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Optimisation of the Sublimation Textile Printing Process Using the Taguchi Method

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Abstract
In this paper, printing parameters for the sublimation printing of polyester fabrics like the number of strokes, the sublimation paper weight in grams per square metre, the fusing temperature and time were optimised using the Tauguchi experimental design technique. In the evaluations the signal-to-noise ratio was used. Sixteen experiments were performed with respect to the L 16 Orthogonal array design for the Tauguchi approach. The results show a considerable improvement in the signal-to-noise ratio as compared to the initial conditions. Through this study, not only can optimum printing conditions for sublimation printed polyester fabrics be obtained but also the significant factors that affect water vapour resistance.

Key words: *knitted fabrics, sublimation printing, experimental design, Taguchi design, water vapour resistance.*

Introduction

Textile printing can be defined as the process of transferring ink to a textile substrate using a specific printing technique. Digital ink jet textile printing offers a higher printing speed of short runs, as well as flexibility, creativity and environment safety. It is important to note that using the digital printing technique enables better visual effects, as well as no limitation of print formats [1-3]. Besides that, it is easier to get unified print quality during production runs. Another advantage of digital ink jet is the ability of printing on a great number of different substrates. One of the fabrics most often used for digital printing is polyester fabric because of characteristics like thermal stability, excellent behaviour during exploitation and uniform quality. For the printing of polyester or polyester mix fabrics, the textile industry has long been using sublimation printing. Recently, digital ink-jet printing has opened completely new possibilities as well as competitive advantages [4, 5]. The quality of sublimation printed textile fabrics depends on factors like the number of strokes, sublimation paper GSM, the fusing temperature and duration. As the number of strokes increases, ink deposition on the sublimation paper increases, resulting in increased colour transformation by compromising the comfort properties. Similarly, variation in the sublimation paper weight in grams per square metre, as well as in the fusing temperature and time affects the colour transformation and water vapour resistance of printed goods. Hence, there is a need to find optimum printing conditions which ultimately enhance the quality but with less interference with the wearer's comfort. These four factors have a varying effect on the colour transformation and water vapour resistance characteristics. There are various approaches to optimize the problems in engineering, one of which being Taguchi's method.

Taguchi methodology

Taguchi methodology for optimisation can be divided into four phases: planning, conducting, analysis and validation. Each phase has a separate objective and contributes towards the overall optimisation process. The primary goal is to keep the variance in the output very low, even in the presence of noise inputs. Thus, the processes or products are made robust against all variations. Taguchi's methods focus on the effective application of engineering strategies rather than advanced statistical techniques [6-8]. Taguchi views the design of a product or process as a three-phase program:

1. System design: This phase deals with innovative research. Here, one looks for what each factor and its level should be rather than how to combine many factors to obtain the best result in the selected domain.
2. Parameter design: The purpose of parameter design is to investigate the overall variation caused by inner and outer noise when the levels of the control factors are allowed to vary widely. Quality improvement is achievable without incurring much additional cost. This strategy is obviously well suited to the production floor.
3. Tolerance design: This phase must be preceded by parameter design activities. This is used to determine the best tolerances for the parameters [9-11].

Two major tools used in the Taguchi method are the orthogonal array (OA) and the signal-to-noise ratio (SNR or S/N ratio). Orthogonal array (OA) is a matrix of numbers arranged in rows and columns.

Materials and methods

100% Polyester fabric knitted with a single jersey structure was selected for this experiment. The fabrics were procured from the manufacturer with the characteristics shown in ***Table 1***. The fabrics were subjected to washing treatment to remove the presence of impurities and then to sublimation printing varying the number of strokes, the sublimation paper grams per square metre, the fusing temperature and time. The effects of the treatment of the water vapour resistance of printed fabrics were studied. The printing parameters were optimised using the Tauguchi approach. The control parameters were selected as the number of strokes, sublimation paper GSM, fusing temperature and duration. The surface morphology of the polyester fabrics was observed under a scanning electron microscope (SEM ZESS Instrument).

Table 1. *Fabric's characteristics.*

Fabric type	Courses/cm	Wales/cm	Stitch density/square cm	Thickness, mm
100% Polyester Single Jersey	18	14	252	48

Table 2. *Printing parameters and levels.*

Factors	Designation	Level 1	Level 2	Level 3	Level 4
Number of strokes	S	2	3	4	5
Sublimation paper GSM	W	57	67	74	94
Fusing temperature, °C	T	190	195	200	205
Fusing duration, s	D	45	50	55	60

Table 3. *Experimental layout using L16 modified array.*

Trial order	Factors			
	S	W	T	D
1	1	1	1	1
2	2	2	2	2
3	3	3	3	3
4	4	4	4	4
5	1	2	3	4
6	2	1	4	3
7	3	4	1	2
8	4	3	2	1
9	1	3	4	2
10	2	4	3	1
11	3	1	2	4
12	4	2	1	3
13	1	4	2	3
14	2	3	1	4
15	3	2	4	1
16	4	1	3	2

Water-vapour resistance (R_{et})

In the sublimation printing process, an ink layer is transferred onto the fabrics, where part of the printed ink covers the surface of the garment, while the other part of the ink fills the pores between fibres. Thereby, the printed ink represents a new material layer, i.e. an additional barrier to heat transfer from the body's surface to the environment. The research presented investigates the influence of this new material layer created by the printing process on the water vapour resistance characteristics of the fabrics as well as on the water-vapour pressure difference between the two faces of the material divided by the resultant evaporative heat flux per unit area in the direction of the gradient. It is a quantity specific to textile materials or composites which determines the "latent" evaporative heat flux across a given area in response to a steadily applied water-vapour pressure gradient. The evaporative heat flux may consist of both diffusive and convective components. Water-vapour resistance is expressed in square metres pascal per watt as per ISO 11092:2014 using the sweating guarded hot plate test [17-19].

Experimental design

Table 2 gives various parameters and their level with designations. The response variable, namely the water vapour resistance, was measured.

Results and discussion

The experimental lay-out using an L16 orthogonal array is shown in ***Table 3***. In order to save time and printing costs, Tauguchi's method was adopted. Ex-

Table 4. *Measured values of water vapour resistance and resulting SNR.*

Trial	S	W	T	D	1	2	3	4	5	6	7	8	9	Mean	SNR
1	2	57	190	45	6.376	6.372	6.638	6.390	6.382	6.374	6.380	6.390	6.386	6.40978	-16.1376
2	3	67	195	50	6.464	6.468	6.462	6.460	6.458	6.454	6.456	6.458	6.458	6.45978	-16.2044
3	4	74	200	55	6.826	6.828	6.830	6.834	6.836	6.822	6.820	6.824	6.826	6.82733	-16.6850
4	5	94	205	60	6.672	6.674	6.678	6.674	6.668	6.664	6.678	6.676	6.674	6.67311	-16.4866
5	2	67	200	60	6.459	6.457	6.453	6.458	6.454	6.453	6.456	6.459	6.458	6.45633	-16.1997
6	3	57	205	55	6.526	6.524	6.526	6.528	6.525	6.523	6.520	6.529	6.528	6.52544	-16.2922
7	4	94	190	50	6.682	6.684	6.686	6.684	6.688	6.689	6.690	6.678	6.676	6.68411	-16.5009
8	5	74	195	45	7.066	7.064	7.068	7.070	7.062	7.064	7.063	7.064	7.065	7.06511	-16.9824
9	2	74	205	50	6.380	6.382	6.384	6.386	6.388	6.328	6.326	6.324	6.322	6.35778	-16.0662
10	3	94	200	45	6.472	6.474	6.478	6.470	6.476	6.470	6.474	6.478	6.479	6.47456	-16.2242
11	4	57	195	60	6.897	6.896	6.898	6.899	6.888	6.886	6.892	6.894	6.896	6.89400	-16.7694
12	5	67	190	55	6.976	6.974	6.972	6.970	6.978	6.976	6.976	6.978	6.972	6.97467	-16.8705
13	2	94	195	55	6.680	6.678	6.676	6.678	6.672	6.670	6.672	6.674	6.676	6.67511	-16.4892
14	3	74	190	60	7.110	7.112	7.108	7.116	7.118	7.118	7.106	7.104	7.106	7.11089	-17.0385
15	4	67	205	45	6.963	6.964	6.966	6.968	6.969	6.958	6.957	6.958	6.957	6.96222	-16.8550
16	5	57	200	50	7.728	7.726	7.724	7.724	7.726	7.724	7.726	7.728	7.729	7.72611	-17.7592

periments were carried out according to the combination of levels indicated in ***Table 3*** for four different levels. An orthogonal array helps in determining the number of trails that are necessary and the factor levels for each parameter. A general L 16 orthogonal array consists of a combination of experiments with four factors each at four levels.

Main effect plots

After performing the experiments as per Tauguchi's experimental design, a main effects plot was made for the ultimate water vapour resistance of the printed fabrics, which ultimately decides the comfort of the printed fabrics. The lower the resistance the better the fabric comfort without compromising the colour transformation. The results obtained from experimentation are shown in ***Table 4***. The typical response of Minitab is shown in ***Table 5*** and ***6***.

Signal/Noise ratio

Taguchi suggests that the response values at each inner array design point be summarised by a performance criterion called the signal-to-noise ratio. The S/N ratio is expressed in decibels (dB). Conceptually, the S/N ratio (η) is the ratio of signal to noise in terms of power. Another way to look at it is that it represents the ratio of sensitivity to variability. The higher the SNR, the better the quality of the product [15, 16]. The idea is to maximise the SNR, thereby minimising the effect of random noise factors, which have a significant impact on the process performance. Therefore, the method of calculating the S/N ratio depends on whether the quality characteristic is smaller-the-better, larger-the-better, or nominal-the-best [12-14].

Lower is better (water vapour resistance).

$$S/N = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \quad (1)$$

Where n is the number of experiments in the orthogonal array and y_i the i^{th} value measured.

Where y is the average of data observed and s^2 the variation.

The S/N ratio plots are shown in ***Figures 1*** and ***2***.

Effect of printing parameters on the response variable

From ***Figure 3*** we can observe that an increase in the number of strokes causes the mean water vapour resistance to increase for 57 GSM; a similar trend is observed for 67, 74 and 94 GSM. The lowest mean water vapour resistance is observed at a number of strokes equal to 2 for 67 sublimation paper GSM. From ***Figure 4*** we can observe that a fusing temperature of 205 degrees celsius with 50 seconds fusing considerably reduces the water vapour resistance.

Interaction plots

Contour plots are plotted for the water vapour resistance response variable against sublimation printing parameters at different levels using Minitab. In ***Figure 5*** contour plots are plotted for ultimate sublimation paper GSM and numbers of strokes against water vapour resistance. Similarly, contour plots are plotted for the fusing temperature and

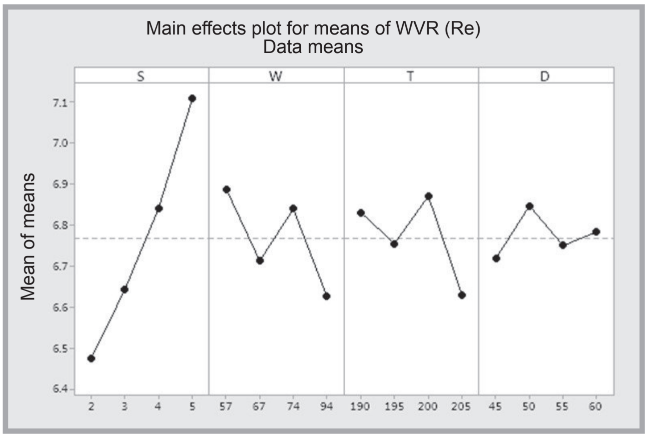

Figure 1. *Main effects plots for WVR means.*

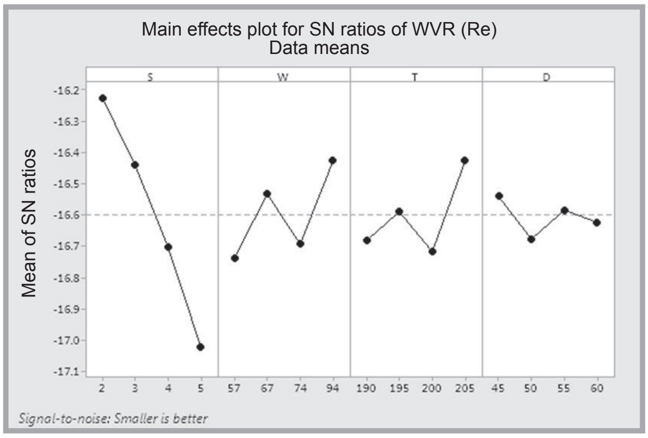

Figure 2. *Main effects plots for SN ratios of WVR.*

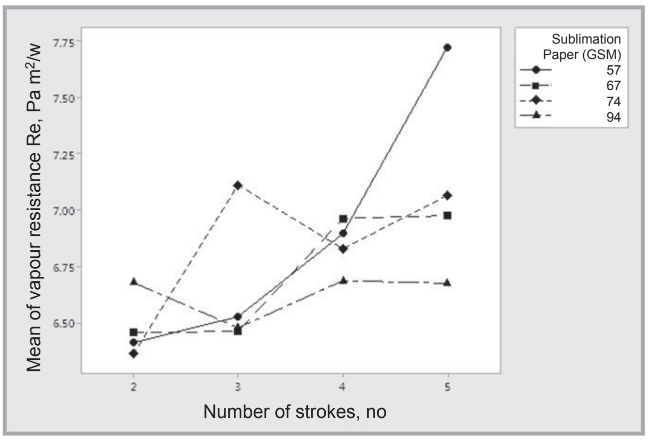

Figure 3. *Effect of number of strokes on WVR.*

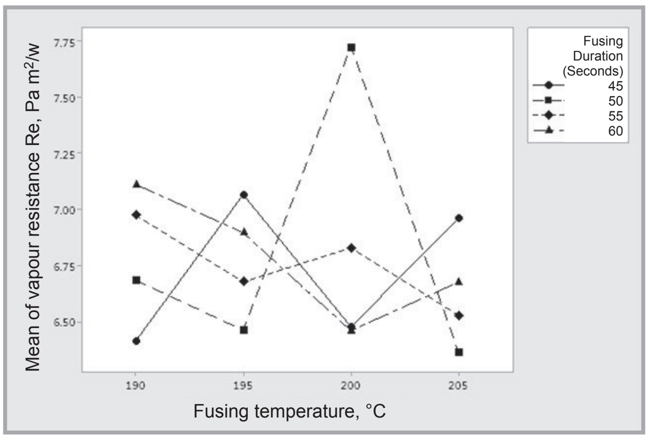

Figure 4. *Effect of fusing temperature on WVR.*

Table 5. Response table for signal to noise ratios.

Level	S	W	T	D
1	-16.22	-16.74	-16.68	-16.54
2	-16.44	-16.53	-16.59	-16.68
3	-16.70	-16.69	-16.72	-16.58
4	-17.02	-16.43	-16.42	-16.62
Delta	0.80	0.31	0.29	0.14
Rank	1	2	3	4

Table 6. Response table for means.

Level	S	W	T	D
1	6.475	6.889	6.832	6.719
2	6.643	6.713	6.756	6.848
3	6.842	6.840	6.871	6.751
4	7.110	6.627	6.630	6.784
Delta	0.635	0.262	0.241	0.129
Rank	1	2	3	4

Table 7. Optimum parameters.

Factor	Level	Optimum value
S	1	2
W	3	74
T	4	205
D	2	50

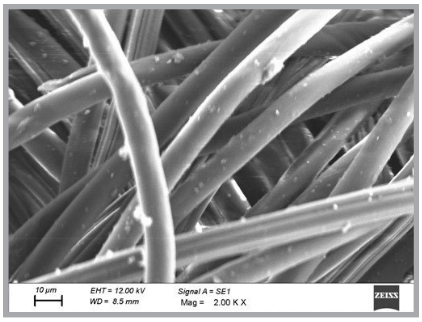

***Figure 7.** SEM Photographs of sublimation printed polyester fabrics.*

fusing time against water vapour resistance (***Figure 6***).

From ***Table 7*** the optimisation of printing parameters is arrived at. For factor (S), with a number of strokes equal to 2, with 74 GSM sublimation paper, with a temperature of 205 degrees celsius and a 50 sec fusing time, the optimum effect on water vapour resistance can be achieved.

Scanning electron microscopy of the printed fabrics shown in ***Figure 7*** under normal printing conditions and optimum printing parameter conditions reveal that sublimation printed polyester fabrics show the entrapment of more ink on their surface. The printing parameters under optimum conditions derived using the Taguchi approach enhance the print colour quality and reduce the water vapour resistance, which are essential parameters for polyester fabrics meant for technical and industrial applications [20-25].

Conclusions

In this research, we intended to create a process for optimising sublimation printing conditions using the Taguchi design to minimise the water vapour resistance of knitted fabrics. We can conclude from this research that by using the Taguchi design, we can determine the optimal variables. Based on the S/N ratio, optimum levels of the various parameters are obtained. As a result of the Taguchi method, the quality of a product is improved by minimising the effect of the causes of variation without eliminating them. In this methodology, the design desired is finalised by selecting the best performance under conditions that produce a consistent performance. The Taguchi approach provides systematic, simple and efficient methodology for the optimisation of near optimum design parameters with only a few well-defined experimental sets and determines the main factors affecting the process. From Tauguchi analysis of the minimum water vapour resistance using the response of means and response of S/N ratios, the predominant factors influencing the quality of sublimation printed single jersey knitted fabrics are the number of strokes of printing on the transfer paper. The minimum water vapour resistance of printed fabrics can be achieved. namely with a number of strokes equal to 2, 74 GSM sublimation paper, a temperature of 205 degrees celsius, and a 50 sec fusing time. From this research work parameter optimisation and factors influencing the response can be well predicted. There is a huge saving of cost and time by minimising the consumption of inks, fusing energy and fusing time.

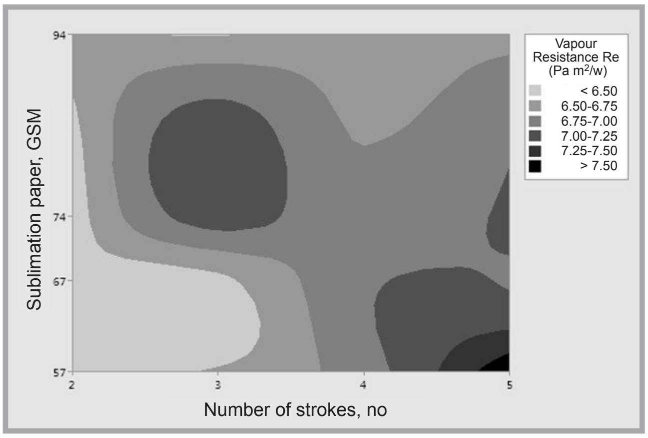

***Figure 5.** Effect of paper GSM and number of strokes on WVR.*

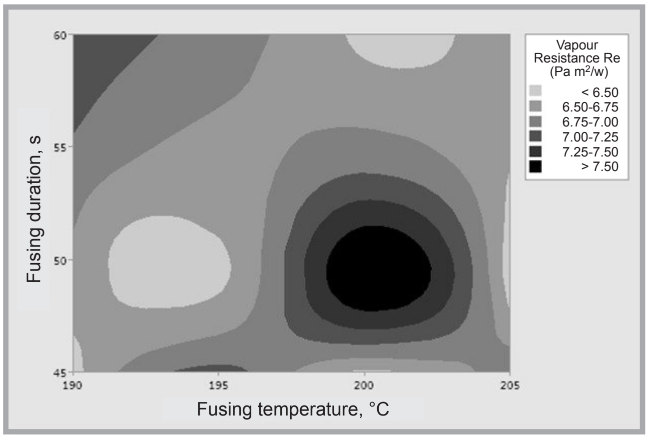

***Figure 6.** Effect of fusing temperature and fusing duration on WVR.*

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