ABSTRACT

Micro investment molding combines traditional injection molding with investment casting to create hollow parts on the microscale. Silicon micromolds are manufactured using photolithography and reactive ion etching. Then, a sacrificial element is placed in the mold. Plastic is injected into the mold and around the sacrificial element using an injection molding press. After removing the plastic part from the mold, liquid etchant dissolves the sacrificial element leaving a hollow plastic part. To demonstrate the process microneedles were formed. Using 32 \( \mu \)m diameter aluminum bond wire as the sacrificial element hollow, in-plane, microneedles were formed out of Cyclic Olefin Copolymer (Ticona Topas®). The longest needle has an overall length of 280 \( \mu \)m, cross-sectional dimensions of 130 \( \mu \)m x 100 \( \mu \)m and an approximate inner diameter of 35 \( \mu \)m.

INTRODUCTION

Polymer microstructures are gaining popularity due to the variety and range of physical properties they exhibit including biocompatibility, strength, toughness, and optical clarity. Their manufacturability is also becoming a major differentiator as the cost of fabricating MEMS-scale parts becomes increasingly important. To this end, focus has been placed on mold-based manufacturing methods such as casting [1], hot embossing [2,3], and injection molding [4,5], which allow for accurate microscale features to be created inexpensively.

One major drawback with current molding techniques is that making hollow parts is difficult. Parts that have hollow cavities parallel to the parting plan of the mold (i.e. in-plane parts) are particularly difficult to fabricate (Fig. 1). To deal with this issue several post-fabrication processes have been developed including, laser-ablation [6], X-ray exposure [7], or bonding of two parts after molding [8,9,10].

This drawback is especially evident in the manufacture of hollow microneedles for painless drug delivery. For this application a 150-500 \( \mu \)m shaft with a sufficiently sharp tip has been shown to breach the hard outer layer of skin (stratum corneum) without inducing pain [11]. By making the shaft hollow with an inner diameter of 10-50 \( \mu \)m a wide array of drugs can be delivered continuously and painlessly [12].

In this paper, we present a method, investment molding, for creating hollow parts in-situ during the molding steps. To demonstrate the potential of this method, we investigate the fabrication of in-plane microneedles.

NOMENCLATURE

\( A_{cross-section} \) = cross-sectional area
\( D_{hydro} \) = hydraulic diameter
\( P_{cross-section} \) = length of perimeter of \( A_{cross-section} \)
INVESTMENT MOLDING OVERVIEW

Investment molding is a three-step process (Fig. 2). First a sacrificial element (investment) is placed into a micromachined insert. The insert contains features that define the outer shape of the part to be molded while the investment defines the hollow cavity. The insert can also contain alignment features to position and secure the investment during molding.

Second, the insert is secured into a mold assembly containing pathways for plastic to reach the microfeatures. This assembly is placed into a standard injection molding machine where plastic is injected into the microfeatures and around the investment.

Finally, the plastic part containing the investment is removed from the mold, and immersed in etchant that dissolves the investment leaving a hollow plastic part.

Matching the hydraulic diameter ensures similar plastic flow to each side of the insert, while allowing different runner geometries to be tested.

MOLD ASSEMBLY DESIGN AND FABRICATION

Figure 3 shows an exploded view of the mold assembly. The outer plates are 200 mm x 200 mm steel injection molding plates manufactured by D-M-E Company (pn. 88-7-7). The B side plate is milled out to contain a sprue, one branch and two runners (Fig. 4). These deliver plastic from the injection molding machine to the microfeatures in the insert. The branch has a semicircular cross-section with a diameter of 10.31 mm (13/32 inches). Both runners have exactly half the hydraulic diameter of the branch though one has a semicircular cross-section while the other is tapered. Hydraulic diameter is defined by the relation:

\[ D_{\text{hydro}} = \frac{4 \times A_{\text{cross-section}}}{P_{\text{cross-section}}} \]  

(1)
A pocket for the insert is formed by placing a locating shim onto the A side plate. The locating shim is made by wire electro discharge machining (EDM) 810 µm (.032 inch) thick laminated shim stock. The laminated layers are then peeled away to obtain a shim that is the same thickness as the insert (each layer is ~ 50 µm thick). The A side plate is polished flat to minimize roughness. This method is preferable to milling a pocket in the A side because it allows for flexibility – new insert geometries can be tested by changing the shim rather than remachining the A-side – and reduces the risk of initiating cracks in the silicon insert due to a rough milled surface.

In this experiment two insert types – straight-channel and aligned – were tested. The straight-channel design consists of an array of open-ended channels 100-300 µm wide and 100 µm deep (Fig. 5). This simple design allows for the testing of the feasibility of investment molding. It also allows for tuning of the injection molding parameters to get the optimal part size and quality.

The straight-channel design is fabricated using a single-mask photolithography process (Fig. 6). A standard 4-inch wafer is patterned using 2 µm of Fuji/Arch OiR 897-10i i-line photoresist (PR) and a Karl Suss MA6 contact printer (KS printer). The channels are etched in a Surface Technology Systems (STS) Advanced Silicon Etch System. As Fig. 6 shows, the recipe can be altered to deliver sidewalls that range from straight to curved. This also allows for the width of the channels to be adjusted between 100 and 300 µm. Channel depth is set to approximately 100 µm by monitoring the etching time. After etching, the wafers are chemically stripped (J.T. Baker PRS-3000™) and diced into two inserts, 44.5 x 31.8 mm (1.25 x 2.75 inches) with a Disco automatic dicing saw (DAD-2H/6).

The aligned insert has needle-like channels with alignment features built into the mold (Fig. 7). These channels consist of a needle body and an exit vent. The needle body is 280 µm long and 100 µm deep with a 30 degree-angled tip. Two needle body widths are tested, a 130 µm thin-body and a 160 µm thick-body. Tapered inlets and tip wells are also present on some of the channels. The exit vent is a straight channel 15 µm wide and 75 µm deep. The aligner consists of two rectangular gates angled at 30 degrees with a secondary fence that is 25 µm high. The gates align the investment to the needle tip while the fence helps set the height of the investment. The exit vent allows gas to escape the needle body during molding as well as provides further alignment of the investment.

The aligned insert requires a dual-mask process to achieve the two level alignment structure (Fig. 8). The first masking layer is defined in a 1 µm layer of thermal oxide on a standard wafer. A 2 µm PR layer is spun-on and patterned using the KS printer. The pattern is transferred into the oxide with a 10 minute wet etch in 10:1 Hydrofluoric Acid. The old resist is stripped and another 2 µm-thick layer is spun-on and patterned to form the second masking layer. The dual-masked wafer is etched in the STS to a depth of 25 µm. The wafer is remove form the etcher, stripped of photoresist, and put back into the STS where it is etched until the overall channel depth is 100 µm. Finally, the wafer is diced into two inserts in the same fashion as the straight-channel insert.
PART FABRICATION

Before injection molding a part, the investment piece is placed into the insert. For our tests 32 µm-diameter aluminum bond wire (98% Al, 2% Si) is used as the investment. Using a West Bond Model 7400B Ultrasonic Bonder the investment is bonded into the insert. For the case of the straight-channel insert the investment is unsupported and free to move in the channel, (Fig. 9). For the aligned insert the alignment features act to capture the bond wires, though not all investments are fully aligned (Fig. 10).

A plastic part is fabricated by placing the prepared insert into the mold assembly which is installed in a 30 ton FANUC α-30iA Roboshot injection molding press. Cyclic Olefin Copolymer (Ticona Topas®) is injection molded into the insert. Topas® was selected for its balance of strength and easy of manufacturing, as well as its biocompatibility.

The injection molded part is removed from the mold and immersed in a 50°C bath of Transene Co. Aluminum etchant (Type A) for approximately 12 hours. This etchant exhibits excellent selectivity between aluminum and most polymers, etching the investment away without impacting the plastic part.

RESULTS AND DISCUSSION

Before performing the investment molding process, several tests were performed on the straight-channel insert without investments. This helped characterize the capability of the injection molding machine to create small rods. By adjusting the temperature and pressure in the injection molding steps, rods with very high aspect were created. 3.5 mm and .975 mm rods have been demonstrated with 100 µm x 200 µm and 100 µm x 100 µm cross-sections, respectively (Fig. 11). This is both an improvement in aspect ratio over previous micro molding efforts [13] and suggests that the injection molding press has the capability of creating needles of sufficient size to meet the requirements necessary for painless microneedles.

Our studies also show an interesting phenomenon whereby needle length varies along the length of the runner (Fig. 12). The difference from center to edge is significant – on the order of a 40% increase in length (Fig. 13). The exact reason for this is not fully understood, however previous work suggest that this may be a result of hotter, lower viscosity plastic being delivered to the end of the runners as the outer layer cools and freezes in place [14,15]. In addition, the angled cross-section delivers longer needles, suggesting that its is a slightly better design. For the molding of microneedles this difference is not significant since even the shortest rods are longer then the 280 µm needle body that we wish to mold.
Fig. 12. Molded Rods and Straight-channel Insert.

![Fig. 12. Molded Rods and Straight-channel Insert.](image1)

**Fig. 13. Center-to-Edge Rod-Length Variation**

With the injection molding process optimized to deliver sufficiently long rods, investment casting was attempted in the straight-channel inserts. Figure 14 shows a typical result. Clearly, the investment does not maintain a centered position in the channel during molding. However, some tests have demonstrated that at least over short distances the investment can be encapsulated into the rod (Fig. 15). Indeed, the length over which the investment is surrounded by plastic is approximately 200 µm, within the length scale of a microneedle. Clearly, what is required is better alignment of the investment during molding.

Fig. 14. Typical Result from Straight Walled Insert

![Fig. 14. Typical Result from Straight Walled Insert](image2)

The aligned inserts delivered better results. Figure 16 shows a thin-bodied microneedle structure after removal of the investment. The whole needle body has been filled creating a shaft that is 280 µm from base to tip with a 100 µm x 130 µm cross-section. The hole created by the investment is approximately 35 µm. Since the center hole exits through the tip, it is hard to characterize how sharp the needle is.

Figure 17 shows a thick-bodied needle with tapered inlet. The needle is also fully formed with a hollow tip, however its tip has been bent. This appears to have happened during the removal of the part from the mold. This suggests that greater care must be taken in the removal step to ensure sharp needle points are maintained. Figure 17 also clearly shows the weld line – the seam where plastic seals around the investment. The fact that the investment did not rip out of the needle during the removal from the mold suggest that the weld fully closed. In any case, heating the mold during injection is known to improve the strength of weld lines and can be employed if necessary [16].

Fig. 15. Investment Encapsulated in Plastic Rod

![Fig. 15. Investment Encapsulated in Plastic Rod](image3)

**Fig. 16. Thin-bodied Microneedle**

(Shoulder to Base length: 280 µm)

![Fig. 16. Thin-bodied Microneedle](image4)
Fig. 17. Thick-bodied Microneedle  
(Shoulder to Base length: 280 µm)

Fig. 18 Errors in Investment Molded Needle

In general, the presence of a tapered inlet, or exit well did not affect the outcome of the molding step. Instead, the main problem is the alignment of the investment. As Fig. 18 shows in some case the investment comes out of the side of the needle forming a split base and a misaligned weld line. This is appears to be due to the inherent slack in the wire bond. The more tightly the wire is stretched across the alignment fence the less likely it is to shift during molding. However, since the wire bonder used is not automated, this is hard to guarantee for each needle. An automated wire bonder should bring this problem under control.

There is also evidence of a misalignment between the two masking layers. This creates a small step in the needle. The small size of this error should not affect the needle performance, however.

CONCLUSION AND FUTURE WORK

Investment molding offers a way to create hollow, in-plane, plastic parts in an injection molding machine without complicated post-processing steps. This method has delivered hollow microneedles with lengths of 280 µm and cross-sections of 130 µm x 100 µm and 160 µm x 100 µm. The critical element to successful investment molding is control of the investment during molding. For this work it is suggested that improved bonding techniques will increase the repeatability and reliability of the investment molding methods.

Though weld lines are evident in some of the needles, they appear to be sufficiently strong to maintain integrity. Heating the mold is suggested as a possible means to reduce the appearance of weld lines and improve the overall strength of the weld.

Another, potential area of improvement is the method of extracting the part from the mold. The bending of needle tips suggests that the manner in which parts are removed from the mold can impact needle quality. To improve this mold-release treatments may be investigated.

Future work will focus on testing these microneedles for robustness and strength. This includes buckling test and skin piercing tests. The use of other plastics such as polycarbonate is also being investigated for investment molding.

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REFERENCES


