Precision Manufacturing of Imprint Rolls for the Roller Imprinting Process

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Abstract: The roller imprinting process is being developed for the efficient and accurate fabrication of microfluidic devices. As the precision of the imprinted features is dependent on the features of the imprint rolls used in the process, it is critical that the rolls are manufactured very accurately, conforming closely to their design. It is also important that imprint rolls are manufactured rapidly and cost-effectively to control the cost and lead-time of roller imprinting. This paper looks at the application of micro-machining technology in the manufacturing of imprint rolls. Sources of error during the manufacturing process are identified, and their effect on the precision of the final imprinted feature is discussed. Toolpath planning strategies are presented for generating very smooth surfaces. The paper presents a framework of precision manufacturing requirements for the roller imprinting process.

Keywords: Roller Imprinting, Micro-machining, precision manufacturing, toolpath planning.

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 focuses on the use of micro-machining in the development of the roller imprinting process, which is being developed for the efficient fabrication of precision microfluidic devices. In this process a cylindrical roll with raised features on its surface creates imprints by rolling over a fixed workpiece substrate (see Figure 1). This paper is motivated by two compelling reasons: the processes used in machining the imprint rolls have a significant effect on the precision of the imprinted features; and, the feature sizes possible with imprinting are limited by the accuracy of the machining processes used.

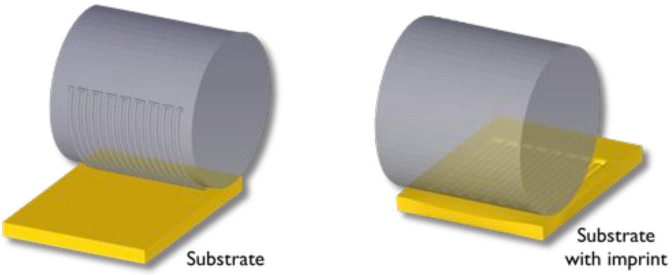
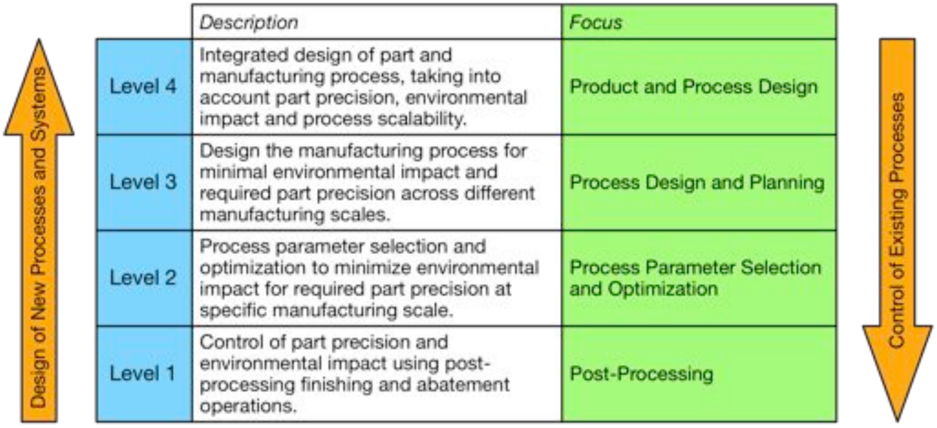


Figure 1 : Roller Imprinting

The design and development of manufacturing process technology can be visualized across 4 “levels of activity”, which are shown in Figure 2. These range from Level 4 which looks at integrated product and process design, through Level 1, which focuses on post-processing operations of a fully manufactured part. This paper focuses on a Level 3 activity, as roller imprinting is being developed for specific needs in fabricating microfluidic devices. Activities in Level 3 require a detailed understanding of the design and manufacturing of all components of the process being developed and micro-machining is a very important component in the development of roller imprinting.



	Description	*Focus*
Level 4	Integrated design of part and manufacturing process, taking into account part precision, environmental impact and process scalability.	Product and Process Design
Level 3	Design the manufacturing process for minimal environmental impact and required part precision across different manufacturing scales.	Process Design and Planning
Level 2	Process parameter selection and optimization to minimize environmental impact for required part precision at specific manufacturing scale.	Process Parameter Selection and Optimization
Level 1	Control of part precision and environmental impact using post-processing finishing and abatement operations.	Post-Processing

Figure 2 : Levels of Activity for Manufacturing Process Design

The paper begins by discussing the need for developing manufacturing processes to fabricate microfluidic devices. The roller imprinting process is then discussed, with a focus on its advantages over the processes prevalent in current practice. Following this, state-of-the-art in micro-machining technology is discussed, and a framework of the key requirements for precision imprint roll manufacturing is presented. Specific requirements in toolpath planning and design are discussed. The paper concludes by highlighting the need for integrated machining process development for imprint roll manufacturing.

2. MANUFACTURING FOR MICROFLUIDICS

Microfluidics deals with the manipulation of small amounts of fluids (in the pico-liter range) using channels with dimensions in the microns domain [Whitesides, 2006]. 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 [Yager et al., 2006]. 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 [Whitesides, 2006]. 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.

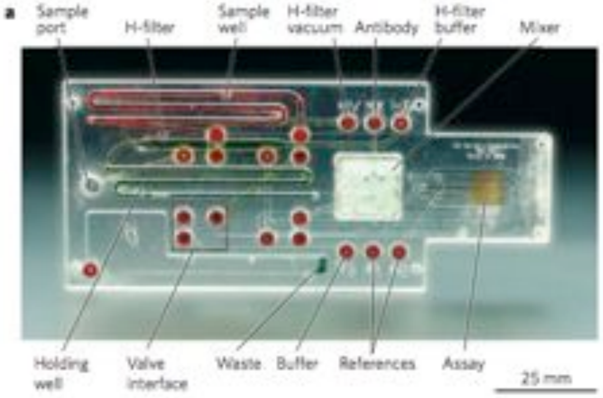


Figure 3: Microfluidic Device for Medical Diagnostics [Yager et al., 2006]

The most common process used for MFD fabrication is soft lithography using Polydimethylsiloxane (PDMS) [Ziaie et al., 2004)]. Features are created by casting the elastomer over silicon masters, which are fabricated by lithography. Imprinting processes have also been used in creating MFDs in the past, albeit to a lesser extent. [Xu et al., 2000] 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.

2.1. Limitations of Conventional Manufacturing

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. This is undesirable as fixed depth channels are not as efficient as contoured channels in enabling the mixing of fluids in the microscale. Efficient mixing of fluid streams is required for biological applications where fast analysis is needed [Kim et al., 2005].

2.2. The Case for Roller Imprinting

Roller imprinting is a capable manufacturing process for fabricating large-featured MFDs (with features larger than 100µm). An advantage roller imprinting holds over conventional fabrication methods is in its capacity to create contoured imprint features. The imprinted features are derived from the machined features of the roll, and it is possible to create contoured features with micro-machining. 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 designing the roller imprinting process. This capability of micro-machining has also been used in manufacturing injection molds for micro-fluidics [Hartnett, 2007]. 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 [Nguyen et al., 2005]. 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.

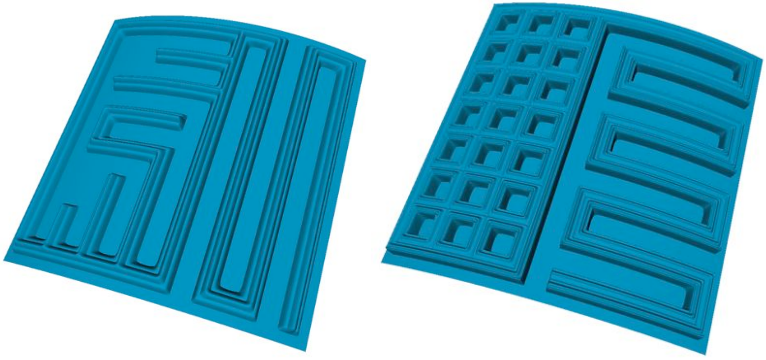


Figure 4: Surface features of imprint rolls with contoured cross-sectional features [Vijayaraghavan et al., 2008b]

To ensure precise imprints, it is critical that the imprinting process is well characterized. The precision of the imprints is influenced by the design and manufacture of the imprint rolls, the properties of the workpiece substrate, and the parameters of the imprinting process. Of these, the design and manufacture of the imprint rolls are most significant. Past research by the authors has focused on developing design methodologies and tools for modeling the imprint rolls [Vijayaraghavan et al., 2007; Vijayaraghavan et al., 2008b], and on using computational tools in designing the imprint roll features to create precise imprints [Vijayaraghavan et al., 2008a]. Figure 4 shows examples of imprint roll surfaces modeled with complex pathway features and cross-sections. Figure 5 shows a solid model of a roll along with a fully machined roll corresponding to the model, and test-imprints created in wax from this roll; the roll had features ranging from 500µm to 1mm. The size of the features possible with imprinting is limited by the precision with which the rolls can be manufactured using micro-machining. The next section reviews the state-of-the-art in micro-machining and identifies the micro-machining requirements for roller imprinting.

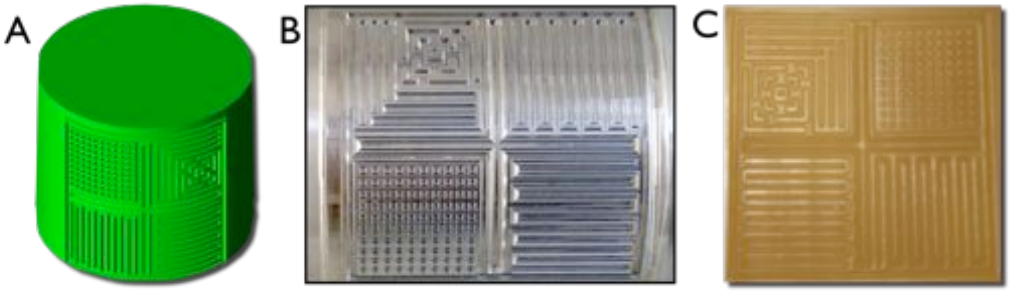


Figure 5: A : Solid model of roll with complex features. B : Machined roll based on A. C : Wax Imprint from B. [Vijayaraghavan et al., 2007]

3. MICRO-MACHINING THE IMPRINT ROLLS

The capabilities of micro-machining technology have been rapidly increasing over the past few years [Dornfeld et al., 2006]. Micro-machining has been extensively applied in manufacturing micro-lens arrays and other repetitive micro-scale features. While micro-machining is not ideal for mass-production of micro-scaled parts, it is very suitable for creating the process tooling required for mass-producing these parts. [Hartnett, 2007] presented in detail the creation of micro-scale injection molds for application in microfluidic device fabrication. [Bissacco et al., 2005] also discussed the precision manufacturing of injection molds for microfluidic device fabrication. Figure 6 shows some examples of repetitive micro-grooves and injection mold features created using micro-machining.

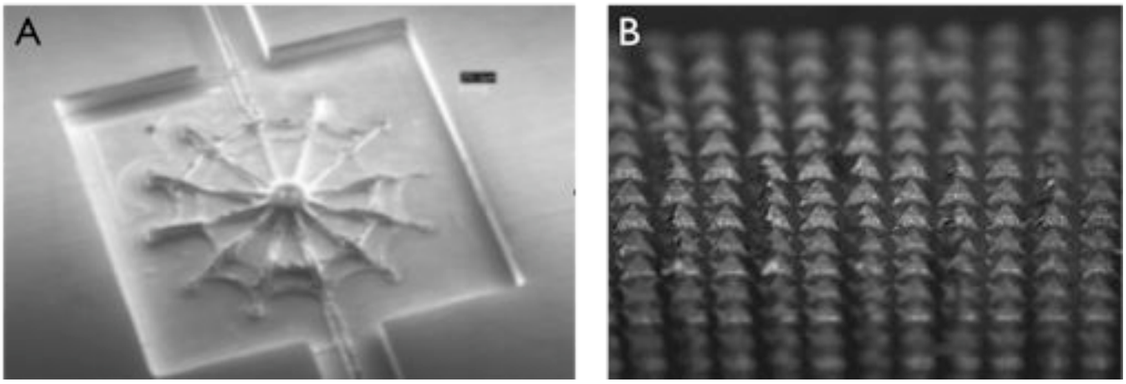


Figure 6: (A) Micro-scale injection mold [Hartnett, 2007] and (B) Pyramidal repeating features [Mertens, 2007] created by micro-machining.

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 1.

Machine tool design and precision has a large influence on the part quality at both the macro- and micro-scales [Dornfeld et al., 2008]; however, this effect is seen more dramatically in the micro-scale. [Dornfeld et al., 2006] identified three critical requirements in micro-machining 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 [Dornfeld et al., 2008].

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 UC Berkeley has extensively studied the influence of cutting parameters on the precision of micro-machined parts and on the occurrence of machining artifacts like burrs [Sangermann, 2006; Mertens, 2007; Hartnett, 2007].

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.

Table I: Micro-machining Requirements

Aspect	*Requirement*
Machine tool design	Use five-axis mills to full 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

4. 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.

4.1. Machining Artifacts in Imprint Rolls

Figure 7 shows three zoomed-up sections of a machined roll (same roll from Figure 5). 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 7A 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 7B 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 7C 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.

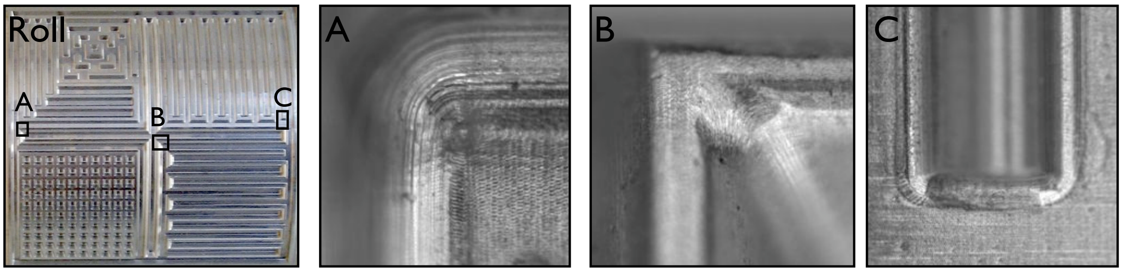


Figure 7: Zoomed-sections of machined roll, as indicated

4.2. 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 [Rangarajan et al., 2004].

5. DISCUSSION

The development of the roller imprinting process requires the parallel, integrated development of manufacturing processes for the imprint rolls as well. While roll manufacturing may seem peripheral to the roller imprinting process itself, 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. Figure 8 shows the "manufacturing pipe-line" for the imprint rolls, which is composed of the process selection, process planning and, toolpath design steps. The entire roll design and manufacturing process in turn, is nested inside of the "manufacturing pipeline" for the microfluidic devices they are applied in manufacturing. 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.

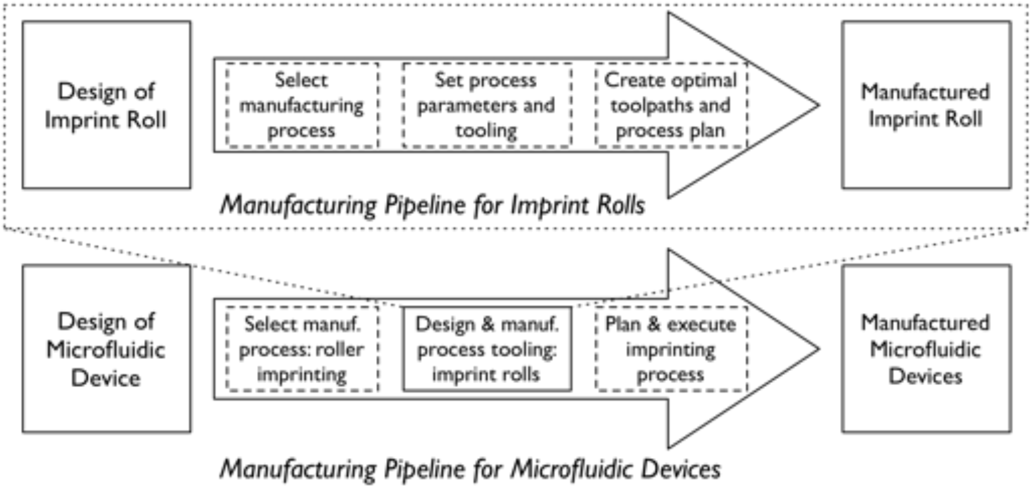


Figure 8: Manufacturing Pipeline for Roller Imprinting

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