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Additive manufacturing of conductive copper traces on 3D geometries by laser-sintering

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Abstract

These days, additive manufacturing processes cover an extensive range of materials. A new trend is a growing interest in the implementation of additional functions like electrical circuits. Combining full-surface primer and copper ink coating from printed electronics with laser processing enables integrating conductive traces directly on the surface of 3D-printed components. Priming reduces the roughness of the 3D printed circuit carrier below 100 nm. Afterward, the metal-containing ink is dip-coated, dried, and sintered locally by laser processing. The used laser system includes a focused and pulsed 1064 nm laser beam controlled by a scanner with three optical axes (x, y and z-direction). This research presents a detailed investigation on the influence of 3D geometrical factors like radii and sidewall angles on the resulting conductive trace resistance.

Keywords: Laser sintering; Printed electronics; 3D printing; Copper ink; Epoxy priming

1. Introduction

A mechatronic integrated device (MID) is a hybrid electro-mechanical component consisting of a rigid part with structured conductive traces and electrical or electro-mechanical components (Islam et al. 2009). In the commonly used laser direct structuring (LDS) technology MIDs are produced by the laser processing of injection-molded parts. These parts are produced from various types of plastic, such as LCP and PEEK. Most of them require specific additives that are added during compounding (Bachy et al. 2018). Currently, there have been advancements in MID development, providing lots of emerging technologies on various substrate materials, including additive manufacturing substrates from 3D printing (Espera et al. 2019).

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Recently, a laser sintering process of conductive traces on primer pre-treated additive manufactured 3D surfaces has been developed (Olsen and Overmeyer 2021). This paper focuses on the examination of different 3D printed circuit carrier geometries with that approach.

2. Materials and methods

All samples in this paper are printed with a 3D printer from Stratasys with multi-jet modeling (MJM) technology. This printing technology combines photopolymer jetting and UV curing (Singh 2011). In general, this paper deals with spatial objects, but a model of a planar sample is designed as well. The 2D sample (A) includes two areas (40 × 30 mm) for structuring. The middle area (44 × 40 mm) is used to mark, numerate, and clamp the sample. The profile (Fig. 1e) of the first 3D sample (B) provides lower degrees of sidewall angles 10°, 20° and 30° with 2 mm fillet radius. This enables investigations depending on the angle of the sidewall surface. The profile (Fig. 1f) of the second 3D sample (C) provides various geometrical shapes for Conductive traces to trespass. They are starting from a relatively smooth fillet with a radius of 3 mm up to challenging 1 mm. There, the sidewall angle is 45°. The symmetrical shape of all designs allows using both sides of samples with the same dipping station.

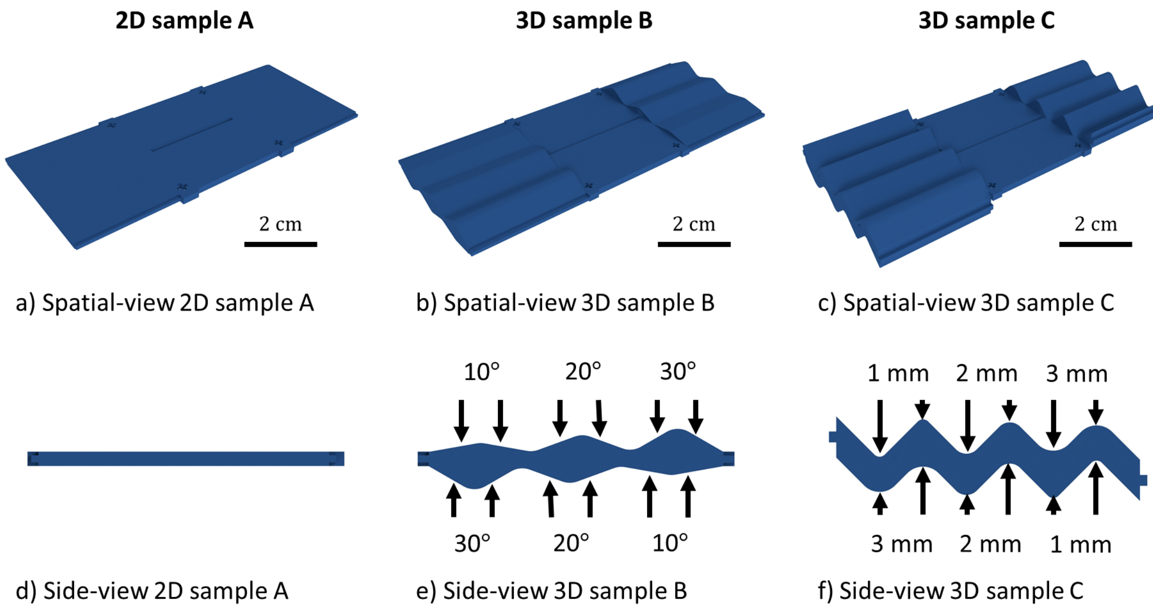

Fig. 1. 2D and 3D sample geometries

Creating a thin (<5 µm) conductive trace on the initial 3D printed surface is impossible due to the high roughness. An epoxy-based UV curable primer is applied to smooth the surface. The used UV source for curing emits primarily in the range of 350 to 400 nm. According to the supplier of the UV-curable primer, the optimal wavelength of the UV-lamp lies in the range from 380 to 395 nm. A short UV light exposure of approximately 30 seconds hardens the insulator. Afterwards follwos a copper ink coating in a dipping bath. Pulling the sample out from the dipping station, filled with ink, is carried out at a constant and slow speed (< 2 cm/s). It allows creating a more even surface. The ink's solids content ranges from 35 - 37 %, and the viscosity is 19 cP at 25 °C.

After ink application, the liquid solvent is evaporated before structuring. A heat gun at 50°C is used for drying the ink. The ink can be dried in the temperature range from 50 °C to 80 °C. Drying at higher temperatures shortens the drying time but could potentially lead to more defects on the structured conductive traces. The heat gun is kept at a distance of 5 - 10 cm from the samples. The airflow rate is set to 300 l/min, and the samples were dried in a vertical position. It takes 5 - 7 minutes to dry one layer of ink at 50 °C at this airflow rate.

A part of CAD design is the creation of data for the sintering of conductive traces. The built-in software of the laser system requires surface body data. It is possible to create the surface bodies in 3D CAD software. In this paper, only straight-lined conductive traces are used for parametric tests. A fiber laser (Nd:YAG) with a wavelength of 1064 nm is employed that includes three optical axes (x, y and z) to scan the 3D structures. All samples were structured with the parameters shown in Table 1.

Table 1. Sintering parameters

Scanning speed [mm/s]	40
Laser beam defocusing [mm]	+4
Hatch distance [µm]	65
Hatch angle [deg]	65
Laser spot size [µm]	126

Laser beam defocusing fixed at +4 mm provides the best possible results for most sample geometries, eliminating the issue with burned and unevenly structured conductive traces due to different beam intensity on the alternating angle of slope. The 65 µm hatch distance (resulting beam-overlap of 46%) is selected due to the least number of defects in preliminary experiments, allowing larger processing windows. Conductive traces are structured on every subsection of the samples that differs in geometrical properties. For example, for the sample with various slope angles, six traces are structured with the same parameters on 10°, 20° and 30° sidewall slopes (Fig. 1b). With a 300 µm width and gap of 300 µm between conductive traces, it is possible to structure eight parameter groups of conductive traces per sample side. In total, every parametric test includes 252 conductive traces. All samples are structured with varied power in the range of 0.22 – 0.48 W with an increment of 0.02 W. Fig. 2 sums up the entire process flow applied in this research.

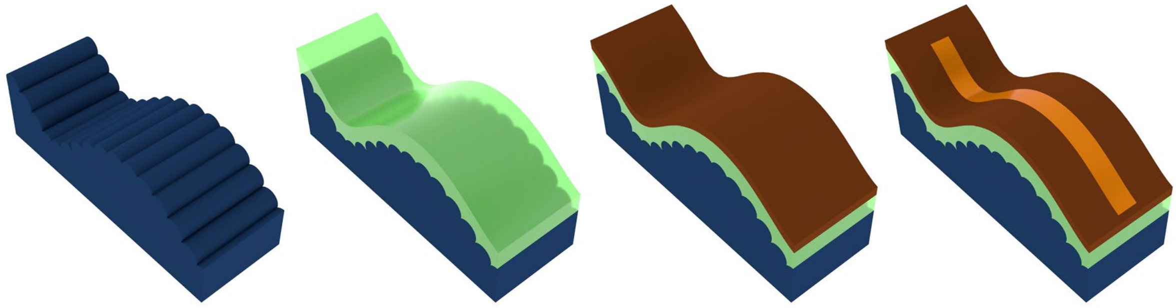

Fig. 2. Process flow to generate conductive traces on additive manufactured surfaces

3. Results and discussion

3.1 Surface roughness

Samples were produced by Stratasys Eden 260V from VeroBlue printing material. Beyond this, other polymer materials supplied by Stratasys are also possible. The look of a planar surface from a 3D printed sample directly from the printer is shown in Fig. 3a. The roughness (Ra) is larger than 2 µm on the planar surface. On the 3D surfaces, the roughness is expected to be even higher due to the steps induced by the 3D printing. After the insulator coating, the surface is smoother (Fig. 3b). The roughness (Ra) decreases by more than one order of magnitude to less than 100 nm. The comparison of pictures and profiles from bare (Fig. 3c and 3e) and primer coated (Fig. 3d and 3f) surfaces show a significant reduction of surface roughness resulting from the primer.

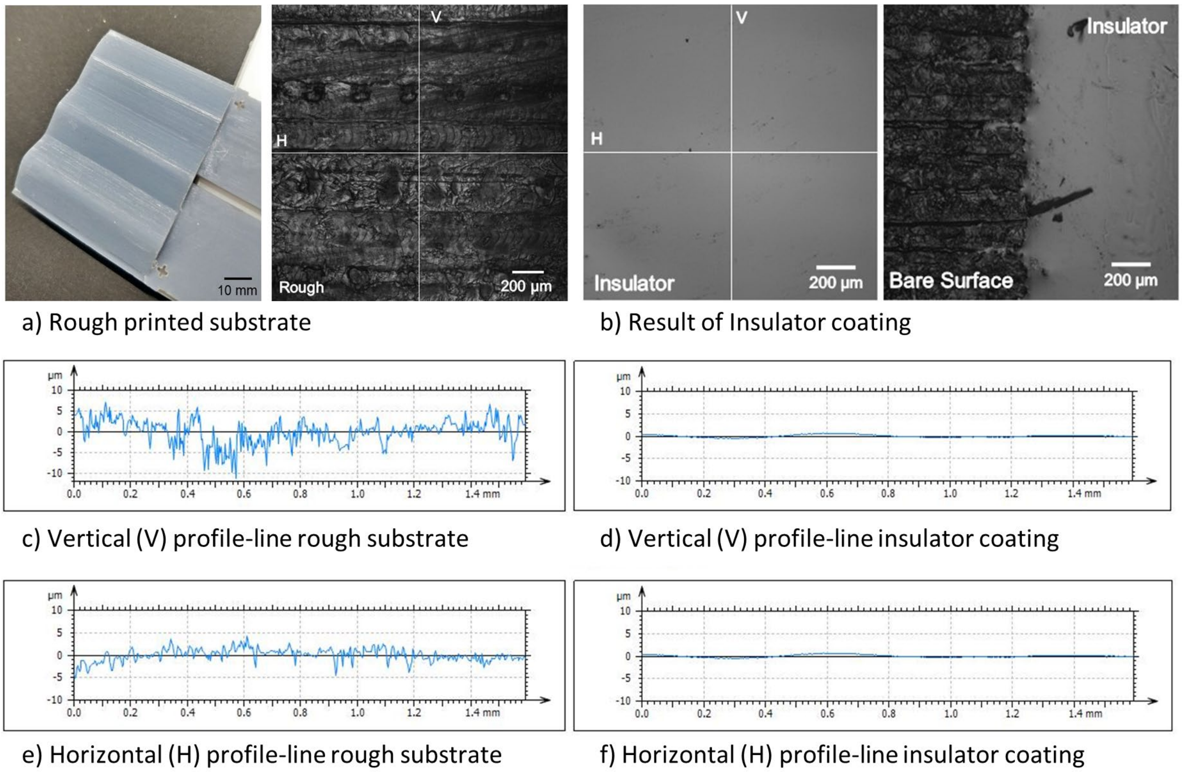

Fig. 3. Roughness analysis of the MJM printed samples and the primer/insulator coating

3.2 Laser structuring parametrization on different 3D geometries

Fig. 4 shows pictures of the parametric test results with the 3D samples B and C. Though the paper deals with the spatial conductive traces, a parametric test on the planar substrate was conducted to provide a relative comparison.

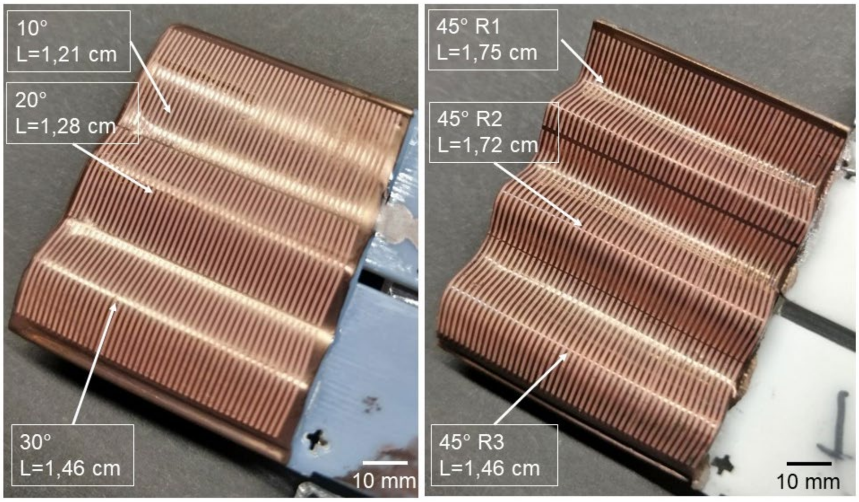

Fig. 4. 3D samples with conductive traces for parametrization measurements

The diagram in Fig. 5 provides a direct comparison between resistances of conductive traces, structured on 0°, 10°, 20°, 30° and 45° angled substrates (A and B). The conductive traces on the planar sample always have the lowest resistance reaching values down to 2 Ω/cm. In the range of 0.24 – 0.44 W, the resistances of the 3D traces are almost the same. Within this range, the resistances vary between 5 and 15 Ω/cm. Differences can be seen at the upper and lower ends of the process window. At 0.22 W and 0.46 W, the traces on the smaller angles perform better and show lower resistances. A continuation of this trend can be seen at 0.48 W. The resistance rise is occurring due to geometrical reasons.

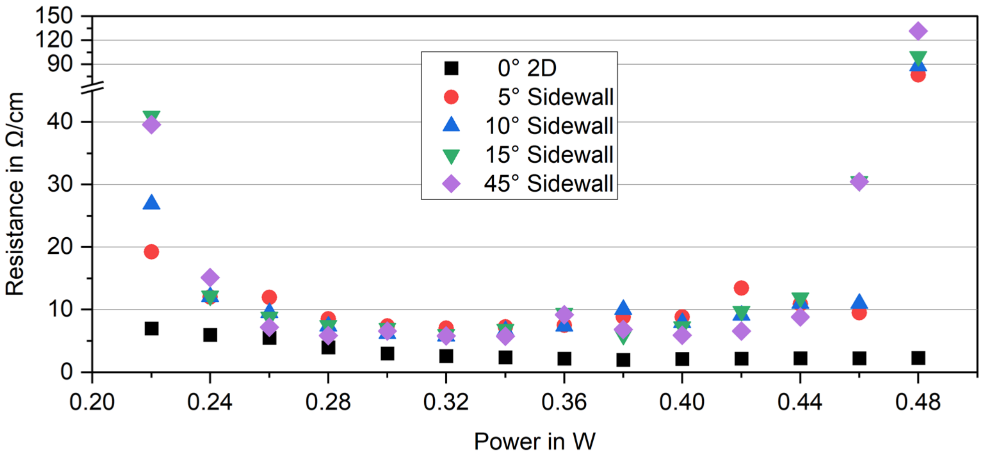

Fig. 5. Resistance measurements for different sidewall angles at various laser sintering power values

The following diagram in Fig. 6 provides a comparison between various fillet angles on sample C. This experiment was conducted on the sample with 45° slopes with various fillet radiuses (1, 2 and 3 mm). The conductive traces, structured on the areas with a 1 mm fillet radius, show the most inconsistent results without a defined operating range. One reason for this could be that with a radius of 1 mm, the risk of defects is very high, which means that high resistances and non-functioning traces occur more often. Although the operating range of conductive traces structured on the fillet of 2 mm is narrower than the traces sintered on the 3 mm fillets, the process window and optimal power values are almost the same for both geometries. This leads to the conclusion that the 2 mm fillets are the minimum for sufficiently functioning conductive traces. A fillet radius of 3 mm provides an insignificantly better result. However, if it is possible to provide the geometry with the smoother fillet, a successful laser sintering result is more likely.

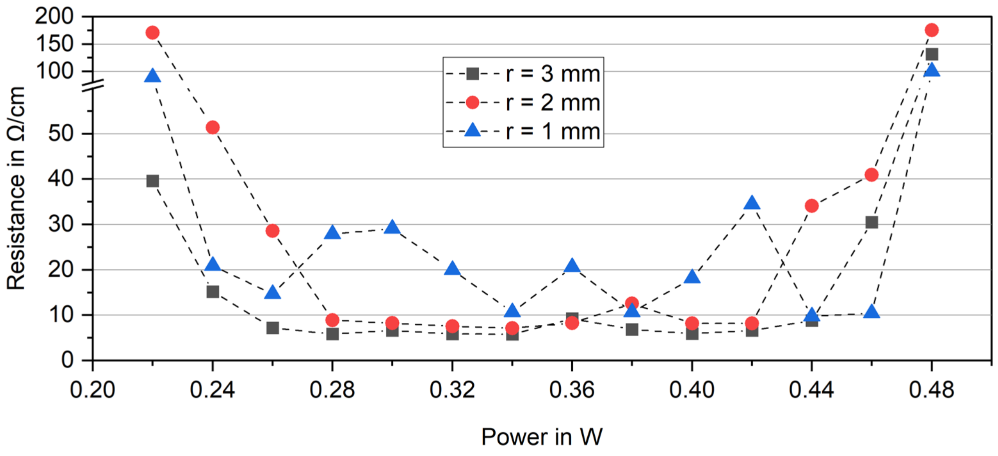

Fig. 6. Resistance measurements for different fillet radius at various laser sintering power values

4. Conclusion

In conclusion, laser structuring of conductive traces is possible on surfaces with a wide range of geometrical properties, but sharp edges and excess power should be avoided. Increasing the structuring power will not improve the resistance values but leads to more defects. Thus, the optimal parameters for working conductive traces are slope angle up to 45°, two or more mm fillet radius between the slopes, 0.26 – 0.3 W power, laser structuring speed 40 mm/s, 0.065 mm hatch distance, 65° hatch angle and +4 mm of defocusing.

This study aimed to create working conductive traces on spatial 3D printed substrates with different geometries. The surface was wetted with a UV-curable insulator to provide smooth surfaces for conductive trace generation. The parametric tests determined geometrical limitations. During the comparison of bulk resistance, it was concluded that the traces provide an average value of bulk resistance in the range of 5 Ω/cm on most of the used geometries. With higher slope angles, the processing window was shrinking, limiting the use of increased power of the laser source.

Nevertheless, the insulator-coated samples provided a consistent and wide operating range even on the perpendicular sidewalls, connected by a fillet with a radius of 2 mm or more. When comparing conductor tracks on 2D and 3D surfaces, differences of approximately 2 Ω/cm can be observed. The present paper shows a successful local laser sintering of copper-containing ink on various 3D printed substrates with various geometrical properties. The insulator coating provides a smooth surface for a successful wetting in copper ink, enabling the creation of conductive traces with reproducible resistance values. Local laser sintering of copper-containing ink shows potential for a flexible and inexpensive process. The wide variety of possible substrate materials and 3D printing technologies could provide a feasible basis for further investigations involving more demanding CT parameters, including narrower conductive traces up to 100 µm or even less. The proposed approach could be easily automated due to the characteristics of the process.

Acknowledgments

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