A Research Factory for Polymer Microdevices: muFac
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ABSTRACT
As part of our research on the manufacturing science of micron scale polymer-based devices, an automated production cell has been developed to explore its use in a volume manufacturing environment. This “micro-factory” allows the testing of models and hardware that have resulted from research on material characterization and simulation, tooling and equipment design and control, and process control and metrology. More importantly it has allowed us to identify the problems that exist between and within unit-processes. This paper details our efforts to produce basic micro-fluidic products in high volume at acceptable production rates and quality levels. The device chosen for our first product is a simple binary micromixer with 40x50 micron channel cross section manufactured by embossing of PMMA. The processes in the cell include laser cutting and drilling, hot embossing, thermal bonding and high-speed inspection of the components. Our goal is to create a "lights-out" factory that can make long production runs (e.g. an 8 hour shift) at high rates (Takt time of less than 3 minutes) with consistent quality. This contrasts with device foundries where prototypes in limited quantities but with high variety are the goal. Accordingly, rate and yield are dominant factors in this work, along with the need for precise material handling strategies. Production data will be presented to include process run charts, sampled functional testing of the products and measures of the overall system throughput.

Keywords: polymer fabrication, manufacturing, micro-fluidics, hot embossing

1. INTRODUCTION
As part of an ongoing research project on the manufacturing science of polymer micro fabrication, we designed and tested a production cell for a simple microfluidic device. The purpose of this effort is to understand how individual process level efforts could or could not be integrated, to expose and explore the problems between the various stages of production and finally to create a facility for volume production so that time-dependent problems could be identified and addressed.

An earlier paper [17] highlights the factory’s inception, with a team of more than 10 research assistants and 4 faculty members. The basis of our work is detailed in a number of papers including those on deformation properties of polymers [1-2], novel machine and process design for hot micro embossing and PDMS Casting [3-5], tooling production and de-molding analysis [6-8], bonding methods [9] and methods for measurement and control of the resulting processes [10-13].

The goal of the factory is to produce functional microfluidic devices in a continuous production line with high yields appropriate product quality, and production rates similar to injection molding systems. The initial focus is on the use of Hot Micro Embossing (HME) and the primary patterning process with polymethylmethacrilate (PMMA) as the material. A companion production cell, based on rapid degassing and curing, is underway to do the same with a PDMS casting process [16].

The canonical product is a simple binary micro mixer. The basic channel dimensions were chosen to be 40 microns deep by 50 microns wide. This product selection was governed by a number of factors. These dimensions present acceptable flow rates and pressures in the final device. They are in the mid-range of micro-device characteristic dimensions, and we have had experience with tooling, patterning and metrology at this scale. The production of tooling masters with DRIE and other processes works well at these dimensions. Finally, functional testing of the final product is simple and will enable a measure of the overall factory yield. The overall size of the product is 25x25 mm. The final design is shown in Figure 1.
The processes in the cell include hot embossing, thermal bonding and high-speed inspection of the components. Transport between process and manipulation in the cell is performed by an Epson SCARA G10-85 robot manipulator and custom designed end-effector.

![Figure 1. Pattern drawing for the micro mixer tooling showing numerous fiducials and registration features. Note also the large reservoirs at the inlets and outlet.](image)

### 2. THE PRODUCT

Along with the channels, there are a number of other features that were added to aid in the manufacturing and in the measurement and functional testing of the components and the final device. While difficult to see at this scale, a number of fiducials were added to aid in measuring the channel cross section and the overall distortion of the substrate. Other features were included to help in registration of the parts in various processes, such as the vernier scales shown in Figure 1 near the periphery of the tool. Finally, a grid of square and round micron scale features was included in the center of the part to be used as a measure of the overall consistency of the process during production.

To simplify the production processes and interfacing with fluid sources, the input and output ports of the mixer are integral with the substrate. They are produced by pre-drilling the substrate by laser prior to embossing. A plain, flat coverplate of PMMA is then thermally bonded to the substrate to complete the device. No tubing or other fittings were required as the application calls for direct connection with the supply and drain via o-ring gasketed interfaces (see Function Testing section below). Since laser cutting was used to create the workpiece and coverplate blanks, adding the step of hole drilling was not onerous. In addition, the drilling of holes prior to embossing allows flash or other imperfections in the hole to be eliminated by the deformation process.

### 3. TOOLING

The design shown in Figure 1 was developed into tooling for the hot embossing process by two methods. One involved a conventional micromachining process with aluminum as the material. The other used the hot embossing of bulk metallic glass (BMG) using a silicon master made by DRIE. This method is being developed at MIT by Hennan and Anand [6] and has been shown to produce tools of excellent shape fidelity and superior mechanical properties.

To our knowledge this is the first time such a process and material has been used to create embossing tools. The expectation is that the tools will not only have accurate shape reproduction, but will avoid the persistent problems of short tool life in the HME process. The tools and some SEM photos of features before embossing and after several hundred cycles are shown in Figure 2.
4. PROCESS FLOW AND LAYOUT

4.1 Embossing Cell

An embossing-cell and process sequence was developed to create the binary micromixers from PMMA. The basic layout of the sequence is shown in Figure 3.

- Substrate and coverplate blanks laser cut from 2mm thick PMMA sheet using an Epilog MiniHelix 8000 laser cutting machine.
- Holes for the two inputs and the output are cut in the substrate by laser and a serial number engraved.
- The substrate assembly is registered on a fixture on the lower platen of an HME machine.
- The HME cycle is executed and the substrate assembly is demolded using a pair of edge restraints. Only one part is produced per cycle.
- The substrate is placed on a large area high-speed stereoscopic scanner for completed geometry verification. Key dimensions are measured to check for process consistency.
- The substrate is registered with a coverplate and placed in a hot press for a thermal bonding cycle.
- The finished product is placed on a large area high-speed stereoscopic scanner for completed geometry verification. Key dimensions are measured to check for process consistency.
- The finished product is placed in a fluid manifold and is functionally tested for proper fluid flow and mixing performance.

Figure 3. Cell layout. Machine timing and system throughout.
The part flow through the factory has been simulated and is shown in Figure 3. Each color (other than the deep blue background) corresponds to an individual part flowing through the cell as a function of time. The hatched blocks in the embossing and the inspection rows indicate that the part is in the station but is idle, waiting for the next station or the robot to finish its current task.

To simulate the flow of materials, we assume that the hot-embossing and the bonding steps take 180 seconds, the inspection takes 100 seconds, and each travel and manipulation from one machine to another takes 20 seconds. From the perspective of the robot, the various machines serve as buffers allowing the robot to manipulate several parts through the stages of the cell simultaneously. Starting from the bottom row, the robot moves the dark-blue (DB) part from the part feeder and places it on the HEM. After embossing completes, the DB part is picked up by the robot and moved to the inspection stage. Immediately thereafter, the next part, light-blue (LB), is moved from the part-feeder and placed on the hot embossing machine - in this way the production of parts is staggered through the cell. After DB part inspection is complete the robot moved the part to the bonding machine. Then the robot picks the coverplate and places it in the bonding machine. After bonding completes, the DB part is in the bonding machine and has to be inspected, while the LB embossed part is in the inspection stage and has to be bonded. Since the robot can handle only one part at a time, a buffer is added to allow the switch of locations. From the buffer, the completed DB part is placed in the inspection machine. From the inspection machine, the robot moves the part out of the cell.

Notice that the flow is established only after 10 minutes: it takes 740 seconds for the DB part to be achieved, but it takes about 860 seconds for the next parts. This difference is due to the time spent idle in a station or in the buffer. For example, the green (G) part stays idle in the HEM for 100 seconds, waiting for the inspection stage to be free. This waiting time is incompressible from the perspective of G part, but from the perspective of the HEM, it is wasted and we could use it to emboss the next part. To do so, we could use a second buffer to temporarily hold the embossed part.

5. FIXTURE, REGISTRATION, AND TRANSPORT

There are three basic operations required to produce this product – drilling of holes, embossing of the mixer pattern in proper registration with those holes, and bonding of a coverplate in proper registration with the substrate. In addition, there is in-process dimensional inspection, the work-in-progress must be transported between steps without damaging the surfaces, and it must be easily loaded and unloaded into the equipment.

We previously [17] used a carrier fixture and magnetic pin alignment strategy. Blanks and fixtures were first placed in the embossing machine. The carrier fixture needed to be thick enough to prevent the melted polymer from substantially flowing over the edges, but thinner than the embossed part to not interfere with the tooling. Expansion during embossing secured the part in the fixture. Using this technique, we were unable to get the repeatable registration of the part to the carrier fixture.

An improved fixturing and registration strategy was developed. We create two reference-edges during the embossing process in fixed relation to the surface features. The HME process causes in-plane flow of the substrate. The flow is constrained by a corner frame on the HME platen. The part will conform to the frame, producing well defined edges for subsequent operations. The tool and edge producing frame are shown in Figure 4. In subsequent processes, precise planar registration is achieved by using a three-ball kinematic alignment strategy. This solution requires a compliant end-effector (or compliant robot or controller) to push the part against a three-ball mount.

Since the alignment of the mixer features and inlet-outlet pads is critical to the proper flow to and from the device, great care is taken to align the embossing tool to the embossing machine platens. The corner frame edges serve to provide initial alignment when the blank is inserted into the embossing machine. This registration method is intended to allow for fully automated handling of the materials during production, however, at this time such automation has not yet been implemented.

5.1 End Effector

The work in process must be transported between steps without damaging the surfaces. Accordingly, a vacuum pick and release end-effector was designed and built. To ensure consistent positioning within each process, compliant fingers and a sliding trajectory are used to push the part against the alignment rods and compensate for small variation in the position of the machines and robot. (The repeatability of the robot is 25 microns horizontally and 10 microns vertically, but absolute accuracy is expected to be much higher). The end-effector is shown in Figure 5.
6. UNIT PROCESSES

6.1 Laser Cutting

As discussed above, all cutting and drilling is performed with a commercial CO$_2$ laser cutting and engraving machine (Epilog Laser Mini24 with 45W laser). With PMMA a very clean cut can be made, and what flash does occur is deformed away during embossing and bonding.

6.2 Hot Micro Embossing (HME)

For this process a novel approach was taken to achieve both rapid cycle times and an overall low capital cost machine. The details of this approach can be found in [4]. The key features are a simple actuation system with limited travel, but precise force control. This is achieved with a servo pneumatic system with direct forming force feedback. Rapid thermal cycling is achieved by having very low thermal mass in the forming region. By using minimal metallic parts during the heating and forming portion of the cycle, and then applying a large movable heat sink during cooling, a cycle time of less than 2 minutes is easily achieved. Uniform heating is obtained with thin ceramic heaters (Ultamic 600), which cover the entire surface of the forming platens. (The platens are 25 x 75 mm in area, sized to form parts up to the size of a standard microscope slide.) The entire stack assembly is shown in Figure 6 along with a photo of the overall equipment setup.
6.3 In Process Measurement

After forming, the substrate is inspected to monitor for any overall defects, and to continuously monitor the overall consistency of the embossing process. For this purpose an optical imaging system was developed. The system uses stereoscopy and controlled-motion super-resolution to calculate the three-dimensional spatial profiles of a part with a resolution greater than the optical subsystem.

A high-speed (500 frame per second) camera with a telecentric lens is mounted on a custom manipulation stage that rotates the camera’s object plane about an axis coincident with the top surface of the part under inspection. The part sits on a stack of two planar translation stages and rotation stage.

We acquire large area mosaic images of a part by scanning the planar stages and stitching together a sequence of small images. We acquire multiple stereo pairs by scanning the camera stage. We control the image acquisition state including the illumination orientation, camera sensor orientation and position, and part orientation and position. An image set is acquired over a wide range of acquisition states. From the image set we calculate the complete physical geometry of a part.

The entire assembly is shown in Figure 7. In Figure 8 we show a laser drilled hole in steel as imaged by the camera oriented at an angle of 22 degrees with respect to the plane of the device. The image resolution is 4800 dpi (5.29 micron/pixel). The apparent width of the hole’s side wall, as projected on the image plane, is 17.5 pixels (0.093 mm). The thickness of the steel is calculated as 0.23 mm, when thickness of the material is known to be 0.22 mm.
6.4 Thermal Bonding

The formed substrates with pre-drilled holes are bonded to flat PMMA coverplate using a thermal bonding method similar to that described in [10]. The unbonded sandwich is placed in a frame (using the part carrier as a reference) and then placed in a conventional hot press. With appropriate pressure, temperature and holding time, successive bonds can be made. However, since the bonding requires temperatures at or above the glass transition temperature of the PMMA, some deformation of the material occurs as seen in Figure 9. The key to successful process control is to limit this deformation while ensuring an adequate bond. Typical bonding cycles are 106°C for 3 minutes at a pressure of 5 MPa.

![Figure 9. Cross section of a thermally bonded device showing the deformation of the coverplate into the channel and the foreshortening of the embossed channel.](image)

6.5 Functional Testing

Functional testing was designed to be performed in-line on a 100% basis if necessary. For this purpose, a constant flow system similar to that of Thacker [14] was developed. The interface to the product is a manifold that creates o-ring seals over the three holes in the substrate. This system is then mounted in either a microscope or scanner for measurement of flow and mixing profiles.

The Fixture is shown in Figure 10. It allows for fast insertion of the product, again using the part carrier as a locating fixture. Flow was provided by a dual syringe pump (Harvard model PHD 2000) and the mixing was visualized by having one clear water stream and one stream with dye.
7. RESULTS

7.1 End-Effector

We designed and built a glass stage with an upward looking microscope camera mounted below the glass and focused at its surface. We modified a part by adding a visual (cross-hair) template in order to perform image-based template-matching to measure position and orientation. The measurement resolution of this system is 1.8 microns. This system is used to characterize the variation of the vacuum pick-and-place operation. This system is also used to measure the repeatability of the registration solution – the operation of sliding the part into a three post kinematic mount. This stage is also used as the buffer location in the cell.

The seven stages of the pick and place operation are 1) part on the glass, 2) end-effector in contact with the part, 3) vacuum turned on, 4) part lifted off glass, 5) part placed on glass, 6) vacuum off, and 7) end-effector removed from part. An image of the part is acquired at every stage except for stage 4). The variation introduced by the vacuum based pick-and-place operation, excluding the variation of the robot that is moving the end-effector, is the vector sum of the part displacement between stages 1) and 3) and between stages 5) and 7). The mean displacement variation introduced by the end-effector was found to be less than the measurement resolution. By analyzing the variation of the pick and place operation over repeated operations we can detect if the platform and end-effector are out of parallel, and if the contact switch is not flush is not coincident with the plane of the end-effector.

We measure the repeatability of the vacuum pick and release and the repeatability of the sliding engagement into the kinematic alignment posts. The factors that impact the repeatability of the registrations solution include the compliant finger material, the nominal start location where the part is dropped, and the sliding trajectory (including the nominal finger compression to ensure that the part is in contact with the kinematic mount). With rubber fingers, a drop location 1.0mm from the posts of the kinematic mount, and a visually observed nominal finger compression of 0.5 mm, we achieve 4.06 micron and 0.14 degrees rotation registration repeatability.

7.2 HME Substrate Production

Using the above protocols, substrates were produced with the laser cutter, and then formed using the HME machine. Over the last year we have produced close to 500 hundred parts while debugging the hardware and control electronics. We produce batches (a batch is 10 or more parts) for stable machine configurations. A recent batch of 12 parts with an average cycle time of 2 minutes has been completed as of this writing. Channel dimensions at the center of the serpentine legs were measured at the beginning (location 1), middle (location 2), and end (location 3) of the mixer channel. In Figure 11 a run chart for channel height and width for this production batch is shown. As is shown in table 1, even without eliminating outliers, we see that the process standard deviation is on the order of 0.6 microns for depth and 1.5 micron for width. This gives relative variations of 1.5% and 3.3% for depth and width respectively. This variation is larger than our prior work (e.g. [12]), on process variation (relative variations of 1.0% for depth and 1.5% for depth) but is attributed to recent un-optimized machine changes.
Figure 11. Run charts for width and depth at Location 2 on HME parts.

Table 1. HME Channel Depth Performance over 12 Parts

<table>
<thead>
<tr>
<th>Site</th>
<th>Height (microns)</th>
<th>Width (microns)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Std. Dev.</td>
</tr>
<tr>
<td>1</td>
<td>39.10</td>
<td>0.52</td>
</tr>
<tr>
<td>2</td>
<td>39.00</td>
<td>0.62</td>
</tr>
<tr>
<td>3</td>
<td>38.96</td>
<td>0.69</td>
</tr>
<tr>
<td>VP</td>
<td>1.6%</td>
<td></td>
</tr>
</tbody>
</table>

The spatial and temporal variation and mean drift of the HME process is analyzed by comparing the measurement statistics of three different sites for three different runs. In Figure 12 we compare 3 batches (or runs): Run C of 22 parts from March 30th 2009, Run D of 12 parts from April 29th 2009, Run E of 12 parts from Dec 18th 2009. The means are fairly stable; note that the variation for the most recent run (E) is about twice that of the beginning of the year. Again this is attributed to recent un-optimized machine changes.

Figure 12. Summary measurement statistics of HME parts for three measurement locations for 3 Batches.

The fidelity of pattern transfer is analyzed by comparing the measurement statistics of three different sites for the part and the tool. In Figure 13 we show the mean height and width at three different sites for Run E against the BMG tool measured just after the run.

Figure 13. Measurement statistics of HME parts from Batch E and Tool at three measurement locations.

7.3 Effect of Embossing on Laser Drilled Holes

The pre-drilled holes in the substrate were measured and found to be of good quality in the pre-formed state, but highly distorted in the embossed state (see Figure 14). This deformation was expected, given the large compressive loads on
the polymer during forming. However, the degree of distortion was found to be highly variable, mostly likely owing to the free flow volume that it represents. This variability and uncontrolled deformation may require another redesign of the I/O port production method.

![Figure 14. Images of drilled holes in the substrate a) before and b) after embossing](image)

An unsupervised dimensioning algorithm was developed [15] to automatically segment and calculate the area of the holes. The process variation of the laser drilling was found to be 0.1 mm², 1.6% relative variation with respect to a mean of 6.8 mm². The combined process variation of the laser drilling and embossing was found to be 1.2 mm², 37% relative variation with respect to mean of 3.4 mm². In Figure 15 a run chart for hole area is shown.

![Figure 15. Run chart for area of laser drilled holes and laser-drilled embossed holes.](chart)

7.4 Bonding Performance

To date we have bonded a fraction of the parts produced. Early devices often failed to allow flow, and this was attributed to a design flow that caused collapse of the coverplate onto the inlet hole during bonding. In effect, the reservoirs formed in the substrate to correspond to the holes served only to create a large span for the coverplate to sag into. This flaw was remedied by simply moving the pre-drilled substrate holes away from these pads to a downstream potion of the inlet channels. With this change, parts were successfully produced, and Figure 16 shows such a product.

![Figure 16. A completed micromixer.](image)
7.5 Functional Tests

Functional tests have confirmed the expected flow in the devices, and a system is being developed to rapidly test both flow resistance and degree of mixing as shown in Fig. 17. The expectation is that these tests can be made on a sample basis to confirm flow performance, but since they add fluid to the device, would not be desirable for non-destructive testing.

The extent of mixing is measured by taking a color image of the part under test. Intensity variations along the length were then measured and plotted to detect the location where the longitudinal intensity reached equilibrium. Figure 17 shows a typical image of a device under test. Figure 17 also shows the standard deviation of the intensity across the channel taken along different sections along the length of the serpentine channel.

![Device under functional test with red dye and clear water mixing. Standard deviation of cross section intensity along the serpentine channel (This is used as a proxy for degree of mixing.).](image)

7.6 Tool Wear

At this time, full automation has not been implemented. However, we have produced nearly 500 parts with the embossing machine and a single BMG tool. Preliminary measurements of the trend for channel dimensions (Figure 12) and measurements of the tool (Figure 18) suggest that the BMG tool is wearing.

![Height and width of tool at three locations at beginning and end of year.](image)

8. CONCLUSIONS

This effort tests our basic process science work in a more production-like environment. This “micro-factory” allows the testing of models and hardware that have resulted from research on material characterization and simulation, tooling and equipment design and control, and process control and metrology. The factory has sharpened the focus of much of our research, and has spawned a number of new research topics in alignment, assembly, fixturing and rapid in-process metrology. This facility will be maintained as a production site for testing both device and production method ideas in the future. Plans are already underway to fabricate other products but with much smaller characteristic dimensions. This paper details our efforts to produce basic micro-fluidic products in high volume at acceptable production rates and quality levels. Our goal is to create a "lights-out" factory that can make long production runs at high rates with consistent quality.
9. ACKNOWLEDGEMENTS

The factory existing thanks to the work of numerous researchers, including Dean M. Ljubicic, Matthew Dirckx, Aaron Mazzeo, David Hennan, Vikas Srivastava, Vijay Shilpiekandula, Hayden Taylor, Eehern Wong, and Sumeet Kumar all Research Assistants at MIT, Dr. Fu Gang of Nanyang Technological University, and MIT faculty Lallit Anand and Todd Thorsen. This work was supported by the Singapore MIT Alliance Programme in Manufacturing Systems and Technology.

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