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Influence of Ink Curing in UV LED Inkjet Printing on Colour Differences, Ink Bleeding and Abrasion Resistance of Prints on Textile

Vpliv sušenja tiskarske barve v UV LED kapljičnem tisku na barvne razlike, razlivanje tiskarske barve in odpornost proti drgnjenju potiskanih tkanin

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Abstract

Digital printing techniques are increasingly present in the field of textile printing. Particularly prominent is the inkjet printing technique using water-based inks, while UV LED inkjet printing also increasingly being in use. UV LED inkjet is primarily not intended for direct clothing printing; however, it can be used especially as a hybrid solution in the soft signage market. It is a great option for the printers that are not engaged only in textile printing, and want a more versatile print portfolio, extending it to non-clothing textile products, e.g. soft signage and non-wearable products. As these types of products often require colour reproduction of logos, accurate colour reproduction, good ink adhesion and sharpness are important just like in other printing technologies. In order to evaluate the impact of UV LED radiation amount on colour differences, ink bleeding and abrasion resistance, six different fabric samples (five woven and one nonwoven) were printed using a UV LED inkjet printer. Based on the results of colour difference, it was established that a reduction of UV radiation (by half the manufacturer's recommended amount) had no effect on this parameter. However, perceptible colour differences were observed with the use of different M measurement conditions defined by the international standard ISO 13655-2017. Reducing the amount of UV radiation had no effect on the adhesion and durability of the printed ink. Small differences detected in these two parameters were mainly a consequence of the properties of textile materials and not of decreased UV radiation.

Keywords: UV LED inkjet printing on textile, ink curing, ink bleeding, colour differences, abrasion resistance

Izvleček

Digitalne tiskarske tehnike so čedalje bolj prisotne na področju tekstilnega tiska. Pri tem ima vodilno vlogo predvsem kapljični tisk s tiskarskimi barvami na vodni osnovi, čedalje bolj pa je prisoten tudi UV LED kapljični tisk. Čeprav njegov prvotni namen ni tiskanje oblačil, je hibridna rešitev za tiskarje, ki poleg tekstilnih potiskujejo tudi druge vrste materialov. Med nabor tekstilnih izdelkov, ki se lahko tiskajo z uporabo tehnologije UV LED kapljičnega tiska, spadajo predvsem *neoblačilni izdelki in t. i. mehke oznake. Tudi pri teh so natančna barvna reprodukcija, obstojnost in kakovost odtisov ključnega pomena. Da bi ovrednotili vpliv sušenja tiskarske barve, ki je eden ključnih procesov v UV LED kapljičnem tisku, smo med raziskavo z različnima količinama UV-sevanja zamreževali oz. sušili tiskarsko barvo, odtisnjeno na šestih (petih tkanih in enem netkanem) tekstilnih vzorcih. Na podlagi rezultatov meritev barvnih razlik smo ugotovili, da zmanjšanje količine UV-sevanja (za polovico glede na tisto, ki jo priporoča izdelovalec tiskalnika) ni vplivalo na ta parameter. Sorazmerno velik vpliv na barvne razlike odtisov pa smo zaznali ob uporabi različnih M merilnih pogojev, ki jih definira mednarodni standard ISO 13655-2017. Zmanjšanje količine UV-sevanja ni vplivalo na adhezijo in obstojnost odtisnjene tiskarske barve. Majhne razlike, zaznane pri teh dveh parametrih, so bile predvsem posledica lastnosti tekstilnih materialov in ne posledica zmanjšanja količine UV-sevanja.*

Ključne besede: UV LED kapljični tisk na tekstil, sušenje tiskarske barve, razlivanje tiskarske barve, barvne razlike, odpornost proti drgnjenju

1 Introduction

The presence of digitisation has been on an increase in virtually every industrial sector in recent years, which is also reflected in the field of textile printing. Digital printing techniques are becoming each year more prevalent in this segment, as evidenced by the Smithers Pira data, which predict more than 10% annual growth by 2023 [1]. Digital printing techniques are replacing analogue printing with the predominance of inkjet printing. Inkjet printing is based on spraying tiny droplets (with a volume of few picolitres) of liquid ink onto the printing substrate. The droplets are placed with great precision, enabling reproduction of high-quality images. The inkjet printing market share is growing mainly because it offers an economic alternative to other print techniques, having the advantage of full variability and low set-up costs. It allows economic printing of single copies on virtually any flat or flexible printing substrate (stone, polymers, glass, ceramics, composites, textiles etc.) [1, 2].

The dominant water-based technologies (with reactive, acid or pigmented inks) have the largest market share, while UV inkjet is a subtype of inkjet printing which is not intended for direct clothing printing but can be used especially as a hybrid solution in the textile soft signage market. It is a great option for printers that are not engaged only in textile printing and want their versatile print portfolio to extend to non-clothing textile products, e.g. soft signage and non-wearable products. As soft signage often includes colour reproduction of logos, an accurate colour reproduction is important just like in other printing technologies [3]. The main disadvantage of UV LED inkjet is the possibility of ink components migration and reaction with the human skin when used for wearable textile printing. Its greatest advantage, however, is that the printing ink dries as soon as it is applied onto the printing substrate and cured with a UV LED lamp. This enables printing with a greater amount of printing ink (better surface coverage and a more accurate colour reproduction with less influence of the printing material) and, above all, printing on (all) non-absorbent printing materials [2, 3]. Immediate drying is enabled by the photoinitiator, a component of printing ink that encourages the crosslinking of the printed layer of ink under the influence of UV radiation from lamps, which are a part of printers. Currently, the following photoinitiators are mainly in use: benzyl dimethyl ketal, 2-hydroxy-methyl-1 phenyl propane and hydroxycyclohexyl phenyl ketone. As a source of UV radiation, LED lamps are primarily used on modern printing devices. They use significantly less energy than conventional mercury lamps while producing less harmful ozone. Their advantage is also the narrower radiation range, with usually only one dominant peak located in the UV A region (320–395 nm) [2].

Two books by Ujiie [4] and Cie [5], along with an article by Malik, Kadian and Kumar [6] defined digital printing technologies and especially inkjet printing in detail, providing an overview of technical specifications of different parameters involved in the printing of textiles. When printed, UV inks are very low in viscosity and penetrate deeply into the fabric to adhere to the surface. The ink must be exposed directly to UV light to obtain a cure from a UV bulb. UV curable inks and their applications in industrial inkjet printing are described also in the book by Zapka [7] where the author mentions that the UV exposure time can influence image quality. An overview of influencing factors is presented in Figure 1.

Regarding published research, the UV inkjet printing on textiles (esp. UV LED inkjet) has not been widely

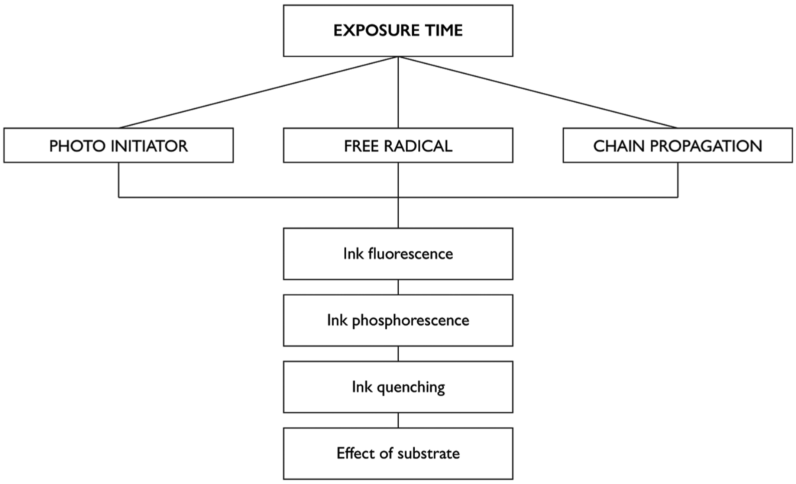

Figure 1: Factors in UV LED inkjet printing influenced by exposure time [7]

researched yet. The article by Hankock and Lin [8] covered the production of UV inkjet inks, while in the paper by Edison [9], the optimisation of UV curable inks was defined in terms of optimal jet output. Yi et al. [10] investigated the importance of monomers and comonomers in UV LED inks. Their work indicates that the monomer has not only a substantial influence on the dispersion and cure rate of UV LED ink but also a major effect on the film-forming properties of the ink. The mechanisms of attachment to textile fibres primarily include the interaction of chemical binding, mechanical interaction and fibre structure diffusion.

The influence of industrial fabrication parameters on the crosslinking density of UV resin was studied by Seipel et al. in 2018 [11]. A UV responsive smart textile was produced with inkjet printing and UV LED curing of a specifically designed photochromic ink on a PET fabric. The authors found out that increased ink deposition, or curing with higher intensity, i.e. higher lamp intensity and/or lower belt speed, increased the crosslinking density of ink. Hence, it formed a thicker or more distinct layer on the PET fabric surface. The effect of the deposited ink amount and curing settings on print durability is also described in this paper. A higher polymer crosslinking density is achieved as the print creates a strong insulation layer on the PET surface. The prints cured with the lowest curing intensity exhibited a lower polymer crosslinking density; however, they were slightly less durable and flexible. Mikuž et al. [12] compared the properties of inkjet printed, ultraviolet cured pigment prints with screen-printed, thermo-cured pigment prints. The colorimetric parameters of printed fabrics showed minimal and acceptable differences. A comparison of colour fastness properties proved that good colour fastness is achieved on pigment-printed fabrics produced with both printing techniques. The flat-screen-printed fabrics had better colour fastness to washing, perspiration and rubbing, while inkjet-printed fabrics showed better colour fastness to dry-cleaning and light. Tse et al. [13] studied the usability of image-based instruments for print quality evaluation. Regarding colour quality, the test results indicate that the fabric structure, yarn size and the hydrophilic/hydrophobic aspect of the fabric are the most important variables. Moreover, it was established that the colour gamut for larger size yarn is greater than for smaller size yarn and that there was an apparent downshift in the a*–b* plane for the knitted sample, indicating a colour shift between the two types of fabric structures. Bae, Hong and Lamar [14] found out that the texture of woven textiles caused a measurable effect on colour in inkjet printing, both using instrumental and perceptual measures. Colour reproduction is not only characterised by the interaction between light, dyes, pigments and textile structure, but also by the measurement conditions and geometry, and by the multi-layering of inks and process parameters. The multi-layering of inks and process parameters, e.g. washing fastness of printed inks, were studied by Kašiković et al. [15] in 2018. Two commercial spectrophotometers with different measuring geometries were used in a paper written by Milić et al. [16] to determine the measuring uncertainty of spectrophotometric measurements of printed textile materials. Study findings suggest that, despite different measuring geometry, instruments had similar measurement repeatability behaviour (repeatability of readings from different parts of the same sample) in the case of used digitally printed polyester materials. The material preparation process (material was folded three times and placed on a black or white backing) had an important influence on measurement variability. In the recent study by Karlovits, Lavrič and Kavčič [17], four differently structured textile materials were printed with a UV LED inkjet printer. The spectrophotometric measurements of prints were conducted according to ISO 13655:2017 [18]. The obtained results revealed that the texture and aperture size had influence on colour differences, while the measurement mode differences were more prominent in the areas with higher than lower ink coverages, especially when using the polarisation filter for ink coverages over 150%.

Even though UV curing is one of the key processes in UV LED inkjet printing, its influence on print properties has not been widely researched in the literature. The aim of the research, therefore, was to describe the influence of the UV LED radiation amount on colour differences, ink bleeding and abrasion resistance of prints printed with a UV LED inkjet printer on six different fabric samples. The study also evaluated the influence of M mode measurement conditions on colour differences in the UV LED inkjet printing. The M mode measuring conditions are defined by the international standard ISO 13655:2017 [18] and are widely used especially for paper and cardboard printing applications. They are a response to the increasing presence of optical brighteners in papers and cardboards, which creates challenges for successful colour management and accurate colour reproduction. Optical brighteners are chemical substances added to different materials (e.g. paper, board, fabrics) to enhance their brightness. They absorb invisible ultraviolet radiation at wavelengths below 400 nm and emit it in the blue end of the visible spectrum at approximately 400 to 450 nm through an electrophysiological alteration (fluorescence process). This process is activated only when the M1 measuring condition is used for spectrophotometric measurements. By choosing this measurement condition, the measurement is performed using the D50 illumination condition with the UV component of light included. At the M2 measuring condition, this part of the light is excluded (UV cut), while the measurement condition M0 is based on the measurements with the Standard Illuminant A. As by scope, ISO 13655:2017 is not applicable just for paper and board types of substrates, and there is no other specific standard regarding the measurement conditions for digitally printed textiles. It is more common that the printer will use a spectrophotometer, which covers more types of printing materials, and these differences are important for evaluation.

2 Materials and methods

2.1 Materials

The influence of UV curing in the UV LED inkjet printing on colour differences, print sharpness and abrasion resistance was evaluated on six different fabric samples (5 woven and 1 nonwoven). Their properties are presented in Table 1.

Printing forme preparation

A digital printing forme (cf. Figure 2) was designed using the computer program Adobe Illustrator CC (Adobe, USA) and saved as PDF without the colour

Table 1: Sample properties

Sample	Weave type (ISO 3572:1976)	Thread count warp/weft (ISO 7211-2:1984)	Thickness (mm) (ISO 5084:1996)	Composition (ISO/TR 11827:2012)	Optical brighteners (ISO 3664:2009)	Mass per unit area (g/m^2) (ISO 3801:1977)
V1	plain weave	25/21	0.354	100% CO	YES	134
V2	plain weave	51/30	0.228	100% CO	NO	121
V3	plain weave	35/21	0.316	50% PES/50% CO	NO	171
V4	plain weave	24/21	0.460	100% PES	YES	204
V5	crepe weave	30/21	0.573	100% PES	NO	199
V6	fleece	/	1.170	100% PES (nonwoven)	NO	151

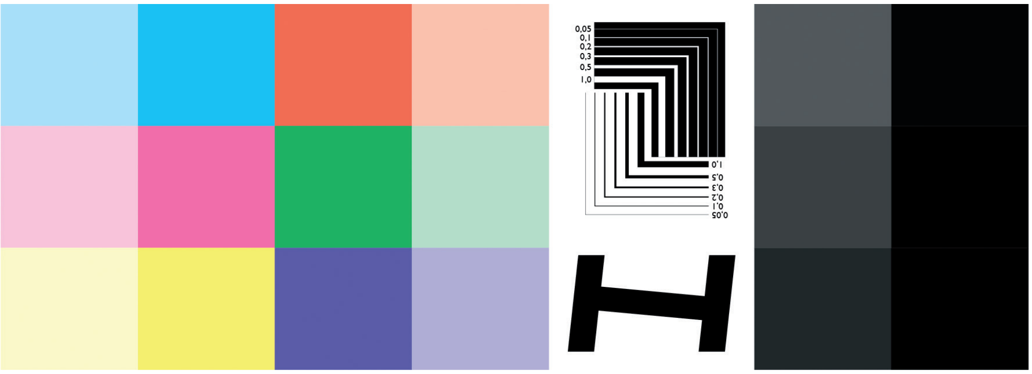

Figure 2: Digital printing forme

profile attached. It consisted of 18 colour patches with the area of 4 cm^2 (CMY patches with 50% and 100% tone value; RGB patches with 50% and 100% tone value, where e.g. 50% R is defined as 50% M + 50% Y and 100% R is defined as 100% M + 100% Y etc.) The total ink coverage scale consists of patches in which the tone values gradually increase (from 50% C + 50% M + 50% Y + 50% + 100% B to 100% C + 100% M + 100% Y + 100% B), lines and a control element for print sharpness evaluation. The file was then processed using a SAi PhotoPRINT DX Plus (SAi, USA) raster image processor. Linearization without colour corrections was performed.

Printing process

The samples were printed with an Apex UV 1610 UV LED flatbed inkjet printer (Apex, China) equipped with Toshiba CE4 on-demand piezo electric inkjet print heads and two UV LED lamps (one on the left and one on the right side of print heads). Sakata soft LED UV inks (Sakata, Japan) were used. They were formulated to cure when exposed to UV light with the wavelength of 395 nm. The printing parameters were set to 8 passes, with the printing speed of 0.84 m/s (one-directional printing – from right to left). The print head height was set 0.8 mm above the material top and the jetting frequency to 10.28 kHz. The printing ink drop size was 6 picolitres. The ink was cured using one or both UV lamps. Five prints were made on each fabric sample.

Spectrophotometric measurements and colour differences calculation

Spectrophotometric data were obtained using a spectrophotometer X-Rite i1 Pro 2 Basic (X-Rite, USA) and BabelColor PatchTool (BabelColor, Canada) software. The measurements were performed with the M0, M1 and M2 measurements modes (cf. Table 2) on standardised white backing. The measuring conditions were set to 45°/0° ring illumination optics, D50 standard illuminant and 2° standard observer. Colour differences (ΔE_{00}) were calculated using BabelColor PatchTool software in accordance with ISO 13655:2017 [18]. Five measurements were made on each colour patch.

Ink bleeding evaluation

The ink bleeding evaluation was done following the method described by Hladnik and Muck in 2011 [19]. It is based on the measurements of the area (mm^2) and perimeter (mm) of a selected printed element that are compared with the measurements of its undistorted digital form from the printing form. The measurements were conducted using an ImageJ 1.48v (ImageJ, USA) computer program on TIFF images with the resolutions of 600 ppi obtained with CanoScan 5600F (Canon, Japan) without any colour distortions and corrections.

Crockfastness evaluation

Crockfastness was measured according to ISO 105-X12:1993 on a CM-5 Crockmeter (AATCC Atlas,

Table 2: Description of measuring conditions

Measuring condition	Light source	Filter
M0	undefined/tungsten	none
M1	D50 + controlled UV	none
M2	tungsten	UV cut

USA). Ten measurements were performed for dry and wet crockfastness tests.

Colour fastness to washing
Colour fastness to washing at 40 °C was tested in accordance with ISO 105-C06:2010.

FTIR ATR analysis
The FTIR ATR printing ink analysis was performed using a Perkin Elmer Spectrum Two FTIR spectrometer (Perkin Elmer, USA). For the purpose of the analysis, printing ink was printed on an inert glass surface with one and two UV lights used for curing, and then peeled from it and analysed. In this way, a potential impact of the textile on the analysis was nullified.

3 Results and discussion

Table 3 shows the average values of colour differences among the prints printed using one or two UV lamps on each textile sample. Colour differences were calculated based on the spectrophotometric values of all colour patches on the printing form. All patches were measured under the M0, M1 and M2 measuring conditions.

Based on the results shown in Table 3, it can be concluded that between two different amounts of UV radiation, there was a minimal effect on the colour reproduction of textile samples. The average calculated colour difference was 0.55 ΔE_{00}. Such a colour difference is almost unnoticeable to the human eye and is most likely a consequence of short-term repeatability of the measuring instrument and the printer. Despite the 50% reduction in UV radiation from the radiation recommended by the printer manufacturer, it still polymerised the ink and thus prevented further penetration, which could lead to greater colour variations. However, this was not fully confirmed by the FTIR analysis, the result of which is shown in Figure 3.

As it can be seen from Figure 3, the sample of printing ink that was less crosslinked (red curve) achieved slightly higher absorbance values across the entire spectrum (from 450 to 4000 cm^{-1}) than the sample that was crosslinked to a greater extent. The vertical shift of curves can be attributed to the difference in the amount of twisting and stretching vibrations

Table 3: Average colour differences (ΔE_{00}) among prints printed using one and two UV lamps

Sample	Measuring condition		
	M0	M1	M2
V1	0.51	0.51	0.53
V2	0.30	0.29	0.30
V3	0.69	0.69	0.69
V4	0.56	0.55	0.58
V5	0.52	0.52	0.52

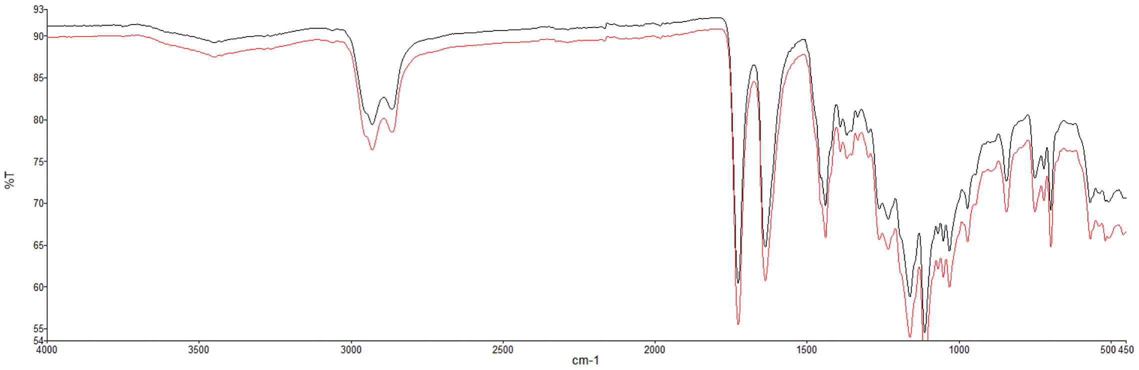

Figure 3: FTIR spectra of black process printing ink cured with one (red curve) and/or two UV LED lamps (black curve)

between molecules and atoms, which was more noticeable at the less crosslinked sample of printing ink. The difference is clearly noticeable also at approx. 807 cm^{-1}, which indicates a greater presence of C=C bonds in the less crosslinked sample. The amount of unreacted C=C double bonds between acrylic molecules is a direct indicator of UV ink polymerisation (several unreacted C=C double bonds indicate a lower degree of ink polymerisation).

A much greater influence on colour differences, especially for samples V1 and V4, which contained optical brighteners, can be observed due to the selection of measuring conditions. The results shown in Table 4 were obtained by measuring the prints dried using two UV LED lamps, the only variable factor being the choice of the measurement condition.

Optical brighteners present in textile samples (V1 and V4) affected the colour reproduction significantly (cf. Table 4). This is the main reason for relatively big colour differences (on average between V1 and V4; M0 : M1 1.10, M0 : M2 2.98 and M1 : M2 4.07 ΔE_{00}). The majority of colour differences (more than 60%) were detected in the least covered fields (50% CMY). Mainly due to the properties of tested materials (structure and weaving), spectrophotometric measurements were also influenced by optical brighteners in more covered fields or patches (the influence of optical brighteners present not only on the surface of the fibres but also on their circumference). Such colour differences are perceptible through close observation (M0 : M1) and at a glance in the case of comparing M2 measuring conditions with M1 and M0. The colour differences of samples without optical brighteners were negligible. Negligible were also the differences in the area and perimeter of selected printed elements which were measured for printing sharpness determination and are presented in Table 5.

Table 4: Colour differences (ΔE_{00}) caused by selection of measuring condition

Sample	Measuring condition		
	M0 : M1	M0 : M2	M1 : M2
V1	1.13	3.03	4.15
V2	0.01	0.03	0.04
V3	0.02	0.05	0.06
V4	1.07	2.92	3.99
V5	0.02	0.05	0.07

Table 5: Areas and perimeters of selected printed element

Sample	Curing – number of active lamps while printing	Area (mm²)	Perimeter (mm)
Ideal, digital element	/	190	115
V1	1	187.8	114.9
	2	188.2	114.3
V2	1	191.0	115.2
	2	190.6	114.2
V3	1	193.7	117.4
	2	194.7	118.5
V4	1	189.8	113.9
	2	189.2	114.9
V5	1	187.6	115.7
	2	189.4	117.5
V6	1	190.6	121.4
	2	190.4	122.4

The differences in areas and perimeters caused by lower UV radiation are minimal and can be attributed to the deviation of the method. Despite the one lamp being turned off, a sufficiently strong crosslinking occurred quickly enough for the printing ink not to spill or bleed. The differences among the samples, however, can be attributed to their different structure. Table 6 represents the colour fastness properties of samples to washing at 40 °C. Reduced ink curing did not influence this parameter on woven samples, while it improved colour fastness to washing of the nonwoven sample V6. The absence of empty spaces between the threads in this sample retained a greater amount of printing ink on the fabric surface. The ink layer was slightly more flexible with reduced curing. This affected the result of colour fastness to washing; however, it did not affect the results of the Crock test shown in Table 6.

The results of the crock test (cf. Table 7) were not affected by the reduction in curing. Small differences can be attributed to the standard deviation of the method, which is based on the visual assessment. Among the samples, the worst result was achieved with the nonwoven sample (V6). The printing ink layer, which remained on the surface of the sample, was more exposed when rubbed than in other samples.

4 Conclusion

Reducing the amount of UV radiation used for printing inks curing (by half the manufacturer's recommended amount) had no significant effect on the colour differences and print sharpness of printed textiles. A selection of different measuring conditions, however, caused perceptible colour differences in two samples which had optical brighteners, the other four had no significant changes. The difference between the applied two levels of radiation did not influence the ink properties, and thus the differences due to additional ink fluorescence and other optical effects. The FTIR analysis showed a difference in the degree of polymerisation of the printing ink, which was cured with one or two lamps, however, from the applicative point of view, the difference proved to be practically irrelevant. It is very important that the presence of optical brighteners is taken into account and that modern and calibrated measuring instruments are used for colour measurements. The

Table 6: Colour fastness to washing at 40 °C

Sample	Colour fastness to washing 2 UV lamps	Colour fastness to washing 1 UV lamp
V1	4/5	4/5
V2	4	4/5
V3	4/5	4/5
V4	3	3
V5	5	5
V6	4	5

Table 7: Crock test evaluation

Sample	Grade			
	Dry 1 UV lamp	Dry 2 UV lamps	Wet 1 UV lamp	Wet 2 UV lamps
V1	3	3	3	2/3
V2	2/3	2/3	3	3
V3	2/3	2/3	2	2
V4	2/3	2/3	1/2	1/2
V5	2	2	1/2	1/2
V6	2	2	1	1

adhesion and fastness tests resulted in small, insignificant differences, indicating that the drying can be done equally efficiently with just one lamp on textile materials. The differences in the crockmeter were mainly due to the material properties and not a result of drying exposure variation.

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