Investigation of Tooling Surfaces on Injection Molded Nanoscale Features

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ABSTRACT

The composition and surface properties of tooling materials become more critical as the size of the molded features decreases [1, 2]. This work investigates the effect of tooling surfaces with micro and nanoscale features. These tooling surfaces were employed as inserts for micro injection molding. Insert materials included etched and coated silicon wafers with pattern depths of 600 nm and minimum features of 200 nm. Electroformed nickel-based digital versatile disk (DVD) masters were employed as a control because this tooling currently can reproduce features that are 140 nm in depth. The micro and nano-featured parts were molded with high flow polycarbonate over a range of processing conditions. Atomic force microscopy (AFM) and root mean square (RMS) roughness were used to characterize the surface topography of molded samples. The goal of this study was to explore the effect of different tooling materials on molded plastic parts with nanoscale features in terms of replication quality and durability of mold surface.

Keywords: nanoinjection molding, nanoscale features

1 INTRODUCTION

In recent years, various kinds of nanotechnology have been developed for replication of nanoscale features, including nano imprint lithography [3, 4]. Few of these approaches, however, are economically viable for manufacturing. Among the many molding techniques, injection molding technology offers the potential to rapidly and economically produce components with nanoscale features. Injection molding can produce complex geometries in a single production step using automated processes [5].

Due to the high heat and pressure developed during injection molding, durable materials, such as steel, aluminum, and beryllium copper alloys, are typically used as mold tooling materials [6]. Conventional machining technologies for these materials are not suitable for nanoscale features. As a result, toolmakers have turned to micromachining techniques, such as UV or X-ray lithography, LIGA, laser ablation, or high precision electro discharge machining (EDM) [7]. Some of these technologies are widely used in the semiconductor industry for fabrication of integrated circuits from silicon wafers. Thus, the use of silicon wafers as a tooling material is an attractive alternative. Shah et al. [8] introduced silicon wafers as a tooling material for injection molding in 1999. Becker and Heim [9] utilized silicon wafers for hot embossing, describing the potential advantages of silicon tooling in terms of hardness, tensile strength, linear thermal expansion coefficient, thermal conductivity, and good mold release characteristics due to the flat surfaces.

When molding at the nanoscale, contamination of the surface becomes a critical issue. Heat transfer may also play a much larger role in terms of replication of the surface features. Heat transfer through the insert and the insert features was one of the main concerns for micro injection molding and thin wall injection molding processes [10]. Brittleness of the silicon wafer is also a potential concern.

The goal of this research was to explore the effect of different tooling materials on molded plastic parts with nanoscale features in terms of replication quality and durability of the mold tooling surface. Molding was carried out in the absence of a clean room to assess the robustness of the process. RMS roughness measurement was used as a way to measure the replication quality.

2 EXPERIMENTAL

2.1 Tooling

Two kinds of mold inserts were used for molding. One was an electroformed nickel-based DVD master, and the other was a micro/nano scale patterned silicon wafer produced by e-beam lithography. The silicon wafer and DVD master were cut into small pieces to fit as an insert (9 mm x 4.6 mm) in a larger mold. The small piece was carefully placed into a vial with various cleaning solutions and cleaned in a Branson ultrasonic sonicator following the procedure shown in Table 1.

Step	Solution	Time	Repeat
1	Detergent (Lysol) (1:3) solution	15 min	1 time
2	Deionized water	15 min	2 times
3	Acetone	15 min	2 times
4	Methanol	15 min	2 times

Table 1. Silicon Wafer Cleaning

The detergent solution (Lysol) was used for removing general dirt and grease from the surface, acetone for non-polar impurities, and methanol for polar impurities, respectively. Most of the cleaning process was done at room temperature. A Teflon sheet was inserted between the insert and mold to protect the insert from the high forces generated during the molding process.

2.2 Compression Molding

Compression molding was conducted to study the feasibility of using a silicon wafer (2.54 cm x 2.54 cm) as a tooling material. A nickel-based electroformed DVD master (2.54 cm x 2.54 cm) was also used for compression molding as a reference material. Polymer pellets were fed into a single screw extruder (C.W. Brabender Instrument Inc., Type 2503) at a melt temperature of 288°C. Optical grade high flow polycarbonate (GE Plastics) was used for the compression molding process to allow better filling of small features due to the low viscosity of PC. After stabilizing the extrusion process, small amounts of the extrudate were collected on the DVD master, placed between two Teflon sheets and then placed in the pre-heated (315°C) compression molding machine (Carver Laboratory, Model: C). A clamping pressure of 6.89 MPa was applied for 5 minutes, the pressure was released, then the DVD master was allowed to cool to ambient temperature. The same procedure was followed for polypropylene (Accpro 9433) on the silicon wafer, but at lower processing temperatures (230°C).

2.3 Injection Molding

A micro injection molding machine (Nissei AU3E) was employed for the molding process. Optical grade high flow polycarbonate (GE Plastics) was used for the molding process after drying in the oven at 120°C. The mold temperature was set at 80°C, and the nozzle, joint, and plunger temperature were set to 315°C. The injection velocity was set from 50 to 100 mm/s, and the shot size was gradually increased to 10.50 mm. Packing pressure was not applied in order to avoid fracture of the silicon wafer. Due to the brittle nature of the silicon wafer, failure of wafer was observed whenever packing pressure was applied. A packing pressure of 50 MPa was applied for the nickel-based DVD master.

2.4 Characterization

A high-precision XE-100 atomic force microscope (AFM) manufactured by PSIA Corp. was used to characterize the tooling and molded surface features. The scan rate was 0.5 Hz and tapping mode was used for the scanning. The RMS roughness was measured by XEI 1.1 of PSIA Corp. The location of measurement was the top surface excluded each pit (pink-colored area). The roughness were measured and analyzed from the same AFM scanned area.

The histogram of each profile shows the distribution of depth of DVD surface.

3 RESULTS AND DISCUSSION

Compression molding trials were performed to assess the overall viability of different tooling materials for injection molding. Figure 1 shows the scanning electron microscope (SEM) image of compression molded polypropylene using the silicon wafer as a tooling surface.

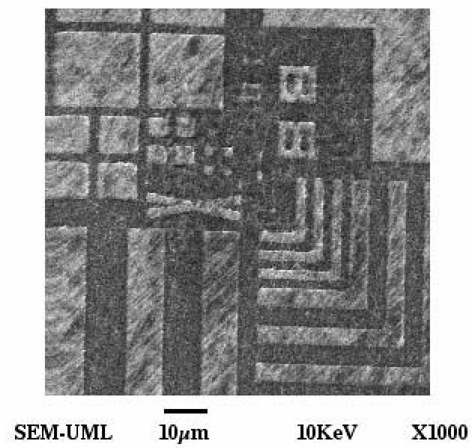

Figure 1. SEM image of molded polypropylene from silicon wafer by compression molding.

Demolding from the silicon wafer was extremely difficult, most likely caused by the high shrinkage of the semi-crystalline polypropylene and adhesion of polymer to impurities on surface, which was not cleaned prior to use. Figure 2 shows the AFM image of molded polycarbonate (PC) from a DVD master by compression molding.

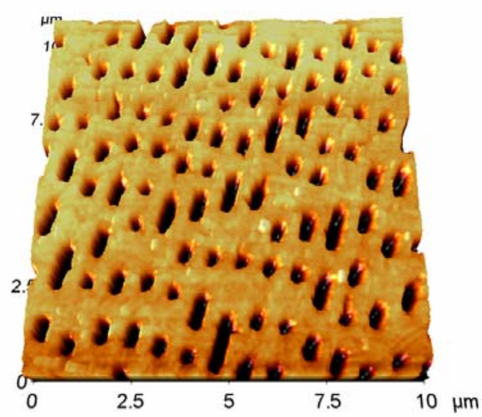

Figure 2. AFM image of molded polycarbonate from nickel-based DVD master by compression molding.

RMS analysis of DVD master measured by XEI 1.1 of PSIA Corp. The flat surface area of the DVD master was measured and used for replication quality. Table 2 shows the rms values of DVD master tooling surface and that of compression molded polycarbonate and injection molded polycarbonate surface. The rms roughness value of the compression molded PC was 12.8 nm, and it was marginally rougher than injection molded PC of 11.1 nm. Injection molding showed better replication quality because of the better thermal control and pressure distribution as compared to compression molding.

Surface	RMS
DVD master	10.7 nm
compression molded PC	12.8 nm
injection molded PC	11.1 nm

Table 2. Root mean square roughness comparison between compression molded PC and injection molded PC

Gallium arsenide (GaAs) wafers were also used as mold inserts for compression molding. These inserts were too fragile and fractured while being placed in the mold. The hardness of silicon wafers (110) measured by nanoindentation techniques is 12 to 14 GPa whereas that of GaAs (001) is only 6.7 to 7.0 GPa [11]. Due to the low fracture toughness, gallium arsenide was not practical for tooling. Based on the compression molding trials both silicon wafers and nickel-based DVD masters were further investigated in the injection molding trials.

Figure 3 shows the AFM three-dimensional topography of the silicon wafer tooling surface used in the injection molding trials.

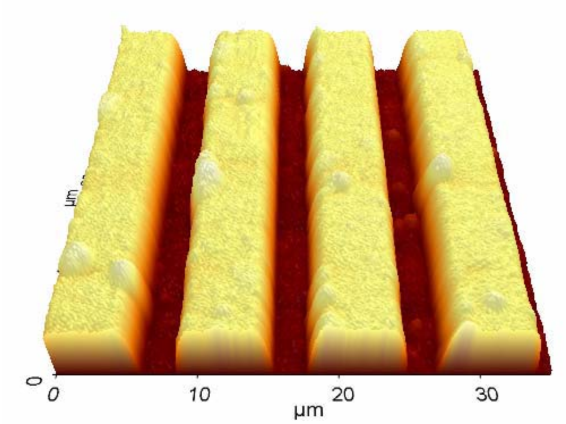

Figure 3. 3D topography of silicon wafer.

Figure 4 presents the polycarbonate surface prepared using the silicon wafer tooling. The well-defined trenches of the molded polycarbonate show that replication of the pattern from the wafer is excellent. The bottom values for the silicon wafer should be compared to the top values for the polycarbonate, as the tooling produces the reverse of the surface features. The data in Table 3 indicate the excellent replication of the tooling surface by the polycarbonate.

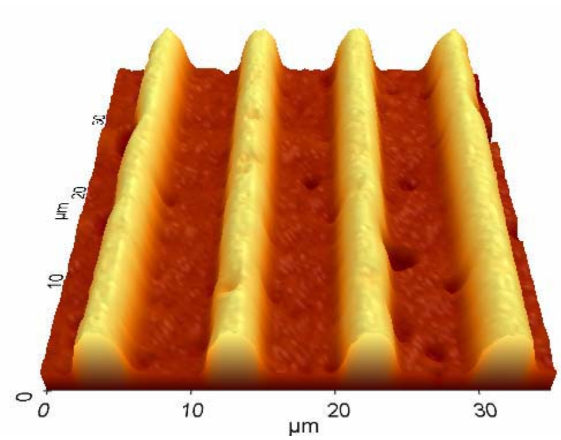

Figure 4. 3D topography of molded polycarbonate from silicon wafer.

	TOP		BOTTOM	
	AVG.	STD	AVG.	STD
Si wafer	25.7	7.2	66.7	9.7
Molded PC	52.4	2	22.4	4.4

Table 3 lists the root mean square roughness (nm) comparison between silicon wafer and molded PC.

Figure 5 shows the three-dimensional topography of the electroformed nickel-based DVD master surface and molded polycarbonate from the DVD master.

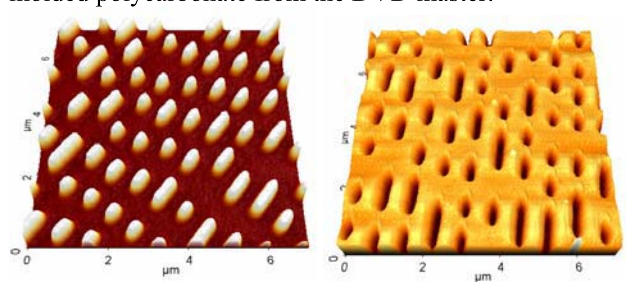

Figure 5. (a) 3D topography of nickel-based DVD master and (b) the molded polycarbonate from the DVD master

As the DVD master tool was a metallic part, 50 MPa of packing pressure could be applied for molding. This packing pressure resulted in excellent replication of the tooling using the DVD master.

The heat transfer problem was not as serious as expected. Since the molded part was neither a thin wall molded part nor micro-injection part in terms of shot size, filling the part was not difficult [10]. High pressure and high injection speed were not required for molding. The thermal conductivity of silicon is 148 W/m-K at 300 K and 90.7 W/m-K for nickel [12]. In both cases, these surfaces produced excellent replication.

Cleaning of the tooling was also not as difficult as anticipated. Once the first cleaning was complete, the collection of dirt on the surface was very low, most likely because of the short time of mold opening during the molding process and the small dimensions of the cavity. The tooling surface seemed to be kept clean by some type of self-cleaning effect. In fact, the surface quality appeared to improve as more parts were made. This may be caused by small particles of dirt being removed by adhering to the polymer melt, rather than remaining on the surface. A more detailed stuffy of this effect will be required.

The silicon wafer showed potential as a possibility for a tooling material under realistic injection molding conditions, however, the brittleness of the silicon wafers may be a limiting factor in the use of silicon wafers as a tooling material. In addition to maintaining low pressure in the cavity, the reduction of micro flaws on wafer surface is critical. Although the wafers used in this research were prepared by manual cutting, machine cutting would reduce the number of flaws significantly.

Wafer cleaning and handling under non-clean room conditions are also difficult problems to solve, but the self-cleaning tendencies could be utilized as a solution. Molding quality could also be enhanced by either better heat transfer from the mold insert to the mold or by a metallic coating on the silicon wafer. The metallic coating would not only enhance heat transfer, but it would also reduce the number of micro flaws on wafer surface. Higher mold temperatures would be also helpful for maintaining the fluidity of the polymer melt to increase the ability to flow around and into nanoscale features during injection molding.

4 CONCLUSIONS

The effect of different tooling materials on molded plastic parts with nanoscale features in terms of replication quality and durability of mold surface were investigated. Compression molding and injection molding were performed with electroformed nickel-based DVD master and silicon wafers as the tooling surfaces. Molding quality of the surface was assessed by AFM image analysis and RMS roughness. Both silicon wafers and DVD masters produced excellent surface replication. The silicon wafers showed potential as an injection mold tooling material. The brittleness of the silicon wafers could be handled by molding without packing pressure.

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REFERENCES

[1] M. T. Martyn, B. Whiteside, P. D. Coates, P. S. Allan, G. Greenway, and P. Hornsby, SPE Technical Papers, 61, 2582, 2003.
[2] M. T. Martyn, B. Whiteside, P.D. Coates, P.S. Allan, G. Greenway, and P. Hornsby, SPE Technical Papers, 60, 480, 2002.
[3] H. C. Scheer, H. Schultz, T. Hoffmann, and C. M. Sotomayor Torres, Nanoimprint Techniques, in: H.S. Nalwa (ed.), The Handbook of Thin Films, Academic Press, New York, NY, 2001.
[4] Y. Chou, P.R. Krauss, P. J. Renstrom, Appl. Phys. Lett. 67, 3114, 1995.
[5] G. Potsch and W. Michaeli, “Injection Molding - An Introduction”, Hanser/Gardner Publications, Cincinnati. OH, 1, 1995.
[6] R. A. Malloy, Plastics Part Design for Injection Molding, Hanser/Gardner Publications, Cincinnati. OH, 312, 1994.
[7] W. Lutz and E. Wolfgang, SPE Technical Papers, 56, 930, 1998.
[8] J. Shah; Y. Su, and L. Lin, Micro-Electro-Mechanical Systems, 1, 235, 1999.
[9] H. Becker and U. Heim, IEEE international Conference on Micro Electro Mechanical Systems, p229, 1999.
[10] Y. K. Shen and W. Y. Wu, International Communications in Heat and Mass Transfer, 29 (3), 423-31, 2002.
[11] S. E. Grillo, M. Ducarroir, M. Nadal, E. Tournie, and J-P. Faurie, J. Phys. D: Appl. Phys., 3, L6, 2003.
[12] G. N. Ellison, “Thermal Computations for Electronic Equipment,” Van Nostrand Reinhold, New York, NY, 3, 1984.