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GENERATION OF HIGH ASPECT RATIO METAL MICROSTRUCTURES EXHIBITING LOW SURFACE ROUGHNESS BY DROP-WISE PRINTING OF LIQUID METAL

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Abstract

This paper presents the results of parameter studies for the drop-wise generation of metal microstructures from liquid metal. In this context, thin walls (170 μm - 180 μm thickness) featuring aspect ratios of over 50 are printed from solder droplets to identify the correlation between printing parameters and resulting material properties. Droplet spacing as well as substrate temperature are varied and the resulting surface quality in terms of roughness is evaluated. Best results, for given boundary conditions, are achieved with a relative droplet spacing of 0.65 in combination with a substrate temperature of 140 °C. Based on printing with droplets of 170 μm diameter a printed area surface roughness of 9.35 μm is achieved.

1. Motivation

Additive manufacturing is gaining increasing popularity for the fabrication of sensors and actuators [1]. A promising approach in this field is the drop-wise direct printing of liquid metal droplets providing low-cost processing by minimizing material usage. Such a process can be utilized for the direct metallization of electrical components, the 3D-integration of microelectronics in hybrid packaging as well as the direct printing of metal microstructures. Asterisk

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microstructures. It is however still challenging to generate droplets from molten metals in the micrometer scale. For this purpose, several printhead concepts have been developed in the past [2–4]. However, the process parameters required to fabricate high surface quality structures with these devices remain largely unexamined. This work aims towards a detailed analysis of parameters necessary to optimize surface roughness of drop-wise printed metal structures.

2. Experimental setup

The picoliter metal droplets required for these studies are produced on-demand via StarJet technology [5, 6]. This technology utilizes a MEMS-fabricated silicon nozzle chip (see figure 1, left) in combination with a pneumatic actuation principle. The nozzle chip features star-shaped bypass channels on the upper side which join into an also star-shaped nozzle orifice in the center of the chip.

The specific geometry of these channels inhibits a priming of the channels by repellent capillary forces when liquid metal enters the nozzle chip. Thus, individual metal droplets are centered inside the nozzle. Additionally, an inert gas flow is established through the bypass channels on top of the chip, which surrounds the metal inside the nozzle. The influent gas constricts the metal column when it enters the nozzle chip and hence facilitates a necking of the liquid column in that region, resulting in the generation of single micro droplets. The inert gas flow inside the nozzle chip further prevents the liquid metal from oxidizing.

The nozzle chip is attached to the printhead as indicated in figure 1 (right). Thereby, the channels on top of the chip are connected to the rinse gas chamber, while the center of the nozzle chip is connected to a reservoir through a drilled channel. The whole printhead is heated up for melting the metal and can be pressurized with actuation gas (e.g. nitrogen) through the upper gas inlet. The lower gas inlet is connected to the rinse gas chamber at the bottom of the printhead via channels, running in the sidewall of the printhead. By applying short pressure pulses of a few milliseconds on top of the reservoir a small amount of metal is pushed into the nozzle and single droplets are generated. This so called StarJet printhead was integrated into a printing system featuring a 3-axis system for the deposition of liquid metal droplets onto a heatable substrate holder. As printing material solder (type: Sn95Ag4Cu, \(T_{\text{melt}} = 210\, ^{\circ}\text{C}\)) was used which was heated up to 320 °C. The mounted chip inside the StarJet printhead exhibited a nozzle diameter of \(d_{\text{nozzle}} = 89\, \mu\text{m}\). The droplet size resulting from this combination was measured to be \(d_{\text{droplet}} = 170\, \mu\text{m}\) as illustrated in figure 2.

![Fig. 1. SEM view of a StarJet nozzle chip made from Si with star-shaped nozzle orifice and surrounding rinse gas channels (left), Exploded view of StarJet printhead (right).]
3. Results

To evaluate feasible process parameters which enable the printing of quality 3D microstructures, parameter studies have been performed to identify the dominating factors on the fusion behavior of printed droplets. In a first step 2-dimensional lines have been printed to reduce the set of operation parameters that has to be varied. As outcome of these studies, relative droplet pitch \( P_r \), i.e. the ratio between droplet spacing and droplet diameter as well as substrate temperature have been identified as major impact parameters for the surface quality. The remaining parameters (e.g., print height: 1 mm, printing frequency: 6 Hz) have been selected based on the results of previous evaluation runs and were kept constant. Subsequently, walls have been printed (length: 20 mm, height: 10 mm, width: 170 μm) using the operation parameters listed in table 1. For evaluation of the surface quality of the printed walls the 3D average surface roughness \( S_a \) of the printed walls was measured using an optical microscope (Alicona, model: InfinityFocus, [7]).

<table>
<thead>
<tr>
<th>Sample</th>
<th>1.1</th>
<th>1.2</th>
<th>1.3</th>
<th>2.1</th>
<th>2.2</th>
<th>2.3</th>
<th>3.1</th>
<th>3.2</th>
<th>3.3</th>
<th>4.1</th>
</tr>
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<tr>
<td>Substrate temperature / °C</td>
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<td>40</td>
<td>40</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>140</td>
<td>140</td>
<td>140</td>
<td>200</td>
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<tr>
<td>Droplet spacing / μm</td>
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<td>130</td>
<td>110</td>
<td>150</td>
<td>130</td>
<td>110</td>
<td>150</td>
<td>130</td>
<td>110</td>
<td>150</td>
</tr>
<tr>
<td>Relative droplet spacing</td>
<td>0.88</td>
<td>0.76</td>
<td>0.65</td>
<td>0.88</td>
<td>0.76</td>
<td>0.65</td>
<td>0.88</td>
<td>0.76</td>
<td>0.65</td>
<td>0.88</td>
</tr>
</tbody>
</table>

Figure 4 (left) demonstrates the increase of uniformity of the printed walls (figure 3) by reducing the relative spacing between the droplets from 0.88 to 0.65. This is due to the fact, that the incoming droplets can better adhere to the previously printed droplets as the overlap increases. This results in the merging of the droplets within each row even at substrate temperatures of 40 °C. By increasing the substrate temperature also the droplets between different rows increasingly merge and solidify with a higher degree of uniformity as illustrated in figure 3. Finally, when the substrate temperature exceeds a temperature of 200 °C, the printed droplets merged completely inhibiting a build-up in z direction. Therefore, it was not possible to print walls at temperatures of 200 °C and above.
The above described results indicate that the thermal energy of the impacting droplet must be high enough to melt the interface between the previously printed droplet and the impacting one. Best results have been achieved with a relative droplet spacing of 0.65 and a substrate temperature of 140 °C. With these parameters, an average surface roughness of $S_a = 9.35 \, \mu m$ was realized (figure 4, right).

4. Conclusion

The experimental studies presented in this work demonstrate the feasibility to generate high-aspect ratio microstructures of up to 1:58 by drop-wise deposition of liquid metal. In a next step, the acquired knowledge will be transferred to the printing of complex 3D structures.

Further studies will focus on the improvement of surface properties of the printed structures, e.g. lowering surface roughness and preventing discontinuities. Therefore, the resolution of the printed structures needs to be improved, which can be best achieved by adapting chips with smaller nozzle orifices to the printhead. Regarding process economy, higher printing frequencies and thus a decrease in printing time are desirable.

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References