

VDP on Packaging— Elementary Velocity Study on Inkjet-printed Papers for Corrugated Board Production

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Abstract

The idea of the “HybSpeed Printing” Project at Innventia AB is to facilitate the combination of a conventional printing process with inkjet printing, in-line, in the converting process. Inkjet print is “the” printing technique for adding variable data to a conventional printed layout (van Daele, 2005). It is already available, but the current processes do not guarantee high-quality print at high speed, but the constant progress in inkjet technology will mean that this is soon provided. The aim of the present project is to evaluate the practicability of attaining high-quality variable-data print (VDP) at high speed.

In 2008, an exploratory test was conducted on a Kodak Versamark DP5240 in Örnsköldsvik, Sweden, in cooperation with the Digital Printing Centre (DPC). As already mentioned, speed is probably the greatest issue facing the inkjet system. Flexo presses, for example, are running at a speed of 1000–1500 fpm, but the maximum speed of the inkjet test rig at DPC is 1000 fpm (5.08 m/s). Hence, this inkjet unit almost achieves the minimum requirements in speed. The question is how does the inkjet print quality at maximum speed differ from that at lower speed?

The results reveal that speed has a slight influence on the print quality and that the line thickness and print density can be compensated for by changing the print layout. To minimize the line raggedness at high speed, other counter-measures

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have to be considered. However, the choice of paper had a greater influence and these issues are also discussed.

Introduction

The key functions of printing on primary and secondary packaging are to provide end-users with all the information they need in a well-structured way and, most important, to attract their attention. The competition between products has become more decisive and it is becoming more difficult to attract the attention of the consumer at the point of sale (PoS). Further, for everyday commodities, most purchases are in-store decisions (Ambrose, et al., 2003; Calver, 2004; Meyers, et al., 1998; Paine, 1992; Shimp, 2008). For example, the amount of cereals offered in a large supermarket sometimes exceeds 30 different kinds. Hence, the product's outstanding features compared with those of competing products are vital. This, of course, is a difficult task, because all competitors have the same objective: to sell their products. Therefore, new developments are always necessary to facilitate new printed features. Such new features could be temporary promotional prints or personalized pharmaceuticals for patients. There are not many ways to achieve such features, but inkjet printing could be a solution.

Inkjet printing is a widely used technique, but not in packaging printing. It is occasionally used for marking jobs on tertiary and secondary packaging (Ashley, et al., 2003). Nevertheless, inkjet printing heads are nowadays very sophisticated and with continuing development they will soon be capable of meeting the requirements for secondary and primary packaging printing (Nicolay, 2008). Therefore, it is necessary to combine high print speed with high print quality and multi-color printing. The major advantages of inkjet are that it is a non-impact process (NIP), that its flexibility allows variable-data printing (VDP), and that it can be used on many different types of substrate. Thermal inkjet (TIJ) and piezo inkjet (PIJ) already show very good progress in print quality compared to conventional printing systems, but the lack of speed is still a critical factor. Both systems are widely used in wide- and grand-format printers, barcoding, and mailing applications (Lynn, 2009). Continuous-inkjet (CIJ), on the other hand, as Lynn (2009) describes, can print at high speeds and dominates small character marking. CIJ would fulfill the requirements for in-line integration, but it is lacking in quality compared to TIJ and PIJ. A mix of all these systems would be necessary, but since speed is more important for in-line integration than print quality, CIJ should be used. In general, inkjet printing is not profitable when printing large quantities, because prints with conventional printing systems pay off when a certain number of copies are reached (Viström, 2004). Inkjet prints, however, always have the same high costs per copy and at a certain point the conventional systems undercut this line and offer cheaper prices per copy. Therefore, inkjet is not a technique to replace printing systems like flexography

or offset. It will more likely be a support system to enhance the print value and to facilitate new printed gimmicks.

In some industry sectors it is common to use hybrid systems to enhance the product or production process. In general a hybrid technique is a combination of two different technologies or processes (Kipphan, 2001; Viström, et al., 2006). In hybrid technology, the elements involved combine to offer completely new possibilities. In printing, this would lead to the logical conclusion to combine different printing technologies in a single print. In general this would mean combining a conventional printing system, such as flexo or offset, with an inkjet system. Inkjet print is the best printing technique to add variable data to a static layout (Aboody, 2005). Personalization and variable data are the new marketing tools in medium mass production and niche products (Eccles, 2008; Starck, 2008). This variable data could consist of regional or seasonal contents, local languages, barcodes, or anything else that could be customized on packaging.

This study examines the applicability of a hybrid system including an inkjet unit on packaging papers for corrugated board. Printing speed is one very important factor because for in-line integration certain speeds are necessary. A conventional printing machine, die-cutter, or gluing/folding machine requires a speed of at least 1000 fpm or higher. As mentioned, CIJ can reach such high speeds, but the question then is: "How good is the print quality?" Therefore, a series of tests was initiated to investigate how the printing speed affects the print quality.

Preparation and Test Setup

The test system used was a Kodak Versamark DP 5240 (CIJ), which can print in a resolution of 240x240 dpi at a speed of 1000 fpm (5.08 m/s). One of these printing systems is installed in a printing rig at the Digital Printing Center (DPC) in Örnköldsvik, Sweden. The single color DP5240 system is equipped with a Printhead Interface Controller (PIC), and it prints with water-based dye ink (surface tension: 42 dyn per cm at 77°F) over a printing width of 1.07-in. (2.71 cm).

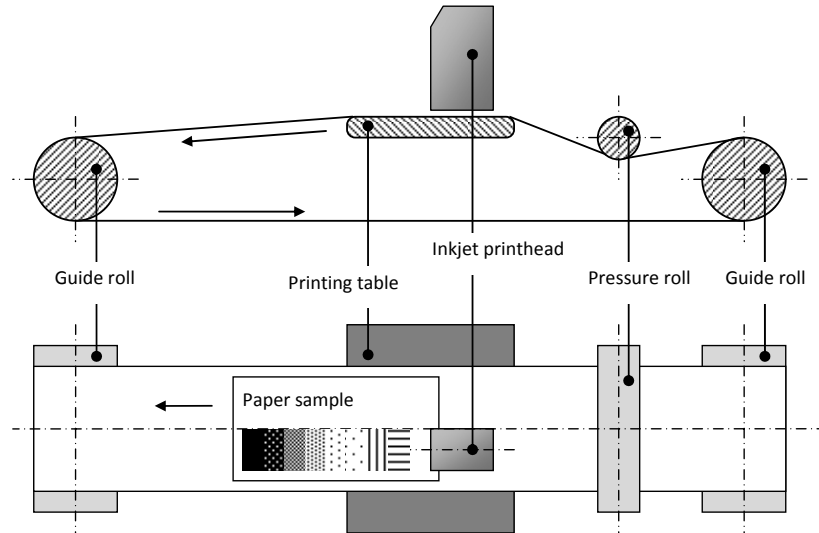


Figure 1. High-speed inkjet printing test rig at DPC. Kodak Versamark DP5240 inkjet unit printing on paper samples mounted on an endless belt.

The printing system is also equipped with a RIP system (raster image processor) to load the printing layout, convert it into an understandable format for the inkjet printer, and send it to the printer head. The high-speed printing test rig, as illustrated in Figure 1, is designed as an endless belt system and paper samples can be attached to this belt. One of the guide rolls is powered with an electrical motor which can accelerate the belt up to 10 m/s (1969 fpm). The speed of the belt can be set with a manual speed actuator.

To trigger the DP 5240 a speed signal is sent from the electrical motor to the printing system. This signal tells the printing head the frequency at which the ink drops are to be accelerated. To ensure accurate triggering, the printing system must be calibrated before printing so that the printed line is the correct length. When printing a full-tone area, for example, the print can be overfilled with ink or the lines can be too far apart and the paper surface becomes visible. Neither of these effects is desired, and therefore the triggering is vital when printing at high speed.

A further communication channel is required to inform the printing head when to start the printing. Therefore, a light barrier is installed at a defined distance from the printing head. When this barrier is broken by the paper sample, the printing system is on standby for a given time before it starts to print the test pattern. Beneath the printing head there is a printing table to provide a flat surface. Moreover, to achieve a 100% flat paper surface, a pressure roll is

installed just before this table and the table is therefore slightly elevated compared to the pressure roll and the subsequent guide roll (see Figure 1).

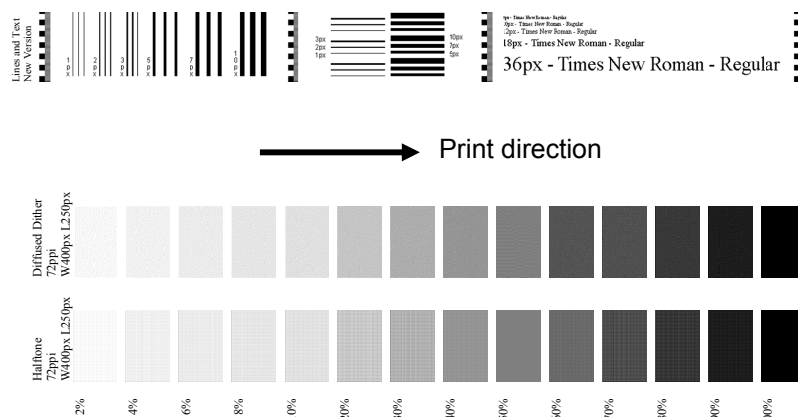


Figure 2. Print layout; top: lines (1–10 px) and text (8–36 px), bottom: gray tones in halftone and diffused dither (generated with Adobe Photoshop; W400px = width 400px and L250px = length 250px)

The arrangement of a high-speed printing test requires not only a reasonable printing system but also a proper print layout. In this study two different papers were printed at different speeds. To assess their performance, the following printing evaluations were chosen: line raggedness and thickness, gray tone mapping, mottling, color ($L^*a^*b^*$), print density, and microscopy images. In addition, the absorbency, surface roughness, mottling, and whiteness of the paper were determined. The print layout is shown in Figure 2. The layout includes lines in different thicknesses (1, 2, 3, 5, 7, 10 px), and each line was printed then three times in a longitudinal and transverse direction. The text was printed in Times New Roman in 8, 10, 12, 18, and 36 px. The second part of the print layout was the gray tone; two different modes were used in Adobe Photoshop CS2 to create the gray tone boxes, which are halftone (HT) and diffused dither (DD). The stepping for both modes between the gray tones was 2% between 0% and 10% and 10% between 10% and 100% (see Figure 2).

As already mentioned, two different types of papers were used: a white-top single-coated liner with a grammage of 170 gsm (N4) and a brown kraftliner (N7) of 140 gsm. The papers were conditioned at 23°C (73.4°F) and 50% R.H. for 48 h before printing, stored in a light-protected casing, and then kept in this environment until all the measurements and evaluations were completed. The notations N4 and N7 are used to facilitate comparison with further upcoming publications. The final print was accomplished in three different speeds—low

(98 fpm, 0.5 m/s), medium (394 fpm, 2 m/s), and high (984 fpm, 5 m/s)—and the water-based ink had a black color.

Paper Testing

In Table 1 are listed the paper tests used, and the first two methods characterize physical properties of the paper and the last two optical properties. The surface roughness was determined using the FRT MicroProf® method. This is a non-contact method, and surface height profiles indicating roughness and waviness can be acquired. It is based on chromatic aberration where white light is split into different colors focused on different heights. The light reflected by the surface is analyzed, and the data are computed into a topographical image (Rehberger, et al., 2006). This method is not a standard method for measuring paper surface roughness, but it was capable of analyzing both papers, N4 and N7, with high precision. The measurements with MicroProf are very dependent on the resolution of the detection sensor. Changing the detection frequency changes the surface roughness values. The higher the frequency the greater is the measurement of the roughness in the micro-scale range. For this testing a resolution of 3x10000 px (x-y) was chosen in a range of 80x20 mm, leading to a resolution of 2 µm in the y-direction. The detection rate was reduced to 100 Hz, because the rougher surface of the N7 paper generated missing values at 1000 Hz. A slower detection rate allows light to be sent over a longer period, and the chance for the instrument to collect sufficient reflected light information from the surface is increased.

Table 1. Methods used for paper properties.

Surface roughness	MicroProf® (FRT, Germany)
Wetting behavior	DAT-1100 (Fibro, Sweden)
Mottling	STFI-Mottle (Innventia AB, Sweden)
Color, whiteness	SpectroDens (Techkon, Germany)

The DAT-1100 is a dynamic contact angle tester measuring the wetting behavior when a de-ionized water drop with a volume of 4 µl is placed on the sample surface. A CCD camera captures images of the drop with a maximum frequency of 1000 Hz and sends these images to a computer, where each drop image is dimensioned. The program measures drop base b and drop height h (Ek, et al., 2009) and calculates from these two values the contact angle θ , drop volume V , and drop area A over the set time range (Figure 3). With these values the absorption can be determined exactly and conclusions can be drawn about the ink setting. In the testing procedure, 8 drops were applied on each of the four paper strips and for each paper type (N4 and N7) a total of 40 drops were examined.

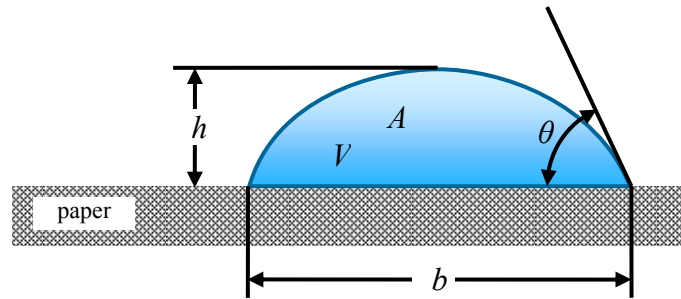


Figure 3. Diagram of the drop on the paper surface during the wetting process; contact angle θ , drop area A , drop base b , and drop height h is measured.

Both paper mottling and paper whiteness are measured with the same device and with the same procedures as described in the next section.

Print Quality Testing

Table 2 lists the test used to assess the print quality. Paper color and print color were both measured with the Techkon SpectroDens, applied respectively on unprinted and printed areas, the 40 % halftone (HT40), 40 % diffused dither (DD40), and full-tone (100). The measurement settings were “LAB-Whiteness/Yellowness,” Polarization filter “Off,” “Absolute White” reference, Density filter for “DIN 16536,” Yule-Nielsen factor at “1.0,” “D50” illumination, and “2 degree” observer. Each paper type was measured 5 times on 3 different samples, giving 15 values for each sample area (paper, HT40, DD40, and 100).

Print density also was measured with the SpectroDens, with similar settings and the same procedure as the previous testing. The device settings for this measurement were changed to “Densities CMYK” and polarization filter “On.”

Table 2. Tests for print properties.

Color	SpectroDens (Techkon, Germany)
Density	SpectroDens (Techkon, Germany)
Mottling	STFI-Mottle (Innventia AB, Sweden)
Line raggedness	Print Sharpness (Innventia AB, Sweden)
Line thickness	Print Sharpness (Innventia AB, Sweden)
Microscopy images	Hardware: Axioplan 2 (Zeiss, Germany); Software: ImagePro-Plus (Media Cybernetics, USA)

The method used to analyze paper mottle and print mottle was the STFI-Mottle method, developed by Innventia AB. Johansson (1999) describes mottle as optical inhomogeneity, unevenness in optical density and print gloss. The software which collects and evaluates the data is called STFI-Mottling Expert 1.0 and it can be run on any PC-System with almost any flatbed scanner. A calibration wedge strip is placed in the flatbed scanner and is a part of the scanned image. This strip consists of ten NCS (Natural Color System™) grayscale cards. Since the reflectances of the ten NCS surfaces are known, the grayscale can be used to calibrate and translate all the scanned grayscale values into correct reflectance values (Christoffersson, 2004). Human perception is sensitive to variations within the spatial wavelength range of 1–8 mm, and other wavelengths are therefore excluded from the frequency analysis. The mottle is reported as the % coefficient of variation in reflectance. Two samples from each paper type were tested for mottling and measurements were made on the plain paper, 40 % HT and 40 % DD and on full tone.

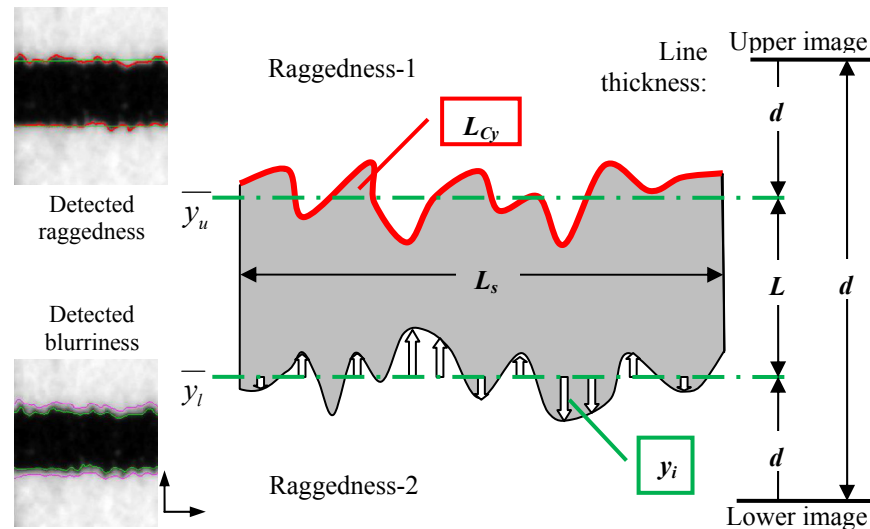


Figure 4. Print Sharpness tool to analyze line raggedness, blurriness, and line thickness. Raggedness-1 (top) and -2 (bottom) are two different ways to quantify the edge imperfections of a line. The line thickness L_t (right) is the distance between the two mean lines.

Print quality is usually not only related to color quality but also to line quality. Innventia developed the Print Sharpness tool where scanned line images are analyzed. The tool can calculate four different values, line raggedness 1 and 2, line thickness, and line blurriness. The line blurriness option evaluates the width of the transition zone (25–75 % reflectance range) between line and paper. Because of the dark brown color of the N7 paper, it was not possible to run this

test. The difference in grayscale between line color, transition zone, and paper color was too little to distinguish any blurriness. This test is therefore not included in the testing procedure.

Raggedness can be calculated according to two different principles, raggedness-1 (R_1) is the relative excess contour length (L_{Cy}) in relation to a straight line (L_S) and the perfect contour is 1. The indicator “y” in L_{Cy} indicated whether the upper or lower part of the line is calculated. Raggedness-2 (R_2), on the other hand, is the standard deviation of the contour from the mean line. The program therefore screens the scanned image of the line by its pixels in the x-y direction. It determines the y-position of the mean of either the upper or lower line edge ($\overline{y_u}$ or $\overline{y_l}$) and the standard deviation of the distance y_i between the mean line and the contour line for the entire length in x-direction. Finally, these values are converted to micrometers, based on the resolution of the original scan.

$$R_1 = \frac{L_{Cy}}{L_S} \quad (1)$$

$$R_2 = \sqrt{\frac{1}{n} \sum_{i=1}^n y_i^2} \quad (2)$$

where

R_1 = raggedness-1; the relative excess contour length in relation to a straight line

R_2 = raggedness-2 [μm]; the standard deviation of the contour from the mean line

L_{Cy} = length of contour line [μm]

L_S = length of straight line [μm]

y_i = distance between mean line and contour line [μm]; $\overline{y_u}$ upper mean line and $\overline{y_l}$ lower mean line

i = index number of distance points in x-direction; each pixel of the image stands for one “p”

n = total number of distance points in x-direction; image size in x-direction

The program also calculates the line thickness (L_t), which is the distance between the two mean lines ($\overline{y_u}$ and $\overline{y_l}$).

$$L_t = d_i - (d_u + d_l) \quad (3)$$

where

L_t = line thickness [μm]; distance between the upper and lower mean line

d_i = distance between the image borders in y-direction [μm]

d_u = distance between the upper image border and $\overline{y_u}$ in y-direction [μm]

d_l = distance between the lower image border and $\overline{y_l}$ in y-direction [μm]

The average dot size was determined in microscopy images of the dots in the 10% gray tone. Images were captured by an optical microscope Zeiss Axioplan 2 using a dark field technique in reflected light, and analyzed by using the ImagePro-Plus (Media Cybernetics, Inc., USA) commercial image analysis system (version 4.5.1). This program measures the diameter of the printed dot of five different angles and calculates an average diameter.

Results

The wetting behavior is shown in Figure 5 which presents data for a single drop on each paper type. As expected, the coated paper (N4) absorbs less than the uncoated paper (N7) of the original drop of 4 μl . The drop volume on the N4 paper is 3.5 μl , whereas on the N7 paper the drop volume is only 2.3 μl , indicating that the uncoated N7 paper instantly absorbs almost half of the original water drop. This rough paper is hydrophilic, whereas the coated paper is at first slightly hydrophobic. After 3 seconds, however, the coating surface becomes also hydrophilic. The drop area on the N4 paper increases with time, indicating that the drop is spreading. Regarding the increased absorptivity of the N7 paper, a high surface roughness is evidence of local variations in the paper structure and through the fibers. Local variations may result into varying wetting behavior, because the drop is so small that the behavior depends on which area the drop falls upon.

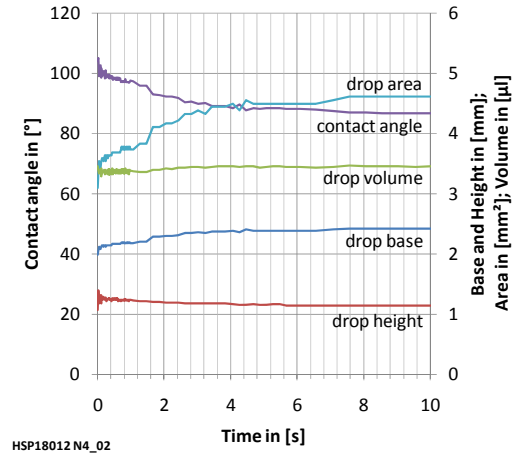


Figure 5. The wetting process of one drop on the N4 paper during 10 seconds.

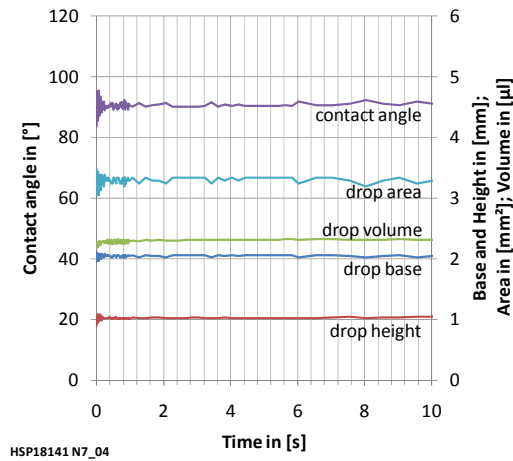


Figure 6. The wetting process of one drop on the N7 paper during 10 seconds.

Figure 5 and 6 present typical values for single drops, whereas in Figure 7 average data are presented for 0.1, 1 and 10 seconds for 40 drops. In this figure only the contact angle and drop volume are shown. What is observable in this diagram is that compared to the N4 paper the results for the N7 paper show a greater scatter which may be due to the higher surface roughness.

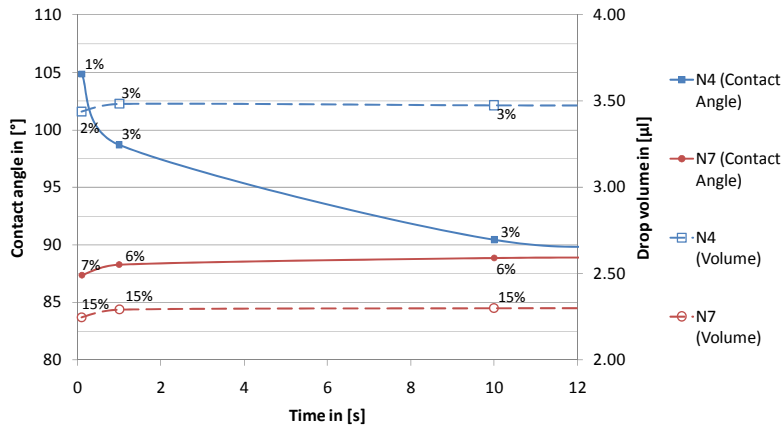


Figure 7. Average values of the wetting process on papers N4 and N7. The solid line represents the contact angle whereas the dashed line the drop volume. The blue lines are for the N4 paper and the red lines for the N7 paper. The figure shows the coefficient of variation.

Although the FRT MicroProf® is not a standard method for determining paper surface roughness, this test was the only reliable method to compare very different types of paper. As expected, the coated N4 paper has a very smooth surface with a surface roughness R_q of $5.8 \mu\text{m}$, whereas the N7 kraftliner is very rough with an R_q of $8.5 \mu\text{m}$, as shown in Figure 8.

In the following test results print quality is discussed, and the experiment was setup to test two papers at three different speeds, low (98 fpm, 0.5 m/s), medium (394 fpm, 2 m/s), and high (984 fpm, 5 m/s). The first two speed settings performed as intended, but the printing at high speed caused some problems. To achieve a flat paper and a uniform print, a pressure roll was mounted in front of the printing table (Figure 1). At the maximum speed of 5.0 m/s, the test sample required less than 1 second to pass between the inkjet print-head and the pressure roll. The rig was not equipped with a brake system, and the ink could not cure sufficiently before reaching the pressure roll. During its passage, the printed paper sample transferred part of the ink to the pressure roll, and this was then returned to the paper sample and overprinted already printed areas. This was not a problem with the N7 paper, because the ink was absorbed rapidly, but with the N4 paper it was not possible to achieve an acceptable sample, except for measurement of the dot diameter.

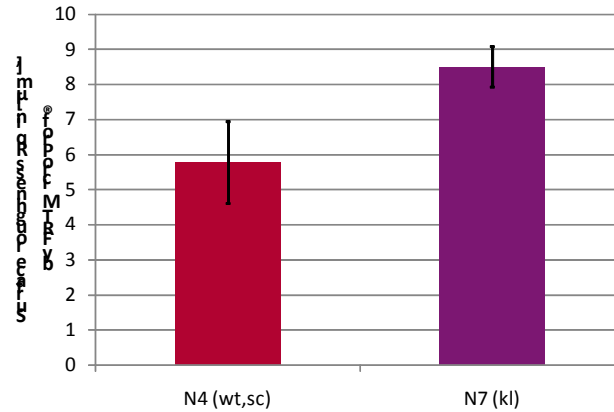


Figure 8. Surface roughness of the papers N4 and N7 measured with the MicroProf® instrument.

Figure 9 shows the mottle results for both plain paper and printed areas. The unprinted N4 paper had a very low level of mottle, whereas N7 had an almost 4 times greater mottle. With regard to the print mottle, the N4 paper shows very different results for 40% halftone and diffused dither. In halftone the mottle is two units lower than in diffused dither. This suggests that the DD is for a human being being visually more irritating than the HT component in the 40% tone. The N7 paper did not show this effect, because all speed values in HT40 are on the same level as in DD40. The paper mottle could be the reason for this effect and might yield an overlapping effect. Further studies are necessary to distinguish between paper mottle and print mottle.

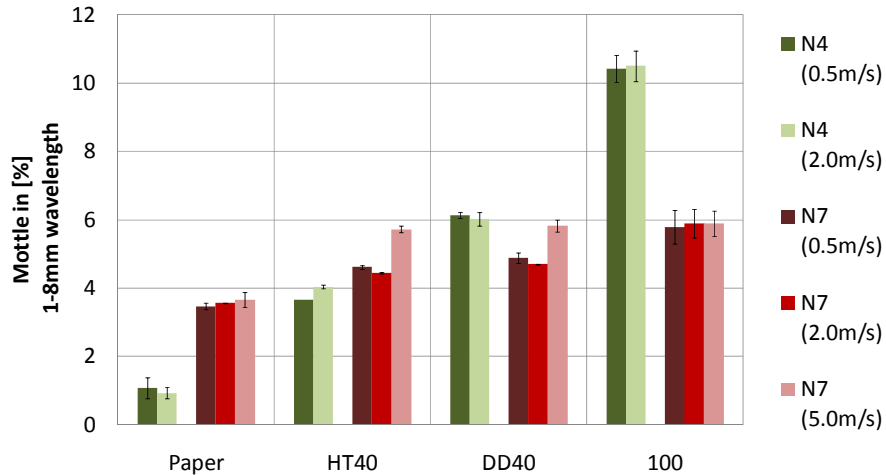


Figure 9. Mottle in the wavelength range of 1–8 mm. Analysis performed on both papers separated into the different speed steps and measured on the plain paper, 40% halftone (HT40), 40% diffused dither (DD40), and on full tone (100).

As mentioned, the N7 paper had similar results in HT40 and DD40, but related to speed they differed among each other and the sample printed at 5 m/s were significantly higher than the samples printed in low and high speed. The high-speed samples had in HT40, DD40, and full tone similar value, but in full tone all the N7 samples had the same value regardless of speed. The high mottle in full tone on the N4 liner can be explained by the fixed drop volume ejected from the inkjet print head, so that a greater amount of ink was applied. This led to a blurry print because converging ink drops formed local macro-dots on the surface. Those macro-dots led to brighter and darker spots in the full-tone area and in consequence an increased print mottle. The results showed not only a dependence on the type of paper but also that the speed has a rather high influence.

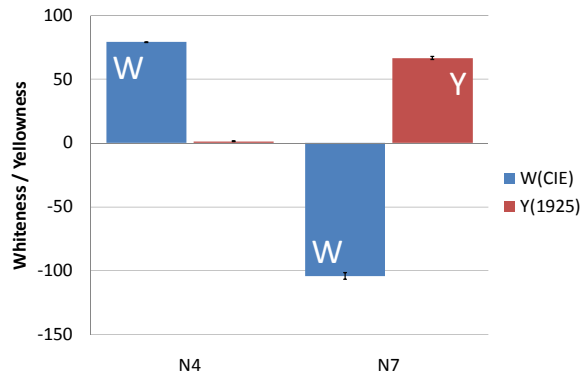


Figure 10. Whiteness (blue bars) and Yellowness (red bars) values for the papers N4 and N7.

Figure 10 shows that N4 had a pure white surface, whereas the N7 had a dark and yellowish surface. In another way presented, a similar outcome can be seen in Figure 11, where the L^* value is above 90 for the N4 but is slightly below 60 for the N7 paper. Furthermore, this figure also shows data for the printed areas. For both papers (N4 and N7), the L^* value for the HT40 point was marginally lower than for the DD40 spot. Therefore, the difference between both papers was significant and the N7 paper throughout had a decreased L^* value and this because the paper surface is partially visible. In the full tone no paper surface is visible, and the print on the N4 paper has an L^* value only 5 units higher than on the N7 paper. There is no clear effect of speed on mottle.

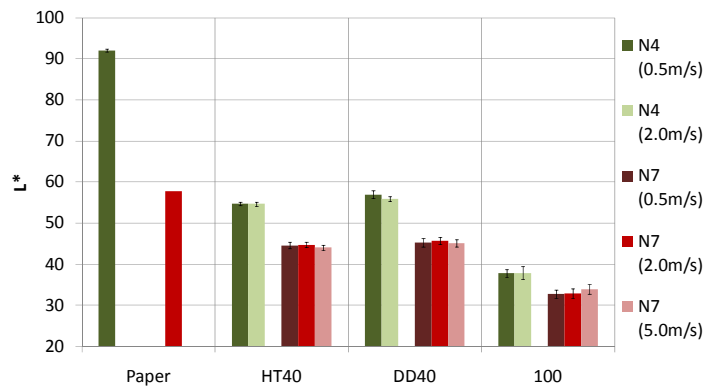


Figure 11. The L^* value for the two papers measured on the plain paper and on 40% halftone (HT40), 40% diffused dither (DD40), and on full-tone (100) printed at different printing speeds.

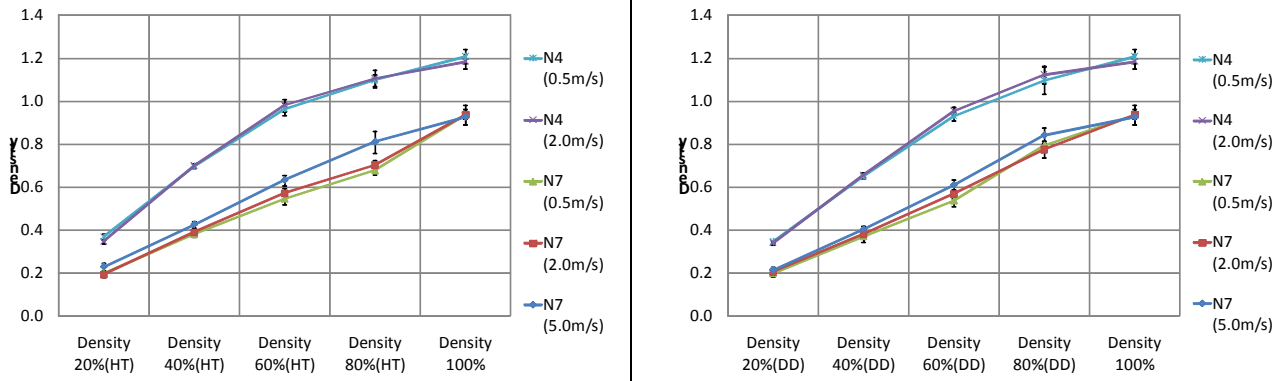


Figure 12. Density measured on 4 different areas, 20%, 40%, 60%, 80%, and 100%, in halftone (left chart) and diffused dither (right chart) and on both papers, printed with different velocities.

Figure 12 shows print density data divided into halftone and diffused dither. The print density on N4 in HT and DD is higher than on N7. This is probably a consequence of the wetting behavior, because a lower absorption leads to more ink on the paper surface and a higher ink film thickness = higher print density. The two diagrams are very comparable because the two papers show similar trends between HT and DD and the values are almost the same. The type of grayscale chosen does not therefore influence the density outcome. The speed did, however, influence the result. It can be assumed that at the higher speed the ink is more spread onto the paper surface and is less absorbed into the paper. The microscopy images might clarify this.

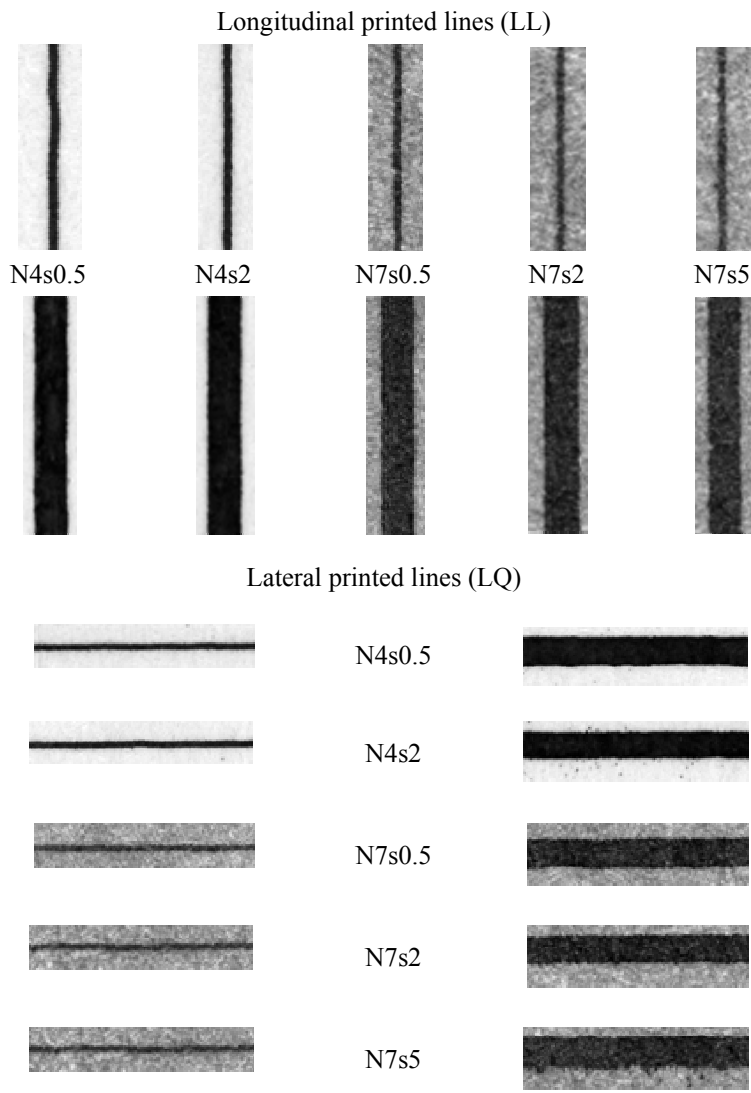
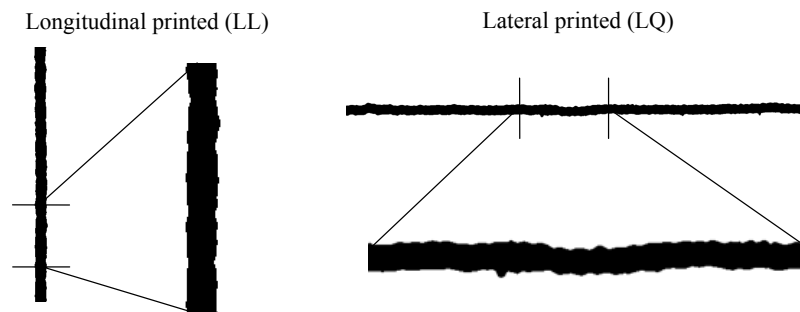


Figure 13. Examples of printed 1 px and 7 px lines on N4 and N7 with different orientations printed at different speeds. The longitudinal printed lines are to the left and the lateral printed lines to the right. The “s” indicates the printing speed (N7s0.5 stands for liner N7 and printing speed of 0.5 m/s)

Line quality is an important print quality factor, and both line raggedness and thickness are significant. Figure 13 shows examples of scanned lines in different

thicknesses and orientations printed on both papers at different speeds. The longitudinal 1 px line of N4s0.5 is rather curved whereas the N4s2 line is straight. This effect can be due to vibrations in the rig system and though the belt, which may be rigid at faster speeds. The longitudinal N7 lines are presumably influenced in the same way, but due to the rough surface it has less impact. The lateral printed lines are in general more wavy and ragged, due to the principle of the printing system. A longitudinal line of, e.g., 1 px is dependent only on the ink drops from a single nozzle, whereas the lateral line depends on several drops and all these drops have to strike the surface at the same time to produce a straight line. If there is only a slight deviation, the line becomes ragged and a greater delay waviness. Figure 14 illustrates this effect, the longitudinal line being straight with a minor ragged edge and the lateral line being wavy and very ragged. Both the lines were scanned from the same paper sample and the same printing. This image was then processed into a B/W image to emphasize the edges of the lines.

Figure 14. B/W images of 1 px lines printed at the same speed, showing the evenness/raggedness between longitudinal (LL) and lateral printed lines (LQ). The LL line is straight but slightly ragged. The LQ line is very ragged and also quite wavy.



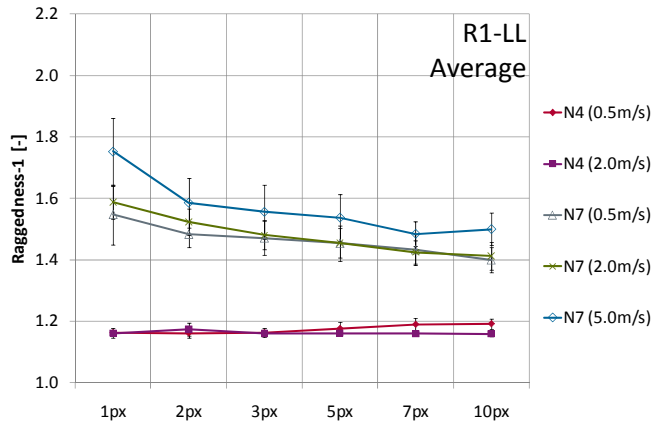


Figure 15. Raggedness-1 results for the two papers for several line thicknesses printed at different speeds. (longitudinal (LL) printed lines)

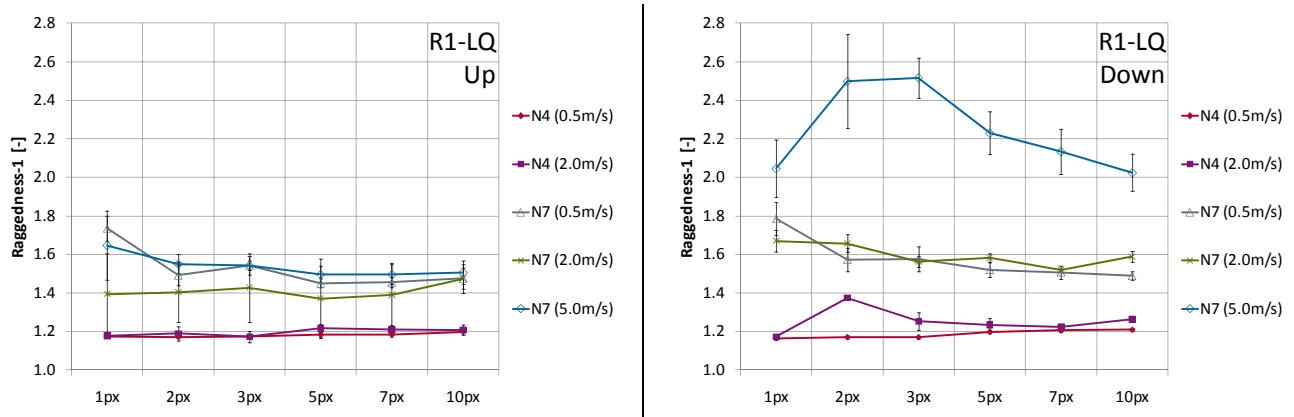


Figure 16. Despite Figure 15, the raggedness-1 results of LQ lines are separated into upper (left diagram) and lower line raggedness (right diagram). Especially the N7 paper at a speed of 5.0 m/s shows a great difference between the two sides of the line.

The raggedness-1 values for both sides of the lines were calculated separately and averaged in the diagrams of Figure 15. The N4 lines at the bottom are almost perfect lines (=1). The N7 lines are in comparison very ragged; the thinner the line the more ragged was being the edge. The raggedness increases with increasing speed, but as with lower speeds it decreases with increasing line thickness.

The R1-LQ chart is not shown as an overall average but is shown separated into the upper and lower lines. The reason for this separation is the high standard deviation and, as can be seen in Figure 16, the two curves are very different. On the upper sides (left chart), the results are similar to those for the LL lines, but no speed effect is distinguishable. The lower side of the line (R1-LQ down, right chart), however, shows a great influence of the speed. The N7s5 has a severe breakout, beginning with the 2 px line, which gradually levels off after the 3 px line.

Figure 17 shows this difference. Two lines are shown of similar thickness, but printed at different speeds. The upper line was printed at a speed of 2 m/s while the lower line was printed at the highest speed of 5 m/s. The difference between these lines is obvious. The lower line has severe breakouts on its trailing edge. One explanation could be that the drop expelled from the inkjet head strikes the paper surface first with its tip and since the paper is moving at a speed of 5 m/s, the drop did not completely settle on the same spot. The N7 paper is very rough and the ink drop is forced into the pits of the fibers, which act as channels for the ink. This is reflected in the sample printed at high speed, and the very ragged lower side of the line.

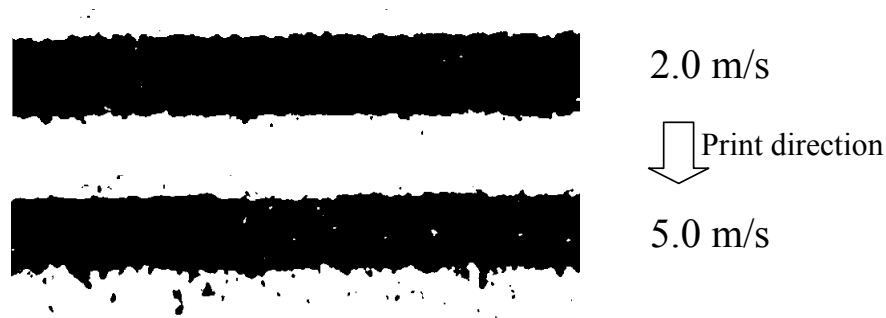


Figure 17. B/W images from the 7 px lines printed on paper N7. The difference between the two speeds is clearly visible. The lower side of the 5 m/s line is much more ragged than the 2 m/s line.

The line thickness results were surprising because the longitudinal printed lines (LL) showed an increasing line thickness throughout the measurements (Figure 18). The 1 px line is only slightly increased, but beginning with the 3 px lines there is a constant thickness increase of about 180 μm . This of course is no problem in real printing, because it can be counteracted by decreasing the number of pixels to achieve the desired line thickness.

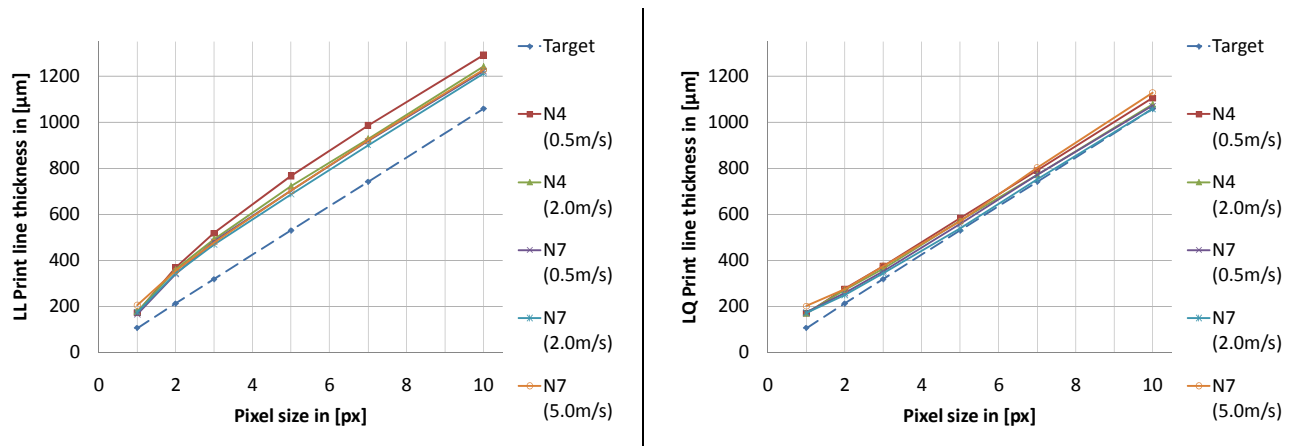


Figure 18. The print line thickness; to the left from LL lines and to the right from LQ lines. The dashed blue line is the calculated target line; 240 dpi \rightarrow 1 px lines have a target thickness of 106 μm .

A similar and very effective approach is used to counteract dot gain in flexographic printing, because when the dot size is too large the film dot is reduced so that the final printed dot size then matches the original dot size. The more surprising fact is that the LQ lines show no similar effect, but show an almost perfect line thickness. This is accompanied by the previous raggedness results, because they gave a very uneven line and in consequence it would be expected that the line thickness in LQ is greater than in LL. These results are the other way round and this requires further tests.

In another part the LL and LQ lines give, however, a similar result. Both show the same increase in line thickness of 1 px lines, and they are enlarged by around 70 μm . There is only one exception, the N7s5 high-speed samples which show a higher increase in the line thickness of 100 μm (orange line in Figure 18).

Figure 19 shows dot sizes calculated from microscopy images of the 10% tone on the printed paper. This figure also includes the N4s5 sample, although it was not possible to obtain any acceptable print sample from the coated N4 sample at high speed. It was, however, possible to measure some single dots and the result is included in the figure.

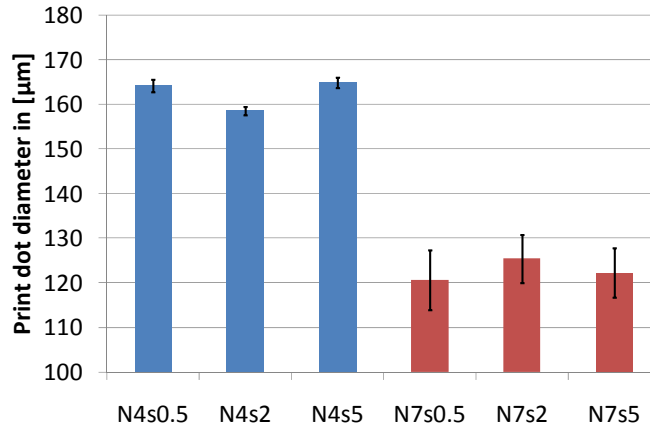


Figure 19. Dot diameter of printed dots on the two paper samples of different speeds. The images were captured with an optical microscope using dark field technique in reflected light. Note the additional sample N4s5, which was only available for this test.

In Figure 19, the most obvious difference is in the paper type. The dots on the coated N4 paper have an area more than 30% greater than the dots on the N7 paper. The N4 samples show a slightly decreased dot diameter at a speed of 2 m/s, whereas the N7 samples have a greater diameter compared to those at the low and high speeds. The standard deviation is greater for the N7 samples because the program could not distinguish the dot border on the kraftliner. It was, therefore, necessary to measure the dot diameter manually with the program. The suspicion that a spreading of the dot at high speed, and hence an increased dot diameter might be the reason for the slight increasing density especially in the mid areas of the gray-scale cannot be confirmed.

Conclusions and Future Work

The results show that, using this device, it has been possible to produce inkjet prints on very different grades of paper, a white coated paper (N4) and a brown kraftliner (N7). The print quality was dependent on the paper whiteness, roughness and absorptivity and was also dependent on the printing speed.

Printing speed was, despite paper properties, the most important reason for this test, but the question remains if inkjet print is capable to print in high quality at high speed and though to meet the requirements for in-line implementation.

The print mottle values for the N7 paper were influenced by speed and the high-speed samples were significantly higher in the 40% grayscale compared to the low and medium speed samples. The N4 paper was not affected by speed, but therefore it had a lower print mottle in HT40 than in DD40 because in halftone (HT) the dots are differently placed than in diffused dither (DD), and DD seems

to be in this particular case more disturbing for the human perception. Why the N7 paper was affected by speed and the N4 not and why the N4 had a difference between HT and DD and N7 not is unclear, but the high paper mottle of the N7 paper must have an influence on the print mottle result. In fulltone this effect disappeared because the paper was covered with black ink. The N4 paper showed in fulltone a much higher print mottle than N7, but this was due to an excess of applied ink. The fulltone area was overfilled by ink and formed locally brighter and darker spots which were visually visible.

The edge sharpness data were separated into longitudinal (LL) and lateral (LQ) lines with respect to the upper and lower edges of the printed line. The lower edge of the LQ line, in particular, was very ragged and especially the high-speed sample had severe breakouts. This may be because air was dragged along with the paper belt and that the resulting turbulence deflected the ink drop. In addition the ink drop was forced into the pits of the paper fibers due to the high speed which altogether caused these severe breakouts. It would be necessary to repeat this high-speed printing test and to use a high-speed camera to visualize the ink drop setting.

The print density was also affected by printing speed, but the difference between the two papers was greater. The N4 paper showed a drastic increase in print density, but this was due to the wetting behavior. In the results chapter it was presumed that an increased dot diameter was a side effect, but this cannot be confirmed because the drop size is in fact decreased at high speed.

The line thickness was not influenced by speed, but therefore the LL lines showed a significant increase in line thickness, although the LQ lines, which should have been more affected, had an almost perfect line thickness.

The print quality though of prints on fiber-based packaging papers is influenced by high-speed printing at speeds of 5 m/s (984 fpm), and factors like print mottle, print density, and line sharpness are most affected. The effects of high speed are visible, and with even more increasing speed they also might increase or new effects might emerge. This test was an elementary study to examine the runnability of inkjet on fiber-based packaging papers, but in a further test should be analyzed the practicality if, e.g., barcodes, 2-D codes are functional or to do print quality assessment by probands.

All print quality tests in this study are, however, more influenced by paper properties than by printing speed, which was expected due to the great difference between both papers. A further publication will therefore discuss the outcome of a test with 9 different paper types.

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Abbreviations

VDP: Variable-data print	HT: halftone	NCS: Natural Color System
TIJ: Thermal inkjet	DD: diffused dither	LL: longitudinal printed lines
PIJ: Piezo inkjet	HT40: 40% halftone	LQ: lateral printed lines
CIJ: Continuous inkjet	DD40: 40% diffused dither	R1: raggedness-1
PIC: Printhead Interface Controller	DAT: Dynamic Contact Angle Tester	R2: raggedness-2

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