Numerical and Experimental Results of Replication a Micro-Featured Surface using Injection Molding Process

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ABSTRACT

This paper describes current efforts to numerically and experimentally investigate micro and nano-scale features replication using the injection molding process. A silicon (Si) mold with micro–features has been fabricated using photolithography followed by deep reactive ion etching (DRIE). Scanning electron microscopy (SEM) was used to validate the fabricated mold cavities were met the targeted dimensional specifications. The Si insert then served as the mold cavity for injection molding. The study investigated if Si tooling is the proper material/method for this process, particularly due to its brittle nature, and relatively high pressures employed in injection molding. For high volume manufacturing, long lasting molds is a key factor in offsetting the high cost of mold cavity micro-fabrication. In this study, the life expectancy of the Si insert is examined, and was found to be adequate for micro-scale injection molding, at for up to 80 cycles. Extending the study to the point of mold failure is planned as a future study.

Keywords: micro/nano injection molding, microfabrication, microstructures, *Moldflow*® analysis.

1 INTRODUCTION

As a manufacturing process, injection molding is considered to be one of the highest growing markets globally related to fields such as micro-electromechanical systems (MEMS), industrial devices, medical applications and microfluidic devices [1]. These applications require tiny plastic parts that are at the microscale, or have features in this range. Micro-scale injection molding is not simply achieved by reducing the scale of the standard process. The process requires unique tooling and processing considerations in each step of the process, until the final product is ejected from the mold [2]. Mold (and the microstructured insert) fabrication is extremely important (in addition to process optimization) to guarantee that a good product is manufactured. It is also the most costly in terms of manufacture (costing approximately about a thousand dollars to manufacture 40 6x6mm inserts), since it requires employing technology typically used in the semiconductor fabrication industry.

Conventional hardened steel tooling is inadequate in this regard due to the material's grain boundary deficiency, and machining tools which are not amenable to microfabrication. Thus micro-tooling turned to alternative micromachining techniques such as UV lithography, LIGA, laser micromachining, and electro-discharge machining (EDM). Si is the primary substrate material for these micromachining methods. However its impact strength, durability, and heat transfer characteristics are inadequate for high volume, and high-speed molding [3,4].

In this study, microstructures on Si wafers were fabricated using photolithography followed by DRIE with depths down to 2 and 15 µm. These wafers then diced to 6x6mm mold inserts. The primary goal is to investigate and optimize the processing parameters for micro-replication using the injection molding process, and analyze the life expectancy of the Si mold.

2 NUMERICAL SIMULATION

Numerical simulation *Moldflow*® has been previously used to provide a better understanding of the melt rheology inside a closed mold under high clamping pressure, to reduce trial and error experimentations [5,6]. Simulations were performed to study the filling process of a mold cavity having a 12mm diameter, with patterned arrays of two different micro-structures: i. an oval profile with a diameter (D) of 15 µm and height (H) of 15 µm , and ii. a circular profile with D = 5 µm, and a H = 2 µm.

A CAD file with the design was generated then imported into *Moldflow*® for the analysis (Figure 1 a and b). *Molding Window Analysis* (*Dual Domain Analysis*), a specific software feature, was initially performed to verify the best preliminary processing parameters for molding the given design. The recommended parameters was then used as the input for the subsequent 3D-analysis.

The filling analysis was found to be significantly affected by the choice of velocity (V) filling stage to pressure (P) filling, or V-P, switchover. The micro-featured region was filled in a total time of 0.1408 seconds (Figure 2). The simulation result indicates that

the micro-featured region is highly dependent on injection velocity control in the initial filling stage. The recommended V-P switchover is 95% of cavity filling via velocity, followed by a switchover to cavity filling via pressure.

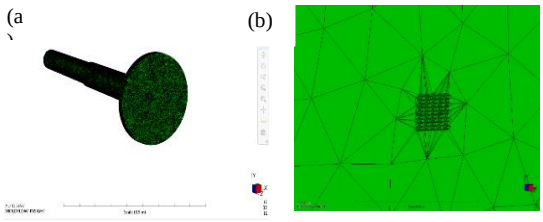

Figure 1: a) CAD model with trigonal mesh in Moldflow. b) Array of ellipses (5x5) at D=15um and H=15um.

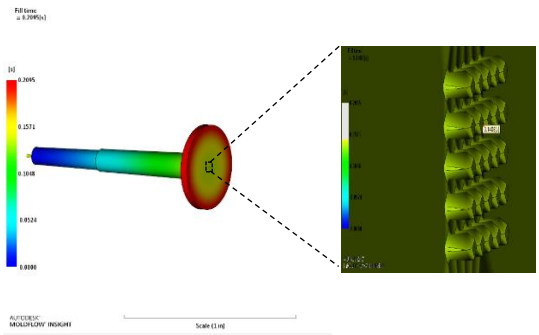

Figure 2: Filling simulation results with micro featured region filled at t = 0.1408 seconds.

3 EXPERIMENTAL

Si Mold Fabrication

Prior to pattern transfer, the Si wafer was first cleaned using distilled water (dH_2O), ammonium hydroxide (NH_3OH), and hydrogen peroxide (H_2O_2), at a ratio of 5:1:1 for 5 minutes at 75 °C. This is followed by rinding 5x in a 1000 mL beaker. This cleaning step removes insoluble organic contaminants from the wafer surface.

The wafer surface, which is hydrophilic at this stage, has to be made hydrophobic to ensure better bonding with the photoresist [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[7–9].

The wafer was then spin-coated with positive photoresist (OCG 825) at 5000 rpm for 40 seconds, followed by baking for 40 min 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.

Deep Reactive Ion Etching (DRIE)

DRIE was employed to etch the targeted geometries down to the required depth. The process uses step-by-step alternating exposure to plasma gases of sulfur hexafluoride (SF_6) for etching, and octafluorocyclobutane (C_4F_8) for passivation of the side walls. A final step of C_4F_8 deposition was also employed to serve as the anti-stiction coating, which serve to facilitate mold release during the injection molding process. The recipe for the procedure is shown in Table 1. Using these parameters, the etch rate of Si was found to be approximately 1.54± 0.05 µm/min. Figure 3 provides sample SEM images of the etched Si.

Plasma	Plasma Flow [sccm]	Duration [seconds]	Source Power [W]	Total Processing Time [seconds]
SF_6	125	3	1200	630 (15 µm)
C_4F_8	100	2	1200	83 (2 µm)
C_4F_8	150	20	1200	20

Table 1: BOSCH Process Parameters.

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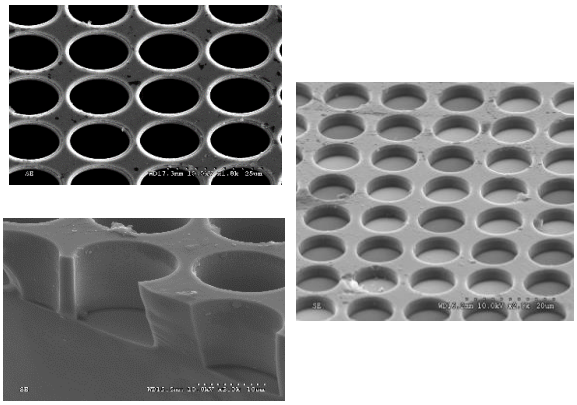

Figure 3: Si mold with 15um diameter ellipses and 5um diameter circles.

Polymer Replication

Injection molding was performing using processing parameters obtained via 3D *Moldflow*® simulation. Polystyrene (PS) STYRON™666D from

Americas Styrenics LLC was used as the molding material.

Injection molding is performed with a Nissei AU3E injection molding machine (Nissei AU3E). The machine is suitable for this application as it has the capability to mold products with weights of at most 0.2g. Micro-injection molding experiments were carried out using melt temperatures (T_{melt}) varying between 215 - 238 C°. The mold temperature (T_{mold}) was set at 75 C°, 83 C°, and 93 C°. Filling velocity was in the range of 100-150 mm/seconds, and cooling time was set at 85 seconds. This was then reduced to 57 seconds when employing a modified smaller sprue which allowed for the reduction in cycle time. Packing pressure was kept low at 5 Mpa to avoid fracture of the silicon wafer.

4 RESULTS AND DISCUSSION

Characterization

To verify polymer replication accuracy SEM imaging was conducted using a *Hitachi 4300*. It is evident that that cooling time is a significant factor in replication accuracy (Figure 4 A and B). Molded parts with longer cooling time were found to acquire better precision in replication, with minimal distortion during demolding. Figure 4 C and D are sample images of the molded elliptical and circular pillars respectively.

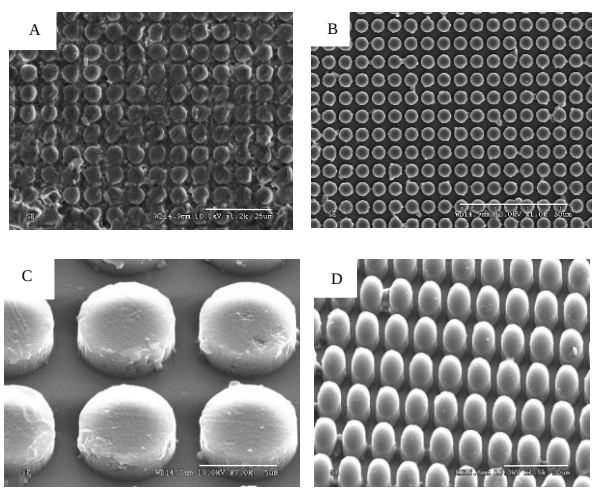

Figure 4: SEM photos of modeled parts: A) cooling time at 45 seconds, B) cooling time at 85 seconds, C) 5 um circular pillars with 2um height and 8um center to center spacing, and D) 15 um elliptical pillars with 15um height and 18um spacing this trails were done at T_{mold}=83C°. (Scale bar for A, B, C, and D is 25, 50, 5, and 20 respectively)

SEM micrographs were also collected at 5 different regions to analyze replication results across the molded parts (Figure 5). The most accurate replication appears to be near the injection gate (center) where the flow is parallel to the micro-cavities. Replication near the periphery of the insert, further away from the sprue gate, appears to be distorted.

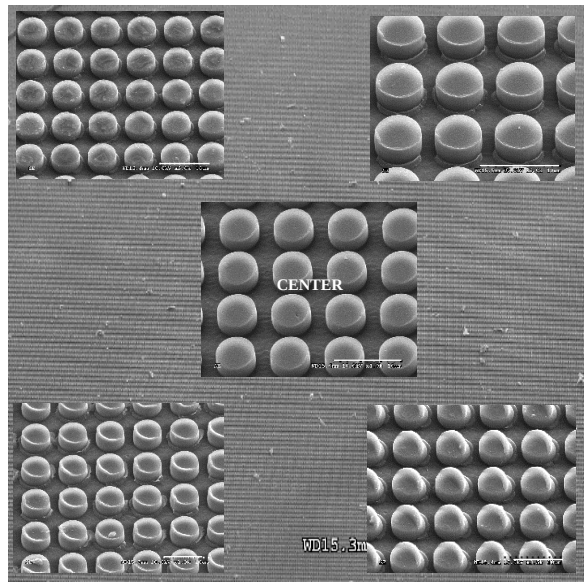

Figure 5: SEM photographs for molded part cycle no.80 at 5 different regions with T_{mold}=93C°. (scale bar 10 um).

Slight distortion on top of the pillars (right bottom enlarged image in Figure 5) may be due to previous replication residue that adhered to the Si mold. This may have caused incomplete replication and/or deflected the pillars during demolding stage. SEM micrographs for the five samples indicate that a Si mold used with an anti-stiction layer can provide high-quality replication.

Mold Life Analysis

Although Si-based tooling may not be the proper method for microreplication via injection molding method due to its brittleness, a study conducted by Sun-hwan et. al found that it can actually survive up to 3000 cycles whilst maintaining replication accuracy [10].

In this work, the Si insert with 5 µm circular cavities at a depth of 2 µm was examined for 80 cycles of replication. Molded samples were characterized for replication accuracy. Samples taken from 10, 30, 50, 70, and 80 cycles of replication were imaged via SEM. The scanned pillar height was calculated based on the SEM stage tilt angle of 40°. Figure 6 shows that the micro-pillars were replicated adequately within a ± 0.02 µm tolerance, even up to 80 cycles of replication.

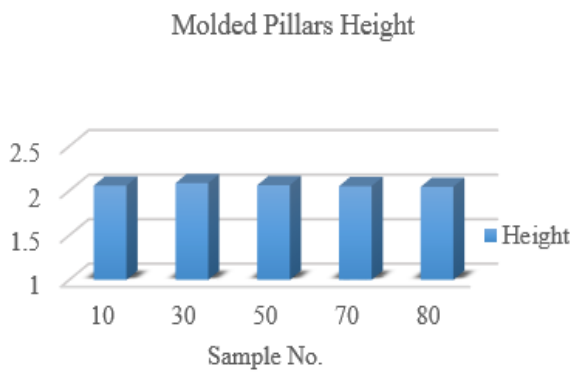

Figure 6: Molded samples height (µm).

5 CONCLUSIONS

Moldflow® is a valuable tool method to provide initial optimum processing parameters for the experiments. It minimizes cost and time, and probability of Si mold breakage during molding experiments. It also provides a preliminary analysis for the filling stage analysis, recommendations for V-P switchover setting.

Processing parameters, such as mold temperature, filling velocity, and cooling time can significantly impact the final product quality and replication capability at the micro-scale. This work found that cooling time had a significant effect on replication quality. Increasing the mold temperature was also found to result in better filling of the micro-cavities.

The Si insert showed potential to survive both the high mold temperature and pressures that were applied in the investigation. 80 injection molding cycles did not cause a significant reduction in replication accuracy. However, additional research is needed to confirm the Si insert durability.

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