Tooling for Injection Molded Micro and Nanoscale Features

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Center for High-Rate Nanomanufacturing
University of Massachusetts Lowell
Devices Containing Small Features

Micro and nanofluidic devices

## Possible Manufacturing Technologies

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<tr>
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<th>Hot Embossing</th>
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Injection molding can provide high-rate manufacturing of a wide range of materials.
Approach: Injection Molding

injection molding machine

mold

molded part
Quantifying Replication

- Feature definition
- Depth ratio

\[ DR = \frac{D_{\text{part}}}{D_{\text{tool}}} \]
Inj. Molding: It’s All About the Tooling

Factors
1. Gate location
2. Vacuum venting
3. Tooling features
4. Tooling materials
5. Gas assisted injection molding
1. Impact of Gate Location

Parallel flow

Impingement flow

H ~ 1000 nm

H ~ 400 nm

2. Effect of Vacuum Venting

Channels without vacuum

Channels with vacuum

Better corner replication with vacuum venting

Yoon et al., *International Polymer Processing*, accepted (2009)
3. Tooling Features

<table>
<thead>
<tr>
<th>Thermoplastic Elastomer</th>
<th>Positive DR</th>
<th>Negative DR</th>
<th>Poorer replication with negative features</th>
</tr>
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<tbody>
<tr>
<td>COPE</td>
<td>1.03</td>
<td>0.60</td>
<td></td>
</tr>
<tr>
<td>TPU-45</td>
<td>0.87</td>
<td>0.67</td>
<td></td>
</tr>
<tr>
<td>TPU-39</td>
<td>0.75</td>
<td>0.68</td>
<td></td>
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Effect of Feature Size

Smaller features are more difficult to replicate

# 4. Materials for Tooling Inserts

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<tr>
<th>Method</th>
<th>Resolution</th>
<th>Aspect Ratio</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>CNC machining</td>
<td>100 μm</td>
<td>N/A</td>
<td>steel</td>
</tr>
<tr>
<td>Micro milling</td>
<td>50 - 100 μm</td>
<td>N/A</td>
<td>steel</td>
</tr>
<tr>
<td>Micro wire EDM</td>
<td>1 - 50 μm</td>
<td>~2.5</td>
<td>nickel alloys</td>
</tr>
<tr>
<td>Electroforming</td>
<td>~20 nm</td>
<td>~2.5</td>
<td>nickel alloys</td>
</tr>
<tr>
<td>Lithography - UV</td>
<td>157 nm</td>
<td>typically low, but up to 30(^1)</td>
<td>silicon, glass</td>
</tr>
<tr>
<td>Lithography - EUV</td>
<td>13 nm</td>
<td></td>
<td>silicon, glass</td>
</tr>
<tr>
<td>Lithography - E-beam</td>
<td>&lt; 10 nm</td>
<td></td>
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\(^1\) RIE inductive coupled plasma source (http://www.oxfordplasma.de/process/sibo_ha.htm)

Created hybrid tooling for better feature replication
Molding with Nickel Tooling

- CD/DVD molding
  - Incomplete replication
  - Max. DR ~ 0.80 (PC)

- Molding with DVD tooling
  - Material-dependent replication

<table>
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<tr>
<th>Polymer</th>
<th>$R_g$, nm</th>
<th>DR</th>
</tr>
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<tr>
<td>PMMA</td>
<td>3.9</td>
<td>0.91</td>
</tr>
<tr>
<td>PC</td>
<td>6.5</td>
<td>0.80</td>
</tr>
<tr>
<td>PS</td>
<td>14</td>
<td>0.60</td>
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Factors Affecting Replication

- Replication of feature depth (i.e., DR) depends on material viscosity
- Replication of channel bottom depends on solidification time
- Replication of lands depends on achieving DR = 100%

Molding with Silicon Wafers

PTFE prevented fracture of fragile tooling inserts → 3000 molding cycles

Effect of Backing Material

PTFE backing

Solidification time: 14 s

PTFE retarded heat transfer from silicon insert to steel mold

Cu backing

Solidification time: < 1 s

Molding with Hybrid Tooling
Fabrication of Hybrid Tooling

1. Lithography and etching
2. Imprint
3. Metal coating

Feature Definition with Hybrid Tooling

Depth Ratio with Hybrid Tooling

Hybrid tooling enhanced replication, but deformed during molding

New Polymer Layers

- **Candidate polymers**
  - Polyetherimide ($T_g$: 216°C)
  - Polyimide ($T_g$: 350°C)
  - Thermosets (Epoxy)

- **Performance of polymer layers**

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<td>500</td>
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<td>°C</td>
<td>151</td>
<td>369</td>
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PI-1 was better than PI-2 in transferring pattern
Parts Molded from PI Hybrid Tooling

- Molded parts’ surfaces were not damaged
- No loss in feature definition over 1000 cycles

PI-based tooling provided consistent DRs for 1000 molding cycles

Temperature at the Tooling Surface

Slower cooling enhanced replication

Effect of Molding on Hybrid Tooling

Tooling surface was not deformed, but showed defects

Analysis of Tooling Surface

Before molding

After 1000 PS molding

After 1000 PC molding

SEM

C

Al
Polymer Only Tooling?

with PI-Al hybrid tooling (after 1,000 cycles)

with PI “hybrid” tooling (after 100 cycles)

Tooling without metal coating produced scaly surfaces
Comparison of Tooling Materials

![Graph showing comparison of tooling materials with depth ratio on the y-axis and tooling aspect ratio on the x-axis. Various data points are plotted representing different materials such as Si-PC Injection, Si-PC Compression, Si Holes-TPU990, Si Lines-TPU990, Si FOTS Lines-TPU990, Hybrid(Al-PC)-PS, Hybrid(Ti-PC)-PS, and Si FOTS Lines-PS.](image-url)
5. Effect of Gas Assisted Injection Molding

GAIM improved depth ratio

Yoon et al., *Plastics, Rubber and Composites: Macromolecular Engineering*, accepted (2010)
Effect of Gas Assisted Inj. Molding

GAIM eliminated sink marks in polypropylene parts

Yoon et al., *Plastics, Rubber and Composites: Macromolecular Engineering*, accepted (2010)
Conclusions

- Gate location – often produces hesitation
- Vacuum venting – improves feature definition
- Tooling features
  - Positive features provide better replication than negative features
  - Smaller features are more difficult to replicate
- Tooling materials
  - Retarding heat transfer enhances replication
- Gas assisted injection molding
  - Improves replication, particularly with semi-crystalline polymers
Path Forward

- Effects of feature angles, radii, and size
- Impact of surface roughness
  - Silicon, steel
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