UV-inkjet Ink Penetration and Its Effect on Print Quality Formation and Drying

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Abstract

The increased usage of UV-inkjet for printing porous fiber based products has created a need to study the interactions between paper coating, ink and process. In this paper we have studied, how coating porosity affects print quality formation and ink curing degree of UV-curable inkjet inks. Results show, that paper requirements for UV-inkjet differ clearly from those, which are usually connected to good inkjet paper. Paper properties have quite a remarkable effect on print gloss and density formation, although the use of pinning lamps reduces this dependency. Ink curing degree depends also on the properties of the paper and interactions between ink and paper.

Introduction

UV-inkjet inks provide many benefits, like good jetting reliability, long open time of nozzles and good adhesion properties with a wide variety of materials. They are also said to be environmentally friendly due to low VOC's. Therefore, their use has expanded and they are used in several applications, like label and wide format printing. Good adhesion and fastness properties could provide them some advantage also in package printing. In package printing it is quite typical that substrate range is wide. Although UV-curable inks are favored especially for their good performance on nonporous substrates like plastics, they are, and will be increasingly used to print porous fiber based products.

Traditionally, high speed inkjet printing requires from the paper a fast absorption and a high absorption capacity, good colorant fixing properties and the control of the ink spreading. While controlled ink spreading is an essential issue also with UV-curable inkjet inks, fast absorption is not necessarily needed. Actually, strong penetration inside the paper structure can reduce print quality [1,2]. We can also assume that strong ink penetration might disturb curing of the ink, causing an increased risk of ink migration and odor problems. Especially in food package printing the curing degree of ink layer is an essential issue, because in addition to print quality, it affects to product safety [3].

Technical development of the inks, the printheads and other components of UV-inkjet has been rapid. The use of light emitting diodes (LEDs) for manufacturing small-sized curing systems, so called pinning lamps, has further increased the range of substrates available for UV-inkjet. While the main goal of pinning system is to control ink spreading, we can assume it has also other effects to print quality formation and to ink curing.

In this study, our objective is to clarify, how coating structure together with printing variables affect ink penetration, and especially, how penetration affects to ink curing degree and print quality formation.

Experimental work

Paper sample preparation

To be able to understand the effect of the coating structure, model type of coatings were produced at pilot scale. One of the targets was to create coating structures with a wide range of porosities. Coating trials were carried out at the KCL Pilot Plant. The coating layer amount was targeted to 8 g/m^2.Short dwell Opti Blade coater was used to coat the top coating layers and they were formed using two different precipitated calcium carbonate (PCC) pigments with different particle size and size distributions, and polyvinyl alcohol (PVA) as a binder. The amount of binder was varied, 7 pph in the coating color with `small´ size PCC and 30 pph with `large´ size PCC. Base paper was a commercial wood free paper. Prior top coating, a pre-coating layer was applied in order to generate a thick coating layer to prevent top-coating penetration inside the base paper. Pre-coating layer was applied with a film press using a rather coarse calcium carbonate (CC60) with 10 parts Styrene-Butadiene latex. In addition to these two papers, one commercial glossy coated paper was selected for printing.

A paper sample coated with small size PCC and 7 parts of PVA is highly porous, and perform well with aqueous low viscous inkjet inks, which need quick absorption. In this paper, it is refer to *porous pilot paper*. 30 parts of PVA makes the coating structure denser, therefore this paper is refer to *semi porous pilot paper*. Finally, commercial glossy wood-free coated paper is an offset grade, therefore rather dense if compared to pilot papers, and is refer to *dense commercial paper*. In addition to air permeance, which describes openness of the paper structure, there are also differences between the papers in other properties, such as gloss and roughness. Some of the most interesting paper properties are presented in following table (table 1).

Table 1. Paper properties.

	Porous	*Semi porous*	*Dense*
Grammage, g/m^2	90	90	115
Air permeance, PPS20, µm/Pa*s	0.34	0.12	0.05
Contact angle of water, °	67.7	86.7	72.9
Hunter 75° gloss, %	5.0	5.4	69.0
Roughness, PPS10, µm	4.3	5.8	1.1

Printing trials

Printing trials were carried out at VTT. Pilot coated papers and one commercial paper were printed with a standard UV-curable inks using a narrow web printing press, Digital Web Press (DWP), manufactured by Imaging Technology International (iTi). DWP is a roll-to-roll system and it is equipped with four Xaar 760 GS8 Drop-On-Demand printheads and the Fusion UV Systems Light Hammer 6 UV curing system. The maximum power of the UV lamp is 200 watts/cm. The press is also equipped with intermediate LED-based pinning system, manufactured by Exfo. Pinning lamps, which are positioned right after each printing unit, emit UV-light, which solidifies ink without drying it properly [4]. The aim is to prevent ink spreading and to avoid harmful effects on print quality before actual drying.

The printing inks were standard UV-curable, free radical inks, compatible and approved to be used with these printheads. According to our analysis, ink viscosity (measured with Bohlin VOR rheometer) at process temperature was 13 mPas and dynamic surface tension (measured with KSV Bubble Pressure Analyzer BPA800) 32 mN/m @0.1 s. The process temperature in trial was 50°C.

Printing variables were printing speed, amount of ink, drying power and pinning. All these variables had two values and all the possible combinations were tested. Otherwise printing parameters were kept constant. Printing variables and their values are presented in table 2.

Table 2. Printing variables used in the printing trial.

Printing speed	20 fpm (~0.1 m/s) / 80 fpm (~0.4 m/s)
Ink coverage	M 100% / M100%+Y100%
Drying Power	30% / 95%
Pinning lamps	On / Off

In addition to the effect of speed itself, printing speed has influence also on the delays between ink application, start of curing and the end of curing. At lower speed, ink has more time set on paper surface before it enters the dryer. At speed 80 fpm, the setting time for magenta ink prior the dryer is approximately 2 seconds, while at speed 20 fpm, corresponding time is almost 8 seconds. Therefore, ink has a possibility to penetrate deeper into the paper structure. On the other hand, once entered into dryer, drying time is then also clearly longer.

Measurements from the printed samples were made from areas which were printed with magenta (M) and yellow (Y), printed in this order. The print layout was simple, consisting square shaped areas with 100% or 200% ink coverage. Full coverage with one ink corresponds roughly to 8 g/m², calculated from maximum drop size and resolution.

Drying and pinning power was not optimized for the trial. When the pinning lamps were on, they were used with full power. As mentioned above, the time for curing depends on printing speed. The curing stabilizes the ink and after curing, it cannot penetrate inside the coating structure anymore.

Methods and analysis

The UV inks are comprised of monomers, oligomers, photoinitiators, additives and pigments [5]. The polymerization process (curing) starts, when photoinitiators are exposed to UV light and iniator radicals are formed. The iniator radicals react with the $CH\text{-}CH_2$ double bonds of monomers and oligomers, resulting in a cured ink layer. The curing degree measurement method used in this study, is based on NIR spectroscopy [3]. The amount of double bonds of uncured and cured ink layers is compared. The curing degree is calculated by the following equation:

$$\text{Curing degree (\%)} = (A_0 - A) / A_0 \times 100 \qquad (1)$$

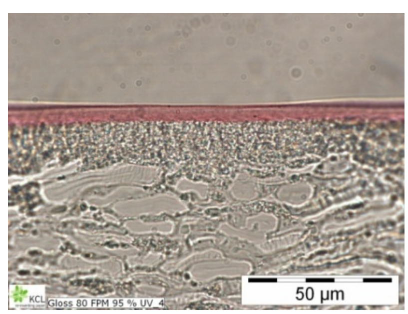
Where A_0 is the intensity of acrylate absorption band at ca. 1620 nm of uncured printed sample and A is same band after UV exposure. The measurements were made with Kusta 4004S NIR reflection spectroscopy device manufactured by LLA Instruments GmbH. The spectra were taken from 80 points of each sample, and the resulting spectra were averaged before further processing.

Paper analyses were made according to ISO 8791-4:1992 (Roughness) and ISO 8254-1:1999 (Specular gloss). Air permeance and contact angle measurements are internal methods. From the printed samples, print density was measured using GretagMacbeth D196 densitometer. Print gloss was measured using 75°/75° geometry with Hunter glossmeter. Cross-section micrographs were taken from printed samples, printed with magenta ink, at speed 80 fpm and using 95% drying power. Prior to cutting of the cross-sections, samples were bedded to Epon rosin. Several cross-sections were taken from each sample.

Results and discussion

Ink holdout

Ink holdout was visualized using cross-section micrographs, taken from printed samples (figure 1). It can be seen from these micrographs, that the differences between papers in ink holdout are significant. On the *dense paper*, ink layer stays on the top of the paper surface. We can estimate from the image that height of the ink layer is approximately 10 micrometers or slightly less, which corresponds quite well with the amount of applied ink and indicates that penetration has been minimal. In the case of *porous paper*, ink has penetrated even inside the base paper. We can also notice that the ink surface is rougher in the case of the *porous paper* and to some extent it has adapted the profile of the coating surface. The ink layer on the *semi porous paper* has partly penetrated in to coating structure, but the ink holdout is better than on the *porous paper*.



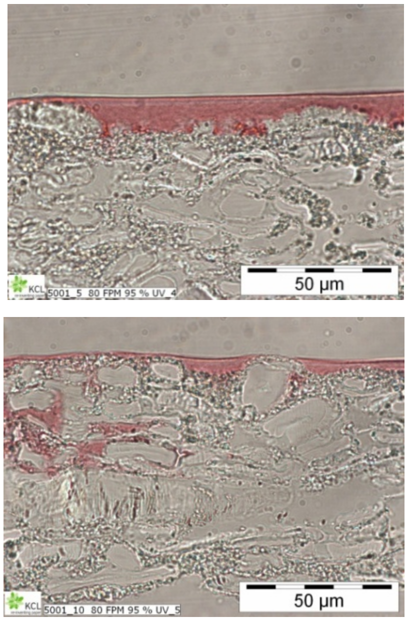


***Figure 1**. Cross-section micrographs taken from the printed papers, from the top to bottom: dense commercial, semi porous pilot and porous pilot paper. Printing speed has been 80 fpm and curing power 95%. The length of the scale bar in the right corner of the images is 50 micrometers.*

Print gloss and density

Paper properties have a quite remarkable effect to print gloss formation, as seen in figure 2. As we can notice, print gloss on a *dense commercial paper* is 100%, being a theoretical maximum value for the gloss, whereas the *porous pilot paper* has the print gloss of 17% in the case of low curing power and no pinning, meaning that printed surface is can be regarded as matt. Specular gloss is dependent of the surface topography and refractive index of the material. If we consider how ink has penetrated in to the paper structure and what sort of surface it forms, we can assume that in this case gloss formation depends strongly on smoothness of the printed surface. On the *dense commercial paper*, the printed surface is really smooth, having a very high specular reflection. On the other hand, the printed surface on the *porous pilot paper* is rough, reflecting light diffusively and having therefore low specular gloss. In addition to this, separation of ink components on the paper surface may change refractive index, and therefore also gloss.

We can also notice that both the final curing and pinning have some influence on print gloss. When the pinning is used, print gloss is clearly higher, especially on the porous pilot paper. We can assume this is due the solidification of ink, which retards ink penetration and therefore helps to form a smooth surface layer. The final curing has a similar effect.

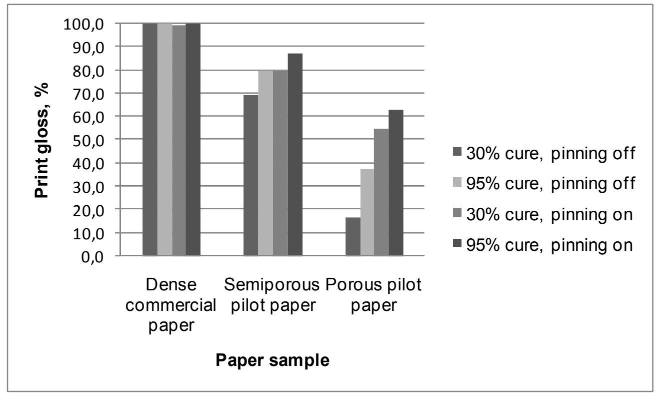


***Figure 2**. Print gloss on different papers, measured from area printed with 100% magenta ink. Percentages in figure refer to power of the final curing. Also pinning is used as a variable (on/off). Printing speed is 80 fpm.*

On the *porous paper*, print gloss is also affected strongly by ink amount and to some extent by printing speed (figure 3). If two ink layers are applied, print gloss reaches almost its maximum value in all three papers. On the other hand, on the *dense paper*, two ink layers do not make any difference compared to one ink layer with respect to print gloss.

Increasing the printing speed from 20 feet per minute up to 80 feet per minute increases the print gloss especially on the *porous paper*. This is presumable due to shorter delay between ink application and curing.

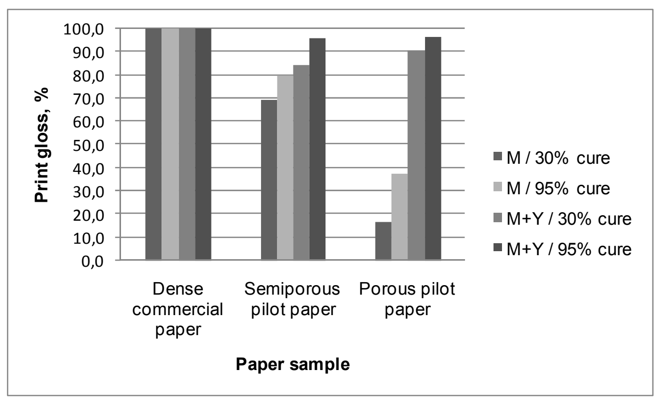


***Figure 3**. Print gloss on different papers, measured from magenta area (100%) and magenta + yellow area (200%).*

The differences between the papers in print density were similar, although not as remarkable as with print gloss (figure 4). The *dense commercial paper* had the highest print density and the *porous pilot paper* the lowest. We can assume that this is due to ink penetration due to coating structure; partly due to colorant penetration, and partly due the whole ink penetration and thus reduction of print gloss (which further affects print density).

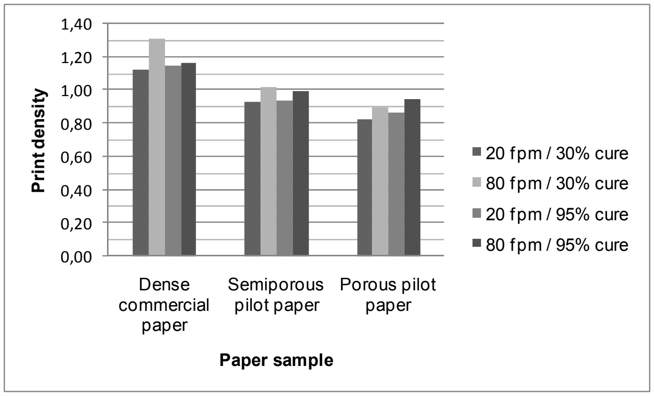


***Figure 4**. Print density on different papers, measured from area printed with magenta ink (100%). Percentages in figure refer to the power of final curing.*

From the figure 4 we can also notice, that printing speed has some effect on print density. In all the cases, the higher speed leads to higher print density. This is probably due to shorter setting time of the ink and therefore, better ink holdout. It is also presumable, that change in printing speed might slightly change the drop volume, and therefore, also the amount of applied ink.

Ink curing degree

Quite naturally, the final curing power had the strongest effect on curing degree (figure 5). Lower power usage leads to lower curing degree. Use of pinning improves curing degree. Pinning has the strongest effect, when curing degree is low, i.e. when the final curing power is at a lower level.

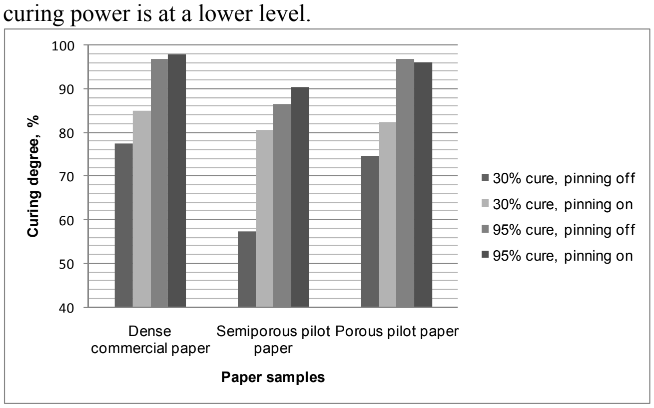


***Figure 5**. The curing degree, measured with NIR spectroscopy. The effect of final curing and pinning on curing degree is presented on different papers.*

Interestingly, paper has also some effect on curing degree, but these effects cannot be explained totally by porosity. The highest curing degree is achieved with the *dense paper*, on which the ink stays at the paper surface. However, the lowest curing degree is reached with the *semi porous pilot paper*, not with the *porous pilot paper*. This indicates that there are some interactions between the ink and paper components, which affect to ink curing. Binder content of semi porous paper is clearly higher than that of porous paper, which could be related to this observation.

Printing speed had some effect on the curing degree. Lower speed resulted a longer curing time, therefore also higher curing degree. The difference is rather small, although consistent. The effect of ink amount (one vs. two inks) is negligible.

Conclusions

Paper requirements in UV inkjet are quite different than for water-based inkjet. High porosity is not a required feature of the paper. Quite the contrary, high porosity reduces strongly print gloss and density due to increased penetration of the ink. Although ink penetration can be reduced by adjusting printing parameters, this makes the process quite sensitive; one change (e.g. variation of the printing speed) might change the output quite radically. Therefore, dense paper is more robust for the process variations and therefore easier to use. As a drawback of dense structures, control of ink spreading is more critical. Actually, offset type grade might work pretty well in UV- inkjet, if the printing system is equipped with intermediate driers. Although curing degree was rather high when the dryer was used properly, care should be taken to avoid curing problems due to under-curing.

Acknowledgements

This study was financed by Paper companies Stora Enso, UPM-Kymmene, M-Real and Myllykoski as well as Tekes - the Finish Funding Agency for Technology and Innovation.

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