Roll-to-Roll Hot Embossing of Microstructured Polymer Sheet
Use of Microstructured Surfaces

- BioMEMS and biosensors
- Microfluidic devices
- Micro total analysis systems (m-TAs)
- Micro-optics
- Superhydrophobic surfaces

Microlens array

Microfluidic device
Hot Embossing Process

Four steps
1. Heating
2. Embossing
3. Cooling
4. Demolding

- Stress concentration and strain hardening of substrate
- Stress relaxation and deformation recovery

https://www.memsnet.org/images/about_mems/hot_embossing_process.png
Hot Embossing Methods

Plate-to-plate (P2P)  Roll-to-plate (R2P)  Roll-to-roll (R2R)

Critical Parameters

- Glass transition temperature of substrate
- Embossing temperature
- Embossing force
- Holding time
This Work

- Investigate roll-to-roll hot embossing of amorphous polyamide sheet for superhydrophobic surfaces
- Characterization of sheet
- Development of flexible tooling
- Optimization of processing parameters

Extruded Polyamide Sheet

D = diameter
H = height
P = pitch
1. Thermal Properties of Substrate

- T_g = 128°C
- T_c = 200°C
- T_m = 245°C

“Amorphous” polyamide
“Viscosity” of Polymer Substrate
Roughness of Polymer Substrate

Extruded 0.300-mm-thick polyamide sheet
• Low melt strength
• Required high chill roll temperatures (~150°C)

<table>
<thead>
<tr>
<th>Sheet</th>
<th>$R_a$ (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PET (commercial)</td>
<td>16.7</td>
</tr>
<tr>
<td>LDPE</td>
<td>4.6</td>
</tr>
<tr>
<td>Polyamide</td>
<td>35.9</td>
</tr>
</tbody>
</table>
2. Flexible Tooling

Polyimide tooling

Electroformed nickel tooling
3. Preheating Substrate

Preheating of substrate
• Preheating substrates with infrared radiation
  • Moderate temperature provided better replication
  • More difficult to control of localized sheet temperature
• Preheating substrate by contact with microstructured tooling
  • Better replication
  • Easier to control localized sheet temperature
  • Time to reach embossing temperature ~ 5 s
Tool Temperature

<table>
<thead>
<tr>
<th>Tool Temperature</th>
<th>Complex Viscosity (MPa-s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>157°C</td>
<td>10.7</td>
</tr>
<tr>
<td>166°C</td>
<td>11.3</td>
</tr>
<tr>
<td>177°C</td>
<td>13.6</td>
</tr>
<tr>
<td>191°C</td>
<td>13.3</td>
</tr>
<tr>
<td>199°C</td>
<td>11.9</td>
</tr>
<tr>
<td>213°C</td>
<td>10.7</td>
</tr>
</tbody>
</table>

H ~ 15 μm

Graph showing the relationship between tool temperature and complex viscosity.
Temperature of Rubber Roll

Unheated rubber roll
• Poor replication
  • Due to excessive heat transfer

Heated rubber roll
• Temperature depended on tooling substrate
  • $T = 140^\circ C$ for polyimide tooling

![Unheated roll](image1)
![T = 90°C](image2)
![T = 140°C](image3)
Embossing Pressure

Higher embossing pressures
- Improved feature replication
- Too-high pressures prevented rotation of rolls

\[ P = 209 \text{ kPa} \]
\[ P = 552 \text{ kPa} \]
Embossing Time

Wrapping sheet around embossing roll
• Greater contact with roll
• Result
  • Improved feature replication
  • Eliminated stretching of features
  • Minimized stretch lines in substrate

w/o wrapping w wrapping
Embossing Time

Increased embossing time
- Increased pillar height

<table>
<thead>
<tr>
<th>t (s)</th>
<th>H (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>5.3</td>
</tr>
<tr>
<td>40</td>
<td>6.9</td>
</tr>
<tr>
<td>60</td>
<td>12.0</td>
</tr>
<tr>
<td>120</td>
<td>15.5*</td>
</tr>
</tbody>
</table>

- Eliminated rounding of pillar tops

Nickel tooling; $T_{\text{tool}} = 193^\circ\text{C}$; $T_{\text{rubber}} = 104^\circ\text{C}$
Effect of Geometry on Embossing Time

Without optimized pressure
- Optimum embossing time increased for features with
  - Higher aspect ratios
  - Less surface area

Nickel tooling; $W = 10 \, \mu m; \ H = 10 \, \mu m$
Optimized Embossing Pressure and Time

<table>
<thead>
<tr>
<th>$P_{nip}$ (MPa)</th>
<th>$t$ (s)</th>
<th>$H$ (mm)</th>
<th>$\theta$ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.3</td>
<td>5</td>
<td>15.5</td>
<td>148</td>
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<tr>
<td></td>
<td>10</td>
<td>15.5</td>
<td>155</td>
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<tr>
<td></td>
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<td></td>
<td>15</td>
<td>15.5</td>
<td>150</td>
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</tbody>
</table>
Conclusions

• Process developed for high-rate, roll-to-roll hot embossing of microscale features into amorphous polyamide sheet
• Critical parameters remained substrate (tooling) temperature, embossing pressure, and contact time
• Process correlated with thermal, mechanical, and rheological properties of sheet
• For better greater understanding of roll-to-roll embossing process