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Influence of processing parameters on the electrical conductivity of 3D printed silver structures

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Introduction

3D printers have become a widely used tool in research, development and production environments. Regarding complex parts 3D printing is sometimes even superior to other technologies and that at reasonable costs. Until today several methods in different variations and combinations have evolved. Raw materials are introduced into these processes as filaments, powders or liquids which are then modeled to obtain the desired object. Sometimes the object has to be subjected to a post-treatment afterwards. We consider a Multi Material Jetting process which combines printing of a silver particle ink (conductive) and a dielectric (non conductive) ink. The 3D buildup is achieved by depositing small ink drops layer by layer using two dedicated print heads. Each layer of silver ink is dried and sintered via an infrared light source directly after its application. The dielectric ink contains a photoinitiator and is cured with ultraviolet light respectively.

It is possible to manufacture fundamental passive electronic elements like resistors, inductors or capacitors. Furthermore antennas, couplers, resonators and even coreless transformers can be directly printed with this technology.

Due to the highly complex nature of this printing process and its mode of operation the essential question arises, how the electrical resistance of conducting structures is affected by variation of their thickness or orientation in relation to the print heads.

Details of Operation

We deployed a DragonFly LDM® 2.0 printer manufactured by NANO DIMENSION®. The basic setup of this device is shown in figure 1. The positioning of the print heads, needed to deposit the ink drops at the predetermined places, is accomplished by moving the tray (D in figure 1) alongside a linear guide and moving the print head assembly (B in figure 1) alongside another guide perpendicular to the other.

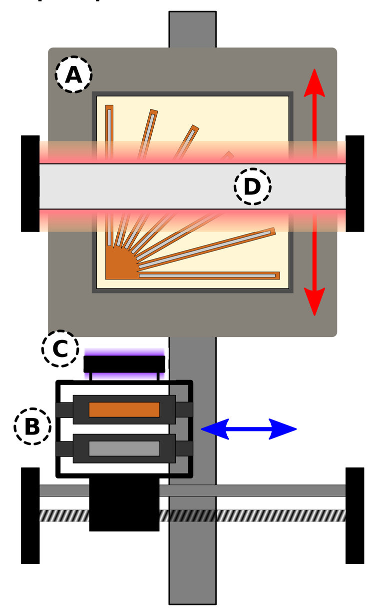

Figure 1: Top view of the setup within the printer and its basic components. A: Printing tray with substrate and printed object, B: Assembly with two print heads, C: UV light source, D: IR light source, red arrows: moving direction of the printing tray, blue arrows: moving direction of print head assembly

The IR lamp (D in figure 1) used to dry and sinter the conductive ink between the single layers is mounted at a fixed position above the pathway of the tray whereas the UV lamp used to cure the non conductive ink is attached to the print heads assembly thus following its movement.

Figure 2 shows the nozzle plate of one print head and the nozzle orifices. Each print head has 512 nozzles which are arranged in two rows. The two rows are shifted against each other, leading to a vertical resolution of 70.5 µm (approx. 360dpi) and a total coverage of approximately 36 mm. By default the printer is configured for a vertical resolution (red direction in figure 1 and 2) of 36 µm and a horizontal resolution (blue direction) of 35.25 µm. The vertical resolution (↑) is determined by the speed of the tray and the firing frequency of the nozzles as the horizontal resolution (→) only depends on the positioning of the print head assembly. Hence to obtain the desired horizontal resolution of 35.25 µm at least two printing strokes are necessary.

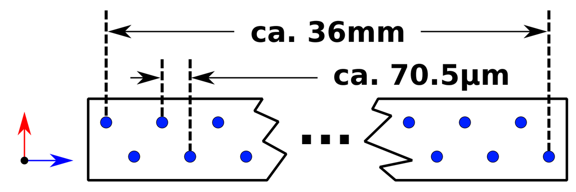

Figure 2: Schematic view showing the the nozzle plate of one print head and its nozzle orifices

Figure 3 shows one layer of conductive ink (left) and one layer of dielectric ink drops (middle) deposited onto a glass substrate. It can be seen that the vertical lines consisting of consecutively deposited drops are merged together whereas the drops in the horizontal lines that are printed in multiple strokes are rather unconnected. The right image shows multiple layers of silver ink.

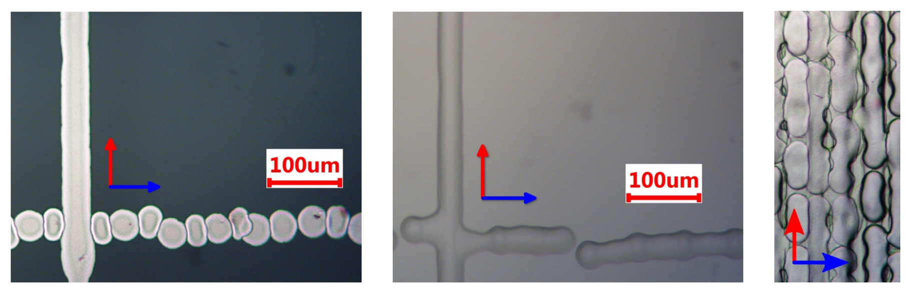

Figure 3: Printed drops on glass surface. left: silver ink, middle: non conductive ink (one layer), right: silver ink (multiple layers)

Influence of conductor thickness and printing direction on electrical conductivity

To analyze the influence of the conductor thickness and printing direction on the conductivity, meander shaped structures were printed. Afterwards the samples were re-treated (sintered) for 3 hours at 160 ℃ in an external convection oven. The particular geometry was chosen because it allows for long conductor lengths within a relatively small area. The long conductive traces reduce the influence of most measurement errors (e.g. contact resistance or resistance of measuring leads) on resistance or conductivity measurements. The needed resistance measurements were carried out with a multimeter using two terminal sensing.

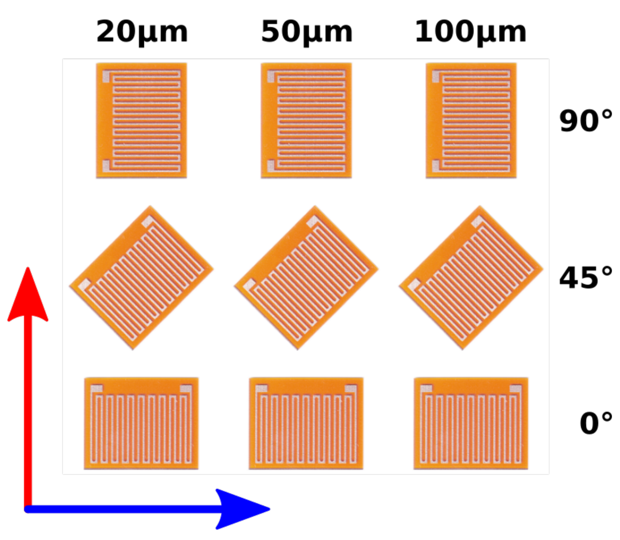

Figure 4: Array of meander structures with different layer thicknesses and angles of orientation with regard to the printing direction

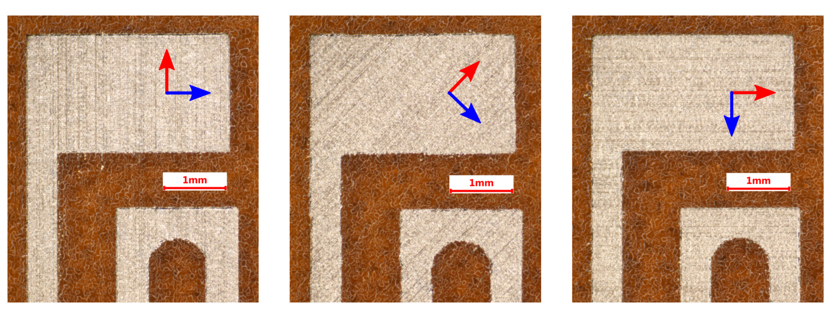

Figure 5: Detailed view of the top left area of three differently oriented (during printing) meander structures (left: 0°, middle: 45°, right: 90°)

An array of meander structures (figure 4) was printed. The printing direction of the final results is clearly determinable (see figure 5). The resistance of each structure was measured and is shown in table 1.

Table 1: Resistance values of meander structures with different track thicknesses and angles of orientation with regard to the printing direction

angle	20 µm	50 µm	100 µm
90°	10,54 Ω	4,71 Ω	3,74 Ω
45°	7,43 Ω	3,34 Ω	2,65 Ω
0°	4,53 Ω	2,22 Ω	1,89 Ω

The results clearly indicate a dependence between angle and resistance and expectedly a dependence of material thickness and resistance. Interestingly the latter relation is not strictly inversely proportional. At this time there are two possible explanations. One possible explanation is the tendency of crack formation with increasing height. Secondly it is intrinsic to the printer that objects are not sintered selectively because the IR lamp affects the whole build plate (see figure 1). Thus leading to the effect that the thinner structures on the left side of figure 4 are finalized earlier and heated more intensely during the ongoing printing on the right side. Furthermore the structures on the right side are possibly less thoroughly sintered during re-treat due to the higher material thickness. In this context the resistance may get affected.

Table 2: Resistance values with their mean and standard deviation (SD) of meander structures with 20 µm material thickness at different angles of orientation and different printing tray positions (left, center, right).

angle	left	center	right	mean	SD
90°	26,17 Ω	26,06 Ω	31,51 Ω	27,9 Ω	3,12 Ω
45°	18,04 Ω	18,86 Ω	22,07 Ω	19,7 Ω	2,13 Ω
0°	10,55 Ω	12,02 Ω	12,68 Ω	11,8 Ω	1,09 Ω

For a deeper understanding of the angular dependency 3 rows of meanders with an equal conductor thickness of 20 µm were printed. The determined resistance values are shown in table 2.

To increase the angular resolution of the measurements and to examine all directions and quadrants a star shaped structure with radial conductive tracks at intervals of 15° was printed.

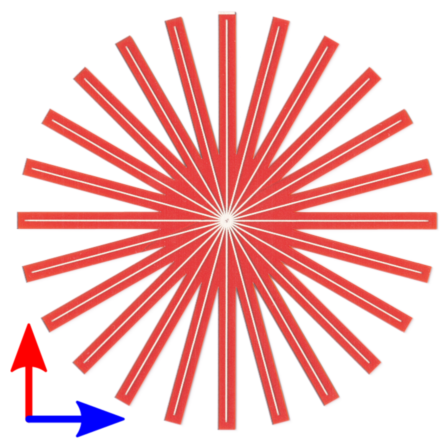

Figure 6: Star shaped structure with radial conductors (length of each radial conductor: 75 mm (midpoint to tip)

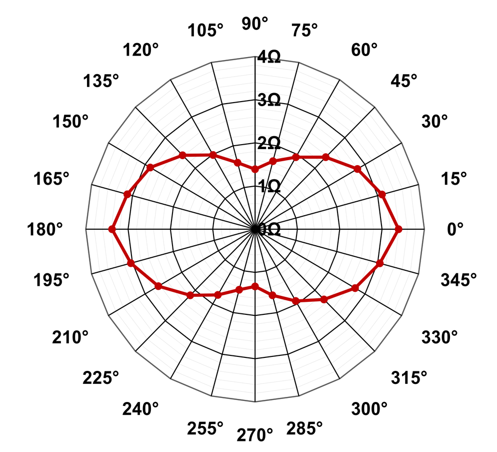

Figure 7: Resistances of radial conductors (median of 3 measurements)

The resistances between the midpoint and the outer tips of the tracks were determined three times, starting at different angles. The median of those values for each angle is shown in figure 7. One can clearly see the vertical and horizontal symmetry of the determined values. Also values of tracks with angles opposing each other look roughly equal. But nevertheless some of these resistance pairs differ as far as 10 % from each other (e.g. 60° and 240°). It is assumed that the cause is either a positional or a much more complex dependence lying within the not completely deterministic printing procedure.

Conclusion and Outlook

The study carried out, has shown that the electrical conductivity of sintered silver traces, printed with the portrayed printer, depends on the amount of applied material (thickness) and the orientation of the printed object with regard to the print heads and printing direction. The latter effect was analyzed more thoroughly in [1]. The variation of the printing parameters and the corresponding results show that further research is needed to predict the resistance of printed silver traces in the future. Additionally the influence of the position on the tray and the movement of the tray or print heads over the whole duration of the printing process will be investigated.

References

[1] Schwan, L. et. al.: Simulation Based Conductivity Tensor Determination of Sintered Nanosilver. Verhandlungen der Deutschen Physikalischen Gesellschaft, 2021, online.
[2] Werner Zapka: Handbook of industrial inkjet printing: A full system approach. Wiley-VCH Verlag GmbH & Co. KGaA, 2018.

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