Investigation of Fidelity of Micro Molded Features Using Microinjection Molding Process

Ali Rajhi[2], Ahmed Almalki[1,3], and John Coulter[1]

[1]Manufcaturing Science Laboratory, Lehigh University, Bethlehem, PA, USA, jc0i@lehigh.edu
[2]King Khalid University, Abha, Saudi Arabia, arajhi@kku.edu.sa
[3]Taibah University, Madinah, Saudi Arabia, aamalki @taibahu.edu.sa

ABSTRACT

This paper investigates the influence of selected processing parameters of microinjection molding on the replication fidelity of micro molded features. Parameters were altered in order to find to what extent the microfeatures can be stretched while maintaining the required geometry with high fidelity. A silicon-based mold insert (Si) with circular cavities of 5 µm diameter and 3 µm edge-to-edge spacing over dense areas was replicated with an aspect ratio (AR) of 4. It was fabricated using photolithography followed by deep reactive ion etching (DRIE) to create the required depth. Prior to molding trails, numerical simulations were performed using Moldflow Insight to obtain optimal processing parameters which then used as a baseline to mold micro featured samples. Packing pressure, cooling time, and injection velocity were varied during molding and replication quotient was used for comparison. It was found that excellent replication quotient occurred at high packing pressure with lower tip stretching. Also, at lower cooling time bulged features occurred while higher cooling time enhanced replication quotient. Sever tip stretching occurred at cooling time of 100 seconds. Lastly, higher velocities resulted in high replication quotient.

Keywords: microinjection molding, processing parameters, micropillars stretching, MoldFlow, replication quotient

1 INTRODUCTION

Injection molding of parts with microfeatures is highly demanded for numerous biomedical applications. The high-volume production in microinjection molding requires high degree of replication quality for such features. Generally, replication quality of the microfeatures is influenced by melt, and mold temperatures, injection velocity, injection and packing pressures, and cooling time. Microfeatures could be affected greatly when altering these processing parameters. Furthermore, during demolding stage, friction forces between the microfeatures and cavity walls are critical for high fidelity replication [1]. Stretching and collapsing can occur when fabricating high aspect ratio micropillars due to roughness of the sidewalls and high frictional forces during demolding stage [2–6].

Molded parts made of Thermoplastic polyurethane (TPU) offer distinct characteristics when it comes to compatibility and flexibility. However, there are some replication challenges that still need to be addressed to optimally mold microfeatures with high aspect ratios and high fidelity [4].

In this research, circular cavities were fabricated on a silicon wafer. It has 5 µm in diameter, 20 µm in depth, and 3 µm edge-to-edge distance. This silicon-based insert was used to mold parts with microfeatures while altering processing parameters to study the effect on micropillars stretching as a function of processing parameters. While features stretching is expected to happen due to sidewall frictional forces during part ejection, cooling time could influence melt relaxation before part ejection and lead to high extent of features height. Thus, this could provide a proper understanding of features stretching as a function of cooling time to achieve final molded features geometry. This stretching could facilitate the ability to improve the replication rate to a further point before the molded features start to collapse. Samples were characterized using scanning electron microscopy (SEM) to measure features stretching and provide visualized understanding of parameters' effect on the replication.

2 NUMERICAL SIMULATION

The solid model of the molded part with microfeatures was created in SolidWorks then it was imported into Autodesk MoldFlow Insight. Arrays of 5 × 5 cylindrical micropillars were modeled with a diameter of 5um, a height of 20 um, and 3um edge-to-edge distance. It was distributed across the 6mm × 6mm contact area with the silicon insert. After that, molding window analysis and dual domain meshing were performed for preliminary recommended processing parameters prior to 3D analysis.

Meshing density was varied to achieve required multi-scale meshing for the sprue and the microfeatures as shown in Figure 1. The edge lengths were 0.0025mm and 0.25mm for microfeatures and for the sprue, respectively. This resulted in more than 2.5 million tetrahedral elements.

Several 3D simulations for filling and packing of the model were conducted until optimal processing parameters were achieved as shown in Table 1. These parameters were used for injection molding of parts with microfeatures.

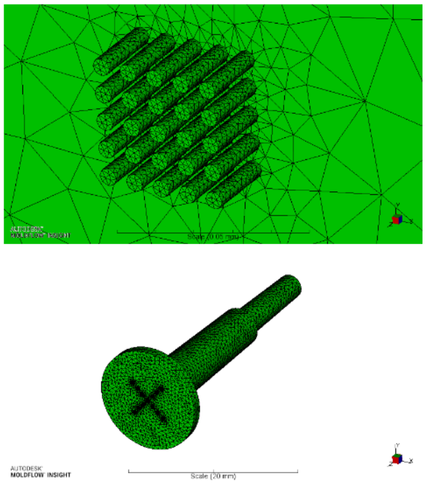

Figure 1: Multi-scale meshing of the molded part with the targeted microfeatures.

Microfeatures were found to be filled at around 0.2 seconds as shown in Figure 2. Although it can be noted that microfeatures were filled differently from location to another, it will not be discussed here since it is not the focus of this study.

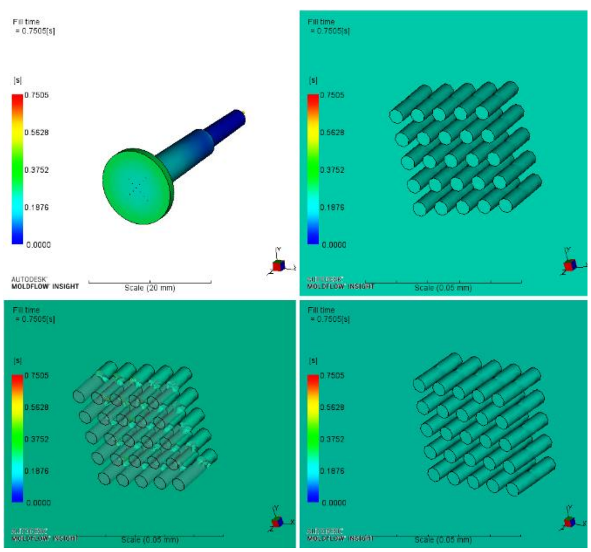

Figure 2: Filling time for molded part with microfeatures at different locations.

Fill time [Seconds]	0.38
Melt Temperature [°C]	205
Mold Temperature [°C]	50
Injection Pressure [MPa]	20
Packing Pressure [MPa]	60
Cooling Time [Seconds]	140

Table 1: Optimal processing parameters from MoldFlow simulation for TPU (Texin 985).

3 EXPERIMENTAL

3.1 Si-based Tooling Fabrication

Wafers were first cleaned using ammonium hydroxide (NH_4OH), hydrogen peroxide (H_2O_2), distilled water (dH_2O) to remove organic contaminants from the wafers surface. The solution is heated to 75C° for five minutes then rinsed in distilled water and dried in a spin dryer for five minutes. wafers were then pre-baked in an oven at 100 C° for 40 minutes to carry out moisture from previous step. In order to ensure better photoresist deposition, the wafer surface has to become hydrophobic [7] The wafer surface was first vapor primed in a closed container for 10 minutes using a1:1 ratio of hexamethyldisilazane (HMDS) and xylene (C_6H_{10}). This procedure causes the formation of ammonia (NH_3) due to HMDS decomposition into trimethylsilyl groups. The methyl groups form a hydrophobic surface, thereby improving photoresist adhesion [4,7]. The wafer was then spin-coated with positive photoresist (OCG 825) at 5000 rpm for 40 seconds, followed by baking for 40 minutes at 100 °C. The coated wafer was then loaded onto a mask aligner and exposed to UV light for 1.5 seconds, set at a power of 25 W. A developer (OCG 809) was then used to remove exposed areas which represent the targeted geometries. A spin dry step is followed by a hard-bake at 130 C° for 30 minutes to remove moisture residues remaining from previous steps.

At this point, the pattern is already transferred to the wafer and deep reactive ion etching (DRIE) was done to achieve required geometries using Adxien I-Speeder 100. An alternating plasma exposure using sulfur hexafluoride (SF_6) for etching, and octafluorocyclobutane (C_4F_8) for passivation to protect the side walls until required depth was achieved. A combination consists of SF_6, C_4F_8 flow rates, duration, power during etch and passivation, temperature and chamber pressure that affected etching process is showing in Table 2. At the end, an anti-stiction layer is sprayed over the wafer to act as mold release for injection molding process. In order to verify the desired depth scanning electron microscope (SEM) inspection was done after finishing the etching process using Hitachi 4300 SEM as shown in Figure 3.

Gas	**Gas Flow [sccm]**	**Duration [Seconds]**	**Source Power [W]**	**Total Processing Time [Seconds]**
Etching (SF_6)	125	3	1200	930
Passivation (C_4F_8)	100	2	1200	
Anti-stiction layer (C_4F_8)	150	20	1200	20

Table 2: BOSCH process parameters.

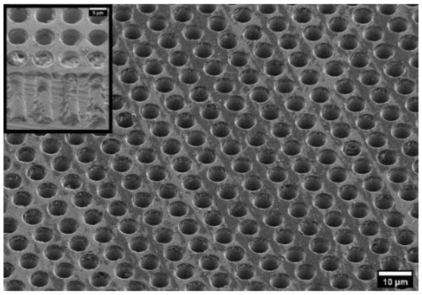

Figure 3: Si mold insert with cross-sectional view

3.2 Microinjection Molding

A 3-ton microinjection molding machine (Nissei model: AU3E) was used to mold the micro featured parts. Molded parts were Thermoplastic Polyurethane (TPU) (Texin 985) elastomer-based material. Optimal processing parameters obtained from MoldFlow simulations were utilized and varied accordingly. Firstly, packing pressure was varied from 40 up to 140 MPa with a 20 MPa interval at a fixed cooling time of 140 seconds. This was to study the effect of packing pressure on micropillars stretching, and replication quotient RQ (RQ = micropillar height/cavity depth). Then, packing pressure was fixed at 140 MPa while varying the cooling time from 20 up to 140 seconds with a 20 seconds interval. This was to analyze the effect of changing cooling time on RQ, and micropillars stretching. Furthermore, injection velocity was varied from 50 mm/s up to 125 mm/s at 140 seconds cooling time, and 140 MPa packing pressure. It was performed to measure micropillars height as a function of injection velocity. Samples were cut, polished, and coated for SEM using Hitachi4300 and FEI Scios dual-beam focused ion beam (FIB-SEM). Also, ImageJ was utilized for image processing.

4 RESULTS AND DISCUSSION

4.1 Packing Pressure

During the packing pressure stage, microcavities are filled with polymer melt and seemly controlled until the gate totally solidified. This helps micropillars to retain the required shape and depth of the microcavities. In this study, packing pressure was extended to a point where the replication rate is reached an AR of 4. Micropillars' RQ was studied at various packing pressure: 40, 60, 80, 100, 120, and 140 MPa. It has been noted that at lower packing pressure (40 and 60 MPa), features were not sufficiently filled as shown in Figure 4a. However, once packing pressure reached and exceeded 80 MPa, RQ remained approximately steady until 120 MPa. At these packing pressures, features were nearly 0.8 filled. Highest RQ achieved when packing pressure increased to 140 MPa. This resulted in more than 1.14 filling of the micropillars height which means stretching occurred.

4.2 Cooling Time

A proper cooling time is needed when molding micro/nano features for optimal demolding. Shorter cooling time can lead to premature material solidification. Hence, improper quality replication of required features. In this investigation, RQ was examined at cooling times of 20, 40, 60,80,100,120, and 140 seconds. It has been noted that at lower cooling times of 20 and 40 seconds, features bulging occurred as shown in Figure 6. These bulged features rested on neighboring ones which led to insufficient RQ and distorted micropillars as shown in Figure 4b. As cooling time increased, features effectively hold microcavities dimensions and RQ improved.

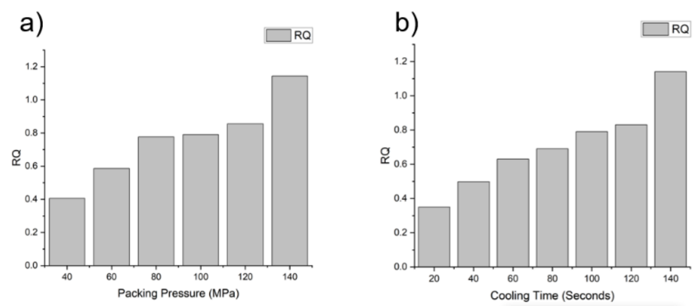

Figure 4: Replication quotient for different a) packing pressures, and b) cooling times.

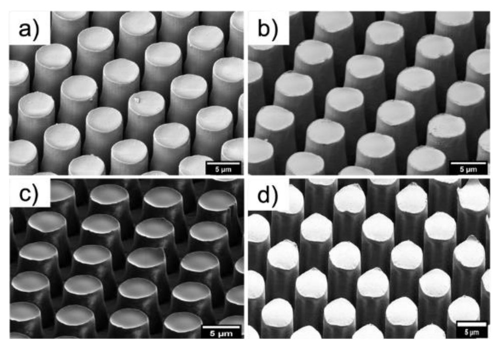

Figure 5: Filled micropillars at different packing pressures and cooling times.

Figure 5 shows different filled microfeatures at different packing pressures and cooling times. a and b have similar cooling time of 140 seconds but different packing pressure at 100, and 120 MPa, respectively. Whereas c and d have similar packing pressure at 140 MPa but different cooling time of 60 and 140 seconds, respectively.

TechConnect Briefs 2021, TechConnect.org, ISBN 978-0-578-99550-2

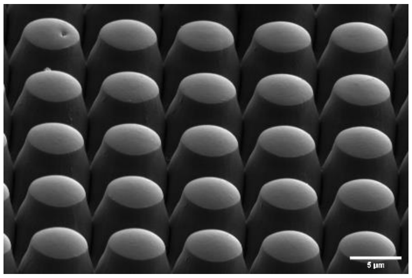

Figure 6: Bulged features occurred at lower cooling times.

4.3 Injection Velocity

In addition to processing parameters discussed earlier, injection velocity has a significant effect on micropillars heights. Injection velocity was examined at 50, 75, 100, and 125 mm/seconds as seen in Figure 7. Higher velocities showed higher extent of micropillars heights as seen in Figure 8.

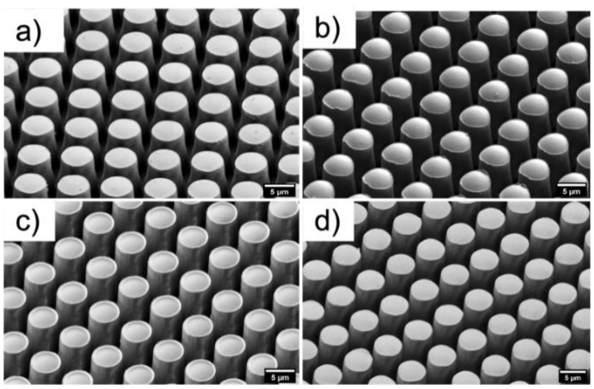

Figure 7: Filled micropillars at different injection velocities: a) 50 mm/sec, b) 75 mm/sec, c) 100 mm/sec, and d) 125 mm/sec.

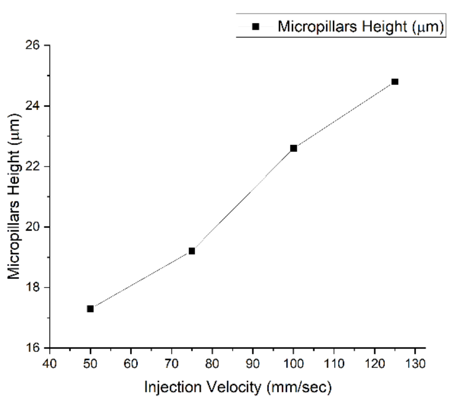

Figure 8: Micropillars height as a function of injection velocity.

4.4 Micropillars Tip Stretching

The presence of nano undercuts scallops on the microcavities walls and the lack of tapered microcavities led to high frictional force during demolding of the micropillars. This caused a severe amount of stretch and distortion in some cases. The amount of stretching could be beneficially controlled when targeting higher aspect ratio micropillars. In this study, micropillars appeared to be stretched to some extent in some cases and being stretched up to the point of failure in others. Examples of the distortion of the micropillars tip at different processing parameters are shown in Figure 9. In this Figure, tip stretching is shown at different packing pressures and cooling times. a and b have similar cooling time of 140 seconds but different packing pressure at 100 MPa, and 120 MPa, respectively. Whereas c and d have similar packing pressure at 140 MPa but different cooling time of 60 and 140 seconds, respectively.

The tip stretching was analyzed at different packing pressures and cooling times. A lower degree of tip stretch was found when varying packing pressure as seen in Figure 10a. On the other hand, sever amount of tip stretch occurred at cooling time of 100 seconds at 5.3 µm and this amount of stretch decreases as cooling time increased to 140 seconds as shown in Figure 10b.

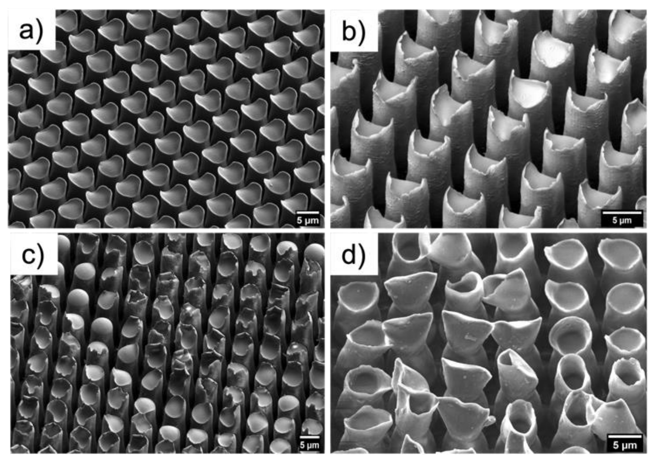

Figure 9: Tip stretching of micropillars at different packing pressures and cooling times.

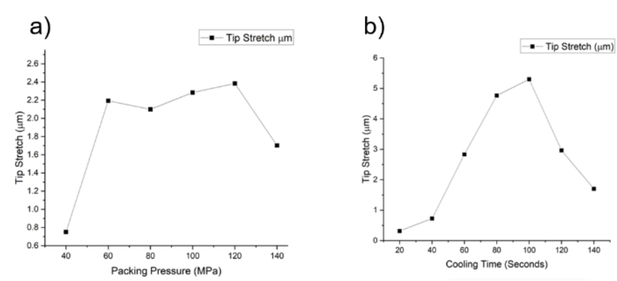

Figure 10: Tip stretching of micropillars.

5 CONCLUSION

High aspect ratio silicon-based insert was used to mold parts with microfeatures while altering processing parameters. Packing pressure, cooling time, and injection velocity were studied in terms of micropillars heights and stretching. The expected significant sidewall frictional forces during part ejection resulted in micropillars stretching. Furthermore, the influence of cooling time on melt relaxation before part ejection led to a high extent of micropillars. A sever tip stretching of 5.3 µm occurred at cooling time of 100 seconds. This stretching could facilitate the ability to improve the replication rate to a further point that exceed the microcavities aspect ratio before the molded features start to collapse.

In addition, packing pressure, and cooling time showed significant effect on micropillars filling and stretching. It was found that excellent replication quotient occurred at high packing pressure with lower tip stretching. Also, at lower cooling time bulged features has occurred while higher cooling time enhanced replication quotient.

Micropillars stretching showed potential to be controlled and increase the replication quotient. However, it needs further investigations to explore the effect of other processing parameters.

REFERENCES

[1] B. Sha, S. Dimov, C. Griffiths, M.S. Packianather, Investigation of micro-injection moulding: Factors affecting the replication quality, J. Mater. Process. Technol. 183 (2007) 284–296. https://doi.org/10.1016/j.jmatprotec.2006.10.019.

[2] H.L. Zhang, N.S. Ong, Y.C. Lam, Mold surface roughness effects on cavity filling of polymer melt in micro injection molding, Int. J. Adv. Manuf. Technol. 37 (2008) 1105–1112. https://doi.org/10.1007/s00170-007-1060-6.

[3] M. Sorgato, D. Masato, G. Lucchetta, Effects of machined cavity texture on ejection force in micro injection molding, Precis. Eng. 50 (2017) 440–448. https://doi.org/10.1016/j.precisioneng.2017.06.019.

[4] A.A. Rajhi, A.A. Duhduh, A. Kundu, J.P. Coulter, Effect of cooling time, packing pressure, and antistiction coating on replication of micro molded substrates., (n.d.) 6.

[5] R. Surace, M. Sorgato, V. Bellantone, F. Modica, G. Lucchetta, I. Fassi, Effect of cavity surface roughness and wettability on the filling flow in micro injection molding, J. Manuf. Process. 43 (2019) 105–111. https://doi.org/10.1016/j.jmapro.2019.04.032.

[6] Q. Wang, J. Wang, C. Yang, K. Du, W. Zhu, X. Zhang, Effect of Process Parameters on Repeatability Precision of Weight for Microinjection Molding Products, Adv. Polym. Technol. 2019 (2019) 1–8. https://doi.org/10.1155/2019/2604878.

[7] Photolithography - Semiconductor Technology from A to Z - Halbleiter.org, (n.d.). https://www.halbleiter.org/en/photolithography/.