

Optimization of Digital Transfer Textile Printing Process using Multi-Objective Function Analysis

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ABSTRACT

Digital textile printing (DTP) is widely used because it is more efficient and simpler than conventional textile printing methods. Digital transfer textile printing (DTTP) is one of the most efficient and simplest DTP methods. In this study, the optimum process conditions for DTTP have been investigated, to minimize the distortion of printed images and maximize the color reproducibility. First, a novel measurement method for fabric shrinkage and image distortion was developed. Then 9 characteristic values were defined and a series of experiments were designed and performed using the Taguchi method. Finally, two different multiple-characteristic value analyses were performed on the results. In one method, 9 characteristic values were converted into a single value. In the other method, the characteristic values were divided into 3 groups for analysis. Finally, results from the two methods were compared to determine which method was more suitable.

INTRODUCTION

Until recently, the textile industry has been dependent upon the mass production of limited types of goods. However, a new concept for mass customization has evolved to meet the demands of modern customers. Although the future of mass customization is very promising, it cannot compete with mass production in terms of price because conventional dyeing processes are too expensive. Therefore, DTP (Digital Textile Printing) is considered to be one of the most important technologies to successful commercialization of mass customization [1]. Since DTP does not require costly manual processes such as color separation and silk screening, it dramatically shortens the time for dyeing or printing. Another advantage of DTP is that there is no limit to the complexity of design, a major limitation of conventional silk screen printing.

There are two major methods in DTP. In one method, images are directly printed on the fabric, whereas in the other method, images are printed on a paper and then transferred to the fabric. The latter is called DTTP (Digital Transfer Textile Printing) and it is widely used because it is easier to print on paper than on a fabric because the fabric has poor dimensional stability. Since there is no specific method to evaluate the dimensional stability of printed fabric during the DTTP process, a novel evaluation method has been developed in this study through modification of existing techniques.

To determine the optimum conditions for the DTTP process, the Taguchi method was used [2-5]. It has been widely used in many research fields, but only in a few applications in garment manufacturing. Yoon et al. used an expert system with the Taguchi method to find the optimum condition for a fusing process to maximize the delamination strength of fusible interlinings [6]. Park et al. tried to find the optimum sewing conditions to minimize seam pucker using the Taguchi method [7]. Yuen et al. tried to find the factors influencing color yield of an ink-jet printed cotton fabric using the Taguchi method [8].

In this study, the skewness, dimensional stability, and color strength of printed fabrics were chosen as the characteristic values and multiple-objective function analysis was performed to determine the optimum process condition to maximize the reproducibility of the DTTP process.

DEFINITION OF CHARACTERISTIC VALUES

Skewness

A square test image was printed on the fabric to measure the skewness of fabric after post processing as shown in Figure 1(a). Skewness was defined as Eq. (1) and was evaluated by three methods. One was the measurement of the magnitude of four corner angles of the square represented by circle marks. Another was the measurement of intersecting angles between the top side of the square and the three lines drawn parallel to the wale direction through two triangle marks. The third was the measurement of intersecting angles between lines drawn parallel to the wale and course directions on four diamond marks. All the measurements were made after 4 hours of conditioning under standard atmospheric temperature and humidity according to ISO139. To prevent deformation of fabric by external forces, heavy weights were applied to both ends of fabric during all measurements in the wale and course directions.

$$s_i = \frac{\theta_{i0} - \theta_i}{\theta_{i0}} \times 100, S = \frac{\sum_{i=1}^n s_i}{n} \quad (1)$$

where, s_i = i th distortion rate after postprocess

S = Average distortion rate after postprocess

θ_0 = Angle before postprocess

θ = Angle after postprocess

$n = 4, 3, 4$ for type 1, 2, 3

Dimensional Stability

To measure the dimensional stability of a fabric after dry heating, a novel evaluation method has been developed as an alternative to the conventional ISO 5077:2007 method for measuring dimensional stability after washing and drying. In this method, a 30cm x 30cm square image was printed as shown in Figure 1(b) and the length of each side was measured along the wale and course directions. Fabric specimens were dry heated according to ISO139 and conditioned approximately 4 hours before measurement. To prevent deformation of the specimen during the measurement, heavy weights were applied on both ends of a specimen. The deformation rate was calculated in course and wale directions respectively using Eq. (2).

$$S = \frac{l_0 - l}{l_0} \times 100 \quad (2)$$

where, S = Deformation rate after postprocess

l_0 = Length of a side of the square before postprocess

l = Length of a side of the square after postprocess

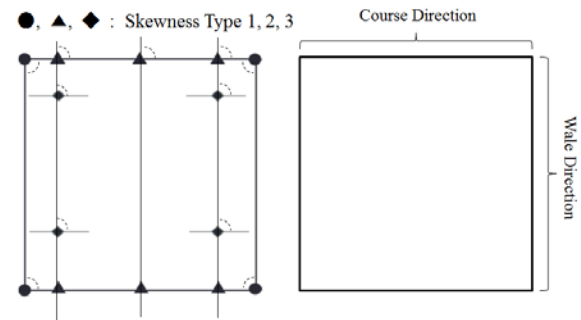


FIGURE 1. Images for measurement (a) Skewness (b) Dimensional Stability.

Color Strength

Apparent color strength (K/S) was measured using a Color-Eye 3100 CCM (Color coordination measurement) apparatus (Macbeth, USA). The entire surface of each specimen was measured thrice and four K/S values were measured in 400~700 nm range including cyan, magenta, yellow, and black [9].

PREPARATORY EXPERIMENT FOR TRANSFER PRINTING CONDITION

Experimental Design

Materials

Fabrics that were sensitive to distortion were chosen for skewness measurement. Fabrics made of spandex yarn the highest sensitivity in preparatory experiments and a polyester/spandex blended fabric DBR-WS36 was chosen.

Transfer Paper

Transfer paper was printed using an SC-S70610 printer (Epson, Japan) with 8 colors including cyan, magenta, yellow, black, light cyan, light magenta, orange, and grey. Images were prepared using Illustrator (Adobe, USA).

A total of 20 rows x 6 columns of 5cm x 5cm square images were printed in black color as the test image (Figure 2) in to evaluate the overall dimensional stability of the fabric.

Post Processing

The only post process to the transfer printing was heating. Images were transferred to the fabric specimen by a heated roller at various temperature and speeds.

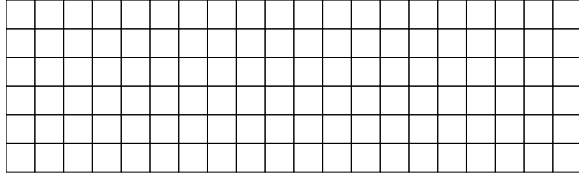


FIGURE 2. Image for the measurement of fabric dimensional stability.

Factors and Levels

The factors and their levels used in this study are as shown in *Table I*. De facto standard temperature of 220°C and speed of 20 m/min were considered to be the base conditions. Temperature was varied in increments of 10°C and speeds were changed in increments 5 m/min. The upper limit of temperature was set to 225°C because excessive heat seemed to damage the fabric.

TABLE I. Factors and levels.

Temperature (°C)	225	220	210	200
	225	220	210	200
	225	220	210	200
Speed (m/in)	15	15	15	15
	20	20	20	20
	25	25	25	25
	25	30	30	30

Results

The deformations in the wale and course directions were measured and analyzed using a t-test. No significant difference was observed across 6 consecutive grids. Therefore the dimension of test image was determined to be 30 cm. The heating drum used in post processing has the shape of a cylinder with center-bulged profile to maintain alignment of the fabric inside the machine. This shape exerts more pressure in the middle of the fabric, resulting in higher color reproducibility in that area. Therefore, only the images near the center of fabric were chosen for measurement in this study.

Fabric deformation was minimized a speed of 15 m/min. Therefore the speeds used were 10, 15, 20, and 25 m/min. The temperature interval of 10°C seemed to be too large for accurate measurement so the temperature increment was adjusted to 5°C.

MAIN EXPERIMENTAL DESIGN

Factors and Levels

Four factors were chosen as shown in *Table II*, including the type of transfer paper, heat treatment, postprocess temperature, and postprocess speed. The number of levels for each factor was 2, 2, 4, and 4.

TABLE II. Factors and levels.

Factor	Symbol	No. of Levels	Level
Postprocess Temperature (°C)	A	4	A ₁ =210, A ₂ = 215, A ₃ =220, A ₄ = 225
Postprocess Speed (m/min)	B	4	B ₁ =10, B ₂ = 15, B ₃ = 20, B ₄ =25
Heat Treatment	C	2	C ₁ =Yes, C ₂ =No
Paper Type (g/m ²)	D	2	D ₁ =58, D ₂ = 90

Experimental Design

An L₁₂(2⁹) orthogonal array was used for experimental design. The number of factors and their levels is shown in *Table III*.

TABLE III. L₁₂(2⁹) orthogonal array.

Exp. No.	1	2	3	4	5	6	7	8	9
1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	2	2	2	2
3	1	1	2	2	2	1	1	1	2
4	1	2	1	2	2	1	2	2	1
5	1	2	2	1	2	2	1	2	1
6	1	2	2	2	1	2	2	1	2
7	2	1	2	2	1	1	2	2	1
8	2	1	2	1	2	2	2	1	1
9	2	1	1	2	2	2	1	2	2
10	2	2	2	1	1	1	1	2	2
11	2	2	1	2	1	2	1	1	1
12	2	2	1	1	2	1	2	1	2
	a	b	ab	c	ac	bc	abc	d	ad

* The number in a cell means the level of a corresponding factor

After converting this into an L₁₂(4²x2³) orthogonal array as shown in *Table IV*, one column appeared beside four factors. This is considered an error term which will be used as a subjective criterion in the pooling process during ANOVA.

TABLE IV. $L_{12}(4^2 \times 2^3)$ orthogonal array.

Exp. No	A	B	C	E	G
1	1	1	1	1	1
2	2	1	1	1	2
3	1	2	2	2	1
4	2	4	1	2	2
5	2	3	2	2	1
6	1	4	2	1	2
7	4	2	2	1	2
8	3	1	2	2	2
9	4	2	1	2	1
10	4	3	2	1	1
11	3	4	1	1	1
12	3	3	1	2	2

* The number in a cell means the level of a corresponding factor

Analysis Method

Taguchi Method

The Taguchi method is a robust design technique used to efficiently determine optimum experimental conditions [1,2,10]. Characteristic values are categorized as one of three types including nominal-is-best, smaller-the-better, and larger-the-better. The nominal-is-best type characteristic value has an optimum value when it becomes equal to the target value and used for length, weight, or thickness. The smaller-the-better type value has an optimum value when it becomes as small as possible and used for noise, wear, and defect ratio. The larger-the-better type value has an optimum value when it becomes as large as possible and used for strength, life, or efficiency [1]. In this study, the S/N (Signal to Noise) ratios of dimensional stability and skewness were regarded as smaller-the-better type values the K/S value was regarded as larger-the-better type value in optimizing of condition.

Grey Relation Analysis

Gray system theory was first proposed by Deng in 1982, which deals with systems with ambiguous and imperfect information. This theory has the advantage over other statistical analysis methods in that it does not assume any kind of statistical distribution to predict the behavior of the system of interest. In this method, normalized S/N ratios are represented by grey relational coefficients to be evaluated into grey relational grade. It should be noted that the relationship among the characteristic values is not considered in this method [3].

Desirability Function Analysis

In this method, S/N ratios are converted into desirability. The information of each characteristic value is reflected in it because the limit of each

characteristic value is considered during the conversion. The relationship among the characteristic values is not considered in this method either [3].

RESULTS AND DISCUSSION

Taguchi Method

Dimensional Stability

Each of 12 experiments was repeated three times to obtain the S/N ratio. Since the dimensional stability was a smaller-the-better characteristic value, the S/N ratio was calculated using Eq. (3).

$$(S/N \text{ ratio})_i = -10 \log \left\{ \frac{1}{n} \sum_{j=1}^n y_{ij}^2 \right\} \quad (3)$$

where, y_{ij} = j th characteristic value of i th experiment

n = repeat count of y in an experiment point

The S/N ratio at each experimental point is shown in Table V.

TABLE V. S/N Ratio of dimensional stability.

Exp. No.	1	2	3	4	5	6
Wale	-8.6	-8.3	-3.9	-5.5	-2.8	-4.7
Course	-6.9	-5.7	-7.9	-8.7	-8.5	-7.9
Exp. No.	7	8	9	10	11	12
Wale	-3.6	-5.7	-6.8	-7	-5.2	-4.4
Course	-6.9	-4.9	-7.8	-8.6	-8.1	-8.8

The sum of squares of the error for a given column in the orthogonal array can be calculated using Eq. (4):

Sum of squares =

$$\sum_{i=1}^p \frac{(\text{sum of characteristic values at level } i)^2}{\text{number of characteristic values at level } i} - \frac{(\sum_{i=1}^p y_i)^2}{N} \quad (4)$$

where, N = total number of characteristic values

p = number of levels in the column

Contribution at each level is calculated using Eq. (5).

$$\text{Contribution} = \text{Average S/N ratio at each level} - \text{Total average S/N ratio} \quad (5)$$

In this study, factors with smaller sum of squares than that of the error term were pooled. For dimensional stability, factor A was pooled in the wale direction and all factors except B were pooled in the course direction.

The average S/N ratio of each dimensional stability factor is shown in *Figure 3*.

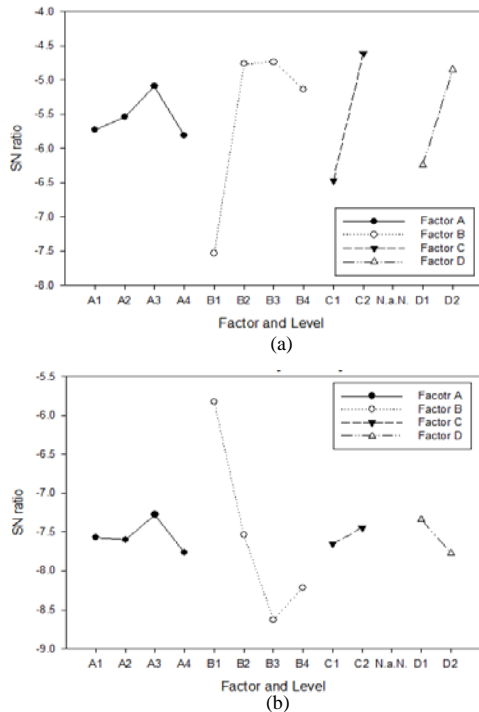


FIGURE 3. S/N Ratio of dimensional stability (a) Wale direction (b) Course direction.

According to the analysis results, the optimum condition for the wale direction was A3 B3 C2 D2 and A3 B1 C2 D1 for the course direction. However, since all factors except B were pooled, the overall optimum condition was B1.

Skewness

Each of 12 experiments was repeated three times to determine the S/N ratio. The skewness was a smaller-the-better characteristic value. The S/N ratio for each experimental point is as shown in *Table VI*.

TABLE VI. S/N ratio of skewness.

Exp. No.	1	2	3	4	5	6
Type1	6.47	6.74	7.98	5.27	5.34	4.56
Type 2	3.46	-1.51	1.78	3.98	0.28	-4.97
Type 3	-2.97	-2.89	-3.14	-1.59	-2.95	-4.02
Exp. No.	7	8	9	10	11	12
Type1	5.85	7.36	3.77	6.03	6.8	5.93
Type 2	-6.29	0.12	-1.66	5.52	2.32	-6.8
Type 3	-3.92	-0.62	-5.47	-3.72	-3.48	-2.95

Average S/N ratio of each factor for skewness is as shown in *Figure 4*.

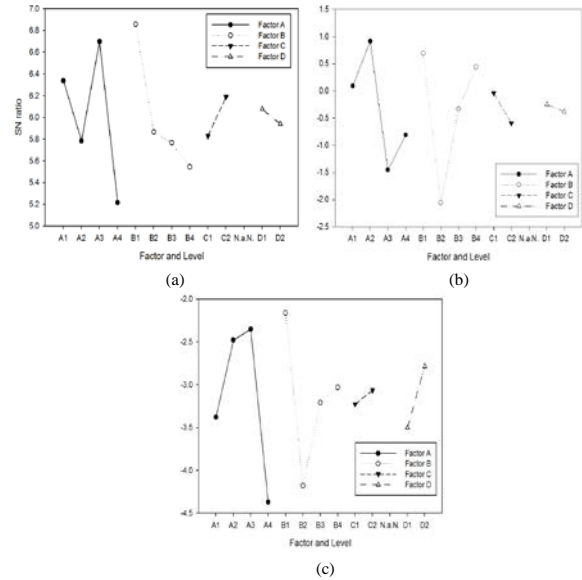


FIGURE 4. S/N ratio of skewness (a) Type 1 (b) Type 2 (c) Type 3

According to the analysis results, the optimum condition for type 1 skewness was A3 B1 C2 D1. The optimum condition for type 2 skewness was A2 B1 C2 D1 but since factor D was pooled, the final condition was A2 B1 C2. The optimum condition for type 3 skewness was A1 B4 C2 D1 but since factors C and D were pooled, the final condition was A2 B1.

K/S

Each of 12 experiments was repeated three times to determine the S/N ratio. K/S was a larger-the-better characteristic value. The S/N ratio for each experimental point is as shown in *Table VII*.

TABLE VII. S/N ratio of K/S.

Exp. No.	1	2	3	4	5	6
Cyan	14.9	14	16.3	16.9	16.5	16.5
Magenta	22.3	22.2	22.6	22.1	22.5	19.5
Yellow	23.6	23.5	23.6	23.2	23.5	20.3
Black	23.4	23.2	23.4	22.9	23.1	20.5
Exp.No.	7	8	9	10	11	12
Cyan	15.3	12.5	13.7	16.9	17.2	15.9
Magenta	22.6	21.7	22.3	23	21	22.3
Yellow	23.8	23.1	23.6	23.9	21.9	23.6
Black	23.7	22.8	23.2	23.9	22	23.3

Factors A, C, and D were pooled for cyan. Factors C and D were pooled for other colors.

The average S/N ratio of each factor for K/S is shown in *Figure 5*.

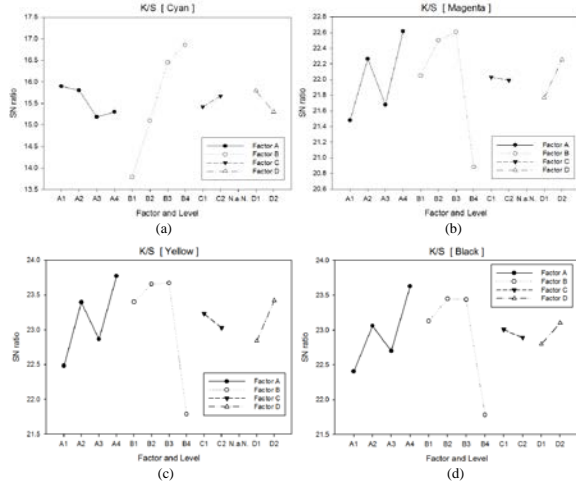


FIGURE 5. S/N Ratio of K/S (a) Cyan (b) Magenta (c) Yellow (d) Black.

According to the the analysis results, the optimum condition for cyan was A4 B3 C1 D2 but since factors A, C, and D were pooled, the final condition was B3. For magenta, A4 B3 C1 D2 was the optimum condition but since factors C and D were pooled, the final condition was A4 B3. For yellow, the optimum condition was A4 B2 C1 D2 but since factor C was pooled, final the condition was A4 B3 D2. For black, the optimum condition was A4 B2 C1 D2 but since factors C and D were pooled, the final condition was A4 B3.

Multiple Characteristic Function Analysis

In this study, two types of multiple characteristic function analysis methods were used. In one method, 9 characteristic values were converted into a single value using a simple average and grey relation analysis. In the other method, 9 characteristic values were divided into 3 groups before simple average, grey relation analysis, and desirability function analysis. A more detailed explanation of these methods follows.

Calculation of Average

The average of 9 characteristic values was calculated using Eq. (6) with normalized S/N ratios.

$$u_{ij} = \frac{SN_{ij} - SN_j^{\min}}{SN_j^{\max} - SN_j^{\min}} \quad (6)$$

where,

SN_j^{\max} = the S/N ratio of experimental point j

having the maximum value in the same factor i

SN_j^{\min} = the S/N ratio of experimental point j

having the minimum value in the same factor i

Calculated average values are shown in *Table VIII*.

TABLE VIII. Average characteristic values.

Exp. No.	1	2	3	4	5	6
Average	0.62	0.59	0.74	0.64	0.66	0.27
Exp. No.	7	8	9	10	11	12
Average	0.62	0.66	0.41	0.69	0.55	0.56

A cause and effect diagram of the average calculation is as shown in *Figure 6*.

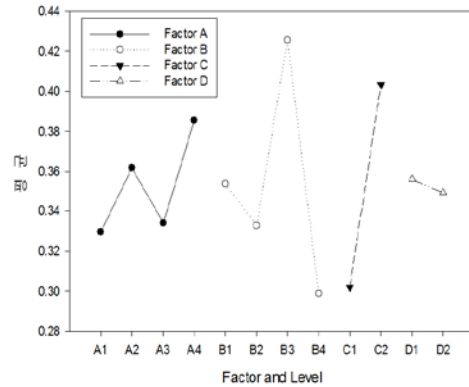


FIGURE 6. Case and effect diagram of average calculation.

In this method, the optimum condition was A2 B3 C2 D2. The final condition was A2 B3 D2 after pooling factor C.

Grey Relation Analysis

S/N ratios were normalized using Eq. (6). The Grey relational coefficient representation of the normalized S/N ratio is calculated using Eq. (7).

$$\begin{aligned} \epsilon_{0,ij} &= \frac{\Delta_{\min} + t\Delta_{\max}}{\Delta_{ij} + t\Delta_{\max}} \\ \Delta_{ij} &= |u_0 - u_{ij}| \\ \Delta_{\min} &= \text{minimum of all } |u_0 - u_i| \\ \Delta_{\max} &= \text{maximum of all } |u_0 - u_i| \end{aligned} \quad (7)$$

t is a coefficient to control the effect of design parameters and has a value between 0 and 1. Ten cases were analyzed with the value of t from 0 to 1 at intervals of 0.1.

The gray relation grade was calculated by a weighted sum using Eq. (8) with calculated gray relational coefficients.

$$r_i = \sum_{j=1}^n w_j \epsilon_{0,ij} \quad (8)$$

$$\sum_{j=1}^n w_j = 1$$

All w_j were set to 1/9 in this study. The optimum conditions obtained using gray relation analysis was A4 B3 C2 D1 with the t value of 0.1 from 0.7 and A2 B2 C2 D2 with the t value of 0.8 to 0.9.

Desirability Function Analysis

The desirability value was calculated using Eq. (9).

$$d_{ij} = 0 \quad SN_{ij} \leq SN_j^L$$

$$d_{ij} = \left(\frac{SN_{ij} - SN_j^L}{SN_j^U - SN_j^L} \right)^s \quad SN_j^L < SN_{ij} < SN_j^U \quad (9)$$

$$d_{ij=1} \quad SN_j^U \leq SN_{ij}$$

where, s = shape parameter

$$SN_j^U = \max_{1 \leq i \leq m} \{SN_{ij}\}, j = 1, 2, \dots, n$$

$$SN_j^L = -10 \log(USL_j^2) \quad \text{for smaller - the - better value}$$

$$SN_j^L = -10 \log\left(\frac{1}{LSL_j^2}\right) \quad \text{for larger - the - better value}$$

Where USL_j and LSL_j refer to the standard upper and lower limits of each characteristic value to set a valid range of experimental results [10].

The minimum and maximum S/N ratios are shown in Table IX.

TABLE IX. Upper and lower Limits of S/N ratio.

	Dimensional Stability		Skewness		
	Wale	Course	Type 1	Type 2	Type 3
SN_j^U	-2.806	-4.936	7.979	5.517	-0.617
SN_j^L	-8.605	-8.836	3.765	-6.799	-5.470
	Dimensional Stability		K/S		
	Wale	Cyan	Magenta	Yellow	Black
SN_j^U	-2.806	17.168	22.972	23.946	23.934
SN_j^L	-8.605	12.473	19.541	20.273	20.458

Analysis was performed with s values of 0.5, 1, and 2. All data was converted into desirability values and unified into overall desirability values using a geometric average based on Eq. (10).

$$D_{i,overall} = \left(d_{i1}^{W_1} \times d_{i2}^{W_2} \times \dots \times d_{in}^{W_n} \right)^{1/W} \quad (10)$$

$$W = \sum_{j=1}^n W_j$$

where, W_j = weight of j th desirability

Every W_j value was assumed to be 1 in this study. The optimum condition obtained by desirability function analysis was A1 B2 C2 D2 regardless of the shape parameter.

Multiple Characteristic Function Analysis after Grouping

Nine characteristic values were divided into 3 groups. One group consisted of dimensional stability in the wale and course direction, a second group consisted of skewness 1, 2, and 3 and the third group consisted of the K/S values of cyan, magenta, yellow, and black. Grouped values were analyzed using the multiple characteristic function analysis method. The resulting three characteristic values were analyzed again using the same functions to calculate the final value.

Grey Relation Analysis

Grey relation analysis was performed to determine 3 characteristic values from each group. Those values were analyzed again to calculate the final value. S/N ratio was normalized using Eq. (6). The Grey relation coefficient was obtained using Eq. (7). The term t is a coefficient that controls the effects of design parameters and has a value between 0 and 1. Ten cases were analyzed with the value of t ranging from 0 to 1 at intervals of 0.1. The Grey relation grade was calculated by weighted sum using Eq. (8) with the calculated gray relational coefficients. Every W_j value was assumed to be 1 in this study. The experimental condition that maximizes the grey relation coefficient is considered the optimum That one was A3 B1 C2 D2 in this study.

Desirability Function Analysis

Characteristic values were grouped and analyzed to calculate a single desirability value. Desirability values were calculated using Eq. (9). Analysis was done with the shape parameter s of 0.5, 1, and 2 per previous research [10]. All data was converted

into desirability values and an overall desirability value was calculated by geometric mean using Eq. (10). Secondary analysis was performed using these 3 overall desirability values. The optimum condition was A1 B2 C2 D2 regardless of the shape parameter.

Comparison of Expected Loss

Expected losses were compared between two analysis methods. Experiments with minimum and characteristic values were compared. The expected loss of each characteristic value is shown in *Table X*. The best results were obtained by using grey relation analysis with the single value conversion method. The largest improvement is found in skewness type 2. K/S values were improved as well. Dimensional stability showed the least improvement.

Results showed that the simple average method was unsuitable for accurate calculation. Simple averaging could not account for the complex variation of the data. Desirability function also seemed inappropriate it discarded too much data during the calculations. Grouping of characteristic values seemed minimally effective because the two-step function analysis could result in considerable errors during the calculation process.

CONCLUSION

In this study, the Taguchi method was used to determine the optimum processing conditions and maximize the reproducibility of DTTP. Four optimum conditions have been obtained for each characteristic value. A series of multi-object function analyses were performed to choose a single optimum condition among them by analyzing 9 characteristic values together. The optimum conditions determined by simple averaging were post process temperature (PPT) of 215 °C, post process speed (PPS) of 20 m/min and paper weight (PW) of 90g. Optimum conditions determined by desirability function analysis were PPT of 215°C and PPS of 20 m/min. Grey relation analysis resulted in two optimum conditions according to the classification coefficient. One was PPT of 225 °C, PPS of 20 m/min, and PW of 90g. The other was PPT of 215 °C, PPS of 20m/min and PW or 90g. After grouping the characteristic values, the simple average method resulted in the same condition mentioned above. Desirability function analysis resulted in optimum PPT of 215 °C and PPS of 20 m/min. Grey relation analysis resulted in optimum PPT of 220 °C, PPS of 10m/min, and PW of 90g.

By comparing the expected loss of all results above, grey relation analysis using the single characteristic value conversion method was shown to be the best method. That yielded an optimum PPT of 215°C, PPS of 20 m/min, and PW of 90g.

TABLE X. Comparison of expected loss.

Characteristic Value		Single Value Conversion			
		Average	Desirability Function	Grey Relation Analysis	
Dimensional	Wale	3.8	3.8	3.8	1.43
Stability	Course	1.09	1.09	1.09	1.06
Skewness	Type 1	1.44	1.44	1.44	1.69
	Type 2	3.8	3.8	3.8	19.3
	Type 3	1.79	1.79	1.79	1.5
K/S	Cyan	2.55	2.55	2.55	2.78
	Magenta	1.98	1.98	1.98	2.2
	Yellow	2.09	2.09	2.09	2.33
	Black	1.83	1.83	1.83	2.23
Characteristic Value		Grouped Analysis			
		Average	Desirability Function	Grey Relation Analysis	
Dimensional	Wale	3.8	3.8	1.95	
Stability	Course	1.09	1.09	2.45	
Skewness	Type 1	1.44	1.44	2.29	
	Type 2	3.8	3.8	3.5	
	Type 3	1.79	1.79	3.06	
K/S	Cyan	2.55	2.55	1	
	Magenta	1.98	1.98	1.64	
	Yellow	2.09	2.09	1.91	
	Black	1.83	1.83	1.7	

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