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Rapid Micromold Tooling for Injection Molding Microfluidic Components

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A methodology for the rapid fabrication of an injection molding tool, a micromold, for microfluidic components and systems applications is presented. The resulting micromold tooling was utilized to create microfluidic channels in rigid and flexible polymer substrates with depths of approximately 27 μm. While not explored in this paper, the process can theoretically be altered to form channels of varying depths ranging from a few micrometers to approximately 1000 μm. In-plane component dimensions can be varied from approximately 50 μm to cm in width. The tool was made using a photosensitive epoxy (SU-8™) material defined using photolithography on the surface of a rigid substrate. Designs containing complex two-dimensional microchannel/chamber shapes and intersections are achievable using the process. Two polymers were successfully used for injection molding the channels, rigid polycarbonate (Lexan) and flexible polypropylene materials. Plastic replicates of the SU-8™ tool were made with the described process. Fabrication time of the tool was approximately 30 min and it survived 22 shots for polypropylene and 8 shots for polycarbonate without failure. Some deformities of the resulting microchannels were observed and were more pronounced in the PP channels. Channel height was increased by 2–3 μm for both plastic parts due to a ridge that was formed during the release stage of the process. The channel width decreased from the SU-8™ master by approximately 7.9% maximum for polypropylene and 1.9% maximum for polycarbonate.

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1. Introduction

The need for faster and less expensive techniques for manufacturing microfluidic components and systems is needed as such devices move from research, to prototyping, and eventually to large-scale production.(1) One common production method that has proven itself in the past for creating miniaturized parts rapidly and cheaply is injection molding. This technique has also been applied to micromachined parts and will most likely play a significant role in the future development of microfluidic systems. This paper explores the use of photodefinable plastic materials, particularly Epon SU-8™, as a means of rapidly fabricating micromold tooling for use in injection molding processes.

Several micromolding techniques have been developed over the years using materials such as silicon, metals, and polymers.(2–7) One popular method for micromolding is the cast-molding technique. Chiang, *et al.*(2) characterized the cast molding of various polymers using micromolds created from different types of materials. Their work used molding features created from silicon, glass, silicon nitride, and SU-8™. Another method for creating micromolds uses inductively coupled plasma (ICP) etching to define molding features into a silicon wafer, which can then in turn be used as a mold master for molding polymers.

As mentioned above, metals can be used in micromold masters. One popular metal used in various electroformed structures is nickel.(4,5) Electroformed nickel micromold templates can be built on the surface of a variety of substrates. One method for micro-electroforming involves depositing a metal seed layer onto silicon and then using thick photoresist as a mold for defining the metal as it is electroformed through the photoresist molds.(6,7) After the electroformed metal is deposited, the photoresist is removed, resulting in a metal micromold master. This methodology can be applied to thick optical, e-beam and X-ray photoresist processes. These molds are often used in hot-embossing(8) and injection molding(9) because of their durability. However, these methods are relatively time consuming, requiring multiple microfabrication processes and taking several hours to complete.

Using SU-8™ as a master micromold for injection molding is an attractive method because of the speed and ease of fabrication. Using this batch fabrication approach, it is possible to create many parts in the same time it would take to make one part using a cast-molding technique. This method also has a clear advantage over using micro-electroforming metals for mold masters, in the simplicity of the process required to fabricate the micromold. Additionally, in this approach the SU-8™ micromold features are patterned on the surface of the substrate instead of into the bulk material as is the case with silicon micromolds.

In the following section, the process for creating micromolds using SU-8™ is described. This is followed by characterization of the SU-8™ micromolds for mechanical durability during the injection molding process and for reproducibility of the resulting injection molded features. The characterization studies are performed using two common plastic materials, polypropylene and polycarbonate representing flexible and rigid polymer materials.

2. Materials and Methods

2.1 *Fabrication of the SU-8™ micromold*

A 76 mm, single-side polished, silicon wafer was coated with a 27-μm-thick layer of SU-8™ by spin coating. The fabrication process for creating the micromold is shown in Fig. 1. The resist was patterned using a dark-field mask and exposed to UV light, creating a negative-image micromold master. The final step in the fabrication process was the hard curing of the SU-8™ master mold at 200°C for 30 min to increase its mechanical durability and thermal stability. The master mold patterns used in these experiments are shown in Fig. 2.

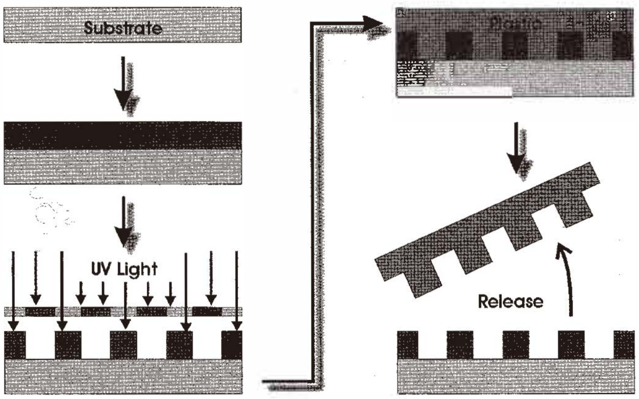

Fig. 1. Fabrication of SU-8 master mold. The mold is placed in the injection molding system. The plastic is molded over the SU-8 and released.

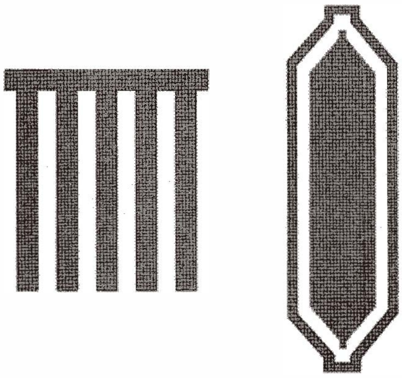

Fig. 2. Sketch of the two patterns used for creating master molds for microfluidic channels. *Left*: Parallel, identical channels with fluidic header. *Right*: Smaller adhesive wicking channel surrounding main active-separation channel.

Aluminum inserts were CNC machined to accommodate the master mold for duplication by injection molding. A circular cavity with dimensions slightly larger than 76 mm wide and 1.0 mm deep was machined into the surface of the first aluminum insert. The SU-8^{TM} master mold was positioned inside the first aluminum insert prior to injection molding, as shown in Fig. 3. A second aluminum insert was machined to form a second cavity directly opposite of the first cavity. The dimensions of the second cavity were slightly less than 76 mm and 1.0 mm deep. The second cavity established the thickness of the plastic part and could be used as a housing for a second SU-8^{TM} defined micromold master for double-sided molding operations. Polyimide tape was used along the edges to fasten the mold to the aluminum inserts.

2.2 *Plastics used and their properties*

Two polymer materials were selected to explore the manufacturing issues of the microfluidic channels over a range of varying polymer properties. Issues of interest are the replication characteristics of the polymer and the survivability of the silicon/SU-8^{TM} tool. The two polymers used were Lexan polycarbonate (PC) and polypropylene (PP).

PC, trade name Lexan, is an amorphous material with a glass transition (T_g) around 150°C. Similar to most amorphous plastics, the materials thermal coefficient of expansion is relatively small over a wide temperature range. PC has a typical shrinkage of 0.005 mm/mm. Small TCEs allows higher dimensional tolerances to be achieved on the resulting molded parts. However, unlike other amorphous plastics such as polystyrene, PC is comparatively rigid. It has a notched *IZOD* impact test of 907 J/m compared to 35 J/m for PP. PC is relatively viscous in the melt having a melt flow index (MFI) of 7 g/10 min and a density of 1.20 g/cm^3. Because of its high melt viscosity, PC requires higher temperatures, faster injection speeds and greater pressures to properly fill and pack the mold. These properties can pose processing challenges in thin molds. PC has a water absorption

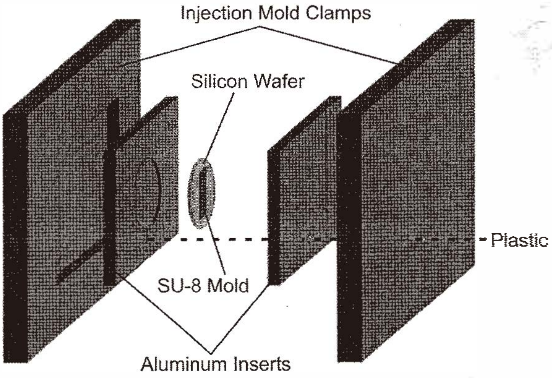

Fig. 3. Illustration of setup for inserting the micromold into an injection molding machine. An aluminum insert is placed within the injection mold clamps. The SU-8^{TM} master mold is then placed within the aluminum insert.

of 0.35 weight percent. It is therefore necessary to dry the polymer before it is injection molded. Prior to molding, a volume of PC was dried for 12 h at a temperature of 121°C. The PP did not require drying.

Polypropylene is a semicrystalline plastic with a melt temperature (T_m) of 177°C and a T_g of –15°C. The soft amorphous regions in PP tie the rigid crystal structures together, acting as a spring. This low T_g allows the amorphous region to be flexible and relatively soft at room temperatures. The percent crystallinity in PP varies depending on the processing conditions. Because of the uniform nature of crystals, these regions are denser than the amorphous regions. The formations of crystal structures cause the part to shrink. PP is much more crystalline than PC and has a typical shrinkage of 0.011 mm/mm. PP has a high MFI of 23 g/10 min and a density of 1.06 g/cm^3. Because of its low T_g, the polymer flows well at moderate temperatures. For this reason, PP can be injected at relatively low processing temperatures and pressures, making it easier to fill and pack the mold. Because of its flexibility, the part can be removed from the tool more easily, thus reducing the possibility of breaking or cracking.

2.3 *Injection molding machine and controller*

The parts were molded using a *Boy 50* injection molding machine modified by the installation of a closed loop servo-valve hydraulic system produced by *MOOG*. The *MOOG* controller allows the injection phase to operate under closed loop velocity control and the hold phase to operate under closed loop hold pressure control.

The machine has a standard mold base that was modified to hold one aluminum insert on each side of the mold. On the movable side, an aluminum insert was created to house the silicon wafer. On the stationary side, the insert had a thin disk cavity machined slightly smaller and directly opposite the silicon wafer as described previously.

2.4 *Process parameters*

The *MOOG* controller installed on the injection molding machine operated under a sequential three-phase cycle. The names and the respective processing order of each phase were the *injection*, *hold* and *cool* phases. The injection phase forces the plastic into the mold constrained to a velocity profile. In this set of experiments, the velocity profile was constant. Both PC and PP were injected at a constant velocity of 3.8 cm/s. This velocity was determined by molding a set of sequential PC parts with a dummy wafer installed. The first set of parts molded under fast injection velocities had surface irregularities. With successive parts, the speed was decreased until the surface defects were no longer present. The PP parts did not show any surface irregularities over the range of injection velocities used in this study.

The *MOOG* controller was programmed to switch from the injection to hold phase by a predetermined screw position. The hold phase constrains the hydraulic pressure to a pressure profile. The hold pressure profile for this experiment was set to be constant through the entire hold phase. The hold phase packs the mold and keeps the plastic from running back out of the gate until gate freeze occurs. If the gate was not frozen when the hold pressure was released, the part would deflate, causing sink marks in the plastic part. The hold pressure was initially set low and short shots occurred. The pressure set point was increased for each successive part until the part was properly packed without flashing. The minimum hold time was determined by successively decreasing the hold time until the molding process produced deflated parts. The hold pressure and time for PC were approximately 6.2 kPa and 7 s while those for the PP were 1.7 kPa and 6 s, respectively. After the hold time expires, the controller changed from the hold phase to the cool phase. Once the part was solidified, it was ejected and the cycle repeated. The cool time for both plastics was approximately 15 s.

Other parameters set in the injection molding machine include barrel and mold temperatures and backpressure. The barrel temperature for PC was 282°C and that for PP was 218°C . The backpressure for both plastics was set to 0.7 kPa with no decompression. The mold had no active cooling or heating and no sensors were included to measure the temperature of the molded part upon ejection.

All of the parameters mentioned in this section are adjusted to control the properties of the plastic part. Some properties of interest include the degree of warping, shrinking, and crystallinity as well as the plastic morphology. An example of a relationship between the parameters and properties is in the pressure-volume-temperature characteristics of the plastic, which will help to predict the shrinkage of the structures. However, the overall injection molding process is much more complex and cannot be completely described in this paper. Several references are provided here to provide further insight into these relationships.(10–15)

After the optimum set points were determined, additional parts were molded and discarded until stable conditions were reached which was indicated by the stable performance of the barrel heaters at their set points. The dummy wafer was removed and the SU-8^{TM} silicon wafer was inserted. A series of samples were molded with the SU-8^{TM} micromold in consecutive order until the tool failed.

3. Results and Discussion

The SU-8^{TM} micromold structure used for surface replication was imaged with a *Tencor P-10*^{TM} profilometer and is shown in Fig. 4. The cross-sectional dimensions of the structure were 27 μm × 0.7 cm. The surface of the SU-8^{TM} mold was very smooth and flat with the exception of a small ridge that appears around the top edge of the mold. The height of this ridge was insignificant when viewed in a two-dimensional profile. The walls were shown to be straight in an SEM image of the same SU-8^{TM} micromold, shown in Fig. 5.

3.1 *Polycarbonate channels*

A three-dimensional profile of a channel from one of the PC parts, duplicated from the mold shown in Fig. 4, is shown in Fig. 6. The bottom surface of the channel appeared very flat and smooth. On the top of the channel walls there were defects present in the form of bumps and pits. These defects were typically caused by dust particles, as the injection molding machine was not located in a clean room environment. These defects were not crucial because of their location on this part; however, defects such as these may be significant in other applications. The walls appeared sloped because of the angle of the profilometer stylus. The walls were straight as shown by the SEM image of the corner of

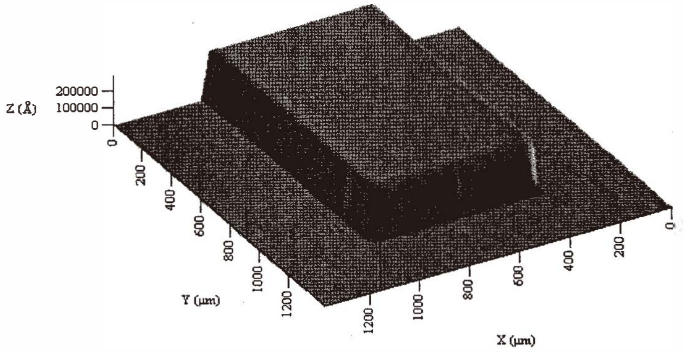

Fig. 4. Profile of SU-8™ mold on a silicon wafer. The dimensions are 27 mm × 0.7 mm. The walls appear to be sloped due to the angle of the profilometer stylus.

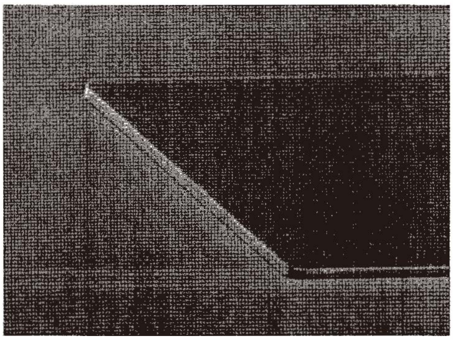

Fig. 5. An SEM image of one end of the SU-8™ mold. The walls are straight and the surface smooth and without defects.

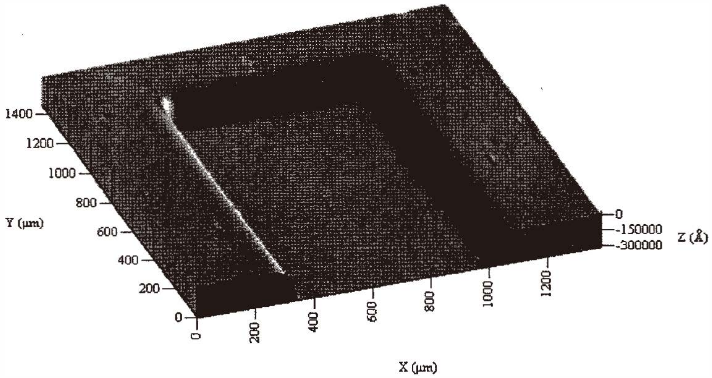

Fig. 6. Profile of PC channel made from the micromold in Fig. 4. The walls are slightly curved at the top due to incomplete filling of the injected plastic.

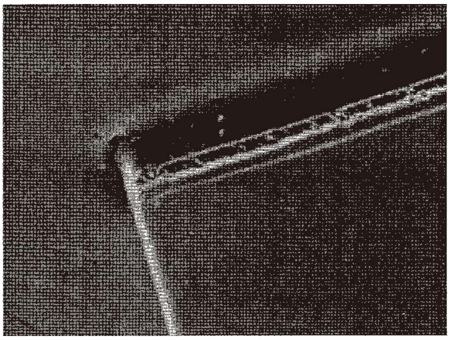

Fig. 7. An SEM image of the corner of the PC channel in Fig. 6.

the channel, Fig. 7. Unlike the walls on the SU-8™ mold in Fig. 4, the walls on the replicated PC part are rounded at the top. This rounded edge may be attributed to incomplete filling with PC at the base corner of the micromold. In addition to the rounded edge, there was also a small ridge at the top edge of the channel. This ridge was likely formed by the shrinkage of the plastic around the mold and the shear force between the plastic and SU-8™ during the mold release.

3.2 *Polypropylene channels*

One end of a channel from a PP part was imaged with the *Tencor P-10*™ profilometer and is shown in Fig. 8. This part was nearly identical to the PC part, although it has a few noticeable differences. Like the PC part, the surface of the channel and channel walls were very smooth and flat. However, defects were again noticeable in the surface, possibly due to dust particles present during the mold process. The walls were rounded at the top as in the PC part; however, the rounding was not as significant in the PP channel as in the PC channel. The PP plastic was more fluid and easier to inject than PC, which allowed the base corner of the mold to be more completely filled. There was a ridge around the edge of the channel, which appeared taller and extended further away from the channel cavity than in the case of the PC part. This effect was noticeable in the SEM image of the corner of the channel, shown in Fig. 9. Polypropylene was much softer and easier to deform than PC. These properties allowed a larger ridge formation from the shear force during the release step of the process.

3.3 *Comparison of PC and PP*

The replicate parts of the SU-8™ mold using PC were more difficult to accomplish than with PP due to the material properties as explained earlier. Tool lifetimes were in the range of one to eight shots, with an average of about four, when PC was used to replicate the mold. The tool used to produce the PP parts showed no signs of failure after 22 shots, at which point the experiment was terminated.

Two-dimensional profiles of the SU-8™ micromold, PC channel, and PP channel are

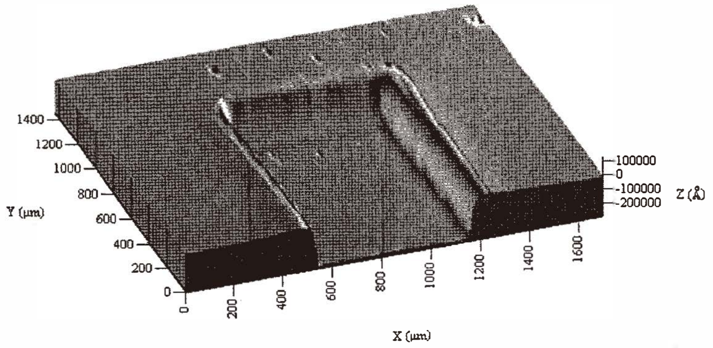

Fig. 8. Profile of polypropylene (PP) channel made using the mold in Fig. 4. The walls are curved, similar to the PC channel in Fig. 6. The surface defects are from dust particles.

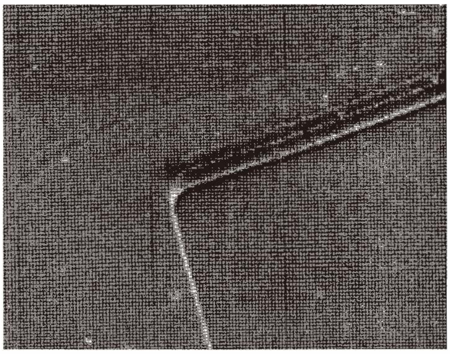

Fig. 9. SEM image of the corner of the PP channel in Fig. 8. The ridge is wider than in the PC channel, Fig. 7.

overlaid in Fig. 10 to make a comparison between the replicate channels and the original mold. In this figure, the ridges observed earlier in the scanning electron micrographs are more easily seen. Although only a small ridge was apparent for the PC channel, the overall channel height was increased by 2–3 μm due to this ridge. The ridge was more pronounced in the PP channel, with the walls being 2–3 μm higher than the mold and then actually dipping below the original micromold channel height further away from the channel. The channel width shrunk in the case of the PP channel by 7.9%, measured at mid-height. The width change for the PC channel was a maximum of 1.9%. Also noticeable was the rounded edge at the top of the walls.

The injection molded components were bonded with a planar, plastic cover plate to achieve enclosed leak-free microchannels. The bonding was achieved using either solvent bonding or UV curable adhesives. In both cases, the bonding liquids were routed around

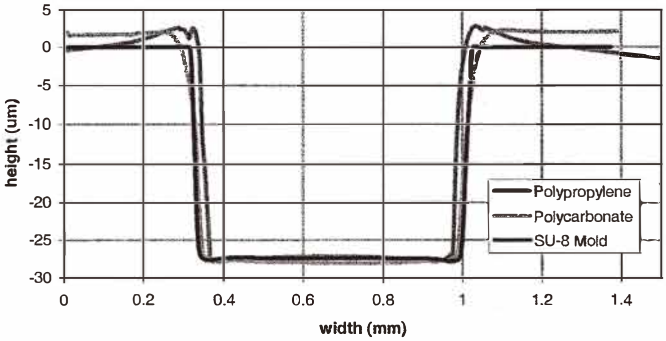

Fig. 10. Two-dimensional overlay profile of the two polymer channels, PC and PP, and the SU-8™ mold.

the perimeter of the microchannels using wicking channels designed as part of the injection molded component. The two halves were aligned and mechanically clamped after application of the bonding solvent and/or adhesive.

3.4 *Tool failure*

Failure of the tool occurred when the silicon wafer broke or when a portion of the SU-8™ micromold was pulled from the silicon substrate. The first mode of failure occurred during the injection phase, in which the wafer was lifted slightly from the aluminum cavity in which it was seated, allowing plastic to flow behind the wafer and break it. This problem was solved by placing thin *Kapton* tape around the edge of the wafer. Substrate breakage still occurred in some cases. In this case, the wafer would typically break at the entrance region for the injected plastic. The reason for this was probably the high shear forces acting on the wafer due to the relatively high plastic velocity at that point.

The second mode of failure was when the SU-8™ mold was pulled from the substrate. The reason for this mode of failure was the molded part shrinking around the micromold during the cool phase and not releasing easily from the mold during the ejection operation. Evidence of wall interaction was found in the channel ridge seen in the SEM images of the PC and PP channels, shown in Figs. 4 and 6, as stated previously.

4. Summary of Results

A summary of the results for the two plastics used in replicating the surface channels is shown in Table 1. The number of shots to failure parameter indicates the range of parts fabricated before the failure of the mold. For PP the experiment was terminated before the mold showed any signs of failure, after 22 shots. For PC the tool typically failed after only a few shots. Percentages reported in the deviation from the master mold parameter are negative for shrinking and positive for expansion. These width values were measured the half of the channel height. Significant structural deviations in the plastic from the master mold are also noted.

The target channel and structure thickness for these experiments was 27 μm. While results for only one channel have been reported, a variety of structures of various widths and lengths have been duplicated for both PP and PC. Channel widths varied from 50, 125, 170, 250, 670, 700, 800, 850, 2000, 4000, 6000, to 6800 μm. The length of the channels also ranged from 0.5 mm to 60 mm.

In addition to the channels, walls for separating adjacent parallel channels were duplicated with widths of 50, 125, 175, 250, 500, 700, and 800 μm. Walls with widths smaller than 50 μm did not form due to incomplete filling of the master mold. Structure and channel aspect ratios ranged from 0.005 to 0.5. No high aspect ratio structures had been demonstrated at that time.

Measurements of channel widths along the length of a channel ($27 \times 670 \times 5000\ \mu m^3$) are shown in Table 2. The average width of the channel is 669 μm with a standard deviation of 9 μm. The channel width for five channels of identical cross section ($27 \times 670\ \mu m^2$) and varying lengths (3–5 cm) in a single plastic piece were measured at the channel midlength. The five channels spanned a distance of approximately 6 cm. The average width of the channels was 671 μm with a standard deviation of 12 μm.

5. Conclusion

The rapid and inexpensive production of plastic microfluidic channels has been accomplished using injection molding of two different types of plastics, polycarbonate and polypropylene. The micromold tooling was manufactured using a rapid fabrication process of patterning SU-8™ on silicon substrates. The SU-8™ mold used in the studies was approximately 27 μm in height and was shown to be very smooth and flat, with little or no defects.

The molded plastic channels showed deformities for both the PC and PP materials. A

Table 1
Summary of results of replicated channels and master mold.

Material		SU-8™	PP	PC
No. of shots to master mold failure		-	>22	1–8
Feature size lower limit		μm^3	$\mu m \times mm^2$	$\mu m \times mm^2$
Deviations from master mold	Height	27 μm	11 %	7.4 %
	Width	6.8 mm	−7.3 %	−1.5 %
	Features	-	Large ridge Rounded	Small ridge Rounded

Table 2
PC plastic channel width measurements on a single substrate.

Position/Channel	1	2	3	4	5	average	std dev
Single Channel	650	660	672	668	668	664	9
Multiple Channels	652	676	672	684	672	671	12

small ridge around the edge of the channel raised the height of both channels by approximately 2–3 μm. The ridge was more pronounced in the softer PP plastic channels. The PP channel width shrunk by approximately 7.3% at midheight. The more rigid PC plastic channels shrunk by approximately 1.9%. In both plastic channels, a rounded edge was noticed at the top of the channel wall. This rounded edge was due to a combination of incomplete filling of the mold during the injection phase and insufficient hold time before releasing the part from the mold.

Two modes of failure were observed for the micromolds. The two modes were the breaking of the underlying silicon substrate and pulling the SU-8$^{\text{TM}}$ from the silicon substrate. When using PC for replicating channels, failure was usually seen after 1–8 shots. However, when using the softer PP plastic, no failure was seen in the mold up to 22 shots.

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