Analysis of Spinning Process Parameters on Development of Spun-Dyed PET Yarn Using the Taguchi Method

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ABSTRACT: The yarn tenacity of a spun-dyed yarn is predicted from the spinning conditions and other properties of the yarn are analyzed through the defined parameters using the Taguchi method. To develop a spun-dyed yarn using the Taguchi method, four factors that can largely influence the yarn properties are selected. From the experimental design based on four factors, the processes are executed to produce the specific yarns whose properties are measured to analyze the relationship between the process conditions and their results. The target properties of a spun-dyed yarn may be obtained through adjusting the spinning parameters that are related to the yarn properties by the Taguchi tool. © 2006 Wiley Periodicals, Inc. J Appl Polym Sci 102: 1419–1427, 2006

Key words: spun-dyed yarn; Taguchi method; polyethylene terephthalate yarn

INTRODUCTION

The improved technique of spin-draft method for melt spinning process has widely been spread so that synthetic fibers have been produced over 30 million tons/year worldwide.[1] The high tenacity poly(ethylene terephthalate) (PET) yarns for the application of technical industry have also reflected on lots of demands in the industrial area. In the melt spinning process, it is highly difficult to set up the manufacturing methods to acquire the various yarn properties required on the markets. A little change in polymer properties and/or in processing parameters would occasionally cause the large effects in the fiber properties. In an initial step of yarn development, it is very important to shorten the developing time of a specific yarn and to reduce the initial fails to obtain the target properties of the yarns. Therefore the optimal processes for the spinning have been recently studied to produce the yarns that are aimed at having specific properties. Ozkan et al. reported that a static model for partially oriented yarn production was examined in a spinning plant.[2] They offered the optimal operating parameters to obtain required yarn properties. Watson tried to improve a fiber master batch (MB) quality and productivity by controlling pigment physics.[3] Catone studied the effect of nanoparticle addictive on the physical properties of PET by controlling process.[4]

In this study, a spun-dyed yarn has developed using the Taguchi method. A spun-dyed yarn has been largely consumed in the market of technical application. As a raw white yarn is usually dyed after spinning for the final purpose, it cause some environmental problems occurred by the by-products. However the spun-dyeing of a yarn is free from such problems because it is spun to have a designed color during spinning. During the spinning process of a spun-dyed yarn, operator has to control several parameters of spinning processes more carefully than one of a raw white yarn. Generally, it is difficult to make the color of a spun-dyed yarn matched with the planned color. The physical properties of a spun-dyed yarn such as tenacity have a tendency to be lowered than ones of a raw white yarn because particles such as carbon black (CB) in polymers act as an inorganic impurity.[5–7]

We have studied the method to find optimal operating conditions to obtain the target tenacity which is one of the most important properties. This research has aimed at examining the relationship between the yarn properties except the tenacity and spinning parameters using the Taguchi method.[8,9] In the first step, several process conditions have been analyzed whether they affect the yarn properties through the spinning or not. After the trial spinning, we determined main factors that influenced the spinning process and experimental levels to minimize the number of experimental runs. From the trial spinning, we could determine four processing variables which significantly affected the properties of spun-dyed yarn. The four factors are draw rate (DR),

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relaxation ratio (RR), contents of CB, and denier per filament (DPF). Although the other factors could influence the yarn properties, they were fixed to be regarded as a trivial factor. As the experiment designed for a spun-dyed yarn development using the Taguchi method, the developing time can be reduced the knowledge obtained on this can be utilized for further development.

EXPERIMENTAL

Taguchi concepts

Taguchi methods focus on improving the fundamental function of the product or process so that it is very useful for reducing product costs, improving product quality, and simultaneously shortening development time.[10] Taguchi methods have three basic phases: system design, parameter design, and tolerance design. The system design looks for what each factor and its level should be. The concepts may be based on past experience, scientific/engineering knowledge, a new revelation, or any combination of the three. The strategy behind system design is to take these new ideas and convert them into something that can work. The parameter design assumes that the factors are already known and production needs a little modification to develop any new product on the basis of technical well-known method like this study. The objective here is to improve performance and product quality by adjusting the levels of known factors. The objective of the tolerance design is to determine the acceptable range characteristics for each factor level selected in parameter design.

In this article, the following Taguchi process is utilized for optimum operation conditions and analysis of the relationship between the spinning conditions and the yarn properties. First of all, this article calculates the SN (signal-to-noise) ratios of repeated experimental runs obtained from the experimental design using an orthogonal array defined by the Taguchi method. Then we find the corresponding conditions influencing each property of spun-dyed yarns and determine the optimum conditions (levels) of the selected factors for reducing the variation and having the greatest effects on the mean tenacity. We calculate the SN ratios and predict the mean tenacity with the optimal levels. Then we can easily determine the optimum spinning conditions for obtaining the target tenacity of the yarn and analyze the spun-dyed yarn properties related to the process parameters.

Selecting factors and levels

The physical properties of melt-spun yarn are essentially affected by polymer properties, constituent spinning utilities, and processing conditions. In this study, polymer property does not vary since it goes beyond our research purpose. The spinning machine and utilities are well-known systems and uncontrollable variables and therefore the factors are not considered in this article. There are lots of the processing parameters in the melting operation. This study selected four factors (RR, DR, CB, and DPF) that have significant influence on the physical properties of the spun-dyed yarns and can be easily controlled during the manufacturing process. The other minor factors are listed as following: temperature conditions of extruder system, variables of spinneret nozzle and pack configuration, hood heater and its length, quenching air related factors, temperature of drawing roller, and winding speed. The conditions of these factors to manufacture the raw white PET fibers have been well established on the base of mass production. Since the knowledge on the relation between these factors and yarn properties has been accumulated during long time, the properties of the produced yarn can be easily predictable. Therefore, the relationship is not dealt here.

It is well known that the factors of DR and RR are strongly related to the yarn's main properties such as strength, elongation, and shrinkage. The knowledge and know-how has been accumulated greatly so that the yarn properties are normally predicable by adjusting both DR and RR parameters. In the case of spun-dyed yarn development, some MB chips including specific carbon black particles are added in raw white chips, which are mixed in extruder and their feature are different from the pure polymer. Therefore, the properties of spun-dyed yarns are not easily estimated by factors of DR and RR. For carbon black particles, their size, shape, and quantity are important factors to influence the spun yarn properties, and the roles of these factors in yarn properties and processing ability may be important. However, our research confines our interesting to the amount of carbon particles since we use the best qualified MB chips available in market whose size and shape are uniform.

With the same amount of carbon particles in yarn, the smaller DPF of spun-dyed yarn results in the higher light scattering so that its surface color becomes less dark.[11] For the normal rang of such as 5.2 DPF (1000 days/192 f) ~ 13.9 DPF (1500 days/105 f), the DPF factor plays very important role in the physical properties, yarn colors, and processing ability. In the development of black spun-dyed yarn, the CB content is one of the important factors to affect the yarn color. As the amount of CB contents in polymer increases, the color of the spun-dyed yarn becomes deep black and the strength of the yarn decreases because the CB acts as impurity particles.

In this study, each factor is designed to have three levels except the RR factor which is set to have two levels. The two levels of RR factor are enough to

TABLE I
Experimental Factors and Their Levels for the Experimental Design

Level of experimental factor	Experimental factor			
	RR (%)	CB (wt %)	DPF (denier)	DR
1	4.0	0.5	8.0	5.3
2	8.0	1.0	12.0	5.6
3	–	1.5	16.0	5.9

RR, relaxation ratio; CB, carbon contents in fiber; DPF, Denier per filament; DR, draw rate.

predict the tendency of yarn properties through the Taguchi tool because the RR is approximately (direct or inverse) proportional to the spun-dyed yarn's properties although a RR level can not predict the absolute values of yarn properties.

As we do not attempt the tolerance design through the noise experimental design, the experimental trials are performed with four factors. The experimental conditions for each level are shown in Table I. Eighteen experimental trials based on the orthogonal array $L_{18}(2^1 \times 3^3)$ in the Taguchi model are used to analyze the effects of the four parameters. If the RR factor had three levels, the orthogonal array could be determined as $L_9(3^4)$. Although these nine experimental runs are very simple, it is not enough trials to understand the effects affecting the yarn properties. Otherwise the full-factorial design will exactly require $2^1 \times 3^3 = 54$ experimental runs, in which the effort and experimental cost for such a design can be unrealistic.

The tenacity is regarded as the most important value among the yarn properties so that the optimal conditions of four factors to obtain the target tenacity are ideally obtained by using ''a nominal is best'' of the Taguchi tool.[8] Thus, ''a nominal-is-best'' characteristics are identified as a suitable method for calculating each SN (defined as term of ''signal to noise'' by Taguchi) ratio which can be obtained from observations according to the experimental design using eq. (1). The factors (called ''control factors'') which have a significant effect on the SN ratio are searched through performing an analysis of variance (ANOVA) of the SN ratios. For each significant factor, its level corresponding to the highest SN ratio is chosen as its optimum level.[10]

$$(\text{SN ratio})_i = 10 \log \left[\frac{\frac{1}{n}(s_{mi} - v_i)}{v_i} \right] \qquad (1)$$

where $\bar{y}_i = 1/n \sum_{j=1}^{n} y_{ij}$, $S_{mi} = n\bar{y}_i^2$, and $v_i = 1/(n-1) \sum_{j=1}^{n} (y_{ij} - \bar{y}_i)^2$.

The y_{ij} is the characteristic value from the experimental observations and n is the repeat number at one run ($n = 3$) as shown in Table II. The term of $\bar{y}_i$ means ''sum of squares total,'' the S_{mi} implies ''the ith mean square,'' and the v_i is ''the ith mean square error'' in experimental runs. The experiments are performed in random order and the results are analyzed with Minitab program package software (Minitab).

Spinning for the samples

PET chips (supplied by Hyosung) with intrinsic viscosities (IV) of 1.00 d lg^{-1}, measured in a 60/40 wt % phenol/tetra chloroethane solvent at 25°C, were used in this study. PET chips were blended with MB chips whose base materials were PET resin and contained 30 wt % carbon black particles. We chose the MB chips (produced by Americhem) that had a feature of good disperse of CB particles in PET resin and their size distribution within the PET resin was designed from 20 to 30 nm. The PET chips were blended with 0.5, 1.0, and 1.5 wt % MB respectively, and they were dried to reduce the moisture regain below 30 ppm using a hot dryer at 140°C for 12 h. The prepared chips were respectively, spun under the specific conditions of experimental design by a spin draft machine that our company possessed to produce the raw white yarn for industrial application.

The spinning machine with five pairs of godet rollers can diversely control the spinning conditions such as the factors of DR and RR so that the physical properties of the spun-dyed yarn could be largely influenced by their conditions. The gear pump of the machine can also control the amount of melt polymer so the linear density of the spun-dyed yarn could be adjusted. The DPF of the spun-dyed yarn was adjusted by the control of the gear pump. Each sample was separately spun according to the conditions of the experimental designs in Table I. The linear density of the samples was ranged from 760 denier/96 filament to 1530 denier/96 filament, which corresponds to 8 and 16 DPF respectively.

Measurements of the sample properties

The prepared yarn samples were measured by several instruments to analyze their physical properties. To examine the distribution of CB particles in a fiber,

TABLE II
Schematic Matrix of Experimental Layout Using an L_{18} ($2^1 \times 3^3$) Array Table

Experimental run	Factor and level				Characteristic value (y_{ij})			SN ratio (SN$_i$)
	RR	CB	DPF	DR	Y1	Y2	Y3	
1	1	1	1	1	$y_{1\ 1}$	$y_{1\ 2}$	$y_{1\ 3}$	SN$_1$
2	1	1	2	2	$Y_{2\ 1}$	$Y_{2\ 2}$	$Y_{2\ 3}$	SN$_2$
:	:	:	:	:	:	:	:	:
17	2	3	2	1	$y_{17\ 1}$	$y_{17\ 2}$	$y_{17\ 3}$	SN$_{17}$
18	2	3	3	2	$y_{18\ 1}$	$y_{18\ 2}$	$y_{18\ 3}$	SN$_{18}$

each fiber sample including the different ratio of CB particles was observed by scanning electron microscope (SEM) at 20,000 magnifications as shown in Figure 1.

A tensile testing machine was used for the measurement of the stress–strain curves of the yarn samples whose specimen length was 250 mm and cross head speed 300 mm/min. In the case of shrinkage percentage, the yarn samples with an initial length of 100 mm were treated in a hot chamber (150°C) for 30 min. The resultant length was measured after conditioning for 24 h at room temperature. Therefore, the dried shrinkage percentage was calculated as the eq. (2):

$$S = \frac{l_0 - l}{l_0} \times 100 \tag{2}$$

where S is the shrinkage percentage, l_0 the initial yarn length, and l the yarn length after heat treatment. Luminosity (L^*) of the color of the spun-dyed yarns was measured using a spectrophotometer. As L^* value approaches 100, it gets lighter, on the other hand the value of $L^* = 0$ means an absolute blackness.

RESULTS AND DISCUSSION

Each sample was spun by the conditions of experimental design using the spinning machine and the yarn properties of every sample were measured under the test methods mentioned earlier. The experimental and analysis results were analyzed in the following section.

Results on tenacity

Table III shows the three characteristic values (tenacity) of the spun-dyed yarns for each experimental run, the SN ratios calculated from eq. (1), and the mean value (mean of three tenacities). We totally obtained 18 sets of yarn tenacity values from 18 experimental runs and the calculated SN ratios. The values in each set were obtained by measuring the properties of the spun-dyed yarn samples that were produced through the three repeated trials under the same experimental conditions. For an example, the SN_1 values in Table III were calculated in the way as shown below.

$$\bar{y}_1 = \frac{1}{n}\sum_{j=1}^{3} y_{1j} = \frac{1}{3}(y_{11} + y_{12} + y_{13}) = 8.22,$$

$$S_{m1} = n\bar{y}_1^2 = 202.7052,$$

$$v_1 = \frac{1}{3-1}\sum_{j=1}^{3}(y_{1j} - \bar{y}_1)^2 = 0.01085,$$

and

$$SN_1 = 10 \log\left[\frac{\frac{1}{3}(s_{m1} - v_1)}{v_1}\right] = 37.9.$$

Thus, we could calculate the all SN_i values in Table III.

Table IV shows the values of SN ratios ($\overline{SN}$) and mean tenacity in the response table, in which the SN ratio ($\overline{SN}$) of each factor at its level was calculated by the average of SN ratios (in Table III) contributed at the corresponding level. Therefore the F_i represented by the level i at the F factor was obtained using eq. (3).

$$F_i = \text{average of total } SN \text{ ratios with regard to the level } i \text{ at the 'F' factor} \tag{3}$$

For examples in Table IV, $A_1 = (37.95 + \ldots + 47.81) \times \frac{1}{9} = 43.6$, and $D_3 = (42.82 + \ldots + 45.02) \times \frac{1}{6} = 46.2$.

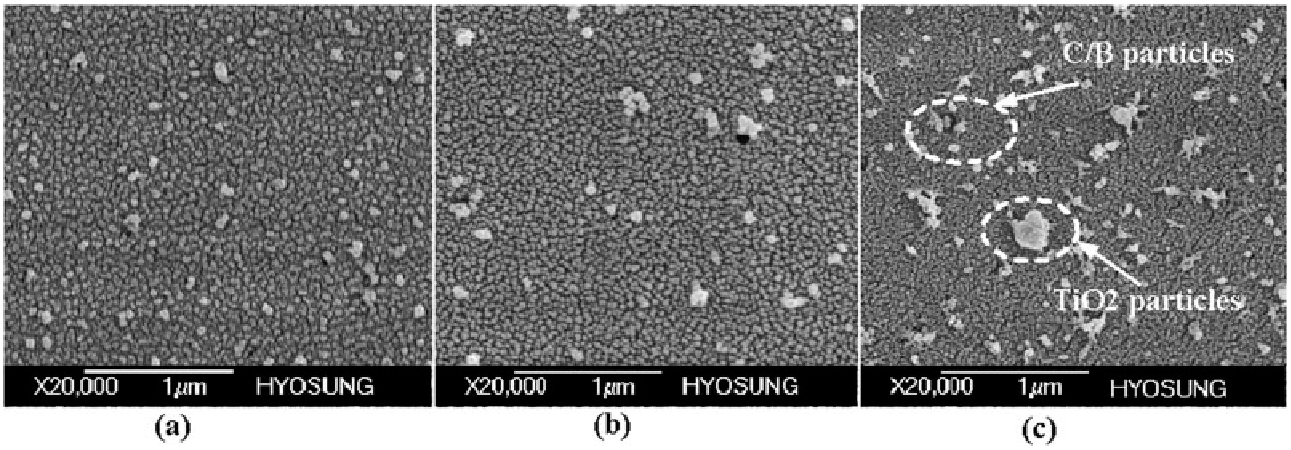

Figure 1 Cross section SEM images of each fiber samples including (a) 0.5 wt %, (b) 1.0 wt %, and (c) 1.5 wt % CB particles.

TABLE III
Experimental Runs and the Results of SN Ratio and Mean Tenacity

Experimental run	Factor and level				Tenacity (g/d)			SN ratio	Mean tenacity
	RR	CB	DPF	DR	T1	T2	T3		
1	1	1	1	1	8.25	8.30	8.10	37.95	8.22
2	1	1	2	2	8.57	8.57	8.43	40.46	8.52
3	1	1	3	3	8.75	8.75	8.86	42.82	8.79
4	1	2	1	1	7.96	8.04	7.81	36.65	7.94
5	1	2	2	2	8.41	8.37	8.40	52.11	8.39
6	1	2	3	3	8.65	8.56	8.67	43.36	8.63
7	1	3	1	2	8.15	8.06	8.11	45.09	8.11
8	1	3	2	3	8.45	8.51	8.43	46.16	8.46
9	1	3	3	1	7.50	7.54	7.48	47.81	7.51
10	2	1	1	3	8.89	8.92	8.87	50.97	8.89
11	2	1	2	1	7.40	7.27	7.43	38.75	7.37
12	2	1	3	2	7.74	7.59	7.65	40.13	7.66
13	2	2	1	2	7.79	7.71	7.80	43.94	7.77
14	2	2	2	3	8.41	8.38	8.35	48.92	8.38
15	2	2	3	1	7.18	7.22	7.16	47.43	7.19
16	2	3	1	3	8.41	8.48	8.39	45.02	8.43
17	2	3	2	1	7.10	7.07	7.09	53.33	7.09
18	2	3	3	2	7.53	7.45	7.49	45.45	7.49

The mean tenacity values in response table were also obtained from the same method with eq. (3). The delta value was calculated by subtracting the largest value from the lowest value among values in each column. All calculation procedures were performed through the Minitab package.

An approach can be taken to determine which factors are most significant for reducing variation related with the S$\overline{N}$ ratio in response table. In analyzing the table, the technique is to select those factors displaying the greatest effect (the highest value) according to the Taguchi method, which can decrease the variation of the tenacity's values with the response table of the S$\overline{N}$ ratio and move the mean values to the target ones with the mean tenacity. According to the Taguchi technique, the halves of the studied factors are approximately selected by the rule of thumb. Therefore the CB factor has the greatest effect at the delta 5.30. Next are the DPF and the DR factors one at 3.35 and 2.57, respectively. In case of the third factor DR, we may choose it as a considerable one or not select to consider it in the response table of mean tenacity. Since the higher signal-to-noise ratio means the greater robustness and the less variability, we want to choose the level with the largest (or larger in the case of RR) value in each case. In this study, we select three factors and their levels in the response table of S$\overline{N}$ ratio as follows: CB_3, DPF_2, and DR_3.

The same techniques used in determining the most important factors for reducing variation can be used here to identify those factors that have strong effect on the mean tenacity. Again, the rule of thumb is selecting roughly half of the factors being investigated. From the response table of the mean tenacity, the DR factor has the greatest effect at the delta 1.05. This is followed by the RR factor at 0.48 and the CB one at 0.39. In the response table of the mean tenacity, we also choose three factors and their levels as following: DR_3, RR_1, and CB_1.

In selecting the finally optimal factor levels, those factors that affect both variation and the mean tenacity have already been set at the best level for reducing variation. In case of the DR factor, the selected level is the same result between both the S$\overline{N}$ ratio and the mean tenacity as the DR_3. In the case of the CB factor, the selection of the CB factor's level is different between both situations. In conflicts of the selected levels regarding the CB factor, the priority is laid at the S$\overline{N}$ response table, where the order is the first but at the mean tenacity is the third, so that the CB factor has to be selected as 3rd level (CB_3). The levels of the DPF factor and the RR one are only affected by the response table of the SN ratio and the mean tenacity, respectively. Thus, the optimum levels for the DPF and the RR conditions are DPF_2 and RR_1, respectively. It is easy for the S$\overline{N}$ ratio and the mean tenacity to be understood from the plots in Figure 2.

We can ultimately compute an estimate of the predicted responses based on the selected levels of the

TABLE IV
Response Table for SN Ratio and Mean Tenacity

Level	SN ratio (S$\overline{N}$)				Mean tenacity			
	RR	CB	DPF	DR	RR	CB	DPF	DR
1	43.60	41.85	43.27	43.65	8.28	8.24	8.22	7.55
2	45.99	45.40	46.62	44.53	7.81	8.05	8.04	7.99
3	–	47.14	44.50	46.21	–	7.85	7.88	8.60
Delta	2.39	5.30	3.35	2.57	0.48	0.39	0.35	1.05
Rank	4	1	2	3	2	3	4	1

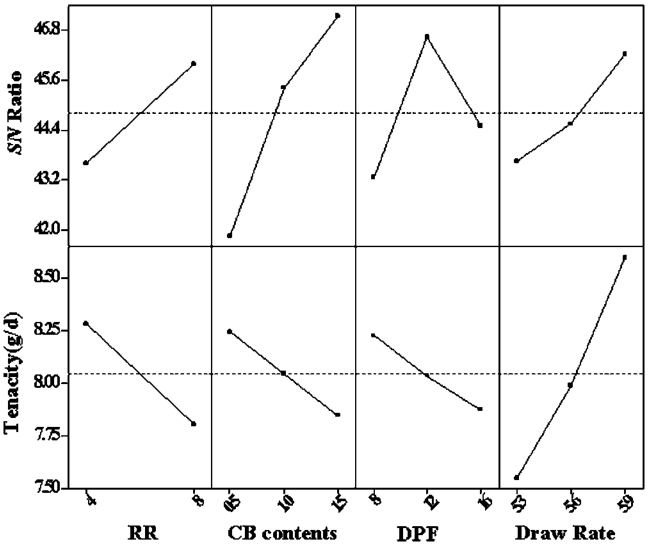

Figure 2 Response graph of the main effects for SN plots and mean tenacity (g/d) according to each factor and its level.

strong effects, which are actually two predictions of both the SN ratio and the mean tenacity as shown in Table V. The optimal mean tenacity is calculated as an 8.6 g/day whose value is the one of the most important physical properties in the development of the spun-dyed yarns.

The estimated SN ratio ($\overline{\mathrm{SN}}$) can be calculated with the optimal selected levels using the eq. (4) defined by the Taguchi method as follows.

$$\begin{aligned}
&\text{The estimated value of } \overline{\mathrm{SN}} \text{ ratio } (\overline{\mathrm{SN}}) \\
&\quad = \text{average of total } \overline{\mathrm{SN}} \text{ ratios } (\overline{\mathrm{SN}}) \\
&\qquad + \text{sum of the contribution of each factor} \\
&\quad = 44.80 + (\mathrm{RR}_1 - 44.80) + (\mathrm{CB}_3 - 44.80) \\
&\qquad + (\mathrm{DPF}_2 - 44.80) + (\mathrm{DR}_3 - 44.80) \\
&\quad = 44.80 + (43.60 - 44.80) + (47.14 - 44.80) \\
&\qquad + (46.62 - 44.80) + (46.21 - 44.80) = 49.17 \quad (4)
\end{aligned}$$

TABLE V
Results of SN Ratio and Mean Tenacity According to the Initial Level and Optimal One

Factor	RR	CB	DPF	DR	SN ratio ($\overline{\mathrm{SN}}$)	Tenacity
Initial level	2	1	2	2	44.59	7.93
Optimal level	1	3	2	3	49.17	8.62

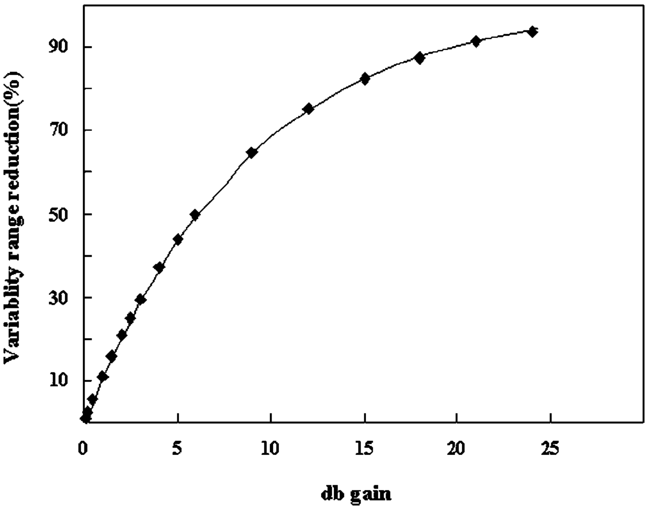

Figure 3 Plot between variability range reduction and a db gained from a process optimization.

At the initial stage for the development of the spun-dyed yarns, we selected the initial levels of the studied factors on the basis of the manufacturing experience at the raw white yarns as shown in Table V. The initialization of spinning was easily built to produce the spun-dyed yarns with those selected levels although we did not consider their properties. On the basis of the estimated SN value ($\overline{\mathrm{SN}}$) of the optimal processing conditions and the initial processing ones, we can obtain the information of robustness as relatively estimating the reduced process variation. From the simulation results, the SN ratio ($\overline{\mathrm{SN}}$) of the optimal conditions is bigger than one of the initial conditions, which leads to reduce the variation. The variance 4.58 (db), which is a difference between both conditions, is called gains. It implies the decrease of variation or noise as much as 40% as shown in Figure 3.[12] Through the simulation results with the selected levels, we can ultimately reduce the noise with regard to the mean tenacity and search the optimal conditions to obtain a target value as a roughly 8.5 g/d.

The prediction for the tenacity uses the selected levels that are determined by the level resulting in the least variation and the greatest effect on the mean tenacity. The following equation was used to predict the tenacity.

$$\begin{aligned}
&\text{The predicted value of optimal tenacity} \\
&\quad = \text{average of total tenacity} \\
&\qquad + \text{sum of the contribution of each tenacity} \\
&\quad = 8.05 + (\mathrm{RR}_1 - 8.05) + (\mathrm{CB}_3 - 8.05) \\
&\qquad + (\mathrm{DPF}_2 - 8.05) + (\mathrm{DR}_3 - 8.05) \\
&\quad = 8.05 + (8.28 - 8.05) + (7.85 - 8.05) \\
&\qquad + (7.88 - 8.05) + (8.60 - 8.05) = 8.62
\end{aligned}$$

As shown in Figure 2, the DR is the biggest factor to influence the means. On the basis of the DR, we try to interpret the relationship between the DR and other factors respectively, to understand the tendency of the tenacity values. At a lower DPF, the tenacity value is higher as shown in Figure 4. In the

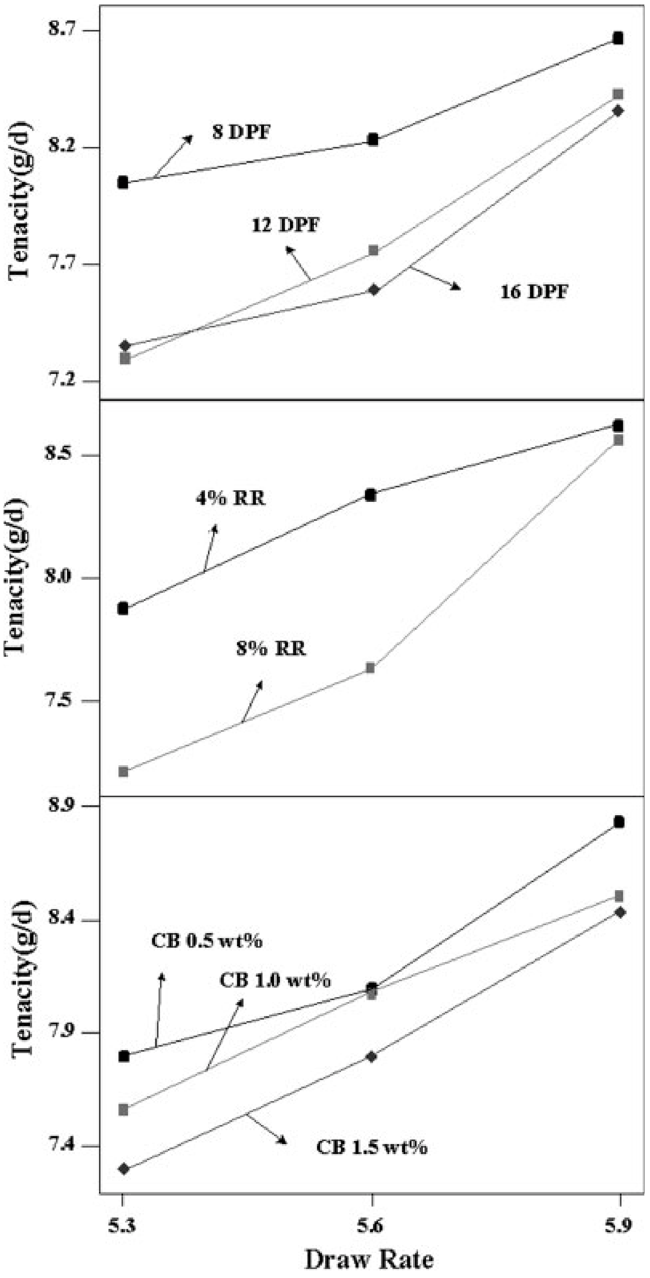

Figure 4 Plots of tenacity values caused from the relationship between the draw rate and other factors.

case of RR, RR 4% shows much higher tenacity value than 8% one. There is almost the same tenacity between both levels at the DR 5.9. In the high DR level, the physical properties of yarn may be largely affected bigger by the DR factor than the RR one. The lower CB contents in yarn illustrate to have an advantage of raising yarn's physical properties.

Results on elongation at breakage

The elongation value at yarn breakage can be normally controlled by the factors of RR, DR, and so on. The factors of RR and DR are closely related to the yarn elongation as shown in Figure 5. Otherwise the factors of CB contents and DPF may slightly influence the elongation but they have a sharp slope in the effect plot for SN ratio. It means that there is bigger deviation among elongation values than the factors of RR and DR. In this article, the correlation between RR and DR is configured to explain how these two factors are related to the yarn elongation in Figure 6. It is found that RR 4% steadily declines the slope of yarn elongation as being raised of the DR but RR 8% shows that the elongation sharply drops according to raising the DR.

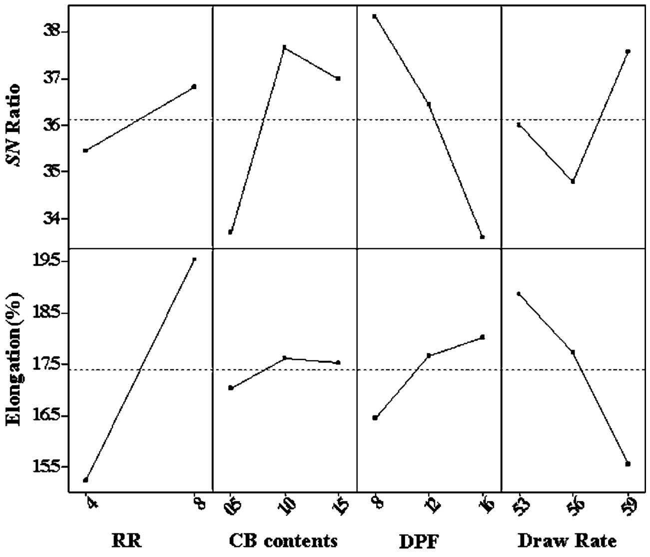

Figure 5 Response graph of the main effects for SN plots and mean elongation (%) according to each factor and its level.

As being chosen the proper level at each factor by the analogical inference using the pattern plots of the elongation, the target elongation of yarn can be planned enough to achieve a specific one.

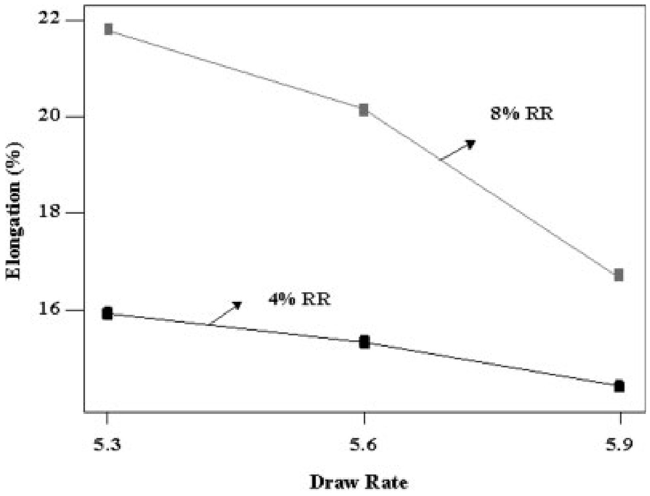

Figure 6 Plots of elongation values caused from the relationship between the draw rate and RR factor.

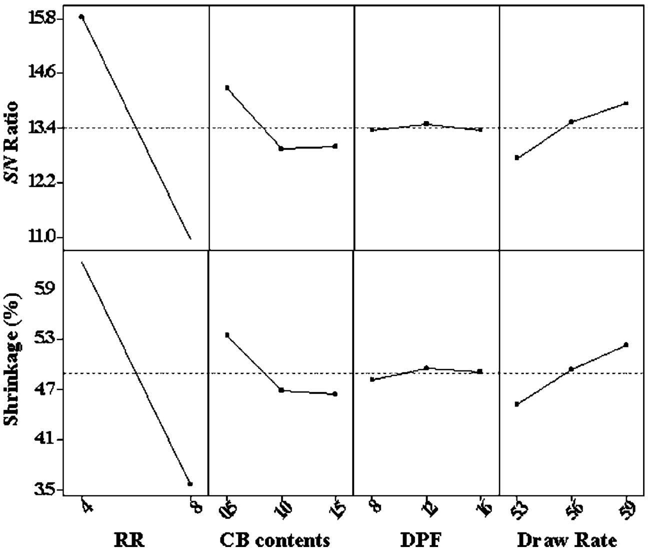

Figure 7 Response graph of the main effects for SN plots and mean shrinkage (%) according to each factor and its level.

Results on shrinkage

In the case of considering yarn's shrinkage under the yarn production, it can be mainly controlled by the godet rollers (GR) that are one of the biggest factors to the yarn's shrinkage. In this article, we cannot consider the GR factor because it makes a little influence on other properties of yarn such as tenacity, elongation, and color value.

Usually, the shrinkage value of yarn has to be controlled because the yarn may be treated under high temperature during after-finishing. The shrinkage value is shown to be strongly related to the RR from the results of Figure 7. Other factors have a little relation with the yarn's shrinkage. The shrinkage is also analyzed on the base of the correlation between the DR and the RR as shown in Figure 8. At a lower RR, the shrinkage value is much higher and influenced larger by raising the DR than at a high RR.

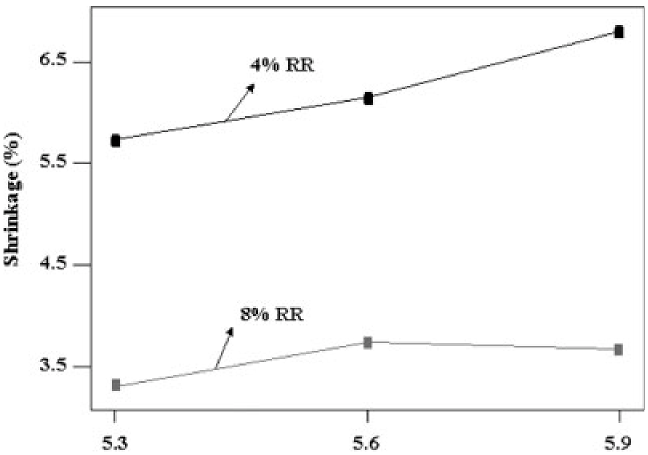

Figure 8 Plots of shrinkage values caused from the relationship between the draw rate and RR factor.

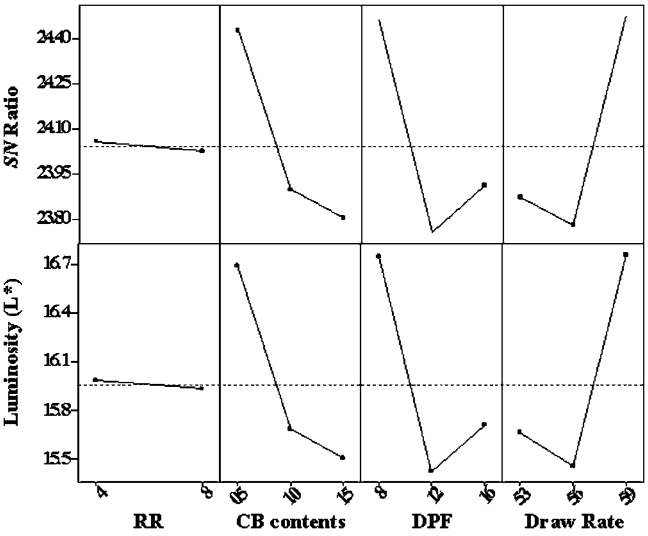

Figure 9 Response graph of the main effects for SN plots and mean luminosity (L^*) according to each factor and its level.

Results on luminosity of the colors (L^*)

The luminosity of the colors is strongly related to the factors of the CB, DPF, and DR, but not influenced by the RR factor. In a small range of CB contents in yarn, the CB particles can enhance the darkness of yarn colors. In the case of the DPF, there are less light scatters on yarn surface with bigger DPF so that the yarn's darkness may be deeper. Particularly, the higher DR gives the larger luminosity of the yarn color. As the DR becomes higher, the orientation of molecular chain is higher and crystal size inside the fiber is bigger so that the lights come to be easier to be reflected than to be absorbed on yarn

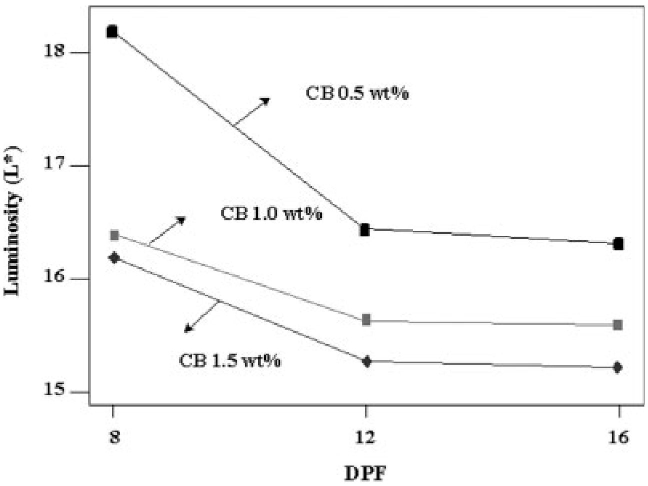

Figure 10 Plots of luminosity values caused from the relationship between DFP and CB contents.

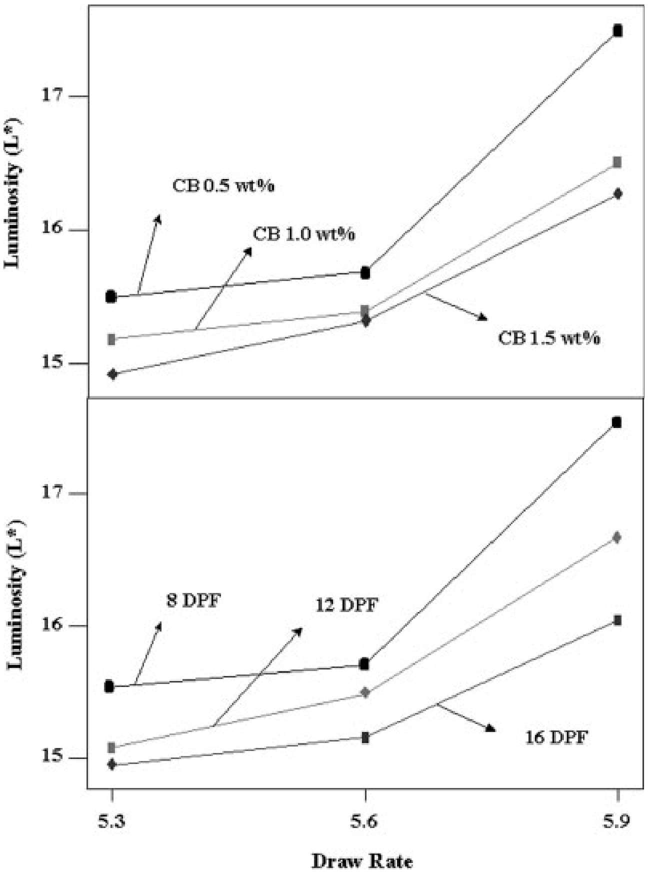

Figure 11 Plots of luminosity values caused from the relationship between DR and other factors.

surface,[13] which means that the luminosity value of yarn color is higher. It is necessary for the further study to interpret an accurate explanation of DR situation on color depth.

From the plot of SN ratio and mean luminosity (*L**) in Figure 9, there is not linear tendency of the luminosity in the stage from the DPF 12 to the DPF 16 and also from the DR 5.3 to the DR 5.6. These phenomena means that there may be interaction effects between (or among) the selected factors. To understand the detail situations, we have to consider the interaction effects or add more factors that may need much costs and times to be evaluated. In this study, however we did not analyze the interaction situation and only selected the four factors because the other physical property of the spun-dyed yarns was simply interpreted as analyzing the four factors excluding the interaction effects.

Figures 10 and 11 are obtained by separating all factors including the complex interaction (in Fig. 9) into both factor and the luminosity to analyze the relations between the two factors. As shown in Figures 10 and 11, the graph is plotted to explain the tendency of both *L** value and each factor. In these graphs, there is a linear trend between the DPF (and the DR) and the luminosity as not considering the interaction effects. With the graph of DR verse CB contents and DR verse DPF, the increase of CB contents and the big DPF make the yarn colors a deep black. The higher DR induces to be brighter color on yarn surface.

CONCLUSIONS

In this article, we have studied a process for optimizing the development of a spun-dyed yarn using the Taguchi method in which four factors are analyzed that influence the physical properties of yarn. For obtaining the designed yarn tenacity, which is one of the most important properties, we try to find the optimal operating conditions and minimize the variance of the results of yarn properties after optimization. We have examined the relationship between the yarn properties and controlled spinning processes using the Taguchi method. Through the Taguchi method, we can analyze the process conditions that may affect the yarn properties during spinning process and determine the main factors to affect the processes and experimental levels to minimize the number of experimental runs.

We conclude from this research that by using the Taguchi tool's processes for developing a spun-dyed yarn, we can determine the optimal variables during spinning process for obtaining a target property and be utilized the information that is the relationship between the yarn physical properties and the process parameters with the simple experiments.

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