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Publication Date
2008-10-07

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Proceedings of the 2008 International Manufacturing Science And Engineering Conference
MSEC 2008
October 7-10, 2008, Evanston, IL, USA

MSEC2008-72202

DESIGN AND FABRICATION OF A ROLLER IMPRINTING DEVICE FOR MICROFLUIDIC DEVICE MANUFACTURING

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ABSTRACT

Microfluidic devices are gaining popularity in a variety of applications, ranging from molecular biology to bio-defense. However, the widespread adoption of this technology is constrained by the lack of efficient and cost-effective manufacturing processes. This paper focuses on the roller imprinting process, which is being developed to rapidly and inexpensively fabricate micro-fluidic devices. In this process, a cylindrical roll with raised features on its surface creates imprints by rolling over a fixed workpiece substrate and mechanically deforming it. Roller imprinting aims to replace processes that were developed for laboratory scale prototyping which tend to not be scalable and have high equipment requirements and overheads. We discuss the limitations of PDMS soft lithography in large-scale manufacture of microfluidic devices. We also discuss the design, fabrication, and testing of a simple roller imprinting device. This imprinter has been developed based on the principles of precision machine design and is implemented using a three-axis machine tool for actuation and position measurement. A framework for the micro-machining of precision imprint rolls is also presented.

1 Introduction

Efficient manufacturing processes are required to bring technologies from the laboratory to the marketplace. The success of new technologies in commercial applications is driven in part by innovations in manufacturing – manufacturing processes need to be designed to meet functional requirements while satisfying cost requirements as well. Microfluidic technology is an area that has been witnessing rapid growth in recent years. Microfluidic devices – which exploit fluid properties at the micro-scale – are gaining popularity in a variety of applications, ranging from molecular biology to bio-defense. However, the widespread adoption of this technology is constrained by the lack of efficient and cost-effective manufacturing processes.

This paper focuses on the roller imprinting process, which is being developed to rapidly and inexpensively fabricate microfluidic devices. In this process, a cylindrical roll with raised features on its surface creates imprints by rolling over a fixed workpiece substrate and mechanically deforming it (please see Figure 1). Past research by the authors has focussed on developing design methodologies and tools for modeling the imprint rolls [1,2], and on using computational tools for designing the imprint roll features such that they create precise imprints [3]. Imprint rolls are manufactured using micro-machining technology. Microfluidic devices are composed of networks of fluid flow channels, and the precision of the imprinted devices is measured by the positional accuracy of the channels, the form error, and the profile of the channel surfaces. For a given substrate material, the precision and accuracy of the imprints are dependent on the features of the imprint roll and the precision of the imprinting device. In this paper, we discuss the design, fabrication, and testing of a simple roller imprinting device.

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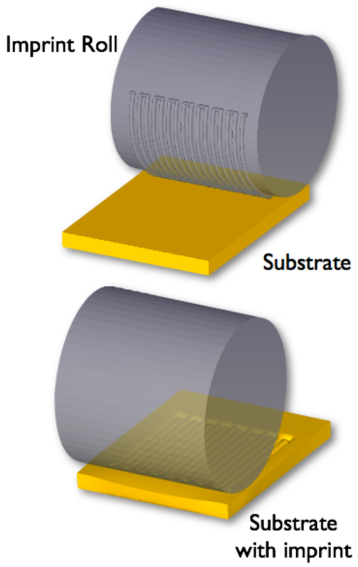

Figure 1. Schematic of the Roller Imprinting process. The imprint roll rotates and moves linearly, while the substrate is fixed.

Given the wide range of applications for microfluidic devices [4], there is a need for developing inexpensive and flexible manufacturing processes. It is difficult for any one manufacturing process to perfectly satisfy the requirements of all microfluidic technology given the wide variety wide variety of feature scales possible. Instead, we need targeted manufacturing processes for specific ranges of feature scales, feature precision and process throughput. Such a targeted approach is especially crucial for the manufacture of microfludic devices for applications in low-cost medical diagnostics, where manufacturing process efficiency is very important [5].

Roller imprinting is being developed for manufacturing devices with features in the range of 100 - 500 μm . Section 2 discusses the field of manufacturing processes for microfluidic devices, and compares their relative advantages and disadvantages. Past focus in process development has been primarily on achieving smaller and smaller feature sizes, and not necessarily on the repeatability and precision of the process. In this paper we discuss the design, fabrication and testing of a roller imprinting device, beginning with a discussion on the precision requirements for such a device. Following this, requirements for precision manufacturing of the imprint rolls is discussed. Finally, we conclude with a discussion on the need for an integrated framework to design and manufacture the imprint rolls.

2 Microfluidic Devices

Microfluidics is the "science and technology of systems that manipulate small amounts of fluids (in the picoliter range) using channels with dimensions in the microns domain" [4]. Microfluidics exploits both its small size as well as the favorable properties it offers in the liquids. Common materials used in microfluidic devices include poly(dimethylsiloxane) (PDMS) and other silicones, poly(methylmethacrylate) (PMMA), poly(vinylchloride) (PVC), and poly(styrene) (PS) [6]. Materials are selected based on their manufacturability and their performance in a microfluidic device. The common method to propagate flow in the micro-scale is by electroosmotic pumping (where an applied electric charge propels the flow) [6]. In systems with electroosmotic flow (EOF), the substrate material has to be a good electrical insulator so that the applied charge does not flow through the device instead of the channels. Heat dissipation is also important, as Joule heating from the EOF can cause warpage in the channels. The material also needs to have a good surface charge in the channels walls to support EOF. Other important properties required in the materials are: molecular adsorption, optical properties (transparency), bio- and chemical- compatibility, and mechanical properties such as adhesion and stiffness [6, 7].

Due to the size of the channels in the micro-scale, fluids in microfluidic devices demonstrate properties not usually seen on the macro-scale [8]. At this scale, viscous forces have a stronger presence than inertial forces, hence only laminar flow is observed in micro-scale flow channels. One consequence of this effect is that fluid mixing can only occur by diffusion rather than by conventional means (stirring, etc.). However, diffusion does not happen fast enough for some applications and micro-mixers are needed to increase the diffusion rates [8]. Passive mixers use the channel geometry to improve the diffusion by repeatedly "folding" the fluid streams over each other. Most of the conventional micro-fluidic manufacturing processes can only create 2D features (with a constant depth). Hence, passive mixers use multiple fabricated layers in the device to induce mixing.

Microfluidic devices were first fabricated in glass using silicon-manufacturing technology from the semi-conductor industry ("hard lithography"), and as the field developed new fabrication methods were developed specific for microfluidic devices [9]. Among these methods, soft lithography based techniques for PDMS fabrication are the most popular. Other fabrication methods include imprinting, hot-embossing, and injection molding. Processes combining embossing and rolling have also been used in the fabrication of micro-scale patterns. We discuss the fabrication methods for microfluidic devices in more detail in this section.

2.1 PDMS Soft Lithography

The most common process used for MFD fabrication is soft lithography [9]. Features are created by casting an elastomer over a silicon master and allowing it to cure. Elevated temperatures speed up the curing, and the elastomer is removed and used to

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create the device, leaving the master for reuse [10]. A schematic of this process is shown in Figure 2. The most common material used in this method is PDMS and the silicon masters are created using standard lithography processes. Soft lithography-based methods are popular because of the small feature scales possible and the potential for reusability of the silicon masters [11]. PDMS-based devices have been extensively used in fabricating valves and actuators in microfluidic devices [12]. Very complex micro-scale circuits with hundreds of valves and actuators have been fabricated using layered PDMS devices [13].

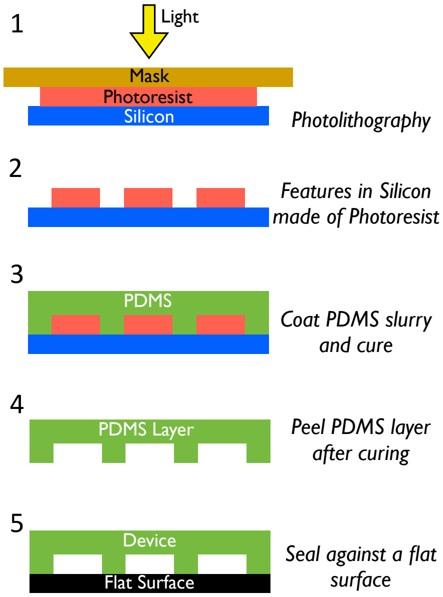

Figure 2. Schematic of Soft Lithography Process (Adapted from [10])

2.2 Limitations of Soft Lithography

The fabrication of masters is the main limiting factor in soft lithography [10]. Masters are typically generated using standard lithography processes. Because traditional chrome masks are expensive and time consuming to produce (lead time of days or weeks), a popular rapid prototyping technique is to directly print a mask design onto transparent polymeric sheets using a commercial printer [14–16]. While this technique can generate a completed microfluidic device within 24 hours at low cost, the resulting mask does not have the durability or dimensional stability to be a successful manufacturing process. In addition, the minimum feature size that can be generated with this technique is 20 μm and the highest resolution is 3387-5080 DPI. The limited resolution of the printer can cause roughness on the micron level as seen in Figure 3. Furthermore, the use of transparent polymeric sheets allows only the use of contact photolithography – a technique not used in industry because of the necessity for level alignment to a surface and the problems associated with this requirement [17].

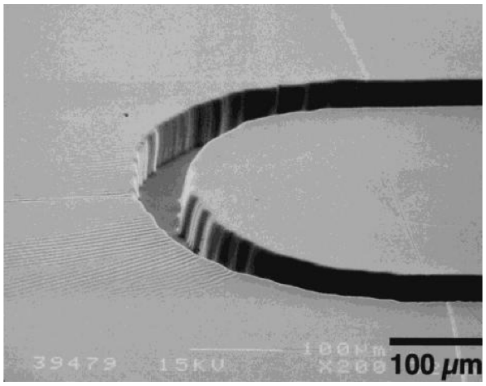

Figure 3. Micron-scale roughness in microfluidic devices from mask resolution [11, 14]

Photolithographic techniques are not the only processing methods used to create soft lithography masters. One alternative approach is the use of solid-object printing to fabricate a master made of thermoplastic build material [18]. Despite the fact that solid-object printing removes the need for masks, alignment, timed exposures, and development, feature sizes less than 250 μm are impossible to create, masters have significant roughness due to the lack of resolution in the printer (300 x 400 x 600 DPI), and the thermoplastic build material is soft and easily deformed. Another approach is to create a metal master through traditional silicon microfabrication techniques. This method, though, is complex, expensive, time consuming, and requires specialized equipment [16].

While the rapid prototype technique for mask production is advantageous in terms of flexibility, cost, and time, mass production processes that use soft lithography techniques will require traditional chrome masks. Despite the added costs and lead times associated with chrome masks, their durability is preferred to ensure process flexibility given the anticipated need for multiple masters. The analogue to masters in imprint rolling – the imprint rolls – are significantly easier to fabricate in the mass-scale. We use mechanical micro-machining processes for the imprint rolls and this requires substantially less time, processes, and equipment. Also, imprint rolls are more durable as they are made of hard steels and have long life when used in creating imprints in soft polymers.

The preferred photoresist for soft lithography masters is the epoxy-based resist SU8 developed by IBM [16]. SU8 is specifically designed for high aspect ratio MEMS applications where

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thick, strong layers are required; literature has shown that structures 1200 μm thick are attainable with aspect ratios in excess of 18 with high chemical and thermal resistance and good mechanical properties [19]. But, these advantageous properties of SU8 are highly sensitive to processing conditions. Furthermore, masters composed of SU8 photoresist patterned on silicon wafers can be used only about 30 times before failure [14]. The two common modes of failure reported are the fragility of the silicon wafer and the release of the SU8 photoresist from the wafer [11]. The relative high frequency of failure of traditional soft lithography masters hinders the application of soft lithography in mass production processes.

Soft lithography is unable to process many suitable polymer materials for microfluidic devices, such as PMMA, and is limited to materials with low elastic modulus like PDMS. While PDMS has many advantageous qualities, it is not suitable for a variety of microfluidic applications. Most importantly, PDMS swells when exposed to non-polar solvents [10]. Also, the elastomeric character of PDMS allows gravity, adhesion, and capillary forces to exert enough stress on patterned features to cause them to collapse and/or generate defects in a microfluidic device. To prevent these faults, the aspect ratio of any designed pattern must be less than 2, limiting the size of any feature of a proposed design. On the other land, imprint rolling can be applied with a variety of materials and can be flexibly deployed for a variety of industrial and laboratory applications.

Soft lithography is further limited because it is an inherently 2D process due to the lithographic techniques used to create masters. The "membrane sandwich" method can be used to create 3D structures using soft lithography. In this technique, a 3D structure is constructed by stacking multiple, thin PDMS layers of thickness 100 μm [10]. Despite the relative success of the membrane sandwich method, multiple masters are required, and the alignment of each layer is difficult to accurately attain; achievable accuracy is reported to range from 10 - 15 μm [20,21]. Bonding each layer is also problematic since it relies on the same mechanisms as sealing, and the thickness and planarity of each layer needs to be precisely controlled. To achieve good control over thickness and planarity, sandwich molding (a process where the master and PDMS prepolymer are held in a clamp between layers of aluminum and other protective layers while curing occurs) can be implemented, but the technique lacks scalability due to the care that must be taken to not introduce bubbles into the PDMS polymer and the extra curing time required. A variation of the membrane sandwich method proposed by Anderson [20] involves the use of two masters (one made of silicon and the other of PDMS) constructed using multilevel photolithography in order to create interconnects between both polymer levels. A thin layer is then fabricated by placing PDMS prepolymer between both masters before putting the entire configuration under pressure during curing. This variation still has many of the same disadvantages of the original membrane sandwich method. Furthermore, the PDMS membrane may stick to the PDMS master despite silanization (used to limit sticking), the pressure required may deform the PDMS master during curing preventing an accurate cast, and the use of multilevel photolithography may overexpose areas of the mask that are not meant to have relief features.

This is a major drawback as non-2D planar structures are critical to improve the mixing rates of fluids in microfluidics [22]. With roller imprinting, it will be possible to imprint contoured surface features as the roller will be manufactured using mechanical micro-machining. A high degree of surface form control is also possible unlike in PDMS soft-lithography as the imprinted features will be derived from the micro-machined surfaces of the imprint roll. Micromachining research has focused on creating accurate surfaces by minimizing machining artifacts and errors [23] and these results can be applied in creating imprint rolls which imprint high-precision contoured surfaces. Hartnett [24] demonstrated the capability of micro-machining processes in creating contoured micro-scale features. A micro-scale injection mold was machined in aluminum with contoured 3D channels, and this is shown in Figure 4.

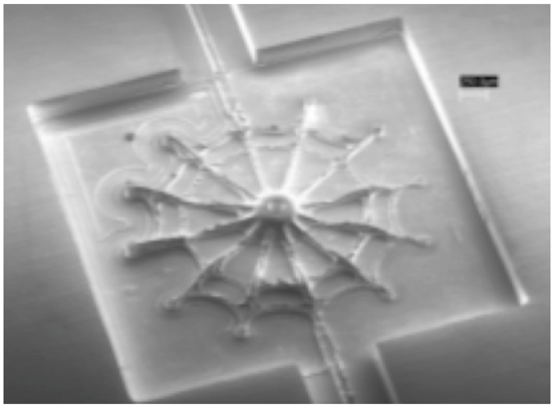

Figure 4. Micro-machined Injection Mold [24]

Soft lithography has many benefits, but it was originally designed as a rapid prototyping method for chemists and biologists to do simple, cheap experiments on the fly as evidenced by having a defect rate higher than photolithography and in its inability to establish itself as a practical application for commercial systems. Imprint rolling, on the other hand, offers promise as a means to mass produce microfluidic devices. Imprint rolls are more durable and strong and offer better process latitude than soft lithography masters. Furthermore, imprint rolling can process a variety of useful polymers and is also able to create 3D features with greater ease than soft lithography.

2.3 Other Fabrication Methods

Xu et al. [25] discussed a room-temperature imprinting methods to create channels in PMMA using a silicon master. The channel depths was found to be dependent of the pressure applied (indicating the visco-elastic behavior of PMMA), and the channels were produced within a variation of 2%. However it was noticed that the channel depths were significantly smaller than the size of the silicon masters features used in their fabrication. The silicon master was created by rapid prototyping a mask using a 1200 DPI printer. While this method has been successfully applied in creating devices, it is faced with the same limitations as PDMS soft-lithography. The device features are derived from silicon lithography and hence contoured 3D features are not possible.

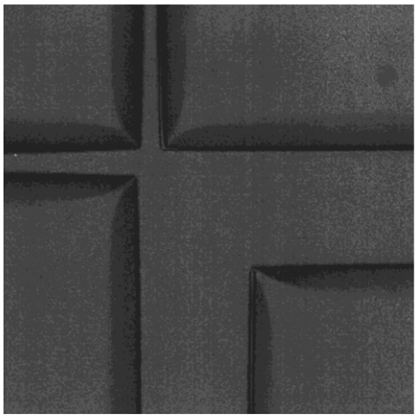

Figure 5. Embossed Features [25]

Hot-embossing has also been similarly used to create micro-scale features in PMMA. The drawback with this method is that the process time is significantly longer compared to room temperature imprinting, and the life of the silicon-master is shorter (due to the increased wear at high temperatures). Specifically in the case of devices in PMMA, hot-embossing (as opposed to room-temperature imprinting) decreases the surface charge of the channels, inhibiting EOF in the device [6].

Roller embossing processes have also been applied in creating micro-scale patterns [26]. In this method an electro-formed nickel mold is wrapped around a cylinder and used to create features in a UV-curable photopolymer. Features are created by curing the embossed areas immediately after rolling. While this process has been successfully applied in creating substrate features that match the mold features, the features in mold themselves are not created by a designed process. The nickel mold features are created based on embossed features in a plastic “mother lens”. The “mother lens” features are in turn created by hot-embossing a plastic film by a silicon master (see Figure 6). Again, the same limitation in creating contoured features is seen. Moreover, there is not adequate control over the features in the nickel mold. This process may be enough for generating simple shapes, but not for the creation of more complex contoured surfaces.

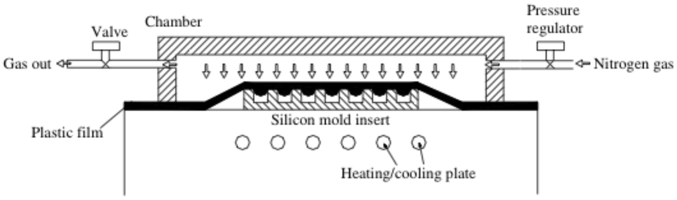

Figure 6. Schematic drawing of gas pressurized hot embossing process [26]. Notice that there is not much control over the shapes of the features created in the plastic film. The nickel molds are designed based on the plastic films.

2.4 Roller Imprinting for Microfluidic Devices

Past work by the authors have focussed on design of the imprint rolls [1–3]. The feature complexity seen in microfluidic devices makes it tedious to manually design imprint rolls. Moreover, the effect of the substrate material properties and imprinting process parameters on the imprint geometry should be accounted for in the roll design, and this makes manual design even more challenging. Robust methods for designing the imprint rolls makes it easy to design them for cases of microfluidic devices with complex contoured channels. Hence, we use procedural methods to design the imprint rolls based on the microfluidic device design, the imprinting process parameters, and the substrate material properties. The local deformation behavior of the substrate during imprinting is used in modeling the roll. Since it is difficult to analytically model the substrate deformation, finite-element simulations are used and the roll is designed piecewise locally. Piecewise design and analysis has the additional benefit of decreasing computational time. It is adequate to only study the local deformation behavior as the roll features only affect a limited region around the imprinted area.

The procedural design methodology is as follows (please see Figure 7). The input for the design process is the microfluidic device design, the device material properties, and the imprinting process parameters. Based on the microfluidic device design, a base-design (or zeroth iteration) of the imprint roll is modeled. The model is then partitioned into sub-sections for analysis. Following this, finite-element analysis (FEA) of the imprinting process is used to iteratively design regions of the roll corresponding to the sub-sections. The roll features are then modified based on analyzing the conformance (or fitness) of the imprinted feature from the finite-element analysis to the required feature. This process is iterated until the imprinted features match the required device features within a specified tolerance. The features mod-

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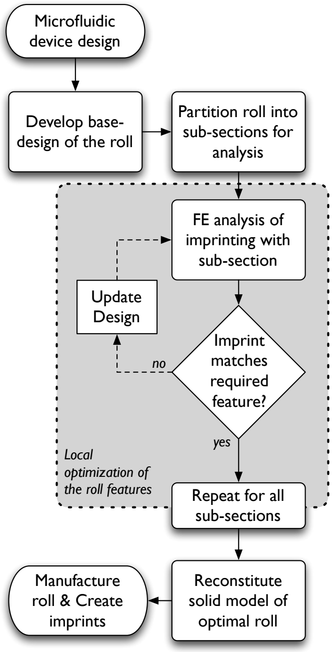

Figure 7. Procedural modeling methodology [2]

ification is carefully controlled to ensure that the iterations converge. All the sub-sections are analyzed this way, and a final imprint roll is composited from these results. Micro-machining processes are then used to manufacture the roll, with which imprints are created. We have discussed an implementation of this methodology in [2].

Roller imprinting is being developed to address some of the disadvantages of conventional processes for mass-scale manufacturing of micro-fluidic devices. While these processes are very capable in the laboratory scale, they are less than ideal for application in mass-scale manufacturing. Our procedural methodology places an emphasis on the precision of the imprinted features, and not necessarily the rapid prototyping of microfluidic devices. A summary of the advantages of roller imprinting is given in Table 1.

3 Requirements for a Roller Imprinting Setup

Designing a high-precision machine tool for creating imprints is a critical step in the development of the roller imprinting process. The dynamics and control of the machine tool will affect the accuracy of the process. Given that we are dealing with small tolerances, these errors can significantly affect the quality of the imprints created. The roller imprinting equipment is designed based on the principles of precision machine design. Precision machine design calls for a systematic identification of how the components of the machine tool (in our case the imprinter) contribute towards imprecision in the part [27]. Nakazawa [28] outlines the following requirements for a precision machine:

Table 1. Summary of Advantages of Roller Imprinting

Aspect	*Drawbacks of Current Technology*	*Advantage of Roller Imprinting*
Durability	Silicon-based masters have a very short life	Imprint rolls are extremely durable as they are made of hard metals
Manufacturing Time	Fabrication time for masters can be long.	Machining processes are efficient in high-speed manufacturing.
Material Types	Most popular method – soft lithography – is limited to PDMS.	Can be used with a variety of deformable materials.
Ability to create non-2D features	Severe limitations as complex layers needed to create contoured fluid pathways	Easy to create contoured surface as roll features can be contoured.
Feature Control	Control over created features is not very accurate	Very accurate control over surface features as feature creation is by material deformation.
Design Focus	Focus is on rapid prototyping.	Focus is on mass-manufacturing of high-precision devices.

1. Possesses a perfect kinematic reference
2. Possesses a perfect kinematic pair which executes perfect movement with respect to the reference
3. Constructed to prevent noise and disturbance
4. Ability to detect movement accurately

In the case of the imprinter design, the key requirement is the positional accuracy of the roll with respect to the substrate. Based on this requirement, and the principles of precision design outlined before, the following requirements are identified for a precision roller imprinting setup:

1. Machine should have a fixed kinematic reference
2. Rigid frame and linkages (where appropriate)
3. Independent actuation of the roll and the substrate with respect to the kinematic reference

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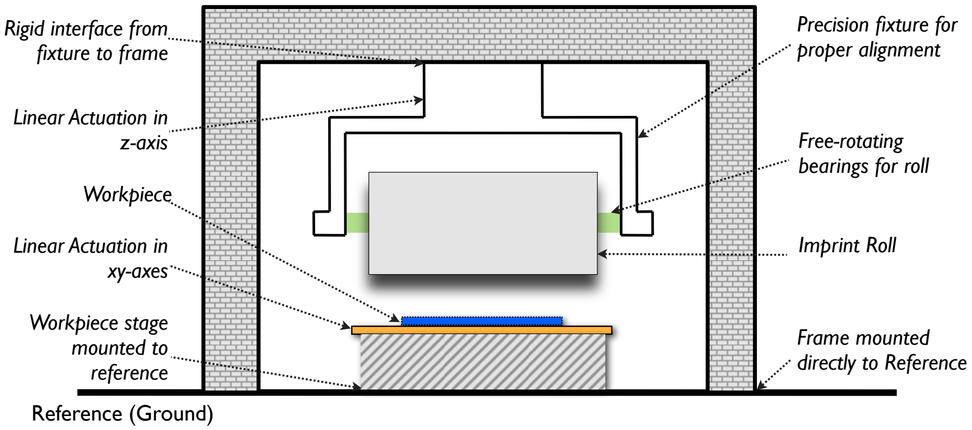

Figure 8. Schematic of Concept Sketch

4. Precision fixturing for the roll and the substrate
5. Minimization of frictional errors (such as slip and lag)
6. Smooth rotation of the roll
7. Unobtrusive measurement of the roll and substrate position
8. Thermal isolation of heated elements

Based on these requirements, a concept sketch of the roll is shown in Figure 8.

4 Design and Fabrication of Imprint Roller Setup

Based on the concept sketch, we have implemented a simple precision roller imprinter by retrofitting a conventional 3-axis end-milling machine. This is a precursor for a custom roller imprinter machine tool, and serves as a simple and modular way of testing the various roll designs. Using a high-precision machine tool also satisfies the precision requirements from Section 3. By using the z-axis to control the roll position, and the xy-stage to control the workpiece position, precise actuation and unobtrusive measurement is possible.

A special purpose attachment was designed to mount an imprint roller to a machine tool. The principal design elements were the orientation and location of the roll in order to ensure an accurate imprint on the substrate. The attachment also needed to be fabricated cheaply and quickly for both ease of implementation and ease of replication. We have designed a “claw attachment” that holds the roll from both sides. The claw attachment consists of an aluminum frame which supports a steel axle. Double-sealed ball bearings are mounted on the ends of the roll using a slip-interference fit. The mounting positions on the frame are designed asymmetrically to constrain axial movement of the roll. Furthermore, the size of the frame is designed to the exact size of the roll to eliminate extraneous movement in the roll. The roll itself is not actuated to rotate and is driven by the interfacial friction between the roll and the substrate. This ensures a slip-free contact and reduces the number of actuators in the system.

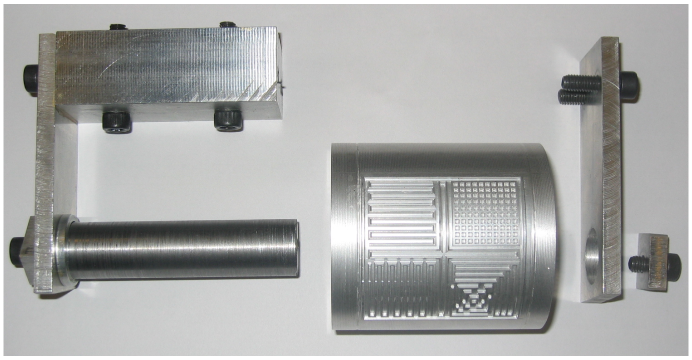

Figure 9. The Claw – Exploded View of the Roll Attachment

The machine chosen for the implementation was a Matsuura 3-Axis vertical milling center, with a positional accuracy of 1 μm in each of the axes. With this level of accuracy, any inaccuracy in the imprinting can be attributed to the design of the imprinter itself, and not the machine tool. The claw attachment was rigidly fixed to the spindle head of the Matsuura, taking care to ensure that the roll axis was parallel to the workpiece plane. The claw attachment, mounted with an imprint roll is shown in Figure 10

5 Manufacturing Imprint Rolls

The imprint roll used in the experiments was machined using a 3-axis milling machine fitted with a rotary indexer in Aluminum 6061 using a 250 μm carbide ball-nose endmill. This roll was designed based on the procedural approach discussed in Vijayaraghavan and Dornfeld [1]. A solid model of the roll is shown in Figure 11.

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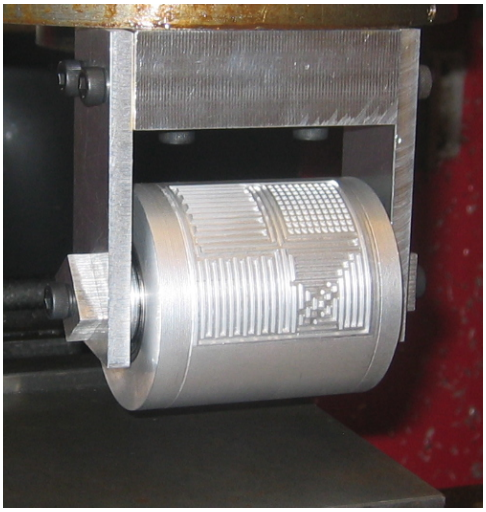

Figure 10. Claw Attachment and Roll Fixed to Machine Tool

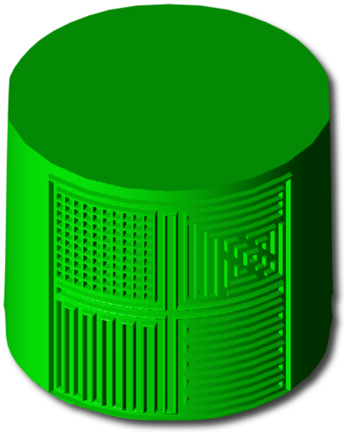

Figure 11. Solid Model of Imprint Roll

Previous work by the authors has discussed the effect of roll feature design on the quality of the imprinted surfaces [3]. However, it is also important to consider the role of the machined surfaces in the quality of the imprinted surfaces. Figure 12 shows “zoomed” sections of three regions in the machined imprint roll. We can clearly identify machining artifacts due to toolpath spacing and layout. Cutter marks and toolpath contours are clearly seen in images A and C, and image B shows a region with incomplete material removal. 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 imprinted devices as well, and need to be controlled.

Requirements for precision manufacturing of the roll features have also been developed, and are shown in Table 2. These requirements have been developed based on past research in high-precision micro-machining [23, 24].

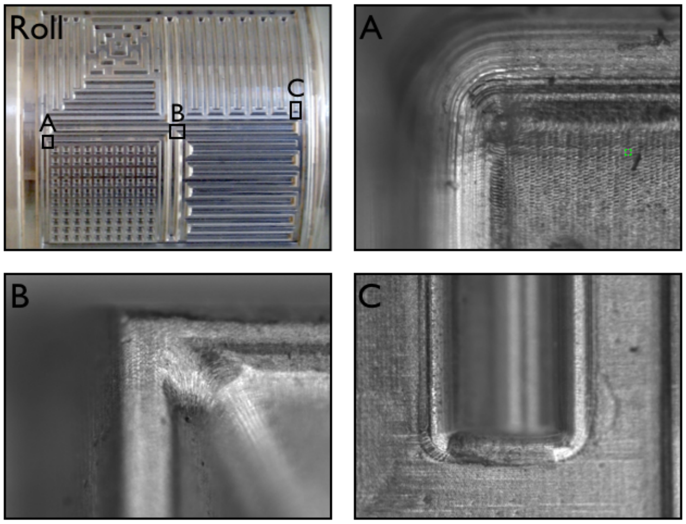

Figure 12. Zoomed Sections of Imprint Roll

Table 2. Precision Manufacturing Requirements

Aspect	*Requirement*
Machine tool design	Use five-axis mills to fully access the roll features. Or use three-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

6 Imprinting Experiments

We performed preliminary experiments using the setup shown in Figure 10 and created imprints in PMMA, ABS and high density polyethylene (HDPE). The experiments were performed using both room-temperature substrates and heated substrates. The imprints created in the heated substrates demonstrate better fidelity to the roll features due to thermal softening. Figure 13 shows an example of an imprinted feature in heated ABS.

A slip-free interface was observed between the roll and the

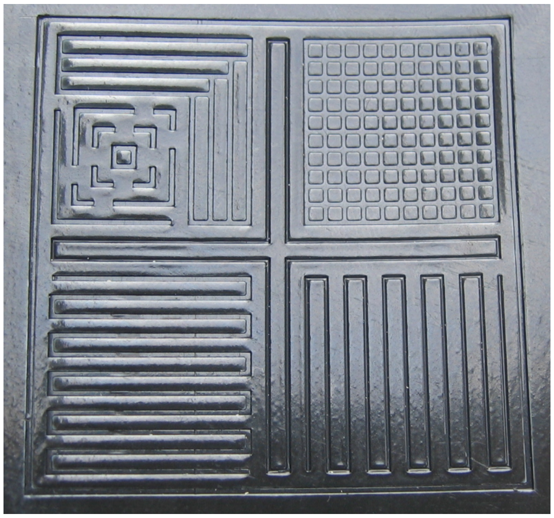

Figure 13. Imprinted Feature in ABS

workpiece during imprinting. This is consistent with the numerical modeling of the imprinting process [3]. Currently, we are integrating thermal sensors to the imprinting setup to measure the temperature of the workpiece. A heated substrate mount is also being designed to control the temperature of the workpiece in real-time. Future work in this field will focus on correlating the imprinted features with the designed features of the roll. The effect of the machined surface, the imprinter precision, and the workpiece material properties will be taken into account in this correlation.

7 Discussion

Roller imprinting has the potential for large-scale mass manufacturing of micro-scale features. It aims to replace processes that were developed for laboratory scale prototyping which tend to not be scalable and have high equipment requirements and overheads. We saw in this paper the limitations of PDMS-soft lithography in the large-scale manufacture of microfluidic devices. Even with the advent of better and faster manufacturing, soft-lithography is restricted to 2D constant-height features. This is a big limitation as it constrains the possible designs of passive micromixers for microfluidics, while increasing the complexity of the devices. It is interesting to note here that there is very little research in developing passive micro-mixers with contoured 3D surfaces – clearly related to the fact that there are no easy methods to fabricate and test the designs. Roller imprinting enables these possibilities in microfluidic devices. Moreover, with improvements in the cost and time of micro-machining, it is possible to create imprint rolls rapidly and apply them in lab-scale prototyping as well.

The development of the roller imprinting process requires the parallel, integrated development of all the facets of the imprinting process. This includes designing the imprint rolls, the manufacturing process for creating the imprint rolls, and the fabrication process for creating the imprints. The precision of the imprinted features is a function of all these aspects, and parallel development allows us to quickly identify which of these aspects has the greatest impact on the quality of the imprinted features. Hence it is very important to fully understand the so-called manufacturing pipe-line, which connects the design of a part to its manufacturing. Figure 14 shows the manufacturing pipe-line for the imprint rolls, which is composed of the process selection, process planning and, toolpath design steps. This process in turn, is nested inside of the manufacturing pipeline for microfluidic devices, and includes the development of the imprinting process itself. This illustrates the high degree of inter-relationship between the process planning and design in the various stages of developing the roller imprinting process, and underscores the need for integrated process design, planning, and development.

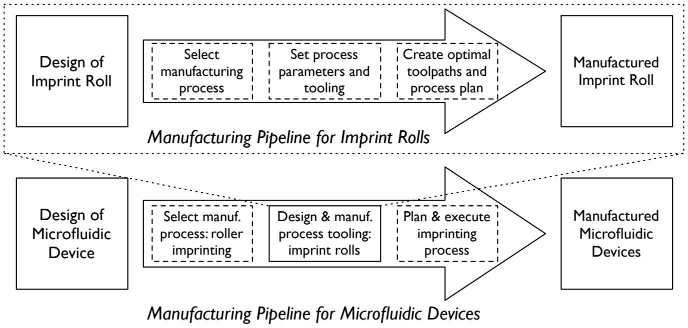

Figure 14. Manufacturing Pipeline

8 Acknowledgments

This work is supported in part by the industrial affiliates of the Laboratory for Manufacturing and Sustainability (LMAS), the Machine Tool Technology Research Foundation (MTTRF), and Lawrence Berkeley National Laboratory. To learn more about the research activities of the LMAS, please visit http://lmas.berkeley.edu.

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