Investigation on the performance of multi-layer printed conductive tracks on multi-layer printed insulator

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Abstract:

The move to multi-functionality in Additive Manufacturing converges a number of technical challenges, notably the accurate and reliable deposition of different materials and their interaction. In this paper, an investigation on the pattern quality and conductivity of multi-layer printed conductive tracks on multi-layer 3D printed insulator was carried out using a drop-on-demand inkjet technique. Results have shown that the surface finish of the printed insulator had a significant effect on the performance of the conductive tracks that have been overlaid. Also the printing strategy used in the processing resulted different width, height, conductivity and pattern quality of multi-layer printed conductive tracks.

Keywords: multi-functionality, multi-layer, conductive tracks, inkjet printing

1. Introduction

Additive Manufacturing (AM) is a group of manufacturing technologies that are capable of producing 3D solid parts by adding successive layers of material. Current AM technologies such as fused deposition modelling or selective laser melting, have some clear drawbacks for the production of multi-material parts, such as the contemporaneous deposition of different types of multi-materials, particularly those that require specific function, i.e. electronics. The development of multi-functionality in AM aims to integrate different materials for a given function, and this development could be achievable by using inkjet technology.

The concept of inkjet printing was presented in the 19th century, described by the formation of uniform droplets from a stream of liquid which had been jetted through a small orifice by Savart [1]. The inkjet printing technology has come to prominence in the past decades, and is now familiar to the general public. It has also been recognised as a capable tool for manufacturing, especially micro-manufacturing [2]. Inkjet printing technology is not a single technology, but a family of different technologies that have a similar function: the precise generation of free-flying fluid droplets [3]. It involves the formation and dynamics behaviour of the droplets, as well as the interaction between the droplet and the substrate.

In multi-functional conductive printing, the main processing issues relates to the conversion of the ink in its non-conductive state to a final conductive print [4-6], especially in multi-layer printing. Previous studies on multi-layer and multi-material printing have developed 2.5D integrated circuitry [7] and 3D metal-insulator-metal crossovers [8]. Those works were still based on 2D printing, while few studies have looked into real 3D printing with both conductive and dielectric materials printed together in parallel. There is therefore a lack of knowledge on multi-layer printed insulator's performance and the impact of different substrates on a conductive tracks' performance.

In this paper, the study focuses on the surface control of the multi-layer printed insulator, and its effect on the pattern quality and conductivity of multi-layer printed conductive tracks deposited on the insulator.

2. Experiments

All the printing in this paper were carried out on a Fujifilm Dimatix materials printer DMP-2831, equipped with one 10pL printing head. One ink cartridge and one print head form a printing assembly, and a change in the printed material requires the change of the assembly. The printing resolution in Dimatix is changed by adjusting the print droplet spacing.

The printing order in this paper was firstly printing an insulating layer on the top of a base substrate, and then printing a conductive layer on the top of the insulating layer.

2.1 Multi-layer insulator printing

A Ultraviolet (UV) curable dielectric ink SunTronic EMD6415 supplied by Sun Chemical® was selected to print the insulating layer. A UV light was equipped next to the print head to provide immediate curing after the droplets were deposited. Polyethylene terephthalate (PET) was selected as the base substrate.

To identify the drop spacing range, individual droplets were deposited on the PET, followed by subsequent curing. Droplets were observed and measured using Philips XL30 SEM, shown in Figure 1.

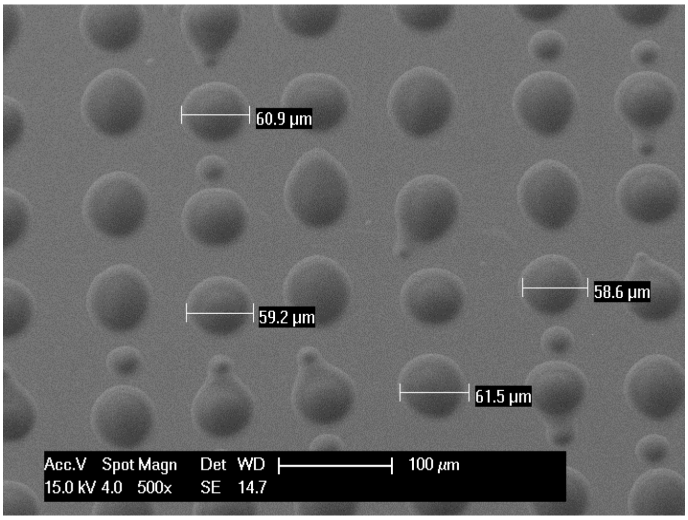


Figure 1 Dielectric ink droplets cured on PET

The average dielectric ink droplets size is 60µm. Six different drop spacing parameters were used in this paper to investigate the drop spacing effect on printed insulator's surface profile. The printing parameters are shown in Table 1.

Drop spacing (µm)	20, 25, 30, 35, 40, 45
Dimensions (mm)	65 x 20
Print Layers	10
Jetting Frequency (KHz)	5
Jetting Nozzles	6

Table 1 Parameters for printing the insulating layer

2.2 Multi-layer conductive tracks printing

A jettable silver (Ag) ink SunTronic EMD5714 supplied by Sun Chemical® was selected to print the conductive layer, which contains 40% weight percentage of silver nanoparticles. Ag ink was deposited directly onto the insulating layer generated in the previous layer, without any heating during the printing. After the printing was complete, the samples were placed in an oven at 150°C for 30 minutes to sinter the Ag nanoparticles.

To identify the drop spacing range, individual droplets were deposited on the printed insulator, followed by oven heating. Droplets were observed and measured using Nikon optical microscope, shown in Figure 2.

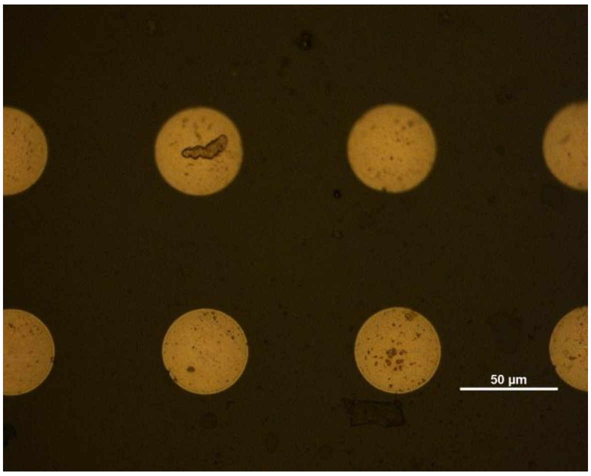


Figure 2 Ag ink droplets on printed insulator

The average Ag ink droplets size was 44µm. 6 different drop spacing parameters were used to investigate the drop spacing effect on printed Ag tracks' conductivity. The printing parameters are shown in Table 2. Also to study the surface effect from the printed insulator on the Ag tracks' performance, fixed drop spacing was used to print on the 6 surfaces generated. The printing parameters are shown in Table 3.

Ag Track Drop Spacing (µm)	10, 15, 20, 25, 30, 35
Insulator Drop spacing (µm)	30
Dimensions (mm)	15 x 1
Print Layers	5
Jetting Frequency (KHz)	20
Jetting Nozzles	4

Table 2 Parameters for printing the Ag tracks on constant surface

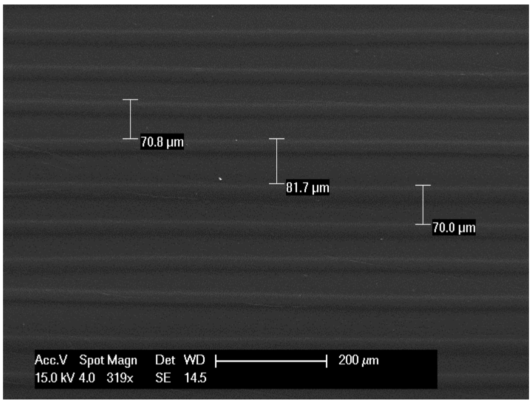
Ag Track Drop Spacing (µm)	30
Insulator Drop spacing (µm)	20, 25, 30, 35, 40, 45
Dimensions (mm)	15 x 1
Print Layers	5
Jetting Frequency (KHz)	20
Jetting Nozzles	4

Table 3 Parameters for printing the Ag tracks on variable surfaces

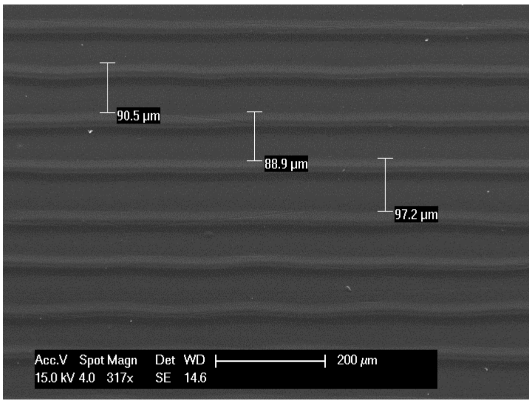
3. Results

3.1 Characterisation of printed insulator

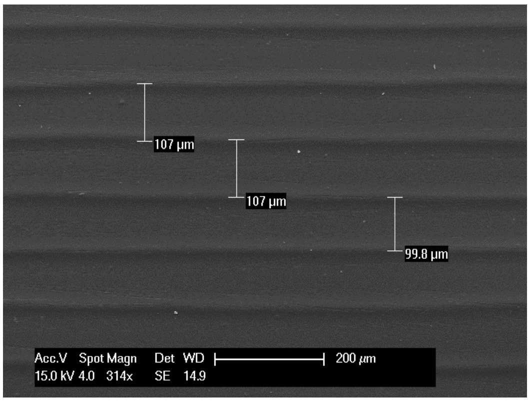
To investigate the drop spacing effect on printed insulator's surface profile, samples generated in Table 1 were observed in Philips XL30 SEM, shown in Figure 3; and their surface profiles was measured by Mitutoyo-Surftest SV-600 Profilometer, shown in Figure 4 and 5.



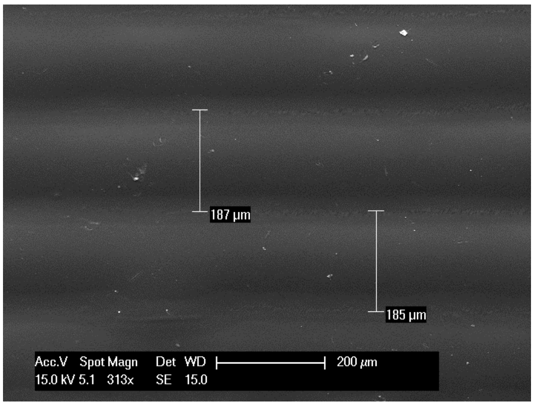
20µm



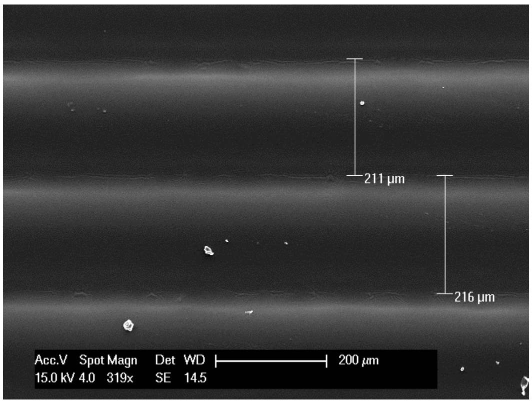
25µm



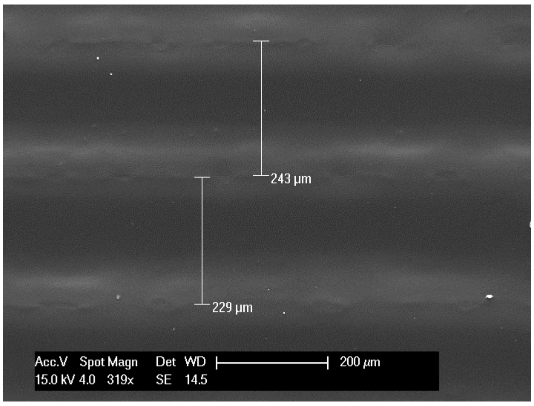
30µm



35µm



40µm



45µm

Figure 3 Printed insulator under SEM

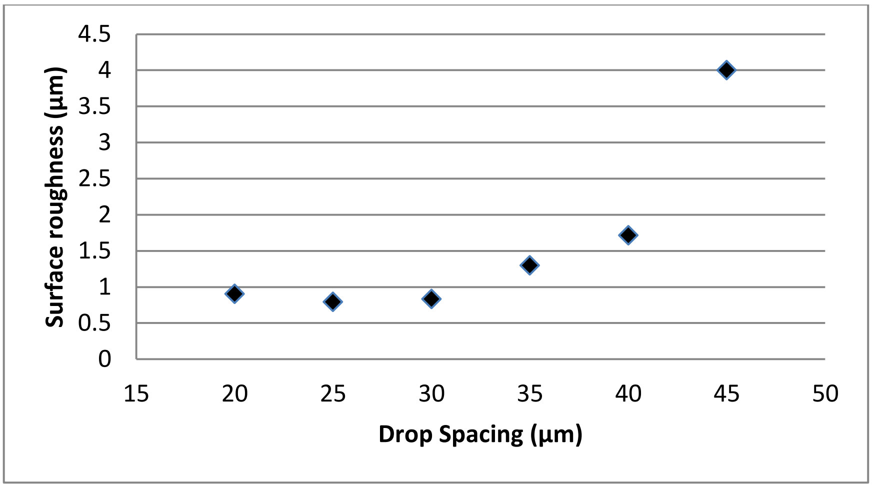


Figure 4 Average surface roughness of printed insulator

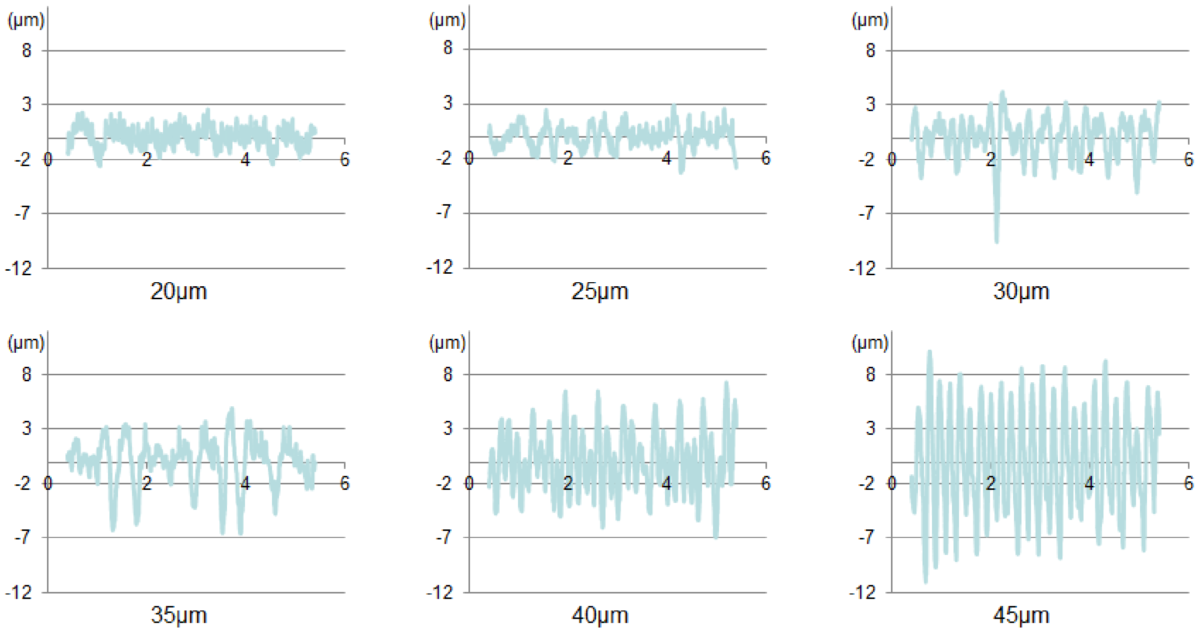


Figure 5 Surface profiles of printed insulator

'Waviness' parallel to the printing direction was observed on the multi-layer printed insulating samples. It was formed by the overlap between each printing hatch. Since the insulating droplets were cured very soon after being deposited, the time for the wetting was limited. Different sizes of the overlap generated different surface profiles of the insulator; therefore adjusting the print drop spacing was able to control the surface finish.

From drop spacing 20µm to 30µm, the waviness lines' average distance increased from 74µm to 105µm. These waviness lines appeared on the top of the insulating layer due to more than 50% of the overlap. Surface profiles showed the variation fell into a narrow range, which indicated the surfaces were relatively flat. The average surface roughness was below 1µm with differences less than 0.11µm due to the different drop spacing.

From drop spacing 35µm to 45µm, the waviness lines were less visible. Parallel bump channels appeared due to less than 50% of the overlap. Since the overlap was not large enough to cover the arc of the droplets, the surface profile variation fell into wide ranges, which indicated the surfaces were not flat. The average surface roughness increased significantly according to the drop spacing increase.

3.2 Characterisation of printed conductive tracks

3.2.1 Drop spacing effect

To investigate the drop spacing effect on multi-layer printed Ag tracks' conductivity, the resistance of the samples generated in Table 2 were measured by the multimeters, average results shown in Figure 6.

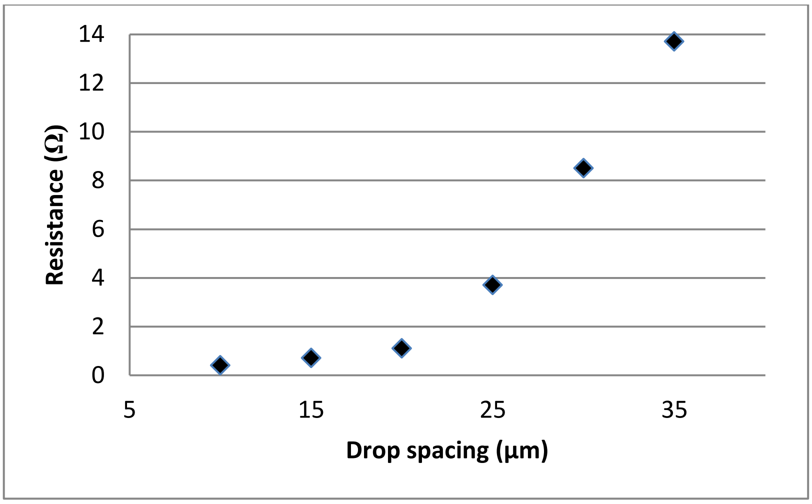


Figure 6 Resistance of Ag tracks under different drop spacing

From drop spacing 10µm to 20µm, the average resistance remained at low values, which were below 1.5Ω, due to more than 50% of the printing overlap. From 25µm drop spacing, the resistance increased significantly according to the drop spacing increase, due to less than 50% of the printing overlap. Therefore, to gain enough conductivity for the Ag tracks, more than 50% of the printing overlap was necessary. Ag tracks using drop spacing 10µm and 15µm presented very low resistance; however, the pattern quality is not ideal due to the overloading of the ink, shown in Figure 7. The balance between the conductivity and track pattern quality is essential, and this study suggested using 20µm drop spacing for this Ag ink.

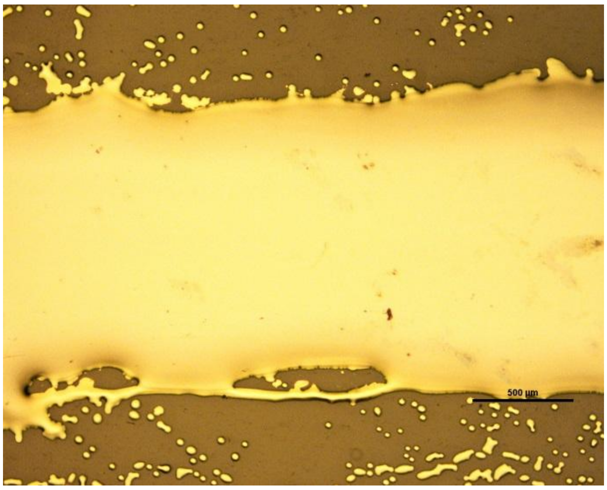


Figure 7 Overloading and subsequent bulging of the ink generated rough pattern

3.2.2 Insulator surface effect

To study the surface effect from the printed insulator on the Ag tracks' performance, the resistance of printed samples generated in Table 3 were measured by the multimeters, average results shown in Figure 8; pattern quality were observed by using Nikon optical microscope, shown in Figure 9.

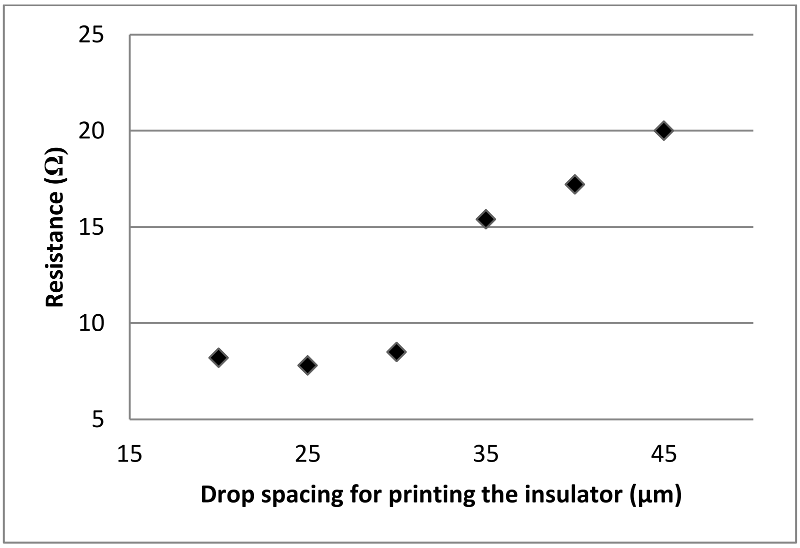


Figure 8 Resistance of Ag tracks on different insulating surfaces

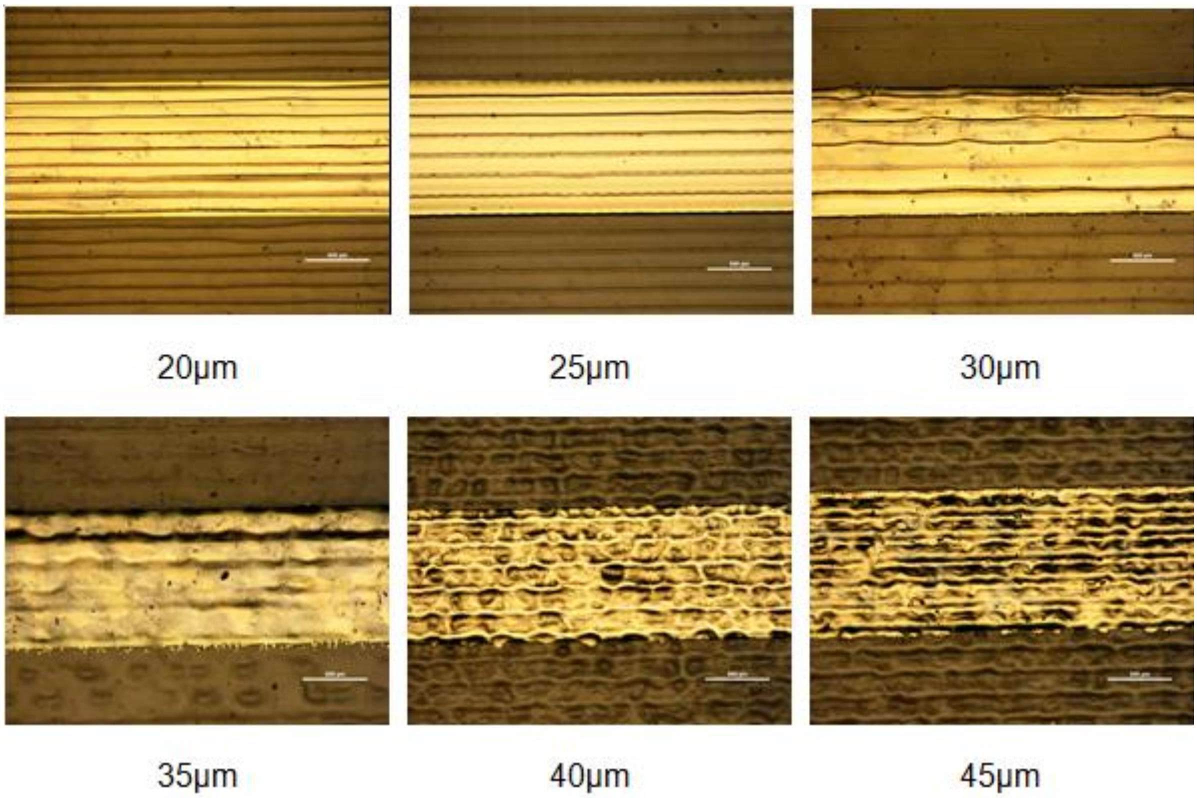


Figure 9 Ag tracks on different insulating surfaces

The conductivity of the Ag tracks showed an agreement with the insulating layer's surface roughness. When deposited on the flat surfaces, the resistance of the Ag tracks remained small, with less than 0.8Ω differences. When deposited on rough bumpy surfaces, the resistance increased significantly. It could be observed from Figure 9, that the Ag tracks followed the shape of the underneath insulating surfaces, and could fall into the channels between the waviness. Flat Ag tracks allowed the Ag nanoparticles to have a uniform distribution and higher chance to sinter together, and presented higher conductivity; while un-flat Ag tracks couldn't provide enough sintering opportunities and the final conductivity.

4. Conclusions

There are many factors may affect a multi-material multi-layer inkjet printing process and the final product quality.

For multi-layer insulator printing, the insulating surface can be controlled by adjusting the printing drop spacing. Using more than 50% of the printing overlap is able to generate a flat surface, while using less than 50% of the printing overlap is not enough to generate a flat surface. The average surface roughness increased according to the drop spacing increase.

For multi-layer conductive tracks printing, the conductivity and pattern quality of the tracks depends on the printing drop spacing and the underneath insulating surface. Using less than 50% of the printing overlap couldn't achieve an ideal conductivity, while overload the ink by largely reducing the drop spacing may generate a rough pattern. The insulating surface underneath the tracks also plays an important role to the conductivity. A flat surface underneath can help to achieve higher conductivity than a rough surface underneath.

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