Analysis of roughness measurements of coated cardboards

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Abstract

In recent years, the interest in printing coated cardboards with water based Inkjet inks has grown. Consequently, the demand for investigations about the interaction between low viscosity inks and the pigmented surfaces also increases. To understand these interactions is necessary to analyze several material parameters as surface energy, ink viscosity, density, porosity and also roughness. The main method to measure surface roughness, Parker Print Surf (PPS), was developed to operate under conditions close of letterpress, lithography and gravure. However offset and Inkjet inks are physically and chemically different. In this paper the correlation between PPS and other optical roughness parameters measured by means of confocal microscopy are analyzed. Moreover roughness measurements are correlated with optical density and minimal remission values. It was demotrasted that the correlation of optical roughness parameters with PPS is weak. PPS measurements show a very strong correlation with density by dye based inks but not by pigment based inks. Among other findings, it was shown that some height and functional optical roughness parameters can provide a proper correlation with the flow behavior from both dye and pigment based Inkjet inks.

Keywords: Parker Print Surf, 3D laser scan microscope, coated cardboard, inkjet print quality

1 Background and relevance

Inkjet print predominantly uses three types of inks: UV / EB-curable inks, organic solvents based inks and water based inks, which also commonly has an organic co-solvent in their formulation. Although the first two ink types show some technical advantages over water based inks such as immediate drying, they have also drawbacks. Set-off or diffusion migration caused by incomplete polymerization or residual amounts of retarders / solvents in print are undesirable co-effects. To avoid these problems there is a growing interest in printing coated cardboards with water based Inkjet inks. Under technical aspects this can be as well demanding and problematically.

The surface of many current coated cardboards is not enough absorbent and the chemistry used in coated boards is not compatible with, for example, anionic Inkjet inks [1, p. 10]. In previous papers it was demonstrated that primer application combined with drying assistance can be used to avoid print defects as smearing or set-off [2] and can also increase the print quality [3].

The amount of water in water based Inkjet inks can reach 80%, so these inks have a low viscosity. The co-solvents, among other functions, reduce the surface energy enhancing ink film formation so that the ink can be absorbed quickly, as by office papers. In coated cardboards this same ink is slowly absorbed.

The color component of the ink can be given by a molecular dye or by a solid pigment particle. In the first case the ink is a solution (dye ink). In the second case it is a dispersion whose particles can reach tens nanometers of diameter (pigment ink).

In Figure 1 these two types of water based inks – dye and pigment based - and their interactions with absorbent surfaces are illustrated. After strike, the ink droplet wets the surface and moves in 3 dimensions, then both begin absorption and evaporation of water and co-solvent. When the vehicle enters the coating layer, it starts also to move it in the three dimensions. This ends after the complete diffusion and ink drying.

Dye based ink and its colorant are absorbed remaining in layers below the surface. This reduces the print optical density and increases the minimum remission values. By pigment inks, the ink vehicle follows the same way, but solid pigments remain close to the surface filtered by the low porosity of the coating layer. This increases print optical density and reduces minimum remission values, but can also cause ink smearing, usual by coated cardboards.

Figure 1 - Inkjet ink flow on porous surfaces (based on [4])

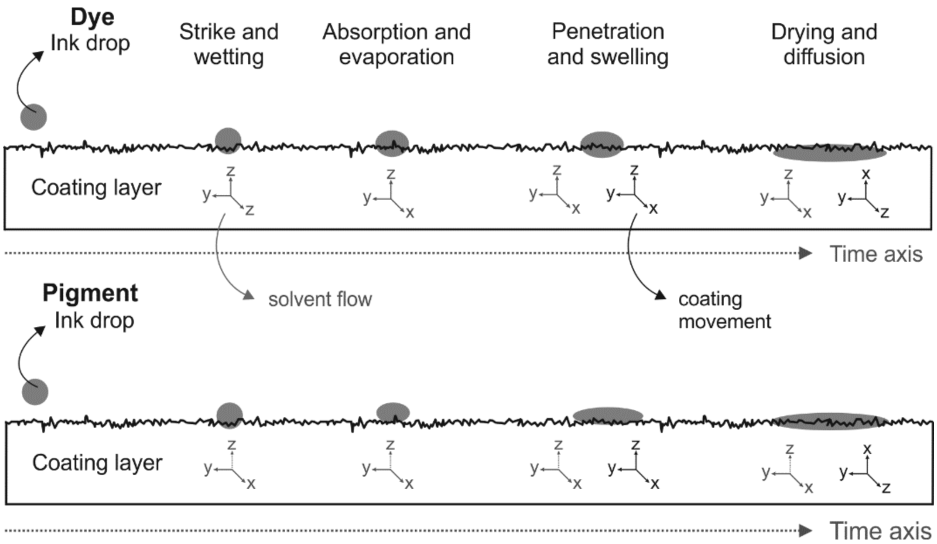


Figure 2 shows a coated cardboard surface and the scale of magnitude of the surface roughness. Left image shows the roughness measurements and the right image a cross section from the same sample. Roughness are in micrometers, since porosity (capillaries) in coated coatings can have only few nanometers. Not only porosity is related to ink permeability, but also roughness, as will be explained as follows.

It is assumed here that the roughness can influence the calculation of absorption rate due to *influence by contact angle*, the absorption rate due to *changes in surface morphology* and also the position of the ink color component on or in the coating layer (Z-axis), as showed in Figure 1.

In the Figure 3 the *influence of roughness on contact angle* is illustrated. Correction methods of contact angle hysteresis as Wenzel or Cassie-Baxter equations are large discussed in the literature and will be not deepened here. In a simplified way depending on the roughness, the angle measurement can vary $[\theta_1 < \theta_2]$. The contact angle is one variable in many equations about absorption as Laplace, Darcy Law, Lucas-Washburn, Bosanquet and Jurin Law as also in more recent approaches about liquid absorption in porous surfaces as short time equation and molecular kinetic theory.

Figure 2 – Example of area roughness measurements and cross section (in µm)

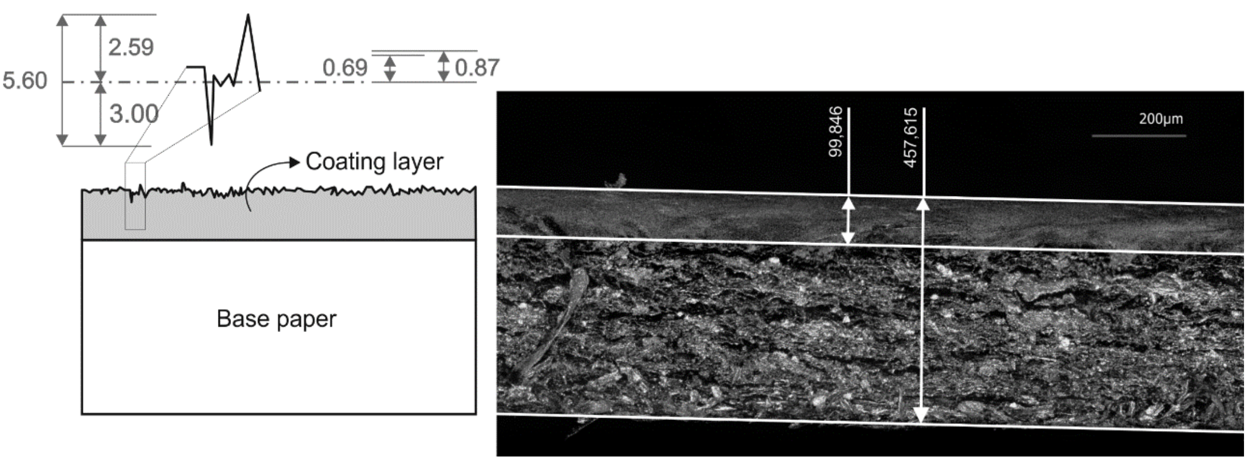
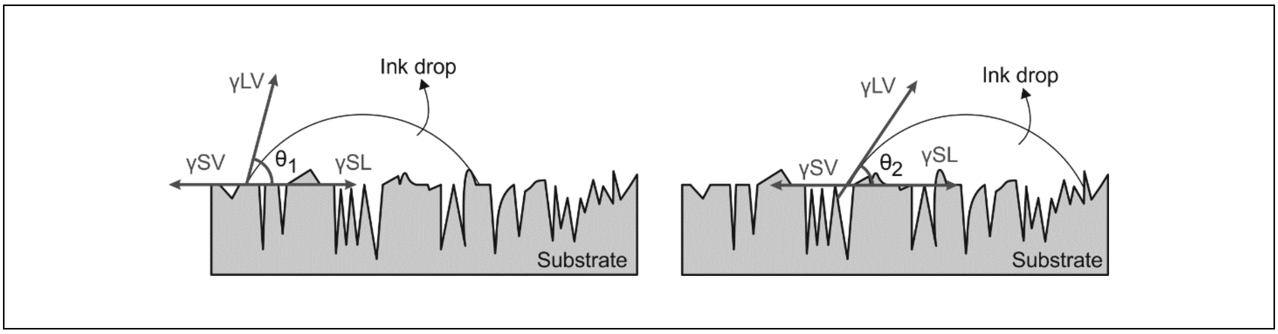
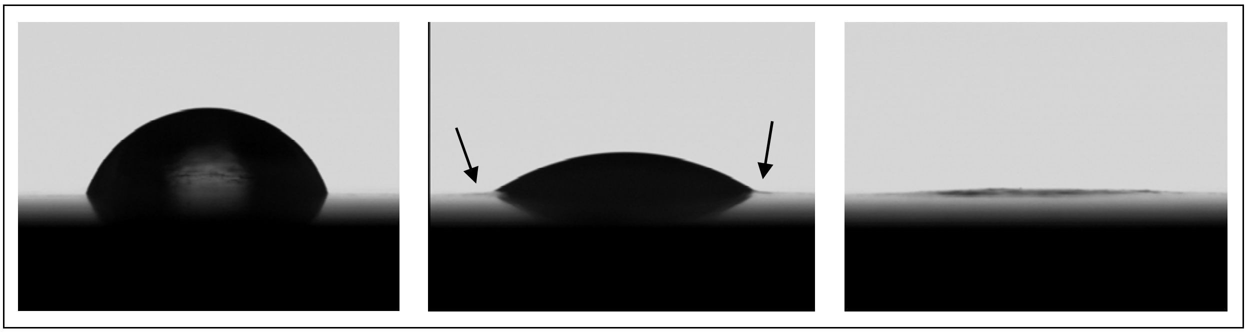


Figure 3 - Influence of roughness on contact angle



The *absorption rate can be also influenced by the roughness* due to modification of surface geometry. Three recorded frames of a 2 µl water droplet being absorbed in a pigment coating layer are shown. It is possible to observe in the second frame (about 1 minute after strike) a swell effect at the droplet edges. After about 4 minutes the droplet was completely absorbed and the surface remains geometrically changed.

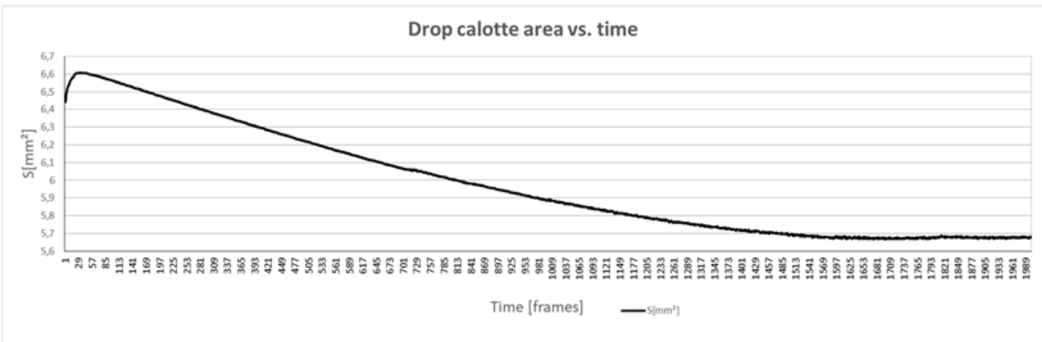
Figure 4 - Surface modification by water absorption



Frame 1 – strike   Frame 2 – after 1 min.   Frame 3 – after 4 min.

Measuring the droplet calotte area surface over time (Figure 5) is possible to see that in the first seconds after drop strike the area increase due to coating swelling. Than the absorption speed decreases and after some minutes reduces near zero. The roughness and surface geometry were changed until the thin capillaries in the bulk lose width decreasing or blocking the ink uptake.

Figure 5 - Droplet surface area over time



The number of ink variables (density, viscosity and surface energy), environmental variables (temperature, pressure, ejection frequency and drop impact velocity) and substrate variables (roughness, pore size, pore distribution, surface energy and charge) demonstrate the complexity of the study of interactions between Inkjet inks and substrates. In this study the variable *roughness* is the central point due to influences previously mentioned.

According to the standard ISO 8791-4:2007, the well-known PPS roughness measurement operates under conditions close of letterpress, lithography and gravure [5]. This method is a reference in offset printing, for example, because it has a good correlation with optical density values. Thus, it is relevant to investigate, in context of digital printing, if other roughness measurement methods have more proper correlation with print qualitative evaluations as optical density and if this other measurements correlate with PPS, as this method still has a large use on the paper and board industry, as well as in the printing industry.

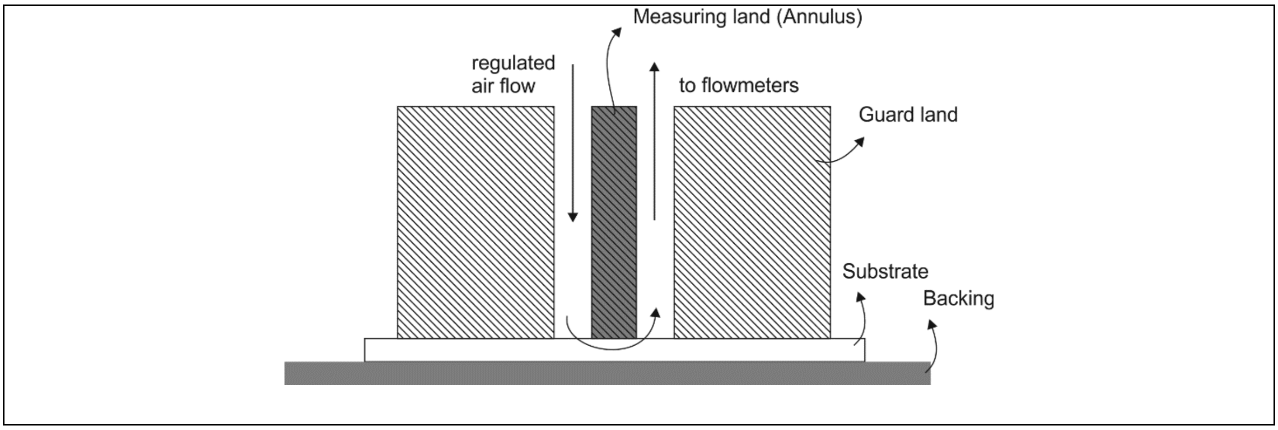
For this, the present investigation aim to analyze the correlation between roughness measurement methods, namely Parker Print Surf (PPS) and area surface roughness / line surface roughness by means of 3D confocal laser scanning microscope technics. Moreover the correlation of these roughness measurements with optical density and remission values of cardboards printed with dye and pigment based Inkjet inks completes the purpose of this experiment.

2 Fundamentals of measurement and calculation

2.1 Parker Print Surf

The PPS roughness meter is illustrated in the Figure 6. The sample is placed below a metal ring (measuring land) and above a resilient surface (backing). A controlled ejected air flow in pressured in substrate direction. The amount of air that can pass between the sample and the measuring land is measured in the other side by a flowmeter. The air flow delta is calculated and expressed in micrometers. PPS is an indirect roughness measurement method.

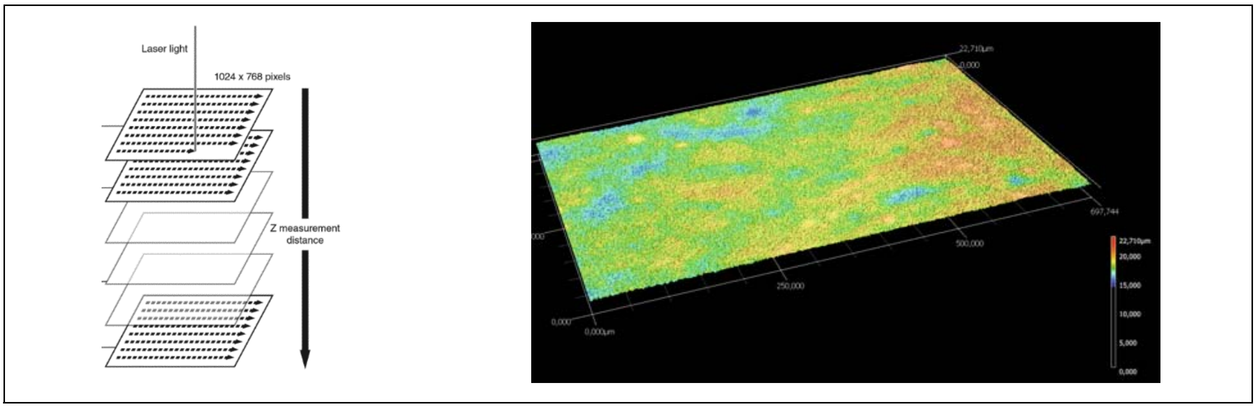
Figure 6 - Diagram of operation of a PPS roughness meter



2.2 3D confocal laser scanning microscope

Confocal scanning technique is based on grouping different focal planes to form an image (Figure 7, left). A laser light scans the surface and a photoreceptor measures the received remission. Among the main elements of image formation, a pinhole installed before the photoreceptor avoids that photons from other planes, outside the focal plane, reach the lens. The Figure 2 (right) is a 3D image of a coated cardboard. Confocal microscopy is a direct roughness measurement method.

Figure 7 - 3D confocal laser scanning microscope XYZ raster system (left) and 3D image (right)



The roughness can be measured as profile roughness or line roughness (definitions presented in the ISO 4287 *[6]*) and areal surface texture or area roughness (definitions presented in the ISO 25178-73 *[7]*). Equations used in this paper are presented in Annex A. For this investigation 40 samples were measured with both methods as illustrated in the Figure 8. The line roughness parameters, called R-Parameters, are calculated over a specified number of multiple cross sections. For this study the average of 11, 21, 31 and 61 lines with a distance from 60, 30, 20 and 10 pixels to each other respectively, in horizontal and vertical directions were conducted. The area roughness parameters, called S-Parameters, are measured over an entire surface area. The Figures 9 and 10 (left) illustrate the R-parameters presented in this paper. The S-parameters have the same properties presenting however other equations.

Figure 8 – R- and S-parameters

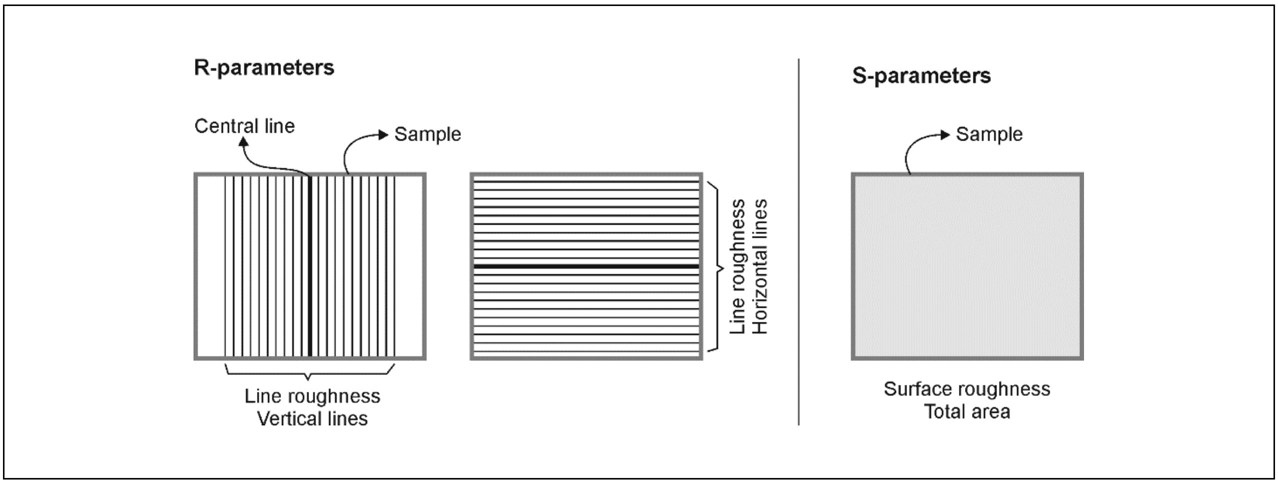
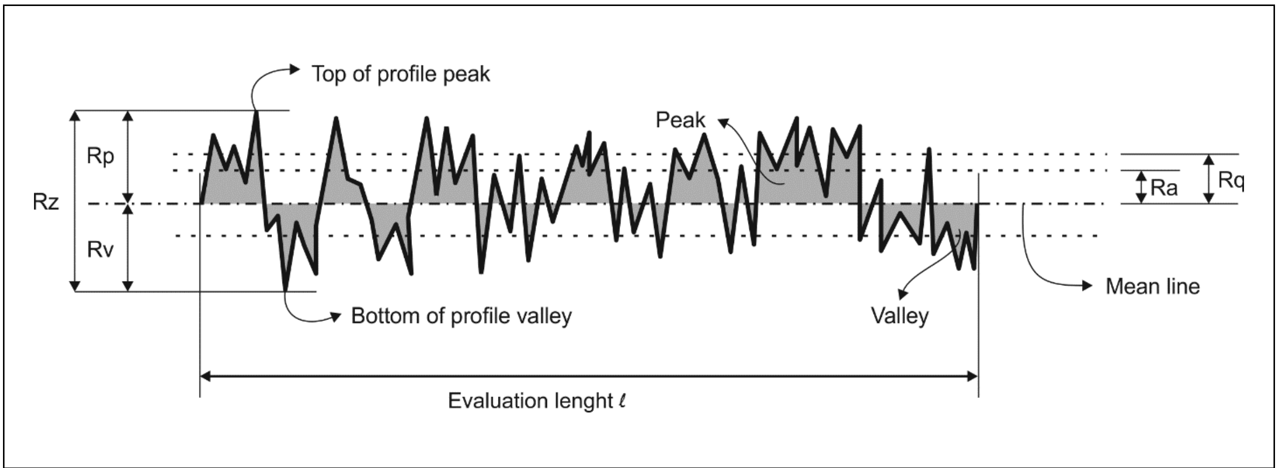
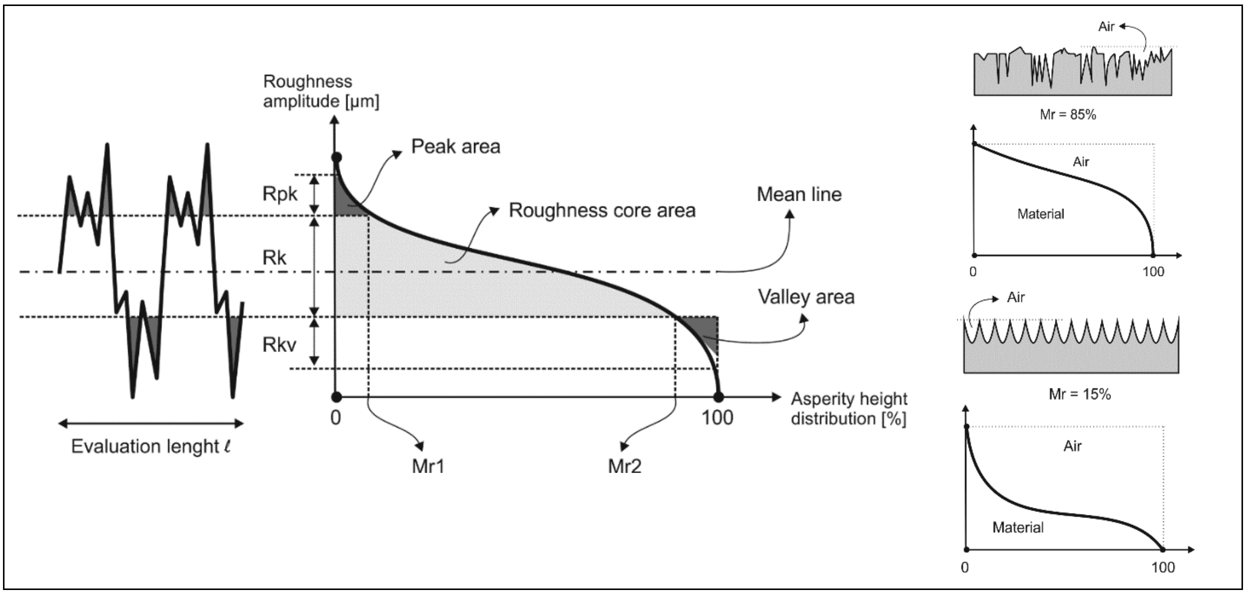


Figure 9 – Amplitude and height roughness parameters ([6], [7])



The called functional roughness parameters (equations and definitions presented in the ISO 13565-2 *[8]* can be explained by means of two material ratio curves (Figure 10, right). These curves not only illustrate the percent of material in three roughness amplitudes (higher peaks, core area and deeper valleys), but also provide a representation about the empty areas at the surface (air-filled), in the first curve the material ratio is 85% and in the second around 15%. The values from Mr1 and Mr2, the limitation edges about peaks and valleys, can vary. Default values were used in the measurements, i.e. 10 and 80% of the asperity height distribution respectively.

Figure 10 - Functional roughness parameters (s. [8])



2.3 Remission and optical density

The reflectance ϱ is the ratio between the incident light flux and the reflected light flux (Equation 1, Figure 11, left). The same principle is used to calculate the remission β, also called R or reflectance factor. Instead using reflected and incident light, β is calculate by the ratio between the light flux reflected by the printed substrate and the unprinted substrate (Equation 2, Figure 11, right). Density, in opaque objects, is given by the negative logarithm of β (Equation 3).

Remission values, usually, are given as a curve over a spectrum of wavelengths from 400 to 700 nm and optical density (from here, just density) is given as single dimensionless value.

$$\varrho = \frac{\Phi_R}{\Phi} = \frac{reflected\ light\ flux}{incident\ light\ flux}$$

Equation 1
[9, p. 465]

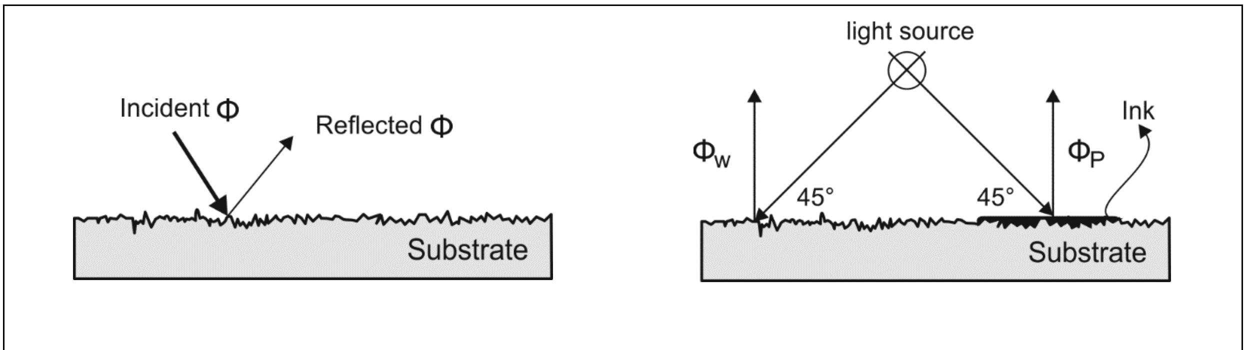
$$\beta = \frac{\Phi_P}{\Phi_W} = \frac{light\ flux\ reflected\ from\ the\ printed\ surface}{light\ flux\ reflected\ from\ the\ unprinted\ surface}$$

Equation 2
[9, p. 465]

$$D = -\log \beta$$

Equation 3
[9, p. 465]

Figure 11 - Incident and reflected remission (left) and luminous flux reflected from the printed and unprinted surface (right), based on [9, p. 465]



In fact, measurement of minimal remission or density of a 100 % black printed is the same thing. In this experiment both values are measure under different influences of OBA, FWA or UV.

The remission is not presented as a curve, but as a single value of λ = 550 nm. In this wavelength the effect of optical brightening agents (OBA) and fluorescent whitening agents (FWA) present on all cardboards and possibly ultraviolet (UV) portion present on dye base inks is not included, even using the measuring illumination condition M1. The density was calculated as usual in M1, where the effects of OBA, FWA and UV are included.

2.4 Calculation of correlation

Correlations were calculated by means of the well-known empiric correlation coefficient von Bravais-Pearson (Equation 4). The result interval is from -1 to 1.

$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i y_i - n\overline{xy})}{\sqrt{\sum_{i=1}^{n} x_i{}^2 - nx^2}\ \sqrt{\sum_{i=1}^{n} y_i{}^2 - ny^2}} = \frac{cov(x,y)}{\sqrt{var(x)\ \ var(y)}}$$

Equation 4
[10, p. 76]

This empiric correlation indicates the strength of the linear relationship between the observation pairs (x, y) and the direction of the correlation. If the correlation is positive, then the observation pairs tend to be on a straight line with a positive inclination. A perfect positive correlation is = 1. Analogously, if the correlation is negative, the observation pairs tend to be on a straight line with a negative inclination. A perfect negative correlation is = -1. The strength of the linear correlation can be classified in many ways. In this study the values were classified as presented in the Table 1:

Table 1 – Classification of correlation values [10, p. 76]

Values	Correlation´s strength
$0.0 \leq \lvert r_{x,y} \rvert \leq 0.2$	any to very weak
$0.2 < \lvert r_{x,y} \rvert \leq 0.5$	weak
$0.5 < \lvert r_{x,y} \rvert \leq 0.8$	medium strong
$0.8 < \lvert r_{x,y} \rvert \leq 1.0$	strong to perfect

3 Materials and equipment

Detailed informations about materials, equipment and software used in the experiments are shown in Table 2 to 6. The Figure 12 shows the printed test chart.

Table 2 – Materials used for the tests

Materials	Identification		Data
Cardboard	“B01” to “B07”		Seven commercial cardboard FBB and SBB (s. Table 2)
Ink	Dye	Black	Canon dye ink: CLI-551
	Pigment	Black	Canon pigment ink: PGI-550

Table 3 - Properties of cardboards

Property [Unit]					
Cardboard	Grammage	Thickness	Moisture	Layers	Type
[ID]	[g/cm2]	[µm]	[%]	[-]	[-]
B01	300 ± 5 %	365 ± 5 %	5.5 ± 1 %	2	SBB
B02	300 ± 4 %	474 ± 5 %	8.2 ± 1 %	2	FBB
B03	295 ± 2 %	505 ± 3%	8.1 ± 1 %	1	FBB
B04	300 ± 2 %	345 ± 3%	N/A	1	SBB
B05	300 ± 4 %	365 ± 4%	6.5 ± 1 %	2	SBB
B06	300 ± 4 %	395 ± 4%	6.0 ± 1 %	3	SBB
B07	295 +3 % / -5%	505 ± 5%	8.2 ± 1%	3	FBB

Table 4 - Production equipment

Equipment Manufacturer / Model	Data
Printer Canon / PIXMA iX6850	Thermal printhead technology – 1200 dpi Quality printing mode: Standard Media quality: Standard

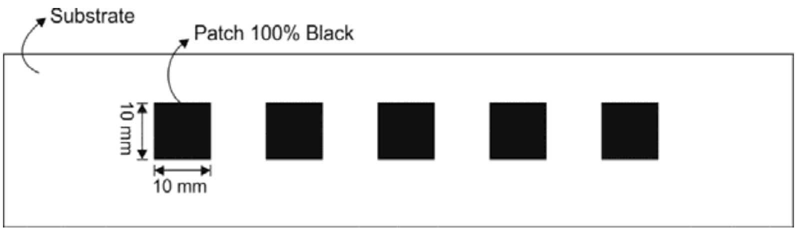
Table 5 - Measurements equipment

Equipment Manufacturer Model	Measurements [number of measurements]	Measurement data
Spectrophotometer Techkon SpectroDens	Optical density [25 per ink per cardboard] [25 per ink per cardboard]	Geometry 0°/45° Illuminant D50/2° - Measurement illumination condition: M1 White Calibration: Absolut
	Minimal reflectance of printed surfaces [25 per cardboard per ink]	Geometry 0°/45° Illuminant D50/2° Measurement illumination condition: M1 Pol-Filter: No White Calibration: Absolut Wavelength: 550 nm (to avoid OBA, FWA and UV [Ink] influence)
3D laser confocal microscope Keyence VKX150	Line and area roughness [40 per cardboard]	Objective: 20x Image resolution: 1024 x 768 pixels Image size: ≈523 x 697 µm per sample Wavelength laser: 658 nm Material ratio 1: 10% Material ratio 2: 80%
L&W PPS Tester	Roughness [10 per cardboard]	Air pressure: 1.0 MPa
Scanner Epson 4990 Photo	Scan - printed patches (Table 9)	Image resolution: Grayscale 16 bit, 1200 dpi Exposure type: photo Compression and adjustment: no

Table 6 – Software

Software and test charts	Data
Test chart design (Figure 12)	Self-design in Illustrator CS3 Output file: PDF without embedded profile
Microscope evaluation software	Keyence Multi file analyzer version 1.3.1.120

Figure 12 - Test chart for density and minimal reflectance measurement



4 Results and discussion

Firstly, the measurements overviews of roughness raw data measurements, density and minimal remission values are presented in Table 7 and 8 respectively.

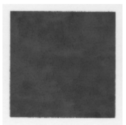
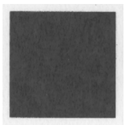
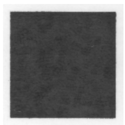
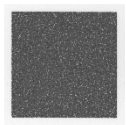
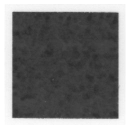
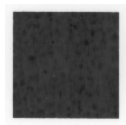
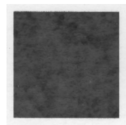
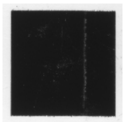
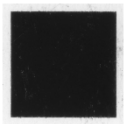
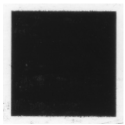
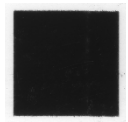
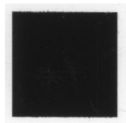
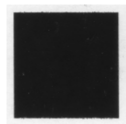
Table 7 – Roughness raw data (average), details s. Table 5

	Parameter	Unit	B01	B02	B03	B04	B05	B06	B07
	PPS	[µm]	1.700	1.330	1.020	0.940	1.360	1.190	1.180
Amplitude	Sa	[µm]	0.839	0.920	0.819	0.344	0.845	0.759	0.911
	Ra	[µm]	0.725	0.800	0.685	0.789	0.669	0.770	0.725
	Δ = (Sa-Ra)/Sa		14%	13%	16%	22%	7%	12%	15%
	Sq	[µm]	4.278	4.930	4.769	1.912	5.762	4.866	5.039
	Rq	[µm]	0.905	1.005	0.863	0.995	0.848	0.961	0.905
	Δ = (Sq-Rq)/Sq		79%	80%	82%	82%	83%	83%	81%
Height	Sz	[µm]	16.061	14.669	12.718	11.778	16.552	15.628	13.030
	Rz	[µm]	5.531	6.233	5.626	6.232	5.486	5.966	5.531
	Δ = (Sz-Rz)/Sz		66%	58%	56%	81%	62%	65%	54%
	Sp	[µm]	4.278	4.930	4.769	1.912	5.762	4.866	5.039
	Rp	[µm]	2.538	2.922	2.686	2.910	2.652	2.923	2.538
	Δ = (Sp-Rp)/Sp		41%	41%	44%	42%	49%	45%	42%
	Sv	[µm]	11.782	9.739	7.949	9.866	10.790	10.762	7.991
	Rv	[µm]	2.993	3.311	2.939	3.322	2.833	3.043	2.993
	Δ = (Sv-Rv)/Sv		75%	66%	63%	88%	69%	74%	62%
Functional	Sk	[µm]	2.663	2.870	2.534	1.072	2.657	2.345	2.846
	Rk	[µm]	2.209	2.370	2.033	2.363	1.972	2.318	2.209
	Δ = (Sk-Rk)/Sk		17%	17%	20%	28%	11%	16%	19%
	Spk	[µm]	0.924	1.089	1.043	0.458	0.972	0.991	1.149
	Rpk	[µm]	0.642	0.795	0.723	0.786	0.735	0.793	0.642
	Δ = (Spk-Rpk)/Spk		30%	27%	31%	36%	19%	26%	31%
	Svk	[µm]	1.169	1.308	1.146	0.458	1.188	1.062	1.207
	Rvk	[µm]	0.908	1.014	0.819	1.000	0.819	0.849	0.908
	Δ = (Svk-Rvk)/Spk		22%	22%	29%	31%	16%	23%	30%

Each value from R-parameters shown in the Table 7 represents the average from the 40 measurements with 31 lines with a distance of 20 pixels to each other in horizontal direction. All others measured values from 11, 21 and 61 lines as also in vertical direction were not showed here. Firstly, the standard deviations by horizontal lines were always smaller than the standard deviations by vertical lines and this phenomena occurs independently of grain direction. Perhaps, these differences are due to the fact that the by vertical lines an area in both sides of the images (s. Fig. 8) is not measured (to keep the same distance between lines in horizontal and vertical direction). This can be objective for future investigations. Second, in general the results did not depend on the number of measured lines.

Area roughness measurements show higher values than line roughness measurements. This could be expected, especially for absolute values (height parameters), because area measure embeds more points, including extreme values.

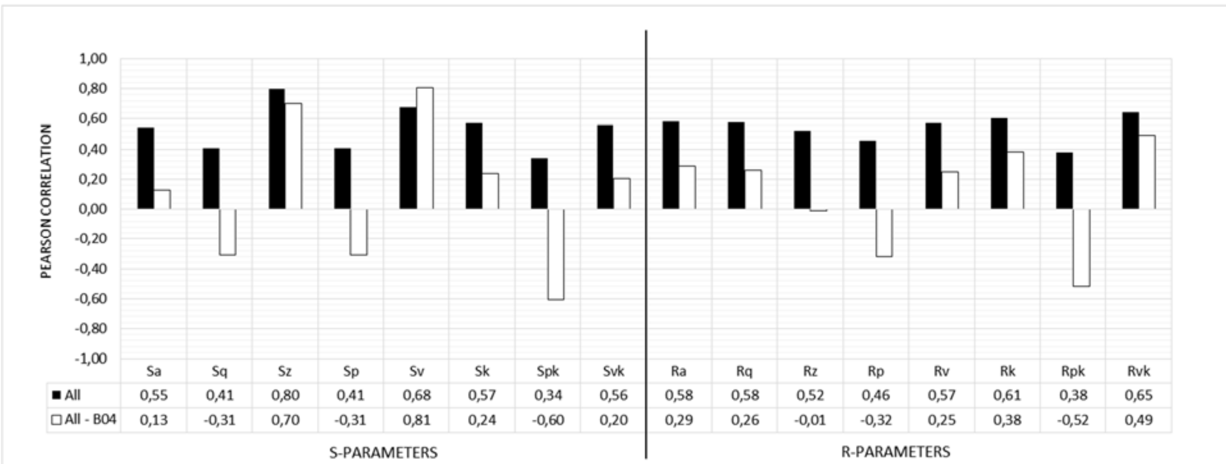
Table 8 – Density and minimal remission raw data (average) patches printed with dye and pigment Inkjet inks

Ink		B01	B02	B03	B04	B05	B06	B07
Dye	Density	1.15	1.07	1.08	0.44	1.08	1.08	1.06
	Remission	0.1003	0.0917	0.0837	0.1553	0.0864	0.0538	0.0982
	Patches							
Pigment	Density	1.95	1.93	1.91	0.34	1.97	1.97	1.91
	Remission	0.0116	0.0134	0.0128	0.0346	0.0116	0.0120	0.0135
	Patches							

In the Table 8 is possible to see the density differences between dye and pigment flow explained in 1 and illustrated in the Figure 1. It is to notice that B04 is a cast coated cardboard with a low surface energy. Pigment inks, without pre or post-treatment, did not wet the surface. Dye inks have on B04 a partial wetting. This feature causes a relevant statistical deviation that cannot be ignored. Thus, it was defined that the correlations should be calculated in 2 data sets: data set "all" with all cardboards and data set "All – B04" with all cardboards except B04.

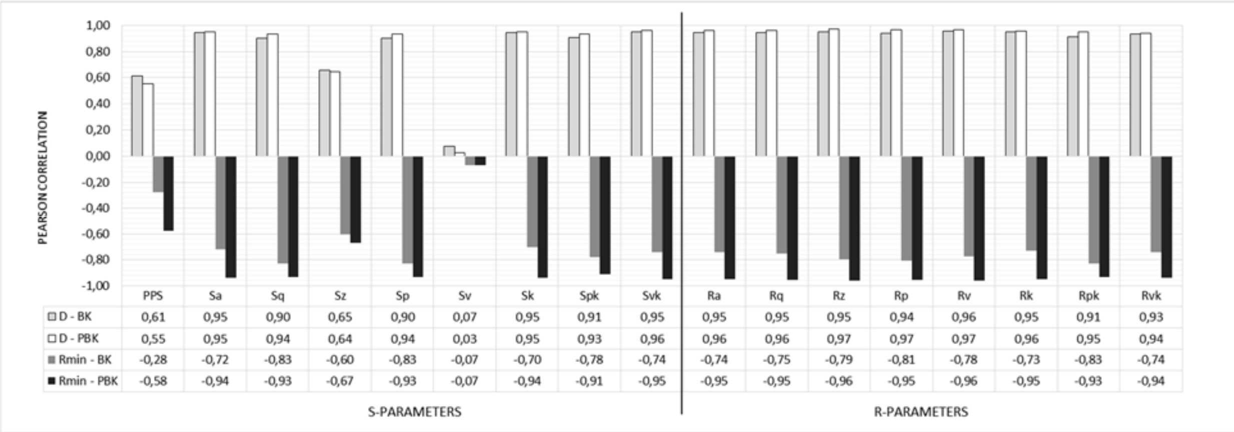
As mentioned in 1, the present investigation aim to analyze the correlation between roughness measurement methods, namely Parker Print Surf (PPS) and area surface roughness / line surface roughness by means of 3D confocal laser scanning microscope technics. These results are showed in the Figure 13. The second aim, the correlation of roughness measurement with density and minimal remission values of cardboards printed with dye and pigment are presented in the Figure 14 and 15, respectively with data set "All" and "All – B04".

Figure 13 - Correlation from PPS with S-parameters and PPS with R-parameters



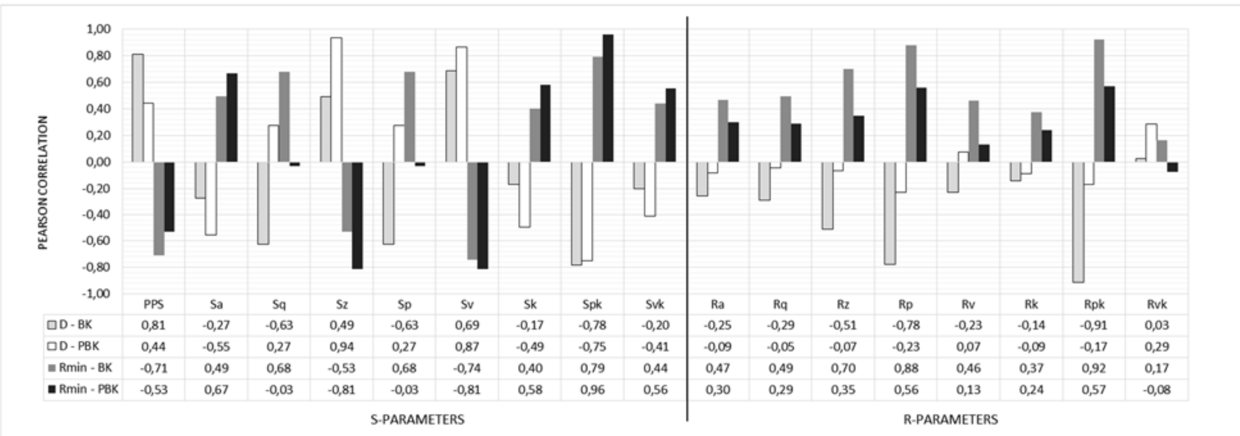
Considering both data set, only Sz (maximal distance between valleys and peaks) and Sv has a medium strong and strong correlation with PPS respectively.

Figure 14 - Correlation from PPS with S-parameters and PPS with R-parameters
Roughness, optical density and remission (all cardboards)



Considering only the data set "all", except by Sv, all S- and R-roughness parameters have a medium strong and predominantly a very strong correlation with the density values of both dye and pigment based inks. The correlation with minimal remission follows the same scheme, but with a negative correlation (s. Equation 3). These values are statistically very high, tending to a perfect correlation, due to the influence of B04. Density and remission values have less correlation with PPS as with the other roughness parameters.

Figure 15 - Correlation from PPS with S-parameters and PPS with R-Parameters
Roughness, optical density and remission (all cardboards except B-04)



Due to the variability of the results, the main observations, only medium strong [+ or – for positive and negative] or very strong [++ or –– for positive and negative] correlations, are summarized in the Table 9.

Table 9 – Summary of main observations, data set "All-B04"

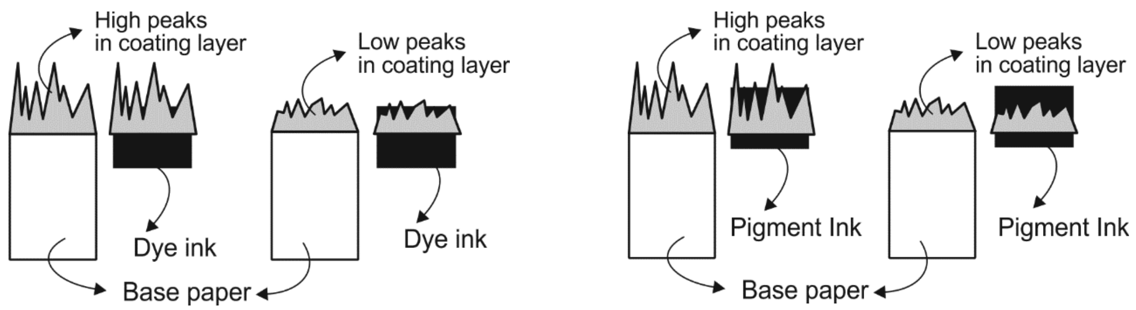
		S-parameters									R-parameters							
		Amplitude		Height			Functional			Amplitude		Height			Functional		
	PPS	Sa	Sq	Sz	Sp	Sv	Sk	Spk	Svk	Ra	Rq	Rz	Rp	Rv	Rk	Rpk	Rvk
With PPS				+		+		-								-	
Dye ink																	
Density	++		-		-	+		-				-	-			--	
Remission	-		+	-	+	-		++				+	++			++	
Pigment ink																	
Density		-		++		++		-									
Remission	-	+		--		--	+	++	+				+			+	

Correlation between S- and R-roughness parameters with PPS is weak. PPS measurements show a very strong correlation with density by dye ink. S-parameters have more points of correlation with density and remission values than R-parameters.

By the dye ink the negative correlation between density and the peaks parameters (Sp, Spk, Rp and Rpk) is noticeable and accordingly positive correlation with a valleys parameter (Sv). The remission values show the opposite behavior. This is expected and can indicate an irrelevant influence of bleaching agents or UV-portion of dye inks in this type of measurement. The correlation with peaks and valleys can demonstrate that the lower the peaks, the higher the density. This appears to be a logical result as illustrated in Figure 16 (left). Since the ink penetrates the coating layer until the saturation point, some of the ink remain close to the surface. High peaks reduces the light flux reflected from the printed surface and increase the light flux reflected from the unprinted surface. The opposite happens by low peaks, where the light flux reflected from the printed surface is higher.

By the pigment ink the depth of the valleys (Sv) has a positive correlation with density. This cannot be explained physically. This correlation is not confirmed by the main peak parameters (Sp) as at dye inks. Since the color component of the pigment ink stays on the coating layer, it seem that the normal peaks (Sp) do not have a higher influence on the density, but they may have with very high peaks (Spk) (Figure 16, right). A possible reason for the low linearity of these results can be the small standard deviation of density values in relation to the deviation of roughness values.

Figure 16 – Influence of peaks on density, dye ink (left) and pigment ink (right)



5 Conclusion

Inkjet and offset inks have different physicochemical characteristics that affect their flow in the substrate. In addition, substrate characteristics such as porosity and roughness also influence the ink flow. Finally, the ink flow influence qualitative print aspects as optical density and remission. In this investigation, the correlation between roughness measurement methods and their correlations with qualitative print aspects namely density and remission were analyzed.

Using a data set with strong standard deviation the correlation between S, R and PPS roughness measurements was very high. With a data set without the main deviation, a cast coated cardboard (B04), this correlation is weak having only few points of medium strong correlation with valleys (Sv) and high peaks (Spk, Rpk) parameters.

PPS roughness values show correlation with density by dye inks, but a weak correlation by pigment inks. The main finding of this study was to demonstrate how the different roughness parameters, measured with a 3D laser confocal microscope, are related to the flow behavior of Inkjet inks. At dye based inks, a solution with molecular colorant components, the peaks reduces the density because the ink flows deeper in the cardboard pigment coating. By the pigment ink, a dispersion, the solid pigment particles remain on the surface above most of the peaks (Sp), but not over the higher peaks (Spk).

6 Literature

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List of acronyms

Acronym	Meaning	Unit
D	Optic density	[-]
Dye	Dye Inkjet Ink	
FBB	Folding box board	
FWA	Fluorescent whitening agents	
OBA	Optical brightening agents	
Pigment	Pigment Inkjet Ink	
PPS	Parker Print Surf	[µm]
Rmin	Minimal remission	[-]
SBB	Solid bleached board	
UV	Ultraviolet (wavelength)	
β	Remission grade	[-]
θ	Contact angle	[°]
λ	Wavelength	[nm]
ϱ	Reflectance	[-]
Φ	Light flux	[-]

Profile or line roughness parameters **|** Surface or area roughness parameters

Sa **|** Ra	Arithmetical mean deviation	[µm]
Mr1	Material ratio 1	[%]
Mr2	Material ratio 2	[%]
Sk **|** Rk	Core roughness depth	[µm]

Sq | Rq	Root mean square deviation	[µm]
Sp | Rp	Maximum peak height	[µm]
Spk | Rpk	Reduced peal height	[µm]
Sv | Rv	Maximum valley depth	[µm]
Svk | Rvk	Reduced valley depths	[µm]
Sz | Rz	Maximum height	[µm]

Annex A

Equations (s. 2.2)

	Profile or line roughness parameters [6] [8]	Surface or area roughness parameters [7] [8]
Arithmetical mean deviation	$Ra = \frac{1}{\ell r}\int_0^{\ell r} \lvert Z(x)\rvert\, dx$	$Sa = \frac{1}{A}\iint_A \lvert z(x,y)\rvert\, dx\, dy$
Root mean square deviation	$Rq = \sqrt{\frac{1}{\ell r}\int_0^{\ell r} \lvert Z^2(x)\rvert\, dx}$	$Sq = \sqrt{\frac{1}{A}\iint_A Z^2(x,y)\, dx\, dy}$
Maximum peak height	$Rp = \max\big(Z(x)\big)$	$Sp = \max A\ Z(x,y)$
Maximum valley depth	$Rv = \big\lvert \min\big(Z(x)\big)\big\rvert$	$Sv = \big\lvert \min A\ \big(Z(x,y)\big)\big\rvert$
Maximum height	$Rz = Rp + Rv$	$Sz = Sp + Sv$
Material Ratio 1	Level in % determined for the intersection line which separates the protruding peaks from the roughness core profile	
Material Ratio 2	Level in % determined for the intersection line which separates the deep valleys from the roughness core profile	

Analysis of roughness measurements of coated cardboards

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University of Wuppertal

BERGISCHE UNIVERSITÄT WUPPERTAL

BACKGROUND AND RELEVANCE

Inkjet inks
water-based
solvent-based
UV/EB
hot melt

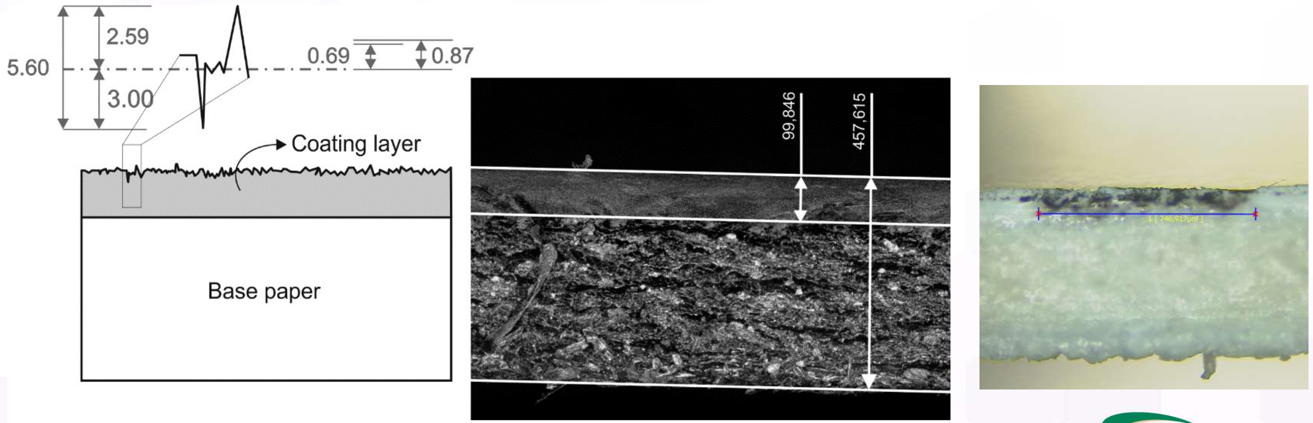
Dye-based (solution)
Pigment-based (dispersion)

Inkjet Systems
thermal
piezo
continuous

Qualitative product parameters

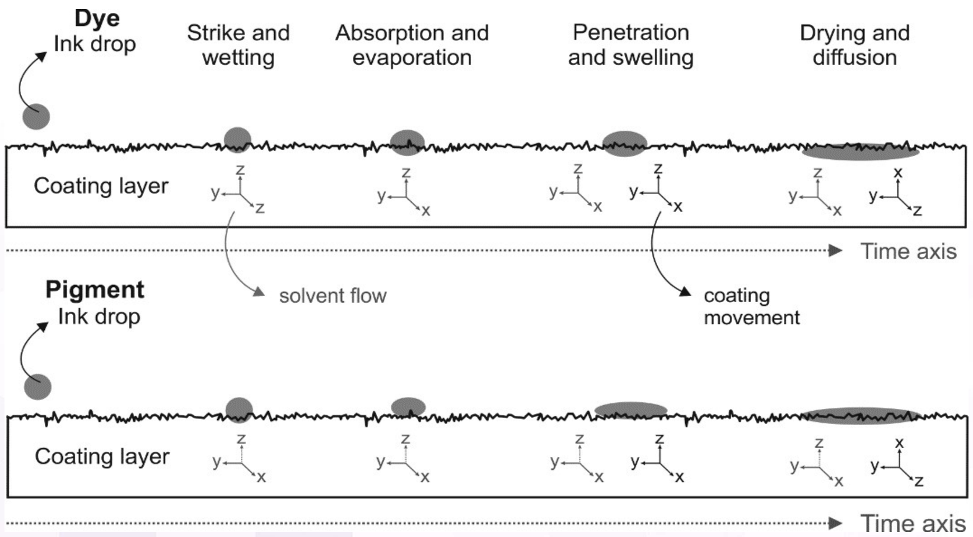
Substrates
Inkjet papers
base paper
corrugated
coated cardboard

Coated cardboard surface and the scale of magnitude of the surface roughness.

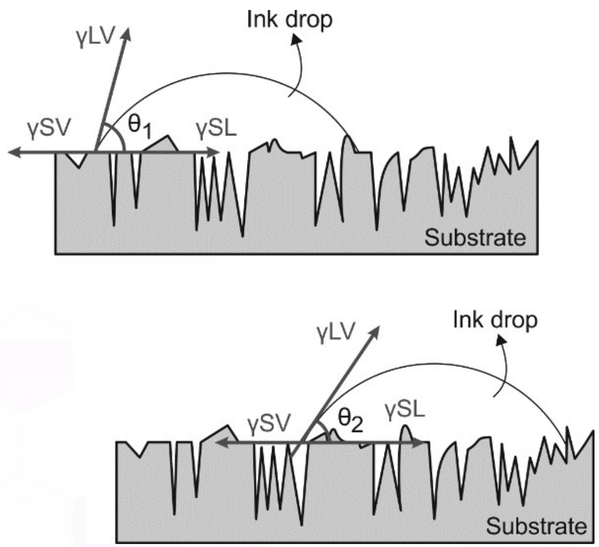


BACKGROUND AND RELEVANCE

1 **Influence of roughness due to changes in surface and bulk morphology**

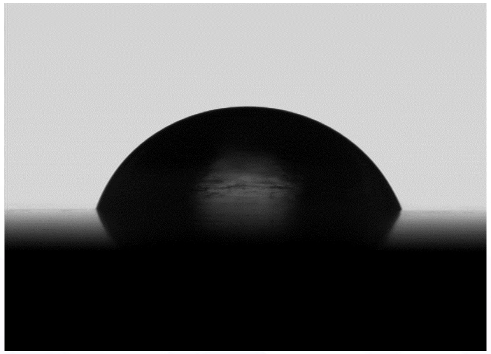


2 **Influence of roughness on contact angle**

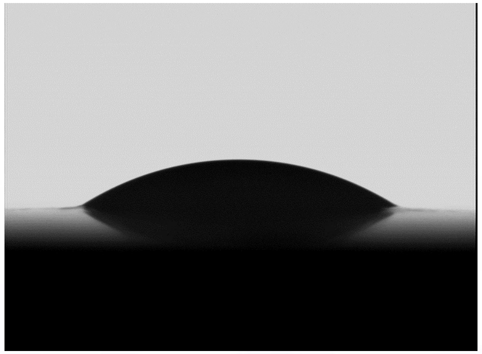


BACKGROUND AND RELEVANCE

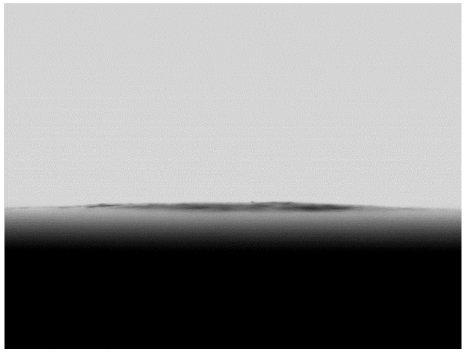
3 **Absorption rate can also be influenced by the roughness**



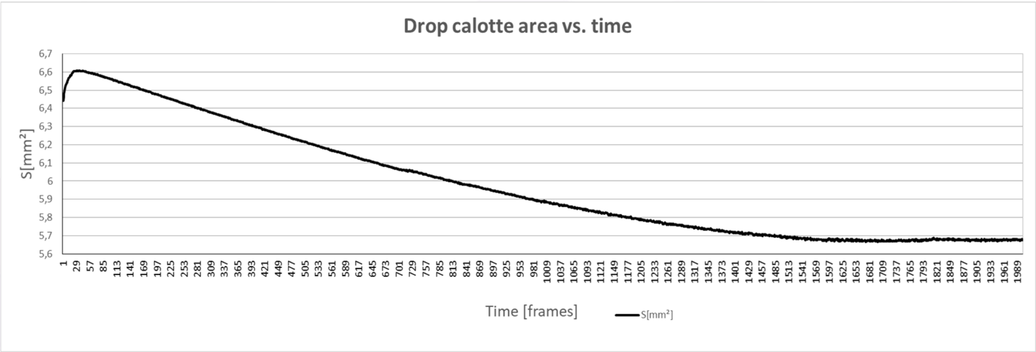
Frame 1 - Strike



Frame 2 – after 1 min.

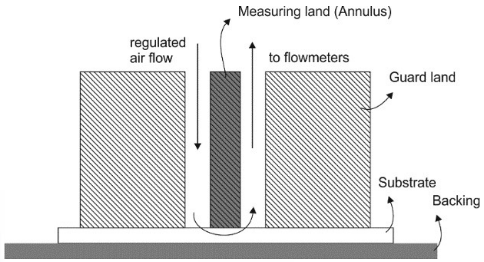


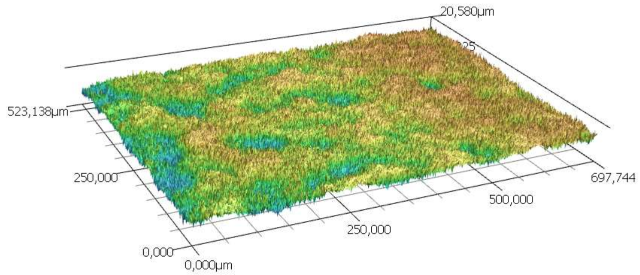
Frame 3 – after 4 min.



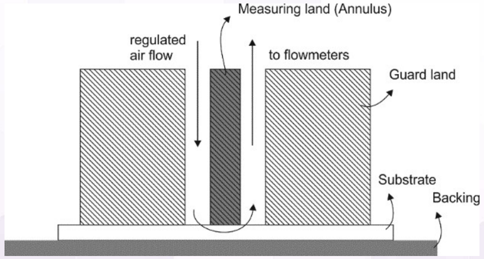
GOALS

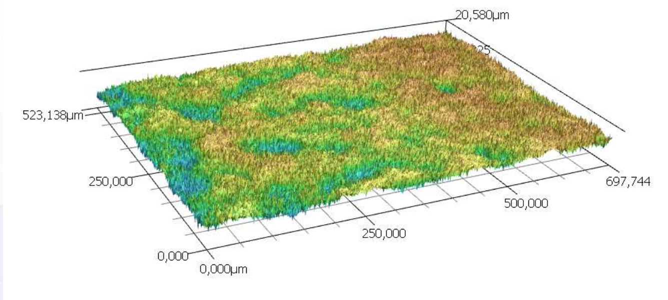
Analyze the correlation between roughness measurement methods, namely Parker Print Surf (PPS) and area surface roughness / line surface roughness by means of 3D confocal laser scanning microscope technics.

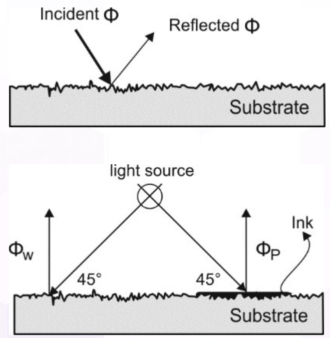




Analyze the correlation of these roughness measurements with optical density and remission values of cardboards printed with dye and pigment based Inkjet inks completes the purpose of this experiment.

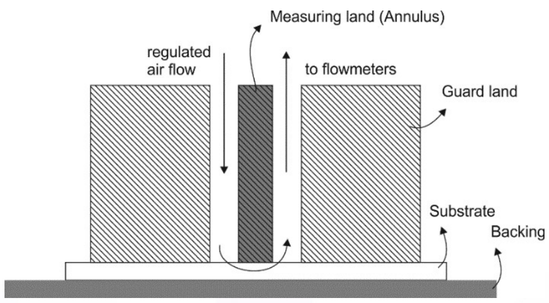






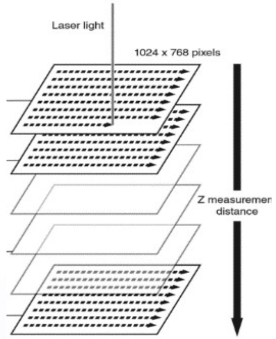
FUNDAMENTALS OF MEASUREMENT AND CALCULATION

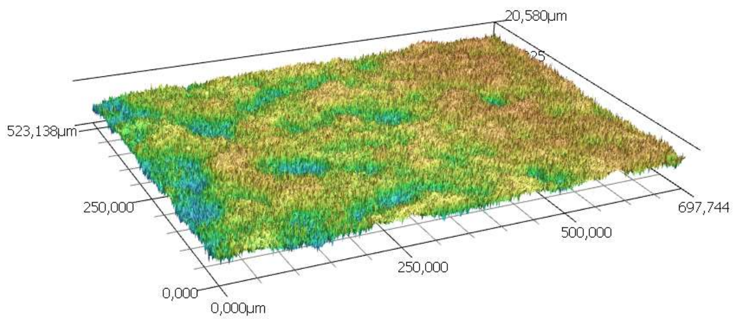
PPS



- Sample is placed below a metal ring (measuring land) and above a resilient surface (backing)
- Controlled ejected air flow in pressured in substrate direction.
- Amount of air that can pass between the sample and the measuring land is measured in the other side by a flowmeter.
- The air flow delta is calculated and expressed in micrometers.
- PPS is an **indirect** roughness measurement method.

3D confocal laser scanning microscope

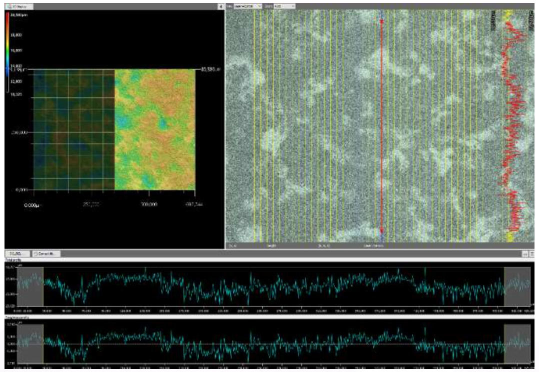


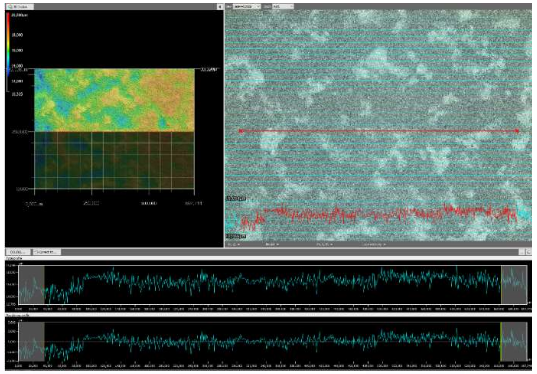


- Confocal scanning technique is based on grouping different focal planes to form an image
- A laser light scans the surface and a photoreceptor measures the received remission.
- A pinhole installed before the photoreceptor avoids that photons from other planes, outside the focal plane, reach the lens.
- The second image (right) is a 3D image of a coated cardboard.
- Confocal microscopy is a **direct** roughness measurement method.

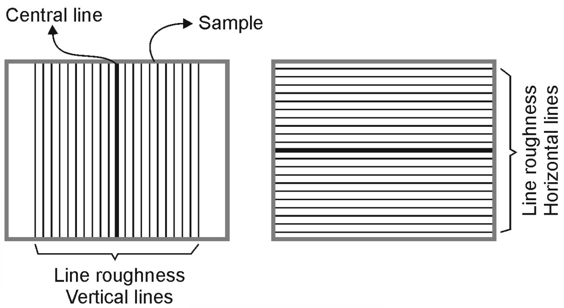
FUNDAMENTALS OF MEASUREMENT AND CALCULATION

Profile roughness or line roughness





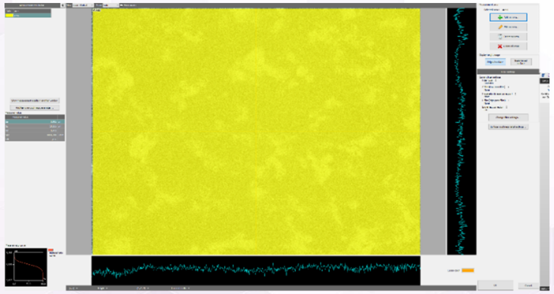
R-parameters

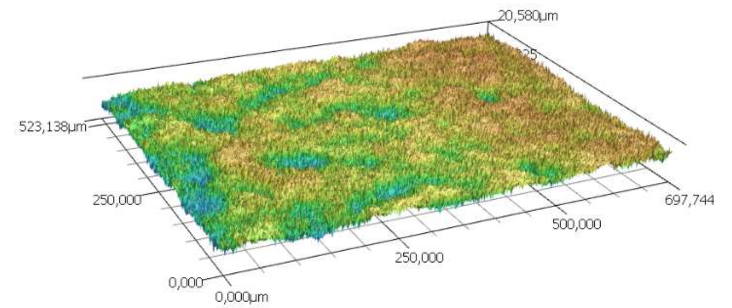


11, 21, 31 and 61 lines with a
tance from 60, 30, 20 and 10
pixels to each other

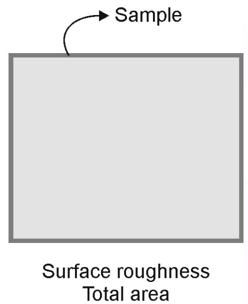
$$Ra = \frac{1}{\ell r} \int_0^{\ell r} |Z(x)|\, dx$$

Area surface texture or area roughness





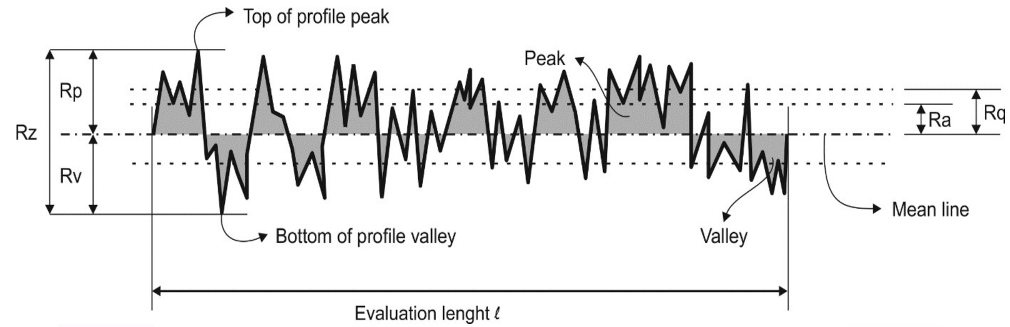
S-parameters



$$Sa = \frac{1}{A} \iint_A |z(x,y)|\, dx\, dy$$

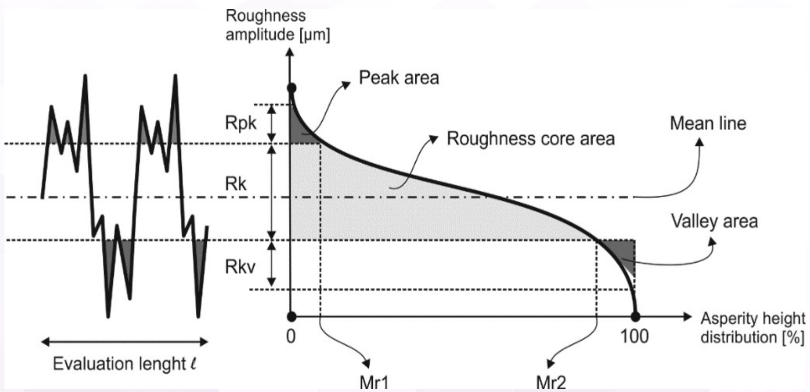
FUNDAMENTALS OF MEASUREMENT AND CALCULATION

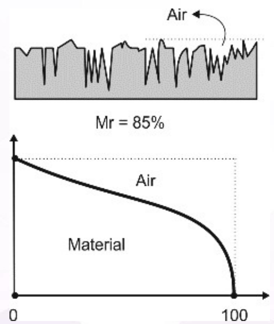
Parameters

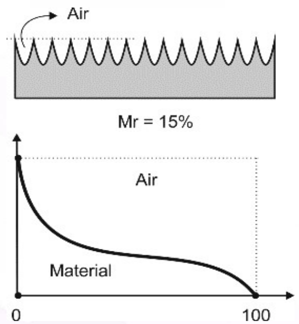


$$Ra = \frac{1}{\ell r}\int_0^{\ell r} |Z(x)|\, dx$$

$$Sa = \frac{1}{A}\iint_A |z(x,y)|\, dx\, dy$$

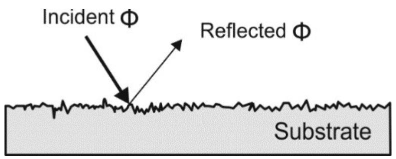




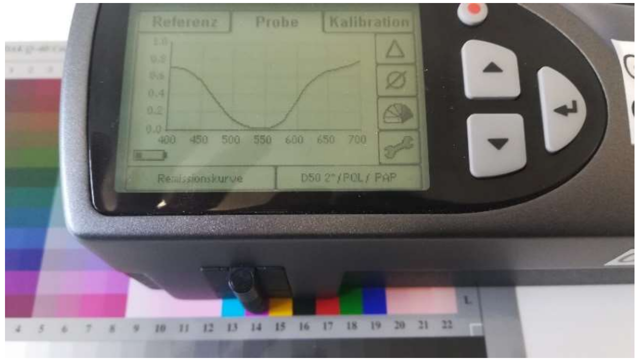


FUNDAMENTALS OF MEASUREMENT AND CALCULATION

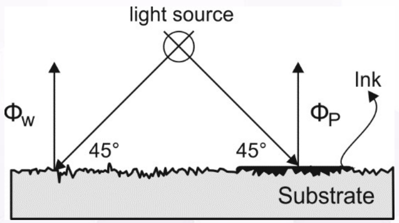
Remission



$$\varrho = \frac{\Phi_R}{\Phi} = \frac{reflected\ light\ flux}{incident\ light\ flux}$$

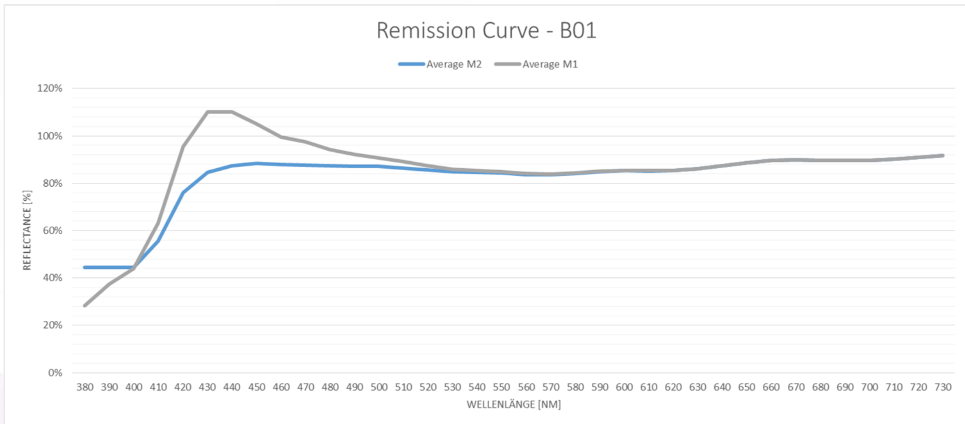


Optical density



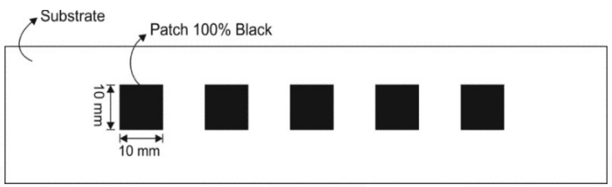
$$\beta = \frac{\Phi_P}{\Phi_W} = \frac{light\ flux\ reflected\ from\ the\ printed\ surface}{light\ flux\ reflected\ from\ the\ unprinted\ surface}$$

$$D = -\log \beta$$



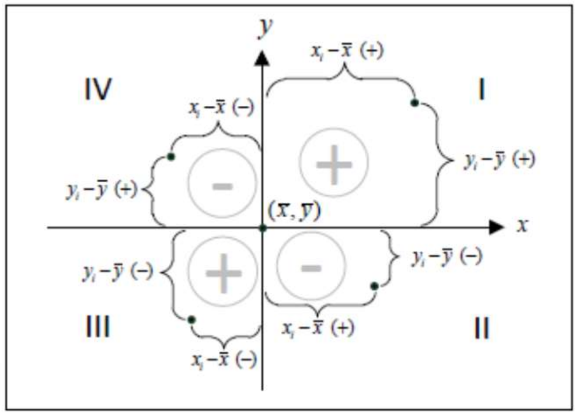
TESTED MATERIALS, TEST CHART and CORRELATION

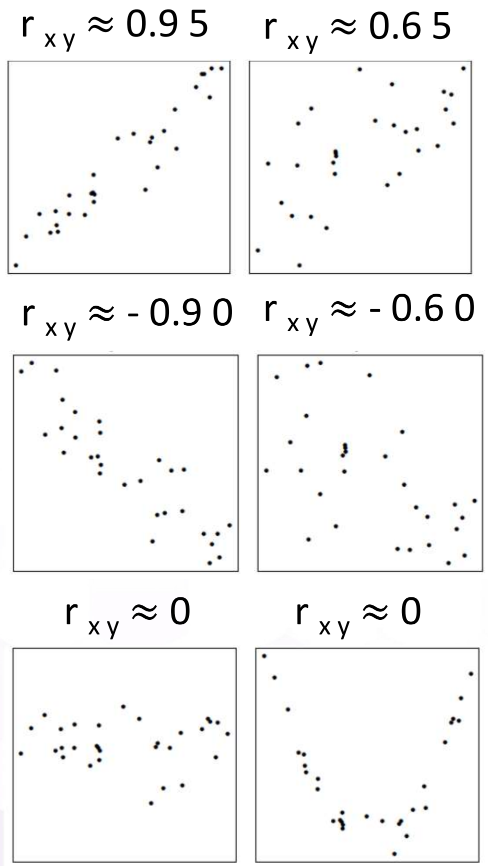
Materials	Identification		Data
Cardboard	"B01" to "B07"		Seven commercial cardboard FBB and SBB (s. Table 2)
Ink	Dye	Black	Canon dye ink: CLI-551
	Pigment	Black	Canon pigment ink: PGI-550



$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i y_i - n\overline{xy})}{\sqrt{\sum_{i=1}^{n} x_i{}^2 - nx^2}\ \sqrt{\sum_{i=1}^{n} y_i{}^2 - ny^2}} = \frac{cov(x,y)}{\sqrt{var(x)\ \ var(y)}}$$

Values	Correlation´s strength
$0.0 \leq \lvert r_{x,y} \rvert \leq 0.2$	any to very weak
$0.2 < \lvert r_{x,y} \rvert \leq 0.5$	weak
$0.5 < \lvert r_{x,y} \rvert \leq 0.8$	medium strong
$0.8 < \lvert r_{x,y} \rvert \leq 1.0$	strong to perfect





RESULTS AND DISCUSSION

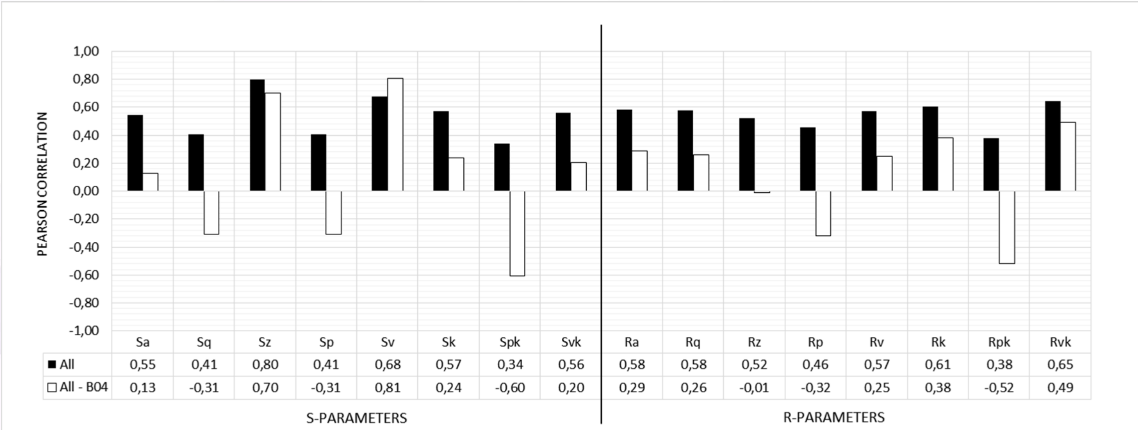
Ink		B01	B02	B03	B04	B05	B06	B07
Dye	Density	1.15	1.07	1.08	0.44	1.08	1.08	1.06
	Remission	0.1003	0.0917	0.0837	0.1553	0.0864	0.0538	0.0982
	Patches							
Pigment	Density	1.95	1.93	1.91	0.34	1.97	1.97	1.91
	Remission	0.0116	0.0134	0.0128	0.0346	0.0116	0.0120	0.0135
	Patches							

Sets

All
B01 to B07

All – B04
B01 to B07 - B04

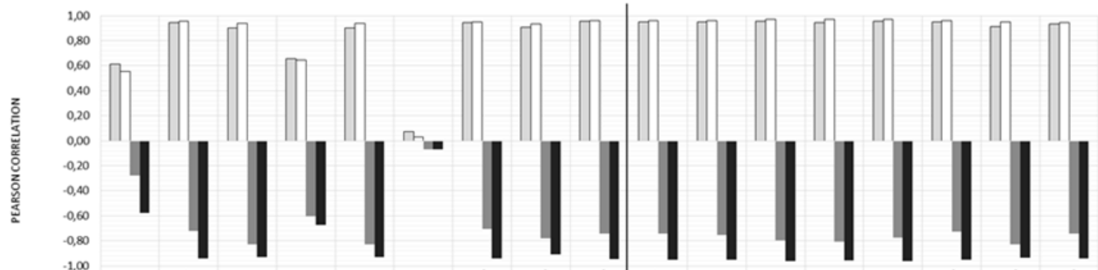
Correlation from PPS with S-parameters and PPS with R-parameters



RESULTS AND DISCUSSION

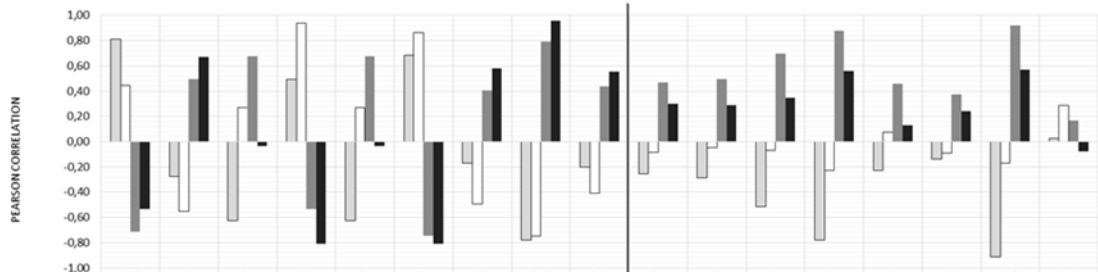
Correlation from PPS with S-parameters and PPS with R-parameters Roughness, optical density and remission

All
B01 to B07



	PPS	Sa	Sq	Sz	Sp	Sv	Sk	Spk	Svk	Ra	Rq	Rz	Rp	Rv	Rk	Rpk	Rvk
Density - Dye	0,61	0,95	0,90	0,65	0,90	0,07	0,95	0,91	0,95	0,95	0,95	0,95	0,94	0,96	0,95	0,91	0,93
Density - Pigment	0,55	0,95	0,94	0,64	0,94	0,03	0,95	0,93	0,96	0,96	0,96	0,97	0,97	0,97	0,96	0,95	0,94
Rmin - Dye	-0,28	-0,72	-0,83	-0,60	-0,83	-0,07	-0,70	-0,78	-0,74	-0,74	-0,75	-0,79	-0,81	-0,78	-0,73	-0,83	-0,74
Rmin - Pigment	-0,58	-0,94	-0,93	-0,67	-0,93	-0,07	-0,94	-0,91	-0,95	-0,95	-0,95	-0,96	-0,95	-0,96	-0,95	-0,93	-0,94

All – B04
B01 to B07 - B04



	PPS	Sa	Sq	Sz	Sp	Sv	Sk	Spk	Svk	Ra	Rq	Rz	Rp	Rv	Rk	Rpk	Rvk
Density - Dye	0,81	-0,27	-0,63	0,49	-0,63	0,69	-0,17	-0,78	-0,20	-0,25	-0,29	-0,51	-0,78	-0,23	-0,14	-0,91	0,03
Density - Pigment	0,44	-0,55	0,27	0,94	0,27	0,87	-0,49	-0,75	-0,41	-0,09	-0,05	-0,07	-0,23	0,07	-0,09	-0,17	0,29
Rmin - Dye	-0,71	0,49	0,68	-0,53	0,68	-0,74	0,40	0,79	0,44	0,47	0,49	0,70	0,88	0,46	0,37	0,92	0,17
Rmin - Pigment	-0,53	0,67	-0,03	-0,81	-0,03	-0,81	0,58	0,96	0,56	0,30	0,29	0,35	0,56	0,13	0,24	0,57	-0,08

S-PARAMETERS | R-PARAMETERS

RESULTS AND DISCUSSION

		S-Parameters								R-Parameters							
		Amplitude		Height			Functional			Amplitude		Height			Functional		
	PPS	Sa	Sq	Sz	Sp	Sv	Sk	Spk	Svk	Ra	Rq	Rz	Rp	Rv	Rk	Rpk	Rvk
With PPS				+		+		-								-	
Dye ink																	
Density	++		-		-	+		-				-	-			--	
Remission	-		+	-	+	-		++				+	++			++	
Pigment ink																	
Density		-		++		++		-									
Remission	-	+		--		--	+	++	+				+			+	

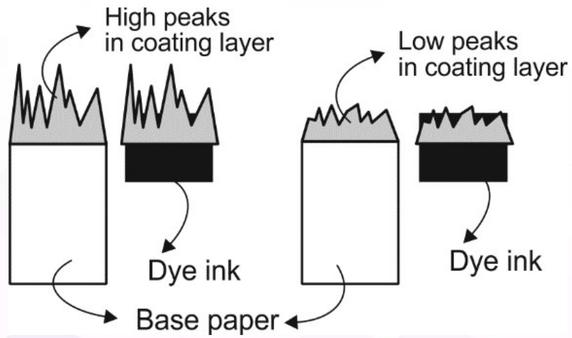
- Correlation between S- and R-roughness parameters with PPS is weak.
- PPS measurements show a very strong correlation with density by dye ink.
- S-parameters have more points of correlation with density and remission values than R-parameters.

RESULTS AND DISCUSSION

		S-Parameters									R-Parameters							
		Amplitude		Height			Functional			Amplitude		Height			Functional		
	PPS	Sa	Sq	Sz	Sp	Sv	Sk	Spk	Svk	Ra	Rq	Rz	Rp	Rv	Rk	Rpk	Rvk
With PPS				+		+		-								-	
Dye ink																	
Density	++		-		-	+		-				-	-			--	
Remission	-		+	-	+	-		++				+	++			++	
Pigment ink																	
Density		-		++		++		-									
Remission	-	+		--		--	+	++	+				+			+	

Dye ink

- Negative correlation between density and the peaks parameters (Sp, Spk, Rp and Rpk)
- Positive correlation with a valleys parameter (Sv)
- Remission values show the opposite behavior (irrelevant influence of bleaching agents or UV-portion of dye inks in this type of measurement)
- The correlation with peaks and valleys can demonstrate that the lower the peaks, the higher the density. This appears to be a logical result
- The ink penetrates the coating layer until the saturation point, some of the ink remain close to the surface.

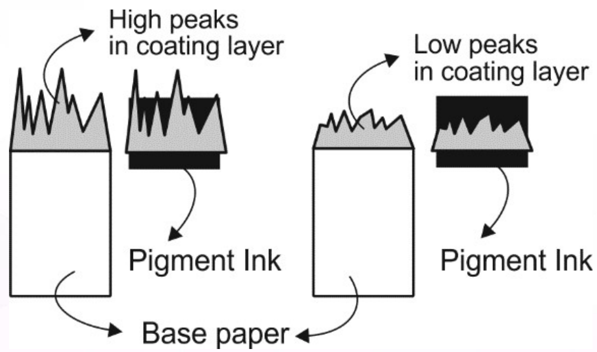


RESULTS AND DISCUSSION

		S-Parameters								R-Parameters							
		Amplitude		Height			Functional			Amplitude		Height			Functional		
	PPS	Sa	Sq	Sz	Sp	Sv	Sk	Spk	Svk	Ra	Rq	Rz	Rp	Rv	Rk	Rpk	Rvk
With PPS				+		+		-								-	
Dye ink																	
Density	++		-		-	+		-				-	-			--	
Remission	-		+	-	+	-		++				+	++			++	
Pigment ink																	
Density		-		++		++		-									
Remission	-	+		--		--	+	++	+				+			+	

Pigment ink

- The depth of the valleys (Sv) has a positive correlation with density. This cannot be explained physically.
- This correlation is not confirmed by the main peak parameters (Sp) as at dye inks.
- Since the color component of the pigment ink stays on the coating layer, it seem that the normal peaks (Sp) do not have a higher influence on the density, but they may have with very high peaks (Spk)
- A possible reason for the low linearity of these results can be the small standard deviation of density values in relation to the deviation of roughness values.



RESULTS AND DISCUSSION

- Substrate characteristics such as porosity and **roughness** also influence the **ink flow**.
- **Ink flow** influences **qualitative print aspects** as optical density and remission.

- Using a data set with strong standard deviation the **correlation between S-, R-parameters and PPS roughness** measurements was very high.
- With a **data set without the main deviation**, a cast coated cardboard (B04), this correlation **is weak**

- PPS roughness values show correlation with density by dye inks, but a weak correlation by pigment inks.

- Main findings
  - demonstrate how the different roughness parameters, measured with a 3D laser confocal microscope, are related to the flow behavior of Inkjet inks.
  - **Dye-based inks**, a solution with molecular colorant components, the **peaks reduces the density because the ink flows deeper in the cardboard pigment coating**.
  - **Pigment-based ink**, a dispersion, the solid pigment particles **remain on the surface above most of the peaks (Sp), but not over the higher peaks (Spk)**.

Thank you for your attention

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