Choosing the Optimal Substrate Surface for Digital Fabrication Printing

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Abstract

Printing inks for digital production printing processes can be classified into two categories. Either the functional ingredient is dissolved in the carrier solvent on a molecular scale, or it is dispersed in the liquid to form of small particles, preferably nano-sized. The latter is the case for most metal inks, the first for most functional polymers. Depending on the type of ink used, selecting either "closed" or a porous substrate surface can strongly influence the functionality and performance of the printed structures .It is shown, that for ink containing dissolved materials a "closed", non-porous substrate surface is preferred, whereas for inks with particles a porous substrate with the right pore size may lead to surprisingly good results. For the ink-substrate interaction in the latter case a filtration mechanism is proposed, which leads to a removal of organic additives from the printed metal layer. This process enhances conductivity already in the uncured state, and facilitates fusing of the metal nanoparticles.

Introduction

Printing of functional material has usually the goal of producing thin contiguous layers on a substrate in a structured and defined way. Beside the structure of printed layer in the surface plane (x-y)-direction also the structure of the produced layers in the z-direction is of key importance for the obtained functionality.

In the design phase in the lab, in many cases glass plates are used as substrate. For mass production, flexible media like plastic foil or paper are preferred, especially the latter for easy operation on web presses, for cost and sustainability reasons.

Transferring a printed product design from rigid glass plates to flexible film or paper for mass production involves a lot of challenges, but also some chances. The specific influence of substrate porosity was investigated for some application sample cases, and options for adjusting porosity are proposed.

Printing Using Solution or Polymer Inks

For “impact” printing processes were the ink is directly transferred from the surface of a printing plate or a transfer surface to the substrate, absorptive substrates are widely used, as the take up the ink efficiently, promoting the transfer. However, when printing solution inks for production of functional layers, penetration of functional solute ingredients into such porous substrate is generally unwanted [1], [2]. It would mean that the printed layers get diffuse in z-direction, and that the functional ingredients are extended by the pore forming material of the substrate. This may greatly impair the function of the layer, as is demonstrated in [2] for the electrical conductive polymer blend PEDOT:PSS. Therefore, printing technologies depending on absorptive media, e.g. offset printing, are not recommendable for this type of functional inks.

Preferred printing technologies for solution inks are e.g. gravure, screen printing and ink jet. With these printing processes, non-absorptive substrates can be used, avoiding ink penetration and resulting in good functionality. The surface of porous and absorptive media like paper can be converted into a non-absorptive substrate by means of e.g. polymer extrusion coating, as demonstrated in table 1, taken from [1].

Table 1: Conductivity of a gravure printing of conductive polymer (PEDOT:PSS) on different substrates

Substrate	Electrical Conductivity (arbitrary units)
Plain paper	0.08
Coated paper (calcium carbonate + clay based coating)	0.40
Extrusion coated paper (polyethylene)	1.03
Polyester foil	1.00

Printing Using Metal Particle Inks

Also for metal particle (e.g. nano silver) inks non-absorptive material, like glass or plastic foils are widely used as printing substrates. In contrast to polymer or solution inks, metal nanoparticle inks contain organic additives beside the conductive metal. These additives serve as dispersants, surfactants and protective colloids, and are needed to avoid sedimentation of the metal particles and to form a stable ink. However, after printing, these electrical insulating vehicles remain in the printed layer and may impair the desired electrical conductivity of the printed structure significantly.

For removing the organic additives, a subsequent heat treatment is generally applied. The high temperatures needed in this step, mostly above 200°C, restrict the choice of flexible substrates to some high temperature stable polymers.

As an alternative, we use an absorptive medium for printing metal nanoparticle inks. The medium was is glossy in jet paper bearing a microporous coating. The coating contains a mixture of flame processed aluminum oxide (AEROXIDE® AluC from Evonik Degussa) and of boehmite (DISPERAL® HP14 from Sasol) as nanostructured pigments. The pore size distribution of the material obtained by mercury intrusion porositometry is given in figure 1.

The peak at pore radius of about 30 nm in figure 1 is given by the pores of the surface coating, whereas the peaks at higher pore

diameters correspond to pores of the sub coat and pores between cellulose fibers in the raw paper.

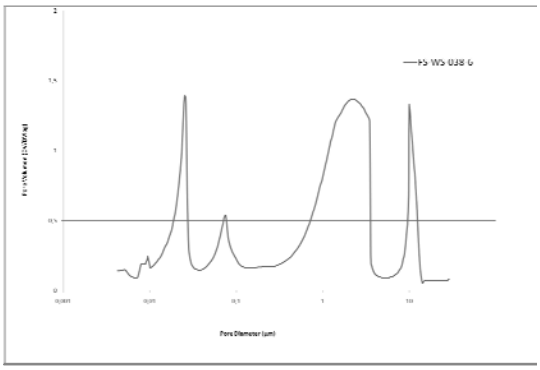

***Figure 1**. Pore size distribution of the microporous paper used for metal inks*

Silver nanoparticle inkjet inks from different suppliers from Japan, Korea, Europe, US and UK inks, were ink jet printed onto this substrate. Unfortunately, details about particle size and additives in these inks are not known, as these data are not disclosed by the ink manufacturers.

We found that at least for some of the inks the resulting silver prints exhibit a remarkably high conductivity already in the uncured state directly after printing. Figure 2 shows the further decrease of electrical resistance during curing at 150°C.

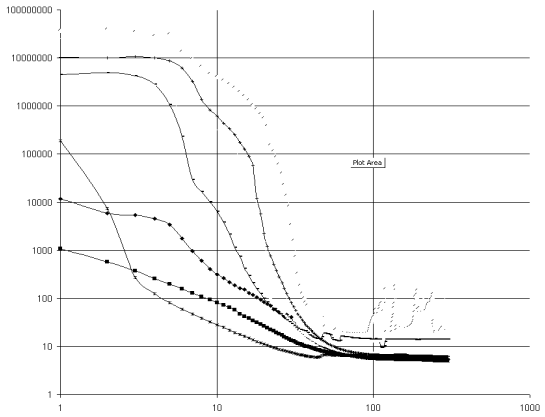

***Figure 2**. Resistance [Ω] vs. curing time [s] at 150°C)*

In most samples, the decrease of electrical resistance vs. time seems to have different sections following different kinetics.
A REM micrograph of the cross section of the silver print on the microporous layer after curing is shown in figure 3 for the ink-paper combination with the highest conductivity in the uncured state. The silver nanoparticles are forming a porous, but contiguous layer (upper layer in figure 3) on the porous alumina paper coating (lower layer in figure 3). Almost no penetration of silver particles into the alumina coating of the paper is observed.

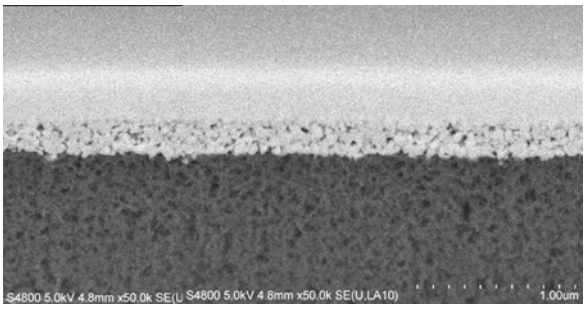

***Figure 3**. REM micrograph of a silver print on microporous coated paper (cross section)*

Conclusions

For inks containing dissolved functional ingredients and polymers a non-porous, "closed" surface is desirable to achieve good performance of the prints.

In contrast, for printing of silver nanoparticle inks using a microporous coated substrate can greatly enhance conductivity and lower curing time. We believe that the underlying mechanism is a filtration process on the surface of the coating, effectively separating the organic ink additives (surfactants, dispersants and protective colloids) from the metal particles. A similar process was earlier observed for ink jet printing of images and graphics using inks containing dye pigments [3].

For an effective separation of the organic ink additives from the metal nanoparticles the properties of the ink and the substrate coating should be optimized as a system, namely the pore size of the microporous coating should be adjusted to the size of the metal particles in the ink.

Acknowledgements

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References

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Author Biography

Wolfgang A. Schmidt, born 1954, holds a Ph.D. in solid state chemistry. For 20 years, e worked in several technical management positions in the photographic industry. In 2004, he joined specialty paper manufacturer Felix Schoeller jr. in Osnabrueck, Germany, managing basic and external R&D projects in the field of imaging and technical papers and coatings. He is president of IS&T Chapter Europe, and member of the German Society for Photography.