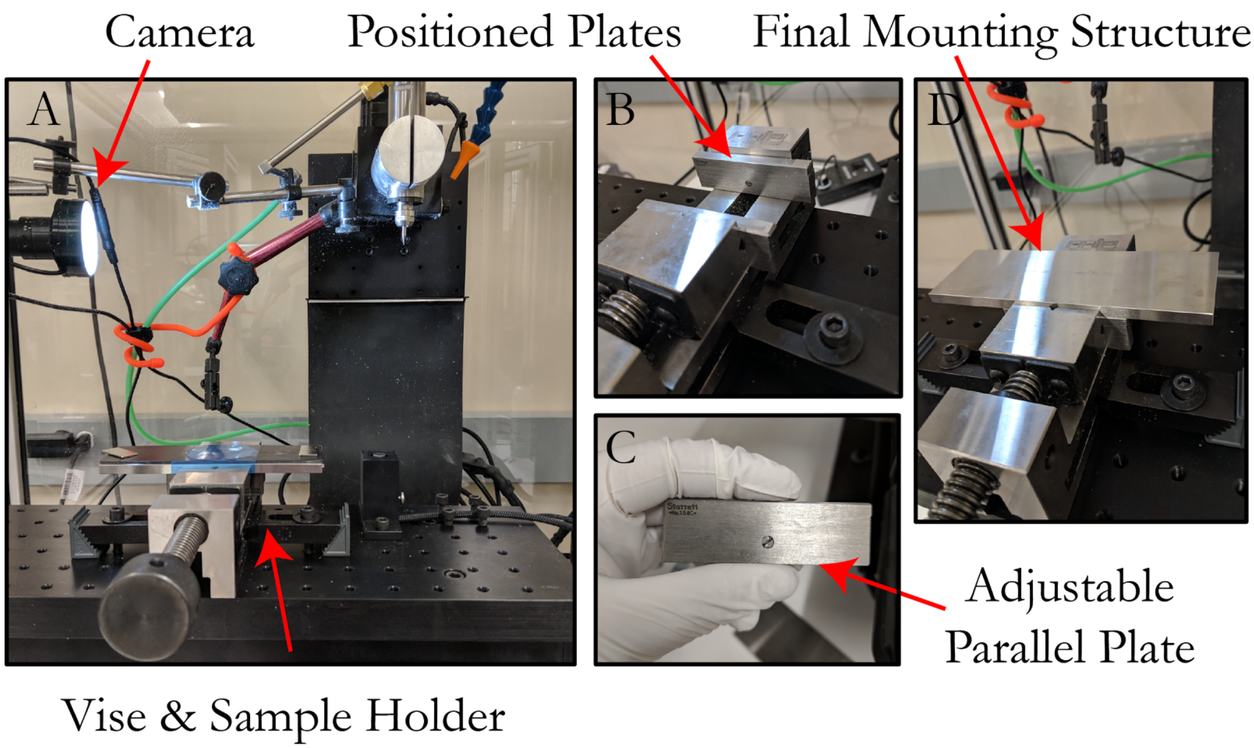

Figure 2. (A) Zoomed out image capturing the vise & sample holder, camera and the location of the end mill. This is the rest configuration when reset and home all have been pressed (in that order). (B) image showing the location of the adjustable plates, against either size of the vise. (C) Image of the adjustable parallel plate. Using loosening the screw will allow for an adjustment of height. (D) Proper configuration when mounting a sample to be machined.

In Figure 3 we show, accompanied by a cross sectional illustration in 3C, how we recommend fixturing thin metallic films for shadow mask applications: Using blue tape, we tape the thin metal down to a soft substrate (in this case black ABS), and to a precisely machined stainless steel plate as our final substrate. The intermittent black ABS is crucial in that damage to the end mill is increased dramatically when using a hard substrate; consequently, fidelity of the end mill is significantly lower, especially as you push to smaller feature sizes. Finally post machining, the blue tape is able to be removed. The Ultron blue tape (supplied via SNF stockroom), is a great candidate for fixturing the thin films, as other tapes typically have an adhesive too strong, thus not allowing for removal of the thin films without any plastic deformation. At the same time the tape adhesive is sturdy enough to work during the machining in combination with the lubricant and coolant that we use. If the substrate you are machining is so thin or so easily deformed (plastically), we recommend the use of UV releasable tape (supplied via Ultron).

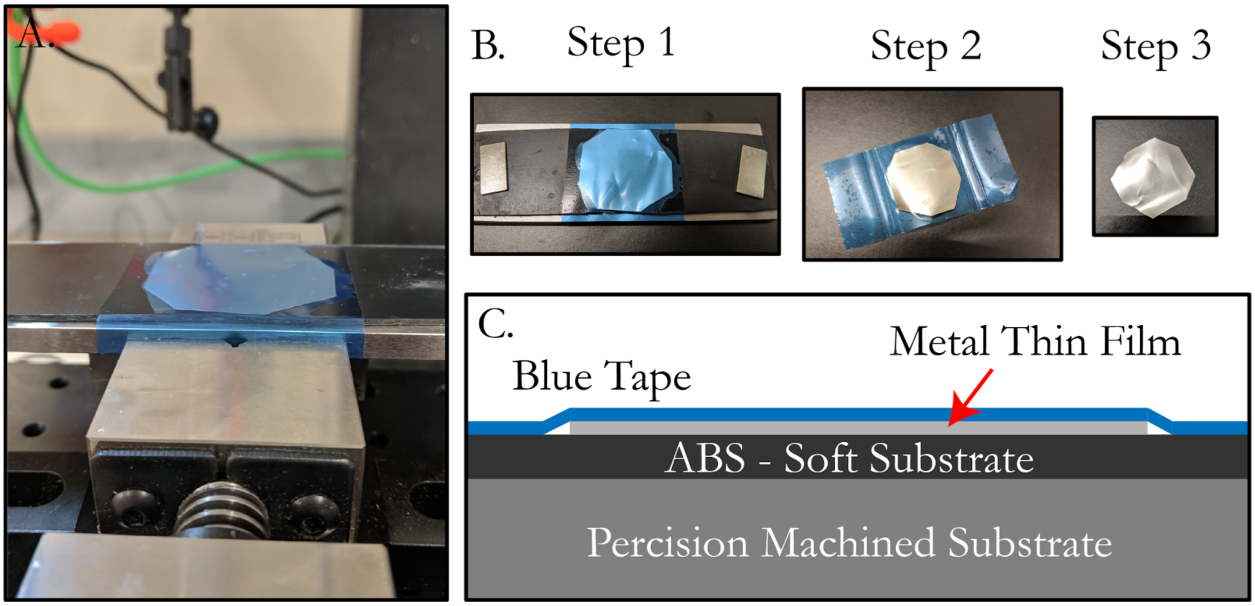

Figure 3. (A) Image of a properly loaded thin film to be machined for shadow mask purposes. (B) Method of removing thin film, please note this Aluminum came off a roll, thus not of optimal quality. (C) cross section of shadow mask fixturing, wherein a soft substrate is placed on the precision machined substrate, and the thin metal (target of machining) is placed under blue tape.

Coolant:

Initially, end mill fidelity was incredibly low, even for the larger end mills (>400 um). We correlated (after many end mills, and further review of the literature) the cause of breaking to be catching of the material we were machining. After discussing with the ENGR 241 industrial consultants it became apparent that a lubricant/coolant was needed. At the same time, for prolonging the lifetime of the tool, and to be amenable to the rest of the XFab, we wanted to ensure that the coolant didn't splatter around the enclosure, and cause a large mess. Initial coolants/lubricants used were supplied by the machine shop, however these oils tended to splatter. The idea then came to use a lubricant we traditionally use for our polishing rig, 'tufoil' a polytetrafluoroethylene (PTFE) based oligomer, liquid at room temperature (Figure 3). This solution contained within its own puddle around the end mill (Figure 4), constantly lubricating the tool. After a sufficient amount of machined debris agglomerates within the solution, a pipette is used to to remove the 'waste' solution, and replace it with a fresh batch (timing of adding the coolant will be discussed in the latter section). It should be noted that, unless a very large amount of material is to be machined away, typically only one puddle is used per GCode run. Use of tufoil greatly prolonged the life of the end mills we used.

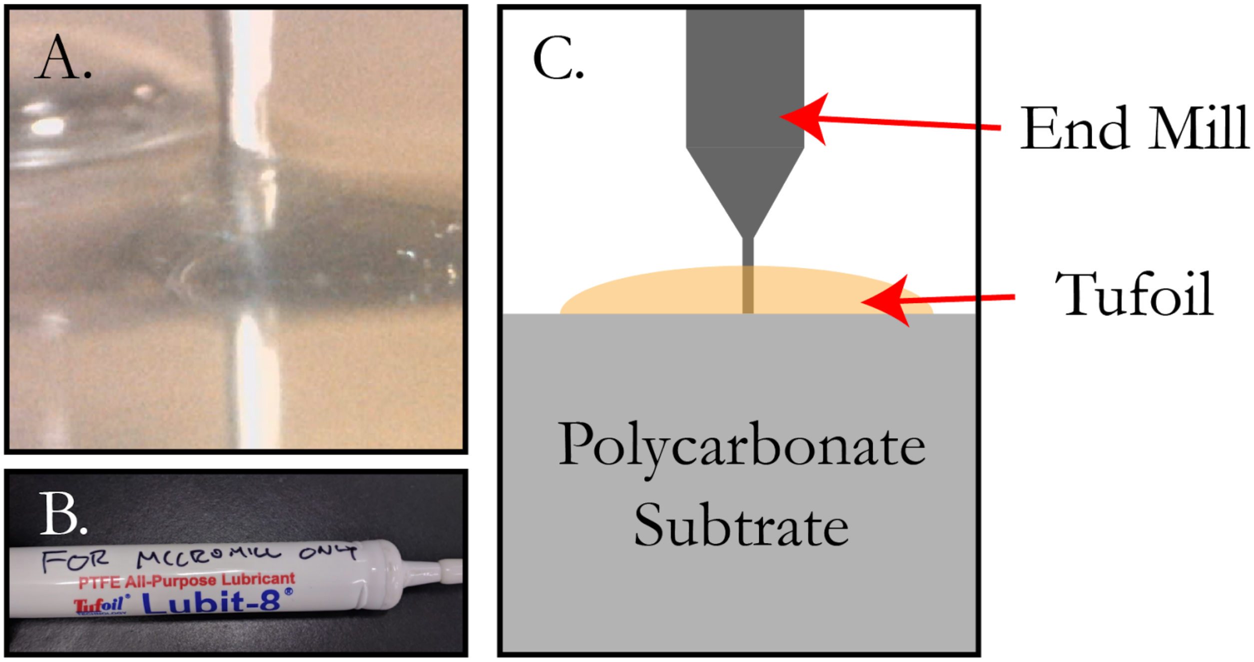

Figure 4. (A) Image of end mill in 'Tufoil', machining the surface of PC. Reflection evident due to reflective surface. (B) Container of Tufoil purchased via McMaster-Carr. (C) Accompanying graphic to further detail (A).

Uses & Limitations:

Figure E1 (contained within the executive summary and shown below for ease of reading as Figure 4) is a summary of findings regarding end mill speed & fidelity with respect to the 3 materials we explored during the duration of this course (stainless steel and aluminum thin films, for shadow mask production, and polycarbonate for direct microfluidic patterning). Green signified great use of end mill, little to no damage, or breaking was ever observed unless there was an evident glitch with the tool. The blocks colored yellow showed possible patterning, but the tool bit tended to break after about an hour of use. With the blocks colored orange, we were able to successfully make very basic patterns, yet edge quality and otherwise patterning quality did suffer. This section simply shows that it is possible, but not recommended unless you need to pattern a very small portion of your pattern with it. Red blocks showed no proof of concept, i.e. the end mill would always break prior to any proof in patterning shown. It should be noted here that microscopic inspection of each end mill used was required if the box is not labeled new, as will end mills with a diameter 50 um or less, it's near impossible to observe it with the camera installed within the micromill tool (even at its highest magnification). Unfortunately, due to cost, the 5 um diameter end mills were not explored during the duration of this ENGR 241 course.

Shadow mask production for Al thin films is limited to 400 um. With the stainless steel films (used due to the stiffness of the film and ease of use), less than 400 um was not practical. Though labeled 'careful use' in the attached figure, post employing best practices we did not observe breaking of the 400 um end mill. All speeds shown in the figure below were based off a calculation correlating the rpm recommended for a larger end mill for these materials in particular. We found this to be much better than the set speeds found within the wizards in the micromill tool, this greatly decreased the probability of breaking an end mill. It should also be noted that the tool cant run faster than 50k rpm.

In addition, with most polymers, melting can be seen when the rpm is too high. Altering of rpm should be done to further optimize the table shown below. Additions of other materials would be fantastic for the user based interested as well. Use of self lubricating materials may also be of interest, as the use of a coolant may not be necessary (probability of catching much lower).

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Material	2 mm	400 um	100 um	50 um	20 um
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	Operation OK	Careful Use	Must Employ Best Practices	No Proof of Concept
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Figure 5. Summary table comparing end mill diameter to the three materials explored with associated thicknesses. End mill speed employed shown, with associated box color detailing the fidelity of the tool bit employed. 'No proof of concept' refers to the fact that the tool bits always broke prior to making an impactful or discernable feature. 'Must employ best practices' showed low tool fidelity but proof of concept. 'Careful use' had higher fidelity, but recommend not pushing the speed or otherwise feed rate of the tool. 'Operiation OK' signified almost no damage to the end mill, recommended starting end mill diameter for day to day use. ** Speeds greater than 50k rpm not possible. Beyond 50k, 50k rpm was used.

Micromill Glitches, Errors, & Workarounds

Of the various glitches encountered during these last 10 weeks, the one we elected to include in this final report was the one we couldn't fix permanently -- dysfunction of the calibration sensor (red outline in Figure 8). Briefly, no error will be present on the screen when this dysfunction occurs, rather any end mill with a diameter equal to or less than 100 um is guaranteed to break, 400 um & 2 mm end mills will become significantly dulled. To address this, manual zeroing when finding the surface should be done, but note that, since the calibration was not done, the tool will begin to show very odd features, not completing some and over extending others. Furthermore, the end mills are much prone to break as the tool tends to jerk when this calibration is not done.

Custom Patterns: DXF → GCode

While the tool offers several shapes and patterns built into the software, you can convert DXF files from CAD programs to machine 2D custom patterns. We used a free software, DXF2GCode, with the download link below. There are many other alternatives to this program that likely work better (such as this: https://cadsofttools.com/products/dxf-dwg-g-code/), but this was the only free one we could find. Nevertheless, it worked pretty well.

1) To start, import your DXF drawing into the program by simply opening the file.
2) Verify the correct pattern is imported. Double check the correct units and tool parameters you want to use under options -> Configurations and options-> Postprocessor Configurations. Check for correct tool diameter, spin speeds, and feed rates. While all of these can be changed after you import your completed gcode file in, we always kept the same parameters to be safe.
3) Export
4) Verify that the pattern was exported properly by inputting the gcode into a gcode simulation, such as this: https://nraynaud.github.io/webgcode/
5) After importing into the micromill software, verify that the proper units were translated in the process (in vs mm)

We only verified this with larger patterns, as it seemed that our patterns were off-center from where we indicated the zero-point to be. This likely means that a protocol for alignment of different patterns (seperate jobs) needs to developed.

https://sourceforge.net/projects/dxf2gcode/

Possible Issues & User Adaptations:

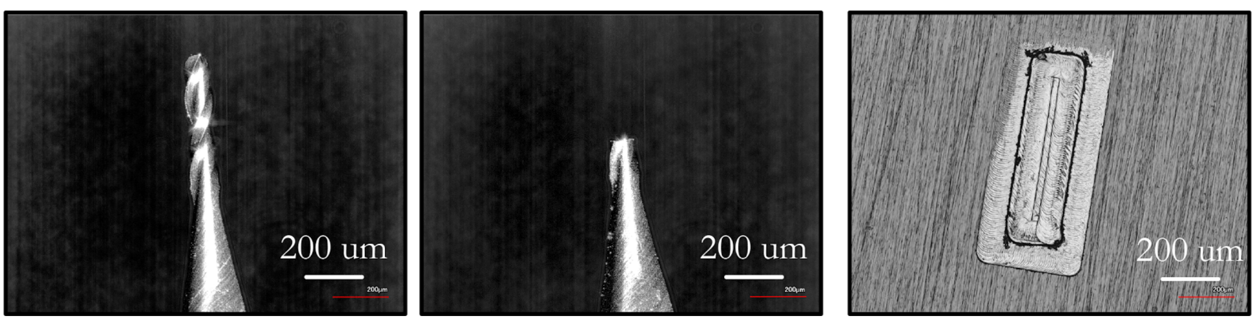


Figure 6: The left & center images are of a 100 um end mill right before and right after breaking. To the naked eye, it's very difficult to tell that any damage is present. This becomes especially difficult with end mills smaller than 100 um. The rightmost figure is what a resulting pattern looks like after a end mill breaks. The edges are extremely rough and uneven. Extra caution must be taken to stop the milling as soon as a break happens, as the tool will continue to operate otherwise.

The biggest issue encountered in this tool are damaged end mills. If the calibration process is run ('set fixture' step) with a broken end mill, the calibration sensor becomes faulty and the tool will directly run into it, instead of detecting the surface. This can not only damage a working end mill, but can also permanently damage the sensor. If this happens, make a comment in badger, as it will likely occur again even with a working end mill, causing any end mill to break with a diameter less than or equal to 100 um, and significantly dulling all others.

In order to avoid this, always verify end mills aren't damaged before and after loading it into the tool. Smaller end mills are extremely fragile, so it's a good practice to always verify they are ok under a microscope before use.

If the calibration isn't working and you still need to operate the tool, you can manually zero the height once you find the surface (see section above) . This can be done by manually zeroing the axes in the top menu. In addition to the issues cited above, the motors seemed to undergo slight hysteresis. For example, see Figure 7. When running multiple milling patterns, the tool began to lose its position over time. On the left side of Figure 7, which is supposed to be a 'T', a gap is present because the tool's position drifted. This wasn't found to occur when the calibration sensor was working and normal operation was followed.

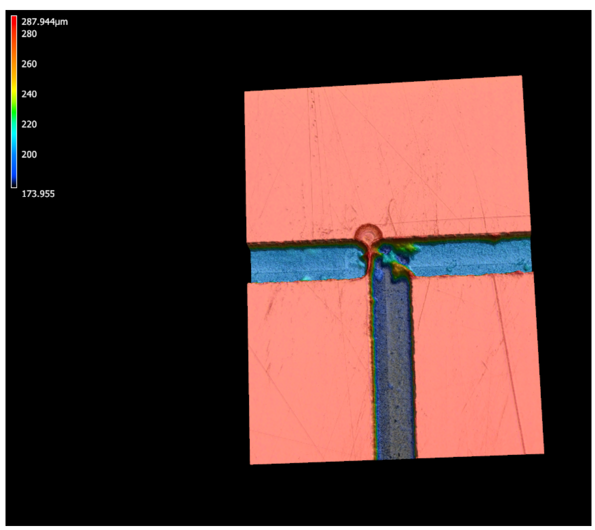


Figure 7: 3D confocal image stack of 100 um microfluidic channels into polycarbonate. When the calibration sensor was inoperable and manual zeroing of the axes was done, the tool position 'drifted' over time. As can be seen, the different cuts are meant to be connected, but the tools position drifted, leaving a gap in the cutting process.

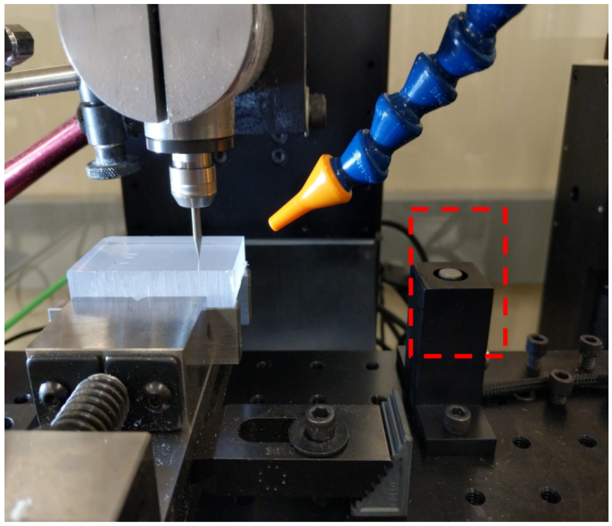
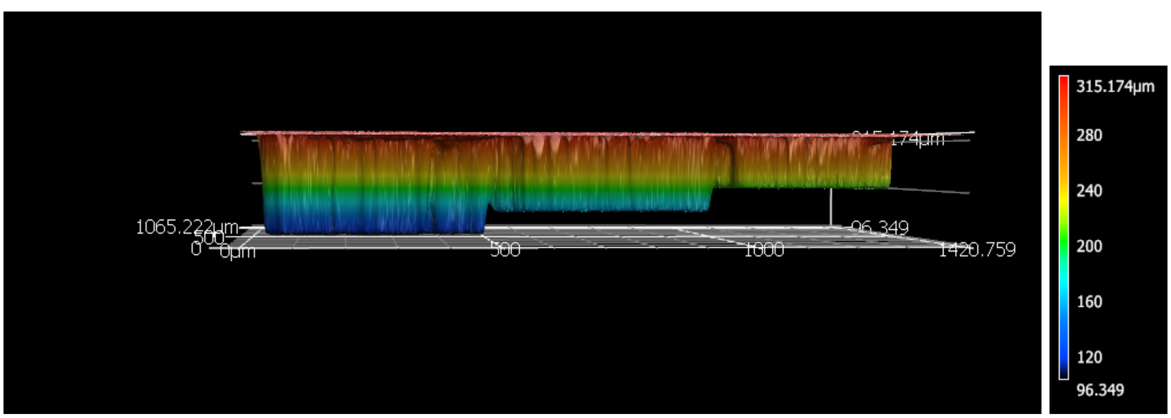


Figure 8: Image of a polycarbonate substrate held onto the tool while milling process is ongoing, Tufoil to be applied shortly (not done for image clarity). The red outlined box is the calibration sensor. When the 'Set Fixture' button is pressed after finding the surface, the tool will raise the spindle and bring the end mill down very slowly to the calibration sensor. After this process is complete, the tool is ready to start the milling.

Direct Microfluidic Fabrication:

We found the micromill to work remarkably well for direct patterning into soft materials. In Figure 9 is an example of milling into a polycarbonate substrate. As referred to in earlier sections, 50 um end mills worked reliably on polycarbonate, and even the 20 um worked without breaking (8C). When using very small end mills, it's important to use very slow feed rates with respect to the z axis (i.e as in take only 5 um steps at a time or less). Unfortunately, depth is quite limited with such small end mills, with a limit of roughly a 3:1 depth to diameter ratio.



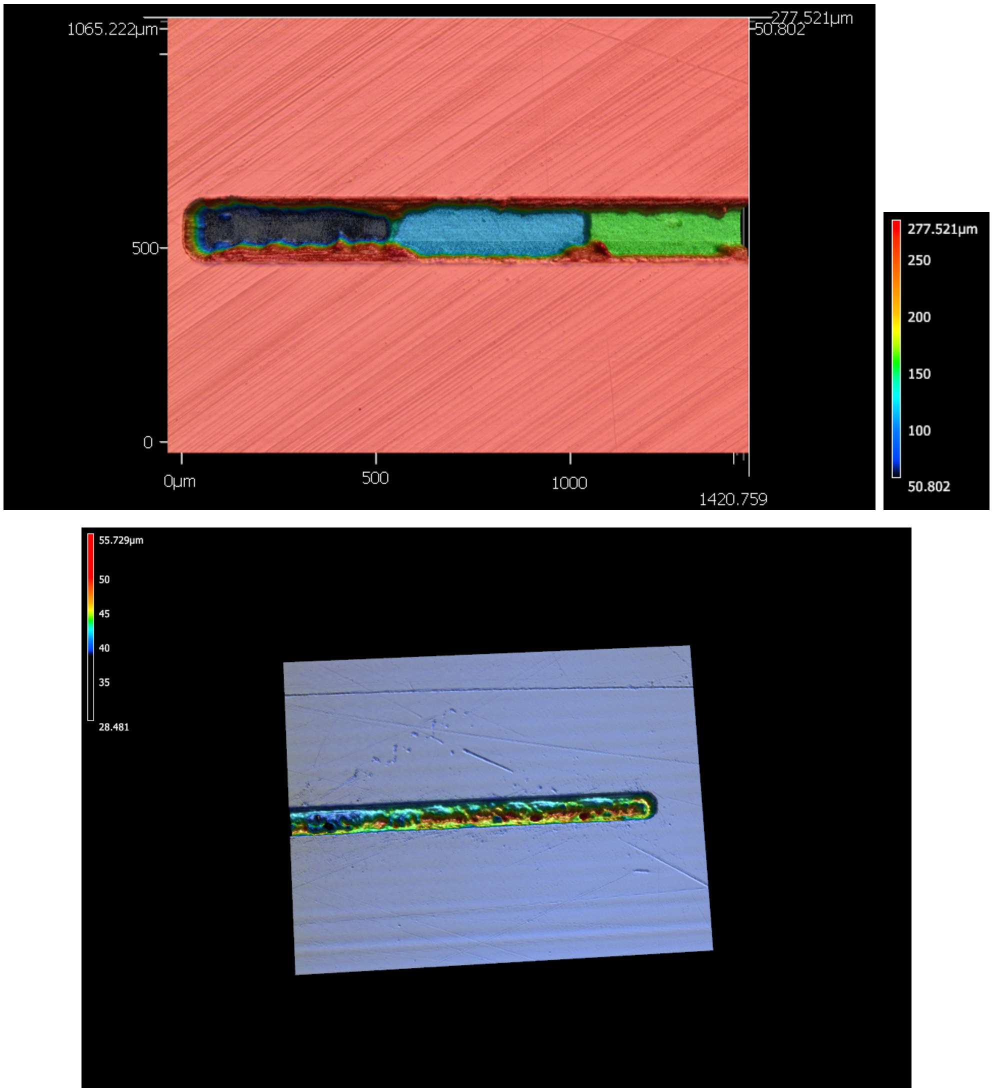


Figure 9: These are 3D profiles of polycarbonate using the Keyence 3D Confocal Microscope in SNC. In this pattern, we drew a 1.5 mm long line, with increasing depths from 50 um to 150 um. In the final image, a 20 um line was drawn.

Shadow Mask Production:

In the interest of adding a capability not yet currently available in the XFab -- shadow mask production -- we determined the minimum feature sizes (material dependent) able to be created without end mill destruction, best practices (see above), and then determined quality of the cut and its relation to line quality created when using a shadow mask. In Figure 10 below we compare the result of using the micromill vs the laser cutter. Prior work in ENGR 241 explored use of the laser cutter for shadow mask production, but observation of the edge quality via sem, and correspondingly the produced line quality was not explored. Figure 10A shows the large feature cut into stainless steel with a 400 um end mill. The quality of the cut can be observed in 9B, wherein the scale bar is 40 um, not adding to the thickness of the material. In 9C, the evaporation of Ti was done using this feature, it can be easily seen that the deposited line quality is vastly superior to that shown in 9F (corresponding to the laser cut feature). 10D & E show the laser cut stainless steel and corresponding edge quality (E, please note the change in scale bar).

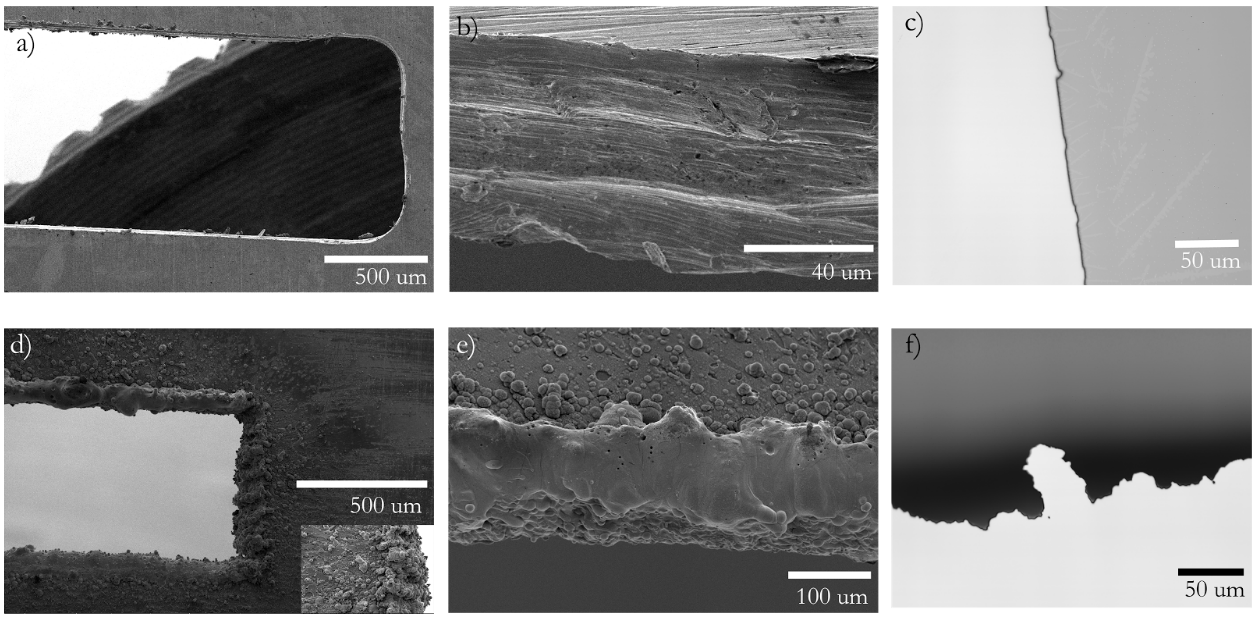


Figure 10: Parts (A-B) are from cutting a 60 um thick stainless steel sheet using the micromill with a 100 um bit. The edges are relatively clean when compared to stainless steel cut with a laser cutter (D-E). Parts (c) and (f) are the resulting films from evaporating Ti using these two patterns as a shadow mask. (C) Ti on the left, (F) Ti on the bottom. Edge quality is significantly improved using the micromill.

With respect to the burr produced (excess material loosely attached as a result of milling), during this class we sonnicated our resulting films in soapy water, resulting with no observable burr. Additionally, after milling is complete, it's suggested that you manually shave off the excess material on the edges, especially if using the micromill to create a shadow mask. This can be done by finding the surface and while keeping the spindle on, to manually change the x-y coordinates. Be extra careful to change the 'step' parameter before doing this so as to only move the x-y coordinates more finely. Any sudden or fast movements will damage the endmill

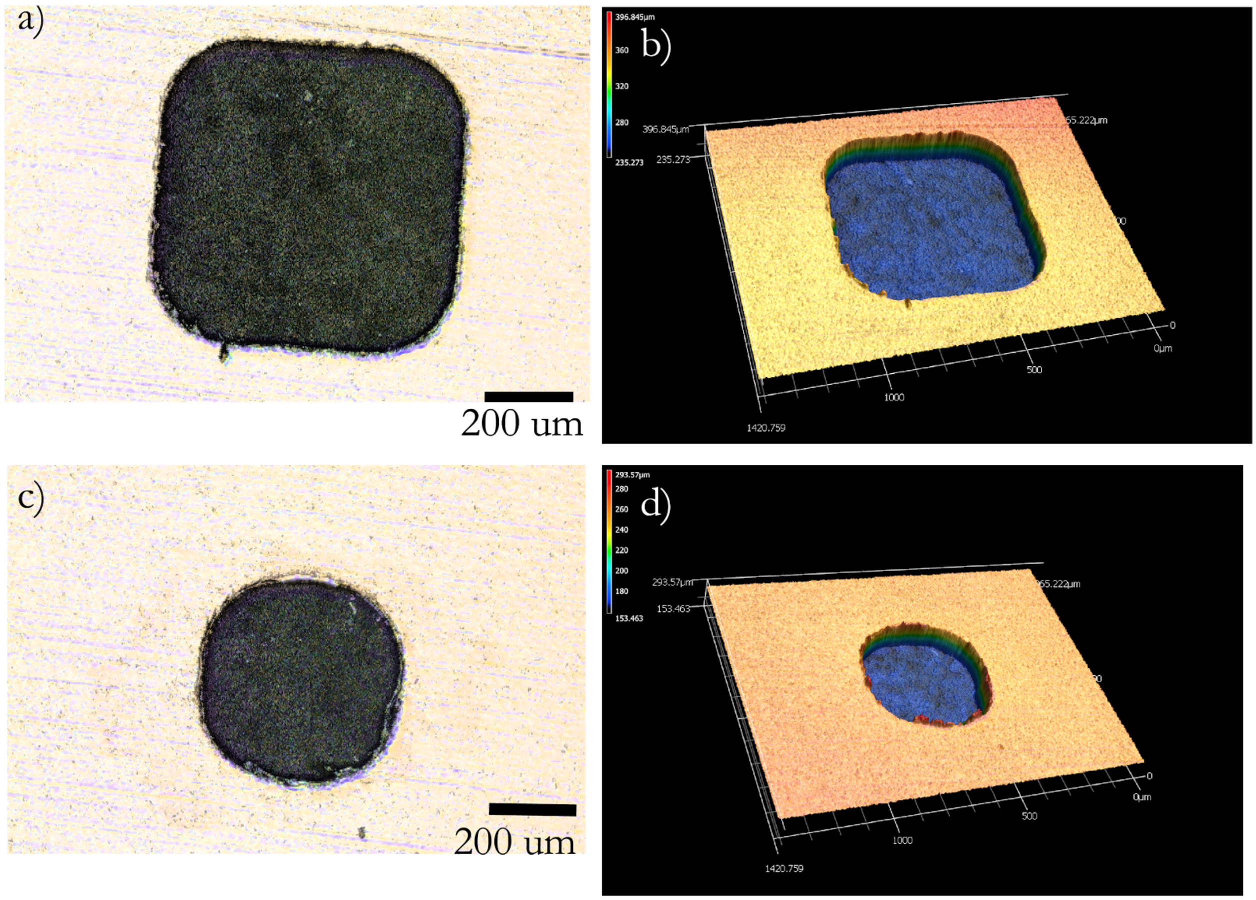


Figure 11: (A) Rectangular frame using a 400 um end, corresponding 3D reconstruction via 3D confocal imaging shown in (B). (C) & (D) show the same but with a 100 um end mill.

Figure 11 demonstrates simple features cut into the aluminum substrate, observed via 3D scanning confocal microscopy, in 10A, a 400 um end mill was used to create the rectangle, 10B shows the resulting 3D reconstruction. Correspondingly, 10C & D demonstrate a rectangle using a 100 um end mill. Despite best efforts and dozens of end mills broken during the duration of this course, pushing beyond 50 um for Al, and 100 um for SS was not possible.

Future Recommendations:

Translating custom patterns from CAD software to GCode proved to be tricky. Further work is needed to verify translating proper tool speeds, as well as feed rates before running a custom file. Additionally, there are many different custom programs already available on the tool, but they are all different interfaces with different inputs. We suggest future users to test these custom programs and post their results, as well as the steps they took, so that future users can take advantage of what is already available on the tool. Of course, there are several contracting services available for those who want to convert their custom CAD files to GCode for the tool. However, those weren't tried in the course of this project, as we were trying to avoid costly solutions.

In conclusion, we demonstrated direct patterning of microfluidic channels as well as basic structures in thin metals. We created 'best practices' in the tool, incorporating a coolant, and various fixturing methods, and, at the cost of many end mills, determined the resolution one can practically deliver on using the micromill. The Micromill provides a flexible and quick way to create custom patterns onto a variety of materials without the need complicated, multi-step processing. A very powerful tool we hope to become of more use in the SNF XFab.

Acknowledgements:

We would like to thank our SNF mentor, Dr. Michelle Rincon, for the immense help with this project. She kept the project progress steady and provided many helpful suggestions throughout the quarter. Special thanks to Elmer for helping us get started with the tool and being very patient as we worked out the kinks of the Micromill. Additionally, we would like to thank Professor Jonathan Fan and Andrew Ceballos for teaching the course, and everyone in the course for all the helpful feedback.