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Investigation of the Anisotropic Conductivity in Printed Nanosilver

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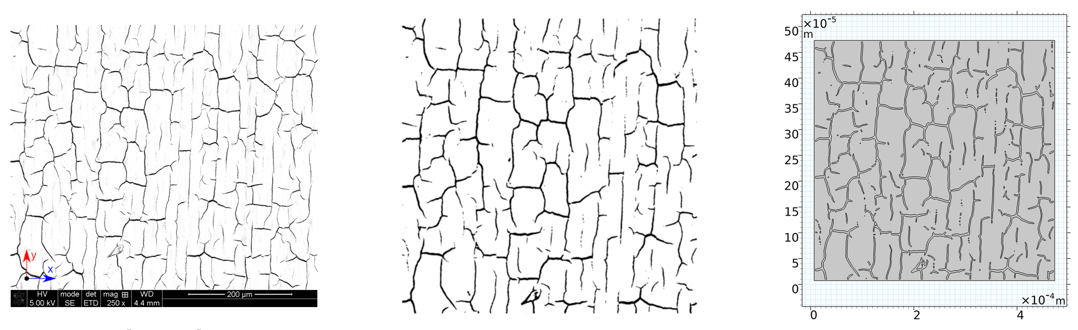
Introduction

3D printing is an emerging technology with a wide range of applications. The modern multi-material jetting process, such as that used in the Nano Dimension Dragonfly Pro LDM, makes it possible to print dielectric and conductive materials in a single process. A special characteristic of the conductive material printed with the Dragonfly PDM is its anisotropic conductivity. Experiments show, dass the conducitiviy in the x-direction ist approx 40 % to 70 % of the conductivity in the y-direction. Our investigation focuses on two possible origins for this.

Influence of the Cracks on the Anisotropy

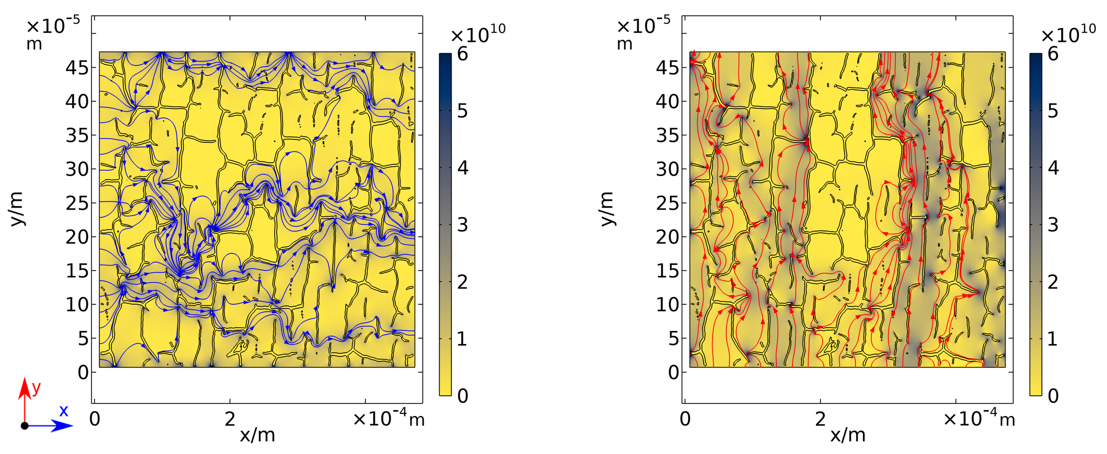
In the SEM a direction-dependent crack structure is visible. In order to investigate the influence of these cracks, a COMSOL Multiphysics® geometry is generated from the SEM image.



(a) (b) (c)

Figure 1: (a) SEM image of the crack structure. (b) Cracks cut out with MATLAB®. (c) COMSOL Multiphysics® geometry created from the image.

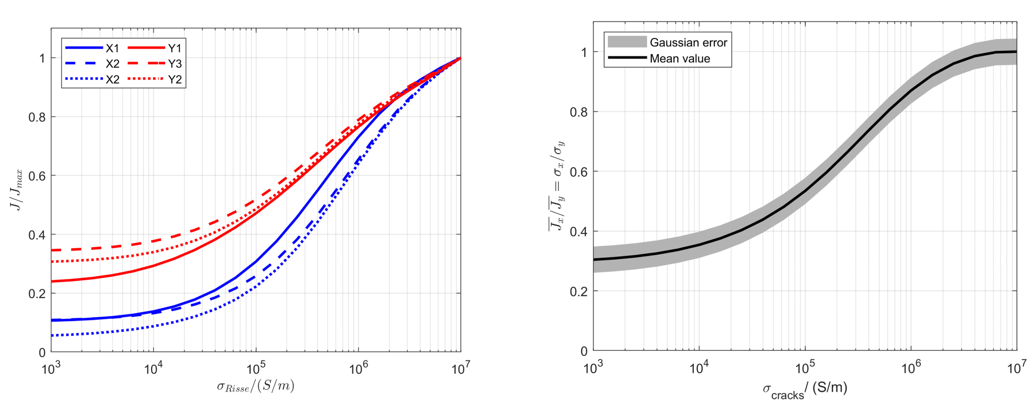
The current flow is simulated in this two-dimensional geometry. The cracks are defined as non-conductive. In the x-direction (blue) the current has to take more detours than in the y-direction (red).



(a) (b)

Figure 2: Simulated current density distribution in $\mathrm{A\,m^{-1}}$ in X- (a) and Y- direction (b).

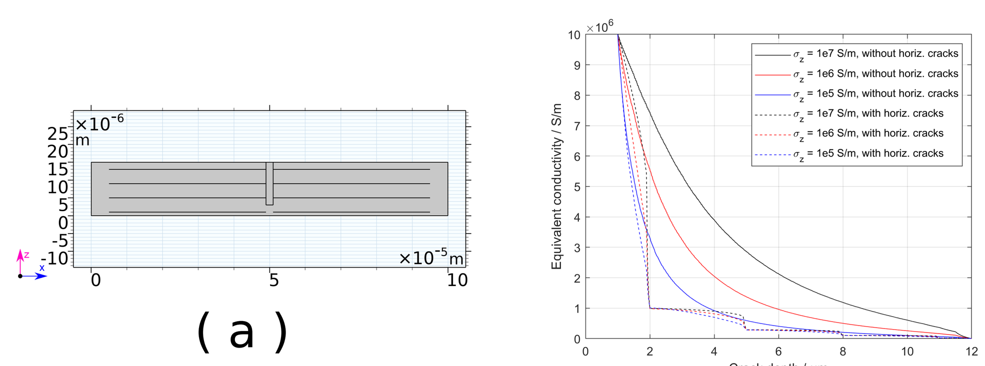
The simulation is carried out for three crack structures and the ratio of the conductivities is calculated from the mean value and the standard deviation of the conductivity in the x- and y-directions. To approximate the crack depth in the 2D geometry, the conductivity is varied in the area of the cracks.



(a) (b)

Figure 3: (a) Current in x- and y-direction, for three crack structures, normalized to the maximum current with variation of the electrical conductivity in the area of the cracks as approximation for cracks that do not go through the entire layer. (b)Ratio of the currents or ratio of the effective conductivities in the x- and y- directions.

A second simulation is used to determine which depth leads to which corresponding conductivity. This also takes into account that horizontal cracks occur in the material [1] and that conductivity is reduced by deposits from the covering agent [2].



(a) (b)

Figure 4: (a)Example of a crack whose depth is varied, with marked horizontal boundary layers or cracks. (b) Effective conductivity of an area ("crack") through the entire layer, which results when the crack depth is varied.

The exact depth of the cracks could not yet be determined. Further investigations have shown that the cracks in a 15 µm thick conductive layer are at least 12 µm deep. Assuming an average crack depth of 5 µm, for example, anisotropies of around 0.9 can be explained in this way.

Influence of the Printing Prozess on the Anisotropy

Another possible cause of the aniosotropy is based on the printing process. Surfaces are produced from lines in the Y-direction, each of which is sintered individually. This results in "wet on dry" connections between the lines.

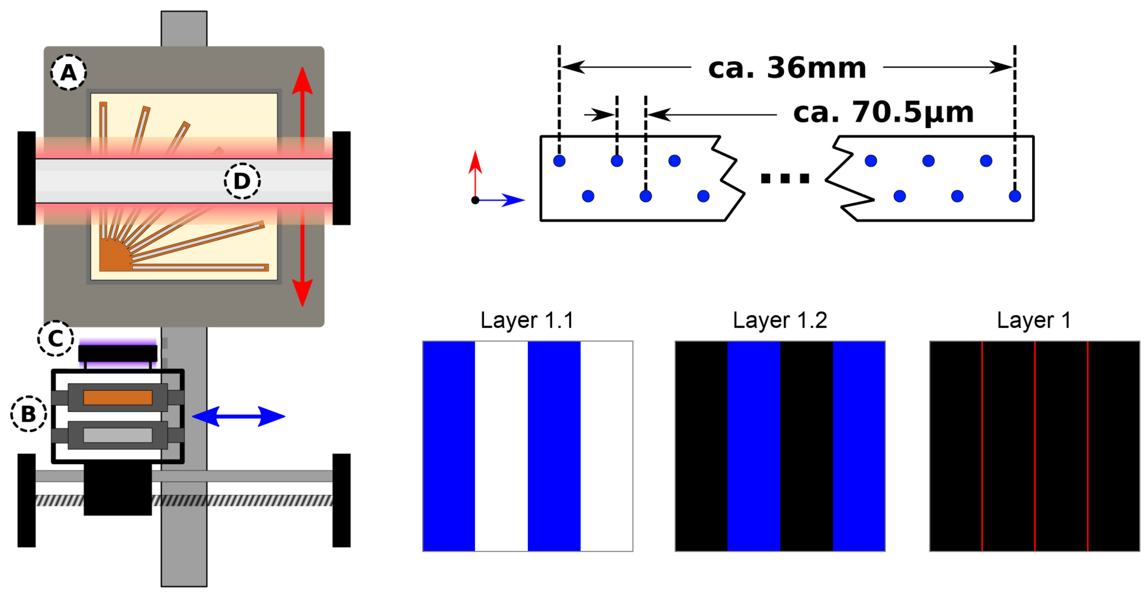
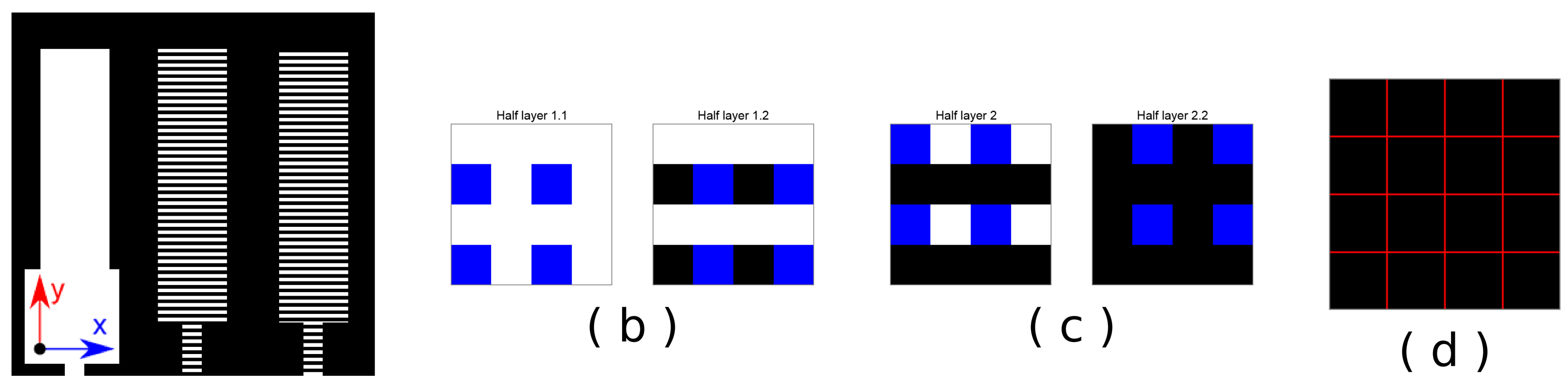


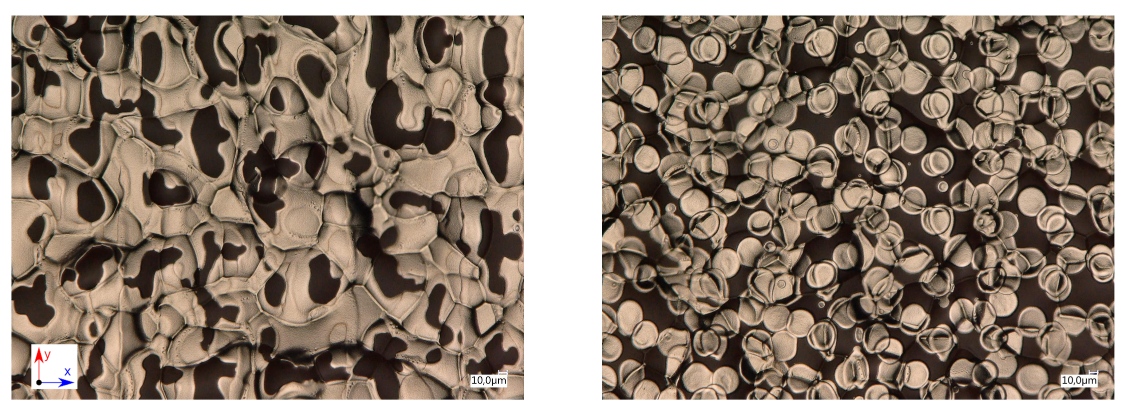
Figure 5: Surfaces are produced from alternating printed lines (layer 1.1 and 1.2) in the Y direction. After each print of a line, the material is sintered. As a result, boundary layers (layer 1 red) are created parallel to the lines where liquid ink meets already sintered material.

To investigate the influence of these connections, the printing process is manipulated in such a way that the lines in the Y-direction are only closed in every second step. This also results in boundary layers in the Y direction.



(a) (b) (c) (d)

Figure 6: The lines are cut into 35 µm long pieces in the y-direction, which are printed one after the other and sintered in between ((b) and (c)). (d) As a result, sintered ink has to bind with liquid ink in both the x- and y- directions and therefore boundary layers form in both directions.



(a) (b)

Figure 7: (a) Print image of a conventionally printed layer and a layer as described above in which the y-direction is also printed in two passes (b).

The conductance of the exemplary conductor track, which was printed conventionally, is $Y = (0.69 \pm 0.04)\,\mathrm{S}$. The additional boundary layers reduce the conductance to $Y = (0.566 \pm 0.006)\,\mathrm{S}$. This reduction to $(82 \pm 5)\,\%$, caused by the additional boundary layers can therefore be identified as a further cause of the anisotropic conductivity.

Outlook

The investigations show two aspects that affect the anisotropy. The influence should be quantified more precisely in further investigations, for example by determining the crack depth. Based on the results, consideration can then be given to reducing or specifically controlling the anisotropy in order to utilize the effect.

References

[1] Dalal, N. et al. Cracks in the 3D-printed conductive traces of silver nanoparticle ink. Journal of Micromechanics and Microengineering, 29, 2019.
[2] Trindade, G.F. et al. Residual polymer stabiliser causes anisotropic electrical conductivity during inkjet printing of metal nanoparticles. Commun Mater 2, 47, 2021

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