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The influence of heat treatment on the quality of screen printed textile substrates

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ABSTRACT

During exploitation, textile products printed with screen printing technique are quite often exposed to various influences, one of which is a heat treatment- firstly during the production process and later on when ironing. Heat is simultaneously affecting deposited colorants (ink) on the surface of the substrate material, as well as textile fibers in the material structure. As a result, colorimetric characteristics of printed colorants are changed. The research presented in this paper aims to determine the influence of heat treatment on color changes of screen printed textile substrates, observed in CIE L*, a*, b* color space. Macro non-uniformity of the printed cotton textile materials was analyzed as a function of temperature levels applied during thermal treatments and textile material characteristics, as well as mesh counts of screens used in the printing process. The results show that thermal treatment affects the color change of printed samples.

Keywords: cotton, screen printing, heat treatment, print quality, macro non-uniformity

1. INTRODUCTION

Textile printing is a crucial and versatile method for introducing color and design to textile fabrics [1]. The most important printing technique in textile printing is the screen printing technique [2,3], which is characterised by low costs and high productivity in the case of high production volume. Amongst various textile materials, cotton is the most frequently used printing substrate [4] and it is known to possess good thermal properties [5-7].

After the printing process, prints are subjected to various influences like sunlight, chemical agents, heat, washing treatments etc., which lead to changes and deterioration of the print quality [8-11]. Heat treatment affects the quality of the finished printed textile products and is applied using a variety of techniques. Heat can be transferred by conduction, radiation and convection [12-14] and influences both the textile fibers of the substrate material and the printed ink. This leads to print quality changes, especially of the printed ink color (K/S values, gloss, CIE Lab coordinates). In order to quantify these color changes caused by heat treatment, spectrophotometric measurements were used in addition to the standard visual gray scale method. If the goals are to achieve high-quality prints and standardized color reproduction, visual judgment as a print quality control method is not sufficient. Therefore, color measurement devices like spectrophotometers and colorimeters are frequently used for color characterization. Although spectrophotometers give the most accurate estimations, they are often replaced by colorimeters because of their affordability.

In order to determine color differences ΔE is calculated. The perceptual interpretation of the color difference ΔE is not clear; roughly said, a noticeable difference is about 1 ΔE, $\Delta E < 3$ hardly perceptible, $3 < \Delta E < 6$ perceptible but acceptable, as well as $\Delta E > 6$ unacceptable [15]. Although the color of the prints is an important parameter, color difference determination is not a sufficient method to determine the overall print quality, as the print quality is not a monotonic function of color parameters [16-19]. Attributes such as

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contrast, sharpness, image noise, micro and macro non-uniformity, and gloss uniformity are not directly tied to color reproduction but they are still very important in terms of overall print quality [19-21]. These parameters are directly related to dot and line reproduction, which are integral parts of the most printed products. Still, there is no consensus amongst researchers which parameter is the most important [22]. Some researchers claim that macro non-uniformity, color range, sharpness and color differences are the most important ones [23]. Macro non-uniformity (print mottle) is often a shortcoming of printed images and it represents unwanted irregularities in the perceived optical density of the print. It can be caused by an uneven absorption of ink by the printing substrate, resulting in fuzzy and "cloudy" areas on the printed surface [22, 24]. It is not possible to perceive more than five quality attributes at the same time [23, 25].

This paper aims to determine the influence of heat treatment on the print quality, i.e. color reproduction and macro non-uniformity. Variable parameters were used, including different screen mesh counts for printing processes, textile substrates with different properties and varying temperature levels for heat treatments.

2. MATERIALS AND METHODS

This section should describe all the materials, procedures and methods used in the experimental or theoretical part of the work. Three different cotton textile materials were used in this experiment. Material characterization was conducted by a contracted laboratory (ProfiLAB, Serbia) according to the following standards: material composition (ISO 1833), fabric weight (ISO 3801) and thread count (ISO 7211-2). The properties are presented in Table 1. The rest of the tests have performed the authors at the University of Novi Sad, Serbia, Faculty of Technical Sciences, Department of Graphic Engineering and Design.

Using the Adobe Illustrator software (CS5, USA), a custom test target was created, containing several elements for print quality evaluation. The influence of heat treatment was analyzed on the patches printed with 100% cyan ink (Texopaque Classic OP Trich Cyan, FUJIFILM Sericol, Japan) sized 30 x 120 mm.

Analyzed samples were printed using the screen printing machine M&R Sportsman (E Series, USA). For the printing process, four screen meshes (500 x 760 mm) with four different mesh counts (90, 120, 140 and 160 threads/cm) were used (Ševa-Grafika, Serbia), which were fixed on aluminum frames (580 x 840 mm) (Ševa-Grafika, Serbia).

Table 1: Characteristics of material used in testing.

TESTS	MATERIAL COMPOSITION (%)	FABRIC WEIGHT (G/M^2)	THREAD COUNT (CM^{-1})	
			WARP	WEFT
Method	ISO 1833	ISO 3801	ISO 7211-2	
Material A	Cotton 100 %	138	14	19
Material B	Cotton 100 %	185	15	16
Material C	Cotton 100 %	207	12	18

The development of the printing master was done using the conventional method with linearized positive film. For transparent film areas, the optical density was 0.03 and for opaque areas, it was 4.1. The liniature of the film was 5 times smaller than the mesh count of the printing screen. Sericol Dirasol 915 (Supercoat, FUJIFILM Sericol, Japan) photosensitive emulsion was then used. Exposure was conducted using Metal halide Vacuum Exposure Unit (Ranar, USA). The Autotype Exposure Calculator (Dirasol, FUJIFILM Sericol, Japan) was used to determine exposure time for the printing master. Printing parameters and heat treatment conditions are presented in Figure 1.

Investigation of print quality includes color reproduction and macro non-uniformity analysis of the prints. The color reproduction of samples was analyzed by measuring the CIE Lab coordinates full tones cyan (100%) as well as spectral curves before and after the thermal effects on the printed patterns.

Color differences were calculated based on the color measurements using the ΔE_{2000} color difference formula. Using a spectrophotometer (HP200, Hanpu, China), CIE Lab colour coordinates were measured (illuminant D65, 10° standard observer, measurement geometry d/8, aperture 8 mm, without UV component). Spectral curves were captured using a spectro-densitometer (SpectroDens, Techkon, Germany) measuring device (illuminant D50, 2° standard observer, measuring geometry 0°/45°, aperture 3 mm). All measurements were repeated 10 times, after which the mean value was calculated. Macro non-uniformity was determined on the printed field of 100% cyan, size 25.4 x 25.4 mm, using software for digital image processing (ImageJ, USA) [26]. Printed samples were scanned at the resolution of 600 spi using a CanoScan 5600F scanner (Canon, Japan), without automatic correction functions. Materials were placed on a matte, opaque white backing according to the ISO 13655 standard. Images used in the analysis were saved as TIFF files without compressions. SEM microscopic analysis, according to the procedure (gold coating to ensure conductivity), was used to both gain insight into the fiber structure [27] and the changes of the substrate surface caused by the printing process and the heat treatment. For this purpose, SEM electronic microscope (JSM 646 OLV, JEOL, Japan) was used. Samples were classified, marked and prepared for SEM analysis.

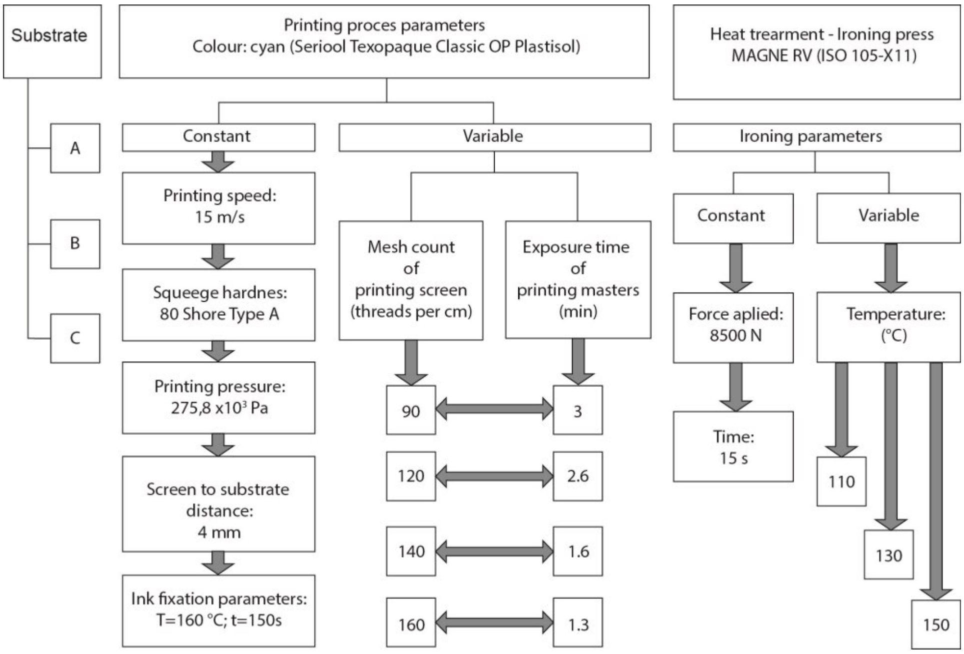


Figure 1: Printing parameters and heat treatment conditions.

3. RESULTS AND DISCUSSION

Quantified changes of the print characteristics caused by heat treatments are presented in separate sections for each considered print quality parameter.

3.1 Spectrophotometric analysis of the samples before and after heat treatment

According to spectrophotometric measurements of printed samples (CIE L, a, b colour coordinates) colour differences, ΔE were calculated between the samples before and after heat treatment and presented in Table 2. The results show that the lowest lightness of the prints corresponds to the lowest screen mesh count. This can be explained by the fact that screens of lower density let through higher amounts of ink.

The analysis of the colour changes measured between samples before and after heat treatment shows that the greatest changes were caused by the highest temperature. The highest colour differences (ΔE) were caused by a temperature of 150 °C, which generated values in colour difference from 2.3 to 3.2. Obtained colour difference values are hardly perceptible (ΔE < 3, and some are perceptible but acceptable (3<ΔE<6). A temperature of 110°C caused small colour differences, ΔE (0.7 - 1) - keeping in mind that ink fixation is usually done at 160 °C.

In the case of exposure to thermal treatments of 130 °C, almost all calculated colour difference values, ΔE, were in the range of 1 - 2, which is hardly a perceptible colour difference to the human visual system. Only samples of material C, printed using screen mesh count of 90 thread/cm, showed colour difference higher than 2 at 130 °C.

When comparing samples printed on different materials under the same printing conditions exposed to the same thermal load level, the greatest colour differences were recorded for material C, which has the highest fabric weight and the most pronounced surface roughness. The smallest colour differences before and after thermal treatment were calculated for materials with the lowest fabric weight (single weave).

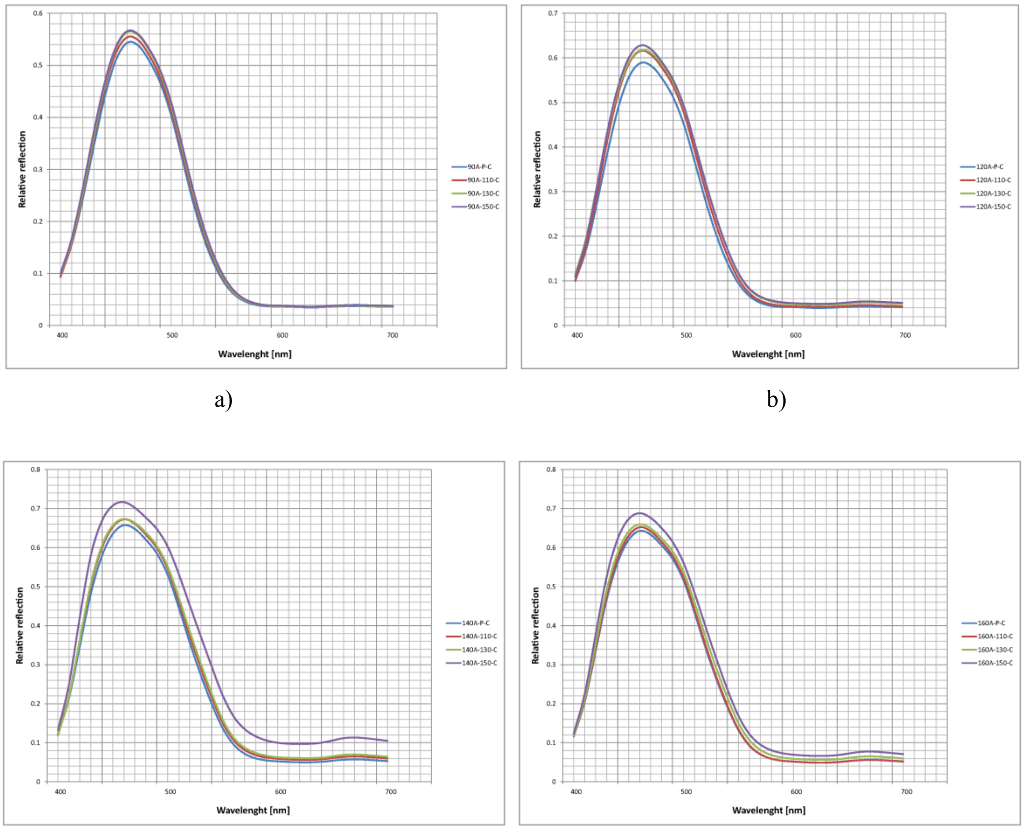
Table 2: Colour differences after printing and thermal treatments of the samples.

SAMPLE	**ΔE VALUE FOR MATERIAL A**	**ΔE VALUE FOR MATERIAL B**	**ΔE VALUE FOR MATERIAL C**
90-P	-	-	-
90-110	0.784128	0.817907	0.981417
90-130	1.833799	1.907594	2.08987
90-150	2.8562	3.0558	3.221036
120-P	-	-	-
120-110	0.764026	0.767429	0.923948
120-130	1.600782	1.668511	1.973833
120-150	2.703501	2.893979	3.083902
140-P	-	-	-
140-110	0.707033	0.759547	0.904834
140-130	1.375026	1.555923	1.882722
140-150	2.504565	2.810615	3.053656
160-P	-	-	-
160-110	0.675384	0.685665	0.762619
160-130	1.336431	1.419828	1.698444
160-150	2.274135	2.361838	2.909556

Note: the first number represents screen mesh count; P is the mark of printed sample; 110, 130 and 150 are values of thermal load in Celsius degrees.

3.2 Analysis of heat treatment influence on spectral curves

Spectral curves were registered before and after subjecting the samples to the heat treatment, using a Techkon SpectroDens measuring device. Figure 2 shows spectral curves for material A.



a) b)

c) d)

Figure 2: Spectral curves after printing and thermal treatments (material A) of the samples printed using different mesh counts: a) 90 threads/cm, b) 120 threads/cm, c) 140 threads/cm, d) 160 threads/cm.

The consequence of the heat treatment is greater surface reflectivity, which can be observed in the changes of spectral curves. This can be caused by several reasons, including flattening of the printed ink layer surface under the heating element, degradation of the ink layer, and evaporation of the printed ink layer, which results in decreasing its thickness.

The other samples show the same trend as presented for material A. An increase in heat treatment temperature caused a higher reflectivity of the prints. This is also confirmed by lightness values of L*a*b* colour space in the previous analysis.

3.3 Macro non-uniformity analysis

The level of macro non-uniformity is defined by the non-uniformity number (mottling index), which should be 0 in the case of ideal uniformity. In Figure 3, recorded non-uniformity number values for the material A samples are presented before and after heat treatment, using different temperatures and using different screen mesh counts.

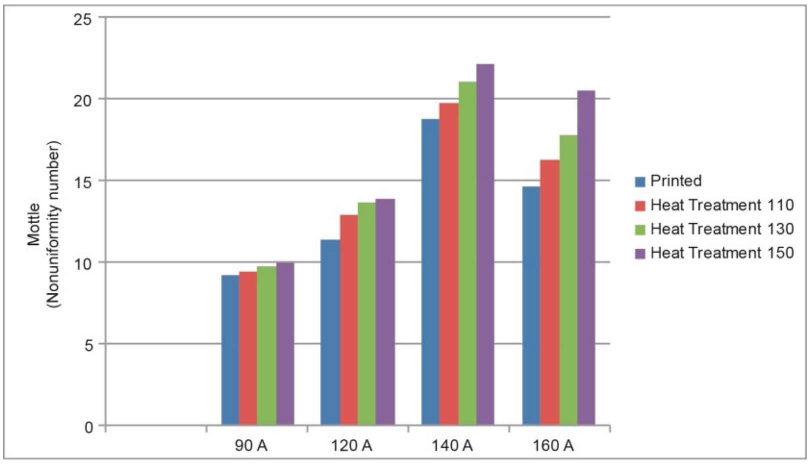


Figure 3: Non-uniformity number values for material A, before and after heat treatment.

The results of the macro non-uniformity analysis indicate that the heat treatment does affect macro non-uniformity. Further, the results show that temperature increase causes higher values of the non-uniformity number of the prints.

The analysis of screen mesh count effect on macro non-uniformity shows that the highest value of macro non-uniformity values was obtained by using screens of 140 threads/cm, followed by screens of 160 threads/cm. The lowest values of macro non-uniformity were obtained by using screens of 90 threads/cm. This could be explained by the amount of critical ink deposited, caused by screen mesh count, after which non-uniformity decreases.

In the case of material B, macro non-uniformity number increases with higher thermal load temperatures, as shown in Figure 4. Samples printed using a mesh count of 90 threads/cm show smaller macro non-uniformity values than the other three sample sets do. The highest values of the macro non-uniformity number were recorded for samples printed using a mesh count of 140 threads/cm, exposed to heat treatment of temperature 150 °C.

The similar macro non-uniformity behavior of samples from the materials A and B could be explained by a more even distribution of ink on the substrate surface, in cases of samples printed using screen mesh of 90 threads/cm.

Macro non-uniformity analysis of material C shows a decrease of non-uniformity number with the increase of heat treatment temperature, as shown in Figure 5. The highest values of non-uniformity number were noticed in cases of samples printed using screens of 140 threads/cm mesh count. Samples printed using screen mesh counts of 160 threads/cm had the lowest value of the non-uniformity number before heat treatment, but after the treatment, samples printed using screen mesh counts of 90 threads/cm had the lowest value of the non-uniformity number.

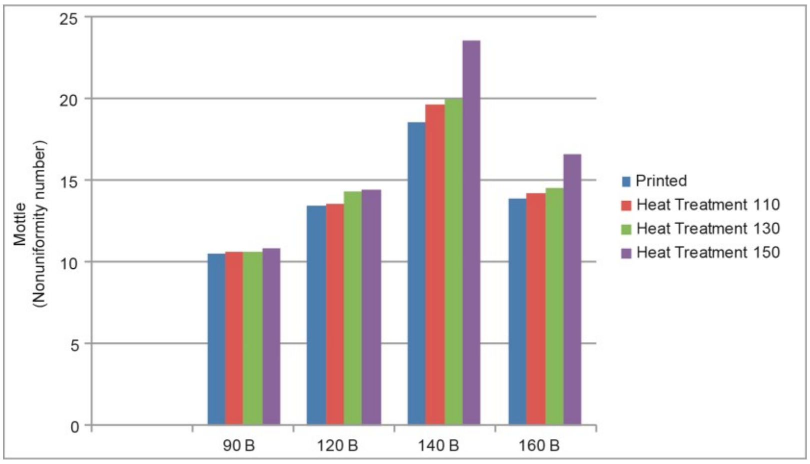


Figure 4: Non-uniformity number values for material B, before and after heat treatment.

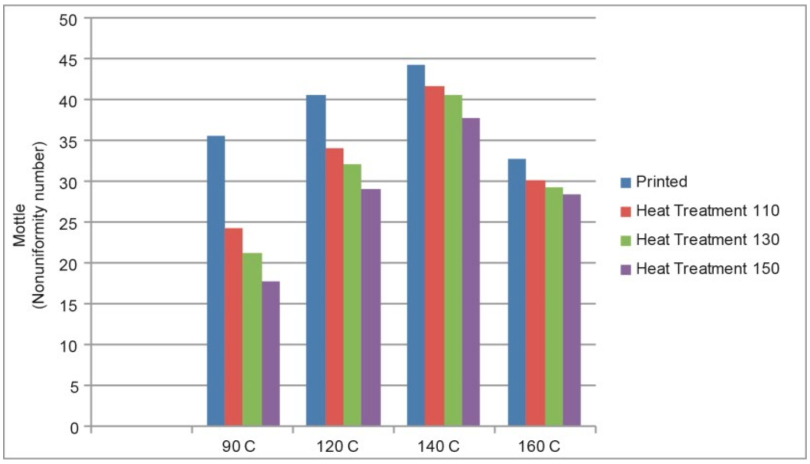


Figure 5: Non-uniformity number values for material C, before and after heat treatment.

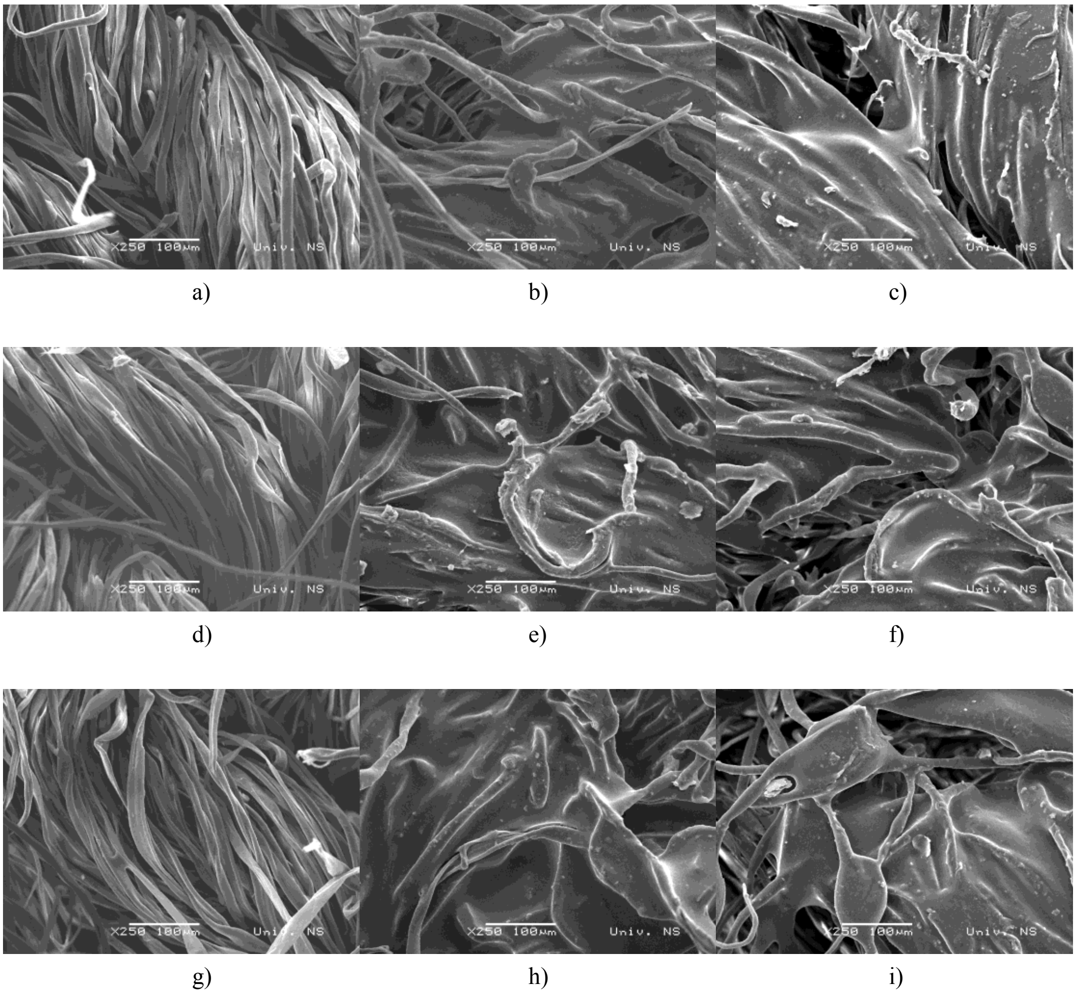
In contrast to materials A and B, material C has a rougher surface and structure. Applying heat and pressure during heat treatment resulted in decreased roughness of the material and penetration of ink into the fabric structure, which caused a decrease in the non-uniformity number value.

3.4 SEM analysis

SEM microscopy images of samples before the printing process, after the printing process using a screen mesh count of 120 threads/cm, and after they were subjected to heat treatment (150 °C) are shown in Figure 6.

Images that are shown in Figure 6, clearly indicate changes in surface morphology caused firstly by the printing process and later on by the heat treatment. Before printing, it can be noted that the surface of the material is even and the fibers are oriented and undisturbed. Figures 6b, 6e, and 6h show deposited ink after the printing process. After heat treatment, some of the ink particles are destroyed (removed), areas with voids and cavities can be seen, as well as areas without ink, and surface flattening under applied heat and pressure is noted.

In order to determine the differences on color prints when printing cotton materials that vary in structure, screen mesh counts or heat treatment temperatures, a mathematical model based on multiple linear regression was designed.



a) b) c)

d) e) f)

g) h) i)

Figure 6: SEM images (250 X): a) material A before printing, b) material A after printing, c) printed material A sample after thermal treatment, d) material B before printing, e) material B after printing, f) printed material B sample after thermal treatment, g) material C before printing, h) material C after printing, i) printed material C sample after thermal treatment.

The multiple regression model in the form of an equation expresses the average, regular and quantitative relationship between the dependent variable Y and k, independent variables X_1, X_2, ..., X_k. For the arbitrary dependent variable Y_i and selected (fixed) values of the independent variables from the basic set, a multiple regression model is given in the form [28]:

$$Y_i = \beta_0 + \beta_1 x_{1i} + \beta_2 x_{2i} + ... + \beta_k x_{ki} + \varepsilon_i \tag{1}$$

where:

Y_i - dependent variable,

$x_{1i}, x_{2i}, ..., x_{ki}$ - independent variables,

$\beta_0, \beta_1, \beta_2, ..., \beta_k$ - model parameters,

ε_i - article stochastic or random error

k - number of independent variables

Multiple regression model with two independent variables is given by the formula:

$$Y_i = \beta_0 + \beta_1 x_{1i} + \beta_2 x_{2i} + \varepsilon_i \tag{2}$$

The regression coefficients b_0, b_1 and b_2 representing the theoretical parameter estimation β_0, β_1

and β_2, are determined on the basis of the experimental results. Coefficients of multiple regression of ΔE as functions of temperature Tt and screen mesh count Mc are reported in table 3. Co-dependence of color differences (ΔE) on the printing screen mesh count Mc and heat treatment temperature Tt is presented in figure 7.

Table 3: Multiple regression coefficients.

ΔE = - 4,11 + 0,05 · TT (ºC) - 0,01 · MC (THREADS/CM)		
multiple regression coefficient	**R^2**	0.956
random error regress.	**s**	0.21878
b_o = - 4,111	**rand.err**	0.295
	t	-13.945
	p	0.00
b_1 = 0,05041	**rand.err**	0.002
	t	26.294
	p	0.00
b_2 = 0,00529	**rand.err**	0.001
	t	-4.373
	p	0.00

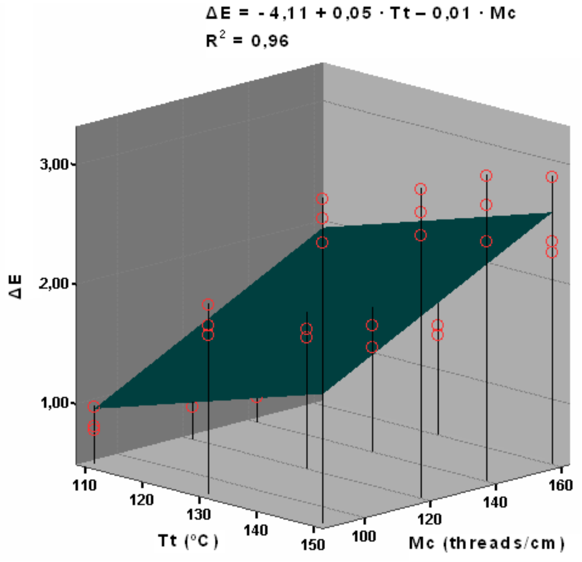


Figure 7: Co-dependence of color differences ΔE and printing screen mesh count Mc and heat treatment temperature Tt.

4. CONCLUSIONS

Cotton textile products are exposed to various influences during an exploitation period. One of the influences is heat treatment, which causes both changes of the cotton materials and printed ink. This research examined the influence of different heat treatment temperatures on print quality of three different cotton materials printed with the screen printing process using four different screen mesh counts. Samples were analyzed spectrophotometrically, in respect to their macro non-uniformity characteristics, as well as at a microscopic level using SEM microscopic images. The samples were analyzed before and after heat treatment in order to determine changes caused by the heat treatment.

It was found that the heat treatment of printed textile materials does cause print quality changes. An increase in both color differences (ΔE) and surface reflectivity was confirmed by the spectrophotometric measurements and the spectral reflection analysis after heat treatment of the samples. The heat treatment caused smaller color differences in the cases of samples printed using higher mesh count screens. This could be due to a smaller amount of ink deposit on the substrate so that a smaller amount of ink was pressed into the material structure during thermal treatment and smaller color changes occurred. Temperature increase also causes greater color and reflectivity changes of the samples, which mean that ink resistance is dependent on the temperature applied.

The behavior of printed samples depends on material characteristics, fabric weight and thread count. Material A, with the smallest fabric weight, highest thread count and relatively smooth surface compared to materials B and C, showed the best results when considering print quality parameters after heat treatment.

Macro non-uniformity analysis showed the influence of heat treatment on this print quality parameter, especially at higher temperatures. The fabric weight of the materials showed no significant influence on color differences. However, in the case of macro non-uniformity prints on the materials A and B, an increase of macro non-uniformity with temperature rise was observed, while material C's macro non-uniformity showed a decreasing trend. This should be examined in further studies.

Non-uniform prints, after they were subjected to heat and pressure during the heat treatment process, showed a decrease of macro non-uniformity number, due to lower surface roughness and ink deposit leveling. When higher temperatures are applied, ink migrates into the material structure, causing a decrease of the macro non-uniformity.

Analysis of the samples using SEM microscopic imaging both before and after printing and after the heat treatment, shows higher ink coverage of the printed material surface before the treatment. After high-temperature heat treatments and pressure applications, ink penetrates into the material structure, decreasing ink layer thickness on the material surface.

Using a mathematical model based on the multiple regression, co-dependence of color differences, ΔE, printing screen mesh count (Mc), and heat treatment (Tt) was determined with a high value of multiple regression coefficient $R^2 = 0.96$.

It can be concluded that heat treatment is a very influential factor on the print quality of textile products printed using the screen printing technique. Keeping in mind that constant color quality of the product is the goal, it is important to notice that a degree of heat treatment influence can be diminished by selecting adequate textile material characteristics and printing process parameters.

5. ACKNOWLEDGMENTS

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