Rapid Printed Tooling for High-rate Production of Microstructured Surfaces

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ABSTRACT

Low cost production of microfluidic devices through injection molding, nanoimprint lithography or hot embossing requires fast and low cost production of tooling. Printing and sintering metal pastes was investigated as a novel approach for the rapid fabrication of metal tooling with microstructured surfaces. Paste composition and printing conditions were evaluated as controls for the size and quality of the surface features. Tooling has been produced from several metals and current work is focused on creating submicron-sized features. Then tooling performance and durability was assessed using injection molding, the steel microfeatures were undamaged after more than 5000 cycles.

Keywords: metal printing, tooling, microinjection molding, microchannels

1 INTRODUCTION

Devices with micro and nanostructured surfaces offer advantages such as small reagent volumes and shorter reaction times for applications in the medical industry and smaller and more effective devices in the electronics industry. Some applications in the medical industry include microneedles and microfluidic channels used for molecular analysis and identification of pathogens and toxins. Applications in the electronics industry include microelectronics and optoelectronics. The market for microfluidic devices is expected to grow to $5.2 billion by 2018 [1]. The high demand for these devices requires high volume and low cost manufacturing. Leading processes for the production of these devices are hot embossing, injection molding and injection compression molding. These processes, however, require development of tooling.

The metal tooling preferred for injection molding of microfluidic devices can be produced using subtractive and additive manufacturing methods. In subtractive methods excess material is removed from the starting "block" of material until the desired geometries are obtained. Common subtractive techniques used to manufacture tooling are micromachining and lithography. In contrast, additive manufacturing techniques fuse layers of material to build the required shape. Some additive techniques include stereolithography, selective laser sintering, fused deposition and selective layer melting. The features sizes and limitations for these techniques are summarized in Table 1.

Subtractive Manufacturing	
Micromachining [2-5]	- Size: 5 µm or greater - Difficulty machining projections - Tool wear affects accuracy - Surface deformation as material layer exposed to heat - Grain size of metal affects smaller surfaces
Lithography [6-8]	- Size: 0.2 to 0.5 µm - Difficult to form drafts - Undercutting - Surface deformation - Limited available materials
Additive Manufacturing	
Stereolithography [9-10]	- Size: 20 µm or greater - Rough Surface - Photosensitive resins (limited materials and material degradation)
Selective Laser Sintering [10-11]	- Size: 20 µm or greater - Metal powder porosity issues - Slow heating/cooling of metal powder - Surface deformation due to uncontrolled thermal effects
Fused Deposition [12]	- Size: 50 µm - Limited feed stock shape - Limited resolution - Need precise temperature control
Selective Layer Melting - Few studies available [12]	

Table 1. Tooling manufacturing techniques.

In general, subtractive manufacturing techniques are limited by the inability to produce complex

TechConnect Briefs 2015, TechConnect.org, ISBN 978-1-4987-4730-1

geometries while current additive manufacturing For the custom paste the effect of binder was studied with a tip diameter and gap of 330 µm and a printing speed of 1.75 mm/s.

techniques lack resolution [13].

This project investigates a novel additive manufacturing process for the fast and low cost production of metal tooling consisting of micro and submicron features. The features are printed with a metal paste in a single run, thus eliminating the layer or step effect (resolution problems) present in existing additive manufacturing techniques.

2 EXPERIMENTAL

Metal pastes with different viscosities were printed in a steel substrate and then sintered. The sintered tooling was then tested for endurance in injection molding. The following sections provide details on the materials and each step of the process.

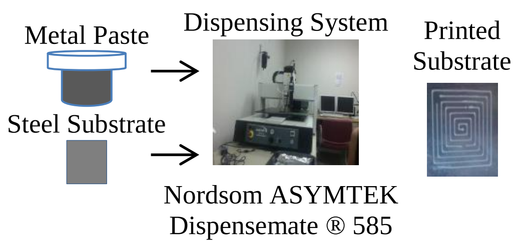

Figure 1. Process description.

2.1 Description of Materials

Metal pastes consisted of a commercial steel powder containing carboxymethyl cellulose binder and surfactant (Quickfire Pearl Grey Steel XT from Metal Clay Suppliers). This powder was mixed for 6.5 minutes with de-ionized water as described in Table 2 in a Speed Mixer (FlackTek Speedmixer® DAC 150 FVZ from Hauschield Engineering).

Formula	[Powder] (g)	[Water] (ml)	η (Pa-s)
1	6	6	90
2	6	5	222
3	6	4	601

Table 2. Metal pastes formulations.

The viscosity (η) of these formulations was measured with a parallel plate rheometer (Ares RD3 from TA Instruments) at room temperature. The viscosity at a shear rate of 3 s^{-1} is presented in Table 2 for the different formulations and is used to describe each formulation. This shear rate (3 s^{-1}) is considered representative of the printing system.

The second part of this work consisted on a custom formulation including a stainless steel powder metal with an average particle size of 3 µm (ANSI 316L type stainless steel powder from Goodfellow Corporation). Binders added to the metals are guar gum (GG) (average Mw~220,000 g/mol), sodium carboxymethyl cellulose (SC) (average Mw~90,000 g/mol), and xanthan gum (XG) (average Mw~l million g/mol) (Sigma-Aldrich Company). Polyvinylpyrrolidone (Mw~40,000 g/mol) (PVP) (Sigma-Aldrich Company) was chosen as a dispersing agent and natural olive oil (Goya Foods Inc.) as a lubricant. The formulations used are described in Table 3. Substrates were 2-mm-thick cold rolled spring steel (ACP Water Jet).

Recipe	1	2	3	4	5	6	7	8	9	10
Metal	95									
PVP	1.75									
Oil	0.25									
GG	3	-	-	2	2	1	-	1	-	1
SC	-	3	-	1	-	2	2	-	1	1
XG	-	-	3	-	1	-	1	2	2	1

Table 3. Formulations for study of binder in a custom paste.

2.2 Printing Procedure

Printing was performed using a Nordson ASYMTEK Dispensemate ® 585 coupled with FMXP software. First, the pattern was designed in the FMXP software and then parameters such as flow rate, printing speed and tip gap were varied. For the commercial paste the effect of printing speed (PS) and viscosity were studied with the parameters presented in Table 4. The tip diameter and the gap between the tip and substrate were kept constant at 200 µm for these trials. Then, the effect of flow rate (Q) was studied as presented in Table 5, with a constant PS of 3 mm/s, and a tip diameter and tip gap of 200 µm. Next, the effect of tip gap was studied with a tip diameter of 200 µm (Table 6).

For the custom paste the effect of binder was studied with a tip diameter and gap of 330 µm and a printing speed of 1.75 mm/s.

Trial	1	2	3	4	5	6
η (Pa-s)	90	90	222	222	601	601
PS (mm/s)	3	15	3	15	3	15

Table 4. Printing conditions for investigating the effect of viscosity of the commercial paste.

Trial	7-9	10-14
η (Pa-s)	222	601
Q (mg/s)	0.94, 2.6, 6.5	0.2, 0.9, 2.0, 2.7, 4.9

Table 5. Printing conditions for investigating the effect of flow rate of the commercial paste.

Trial	15-19	20-23
η (Pa-s)	601	601
PS (mm/s)	0.5	3
Q (mg/s)	0.9	2.7
TG (µm)	250, 300, 400, 500	300, 400, 500, 600

Table 6. Printing conditions for investigating the effect of tip gap with the commercial paste.

After printing the green tooling was heated for debinding and sintering. The debinding step removed the binder while the sintering step fused the particles together and provided adhesion of the metal particles to the substrate. The optimum debinding and sintering conditions are summarized in Table 7.

Step	Temperature (°C)	Time (min)
Debinding	572	30
Cooling	Room Temperature	Varied
Sintering	976	120

Table 7. Post-printing processes.

2.3 Injection Molding

The tooling was tested for endurance by molding using a three-ton microinjection molding machine (Nissei, type: AU3E) with a two stage injection unit. The tooling produced are inserted in the B-plate of the mold using a steel cartridge to hold it in place and a PTFE sheet was placed next to the tooling to provide thermal insulation.

Material used for injection molding is polystyrene. Processing conditions were optimized and are summarized in Table 8. Up to 5000 parts were produced.

Melt Temperature (°C)	275
Mold Temperature (°C)	70
Injection Velocity (mm/s)	140
V/P Switchover Pressure (MPa)	65
Pack Pressure (MPa)	100
Pack Time (s)	3

Table 8. Injection molding conditions.

2.4 Characterization

Overall surface appearance was investigated using an optical microscope (Zeiss), whereas line height and width were measured using a contact profilometry (Dektak, model: Veeco 500).

2. RESULTS AND DISCUSSION

Higher viscosity pastes accompanied by lower speeds provided better replication of pattern with less spreading of the paste on the substrate and no voids (Figure 2).

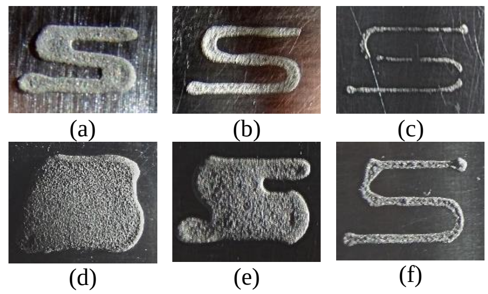

Figure 2. Effect of viscosity and speed using commercial paste: (a-c) speed of 3 mm/s (Trials 1, 3 and 5) and (d-f) speed of 15 mm/s (Trials 2, 4 and 6).

The effect of flow rate on width and height is presented on Figure 3. The line width increased at a linear rate of 282.5 µm/(mg/s) for the 222 Pa-s paste and 206.0 µm/(mg/s) for the 601 Pa-s paste. The line height, however, did not show any significant change for any of the pastes. Minimum feature width was 427 µm and 551 µm for 601 Pa-s and 222 Pa-s, respectively.

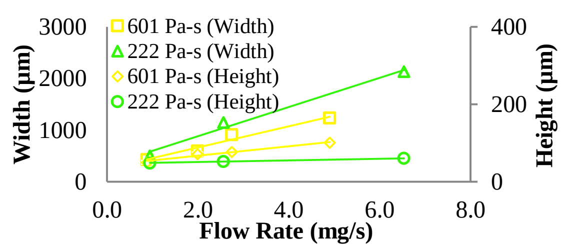

Figure 3. Effect of flow rate for pastes with viscosity of 222 and 601 Pa-s.

The effect of tip gap was found to be dependent on the flow rate. At low flow rate (0.9mg/s) feature dimensions were constant, whereas at high flow rate (2.6 mg/s) line width and height increased linearly at a rate of 4.7 µm/µm and 0.3 µm/µm, respectively (see Figure 4).

These results show that parameters such as paste viscosity, flow rate and tip gap control the dimensions of the printed patterns. However, this paste presents problems with porosity -i.e particle distribution differs from line edge to center of line

(Figure 5). This porosity issue cannot be fixed with the processing conditions or sintering step, for this reason, a custom paste was investigated.

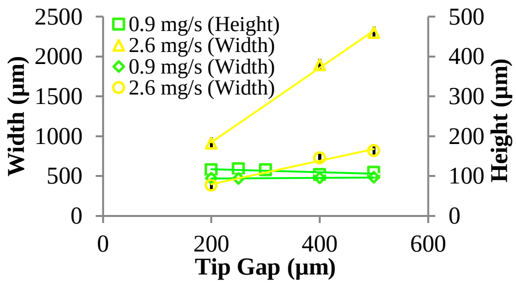

Figure 4. Effect of tip gap when printing with different flow rates.

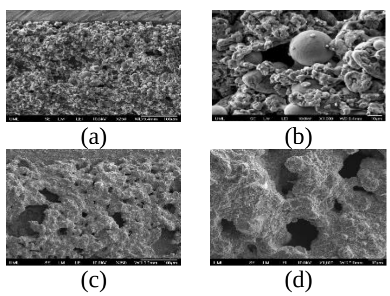

Figure 5. Images of (a-b) green stage and (c-d) sintered stage.

The effect of viscosity when a custom paste was used is presented in Figure 6. The combination of three binders (GG, SC and XG) in equal amounts produced the best results with a viscosity of 25 Pa-s (Figure 6i).

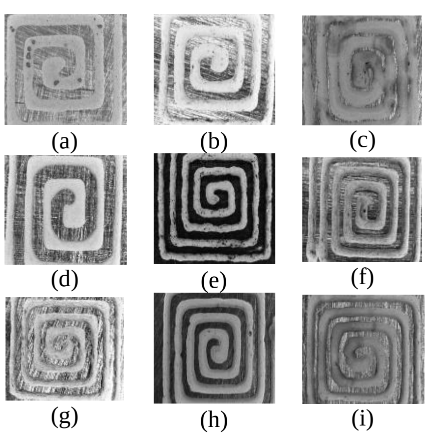

Figure 6. Effect of custom formulation on printed features for viscosities of: (a-c) <10 Pa-s, (d-f) 13-16 Pa-s, (g-i) 22-26 Pa-s.

Endurance was tested. Tooling was not deformed after 5000 cycles in the injection molding machine and parts were produced with 100% replication (tooling/feature height/depth were approximately 150 µm) (Figure 7).

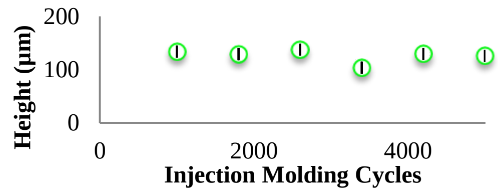

Figure 7. Replication and endurance test.

3. CONCLUSIONS

This work investigated printing parameters as a control of feature size and a custom paste as a control of uniformity and porosity of microchannels. Tooling endured for 5000 injection molding cycles, thus representing a great potential as tooling for microfluidic devices.

4. ACKNOLEDGEMENT

National Science Foundation and Nissei America, Inc.

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