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Textile Sublimation Printing: GLCM Print Mottle Assessment of Black Printed Fabric

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The white fabric was printed with different printing temperatures and pressing times using the sublimation printing process in solid-tone black color with a 100 % total ink limiting level. Non-uniformity of the print was examined through print mottle determined by grey level co-occurrence matrix (GLCM) image processing method. The color strength of the print was also determined by reflectance spectrophotometry. The print with the lower print mottle was obtained at a printing temperature of 190 °C at a longer pressing time of 120 s or at an increased printing temperature of up to 210 °C at the reduced pressing time of 60 s. The print with the lower print mottle had the lowest entropy, contrast, correlation and the highest energy and homogeneity. The print with a higher color strength was accompanied by decreased print mottle. Choosing a suitable printing temperature and pressing time for sublimation printing is helpful in achieving print with low print mottle and high color strength and balancing cost, price, and price.
Keywords: print quality, GLCM, color strength, sublimation, polyester.

1. INTRODUCTION

Sublimation printing is increasingly considered necessary in the printing technology in the textile industry [1, 2]. Sublimation is suitable for printing on textiles, especially where it is not easy to achieve a high-fidelity image on the textile by printing techniques, such as inkjet printing [3, 4], rotary screen printing [5], and roller printing. In a typical case, the print textile may be a textile with a shape or texture challenging to feed to a printer or a textile that does not readily receive high-fidelity images by some printing techniques. This printing process offers high printing speed, flexibility, creativity, environmental security, and various effects, and there is no restriction on the printing form. Sublimation printing is a process where the desired image is reverse printed on sublimation transfer paper by inkjet printing to provide a reverse printed sublimation transfer paper. The reverse printed sublimation transfer paper and textile to receive the desired image are combined with a heat press under temperature and pressure, where sublimation dyes transfer from the sublimation transfer paper to the textile material [6 – 8].

Sublimation printing also demands the technologist to develop an appropriate process to ensure that the final quality of the print matches the high level of print quality [9 – 12]. A measure of success for sublimation printing is print quality. It is an essential customer requirement along with other requirements, such as price and productivity [13 – 16]. Non-uniformity of printing density called print mottle is a common print defect. Print mottle usually occurs through systematically structured patterns, which the human version system notices quickly due to its perfect responsiveness for pattern detection. Print mottle can be defined as the effect of perceived inhomogeneity in print leading to a determination in the perceived quality of the print [17, 18]. Different reasons can be caused by the print mottle: the amount of ink that is transferred onto the textile during the printing process, inhomogeneous ink penetration into the substrate material, variation in surface porosity, substrate deformation, and printing parameters.

Over time, many investigations have been performed on textile sublimation printing, yet there is still much room for process improvement and studies [19]. The research was conducted to create a process for optimizing sublimation printing conditions using Taguchi design to minimise the water vapour resistance of knitted fabric [20]. From Taguchi's analysis, the predominant factor influencing the sublimation of printed single jersey knitted fabrics was the number of strokes of printing on the sublimation transfer paper. Another research emphasised the necessity to consider changes in fabric properties after the sublimation printing process [21]. There is interest in studies related to changes in fabric properties, and some have been performed. The influence of the sublimation process on air permeability and water dynamic of knitted fabrics, compression properties, and the structural and physical properties of knitted fabrics has been discussed in papers by a research group [22 – 24]. Sublimation printing has been reported to influence the alteration of the structural and physical properties of polyester, cotton, and cotton/polyester knitted fabrics [23]. The results showed that smaller changes in structural and physical properties were noticed for polyester knitted fabrics, while major

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changes in structure were observed in cotton knitted fabrics (where weight was gained and geometrical value was reduced). A significant change in density was recorded for polyester knitted fabrics. Tests were conducted to investigate the effect of sublimation printing on the mechanical properties, physiological properties and color fastness of the polyester knitted fabrics [22]. Tested samples showed good color fastness to rubbing, domestic and commercial laundering (grade 5). In terms of abrasion resistance, the material also showed high resistance. The air permeability decreased by about 40 % compared to the value obtained before printing, and the mechanical properties slightly increased (about 8 %). This change was due to an increase in the stitch density, and a decrease in the thickness, therefore reducing the porosity of the material for printing conditions, mainly due to the influence of pressure and temperature within the heat press machine. A study of the sublimation printing influence on the change in compression properties of polyester, cotton and cotton/polyester knitted fabrics using KES-FB3A compression tester has been conducted [24]. The printing process had a smaller influence on the change of compression parameters of polyester to cotton and cotton/polyester knitted fabrics. The printing process affected on thickness reduction for all knitted fabrics to varying degrees. The printing process contributed to a small decrease in compressibility and special volume values for polyester knitted fabrics compared to cotton and cotton/polyester. There is no paper covering the print mottle assessment of sublimation printed fabric. Many studies are related to investigating print mottle of screen printed fabric [25 – 28]. It was found that contrast, correlation, energy, entropy, and homogeneity parameters from the grey level co-occurrence matrix (GLCM) image processing method can be used for print mottle (print unevenness) assessment [29]. Energy and entropy parameters of the black printed sample can be used as predictors of solid-tone print non-uniformity [30]. In inkjet printing the CMYK color model is commonly used. The basic primaries in inkjet printing are cyan, magenta, yellow, and black. Yellow is usually added to control the hue and lightness of the produced colors. Black ink is added to increase the contrast and details in dark shade and reduce general ink consumption.

The customer's desire to achieve print quality matches the minimal print mottle and a maximal color strength of print. When printing, it is essential to have the most suitable printing temperature and pressing time printing parameters, as this will significantly differ in print's print unevenness and color strength. So, it is essential to know the printing temperature and pressing time to achieve print with maximal color strength and minimal print mottle. The printing temperature and pressing time affect the company's economic performance and customer requirements. In the case of orders, the inappropriate choice of the printing temperature and pressing time will significantly affect the print mottle and color strength of print and thus print quality.

Nowadays, sublimation printing in the textile industry keeps the attention of manufacturers and customers. This research has been done to investigate the change in print mottle and the color strength of sublimation printed fabric depending on the different printing temperatures and pressing times settings when sublimation printing on fabric in solid-tone black color with a 100 % total ink limiting level. Print mottle has been evaluated by examining the grey level co-occurrence matrix (GLCM) image processing method. Print color strength was determined by a reflectance spectrophotometer. This research provides an analysis of the influence of printing temperature and pressing time from the sublimation printing process on print mottle and a color strength of print that manufacturers can use to improve and develop more cost-effective sublimation printing process as well to achieve different levels of print quality, matching the required print quality, while balancing cost, price, and quality.

2. EXPERIMENTAL PART

2.1. Materials

The commercially available optically bleached and thermostabilized fabric in twill woven type was used to investigate the influence of printing temperature and pressing time in the sublimation printing process on print mottle and color strength. The technical properties of the used fabric and standards for their determination are given in Table 1. The presented results in Table 1 are the mean values of 3 measurements, at a confidence level of 95 %, with a margin of error.

2.2. Methods

The test image for printing was created in Adobe Illustrator software in the CMYK color system and consisted of the rectangle (3.5 cm × 3.5 cm dimensions) in solid-tone black color with 100 % total ink limiting level (C = 0 %, M = 0 %, Y = 0 %, K = 100 %). The test image was printed on commercially available A4 sublimation transfer paper weighing 105 g/m^2 with an A4 format EPSON inkjet printer for sublimation with four CMYK inkjet channels.

Table 1. Technical properties of the fabric used in this study

Technical properties	Fabric	Standard
Fiber type	97 % PES/3 % Elastane	ISO 1833-20
WI_{CIE}	123.26 ± 0.19	ISO 105-J02
L^*	95 ± 0.11	ISO 105-J01
a^*	1.34 ± 0.02	ISO 105-J01
b^*	-7.53 ± 0.01	ISO 105-J01
Mass per unit area, g/m^2	160 ± 0.96	ISO 3801
Warp density, cm^{-1}	22 ± 1.05	BS EN 1049-2
Weft density, cm^{-1}	42 ± 1.05	BS EN 1049-2
Thickness, mm	0.36 ± 0.04	ISO 5084

Inkjet printer was with printing method: Micro Piezo™ print head and nozzle configurations: 180 nozzles for black and 50 nozzles for color, model L3151. The printer was installed and dye sublimation ink SUBLYFUN by Print Equipment Gmbh&Co was used. Pre-pressing and sublimation printing processes were performed by the press model BESTSUB SB3A (38 cm × 38 cm) and medium pressure (2.3 – 3.5 bar). The pre-pressing of the fabric was conducted at printing temperature for 6 s, and then sublimation printing was performed at 170 °C, 180 °C, 190 °C, 200 °C, and 210 °C temperature and pressing time of 30 s, 40 s, 60 s, 80 s, and 120 s. Afterwards, the fabric was cooled to room temperature, and the baking paper was removed.

The sublimation printed fabrics were conditioned and tested in a standard atmosphere (temperature 20 °C and 65 % relative humidity) for 24 hours.

The color strength (K/S) of sublimation printed fabric was determined by measuring the corresponding reflectance value using the X-Rate Color i7 reflectance spectrophotometer and calculating the K/S value using the Kubelka Munk Eq. 1:

$$K/S = \frac{(1-R_{\lambda\ max})}{2R_{\lambda\ max}}, \quad (1)$$

where K is the absorption coefficient; S is the scattering coefficient; R is the reflectance value of the print at the wavelength at maximum absorption.

The presented K/S results are the mean values of 3 measurements at a confidence level of 95 %.

Print mottle was assessed by the image analysis method using a grey level co-occurrence matrix (GLCM). After sublimation printing, printed fabrics were digitalized by flatbed scanner EPSON L3151 at 600 dpi scanning resolution without auto-correction. The actual rotation angle determined by the orientation of the sample set in the sample input was 90°. Scanned images in the TIFF files were scaled at 500 × 500 pixels for easier processing in MATLAB. Then, samples were subjected to GLCM analysis to obtain quantitative print uniformity results. GLCM analysis was done in MATLAB software with code according to Uppuluri [31] using the following parameters: the number of grey levels was set to 8, the distance between two pixels (d) was set to 1, and four angles of orientation were used (horizontal 0°, right-diagonal 45°, vertical 90°, and left-diagonal 135°). Print mottle using MATLAB code was assessed through contrast, correlation, entropy, energy, and homogeneity parameters. The results presented for each GLCM parameter are the mean value of 3 measurements at a confidence level of 95 %.

GLCM parameters were computed using the following Eq. 2 – Eq. 6:

$$\text{Energy} = \sum_{i,j=1}^{n} (P_{ij})^2, \quad (2)$$

$$\text{Entropy} = \sum_{i,j=1}^{n} -ln(P_{ij})P_{ij}, \quad (3)$$

$$\text{Contrast} = \sum_{i,j=1}^{n} P_{ij}(i-j)^2, \quad (4)$$

$$\text{Homogeneity} = \sum_{i,j=1}^{n} \frac{P_{ij}}{1+(i-j)^2}, \quad (5)$$

$$\text{Correlation} = \sum_{i,j=1}^{n} P_{ij}\frac{(i-\mu)(j-\mu)}{\sigma^2}, \quad (6)$$

where P_{ij} is the element of the normalized symmetric GLCM: N is the number of grey levels (the dimension of the GLCM); μ is the GLCM mean (being an estimate of the intensity of all pixels in the relationships that contributed to the GLCM), calculated according to Eq. 7, and σ^2 is the variance of the intensities of all reference pixels in the relationships that contributed to the GLCM, calculated according to Eq. 8.

$$\mu = \sum_{i,j=1}^{n} iP_{ij}, \quad (7)$$

$$\sigma^2 = \sum_{i,j=1}^{n} P_{ij}(i-\mu)^2. \quad (8)$$

3. RESULTS AND DISCUSSION

The effect of the different printing temperatures and pressing times on the color strength of the printed fabric is shown in Table 2. The higher K/S value indicates intensive color strength [32, 33]. Increasing the pressing time to 60 s and increasing the printing temperature to 210 °C, the K/S value of the print increased. Increasing the pressing time to 120 s, the K/S of the print increased with increasing the printing temperature up to 190 °C; above this temperature, the color strength of the print decreased. The highest K/S value was reached in 120 s up to the temperature of 190 °C, while with a further increase in temperature up to 200 °C and 210 °C, the highest K/S value of print was reached in 80 s and 60 s respectively. Amorphous areas of polyester fibers exist when the temperature rises to about 200 °C, and the amorphous zone moves vigorously, allowing the gaseous sublimation dye to enter the fiber. At this temperature, the dye sublimation is gaseous; because of the attraction of dye sublimation power, the dye in such a gaseous state has the potential to move toward the polyester fiber, then diffuses and get into the amorphous area, and along with the reduction of temperature, the dye molecules desublimates and is wrapped in amorphous area, reaches the printing effect [20].

The overall print mottle changes of the sublimation printed fabric are assessed by the GLCM image processing method [30, 34]. In Table 3 are shown the values of contrast GLCM parameters of prints. Comparing the obtained prints depending on different temperatures and pressing times, certain differences can be observed for the contrast parameter, indicating that the higher printing temperature and shorter pressing time had a more intensive impact on the contrast value. The value for the contrast of the print decreased by increasing the time to 60 s and increasing the printing temperature to 210 °C. Increasing the pressing time to 120 s, the contrast value decreased by increasing the printing temperature to 190 °C; above this temperature, the contrast value increased. It can be seen that the lowest contrast value, up to a printing temperature of 190 °C, was reached in a pressing time of 120 s, while with an increase in printing temperature to 200 °C and 210 °C, the lowest contrast value was achieved in 80 s and 60 s respectively. Based on the results shown in Table 3, it can be concluded that the print obtained at a higher printing temperature and shorter pressing time had a lower variation in grey levels in the image and that the print obtained at a lower printing temperature and shorter pressing time had a higher variation in grey levels in the image. Print obtained at a higher printing temperature for a shorter pressing time had the lowest contrast between pixels in the image; therefore, it can be regarded as the sample with the lowest contrast. The reason why contrast was lower when printing at a higher temperature and shorter pressing time was connected with sublimation dye on the fabric surface, and hence with grey levels in an image. So, the amount of sublimation dye was higher and was evenly distributed over the fabric than print obtained at a lower printing temperature and shorter pressing time, which resulted in a higher variation of grey levels in an image. Unequal transfer of sublimation dye on the surface of the fabric led to a higher contrast value. The intensity of contrast value between pixels in the image represents the contrast. The grey level variations in an image were measured by contrast. The print is considered to be evenly printed if the contrast value is zero [30].

The values of the homogeneity GLCM parameter of prints obtained at different printing temperatures and pressing times are shown in Table 4. Homogeneity measures the closeness of the distribution of pixels in the GLCM [30]. Homogeneity values had the opposite trend from contrast values. The homogeneity values increased, as contrast values decreased. The value for the homogeneity parameter of the print increased by increasing the pressing time to 60 s and increasing the printing temperature to 210 °C. Increasing the pressing time to 120 s, the homogeneity value increased to the printing temperature of 190 °C; above this printing temperature, the homogeneity decreased. The highest value for the homogeneity GLCM parameter, up to the printing temperature of 190 °C, was achieved in 120 s, while with a further increase in printing temperature to 210 °C, the highest homogeneity value was reached in 60 s. The homogeneity value of 1 corresponds to the homogeny print surface with no variations [30, 34, 35].

Energy measures the uniformity of pixels in GLCM. The energy values are also large as the pixels get more similar [34, 35]. The results of the energy GLCM parameter of prints obtained at different printing temperatures and pressing times are shown in Table 5. The energy value increased by increasing the pressing time to 60 s and increasing the printing temperature to 210 °C.

Table 2. Color strength of sublimation prints obtained at different printing temperatures and pressing times

Pressing time, s	T, °C				
	170	180	190	200	210
30	3.00 ± 0.2241	3.55 ± 0.2431	6.38 ± 0.2787	9.91 ± 0.1892	13.98 ± 0.2592
40	3.90 ± 0.2590	4.32 ± 0.2625	8.11 ± 0.4511	12.36 ± 0.2292	14.83 ± 0.1660
60	5.48 ± 0.3028	5.68 ± 0.2836	10.52 ± 0.3186	14.96 ± 0.2664	15.72 ± 0.1471
80	5.68 ± 0.2899	9.85 ± 0.4031	13.42 ± 0.1478	15.48 ± 0.1818	14.33 ± 0.1710
120	10.03 ± 0.3497	13.56 ± 0.3933	15.42 ± 0.2859	15.15 ± 0.0556	12.24 ± 0.1191

Table 3. Contrast GLCM parameter of sublimation prints obtained at different printing temperatures and pressing times

Pressing time, s	T, °C				
	170	180	190	200	210
30	0.689143 ± 0.0345	0.669054 ± 0.0291	0.568894 ± 0.0200	0.376735 ± 0.0078	0.319478 ± 0.0058
40	0.696219 ± 0.0343	0.615330 ± 0.0271	0.405033 ± 0.0139	0.330603 ± 0.0066	0.310850 ± 0.0064
60	0.575724 ± 0.0301	0.482515 ± 0.0214	0.351345 ± 0.0104	0.323361 ± 0.0069	0.303300 ± 0.0051
80	0.533401 ± 0.0235	0.383984 ± 0.0141	0.328766 ± 0.0089	0.306829 ± 0.0045	0.323234 ± 0.0007
120	0.371734 ± 0.0159	0.338566 ± 0.0123	0.304148 ± 0.0077	0.340284 ± 0.0047	0.371169 ± 0.0047

Table 4. Homogeneity GLCM parameter of sublimation prints obtained at different printing temperatures and pressing times

Pressing time, s	T, °C				
	170	180	190	200	210
30	0.784724 ± 0.0220	0.726258 ± 0.0194	0.791938 ± 0.0179	0.83649 ± 0.0172	0.857548 ± 0.0089
40	0.733597 ± 0.0183	0.760058 ± 0.0189	0.830388 ± 0.0174	0.851952 ± 0.0157	0.863067 ± 0.0128
60	0.79025 ± 0.0205	0.809855 ± 0.0185	0.844377 ± 0.0201	0.857872 ± 0.0154	0.861669 ± 0.0099
80	0.800138 ± 0.0190	0.835959 ± 0.0181	0.854301 ± 0.0159	0.863040 ± 0.0154	0.856665 ± 0.0111
120	0.82823 ± 0.0185	0.825292 ± 0.0181	0.865282 ± 0.0088	0.852511 ± 0.0016	0.838688 ± 0.0119

Table 5. Energy GLCM parameter of sublimation prints obtained at different printing temperatures and pressing times

Pressing time, s	T, °C				
	170	180	190	200	210
30	0.132695 ± 0.0077	0.098049 ± 0.0053	0.240787 ± 0.0088	0.318852 ± 0.0113	0.389585 ± 0.0093
40	0.099451 ± 0.0051	0.167022 ± 0.0078	0.308733 ± 0.0111	0.366533 ± 0.0097	0.398976 ± 0.0073
60	0.224454 ± 0.0115	0.265145 ± 0.0130	0.343398 ± 0.0157	0.396111 ± 0.0141	0.403472 ± 0.0067
80	0.237183 ± 0.0110	0.321301 ± 0.0145	0.381570 ± 0.0178	0.400783 ± 0.0152	0.386895 ± 0.0077
120	0.320727 ± 0.0137	0.370057 ± 0.0145	0.413962 ± 0.0058	0.375281 ± 0.0080	0.336564 ± 0.0121

Table 6. Entropy GLCM parameter of sublimation prints obtained at different printing temperatures and pressing times

Pressing time, s	T, °C				
	170	180	190	200	210
30	2.341268 ± 0.0949	2.590058 ± 0.0868	1.871254 ± 0.0561	1.514141 ± 0.0365	1.337263 ± 0.0236
40	2.621573 ± 0.0976	2.214264 ± 0.0717	1.575509 ± 0.0413	1.380230 ± 0.0317	1.320243 ± 0.0244
60	1.943960 ± 0.0673	1.735069 ± 0.0422	1.433721 ± 0.0334	1.337590 ± 0.0214	1.288881 ± 0.0123
80	1.864900 ± 0.0559	1.525545 ± 0.0365	1.362416 ± 0.0277	1.323503 ± 0.0249	1.345172 ± 0.0176
120	1.510187 ± 0.0394	1.381865 ± 0.0233	1.295296 ± 0.0115	1.402025 ± 0.0183	1.477489 ± 0.0170

Table 7. Correlation GLCM parameter of sublimation prints obtained at different printing temperatures and pressing times

Pressing time, s	T, °C				
	170	180	190	200	210
30	0.745571 ± 0.0192	0.722859 ± 0.0176	0.542171 ± 0.0110	0.486048 ± 0.0071	0.473447 ± 0.0056
40	0.734960 ± 0.0161	0.635575 ± 0.0121	0.504782 ± 0.0075	0.470973 ± 0.0058	0.483763 ± 0.0053
60	0.589225 ± 0.0108	0.517431 ± 0.0091	0.463320 ± 0.0056	0.479927 ± 0.0047	0.456518 ± 0.0036
80	0.581228 ± 0.0082	0.495124 ± 0.0064	0.478782 ± 0.0056	0.503087 ± 0.0047	0.472715 ± 0.0049
120	0.493160 ± 0.0066	0.464077 ± 0.0058	0.488681 ± 0.0036	0.507816 ± 0.0053	0.480594 ± 0.0044

Increasing the pressing time to 120 s, the energy value increased to the printing temperature of 190 °C; above this printing temperature, the energy decreased. The energy value parameter, like homogeneity, was the highest for the print obtained at the temperature of 190 °C and pressing time of 120 s, followed by the prints obtained at 200 °C and 80 s, and 210 °C and 60 s. The energy parameter showed the same trend as in the case of the homogeneity parameter.

The opposite trend of energy represents entropy. System disorder measures entropy. Extraction of entropy parameter value from images depends on the selection of printing temperature and pressing time. In Table 6 are shown the results of the energy GLCM parameter of prints depending on printing temperatures and pressing times. The lowest value for the entropy was achieved in 120 s at the printing temperature of 190 °C. Increasing in printing temperature to 210 °C, the lowest entropy value was reached in 60 s. Human perception of texture correlates best with the entropy parameter [35]. The unevenness of the print is higher if the value for the entropy is higher, and thus the unevenness is more visible. The entropy parameter followed the trend for contrast.

The results of the correlation GLCM parameter of prints depending on printing temperatures and pressing times are shown in Table 7. The correlation decreased by increasing the pressing time to 60 s and increasing the printing temperature to 210 °C. The correlation parameter showed a similar trend as in the case of the contrast and entropy parameters. A linear dependency of grey levels with those of neighbouring pixels is determined by correlation. Correlation gives information about how correlated a pixel is to its neighbouring pixels [30]. Correlation values range from -1 (negatively correlated) to 1 (positively correlated). Low values of correlation correlate to the uniform print surface.

4. CONCLUSIONS

The effect of change in print mottle was analyzed on 97 % polyester and 3 % elastane fabric to determine print quality obtained by sublimation printing at different printing temperatures and pressing times in solid-tone black color with a 100 % total ink limiting level. The contrast, homogeneity, energy, entropy, and correlation GLCM parameters from the grey level co-occurrence matric (GLCM) image processing method were used for this purpose. The color strength of the print was also determined. The results of GLCM parameters are dependent on the selection of the correct printing temperature and pressing time. Increasing the printing temperature to 190 °C allowed the minimal print mottle and a maximum color strength of print to be reached in a longer pressing time of 120 s. With a further increase in temperature to 210 °C, the minimal print mottle and a maximum color strength of print are achieved in a shorter pressing time. Considering the importance of printing temperature and pressing time for the sublimation printing in terms of print mottle and color strength of print, working with a printing temperature of 190 °C for 120 s pressing time will achieve a high print quality at the lowest energy consumption and match the rigorous requirements of costumers. Choosing a suitable printing temperature and pressing time for sublimation printing is helpful in improving and developing a more cost-effective sublimation printing process, reaching the required print quality, achieving different print quality, and balancing cost, price, and quality.

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