Fast Evaluation of Spatial Coating Layer Formation using UV Scanner Imaging

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ABSTRACT

Print quality demands are steadily growing and several print quality problems (e.g. print mottle) are known to be closely related to coating layer uniformity. The present study evaluates the potential of using ultraviolet (UV) scanner imaging as a fast method for characterization of the spatial coating layer formation. The principle of this method is based on the measurement of the spatial concentration of fluorescent whitening agent (FWA) in the coating color especially in regions of higher local coat weight. UV scanner imaging was compared to two reference methods for determining the coating layer uniformity, the burnout test and β-radiography. Within the study a commercially produced light-weight coated paper, a lab coated commercial wood free base paper and lab coated hand sheets have been examined. Image analysis showed that in the region of interest for visual perception of print mottle, UV scanner imaging provides valuable information regarding the spatial coating layer formation, especially for lower coat weights. Furthermore, the influence of varying amounts of FWA in the coating color and in the base paper on the measurement results was investigated. The results indicate that UV scanner imaging needs closely defined conditions regarding applied coat weight and FWA concentration in the coating color and the base paper respectively.

INTRODUCTION

Coating layer uniformity is one of the key parameters determining the quality of coated papers grades. Several quality problems have been attributed to non-uniformities in the coating layer structure, such as print mottle [1, 2] or gloss variations [3]. In order to clarify the interrelation between these quality issues and the spatial coating layer formation a significant number of research activities have focused on the development of analysis routines being able to quantify the uniformity of the coating layer distribution. Thus, a variety of sophisticated methods to characterize coating layer distribution based on different measurement principles have been developed in the last decades:

In general, the analysis of coating layer distribution can be divided into two groups. The first group consists of methods for direct measurement of coating thickness in cross sections of paper. Scanning electron microscopy (SEM) combined with serial section techniques is frequently used as a direct method. The single cross sections have a high resolution but a limited sample size. In order to facilitate the differentiation between coating layer and base sheet, imaging is performed in the back scattered electron mode [4, 5]. Allem [6] introduced a concept which has been used to characterize local coating thickness and the correlation to base sheet properties [7], [8].

Another direct method using serial sectioning combined with light microscopy and a novel image analysis technique was presented by Wiltsche et al. [9]. The method is capable of automatically obtaining 3D paper structure data for sample areas of several mm² (e.g. 5x20 mm) in a reasonable timeframe. In this method, the coating layer is identified by a color segmentation algorithm extracting the coating layer information from the paper cross sections images.

The second group consists of indirect methods which allow the characterization of relatively large sample areas (e.g. 50x50 mm). The burnout test combined with image analysis is one of the most commonly used indirect methods to determine the coating coverage [10]. The principle of the burnout test is described later. The drawback of this method is, that the blackening of the base paper might be non-uniform and the porosity of the coating layer influences the result of the burnout treatment. Despite this fact, the burnout test has successfully been applied as a reference method (e.g. [11, 12, 13]).

Furthermore, radiography has been used with X-ray imaging by Azimi et al. [12]. A paper sample was exposed to X-rays and the transmitted X-rays are detected providing a gray scale image. To eliminate the base sheet absorption effect, the average absorption due to the base sheet was subtracted from the X-ray image of the coated paper. Kartovaara [14] used β-radiography for determination of local coating mass distribution, by subtracting the local grammage of the uncoated base paper from the local grammage of the coated paper. Tomimasu et al. [15, 16] used electron beams (50-200 keV) for a similar approach. They concluded that the advantages compared to β-radiography are a higher image resolution and a reduced exposure time.

Another indirect method is inspection under UV light of coated paper making use of the fluorescence behavior of the FWA contained primarily in the coating layer. It is a standard procedure in many paper mills targeting the detection of coating layer defects. The coated paper is placed under UV light under controlled lighting conditions and visually checked for coating faults and coating layer uniformity. UV fluorescence imaging has also been utilized for measuring coating layer distribution with a simple set up [11, 17]. The coated samples were illuminated by two UV light sources and images were captured with a camera. Afterwards the burnout test was performed on these samples. The coefficients of variation of both images were compared and indicated a reasonable correlation between both methods.

The purpose of this study was to evaluate the suitability of high resolution UV scanner imaging as a fast, simple and non-destructive way to estimate the spatial uniformity of the coating layer. Different coated paper grades - commercial as well as hand sheets - were evaluated. The FWA present in the coating color was used as an internal marker providing valuable information regarding the spatial coating layer formation. Initial results of the application of this method [18] showed a high correlation of results obtained by UV scanner imaging to burnout test images, especially for light-weight coated paper.

It is obvious that the FWA amount contained in the coating formulations and in the base paper will influence the intensity of fluorescence and thus the results of UV scanner imaging and the subsequent estimation of spatial coating layer formation. In order to evaluate this influence, we have carried out laboratory trials in this study varying the concentration of FWA in the coating color (e.g. less FWA corresponds to lower fluorescence intensity) and in the base paper respectively. As the intensity of fluorescence is likely to be also influenced by the applied coat weight, lab trials with varying coat weight were also conducted.

EXPERIMENTAL

Materials

Three different substrates were used in this study:

1.) Lab coated hand sheets (HS), 80 g/m², 100% refined eucalypt kraft pulp (2000 revolutions in a PFI mill), part of the handsheets contained no FWA. These hand sheets had a brightness of 87.85%. The other part contained 1% FWA (*Blankophor® PT*) and had a brightness of 108.38%.

2.) Lab coated commercial wood free baser paper (WFC), 70 g/m², containing 30% broke and 15% filler (i.e. $CaCO_3$ and clay). WFC base paper contained a small amount of FWA due to the usage of broke (brightness 83.0%).

3.) 4 samples of commercially produced light-weight coated (LWC) paper, 80 g/m², furnish composition: 40% groundwood pulp, 50% recycled pulp and 10% bleached softwood kraft pulp, coat weight per side 14 g/m². LWC contained FWA in the base paper due to the usage of broke.

Table 1 shows the coating color recipes. The FWA content in the coating formulation varied from 0.1-0.3%.

Table 1. Coating formulation.

In [%]	Color 1	Color 2	Color 3
GCC	100	100	100
FWA (*Blankophor® PT*)	0.1	0.2	0.3
PVOH	0.5	0.5	0.5
SB Latex	8	8	8
Solids content	70 (65)	70	70

The HS samples (with and without FWA) were blade coated on one side on a laboratory blade coater (Enz Technik AG, Switzerland) in the stiff blade mode using a blade of 0.4 mm thickness. The applied blade pressure was identical for all samples. The target coat weight for these samples was 19 g/m².

The commercial WFC base paper was coated with Color 1 (see *Table 1*) using a laboratory flat-bed rod coater (*Control Coater,* RK Print Coat Instruments Ltd, England). Three standard metering rods were used to apply the target coat weights from 13 to 32 g/m². The solids content of the coating color was reduced to 65% to achieve the lower coat weights. The coated samples were dried in a drying chamber at 150°C for about 2 minutes.

UV Scanner Imaging

The UV flatbed scanner (*Chromimage®,* AR 2i, France) used for this study was equipped with a low pressure mercury vapor lamp. It is conventionally applied in thin layer chromatography analysis. The spectral energy distribution of the mercury vapor lamp is shown in *Figure 1(a)*. The primary energy emission is located in the UV region of the electromagnetic spectrum with the maximum intensity located at a wavelength of 253.7 nm. Hence, the emittance of the lamp is in the region, where the FWA absorbs the energy (see *Fig. 1(b)*). A small amount of energy is also emitted in the visible range of the EM spectrum. The fluorescent light source is located at an angle of about 45° and the detector is located at 90°.

The sample size may be varied up to a maximum size of an A4 sheet and the scanning speed depends on the chosen resolution. For the used settings, one scanning cycle lasted three minutes. All samples were scanned at 1200 dpi

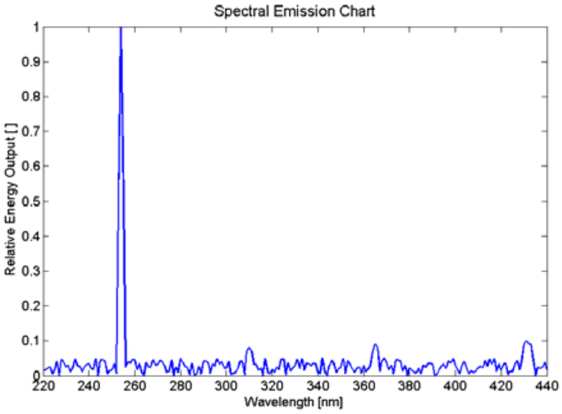


Figure 1(a). Spectral energy distribution of the low pressure mercury vapor lamp installed in the UV scanner.

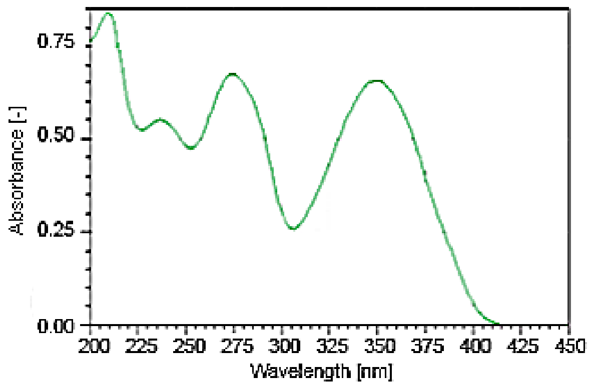


Figure 1(b). Absorbance spectrum of a Fluorescent Whitening Agent (*Blankophor® P*)[19].

(pixel size of 21 µm) in full RGB color. Since the excited FWA emits energy mainly in the blue region of the visible light, only the blue channel has been used for evaluation of spatial coating layer formation.

Reference Methods

Two methods are used as independent reference methods. First the burnout test for imaging spatial coating layer formation and secondly the β-radiography method for calculation of local coat weight maps.

Burnout Test

The burnout test is an easy and fast method used to visualize the uniformity of the spatial coating layer formation on coated papers. The paper samples are soaked in a charring agent and afterwards placed in an oven at a temperature of 225°C. High temperature dehydration of the paper samples causes the cellulosic materials to become black while the inorganic coating color remains white. In case of using samples containing mechanical pulp fibers, inadequate blackening is caused by the presence of lignin [20]. Trimmel et al. [21] presented a burnout test for wood containing papers and this procedure has been chosen for carbonization of all samples containing mechanical pulp (LWC) as well as for the wood free samples (WFC and HS). Imaging of the burnout test samples was carried out with an infinite focus measurement microscope using diffuse lighting conditions (*IFM G3 Measurement Device*, Alicona Imaging, Austria) with a pixel size of 2.5 µm.

β-Radiography

β-radiography was utilized as a second reference method in the evaluation of the UV scanner imaging method for the WFC samples. Basis weight maps with a pixel size of 50 µm before and after coating were captured by β-radiographic transmission and recorded on a phosphor storage screen. The phosphor storage screen was exposed in a Formex Box (*Science Imaging*) and afterwards scanned in a Fuji BAS-II scanner. Local coat weight maps were calculated after registration (see Sample Handling and Image Analysis) of the images by subtracting the basis weight map before coating from the basis weight map after coating.

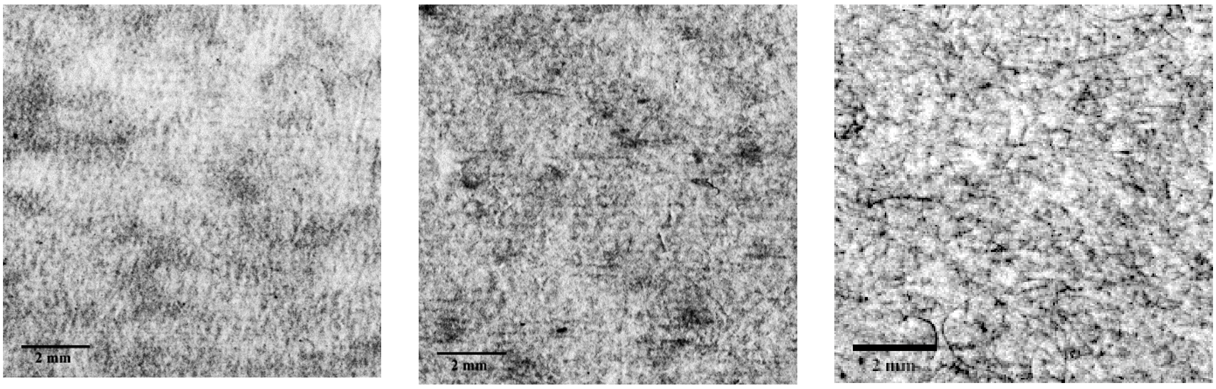
Sample Handling and Image Analysis

Prior to any measurement, all paper samples were marked with holes (0.5 mm diameter) introduced by a CO_2 laser as described by Hirn et al. [22]. These holes were needed for subsequent image registration which is performed by a shape preserving coordinate transform according to Hirn et al [23]. This assures a point by point correlation of the images obtained from the measurements. The marked samples had a size of 45x45 mm and the examined area was 40x40 mm.

Knowing that coating uniformity is crucial for print quality, spectral filtering (i.e. a FFT bandpass filter) was performed with a pass band ranging from 2-8 mm (i.e. the region of interest for visual perception of print mottle according to Johansson [24]). Afterwards the images were rescaled to a pixel size of 250 µm in order to minimize the registration error.

After spectral filtering and rescaling, the images acquired from the UV scanner, β-radiography and the burnout test were point wise correlated. The coefficient of determination (R^2) of UV scanner images and burnout test images was calculated for the HS, LWC and WFC samples. In addition, R^2 of UV scanner images and β-radiography images was calculated for the WFC samples.

The contrast of all images depicted in this study was enhanced in order to achieve a better visibility.



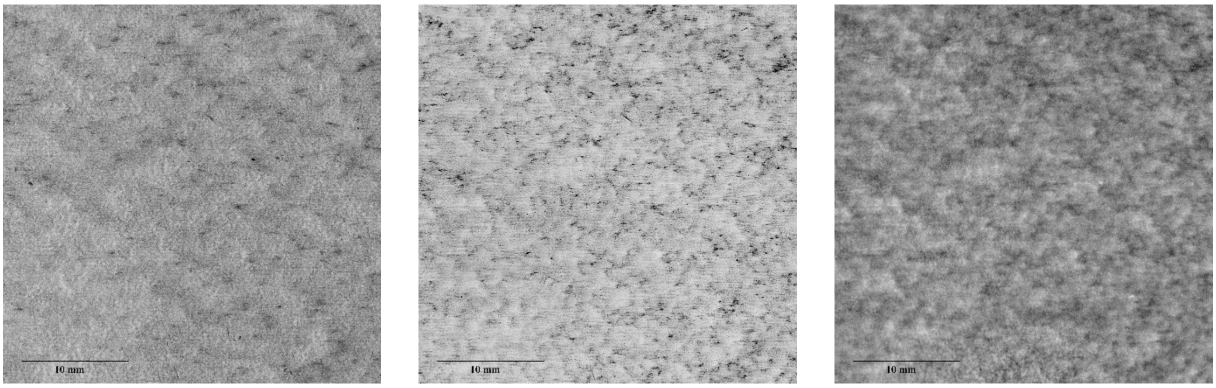
(a) HS sample (coat weight19 g/m² , Color 1, no FWA in base paper) (b) WFC sample (coat weight 13 g/m², Color 1) (c) LWC sample

Figure 2. UV scanner images of lab coated (a) and (b) samples and a commercial coated sample (c).

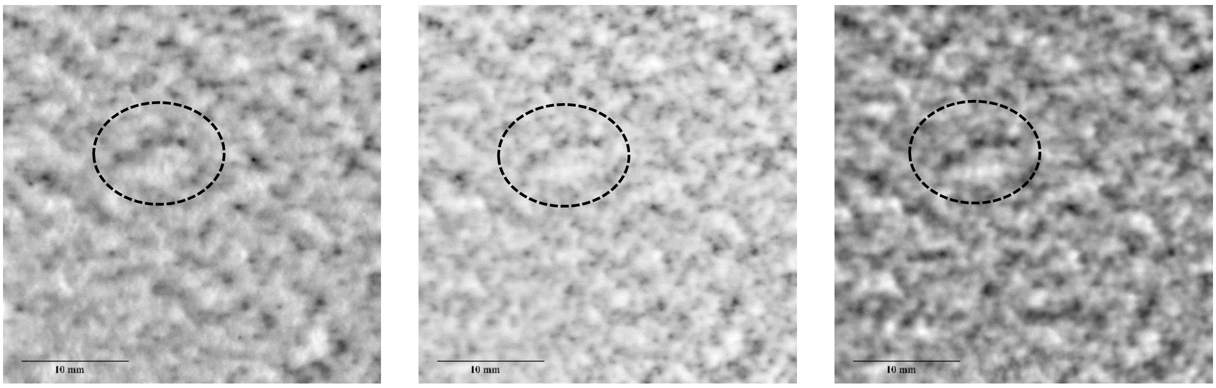
RESULTS AND DISCUSSION

UV Scanner Imaging

In *Figure 2*, UV scanner images using only the blue channel of a HS sample *(a)*, a WFC sample *(b)* and a LWC sample *(c)* are shown. In the UV images, darker regions represent regions containing less FWA and brighter regions those containing more FWA. Darker areas, especially in the WFC *(b)* and LWC *(c)* images look like fibers or fibrous features, which are supposed to be less covered with coating color. Since the FWA is mainly contained in the coating color, lower luminosity should be related to locally lower coat weight.



(a) Raw UV scanner image. (b) Raw burnout test images. (c) Raw β-ray coat weight map.



(d) UV scanner image filtered. (e) Burnout test image filtered. (f) Coat weight map filtered.

Figure 3. Images of registered WFC sample (coat weight 13 g/m², Color 1) before and after spectral filtering (2-8 mm band pass). R^2 between (d) and (e) is 0.64 and between (d) and (f) 0.62.

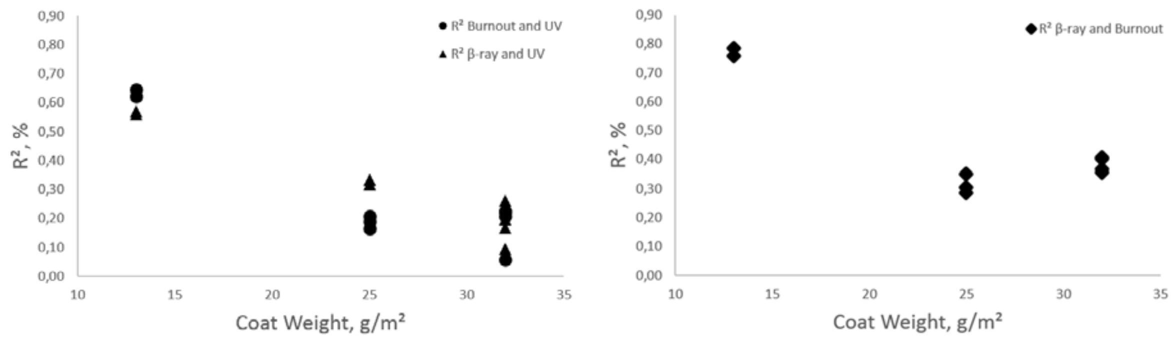
Correlation between UV Scanner; Burnout Test and β-radiography

The burnout test was performed on all samples (LWC, HS and WFC). Furthermore, β-radiography was performed on the flat-bed rod coated samples (WFC), before and after coating to calculate local coat weight maps. In *Figure 3* the images of all measurements of one WFC sample (13 g/m² coat weight with Color 1) are depicted. The images are registered (see Sample Handling and Image Analysis) and have a size of 40x40 mm. *Figure 3 (a), (b)* and *(c)* show the raw images and *(d)*, *(e)* and *(f)* show the images after spectral filtering (2-8 mm band pass). When comparing the images *(d)*, *(e)* and *(f)*, a similarity between the images can be observed (see dashed ellipse as an example). R^2 between UV scanner image *(d)* and burnout test image *(e)* is 0.64 and between UV scanner image *(d)* and coat weight map (β-radiography) *(f)* 0.62. This indicates that the spatial concentration of FWA in the coating layer is related to the spatial coating layer formation. The correlation of the burnout test image *(e)* and the β-radiography image *(f)* results in a R^2 of 0.79.

<u>Influence of coat weight variations on the correlation</u>

Figure 4 shows the coefficient of determination (R^2) of the UV scanner images to the burnout and β-radiography images in dependence of the applied coat weight for the WFC samples. Each point represents the R^2 of the point wise correlation of one sample. In *Figure 4 (a)* a good correlation between UV scanner imaging and burn out test images can only be observed for low coat weight samples. There is also a reasonable correlation between UV scanner images and local coat weight maps obtained from β-radiography images ($R^2 = 0.58$) again only at low coat weights. R^2 clearly decreases with increasing coat weight. One likely reason for that is the better coverage of the base paper at higher coat weights leading to a lower variance in fluorescence intensity. This effect could be explained on the basis of the images depicted in *Figure 5*.

Figure 4 (b) shows the R^2 between β-radiography images and the burnout test images. The R^2 values are generally higher and there is a similar trend as can be seen in *Figure 4 (a)*. With increasing coat weight, the correlation decreases. The higher the coat weight, the lower the ability of the blackened base paper in the burnout test to shine through the coating layer and to provide enough contrast for a proper analysis of the coating layer distribution.

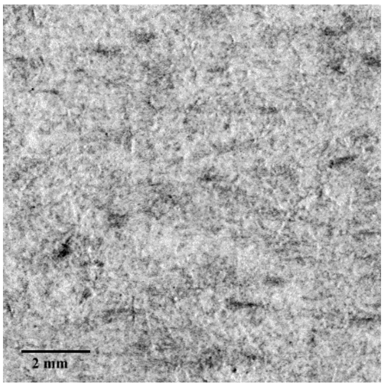


(a) Correlation of burnout – and UV scanner images and β-radiography – and UV scanner images.

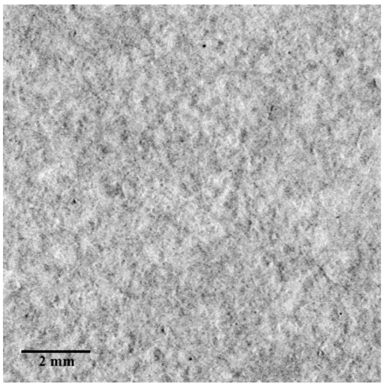
(b) Correlation of β-radiography – and burnout test images.

Figure 4. R^2 of point wise correlation of burnout test –, β-radiography – and UV scanner images of WFC samples coated with Color 1.

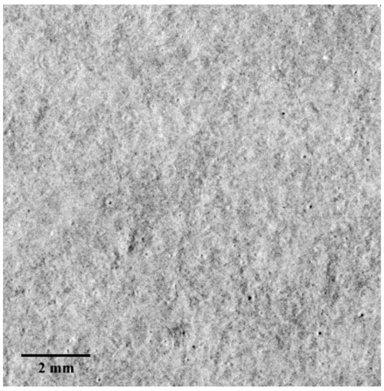
Figure 5 shows examples of the UV scanner images of WFC samples with different coat weights, coated on the flat-bed rod coater (Color 1). From the images it is apparent that the fluorescence intensity becomes more homogeneous with increasing coat weight. Furthermore, fibrous features in the image representing the sample having the highest coat weight (*Figure 5 (c)*) are not visible, whereas those features are present in the image of the sample with the lowest coat weight (*Figure 5 (a)*). This is due to the higher coat weight that leads to a better coverage of the base paper. This implies that the determination of the spatial coating layer formation with UV scanner imaging is only suitable for paper grades of lower coat weights.



(a) WFC sample (13 g/m²)



(b) WFC sample (25 g/m²)



(c) WFC sample (32 g/m²)

Figure 5. UV scanner images of flat-bed rod coated (Color 1) WFC samples with coat weights (a) 13 g/m², (b) 19 g/m² and (c) 32 g/m².

<u>Influence of variation of FWA concentration in the coating color</u>

The coefficient of determination (R^2) of the UV scanner images to the burnout test images in dependence of the FWA amount in the coating color applied to the hand sheet samples containing no FWA is shown in *Figure 6*. Each bar in *Figure 6* represents the mean R^2 of the point wise correlation of at least two HS samples. R^2 decreases with increasing FWA amount in the coating color for the blade coated HS samples. The lower the FWA concentration in the coating color, the higher is the correlation between the measurement methods.

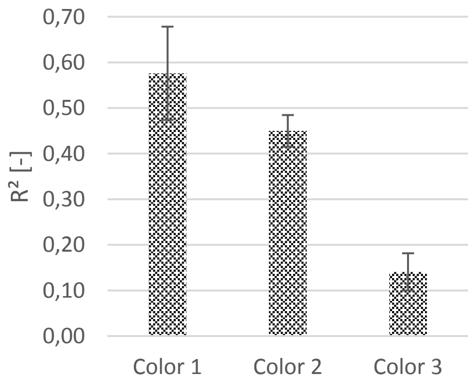
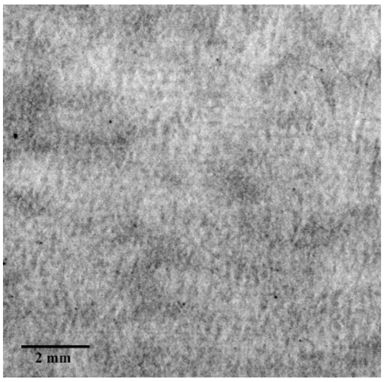


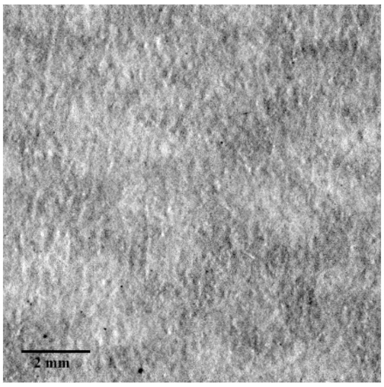
Figure 6. R^2 of point wise correlation of burnout test – and UV scanner images of HS samples (without FWA in base paper) coated with Color 1, Color 2 and Color 3.

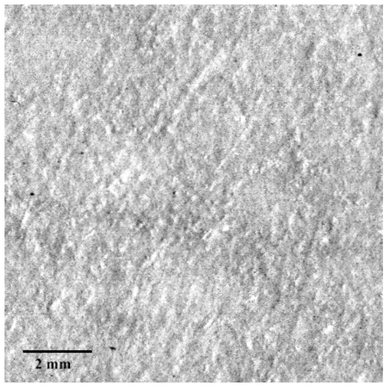
A possible reason for this can be seen in the images depicted in *Figure 7* showing images of blade coated HS samples (19 g/m² coat weight) with different FWA content (0.1-0.3%). For these images a similar effect occurs as found for those in *Figure 5*. Areas having higher and lower luminosity can clearly be distinguished in the image of the sample containing a lower concentration of FWA (see *Figure 7 (a)* and *(b)*), whereas at higher FWA concentration the difference between these regions is almost impossible to detect (*Figure 7 (c)*). The higher the concentration of FWA in the coating color, the higher the average fluorescence intensity level and therefore, a difference in the intensity level cannot be observed between regions of locally higher or lower coat weight. As a result, the determination of local coat weight distribution determined by UV scanner imaging appears to be more precise at lower FWA concentrations in the coating color. This is contrary to our expectations that a higher amount of FWA in the coating color gives a better contrast and thus a higher correlation.

<u>Influence of the FWA concentration in the base paper</u>

In commercial coated paper grades the FWA is usually added predominantly into the coating color. Due to the usage of coated broke a small amount of FWA is also contained in the base paper. In the present study, part of the hand sheet samples contained a rather high amount of FWA (1% *Blankophor® PT*) in the base paper, resulting in a brightness of 108.38% compared to 87.85% for the hand sheets with no FWA. When these hand sheets are coated two contrary mechanisms can occur during UV scanner imaging. On the one hand, the FWA in the coating color generates a signal. On the other hand, the excited FWA in the base paper shines through the coating to some extent.







(a) HS sample (Color 1, 0.1% FWA) (b) HS Sample (Color 2, 0.2% FWA) (c) HS Sample (Color 3, 0.3% FWA)

Figure 7. UV scanner images of blade coated HS samples (19 g/m² coat weight) with increasing FWA concentration in the coating color (no FWA in base sheet).

Figure 8 shows the coefficient of correlation (*R*) of UV scanner and burnout test images of the HS samples containing FWA in the base paper. As the correlation is negative in this case and R^2 does not take into account a negative correlation, *R* has been chosen for visualization of the correlation.

The negative correlation implies that brighter areas in the UV scanner images correspond to darker areas in the burnout images. The large amount of excited FWA in the base paper seems to shine through the coating layer in regions of lower coat weight. There is no clear trend for the three coating colors with different FWA amounts. Further testing is needed in order to clarify this observation. In summary it has to be concluded that excessive amounts of FWA in the base paper also has a negative effect on the estimation of the spatial coating layer formation using UV scanner imaging.

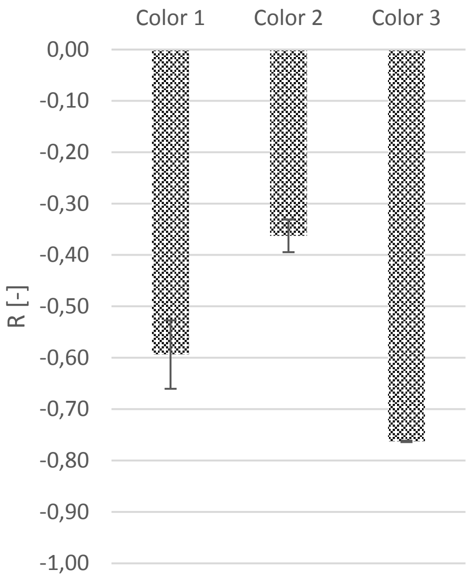


Figure 8. *R* of point wise correlation of burnout test – and UV scanner images of HS samples (with 1% FWA in base paper) coated with Color 1, Color 2 and Color 3.

<u>Evaluation of commercial LWC samples</u>

The results of the point wise correlation of four LWC samples between UV scanner and burnout test images are shown in *Figure 9*. The mean R^2 for the LWC samples is 0.77. This result demonstrates a high similarity between those methods. Therefore, the UV scanner imaging seems to be suitable for the spatial coating layer formation for commercial LWC samples.

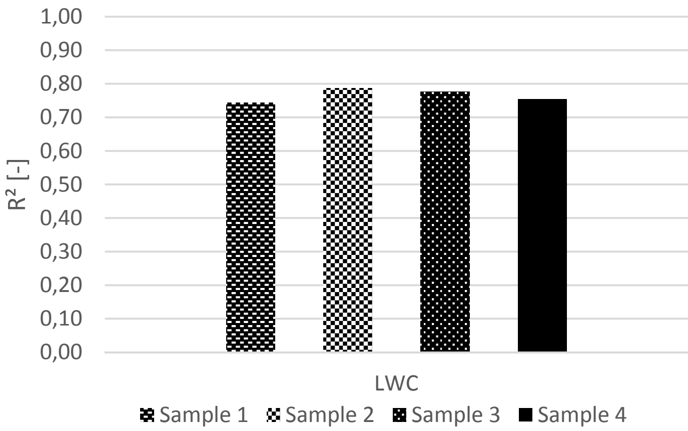


Figure 9. R^2 of point wise correlation of LWC burnout test - and UV scanner images.

CONCLUSION AND OUTLOOK

A method to determine the spatial coating layer uniformity using UV scanner imaging has been evaluated. The results indicate that this method is only applicable under closely defined conditions regarding applied coat weight and FWA amount in the coating color and the base paper respectively.

For coating colors with low FWA content applied to base papers containing no to little FWA and low coat weights (< 19 g/m²), a good correlation between UV scanner images, burnout test images and also β-radiography measurements was observed. This shows UV scanner imaging could be a useful tool for a non-destructive and fast evaluation of the coating layer uniformity under these defined conditions.

For samples with higher coat weights and for samples with high amount of FWA in the coating color or in the base paper, the correlation to the burnout test and the local coat weight maps is poor. For rather high amounts of FWA in the base paper the correlation is even reversed.

In order to better understand the UV scanner imaging method further research will be carried out to evaluate the influence of the FWA in the base paper. In addition the influence of the carrier (e.g. PVOH, CMC or starch) for the FWA in the coating formulation on the UV scanner imaging method will be studied.

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