Key Factors Affecting Color Reproduction on Polyester Fabrics Using Heat Transfer Printing

Yu Ju Wu* and Gabriel Grant*

Keywords: Color reproduction, heat transfer, polyester fabrics

Abstract

Dye sublimation heat transfer printing technology was developed for use in textile printing for many years. Although digitally printed textile technology grabs a lot of attentions recently, this simple, flexible process offers many advantages, such as quietness, low price, ease of color reproduction, reduced post processing, and low maintenance requirement. The textile thermal transfer printing method has been expanding into an increasing number of applications with its dry process and quick output digital image data. Color reproduction capability of a heat thermal print is highly related to the amount of dye transferred. To achieve high dye transfer efficiency and obtain best color reproduction capability, three primary parameters- the heat transfer temperature, the dwell time in the heat zone, and the pressure, need to be taken into account. The main purposes of this experimental study are to (1) identify the most important factors that influence color reproduction of polyester fabrics using heat transfer printing, and (2) establish optimum process operating conditions so that the maximum yield of color gamut and optical density could be obtained. The experiment was conducted using a randomized 2^3 factorial design in which every factor is run at two specified levels (1 = high level, –1 = low level). The factorial levels were determined based upon the practical operating conditions of the heat transfer press. The three independent factors of this study are: 1) the dwell time in the heat zone (X_1), 2) transfer temperature (X_2), and 3) the pressure (X_3). The dependent variable (Y) is the color reproduction capability (optical density and gamut volume) of polyester fabrics. It was found that heat transfer temperature (X_2) and dwell time (X_1) are the two dominant key factors

*School of Technology, Eastern Illinois University

affecting color reproduction on polyester fabrics; the treatment combination of (X_1, X_2, X_3) = (1, 1, 1) is suggested to achieve the maximum yield of optical density and color gamut.

1. Introduction

Dye sublimation heat transfer printing technology was developed for use in textile printing for many years (Mount, 1975). In the heat transfer printing process, the required image is first printed onto a paper carrier (can be done by either screen printing or ink-jet printing) using dye inks, which comprise sublimable dyes. The paper carrier is brought into intimate contact with textile fabrics, through a heated press. The paper carrier releases a color dye when heated, and the dyes sublime and diffuse into the fabric, permanently coloring it. Figure 1 shows the schematic representation of the heat transfer printing system (Massa, 2006; Elsayad & El-sherbiny, 2008; Shih & Kung, 2006, Thompson, 1998). Although digitally printed textile technology grabs a lot of attentions recently, this simple, flexible process offers many advantages, such as quietness, low price, ease of color reproduction, reduced post processing, and low maintenance requirement. The textile thermal transfer printing method has been expanding into an increasing number of applications with its dry process and quick output digital image data (Hunting, et al, 1999; Shirai, 1999).

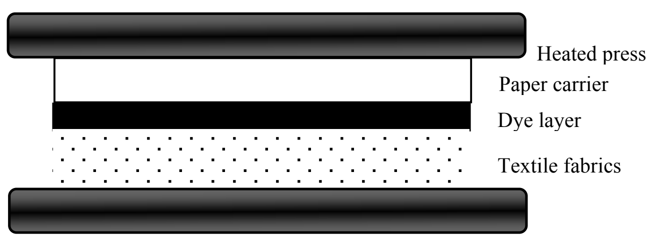

Figure 1. *The schematic representation of the heat transfer printing system.*

With heat transfers, the printed ink film must be brought up to a "gel" state in order to transfer to the textile and bond well with the textile fabric. To achieve high dye transfer efficiency, it requires an intimate and sufficient contact between the heat transfer press and the paper carrier, and between the paper carrier and the textile, to ensure efficient heat transfer across the interfaces and high activity of dye diffusion from the dye layer of the paper carrier to the dye-receiving layer of the textile fabric. Three primary parameters for controlling heat transfer are the heat transfer temperature, the dwell time in the heat zone, and the pressure. Any unexpected variations in these three variables can adversely affect the quality of the finished product. Depending on the type of textile being used, the optimum parameters for a specific textile material need to be established. For example, a fine dress fabric would be printed using the highest temperature compatible with the fiber, with a relatively short dwell time in the heat zone, this to give a well-defined print on the surface of the fabric.

Conversely, a needle punch fabric where dye penetration is important, the temperature would be below optimum, and the time dwell increased to hold the dyes in the vapor form longer to assist penetration (Shirai, 1999; Davis, 2001; Hunting, 1999). In order to get good adhesion and a durable applied print, these three parameters need to be taken into account and to be well defined.

Image color density of a thermal print is highly related to the amount of dye transferred. The quality of color reproduction can be evaluated in terms of color gamut. The color gamut is the range of colors that a particular combination of printer, ink, and print media can achieve. Color gamut of a given printing system is evaluated in terms of gamut volume, which can be interpreted as the number of independent colors that can be printed on the designated substrate within a ΔE tolerance of √3 (i.e. the diagonal of a unit cube). Volume is then expressed per cubic CIELAB units (cCu). Higher volumes indicate the possibility of making more color combinations. Therefore, color gamut can be treated as an indicator predicting color reproduction capability of a device (Chovancova, et al, 2005). Establishing the optimum parameters can help to predict and control color reproduction for heat transfer printing on polyester fabrics.

2. Methodology

This study utilizes a randomized 2^3 factorial design which contains eight treatment combinations (Table 1). The run order for the eight treatment combinations was randomly determined by computer (randomized design) to reduce bias introduced by unplanned changes in the experiment. Five observations were systematically recorded for each of the right treatment combinations for a total sample size of 40.

Table 1. *2^3 Factorial design.*

	Long Dwell Time		Short Dwell Time	
	Low Temperature	High Temperature	Low Temperature	High Temperature
Low Pressure				
High Pressure				

Factors	Factor Level	
	–1	1
Dwell Time (X_1):	30seconds	40seconds
Temperature (X_2):	400°F	420°F
Pressure (X_3):	60 psi	100 psi

A digital four-color test chart was designed for this study. The test chart included a TC 2.83 RGB test target designed for X-Rite i1iO Spectrophotometer and photographic images. The list of the equipment and materials used in this work is presented as follows.

- Textile media: 100% polyester fabrics were chosen because dye sublimation inks are designed to only bond with polymers.
- Heat transfer paper: EZ-Trans™ Paper from LRi/Laser Reproductions Inc.

- Ink-jet printer: Epson Stylus Pro 4880 printer with dye sublimation inks.
- Heat transfer press: DC16AP press from Geo Knight & Co Inc.

The designed test target was first printed onto EZ-Trans™ transfer paper by using Epson Stylus Pro 4880 ink-jet printer. The printed transfer paper was brought into contact with polyester fabrics through the DC16AP heat transfer press using eight different treatment combinations.

Color measurements were made using an X-rite i1iO Spectrophotometer using illuminant D65 and a 10-degree observer for textile prints. The measurement files were used to generate profiles using ProfileMaker Pro 5.0.8. The color quality of 100% polyester was evaluated in terms of optical density and color gamut. The color gamut was determined by using CHROMiX ColorThink Pro 3 software. The software packages employed to analyze the data was Minitab 15.0. The 2^3 factorial analyses were performed. Table 2 displayed the treatment combinations, their run orders, and mean values of optical densities and gamut volume.

Table 2. *The mean optical densities and gamut volume for the eight runs.*

No	Factor			Treatment Combination	Run order	Mean Density of Y	Mean Density of M	Mean Density of C	Mean Density of K	Mean Gamut Volume
	X_1	X_2	X_3							
1	–1	–1	–1	(1)	2	0.87	1.28	1.45	1.20	296,291
2	1	–1	–1	a	1	0.89	1.37	1.48	1.33	326,978
3	–1	1	–1	b	8	0.89	1.39	1.47	1.35	333,682
4	1	1	–1	ab	7	0.90	1.43	1.50	1.40	337,360
5	–1	–1	1	c	5	0.87	1.28	1.46	1.20	308,218
6	1	–1	1	ac	3	0.89	1.38	1.50	1.33	335,838
7	–1	1	1	bc	6	0.90	1.39	1.48	1.35	339,058
8	1	1	1	abc	4	0.91	1.45	1.50	1.42	342,070

Factor	Factor Level	
	–1	1
X_1: Dwell Time	30 seconds	40 seconds
X_2: Temperature	400°F	420°F
X_3: Pressure	60 psi	100 psi

3. Results and Discussion

This section discusses the results of the ANOVA and Regression analyses for the main effects of the independent variables and their interaction effects on the dependent variables. The significant level was set to be .05 for all the analyses, i.e., $\alpha = .05$. The full model derived from 2^3 the factorial design is:

$$\hat{Y} = \alpha + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_1 X_2 + \beta_5 X_1 X_3 + \beta_6 X_2 X_3 + \beta_7 X_1 X_2 X_3 + \varepsilon,$$

where X_1 = dwell time; X_2 = temperature; X_3 = pressure.

The Findings and Discussion for the Optical Density of Yellow

Table 3 shows that the p-values of 0.000 for the set of main effects and the set of two-way interactions are less 0.05. In other words, at least one factor or two-way interaction has a significant effect on the optical density of yellow. The p-value of 0.576 for the set of three-way interactions is not less 0.05, which means there is no evidence that the interaction among dwell time, temperature, and pressure has a significant effect on the optical density of yellow.

Table 3. *Analysis of variance for the optical density of yellow (full model).*

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	3	0.00789000	0.00789000	0.00263000	84.16	0.000
2-Way Interactions	3	0.00089000	0.00089000	0.00029667	9.49	0.000
3-Way Interactions	1	0.00001000	0.00001000	0.00001000	0.32	0.576
Residual Error	32	0.00100000	0.00100000	0.00003125		
Total	39	0.00979000				

Table 4 and Figure 2 show that the temperature (X_2) has the greatest effect (0.02) on the optical density of yellow. In addition, setting the heat transfer temperature high produced higher optical density than setting the temperature low. Dwell time (X_1) has the second greatest effect (0.017) on optical density of yellow. The pressure (X_3), the interaction between temperature and pressure (X_2X_3), and the interaction between dwell time and temperature (X_1X_2) also have effect on the optical density of yellow.

Table 4. *Estimated effects and coefficients for the optical density of yellow (full model).*

Term	Effect	Coef	SE Coef	T	P
Constant		0.890500	0.000884	1007.49	0.000
X_1	0.017000	0.008500	0.000884	9.62	0.000
X_2	0.020000	0.010000	0.000884	11.31	0.000
X_3	0.010000	0.005000	0.000884	5.66	0.000
X_1*X_2	–0.006000	–0.003000	0.000884	–3.39	0.002
X_1*X_3	–0.002000	–0.001000	0.000884	–1.13	0.266
X_2*X_3	0.007000	0.003500	0.000884	3.96	0.000
$X_1*X_2*X_3$	0.001000	0.000500	0.000884	0.57	0.576

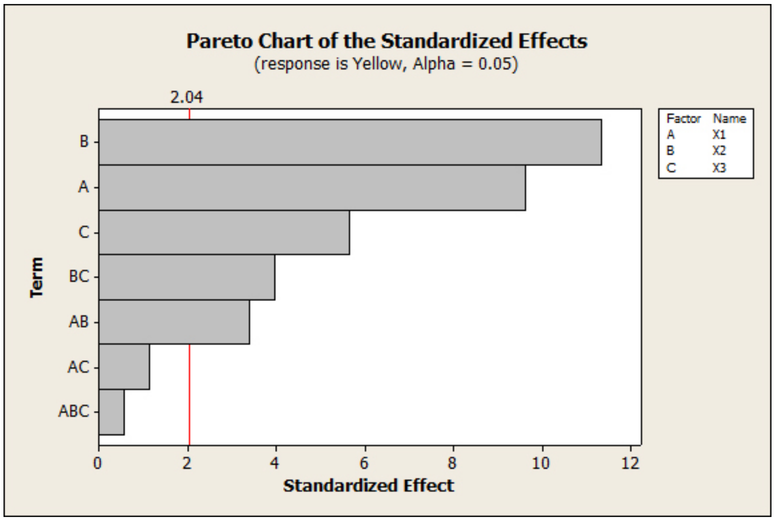

Figure 2. *Main effects plot for the optical density of yellow.*

Based on Figure 2 and Table 4, it was suggested that the terms of X_1, X_2, X_3, X_1X_2, and X_2X_3 should be included in the reduced model. Therefore, a Fit Factorial procedure and a regression analysis that included only the terms of X_1, X_2, X_3, X_1X_2, and X_2X_3 were performed and obtain the prediction information for the optical density of yellow. Table 5 displays the ANOVA information, and the estimated effects and coefficients are exhibited in Table 6. Again, Table 5 confirmed that three factors (X_1, X_2, X_3) and interactions of X_1X_2, and X_2X_3 have a significant effect on the optical density of yellow. The regression equation used to predict the optical density for yellow is

$$\text{Optical density of yellow} = 0.891 + 0.00850\, X_1 + 0.0100\, X_2 + 0.00500\, X_3 - 0.00300\, X_1X_2 + 0.00350\, X_2X_3 \qquad \text{(Equation 1)}$$

The R^2 value (89.3%) in Table 6 implies that the reduced model explains approximately 89.3% of the total variability in the optical density for the yellow.

Table 5. *Analysis of variance for the optical density of yellow (reduced model).*

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	3	0.00789000	0.00789000	0.00263000	85.16	0.000
2-Way Interactions	2	0.00085000	0.00085000	0.00042500	13.76	0.000
Residual Error	34	0.00105000	0.00105000	0.00003088		
Total	39	0.00979000				

Table 6. *Estimated effects and coefficients for the optical density of yellow (reduced model).*

Term	Effect	Coef	SE Coef	T	P
Constant		0.890500	0.000879	1013.46	0.000
X_1	0.017000	0.008500	0.000879	9.67	0.000
X_2	0.020000	0.010000	0.000879	11.38	0.000
X_3	0.010000	0.005000	0.000879	5.69	0.000
X_1*X_2	–0.006000	–0.003000	0.000879	–3.41	0.002
X_2*X_3	0.007000	0.003500	0.000879	3.98	0.000

Prediction Equation:

Optical density of yellow = $0.891 + 0.00850\ X_1 + 0.0100\ X_2 + 0.00500\ X_3 - 0.00300\ X_1X_2 + 0.00350\ X_2X_3$

R-sq. = 89.3%, R-sq. (adj.) = 87.7%

The Findings and Discussion for the Optical Density of Magenta

Table 7 indicates that the p-values of 0.000 for the set of main effects and the set of two-way interactions are less 0.05. Therefore, there is evidence of a significant effect. The results indicate that the three-way interactions are not significant ($p = 0.755$).

Table 7. *Analysis of variance for the optical density of magenta (full model).*

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	3	0.128287	0.128287	0.0427625	189.01	0.000
2-Way Interactions	3	0.007888	0.007888	0.0026292	11.62	0.000
3-Way Interactions	1	0.000022	0.000022	0.0000225	0.10	0.755
Residual Error	32	0.007240	0.007240	0.0002262		
Total	39	0.143437				

Table 8 and Figure 3 clearly identify that the variable "temperature" (X_2) has greatest effect on the optical density of magenta, followed by dwell time (X_1) and interaction of dwell time and temperature (X_1X_2). Both main effects of dwell time (X_1) and temperature (X_2) were positive, while interaction effect of dwell time and temperature was negative (−0.0275). The Pareto plot of the effects (as shown in Figure 3) confirms that dwell time, temperature, and their interactions are significant at the 0.05 α-level.

Table 8. *Estimated effects and coefficients for the optical density of magenta (full model).*

Term	Effect	Coef	SE Coef	T	P
Constant		1.37125	0.002378	576.57	0.000
X_1	0.07250	0.03625	0.002378	15.24	0.000
X_2	0.08650	0.04325	0.002378	18.19	0.000
X_3	0.00950	0.00475	0.002378	2.00	0.054
X_1*X_2	–0.02750	–0.01375	0.002378	–5.78	0.000
X_1*X_3	0.00550	0.00275	0.002378	1.16	0.256
X_2*X_3	0.00150	0.00075	0.002378	0.32	0.755
$X_1*X_2*X_3$	0.00150	0.00075	0.002378	0.32	0.755

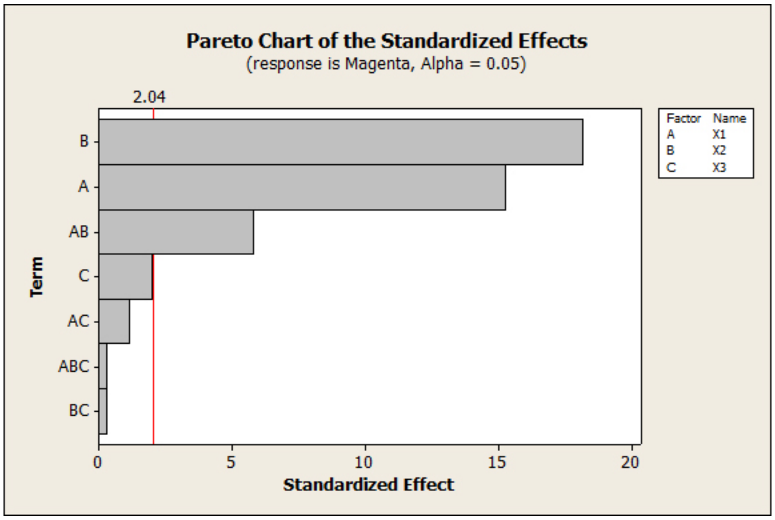

Figure 3. *Main effects plot for the optical density of magenta.*

Based on Figure 3 and Table 8, it was suggested that the terms of X_1, X_2, and X_1X_2 should be included in the reduced model. Table 9 confirmed that dwell time (X_1), temperature (X_2), and interaction of dwell time and temperature (X_1X_2) have a significant effect on the optical density of magenta. As shown in Table 10, the regression equation used to predict the optical density for magenta is

$$\text{Optical density of magenta} = 1.37 + 0.0363\, X_1 + 0.0432\, X_2 - 0.0138\, X_1X_2 \quad \text{(Equation 2)}$$

The R^2 value (94.1%) in Table 10 indicates that the reduced model explains approximately 94.1% of the total variability in the optical density for the magenta.

Table 9. *Analysis of variance for the optical density of magenta (reduced model).*

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	3	0.127385	0.127385	0.0636925	270.07	0.000
2-Way Interactions	2	0.007563	0.007563	0.0075625	32.07	0.000
Residual Error	34	0.008490	0.008490	0.0002358		
Total	39	0.143437				

Table 10. *Estimated effects and coefficients for the optical density of magenta (reduced model).*

Term	Effect	Coef	SE Coef	T	P
Constant		1.37125	0.002428	564.73	0.000
X_1	0.07250	0.03625	0.002428	14.93	0.000
X_2	0.08650	0.04325	0.002428	17.81	0.000
X_1*X_2	–0.02750	–0.01375	0.002428	–5.66	0.000
Prediction Equation:					
Optical density of magenta = $1.37 + 0.0363 X_1 + 0.0432 X_2 - 0.0138 X_1X_2$					
R-sq. = 94.1%, R-sq. (adj.) = 93.6%					

The Findings and Discussion for the Optical Density of Cyan

Table 11 shows that the p-value of 0.000 for the set of main effects is less 0.05. That is, at least one factor has a significant effect on the optical density of cyan. The p-value of 0.023 for the set of main effects is still less 0.05, in other words, at least one two-way interaction has a significant effect on the optical density of cyan. The results also indicate that the three-way interactions are significant ($p = 0.002$).

Table 11. *Analysis of variance for the optical density of cyan (full model).*

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	3	0.0124675	0.0124675	0.00415583	158.32	0.000
2-Way Interactions	3	0.0002875	0.0002875	0.00009583	3.65	0.023
3-Way Interactions	1	0.0003025	0.0003025	0.00030250	11.52	0.002
Residual Error	32	0.0008400	0.0008400	0.00002625		
Total	39	0.0138975				

Table 12 and Figure 4 indicate that all variables have effect on the optical density of cyan, with exception of X_1X_3 and X_2X_3. The results show that the dwell time (X_1) has the greatest effect (0.0275) on the optical density of cyan. Temperature (X_2) has the second greatest effect (0.0195) on optical density of cyan. The variable of pressure (X_3) has the third greatest effect (0.0105), while interactions between dwell time and temperature (X_1X_2) and three-way interactions ($X_1X_2X_3$) have smaller effect on the optical density of cyan.

Table 12. *Estimated effects and coefficients for the optical density of cyan (full model).*

Term	Effect	Coef	SE Coef	T	P
Constant		1.47975	0.000810	1826.64	0.000
X_1	0.02750	0.01375	0.000810	16.97	0.000
X_2	0.01950	0.00975	0.000810	12.04	0.000
X_3	0.01050	0.00525	0.000810	6.48	0.000
X_1*X_2	–0.00450	–0.00225	0.000810	–2.78	0.009
X_1*X_3	0.00250	0.00125	0.000810	1.54	0.133
X_2*X_3	–0.00150	–0.00075	0.000810	–0.93	0.361
$X_1*X_2*X_3$	–0.00550	–0.00275	0.000810	–3.39	0.002

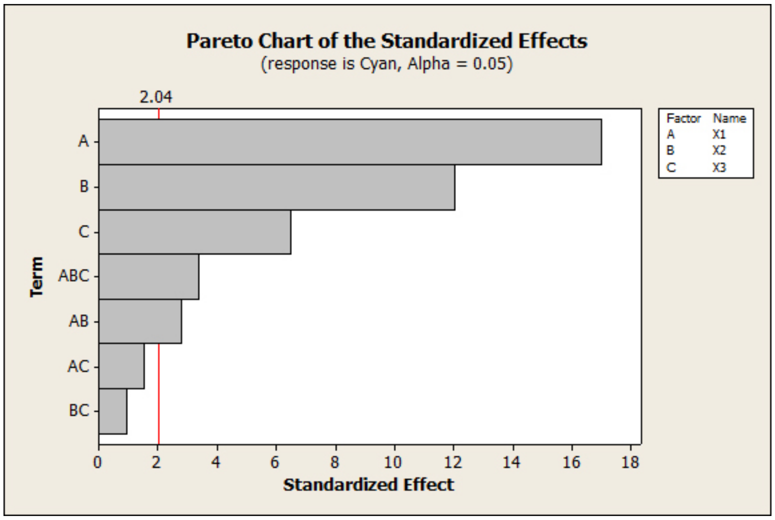

Figure 4. *Main effects plot for the optical density of cyan.*

Based on Figure 4 and Table 12, it was suggested that the terms of X_1, X_2, X_3, X_1X_2, and $X_1X_2X_3$ should be included in the reduced model. Table 13 displays the ANOVA information, which confirms that three factors (X_1, X_2, X_3) and interactions of X_1X_2, and $X_1X_2X_3$ have a significant effect on the optical density of cyan. The regression equation used to predict the optical density for cyan is

$$\text{Optical density of cyan} = 1.48 + 0.0137\,X_1 + 0.00975\,X_2 + 0.00525\,X_3 - 0.00225\,X_1X_2 - 0.00275\,X_1X_2X_3 \qquad \text{(Equation 3)}$$

The R^2 value (93.3%) in Table 14 implies that the reduced model explains approximately 93.3% of the total variability in the optical density for the cyan.

Table 13. *Analysis of variance for the optical density of cyan (reduced model).*

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	3	0.0124675	0.0124675	0.00415583	152.75	0.000
2-Way Interactions	1	0.0002025	0.0002025	0.00020250	7.44	0.010
3-Way Interactions	1	0.0003025	0.0003025	0.00030250	11.12	0.002
Residual Error	34	0.0009250	0.0009250	0.00002721		
Total	39	0.0138975				

Table 14. Estimated effects and coefficients for the optical density of cyan (reduced model).

Term	Effect	Coef	SE Coef	T	P
Constant		1.47975	0.000825	1794.27	0.000
X_1	0.02750	0.01375	0.000825	16.67	0.000
X_2	0.01950	0.00975	0.000825	11.82	0.000
X_3	0.01050	0.00525	0.000825	6.37	0.000
X_1*X_2	–0.00450	–0.00225	0.000825	–2.73	0.010
$X_1*X_2*X_3$	–0.00550	–0.00275	0.000825	–3.33	0.002

Prediction Equation:

Optical density of cyan = $1.48 + 0.0137 X_1 + 0.00975 X_2 + 0.00525 X_3 – 0.00225 X_1X_2 – 0.00275 X_1X_2X_3$

R-sq. = 93.3%, R-sq. (adj.) = 92.4%

The Findings and Discussion for the Optical Density of Black

Table 15 indicates that the p-values of 0.000 for the set of main effects and the set of two-way interactions are less 0.05. Therefore, at least one factor or two-way interaction has a significant effect on the optical density of black. The results indicate that the three-way interactions are not significant ($p = 0.554$).

Table 15. Analysis of variance for the optical density of black (full model).

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	3	0.219748	0.219748	0.0732492	418.57	0.000
2-Way Interactions	3	0.009668	0.009668	0.0032225	18.41	0.000
3-Way Interactions	1	0.000062	0.000062	0.0000625	0.36	0.554
Residual Error	32	0.005600	0.005600	0.0001750		
Total	39	0.235078				

Table 16 clearly identifies that the variable "temperature" (X_2) has greatest effect (0.1165) on the optical density of black. Optical density of black increases as temperature increased. Dwell time (X_1) has the second greatest effect (0.0915) on optical density of black, followed by the interaction of dwell time and temperature (X_1X_2). The Pareto plot of the effects (Figure 5) confirms that dwell time, temperature, and their interactions are significant at the 0.05 α-level.

Table 16. Estimated effects and coefficients for the optical density of black (full model).

Term	Effect	Coef	SE Coef	T	P
Constant		1.32325	0.002092	632.63	0.000
X_1	0.09150	0.04575	0.002092	21.87	0.000
X_2	0.11650	0.05825	0.002092	27.85	0.000
X_3	0.00550	0.00275	0.002092	1.31	0.198
X_1*X_2	–0.03050	–0.01525	0.002092	–7.29	0.000
X_1*X_3	0.00250	0.00125	0.002092	0.60	0.554
X_2*X_3	0.00550	0.00275	0.002092	1.31	0.198
$X_1*X_2*X_3$	0.00250	0.00125	0.002092	0.60	0.554

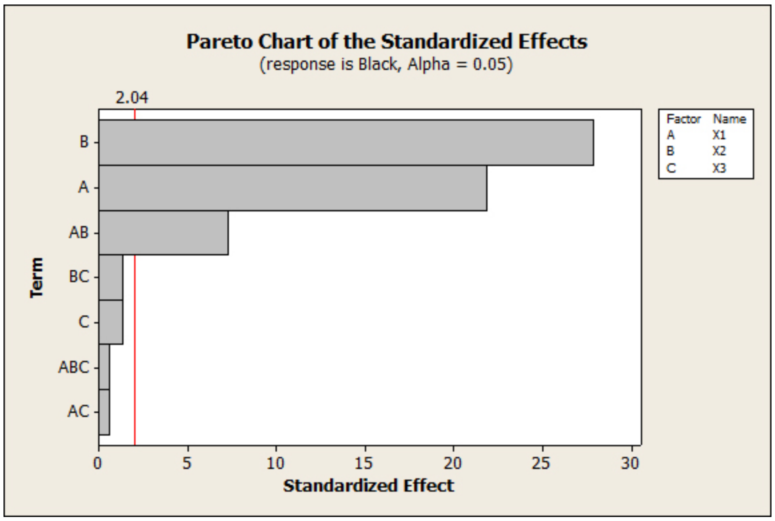

Figure 5. *Main effects plot for the optical density of black.*

Based on Figure 5 and Table 16, it was suggested that the terms of X_1, X_2, and X_1X_2 should be included in the reduced model. Table 17 confirmed that dwell time (X_1), temperature (X_2), and interaction of dwell time and temperature (X_1X_2) have a significant effect on the optical density of black. As shown in Table 18, the regression equation used to predict the optical density for black is

$$\text{Optical density of black} = 1.32 + 0.0457\,X_1 + 0.0582\,X_2 - 0.0153\,X_1X_2 \quad \text{(Equation 4)}$$

The R^2 value (97.3%) in Table 18 indicates that the reduced model explains approximately 97.3% of the total variability in the optical density for the black.

Table 17. *Analysis of variance for the optical density of black (reduced model).*

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	2	0.219445	0.219445	0.109723	624.01	0.000
2-Way Interactions	1	0.009303	0.009303	0.009303	52.91	0.000
Residual Error	36	0.006330	0.006330	0.000176		
Total	39	0.235078				

Table 18. *Estimated effects and coefficients for the optical density of black (reduced model).*

Term	Effect	Coef	SE Coef	T	P
Constant		1.32325	0.002097	631.13	0.000
X_1	0.09150	0.04575	0.002097	21.82	0.000
X_2	0.11650	0.05825	0.002097	27.78	0.000
X_1*X_2	–0.03050	–0.01525	0.002097	–7.27	0.000
Prediction Equation:					
Optical density of black = $1.32 + 0.0457 X_1 + 0.0582 X_2 – 0.0153 X_1X_2$					
R-sq. = 97.3%, R-sq. (adj.) = 97.1%					

The Findings and Discussion for Color Gamut

Table 19 shows that the p-values of 0.000 for the set of main effects and the set of two-way interactions are less 0.05. That is, at least one factor or two-way interaction has a significant effect on the color gamut. The p-value of 0.625 for the set of three-way interactions is not less 0.05, which means there is no evidence that the interaction among dwell time, temperature, and pressure has a significant effect on the color gamut.

Table 19. *Analysis of variance for color gamut (full model).*

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	3	7735225586	7735225586	2578408529	174.78	0.000
2-Way Interactions	3	1745499592	1745499592	581833197	39.44	0.000
3-Way Interactions	1	3603601	3603601	3603601	0.24	0.625
Residual Error	32	472066979	472066979	14752093		
Total	39	9956395758				

Table 20 shows that the temperature (X_2) has the greatest effect (21,211) on the color gamut. Dwell time (X_1) has the second greatest effect (16249) on the color gamut. The interaction between dwell time and temperature (X_1X_2) has the third greatest effect (−12904), while pressure (X3) and the interaction between temperature and pressure (X_2X_3) have smaller effect on the color gamut. The Pareto plot of the effects (Figure 6) confirms that temperature (X_2), dwell time (X_1), the interaction between dwell time and temperature (X_1X_2), pressure (X3), and the interaction between temperature and pressure (X_2X_3) are significant at the 0.05 α-level.

__Table 20.__ Estimated effects and coefficients for color gamut (full model).

Term	Effect	Coef	SE Coef	T	P
Constant		327437	607.3	539.18	0.000
X_1	16249	8124	607.3	13.38	0.000
X_2	21211	10606	607.3	17.46	0.000
X_3	7718	3859	607.3	6.35	0.000
X_1*X_2	–12904	–6452	607.3	–10.62	0.000
X_1*X_3	–933	–467	607.3	–0.77	0.448
X_2*X_3	–2675	–1338	607.3	–2.20	0.035
X_1*X_2*X_3	600	300	607.3	0.49	0.625

According to Figure 6 and Table 20, it was suggested that the terms of X_1, X_2, X_3, X_1X_2, and X_2X_3 should be included in the reduced model. Table 21 displays the ANOVA information, which confirms that three factors (X_1, X_2, X_3) and interactions of X_1X_2, and X_2X_3 have a significant effect on the color gamut. The regression equation used to predict color gamut is

$$Color\ gamut = 327437 + 8125\ X_1 + 10606\ X_2 + 3859\ X_3 - 6452\ X_1X_2 - 1338\ X_2X_3 \qquad (Equation\ 5)$$

The R^2 value (951%) in Table 22 implies that the reduced model explains approximately 95.1% of the total variability in color gamut.

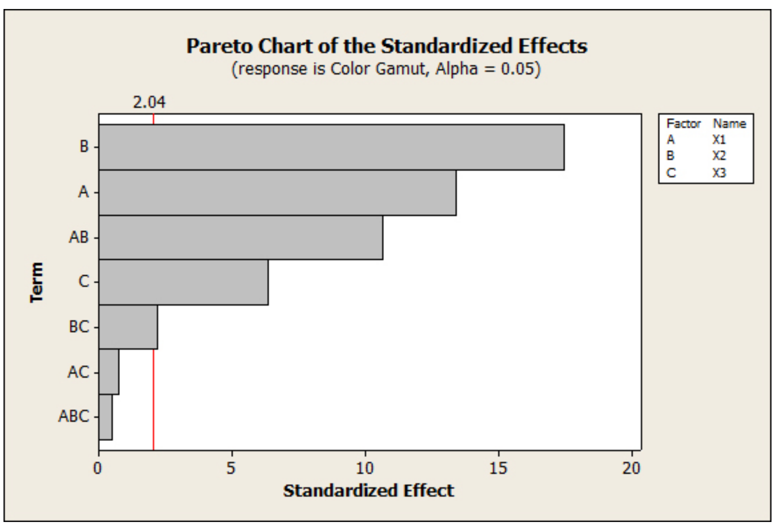

Figure 6. *Main effects plot for color gamut.*

Table 21. *Analysis of variance for color gamut (reduced model).*

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	3	7735225586	7735225586	2578408529	180.98	0.000
2-Way Interactions	2	1736787237	1736787237	868393618	60.95	0.000
Residual Error	34	484382935	484382935	14246557		
Total	39	9956395758				

Table 22. *Estimated effects and coefficients for color gamut (reduced model).*

Term	Effect	Coef	SE Coef	T	P
Constant		327437	596.8	548.66	0.000
X_1	16249	8124	596.8	13.61	0.000
X_2	21211	10606	596.8	17.77	0.000
X_3	7718	3859	596.8	6.47	0.000
X_1*X_2	–12904	–6452	596.8	–10.81	0.000
X_2*X_3	–2675	–1338	596.8	–2.24	0.032
Prediction Equation:					
Color gamut = $327437 + 8125\ X_1 + 10606\ X_2 + 3859\ X_3 - 6452\ X_1X_2 - 1338\ X_2X_3$					
R-sq. = 95.1%, R-sq. (adj.) = 94.4%					

4. Conclusions

This study conducted a randomized 2^3 factorial design to identify key factors affecting color reproduction on polyester fabrics using heat transfer printing. Table 23 shows the ANOVA and Stepwise Regression summary for the main and interaction effects on the optical density and color gamut. According to Table 23, the dominant effects on the color reproduction of polyester fabrics were heat transfer temperature (X_2) and dwell time (X_1), because its significance is ranked as either the top one or two on the optical density or color gamut attributes. The treatment combination of (X_1, X_2, X_3) = (1, 1, 1) is suggested to achieve the maximum yield of optical density and color gamut. In other words, the highest dye transfer efficiency can be achieved when the dwell time was established at 40 seconds ($X_1 = 1$), heat transfer pressure was set at 420°F ($X_2 = 1$), and the pressure was set at 100 psi ($X_3 = 1$) on the DC16AP heat transfer press. Further investigation will include subjective visual assessment to assess the image for overall color reproduction.

__Table 23.__ Summary of ANOVA and regression analyses.

	Optical Density				Color Gamut
	Yellow	Magenta	Cyan	Black	
Sig. Level	α = 0.05	α = 0.05	α = 0.05	α = 0.05	α = 0.05
Significant Effects	X_2 = 0.02 X_1 = 0.017 X_3 = 0.01 X_2X_3 = 0.007 X_1X_2 = –0.006	X_2 = 0.0865 X_1 = 0.0725 X_1X_2 = –0.0275	X_1 = 0.0275 X_2 = 0.0195 X_3 = 0.0105 $X_1X_2X_3$ = –0.0055 X_1X_2 = –0.0045	X_2 = 0.1165 X_1 = 0.0915 X_1X_2 = –0.0305	X_2 = 21211 X_1 = 16249 X_1X_2 = –12904 X_3 = 7718 X_2X_3 = –2675
Prediction Equation ($\hat{Y}$)	0.891 + 0.00850 X_1 + 0.0100 X_2 + 0.00500 X_3 – 0.00300 X_1X_2 + 0.00350 X_2X_3	1.37 + 0.0363 X_1 + 0.0432 X_2 – 0.0138 X_1X_2	1.48 + 0.0137 X_1 + 0.00975 X_2 + 0.00525 X_3 – 0.00225 X_1X_2 – 0.00275 $X_1X_2X_3$	1.32 + 0.0457 X_1 + 0.0582 X_2 – 0.0153 X_1X_2	327437 + 8125 X_1 + 10606 X_2 + 3859 X_3 – 6452 X_1X_2 – 1338 X_2X_3
Best Treatment Combinations	X_1= 40 s X_2= 420°F X_3= 100 psi (1, 1, 1)	X_1= 40 s X_2= 420°F X_3= 100 psi (1, 1, 1)	X_1= 40 s X_2= 420°F X_3= 100 psi (1, 1, 1)	X_1= 40 s X_2= 420°F X_3= 100 psi (1, 1, 1)	X_1= 40 s X_2= 420°F X_3= 100 psi (1, 1, 1)
Estimated Max. Value	0.915	1.436	1.504	1.409	342237
R^2	89.3%	94.1%	93.5%	97.3%	95.1%

The dye particles that are used in the dye sublimation inks are designed to bond with polymers, so that the higher the polyester content in the material, the more dye will bond with material, giving a brighter image. In the textile industry, however, the most common printed textiles are made of cotton and cotton blends. 100% cotton accounts for approximately 45% of the market (Hunting, 1999). Recent developments in heat transfer paper made it possible for using heat transfer printing on 100% cotton fabrics. Further research is needed to establish the optimum parameters for 100% cotton fabrics using heat transfer printing.

References

Chovancova, V., Howell, P., Fleming, P.D. & Rasmusson, A.

2005. Color and Lightfastness of Different Epson Ink Jet Ink Sets, J. Imaging Sci. Technol., 49 (6), 652–659.

Davis, R.

2001. Hot Tips for Heat Measurement, Part 2, Screen Printing, 91 (2), 34–36.

Elsayad, H.S. & El-sherbiny, S.

2008. A Study into the Influence of Paper Coatings on Paper Properties and Print Quality of Dye Sublimation Thermal Prints, Polymer-plastics Technology and Engineering, 47 (2), 122–136.

Hunting, B., Derby, S., Puffer, R. & Loomie, L.

1999. Thermal Ink Jet Printing of Textiles, Recent Progress in Ink Jet Technology II, 568–573.

Massa, D. J.

2006. Importance of Dye Partition Coefficient in Thermal Dye Transfer Printing Efficiency. Proceedings of 22nd International Conference on Digital Printing Technologies, September 17–22, 2006, Denver, Colorado, 265–267.

Mount, W. J.

1975. The Transfer Printing of Textile Materials, Heat Transfer Printing, 85–90.

Shih, P. J. & Kung, T. M.

2006. A Coupled Thermal-structural Nip Analysis of Thermal Dye Transfer Printing, Proceedings of 22nd International Conference on Digital Printing Technologies, September 17–22, 2006, Denver, Colorado, 296–299.

Shirai, K.

1999. New Thermal Dye Transfer Printing Applications by Using an Intermediate Transfer Printing Method, Proceedings of 15nd International Conference on Digital Printing Technologies, 255–257.

Thompson, B.

1998. Printing Materials: Science and Technology. Pira International, Leatherhead, 468–472.