eu**spen**’s 22nd International Conference &
Exhibition, Geneva, CH, 2022
www.euspen.eu

Micro-injection moulding simulation and manufacturing of polymer chips for acoustic separation

Komeil Saeedabadi[1], Fabian Lickert[2], Mathias Ohlin[3], Henrik Bruus[2], Guido Tosello[1], Matteo Calaon[1]

[1]*Technical University of Denmark, Department of Mechanical Engineering, DK-2800 Kgs. Lyngby, Denmark*
[2]*Technical University of Denmark, Department of Physics, DK-2800 Kgs. Lyngby, Denmark*
[3]*AcouSort AB, Medicon Village, S-223 81 Lund, Sweden*

komsae@mek.dtu.dk

Abstract

This abstract presents advancement in the design and manufacturing of a fully polymer-based micro-injection moulded acoustofluidic chip for acoustic blood plasma separation in diagnostic Point-of-Care platforms. In order to move from conventional glass chips to a whole-polymer platform, appropriate materials for micro-injection moulding (µIM) were considered. Polymethyl methacrylate (PMMA) by LG IG 830 was selected as the primary µIM material. Our FEM modelling of particle acoustophoresis behaviour in the channels with the selected material yielded the channel dimensions with an acoustic resonance frequency of 1.26 MHz for a water-filled channel. The separation channel was designed to be of 150 µm height, 375 µm width and 36 mm length. The design was simulated and optimized using injection moulding simulations and virtual design of experiment (DOE). After moulding the parts using the optimized process settings, the chips were then sealed off using a 175 µm thin foil of the same material and through UV-aided hot press process. The bonding strength of the chips were then characterized using delamination test. A delamination pressure of 36 MPa ± 7 MPa was achieved for the optimal bonding parameters. Ultimately, the chips were examined in regards to their functionality. They first stood the leakage test with a maximum pressure value of 2 bar and showed no sign of leakage. Secondly, the chips were tested for acoustofluidic performance using polymer beads as cell model. Ultimately, the acoustofluidic results were compared to FEM simulations with positive agreements.

Micro-injection moulding, polymer bonding, PMMA, lab-on-a-chip, metrology, acoustofluidics, FEM simulation

1. Introduction

Lab-on-a-chip (LOC) systems, as a device that encompasses one or several laboratory functions, have received immense attention in the recent years for their versatility, cost-effectiveness, reproducibility and last but not least, scalability [1]. UV-lithography techniques have been the favourable process choice for manufacturing such platforms thanks to tooling procedures derived from the microelectronics industry. The material employed for such processes are silicon and glass which together with polydimethylsiloxane (PDMS), form the majority of microfluidics chips used in laboratories today[1]. Over the past few years, the advancements in the field of rapid prototyping have helped to scale up the studies and the use of LOC and organ-on-a-chip (OOC) production [2].

Rapid prototyping techniques for polymers with the advantages they offer such as low manufacturing cost in large scale, have given rise to studies for manufacturing low-cost POC diagnostics devices that separate and enrich cells using acoustic forces. However, the lack of a predictive model for resonant acoustofluidic polymer platforms had been problematic and for that reason, the full potential was not reached yet [3]. In 2019, Bruus et. al. presented a review of the theory of the acoustic radiation force and derived a second-order time-averaged relation to explain acoustophoretic motion of micrometre-sized materials inside an ultrasound field [4]. In 2019 Moiseyenko and Bruus [5], introduced a model for whole-system ultrasound resonances which could serve as a foundation for a full-polymer acoustophoresis platform. Through a well-tested and experimentally validated numerical method [6], it was demonstrated numerically and experimentally that good acoustophoresis can be attained inside a microchannel that is embedded within an all-polymer chip using excitation of whole-system resonances [5, 7]. The advent of the recent manufacturing capabilities along with the theoretical groundwork gave birth to the AcouPlast project to design and manufacture an all-polymer device for acoustic blood plasma separation using whole-system resonances in polymer chips [7].

Injection moulding (IM) is a manufacturing process used for producing parts through injection of molten polymer material into a mould and in this study, it is presented as an alternative to the silicon/glass chip for the purpose of a more cost-effective and high-scale production. However, transitioning from silicon/glass etching to plastic chips causes some inherent problems. That is, with IM both shrinkage and warpage upon cooling are induced due to the polymers' high thermal expansion. These issues are non-existent when working with silicon/glass chip fabrication [8]. Shrinkage and warpage of the functional micro-features of the channel cavity is detrimental to the acoustic cell separation performance, as whole-system resonance is sensitive to dimensional deviations. Hence, the problem to be solved is minimizing the deformation of the whole chip including the functional micro-features.

The study utilizes a feedback loop, as illustrated in figure 1, to leverage simulations and virtual DOEs to enhance the quality of the chips in both quality and acoustic performance. This occurs through FEM numerical simulations, IM simulations using virtual DOEs, quality assurance and lastly, acoustofluidic performance tests of the chip. [9, 10, 11].

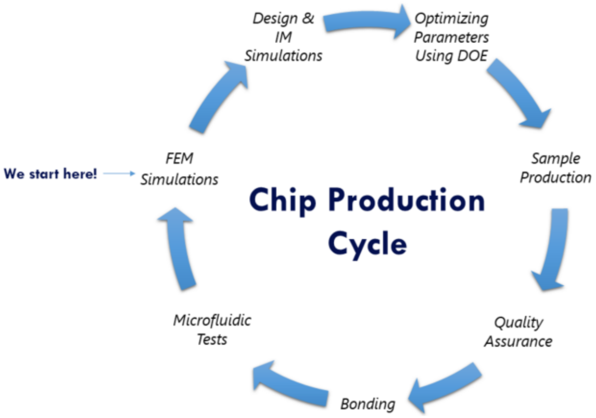

Figure 1. The schematic of the established feedback loop to exploit the production data as well as the simulation data in tandem.

2. Injection moulding simulations and DOE

As a pre-requisite to an accurate numerical simulation, a fine meshing network is crucial. To fulfil the goal, Moldex3D software allows users to employ multi-scale meshing that helps us define various meshing regions contingent on the size of the feature. This segmentation would ensure that we would have an accurate analysis while avoiding unnecessary computations for regions that are bigger than others. In this study as can be seen in figure 2 , 0.2 mm was used as the global mesh size which corresponded to 10% of the largest thickness feature that is the chip thickness (=1.9 mm) and for the microfluidic channel, 15 µm was selected since it corresponded to 10% of the channel's thickness to obtain a more refined mesh.

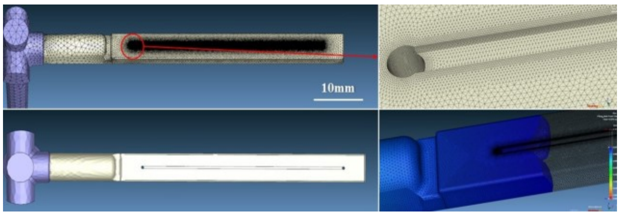

Figure 2. Highly refined mesh as small as 15 µm used to increase the accuracy of the simulations. A total of 3 million mesh was created throughout the sample.

Thanks to the database of the polymer grades available in Moldex3D, similar manufacturing grade as the one used for injection moulding of the parts was selected for the IM simulations. Moreover, the archive of IM machines within the software allowed us to select ARBURG 370 A 600-70-18 which was also utilized for the production. A full analysis was performed for each of the simulations, consisting of the following phases: cooling, filling, packing, cooling and warpage (CFPCW).

The goal was to understand the effects of the four primary parameters namely, mould temperature, melt temperature, injection velocity and packing pressure. These parameters are referred to as factors in the study of the DOE. The goal for this part was to minimize the volumetric shrinkage value as the main response. The values of the volumetric shrinkage as a function of these factors were first obtained by running simulations on Moldex3D. The output values were then input to Minitab statistical analysis software to understand the individual and combined effects of the four parameters on the volumetric shrinkage as the primary response.

In order to perform a full-factorial analysis, each of the four factors were assigned two levels. Consequently, the number of runs necessary for a full factorial analysis is 2^4=16 runs. In other words, a total of 16 simulations with different process settings were run for PMMA LG IG 840. A set of values (levels) was selected for PMMA LG IG 840 as our target material as can be seen in table 1.

Table 1. Different process setting (levels) used as IM factors for the DOE in regards to PMMA LG IG 840.

Factor	Levels	Values
Melt temperature/°C	2	210 – 230
Mould temperature/°C		65 – 90
Injection velocity/mm.s^{-1}		60 – 120
Packing pressure/MPa		60 – 120

The results of the analysis of the four primary factors of the virtual DOE with the volumetric shrinkage being as the response are shown in figure 3. The data helped with better understanding of which factors play a more noticeable role in the increase/decrease of the shrinkage.

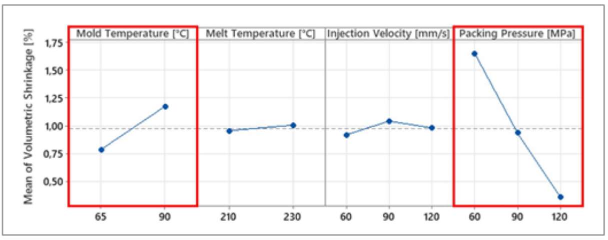

Figure 3. Virtual DOE primary effect analysis demonstration using Minitab software. The two highlighted graphs indicate the two factors with more pronounced effect on volumetric shrinkage.

3. Production

The chips were manufactured via an injection moulding machine Allrounder® 370A from Arburg GmbH, Lossburg, Germany. The machine offers a maximum clamping force of 600 kN, a maximum injection pressure of 250 MPa and injection speed of 300 mm/s. The machine benefits from a reciprocating screw with a diameter of 18 mm and a length to diameter ratio of 24.5.

In this investigation, we decided on using an insert-based mould as it provides with faster turnarounds which is advantageous for rapid prototyping as shown in figure 4.

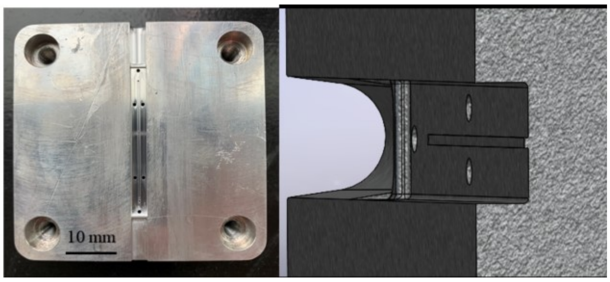

Figure 4. The insert used for moulding the LOC. A section cut of the insert is also demonstrated in the right image where the features such as the channel and the ejector pin holes are visible to provide a better overview of the details.

Table 2. Channel average dimensions. For the molded parts, the values are average of 9 different points registered from 5 different samples.

	l/mm	w/µm	h/µm
CAD file (nominal value)	36	375	150
Mould (measured values)	35.99 ±0.01	398 ±3	147 ±6
Moulded PMMA (before optimization)	35.74 ±0.01	398 ±3	129 ±6
Moulded PMMA (after optimization)	35.77 ±0.01	399 ±3	147 ±6

4. Quality assurance

The initial metrology analysis results were used to improve and understand the simulations. The simulation results were further used in a reciprocal manner to improve the productions. Moreover, the IM parts are used as a proof of the IM simulations performance and accuracy. A thorough quality evaluation of the parts (an example of the part can be seen in figure 5) is the paramount step to assess the efficacy of the feedback loop. The measurements of channel height and width were performed using LEXT OLS 4100, a laser scanning confocal microscope, by Olympus, Tokyo, Japan. The DeMeet 220 coordinate measuring machine Schut Geometrische Meettechniek was also used in conjunction with ApproveforDeMeet software for the estimation of the linear shrinkage and the measurement of the length of the channel.

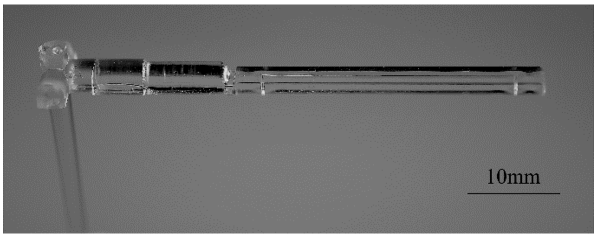

Figure 5. Post-optimization chip moulded in PMMA LG IG 840.

As can be seen in table 2, the length, the width and the depth of the channel were measured for the parts, before and after optimization, as well as the mould. This would allow for a true assessment of dimensional variance. The results of the post-DOE production showed a clear enhancement of depth dimension. The recorded channel depth was 129 µm in the first production batch while this value was measured to be 147 µm after using the optimized process settings for PMMA LG IG 840 which are (See figure 6.)

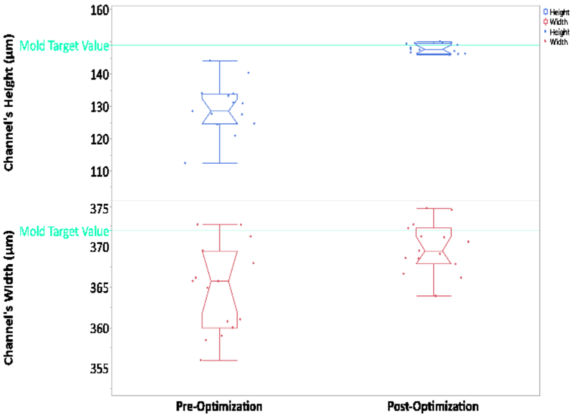

Figure 6. Dimensional inspection of the channel's height and width for PMMA LG IG 840 before and after optimization through the use of virtual DOE and IM simulations.

5. Bonding

After the parts were moulded and their quality have been thoroughly inspected, the chips have to be sealed off in order to have a functional microfluidic platform. Various techniques for polymer-polymer bonding exist, involving e.g. plasma-bonding, chemically-assisted bonding and temperature-assisted bonding. In order to minimize the deformation of the micro-channel as much as possible, UV-assisted thermal bonding has been selected as the favoured technique. The foils are cut using CO_2 laser to maintain dimensional accuracy that is needed to place on the chip. Here the polymer chip as well as the foil get exposed to UV of a certain wavelength. Afterwards the UV exposed surfaces brought into contact with each other. To create a strong bond the stack of chip and foil is placed in a hot embosser in order to apply a controlled pressure on the surface, while maintaining a set temperature on both sides.

In order to generate an even pressure distribution on the surface, the polymer samples are sandwiched between two nickel shims and covered by two Teflon sheets on the outside, see figure 6 for reference. The nickel shim is used due to its smooth surface finish, while the purpose of the Teflon sheet is to cancel out slight mismatches in the height distribution by acting as a soft buffer layer.

Table 3. Bonding parameters used for the UV-assisted thermal bonding of PMMA LG IG 840.

Parameter	PMMA LG IG 840
t for UV exposure/s	50
t inside hot embossing/s	600
T/°C	110
P/bar	50

As illustrated in figure 7, different samples were put into the hot embosser one by one and an automated temperature and pressure profile was started. The process parameters used for the hot embossing of PMMA can be seen in table 3.

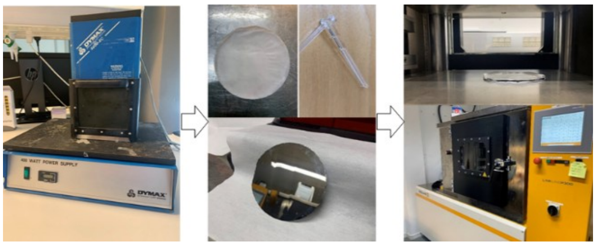

Figure 7. Bonding process starts with UV using Dymax 5000-EC laser. A sandwich of the chip, lid foil and Nickel shim and Teflon sheets are then placed inside Collin P300 SV hot-embossing machine to finish the bonding.

6. FEM simulation

In recent work a numerical simulation model has been presented, showing good agreement between theory and experimental results on the acoustofluidic platform [6]. The resonance frequencies, where good acoustic focusing inside the microchannel is observed, are governed by the resonances of the whole polymer chip. This whole-system ultrasound resonance (WSUR) depends on multiple factors, including the outer dimensions of the polymer chip as well as the dimensions of the fluid channel itself. At this WSUR a resulting pressure field is observed inside the fluid channel that is close to a standing pressure half-wave, leading to acoustic focusing of µm-sized particles in the pressure node. [4, 6]

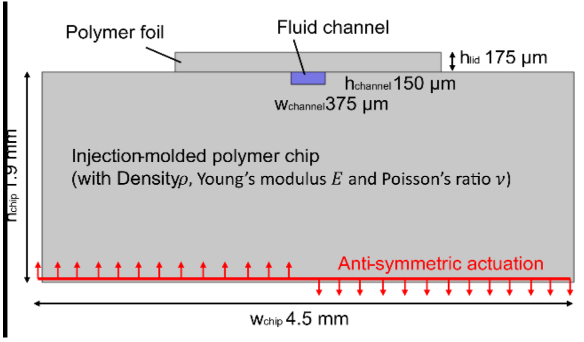

Figure 8. 2D-cross section of the acoustofluidic device, consisting of the injection-moulded polymer chip, and a thin polymer foil bonded to the chip to seal the fluid channel.

Figure 8 shows a 2D-cross section of the modelled polymer chip. It has been observed that the mechanical and acoustic properties of the underlying polymer, such as density ρ, Young's modulus E, and Poisson's ratio ν can have a large impact on the performance of the acoustofluidic device. This is visualized in figure 9. The bottom-up approach in the fabrication allows to adjust the chip dimensions as well as the material properties and optimize the process parameters to achieve acoustic properties that are ideal for acoustophoresis experiments.

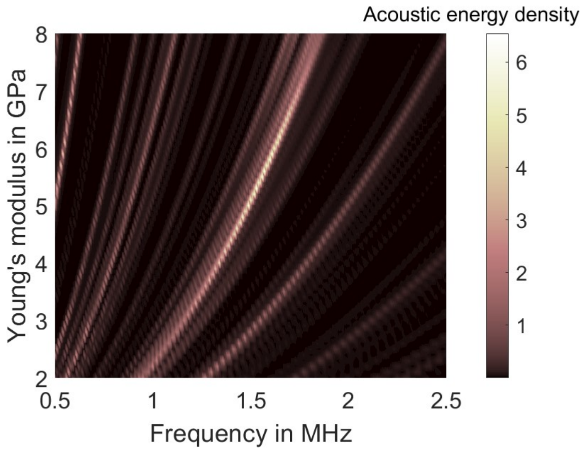

Figure 9. 2D simulation results of the acoustic energy density inside the fluid channel for actuation frequencies between 0.5 MHz and 2.5 MHz and Young's moduli of an isotropic solid between 2 GPa and 8 GPa (with constant density $\rho = 1186\frac{kg}{m^3}$, and Poisson's ratio $\nu = 0.36$). A shift towards higher resonance frequencies can be observed when increasing the Young's modulus of the polymer chip.

7. Conclusion

Through FEM numerical simulations [7] certain dimensional inputs were given for a polymer chip which is aimed to be used for acoustic segregation of blood particles. The target design encompasses a microfluidic channel with a relatively high length compared to the height and the width. As such, the primary challenge is maintaining the channel dimensional conformance with the nominal dimensions throughout the entire length after injection moulding of the part. In order to tackle the challenge and optimize the results, a feedback loop was developed for the device process development where the data of the preliminary µIM production was exploited to implement a simulation-based full-factorial virtual DOE PMMA LG IG 840. The four essential IM parameters namely, mould temperature, melt temperature, injection velocity and packing pressure were used as factors. Two levels were assigned to each of the four process parameters that resulted in a DOE consisting of 2^4=16 virtual experiments for a full-factorial study. The primary response that was chosen for the current investigation was the linear shrinkage, which would help spot potential production anomalies and product defects such as part warpage.

Overall, IM simulations were performed based on the virtual DOE inputs on Moldex3D for PMMA LG IG 840 and later, parts were moulded and characterized where for linear shrinkage a respective width and height difference of 1 % and 3.3 % between the simulations and the production results was observed. The results in this case confirms the positive impact of the virtual DOE as a part of our feedback loop that is being developed and could be equipped to optimize the outputs in µIM production. Furthermore, the results of the IM simulations through Moldex3D showed reliable compatibility with the production in µm range.

The parts ultimately were examined in regards to their functionality. They first stood the leakage test with a maximum pressure value of 2 bar and showed no sign of leakage. Secondly, the chips were tested for acoustofluidic performance using polymer beads as cell model. As the last step, the acoustofluidic results were compared to FEM simulations with positive agreements. This study paved the way for achieving a reliable method for manufacturing and optimizing injection moulded parts and the functional tests that followed, demonstrated promising results for the first prototype. This results will help us in the design of the next prototypes and moving towards having the full-functional POC platform using injection moulding.

Acknowledgment

This work is part of the Eureka Eurostars-2 E!113461 AcouPlast project funded by Innovation Fund Denmark, grant no. 9046-00127B, and Vinnova, Sweden's Innovation Agency, grant no. 2019-04500.

References

[1] Díaz Lantada A, Pfleging W, Besser H, Guttmann M, Wissmann M, Plewa K, Smyrek P, Piotter V, García-Ruíz J P 2018 *Polymer* **10** 1238
[2] Huh D, Kim H J, Fraser J P, Shea D E, Khan M, Bahinski A, Hamilton G A, Ingber D E 2013 Nature Protocols **8** 2135-2157
[3] Silva R, Dow P, Dubay R et al. 2017 *Biomicrofluidics* **19** 70. [4] Bruus H 2012 Lab on a Chip **12(6)** 1014-1021
[5] Moiseyenko R P, Bruus H 2019 *Phys. Rev. Appl.* **11** 014014
[6] N. R. Skov, J. S. Bach, B. G. Winckelmann, and Bruus H 2019 *AIMS Math* **4(1)** 99-111
[7] Lickert F, Ohlin M, Bruus H Ohlsson P 2021 *J. Acoust. Soc. Am.* **149**, 4281-4291
[8] El Bahra S, Ludwig K, Samran A, Freitag-Wolf S, Kern M 2013 Dental Materials **29** 1091-1097
[9] Loaldi D, Regi F, Baruffi F, Calaon M, Quagliotti D, Zhang, Y, Tosello, G 2020 Micromachines **11** 614
[10] Baruffi F 2019 Integrated micro product/process quality assurance in micro injection molding production. Ph.D. Thesis. Technical University of Denmark
[11] Calaon M, Baruffi F, Fantoni G, Cirri I, Santochi M, Hansen H N, Tosello G 2020 Micromachines **11(12)** 1115
[12] Zhang H, Fang F, Gilchrist M D, Zhang N 2019 Materials and Design **177** 10782