Novel Additive Manufacturing of Tooling with Micro and Nanostructured Surfaces

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Abstract
Tooling with micro and nanostructured surfaces is employed for high-rate fabrication of products using injection molding, hot embossing, and related processes. Current subtractive (machining, lithography) and additive (prototyping) methods for manufacturing tooling are expensive and have significant limitations. So, a new technique was investigated for the rapid fabrication of tooling inserts with microfeatures. Green steel microscale patterns were printed onto steel substrates as a single layer using a 2D dispensing system and then sintered to produce the tooling. The resultant feature dimensions were measured using contact profilometry. For this method, the paste formulation (binder, particle size and loading, and solvent) and printing conditions (e.g., speed and pressure) were evaluated for their effects on feature dimensions, uniformity and smoothness. These results were correlated with paste viscosity. Moreover, this novel survived 5000 injection molding cycles without damage to the features.

Introduction
Biosensors, biochips, flexible electronics, and micro-fluidic devices have been miniaturized to the micro and nanoscale. In microfluidic devices, 10 to 100-μm-wide channels [1] are used to manipulate small amounts (10⁻⁹ to 10⁻¹⁸ liters) of fluid [2] and can be utilized for early detection and identification of pathogens and toxins [1]. The current market for microfluidic devices is $1.4 billion and is expected to grow to $5.2 billion by 2018 [3].

With the growing demand, microfluidic devices are increasingly manufactured using injection molding, hot embossing, and other high-rate processes [1]. Tooling for these processes, however, is relatively expensive. Currently, this tooling is produced by micromachining, lithographic, and additive manufacturing techniques. Micromachining is capable of fabricated features of 34 μm and greater [4], but issues include tool wear and surface deformation [5]; difficulty in machining the projections required for microchannels; and long fabrication times - e.g., 10.2 hours for a 144 μm channel [6]. In contrast, lithography can produce nano and microfeatures, depending on the substrate and exposure process [7]; the minimum feature size for lithography with metals is 0.02 μm [4]. Patterned substrates with nanoscale features can be used as masters for electroformed nickel tooling. Lithographic processes have difficulties with appropriate drafts; are very expensive [8]; and are time consuming.

More recently, additive manufacturing techniques have been used to create parts and tooling with microfeatures. These “prototyping techniques have the potential to produce microtools at a faster pace than machining and lithographic techniques. In selective layer sintering (SLS) and Stereolithography (SLA), the features are built as successive layers of material. SLA uses laser curing of photosensitive resins which are typically brittle and can shrink and deform during processing. SLS’s laser sintering of steel, copper, and bronze powder is slower with heating of the powder requiring 2 hours and parts cooling time taking 5 to 10 hours. It also is difficult to achieve good surface finishes with SLS. The layer thickness of SLS is approximately 0.08 mm [9]. The lead time depends on the geometry and size of the tool, but the lead time for a 200 mm x 250 mm x 125 mm tool is 2-3 days when using SLS. Ink jet processes have been used for making prototype tooling, but its lack of material strength resulted in limited part replication of 15 to 30 parts [10].

New Approach for Tooling Fabrication
This research investigated a new additive manufacturing approach for the creation of tooling with microstructured surfaces. The new tooling is fabricated using dispensing equipment designed for solder pastes, solder masks, and under fills in circuit boards. This equipment lays down one layer of solder or paste into a pattern on a planar substrate; the pattern is described in a CAD file. Fabrication of the new microstructured tooling requires two steps: printing and sintering. The microfeature design is created when a viscous paste containing a high loading of metal particles is printed (deposited) onto a substrate. In the sintering step, the binder is removed and the metal particles are fused together to create solid microfeatures and promote adhesion of these features to the substrate.

This approach shows potential for decreasing the cost and time of fabricating microfeature tooling and it eliminates the step (layer) effect present in other additive processes. The major challenge is fabricating this new tooling was printing of uniform microfeatures. This research examined the effects of the materials, printing parameters, and pumping system on the dimension of the printed (green) microfeatures and durability of the tooling during injection molding.

Experimental Approach
A series of experimental runs were done using DispenseMATEDS585 (Manufacturer: Nordson, Model). The dispensing system mainly consists of a pneumatic base system, XYZ worktable, 3-axis control system, camera, and FmXP software. A substrate was clamped onto the equipment’s worktable and the pneumatic system applies pressure to force materials from the system. A camera is attached to the equipment for straight on view of the work piece. The FmXP
Materials

Pastes 1-3 was created from preformulated steel powder which contained carboxymethyl cellulose binder and surfactant (Metal Clay Suppliers, Model: Quickfire Pearl Grey SteelXT) and di-ionized water. The viscosities of the formulations at room temperature were measured using a parallel plate rheometer. Table 1 lists the paste formulations with their power contents [powder], water contents [water], mixing times \( t_{\text{mix}} \), and the viscosities \( \eta \) at a representative shear rate of 3 s\(^{-1}\). Paste 4 was custom blend formulation with two stainless steel powders, a combination of guar gum, sodium carboxymethyl cellulose, and xanthan gum as a binder, a polyvinylpyrrolidone surfactant, and olive oil lubricant.

The substrate was 2-mm-thick cold rolled steel plate (ACP Waterjet). This steel plate was water jet cut into 14 mm by 14 mm pieces that would fit into an existing injection mold.

<table>
<thead>
<tr>
<th>Paste</th>
<th>[Powder] (g)</th>
<th>[Water] (ml)</th>
<th>( t_{\text{mix}} ) (min)</th>
<th>( \dot{\gamma} ) (s(^{-1}))</th>
<th>( \eta ) (Pa-s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6</td>
<td>6</td>
<td>6.5</td>
<td>3</td>
<td>90</td>
</tr>
<tr>
<td>2</td>
<td>6</td>
<td>5</td>
<td>6.5</td>
<td>3</td>
<td>222</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>4</td>
<td>6.5</td>
<td>3</td>
<td>601</td>
</tr>
</tbody>
</table>

Table 1: Critical Data for Pastes

Printing of Pastes

For most printing trials, an S-shaped pattern programmed using the FMXP software was printed using the dispensing system and pneumatic pump. The first trials focused on the three pastes shown in Table 1. The effects of printing parameters - flow rate, printing speed, tip-to-substrate gap, and tip diameter - on feature dimensions were examined in the second trials (Table 2). The third trials investigated the effects of the auger "pump" and custom paste formulation.

<table>
<thead>
<tr>
<th>Trial</th>
<th>( \eta ) (Pa-s)</th>
<th>Flow Rate (mg/s)</th>
<th>Speed (mm/s)</th>
<th>Dia. (( \mu )m)</th>
<th>Gap (( \mu )m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1</td>
<td>222</td>
<td>6, 16, 32</td>
<td>3</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>1-2</td>
<td>601</td>
<td>6, 16, 22, 38</td>
<td>3</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>2-1</td>
<td>222</td>
<td>15.6</td>
<td>5, 10, 12</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>2-2</td>
<td>601</td>
<td>2.0</td>
<td>0.5, 1.0, 1.5</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>3-1</td>
<td>222</td>
<td>15.6</td>
<td>3</td>
<td>200</td>
<td>200-600</td>
</tr>
<tr>
<td>3-2</td>
<td>601</td>
<td>2.0</td>
<td>0.5</td>
<td>200</td>
<td>200-600</td>
</tr>
<tr>
<td>4-1</td>
<td>601</td>
<td>--</td>
<td>1</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>4-2</td>
<td>601</td>
<td>--</td>
<td>2</td>
<td>150</td>
<td>150</td>
</tr>
</tbody>
</table>

Table 2: Printing Parameters

The green tooling was sintered in oven. The first heating step (572°C for 30 min) removes the binder. After the tooling was cooled to room temperature, a second heating step of 976°C for 120 min produced fusion of the particles. Activated charcoal (placed in the oven) prevented oxidation of the steel.

Injection Molding

Tooling durability was evaluated using injection molding. Injection molding was performed using a three-ton microinjection molding machine with a two-stage injection unit (Nissei, Model: AU3E), an existing insert mold, and polystyrene resin. For initial durability testing, the tooling inserts were used to produce 1 to 100 parts. The parts were examined for the presence of metal ion the polystyrene surface and the presence of tooling features was examined after the molding trial. In a longer trial, the tooling continuous produced 5000 parts. Feature height in the tooling and parts was measured every 100 cycles for the first 1000 cycles and every 1000 cycles thereafter.

Characterization

Parts and tooling were characterized using a contact profilometer (Dektak, model: Veeco 500) and optical microscope (Zeiss). Microscopy provided an overview of the surface, whereas contact profilometry measured profile of the printed features or associated parts. These measurements provided the height and width of the printed and molded features. Scanning electron microscopy (SEM) was used to examine the surfaces of the printed features.

Results and Discussion

Figure 1 presents the effect of material viscosity on the definition of the printed green features. With a constant pressure of 34 kPa, constant tip gap of 200 \( \mu \)m, tip diameter of 200 \( \mu \)m, and printing speed of 5 mm/s, increasing the viscosity from 90 Pa-s to 601 Pa-s caused a decrease in line width (Figures 1a-1c). As the viscosity increased, the corners of the patterns also became thinner and similar in line width with the rest of the pattern. The printed pattern, however, was not consistent when the viscosity was 601 Pa-s (Figure 1c). Using a greater pressure (103 kPa) and faster printing speed (15 mm/s), the lower viscosity materials exhibited extensive spreading in the corners, which resulted in merging of feature lines (Figures 1d and 1e). Overall, the lower viscosity pastes could not hold the printed shapes and the 601-Pa-s paste provide the best performance.

![Figure 1](image-url)
Figure 2 shows the effects of flow rate from the pneumatic pump on the line width in the green stage; the printing speed, tip diameter, and tip gap were held constant at 3 mm/s, 200 μm, and 200 μm, respectively. At the lowest flow rate, the line width was 501 μm when the nominal viscosity was 222 Pa-s and 427 mm for a nominal viscosity of 601 Pa-s. Both line widths were greater than the tip diameter of 200 μm. Higher flow rates caused a linear increase in line width. The rates of increase in line width were 62.5 μm/s/mg and 25.7 μm/s/mg for pastes with nominal viscosities of 222 and 601 Pa-s, respectively. The actual line height also varied from the expected height of 200 μm, which was equivalent to the tip gap. At the lowest flow rate, the line heights were 48μm and 50μm for paste viscosities of 222 and 601 Pa-s, respectively. Line height also increased with increasing flow rate. The rates of increase in line height were 0.46 μm/s/mg and 1.49 μm/s/mg for pastes with nominal viscosities of 222 and 601 Pa-s, respectively. The changes in line height and width compared to the gap and tip diameter were due to flow of the pastes immediately after printing.

![Graph]

Figure 2. The effect of flow rate on the line width and line height of pastes with viscosities of 222 and 601 Pa-s.

In contrast, line height remained constant, whereas as line width decreased with increasing printing speed (Figure 3). For the printing speeds measured, the rate of decrease in line width was 224 μm/s/mg for the 601-Pa-s paste and 45 μm/s/mg for the 222-Pa-s paste. With the 601-Pa-s paste, the line height was about half to the tip gap of 200 μm, but the line height was approximately 50 μm for the lower viscosity paste. The line width at the slowest printing speed was 3-4 times the tip diameter of 200 μm. Faster printing speeds deposited the same amount of paste over a larger area. Although the initial dimensions probably matched the tip diameter and tip gap, flow of the paste after deposition produced similar reductions in line height, but greater decreases in line width.

As shown in Figure 4, the line width and height of the 601-Pa-s paste did not change with increasing tip gap. The line width was three times the tip diameter and the line height was about 100 μm. Similar results were observed for the lower viscosity paste. These results suggest that the flow rate and printing speed controlled the feature (line) dimensions. In contrast, changes in tip diameter produced significant changes in process parameters.

![Graph]

Figure 3. The effect of printing speed on the line width and line height of pastes with viscosities of 222 and 601 Pa-s. The respective flow rates were 15.6 and 2.0 mg/s.

![Graph]

Figure 4. The effect of tip gap on the line width and line height of the 601-Pa-s paste.

Table 3 presents the changes in processing conditions required to produce features with line widths of about 425 μm from a 200-μm-diameter straight (clear) tip and a 150-μm-diameter chamfered tip. The smaller tips required higher pressure, lower printing speeds, and smaller tip gaps. The changes in processing conditions were attributed to changes in paste viscosity and are still under investigation. The minimum line width achievable using the 200 and 150-μm tips were 351 and 324 μm, respectively.

<table>
<thead>
<tr>
<th>Tip (μm)</th>
<th>Width (μm)</th>
<th>Pressure (kPa)</th>
<th>Speed (mm/s)</th>
<th>Gap (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 clear</td>
<td>421</td>
<td>103</td>
<td>1</td>
<td>200</td>
</tr>
<tr>
<td>150 chamfer</td>
<td>430</td>
<td>448</td>
<td>2</td>
<td>150</td>
</tr>
</tbody>
</table>

Table 3: Effect of Tip Diameter on Printing Conditions
Upon drying (prior to sintering), all features showed did not exhibit a domed profile, but rather showed a depression in the center of the feature. This depression is illustrated in Figure 5a and could be measured using contact profilometry. There were often holes in the dried green tooling. Sintering the tooling did not eliminate the depressions or holes. Possible explanations for this height non-uniformity were the spreading that occurred after printing, the particle weight, and the particle size distribution in the paste. Spreading of the paste created a increase in line width and decrease in line height, however, the movement of the material was probably not consistent across the width of the line. Slower drying at the center of the line may have permitted sinking of the heavy steel particles to the substrate, whereas faster drying at the edges prevent major particle movement. Variations in particle size would have affected particle packing and particle movement. The porosity of the green features are shown in Figure 5b. Although the higher viscosity paste (601 Pa-s) exhibited fewer depressions and holes than the lower viscosity pastes, these defects could not be eliminated by changes in printing conditions.

![Figure 5. SEM images of (a) green lines showing a depression and (b) steel particles and binder in the green lines.](image)

Printing the modified commercial paste (viscosity: 601 Pa-s) using the auger "pump" did not eliminate the depressions in the green features. As shown in Figure 6a, the custom paste printed with pneumatic pump did exhibit lines with uniform width and height, but these lines had no apparent depressions. Printing the custom paste with the auger "pump", however, produced lines with no depressions (Figure 6b). This improvement was attributed to the bimodal particle size distribution (5 and 45 μm) and the stiffer binder in the custom paste.

![Figure 6. The custom paste printed using the (a) pneumatic and (b) auger pumps.](image)

The tooling was tested for endurance using injection molding. After 5000 molding cycles, there were no signs of feature wear and deformation (Figure 7). There was a 100% replication as the part depth and the tooling height was the same at approximately 140 μm. Parts (not shown) also exhibited good feature definition.

![Figure 7. Feature height in tooling at after molding.](image)

**Conclusions**

Novel metal tooling with microstructured surfaces was successfully fabricated using an additive manufacturing process. Feature (line) dimensions and quality were controlled by the paste composition and viscosity, pumping system, and printing parameters, specifically the flow rate and printing speed. This tooling was unchanged after 5000 injection molding cycles, and so, has great potential as microstructured tooling for high-rate production of microfluidic devices.

**Acknowledgements**

This work was funded by the National Science Foundation (EEC-0832785). The authors also thank Nissei America, Inc.

**References**