Title

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Abstract

Microfluidic devices are gaining popularity in a variety of applications, ranging from molecular biology to bio-defense. However, widespread adoption of this technology is constrained by the lack of efficient fabrication methods. This paper reviews research on the application of micromachining technology in fabricating microfluidic devices, done using the Mori Seiki NV1500 DCG Vertical Milling Machine as part of the MTTRF machine loan program at UC Berkeley. Micromachining is applied in the precision manufacturing of process tooling for two fabrication methods: microinjection molding and roller imprinting. The versatility and capabilities of micromachining in enabling high-volume microfluidic device fabrication is discussed.

Keywords: Microfluidics, Micromachining, Microinjection Molding, Roller Imprinting

1 INTRODUCTION

High precision machining is an integral component in the development of new products and process technology. Even when not applied in the manufacture of the product itself, machining is extensively used in the manufacture of process equipment and tooling, and contributes significantly to the precision of the part ultimately being manufactured. This paper discusses the use of micro-machining technology in developing fabrication processes for microfluidic devices. Micromachining is being applied for creating injection molds for use in microinjection molding, and for creating imprint rolls for use in roller imprinting. In this paper, we discuss the suitability of micromachining for application in these two methods, and we highlight the challenges in high-precision fabrication of process tooling for microfluidic applications. This paper is motivated by two compelling reasons: the processes used for machining the process tooling for microfluidic device fabrication have a significant effect on the precision of the devices; and, the feature sizes possible in the devices are limited by the accuracy of the machining processes used.

The paper begins by discussing the need for developing manufacturing processes to fabricate microfluidic devices. This is followed by a study on using micromachining to create injection molds for microinjection molding. Issues in selecting appropriate process parameters and toolpath strategies are discussed. Various types of form and finish errors are also highlighted. Following this, the roller imprinting process is introduced and requirements for the high-precision manufacturing of imprint rolls are discussed, along with preliminary investigations into the effect of process parameters on imprint roll precision. Specific requirements in toolpath planning and design are also discussed. The paper concludes by highlighting the need for integrated machining process development for microfluidic device manufacturing.

2 MICROFLUIDIC DEVICES

Microfluidics deals with the manipulation of small amounts of fluids (in the pico-liter range) using channels with dimensions in the microns domain [1]. A major application of MFDs is in developing miniaturized lab-on-chip devices for chemical and biological analysis. Of particular interest is in applying microfluidic devices for fabricating low-cost medical diagnostic technology [2]. For these applications it is important that the manufacturing process is inexpensive so that the per-device cost is low. The microfluidics research community has identified effective manufacturing processes as being a critical component for the widespread adoption of microfluidic technology [1]. It is equally important that the processes create *precise* devices, as the functionality of the devices is determined by the manufacturing precision. Microfluidic devices are composed of networks of fluid flow pathways, and the precision is determined by the positional accuracy of the pathways, the form error in the pathway channels, and the profile of the channel surfaces.

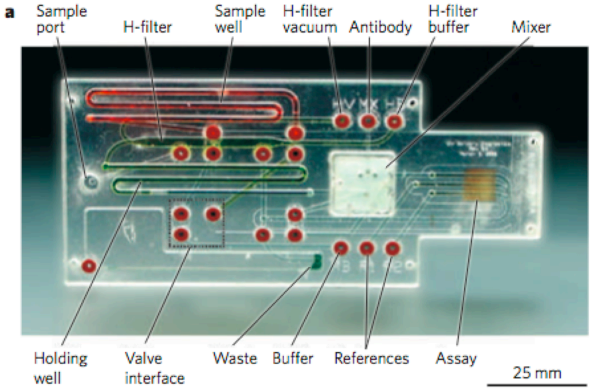


Figure 1: Example of Microfluidic Device [2]

The most common process used for MFD fabrication is soft lithography using Polydimethylsiloxane (PDMS) [3]. Features are created by casting PDMS over silicon masters, which are fabricated by lithography. Lithography-based methods however, have significant equipment requirements and tend to have a long lead-time due to the multiple steps involved (mask-making, photo-resist preparation, baking etc.). Semiconductor processes are also sub-optimal for creating features larger then 100 μm due to long lead-times. Moreover semiconductor processes can only create 2.5-dimensional features due to the physics of the lithography process, resulting in fixed-depth channels in the devices.

Imprinting processes have also been used in creating MFDs in the past, albeit to a lesser extent. Xu et al. [4] discussed the development of a room-temperature imprinting process for PMMA (Polymethyl methacrylate) and reported that this was successful in accurately creating micron-scale features. Since these methods also rely on lithography processes for creating the masters, they can only be applied in creating fixed-depth channels.

Microfluidic device fabrication processes derived from mechanical micromachining have an advantage over conventional processes in being able to fabricate devices with contoured features and surfaces. Precise control over surface quality and machined features has long been a focus of the micro-machining community, and this understanding can be applied in machining the process tooling. Contoured features are useful in micro-fluidics as they can improve mixing rates of fluids in the system. Currently, mixing is achieved by using creating complex out-of-plane features in the devices [5]. While these techniques have been successful in achieving rapid mixing, the devices tend to be very difficult to manufacture – multiple individually fabricated layers need to be manufactured and aligned, which can be cumbersome and error-prone.

3 MICRO-INJECTION MOLDING

In this section we discuss the design and fabrication of an injection mold for a microfluidic device, applying the lessons learnt from the experiments detailed in MTTRF 2007 [6]. The device was specifically designed to showcase the advantages of using micromachining for the manufacture of a typical bio-engineering device (please see Figure 2). All of the elements and features in the design are meant to represent difficult-to-manufacture features, which can also potentially provide innovative solutions to microfluidic issues. The section also discusses form errors and burr formation observed during in the manufacturing process.

3.1 Device Fabrication

The goals of the device fabrication were:

1. Fabricate a mold with features that are difficult to manufacture with traditional microfluidic manufacturing techniques:
    a. Non-rectangular cross-section trenches
    b. Trenches and pockets with varying height
    c. Geometry with complex curvature (splines)
2. Design a mold that combines these above features into a device that closely models a functioning microfluidic device, and proves that the technology can easily be used to create functioning devices.

The work-piece material for the injection mold was Al 6061-T6, fastened to an acrylic gasket with epoxy. The acrylic has a recess pocket to allow machining of the aluminum work-piece. It adds greater stiffness to the work-piece to reduce flexure of the device during clamping. The gasket was fabricated with a laser cutter, and then fastened with epoxy to the aluminum. The feature array is composed of a "spider-web", with 12 ribs extending in the radial direction from the center of the array. Each rib varies in z-height in a sinusoidal shape from 125µm to 15µm in height. It also has a u-shaped cross section, with a radius of either 10µm or 25µm.

Either end of the rib is supported by a cylindrical post, which creates a reservoir type feature in the molded part. These reservoirs are typically found in micro fluidic devices anywhere along a trench where fluid needs to be stored, and intermittently released into the trench for examination, or flow to an area of examination. Each rib is connected to the adjacent rib by an arc shaped positive feature. Height varies from 10µm to 50µm and each feature is 35µm wide. They also have a u-shaped cross section with a radius of 17.5µm. These features represent the ability to create complex 3-dimensional rib and trench features, which are necessary in micro fluidics for creating arrays that mirror cells and structures found in nature. For instance, replication of the 3-dimensional shape of a blood vessel may be desirable. This type of shape is similar to the web pattern, and micro-milling the web should prove adequate for similar machining operations.

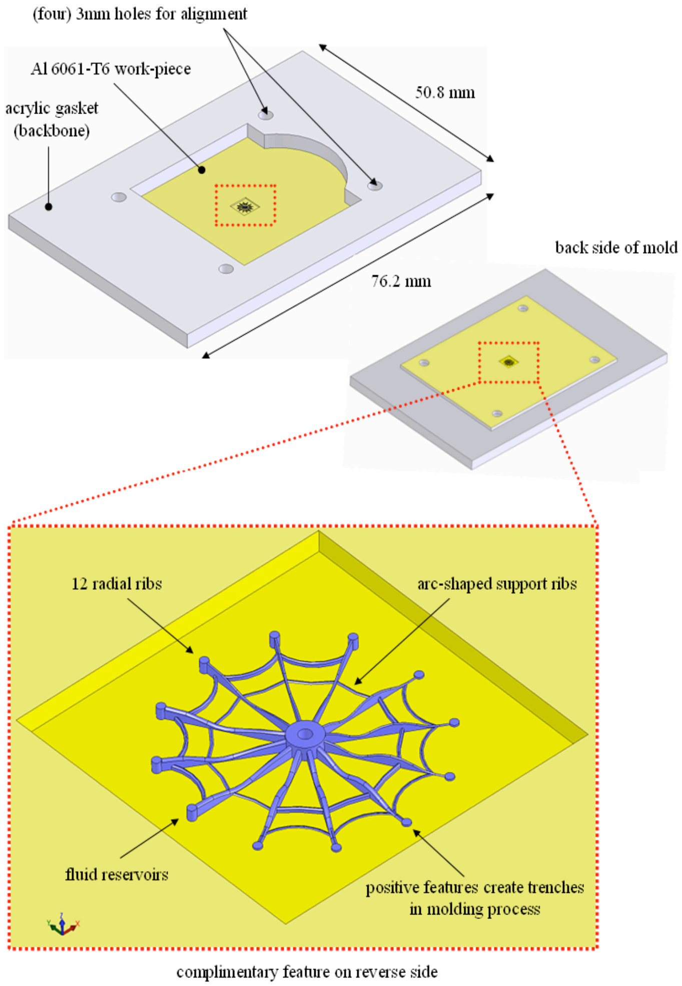


Figure 2: Microfluidic Device Design

The following is a summary of the cutting parameters used for the experiment – developed based on past research in the LMAS [7-12] – and are summarized in Table 1:

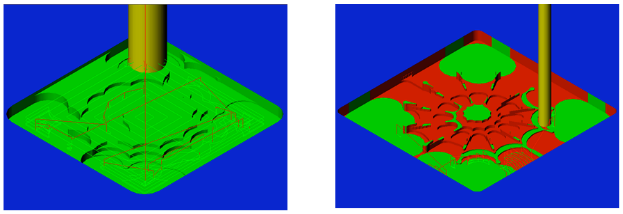
- <u>Cutting Velocity:</u> The maximum spindle speed of the available machine tool is 24,000 RPM. For the range of tool diameters used in this experiment, all calculated values of cutting velocity based on this maximum spindle speed fall well below the values extrapolated from the machinist handbook for an aluminum work-piece. Therefore further investigation of this parameter would not provide any additional useful information regarding cutting speed, because all values will be much lower than recommended cutting velocity values. A summary of the spindle speed and calculated cutting velocity are summarized in Table 1.
- <u>Feed-per-tooth:</u> A conservative feed rate (and thus feed-per-tooth) was used; values were selected to maximize surface finish and minimize burr formation.
- <u>DOC/WOC:</u> To minimize burrs and maximize surface quality a value of ¼ the tool diameter was used for both DOC and WOC.

- Cutter Direction: Based on the need to maximize the finish of the sidewalls of each feature a climb/down milling strategy is used.

Table 1: Cutting Parameters

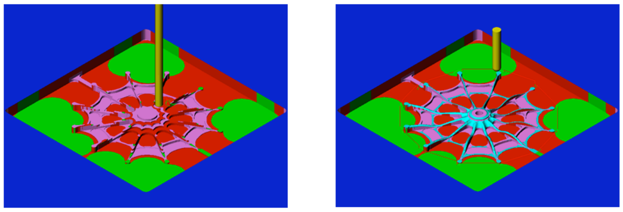
Tool Dia (mm)	Tool end geometry	Cutting Velocity (mm/min)	Feed rate (mm/ min)	Feed per tooth (µm)	DOC (mm)	WOC (mm)
0.7112	square	56	5	0.1	0.1778	0.1778
0.254	square	20	5	0.1	0.0635	0.0635
0.1524	ball nose	13	5	0.04	0.0381	0.0381
0.127	square	12	2	0.04	0.0318	0.0318
0.0508	square	7	2	0.04	0.0127	0.0127

Due to the complexity of the geometry, and the number of tools needed to create this device, the tool path was the most difficult parameter to finalize. As the overall shape of the feature was radially symmetric, an offsetting cutting strategy was used for all the passes. Each cutting pass is offset closer to the final feature by the depth-of-cut and width-of-cut. The spiral offset tool motion pattern was chosen over multiple alternatives, such as a parallel, zig-zag, window-framing, and translation paths.



rough: 711µm end-mill (1:00 hrs)

rough: 254µm end-mill rough (4:00 hrs)



finish: 127µm end-mill (8:00 hrs)

finish: 150µm ball-end-mill (8:00 hrs)

Figure 3: Tool Paths for Web Fabrication

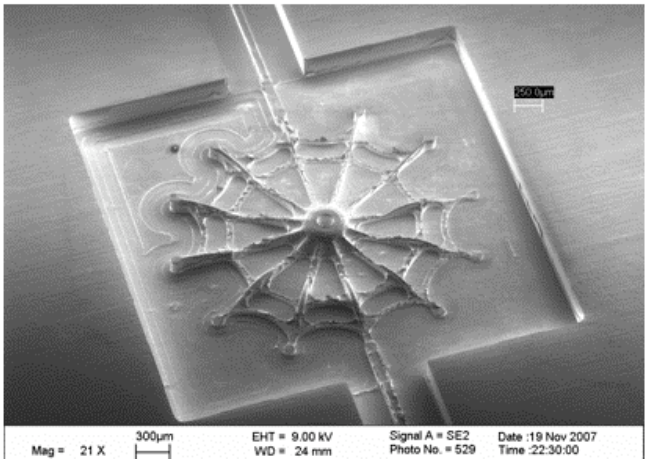


Figure 4: Machined Device

Each tool path was constructed in the Esprit CAM program, starting with the largest diameter end-mill. The end-mill size was reduced, and therefore tool path complexity increased with each cutting pass. The 711µm and 256µm end-mills are used for roughing cuts, to remove bulk material from the feature pocket. Then the 127µm end-mill is used to do a finishing pass on the side-walls of each rib and feature. Finally a 150µm ball-end-mill is used to give the circular cross section to the top of each rib. Tool paths are shown in Figure 3, with machining time in parentheses. The fully machined device is shown in Figure 4.

3.2 Example of Form Error

Errors due to tool run-out were most obvious in areas where small features were incrementally machined with increasingly smaller diameter tools. Examples of this error are shown in Figure 5. The figure on the left is a close-up of the corner of the pocket, which is machined away to leave the final feature. The figure on the right is a close-up of the lower-right-hand quadrant of the web-shaped feature. Each has examples of form error due to run-out of the tool, as highlighted in the figure.

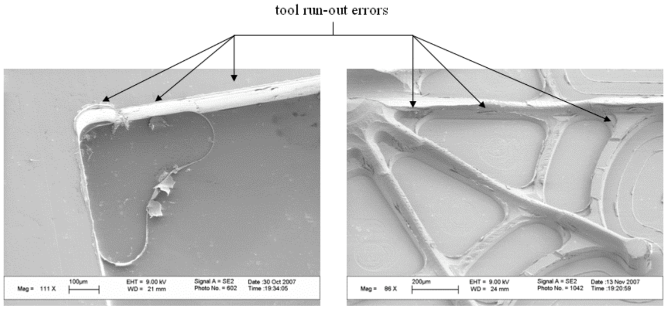


Figure 5: Evidence of Tool Run-Out Error

Looking closer at the corner feature, it is obvious where each tool attempts to machine a smaller radius on the corner of the pocket. The design calls for a square corner, so each tooling pass will step closer to convergence on the design geometry. The CAM program generates the tool path offsets based on the input diameter of the tool, however, since the maximum diameter of rotation due to run-out was unknown, the offsets are generated incorrectly, and therefore the form errors seen in Figure 5 are generated. Therefore it was critical to closely evaluate the run-out of each tool used for machining the web feature prior to machining it, as described in greater detail in [13] Following this, the CAM program can correctly generate the tool offsets and appropriate machining code, and the problems associated with tool run-out can be eliminated.

3.3 Example of Burr Generation

Several types of burrs were observed during the machining of the complex microfluidic device. One type was feather shaped burrs formed on the floor of the pocket during machining, which are consistent with burrs found when machining similar structures [14]. The tool path motion had an important influence on the generation of feather burrs. Burrs are found on the floor of the recessed pocket in the complex microfluidic device, and are generated by the material removal mechanism between subsequent passes of the cutter. They are exclusively located on the outer fringes of the design, and not within smaller pockets between web protrusions. The burr formation appears to less than consistent, with burrs varying in length from 1-

20µm. There is also evidence of burrs fracturing, most likely during an ultrasonic cleaning process done prior to imaging the mold. Removal of the burrs was extremely difficult. Options for removal include re-machining the floor with a slightly different height-offset value. This was not successful due to small errors in the tool-offset lengths. Burrs were ultimately removed by reducing the feed to an appropriately low enough level so that the burrs were small enough to flake off during cleaning.

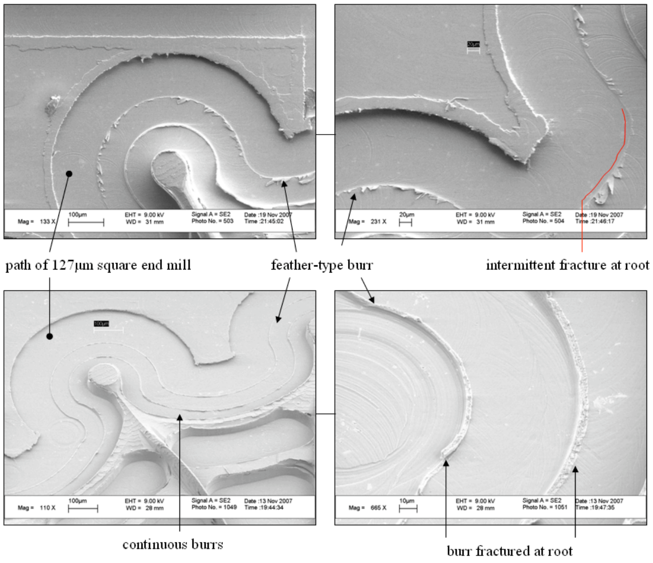


Figure 6: Evidence of Feather Burr Formation

4 ROLLER IMPRINTING

In the roller imprinting process, a cylindrical roll with raised features on its surface creates imprints by rolling over a fixed workpiece substrate (see Figure 7). Similar to injection molding, as the imprint rolls are manufactured using micromachining processes roller imprinting can be applied in fabricating microfluidic devices with contoured surface features and cross-sections. Hence, the precision of the imprinted features is dependent on the precision of the machined features in the imprint rolls. In this section we discuss the requirements for micromachining very precise imprint roll features, and we outline preliminary results in machining the roll features. Based on these results, the Mori Seiki NV1500DCG will be used to machine precision imprint rolls. Past work in roller imprinting has focused on the design of the imprint rolls [15-17].

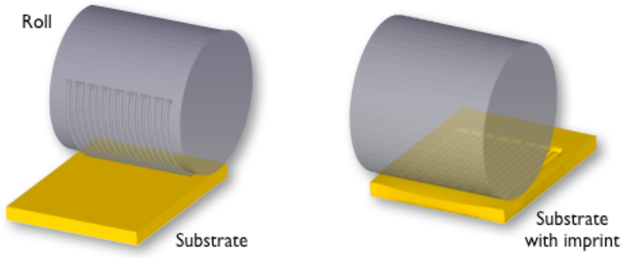


Figure 7: Roller Imprinting

Figure 8 shows an example of a complex machined roll along with imprints created with this roll in PMMA (poly methyl methacrylate). The features on the roll are representative of the fluid pathways seen in microfluidic devices. Square and curved cross-sections have been used for the channel profiles, and a constant spacing has been maintained between adjacent channels.

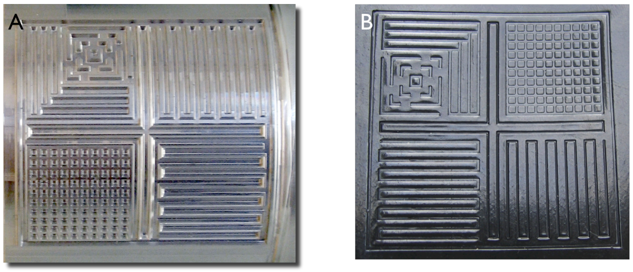


Figure 8: Machined roll (A); imprinted feature in PMMA (B)

4.1 Micromachining for Imprint Rolls

The micromachining requirements for imprint roll manufacturing can be studied in the following categories: machine tool design, workpiece materials, cutting tool design and geometry, cutting parameters, toolpath planning, and metrology. The requirements in each of these categories are briefly discussed, and are summarized in Table 2.

Machine tool design and precision has a large influence on the part quality at both the macro- and micro-scales [18]; however, this effect is seen more dramatically in the micro-scale. Dornfeld et al. [19] identified three critical requirements in micromachining tools for precision machining: thermal stability, precise spindles and bearings, and high resolution linear and rotary motors. Spindle run-out can be especially a problem in the case of the imprint rolls, as the roll features consist mainly of fixed-width channels. Run-out can lead to a widening of the channels, and if its on the same order of magnitude as the channel widths themselves, can lead to extreme distortion of the roll features. Three-axis machine tools will not be adequate for machining the rolls as well. Undercuts in the roll features need to be avoided by either using 5-axis machine tools, or three-axis tools with a rotary indexer. The latter method has been employed successfully in creating the imprint roll features (results from these experiments are presented in the following section). In any case of machine tool selection, the tool-workpiece positional error need to be well characterized using a systematic analytical approach, such as the error-budget approach [18].

The materials used for the imprint rolls can vary from soft Aluminum alloys to harder tool steels. The micro-fluidic devices will be initially fabricated in PMMA (poly-methyl methacrylate), which is softer than most metals – hence a wide range of materials can be used to fabricate the roll. Given this flexibility, it is advantageous to select the roll material based on manufacturing considerations. Choosing an easy to manufacture materials for the roll will decrease the cost and time of roll manufacturing. Micro-machining of aluminum alloys is relatively easier than that of ferrous alloys. Diamond tools are an excellent choice for micro-machining, but are not suitable for machining ferrous materials. Using diamond tools with ferrous alloys requires special environments, which make it infeasible for commercial use. Ni-P plated steel is also being considered as a material for the imprint rolls. The roll features can be rough-cut in steel using traditional tungsten carbide micro-end mills, and finish-machining can be done after electroless Ni-P layer is coated (this method is used in optical plastic molding industry). This is a good approach as it combines the hardness of steel with the superior machined surface quality and form accuracy of diamond machining.

Selection of cutting tool design and geometry can also greatly improve the efficiency of the machining process. Twist-tools such as ball-nose end mills are very versatile and a variety of features can be created with them. A limitation though, is that the roundness of the tool can affect the smallest features realizable. A way of avoiding this limitation is to select a tool in the shape of the feature that is required, for example a grooving tool. These tools have to be custom-manufactured for an application, but are very efficient for creating specific repeating features. However with imprint rolls, although the fluid pathways patterns are repeating, the cross-sections and contours of the pathways are not necessarily uniform. Hence grooving tools cannot be exclusively relied upon, and need to be used in conjunction with the more generic tools.

Past work at the LMAS has extensively studied the influence of cutting parameters on the precision of micro-machined parts and on the occurrence of machining artifacts like burrs [7-12]. Suitable process parameters for the machining need to be selected based on these results. The selection methodology should balance the fidelity of the machined surface with the time and cost for machining. The machined features are also strongly determined by the toolpaths used during cutting. Strategies for toolpath design in the macro-scale cannot be used in the micro-scale due to differences in the material removal mechanism. Given the complexity and diversity of the roll features, the toolpaths need to be designed specific to local feature design while adhering to a global requirement, such as maximizing the surface finish. Toolpath planning strategies are discussed in more detail in the following section.

Finally, appropriate metrology test procedures need to be developed for studying the fully machined rolls. Contact-based methods may not be suitable due to the large travel distances needed in the probes during measurement of the part. Probe tips will also need to be smaller by at least an order of magnitude than the minimum feature size in the rolls. Optical methods may be more suitable as smaller features can be measured. But the challenge here lies in ensuring that all of the roll features are captured without measurement error.

Aspect	*Requirement*
Machine tool design	Use 5-axis mills to full access the roll features. Or use 3-axis mill with rotary indexer.
Workpiece material	Aluminum alloys or Ni-P plated steel
Tool material	Tungsten carbide tools for rough-cut and SCD or PCD for finish-cut
Tool geometry	Combination of generic ball-nose end-mills and special purpose grooving tool.
Cutting parameters	Select to balance workpiece feature precision and machining time/cost.
Toolpath planning	Surface-finish based toolpath strategy with local refinement
Metrology	Optical scanning and other non-contact methods

4.2 Machined Features and Imprint Precision

Toolpath planning and design is a key area to be considered in the development of micro-machining techniques for imprint roll manufacturing. While material considerations may limit the choice of workpiece, process tooling, and process parameters, there is immense control in the selection and design of toolpath strategies to machine the imprint rolls. In this section, toolpath generation strategies are discussed for creating high-quality imprint surfaces. First, lessons learnt from preliminary machining experiments of the rolls are discussed.

Machining Artifacts in Imprint Rolls

Figure 9 shows three zoomed-up sections of a machined roll (same roll from Figure 8). This roll was machined using a 3-Axis milling machine fitted with a rotary indexer in Aluminum 6061 using a 250 μm carbide ball-nose endmill. Figure 9A shows the bottom surface of the roll along the walls of an internal feature. We can clearly see cutter marks in both the feed and in the step-over direction. Figure 9B shows the top surface of an imprint feature, and corresponds to the intersection of two orthogonal channel sections. The section of the intersection sloping downwards diagonally is not fully machined as the contour toolpath used for machining is “turning” around that feature. Figure 9C shows the bottom surface around an imprint feature; cutter marks and toolpath contours can be identified around the feature. Clearly, the toolpath design has a strong influence on the micro-scale features seen in the imprint rolls. It is possible that these features will be replicated in the microfluidic devices as well, and need to be controlled.

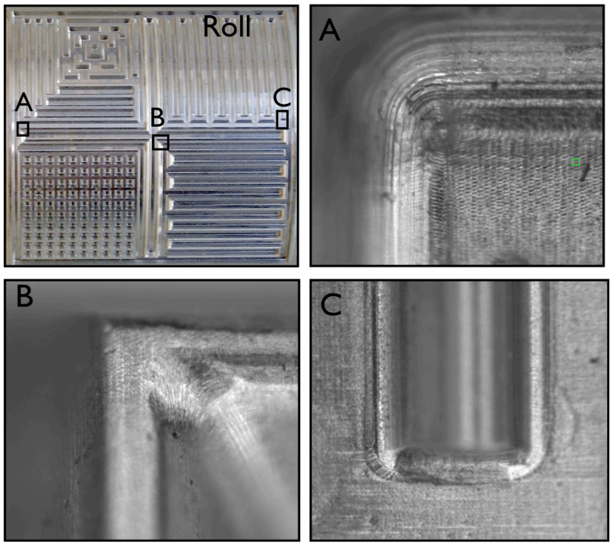


Figure 9: Zoomed sections of machined Imprint Rolls

Toolpath Strategies for Imprint Rolls

From the discussions of the previous section the importance of toolpath design on the imprint roll features can be seen. An important decision to be made regarding toolpath design for ball-nose endmilling of the imprint rolls is in choosing between using raster and contour toolpaths. While contour toolpaths are very suitable for machining complex surfaces, raster toolpaths are easier to apply in generalized cases. There is also ambiguity in specifying regions to decompose for contouring. Specifically in the case of imprint rolls, it is difficult to decompose the individual roll features for contouring, as the spacing between the roll features is not large enough to accommodate for the overlapping of toolpaths from adjacent contours. Moreover, as seen in the previous section, contour toolpaths can cause regular artifacts around the roll features.

On the other hand, raster toolpaths are easier to develop for generalized cases and lead to uniformly directed machining artifacts. The step-size in raster toolpaths can be also locally varied based on the surface features to achieve a required finish. These adaptively varying toolpaths are very suitable for application with the rolls, due to the wide range of features seen in microfluidic devices.

Five-axis machining the rolls holds advantages over three-axis machining, as it allows local control of the tool-workpiece engagement angle. Optimizing this angle improves tool life and machined surface finish. It is also important to design toolpaths that require the least interpolation and movement of the machine tool axes, as excessive interpolation can also affect the machining precision. Decreasing axis interpolation also helps in reducing the machine tool load during cutting.

5 DISCUSSION

We can see that the type of micromachining processes used in fabricating the process tooling for microfluidic devices have a strong influence on the precision of the fabricated devices. The injection mold machining experiments showcased the potential for micromachining in creating complex features. Roller imprinting is another example of this technology being applied in microfluidics manufacture.

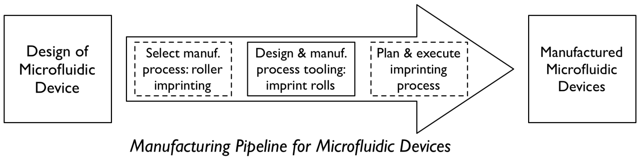


Figure 10: Manufacturing Pipeline

The development of these fabrication processes required the parallel, integrated development of manufacturing processes for the process tooling (imprint rolls, injection molds) as well. While tooling manufacture may seem peripheral to the actual fabrication process, it is an important contributor to the precision of the imprinted features, and cannot be ignored. Hence it is very important to consider the manufacturing implications during the design stage, and fully understand the so-called “manufacturing pipe-line”, which connects the design of a part to its manufacturing. We can see from Figure 10 that in the “pipeline” for microfluidic devices, the design of the manufacturing process (including its process tooling) is a key step. Verily, each component that needs to be designed has its own “pipeline”; micromachining features prominently in the “pipeline” for the imprint rolls and injection molds, making this nested inside the “pipeline” for the microfluidic devices. This illustrates the high degree of inter-relationship between the process planning and design in the various stages of developing these processes, and underscores the need for integrated process design, planning, and development.

ACKNOWLEDGEMENT

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