

Development of an injection molding tool for complex microfluidic geometries

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Abstract This paper will track the design and results of an injection molding tool developed to manufacture microfluidic chips. The mold design and injection molding process was complicated by the presence of integrated capillary fluidic interconnects. We determined that design of the runner and gate system responsible for delivering molten plastic to the cavity had a significant impact on the quality of parts produced by the mold and the size of the process window. Numerical results confirm our findings that reducing gate lengths and increasing part thickness dramatically improved the filling profile and lowered injection pressures by 37%. Finally, the influence of gate location on part shrinkage is analyzed and discussed.

1 Introduction

Injection molding is one of the least expensive manufacturing technologies for the mass production of microfluidic devices (Becker and Gärtner 2008; Fiorini and Chiu 2005; Hecke and Schomburg 2004). This has been a driving

reason behind many of the publications that report using injection molding technology for the fabrication of a wide-range of microdevices, including microfluidic devices (Attia et al. 2009; Chen et al. 2010; Kim et al. 2006; Lee et al. 2005; Su et al. 2004; Tosello et al. 2010). However, these papers generally focus on the design of the device with limited or no discussion of the design of the mold. One reason for this omission is that the molds represent a significant cost, and therefore conducting experiments related to mold design are expensive. Furthermore, most commercial injection molders design their molds from extensive experience or with expensive simulation software, both of which are beyond the reach of most academic researchers. While there are resources available for conventional injection molding design (Rosato et al. 2000), most microfluidic researchers are often left pursuing an expensive and time consuming trial and error approach when designing a microinjection mold for the first time.

This paper will examine two revisions of an injection molding tool we developed. The resulting parts have been the basis for several publications over the past few years (Chen et al. 2008; Geiger et al. 2010; Mair et al. 2007; Mair et al. 2006; Mair et al. 2009; Stachowiak et al. 2007). The mold design was complicated by the inclusion of integrated capillary fluidic interconnects. While a thorough injection mold design guide is beyond the scope of this paper, our intent is to provide some insight into the injection molding design process for the microfluidic community as they approach designing their own molds.

2 Original injection mold tool

The first mold was designed to address the limitations of a legacy mold, shown in Fig. 1, that existed before the work

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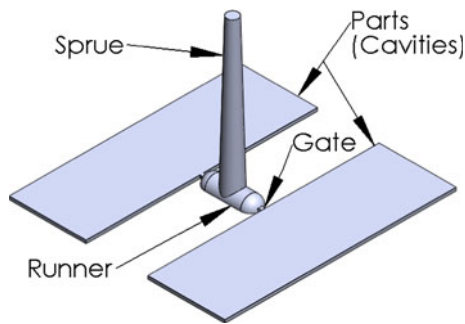


Fig. 1 Model of legacy mold with key injection molding terminology *highlighted*. Note that the single gate in the center of the part led to dramatic variations in thickness along the length of the part

presented here. Due to the high pressures needed to completely fill the mold and the gate location, the parts produced were thicker in the middle than the ends. Any reduction in pressure led to incomplete filling of the mold rather than flatter parts. Hence, a primary goal of the initial design was to improve thickness uniformity along the part length and width. To this end, the runners and gates were designed to deliver the polymer melt at multiple locations. The gate length was constrained by the geometry of the micromold insert, which was simply clamped between the two sides of the injection mold. Along with this design, other features were added to the mold. Most notably, capillary fluidic interconnects were integrated with the part. This allowed us to reduce the amount of post processing necessary for working devices (Mair et al. 2006). Additionally, the mold was designed as a “family” mold so that both halves of the chip were molded at the same time, even though they had vastly different geometries and volumes. The main features of the mold are detailed in Fig. 2.

While it was possible to successfully mold usable microfluidic devices with this initial design, the mold suffered from particular weaknesses. First, the parts contained high levels of internal residual stresses near the gates. These stresses would result in significant part shrinkage at the gates upon heating during the thermal bonding process. Essentially, the bonding process allowed the highly stressed polymer to relax, deforming the parts. Second, while the parts were flatter and more consistent, the parts were surprisingly thicker at locations further from the sprue. Third, we observed shrinkage at the integrated ports, which were thicker than the chip in cross-section. This shrinkage presented itself sometimes as a void and at other times as a sink mark. Finally, there was no retention mechanism on the micromold insert. Therefore, the micromold insert would often be removed from the mold with the part, necessitating manual removal.

Over the course of approximately a thousand cycles, the mold began to wear making it difficult to properly fill the

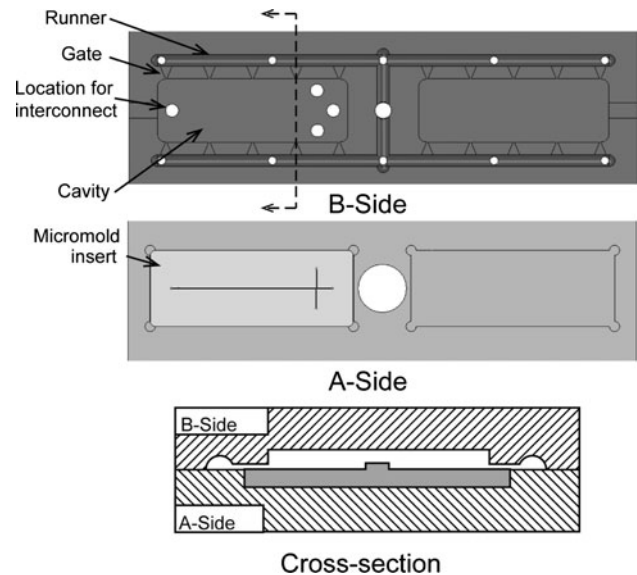


Fig. 2 The original mold design showing both halves of the mold along with a cross-section. The runners were extended along both sides of the cavity with five gates on each side in an effort to improve thickness uniformity. The micromold insert was simply clamped between the two mold halves, dictating the length of the gates. The two cavities were molded simultaneously despite the difference in volume due to the integrated ports. Note that the cavity has been thickened in the cross-section for clarity. In the actual mold, the gates and cavity were the same depth

mold without flashing. We decided at this time to revise the mold to improve its performance. However, in order to gain additional insight into the mold design process, Moldflow software (recently acquired by Autodesk, Waltham, Massachusetts) was used to model the injection molding process. To this end, a post-mortem analysis was performed on the initial design and the results agreed very closely with the experimental results. Most notably, it was discovered that poor gate design was the root cause for the observed problems. Specifically, the gates were too long, a design decision dictated by the geometry of the clamping technique used to hold the micromold insert. Therefore, the pressure drop across the gates was too high leading to a “hesitation” effect at the first gates. In other words, as the plastic flowed through the runner and came to the first gate it would continue down the runner instead of filling the part. This led to a significant skin forming over the gate due to the “fountain-flow” profile of the flowing molten plastic (Tadmor 1974), and the parts actually filled from the “back” to the “front”. These results are demonstrated both numerically and experimentally in Fig. 3.

The observed shrinkage at the integrated ports was also confirmed by the Moldflow analysis. In a typical injection molding setup, shrinkage of the part is mitigated by continuing to fill the part through the interior of the part as the plastic cools from the outside. This process is referred

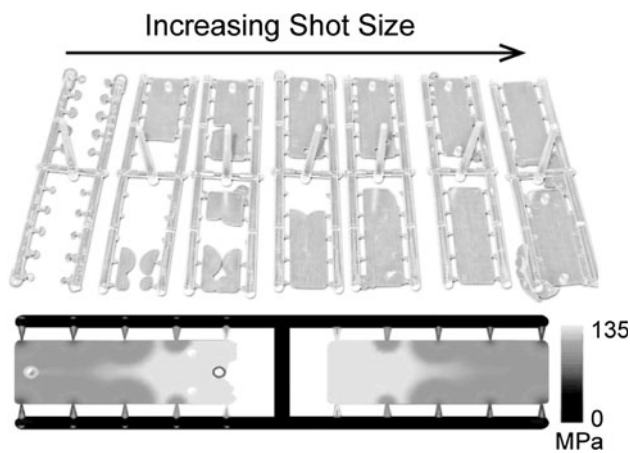


Fig. 3 Comparison of experimental results (*top*) with numerical analysis (*bottom*). By successively increasing the shot size, it is clear that parts tend to fill from the “back” to the “front”. This result was confirmed numerically as higher pressures are required to fill the front of the part. This agreement gave us a high confidence in the value of the results provide by the Moldflow software

to as “packing” out the part. In this case, however, for the plastic to fill out the ports it must first flow through the thickness of the chip. Because the chip has a thinner cross-section than the ports, it is difficult to properly pack out the ports which continue to cool and shrink after the chip itself freezes. The filling/packing process was further complicated by the dissimilar volumes of the cavities, as the cavity with the ports filled much slower than the featureless cavity.

3 Revised injection mold tool

Based on the results and post-mortem analysis of the original design, it was clear that the runner/gate system was limiting the performance of the original mold design. Because the micromold insert clamping technique was a driving factor for the first gate design, we focused our efforts on redesigning the mold insert clamping mechanism and runner/gate system. The resulting design is shown in Fig. 4. This design used mechanical clamps to hold the insert in place which also served to form the mold cavity and gates. The gates themselves were shortened from 2.5 to 0.5 mm to minimize any hesitation as the plastic flowed down the runner. Finally, the cavity thickness for the side with the ports was doubled from 0.5 to 1 mm, greatly improving flow and balancing the flow between the two cavities. As shown in Fig. 4, the new gate design and thicker cavities reduced the necessary molding pressure by 37%, greatly opening up our processing window. Although, it was not possible to inject at the thickest cross-section, we hoped that the lower pressure requirement and thicker

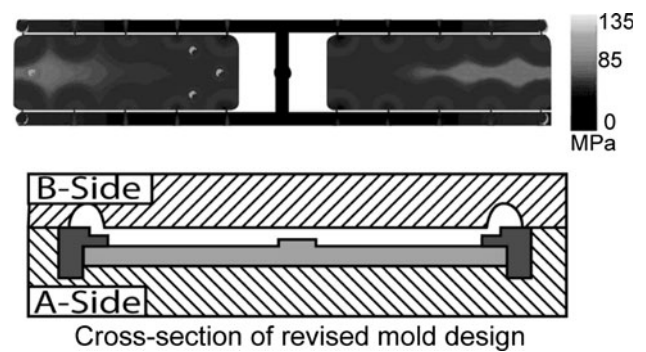


Fig. 4 Numerical model of the revised runner/gate system (*top*) and clamping mechanism (*bottom*). Shortening the gates reduced the required injection pressure from 135 to 85 MPa. The addition of the clamps (*dark grey*) allowed the insert to be securely fastened and easily exchanged with other inserts having different microchannel designs

cavity would allow us to mitigate any shrinkage observed at the thicker port section.

With the revised design, the injection molding process had a significantly larger process window, yielded higher quality parts, and improved shot-to-shot reproducibility to ultimately improve yield and minimize waste. Unfortunately, shrinkage defects at the ports in the form of voids and sinks continued to occur occasionally due to the varying cycle time that resulted from the semi-automatic operation of the mold base. The new clamping system outperformed the previous design, significantly reduced our cycle time, and extended the life of the microfabricated mold inserts.

4 Conclusions

As detailed in this paper, mold development can be a costly and time consuming endeavor, particularly for those with little experience with the complexities of mold design and polymer processing. The major conclusions of this work are:

1. The importance of a proper runner/gate design: Improperly designed runners and gates can lead to unsuccessful and unexpected results. The revision to our gating system was the most significant change we made in terms of mold performance. As a general rule, gates should be as short as possible to prevent premature freezing of the polymer in the gate.
2. Shrinkage mitigation: When possible, cavities should be filled at the thickest cross-section first. This ensures that the thickest cross-sections can still be packed even after thinner cross-sections have fully frozen.
3. Family molds introduce difficulties: When molding multiple cavities with different geometries and

volumes, it is difficult to properly balance the runner/gate system to fill the cavities simultaneously. These difficulties can be resolved by designing the mold with a sprue shut-off valve to selectively isolate a cavity for production.

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References

- Attia UM, Marson S, Alcock JR (2009) Micro-injection moulding of polymer microfluidic devices. *Microfluid Nanofluids* 7:1–28
- Becker H, Gärtner C (2008) Polymer microfabrication technologies for microfluidic systems. *Anal Bioanal Chem* 390:89–111
- Chen G, Svec F, Knapp DR (2008) Light-actuated high pressure-resisting microvalve for on-chip flow control based on thermo-responsive nanostructured polymer. *Lab Chip* 8:1198–1204
- Chen CS, Chen SC, Liao WH et al (2010) Micro injection molding of a micro-fluidic platform. *Int Commun Heat Mass Transf* 37: 1290–1294
- Fiorini GS, Chiu DT (2005) Disposable microfluidic devices: fabrication, function, and application. *Biotechniques* 38:429–446
- Geiger EJ, Pisano AP, Svec F (2010) A polymer-based microfluidic platform featuring on-chip actuated hydrogel valves for disposable applications. *J Microelectromech Syst* 19:944–950
- Heckele M, Schomburg WK (2004) Review on micro molding of thermoplastic polymers. *J Micromech Microeng* 14:R1–R14
- Kim DS, Lee SH, Ahn CH et al (2006) Disposable integrated microfluidic biochip for blood typing by plastic microinjection moulding. *Lab Chip* 6:794–802
- Lee DS, Yang H, Chung KH, Pyo HB (2005) Wafer-scale fabrication of polymer-based microdevices via injection molding and photolithographic micropatterning protocols. *Anal Chem* 77: 5414–5420
- Mair DA, Geiger E, Pisano AP et al (2006) Injection molded microfluidic chips featuring integrated interconnects. *Lab Chip* 6:1346–1354
- Mair DA, Rolandi M, Snauko M et al (2007) Room-temperature bonding for plastic high-pressure microfluidic chips. *Anal Chem* 79:5097–5102
- Mair DA, Schwei TR, Dinio TS et al (2009) Use of photopatterned porous polymer monoliths as passive micromixers to enhance mixing efficiency of on-chip labeling reactions. *Lab Chip* 9: 877–883
- Rosato DV, Rosato DV, Rosato MG (2000) Injection molding handbook. Springer-Verlag, USA
- Stachowiak TB, Mair DA, Holden TG et al (2007) Hydrophilic surface modification of cyclic olefin copolymer microfluidic chips using sequential photografting. *J Sep Sci* 30:1088–1093
- Su YC, Shah J, Lin L (2004) Implementation and analysis of polymeric microstructure replication by micro injection molding. *J Micromech Microeng* 14:415–422
- Tadmor Z (1974) Molecular orientation in injection molding. *J Appl Polym Sci* 18:1753–1772
- Tosello G, Gava A, Hansen HN, Lucchetta G (2010) Study of process parameters effect on the filling phase of micro-injection moulding using weld lines as flow markers. *Int J Adv Manuf Technol* 47:81–97