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Improving the Quality of Combed Yarn Spun by OE Rotor Spinning Using the Grey-Taguchi Method

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Abstract
Open-end (OE) rotor spinning is a high-productive-efficiency as well as a space and energy saving method of producing combed yarns with better evenness, regularity and abrasion resistance, as well as a brighter shade and sharpness. However, the setting of process parameters decides yarn quality, which can be done only after accumulating experience involving tremendous cost, time and manpower. Firstly, the L9(3^4) orthogonal array is used to plan the process parameters that have an impact on OE rotor spinning. In this study, the experimental quality characteristics focused on are the strength and unevenness of combed yarns. Afterwards grey relational analysis is used to establish individual quality characteristics, the demerit of the Taguchi Method, and an optimal set of process parameters of multiple quality characteristics obtained from a response graph of the grey relational analysis. Moreover, a signal-to-noise ratio computation and analysis of variance (ANOVA) are conducted to evaluate the results of the experiments. Using ANOVA, the significant factors impacting the quality characteristics of combed yarns are obtained; that is, control over the preceding factors indicates valid control over the quality characteristics of combed yarns. Finally, the reliability and reproducibility are verified at a 95% confidence interval of the confirmation experiments.

Key words: *OE rotor spinning, combed yarns, fibre quality Taguchi method, grey relational analysis.*

Introduction

Due to the advantages of short and reduced processes, automation, a low breakdown rate, cost reduction, yarns produced with good quality, nice evenness, strong abrasion resistance, little impurity, better dyeability and brighter shades and sharpness, open-end (OE) rotor spinning is a high-productive-efficiency as well as a space and energy-saving method which increases the value of yarns. Moreover, the appearance of OE yarn is clean, smooth and even better than that of ring-spinning yarn. Therefore, its cost benefit is better than that of ring spinning [1 - 5]. This study employed mostly green fibre of the Lyocell type, whose changeable countenance comes from its unique strength. Through the combined advantages of natural and man-made fibres and the applicability of OE rotor spinning machinery to feed clean material matching adequate worsted-yarn conditions, 18.44 tex yarn was spun. Afterwards the employment of high quality woven and knitted fabrics was undertaken and the advanced use rate of OE rotor spinning machinery established.

Nevertheless, there are plenty of factors impacting the OE rotor spinning process. Yarn quality characteristics differ due to the diverse process parameters, such as fibre properties, the spinning speed and opening roller speed. Especially, during the alteration of cotton feeding, winding and drafting, the rotor speed will influence such properties as the strength and evenness of yarns. Furthermore, the rotor speed, feeding speed, winding speed, spinneret and spinning speed are also factors that affect the yarn process [6 - 9]. Generally speaking, the setting of optimal parameters for spinning yarns results from accumulated experience by the trial and error method, which lacks a systematic inheritance technique.

In view of the disadvantage of the conventional trial and error method, this study employed the Taguchi Method [10, 11] to resolve the difficulty. Furthermore, it gives optimal process parameters while maintaining quality stability.

The grey system theory proposed by Deng [12, 13] solves the problem of uncertainty arising from few data. Previously, the Taguchi Method has been used to analyse optimal process parameters of a single quality characteristic; therefore, Chen *et al.* [14] propose the integration of grey relational analysis and the Taguchi Method to resolve multiple quality characteristics. The method proposed can transform multiple quality characteristics into single grey relational grades. By comparing the grey relational grades, the arrays of respective quality characteristics are obtained in accordance with response grades to select an optimal set of process parameters.

Since there are two quality characteristics of combed yarns - strength and unevenness, this study employs the Taguchi Method and grey relational analysis to integrate multiple quality characteristics and obtain an optimised OE rotor spinning process for improving the quality of combed yarns.

Experimental

The setting of the process parameters of an OE rotor spinner so that the combed yarn has a high strength and evenness is very important. Trial and error has traditionally been used to experiment with processing conditions. However, this is time consuming and wastes money. Therefore, the present authors used TM and GRA to achieve an effect equivalent to that of a full factorial experiment while actually using a very small number of experiments and, at the same time, maintaining stable quality.

The signal-to-noise ratio (SN ratio) was then analysed to draw up a response

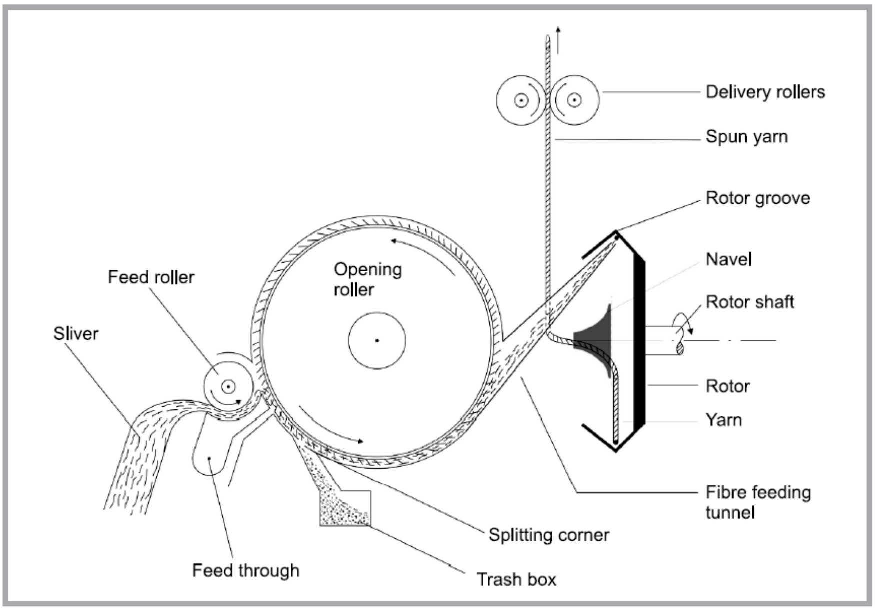

Figure 1. *OE rotor spinning components [5].*

graph. Analysis of variance (ANOVA) was used to assist in deciding the optimal processing parameters. Finally, based on the magnitude of each process parameter effect of the OE rotor spinner, a reasonable analysis and assessment were made. The material used was 100% Lyocell 1.3 dtex with a staple length of 38 mm; the opening roller speed was 8,000 r.p.m., the rotor diameter - 31 mm, the sliver weight - 3.9684 g/m, and the finished product was rotor OE yarn 18.44 tex.

The equipment used was an Uster Quick Spinning Frame. A cotton sample was spun by drawing using an Uster Quick Spin for OE yarn spinning. Practical data and results were rapidly obtained for cost reduction and as the basis of process parameter design and modification. The test was conducted according to CNS.

The yarn properties were assessed using the USTER TEST(yarn tester) and an Orientec Tensilon RTA-1T (strength tester). The strength of single yarn was tested according to CNS-11263. The tester interval was set at 20 cm and the speed at 200 mm/min.

Research method

OE rotor spinner

Compared to the ring spinning method, new open-end spinning is more business friendly. As regards the difference in the fibre structure method, the quality and characteristics of open-end spinning are mostly better than those of ring spinning. No doubt its economic conditions have become the mainstream for yarn. The term 'open-end' is named after the momentary break-end formed on the continuous way between the fibre bundle supplied by the front roller to the yarn. The basic principle is to produce a break in the scattered fibre flow and then connect fibre to the open end to twist into yarn.

An Open-End Spinning Frame is shown in ***Figure 1***, the principle of which is that the fibres after the opening function of the opening roller, through the centrifugal force of rotor rotation, are clustered at the wall of the rotor, to which is applied a twisting effect with rotor rotation. The fibres are then stripped to form a continuous run of new yarn to be sent out. The fibre bundles clustered at the wall of the rotor, before spinning at 100 to 300 times of doubling, can remove bad spots from the sliver, which is the main factor resulting in few open-end spinning spots, to obtain good uniformity. It is also helpful to lower the broken yarn rate in the subsequent warping and weaving processes; hence, the performance of weaving production is better than that of ring spinning. Moreover a different fibre structure will make the average strength value of open-end spinning about 10 ~ 20% lower than that of ring spinning. The way that open-end spinning forms the fibre arrangement is inclined towards mutual dependency, making the strength of the fibre constitution not entirely evident.

The dividing device of the opening roller separates the sliver fibre, which needs to be sent to a spinning body to continue spinning, the major function of which includes five regions as follows:

1. Supply area

A sliver of uniform density can be put into the feed roller with an average speed.

2. Dividing area

When the fibre group goes into opening roller, it will be opened by the card clothing on the opening roller and towed into fibre bundles. If there is a layer of thin fibres densely covered, this will form the best conditions; but if the opening function of the opening roller is too intense, the fibre continuity will be disturbed.

3. Delivery area

At this point, fibres are waiting to be stripped and separated, which is due to the fact that the fibres attached to the surface of needle tips are affected by the strong rotation of the centrifugal force of the roller and then easily separated.

4. Splitting area

After separation from the roller, fibres go into the splitting zone, which means fibres are not under the control of tips, and then enter straight line access. Fibre bundles are towed by two external forces in this area, that is, the centrifugal force and power of air pushes them forward, and fibres are naturally removed by the separators.

5. Air transport area

As a function of air, after splitting, fibres will be accelerated to go into the channel, the speed of which will be much larger than the tangential speed during splitting; at this time, fibre bundles will enter onto the collection surface and separator of the rotor.

The rotor is a unique twisting body whose scattered fibres form a group of dense fibres, after which they are quickly twisted into yarn. The internal part of the rotor is divided into the fibre feeding room and yarn forming space. Fibres enter the groove from a channel and then reach the collection surface of the yarn forming space; at this time, the motion amount of fibres is great, and the direction is transformed. When fibres reach the yarn spinning and twisting zone, at a safe distance from the collection surface, the fibres slip into a cone-shaped chute, and due to the impact of the centrifugal force and slope movement, the fibres display a log of spiral coil movement running along the chute wall.

Taguchi method

The main feature of the Taguchi Method is to plan experiments using orthogonal arrays and to find optimal sets of process parameters by main effect analysis. The orthogonal-array experimental design renders the designer the possibility of studying the impact of multiple controllable factors on the quality characteristic in a fast and economical way. Since the Taguchi Method can find the cause of those factors impacting the quality and obtain data of process parameters and quality improvement to find optimal sets of parameters, this study refers to the OE rotor spinning process for resolving the optimisation of process parameters and, hence, improving the quality and productive efficiency of combed yarns.

Grey relational analysis

In the analysis of OE rotor spinning process parameters, the relation between two quality characteristics and the targeted grades of combed yarns obtained by orthogonal arrays is studied using an adequate mathematic model. The primary task is to analyse the different qualities of combed yarns arising from respective process parameters and to realise the relation between the targeted and actual grades. This study employs grey relational analysis, as proposed by the grey theory. to find the relation between the targeted grades and the experimental quality characteristics of combed yarns obtained by orthogonal arrays [15]. Therefore grey relational analysis was adopted for this study to compare the relational grades between the reference sequence $x_0(k)$ and the comparative sequences of $x_1(k)$, $x_2(k)$, ..., $x_m(k)$.

Among these, the reference sequence stands for the maximum mean value of the strength as well as the minimum mean values of the unevenness obtained from the L_9 orthogonal array experiments, that is, X_0 = (0.379,5.17). The comparative sequences were the quality characteristics obtained from the L_9 orthogonal array experiments.

The computing steps of grey relational analysis are as follows [16]:

Step 1: Obtaining the average grade of the array

$$\text{Let } X'_i = X_i/x_i(1) = = (x'_i(1), x'_i(2), ..., x'_i(n)), \quad i = 0, 1, 2, ..., m \qquad (1)$$

Step2: Obtaining a different array

$$\Delta_i(k) = |x'_0(k) - x'_i(k)|, \quad \Delta_i = (\Delta_i(1), \Delta_i(2), ..., \Delta_i(n)), \quad i = 0, 1, 2, ..., m \qquad (2)$$

Step 3: Obtaining the maximal and minimal difference of the two levels

$$M = \max_i \max_k \Delta_i(k)k \qquad m = \min_i \min_k \Delta_i(k) \qquad (3)$$

Step 4: Obtaining a relational coefficient

$$\gamma_{0i}(k) = \frac{m + \zeta M}{\Delta_i(k) + \zeta}, \zeta \in (0,1), \quad k = 1, 2, ..., n; \; i = 1, 2, ..., m \qquad (4)$$

where ζ is the distinguishing coefficient; 0.5 is adopted for this study.

Step 5: Computing the relational grade

$$\gamma = \frac{1}{n}\sum_{k=1}^{n} \gamma_{0i}(k), \; i = 1, 2, ..., m \qquad (5)$$

By inputting the targeted grades of strength and evenness of combed yarns as the reference arrays, the relation between the former and the grades obtained in the L_9 orthogonal arrays, respectively, is computed. Afterwards main effect analysis is performed to obtain optimal sets of process parameters for combed yarns using the response graph.

Analysis of variance

The experimental data obtained by the Taguchi Method must be processed by ANOVA to achieve a complete result. The 2 major objectives of ANOVA are the assessment of the experimental bias and the test of the importance. Using ANOVA, the impact of control factors on experimental bias is separated impersonally; the respective factorial importance is indicated by quantitative grades to ensure no leakage of key factors, thereby increasing the accuracy of predictions.

Confirmation experiments

In ANOVA there is an assessment standard for selected control factors in the OE rotor spinning process. Therefore, by using response arrays and the response graph, a factorial set for improvement is predicted for the confirmation experiments. The result is observed to be in the confidence interval. Furthermore, in the verification, there is the rationality of the mathematic pattern constructed by experimental data obtained from the orthogonal-array experiment. Meanwhile, based on the grades of the optimal factorial level combination obtained, the additive pattern is used to predict the signal-to-noise (SN) ratio under optimal conditions. The computing formula is as follows:

$$\hat{SN} = \overline{T} + \sum_{i=1}^{n}(F_i - \overline{T}) \qquad (6)$$

where $\overline{T}$ is the total mean of the SN ratio and F_i - the significant factorial level grade of the SN ratio.

The confidence interval of the confirmation experiments is

$$CI = \sqrt{F_{\alpha;1,v_2} \times MSE \times \left(\frac{1}{n_{eff}} + \frac{1}{r}\right)} \qquad (7)$$

where $F_{\alpha;1,v_2}$ is the F value of the significant level α, α - the significant level, 1-α - the confidence level, v_2 - the free degree of the combined mean-square error, MSE - the combined mean-square error, n_{eff} - the valid observing grade, and r is the confirmed experimental frequency, $r \neq 0$.

Finally, a 95% confidence interval (CI) is used to verify the validity of the predicted mean, the formula for which is

$$\hat{SN} - CI \le \mu \le \hat{SN} + CI \qquad (8)$$

where μ is the average value of the confirmation experiments.

Results and discussion

Prior to the experiment, it was necessary to accept the control factors and their respective levels. Accordingly, four control factors i.e. the rotor speed, output speed, drafting roller speed and feeding speed were selected. Moreover, the quality characteristics are the strength and unevenness per yarn. Afterwards, other level grades of the quality variation of combed yarns were located by actually running the OE rotor spinning process to find an adequate process range. Finally, the control factors and level grades decided are shown in ***Table 1***. Due to the maximal

Table 1. *Combinations of control factors and levels.*

Control factor	Unit	Level 1	Level 2	Level 3
A. Rotor speed	rpm	55,000	60,000	65,000
B. Output speed	m/min	80	85	90
C. Drafting roller speed	m/min	85	90	95
D. Feeding speed	m/min	0.3	0.4	0.5

Table 2. Experimental results with four control factor.

Experimental no.	Factors with levels				Strength		Unevenness	
	A	B	C	D	Average, N	SN ratio, dB	Average, %	SN ratio, dB
1	1	1	1	1	0.0372	-8.755	15.255	-23.668
2	1	2	2	2	0.0386	-8.420	14.330	-23.125
3	1	3	3	3	0.0332	-9.850	15.845	-23.998
4	2	1	2	3	0.0290	-10.958	14.900	-23.464
5	2	2	3	1	0.0329	-9.867	18.385	-25.289
6	2	3	1	2	0.0352	-9.264	17.610	-24.915
7	3	1	3	2	0.0303	-10.555	14.090	-22.978
8	3	2	1	3	0.0283	-11.153	13.865	-22.838
9	3	3	2	1	0.0311	-10.308	17.155	-24.688

strength of combed yarns expected, the larger-the-better (LTB) is selected; likewise, due to the minimal unevenness of combed yarns expected representing the maximal evenness, the small-the-better (STB) is selected. The SN ratios of LTB and STB are shown below, respectively,

$$\eta_{LTB} = -10\log(\sum(1/y^2)/n)$$

$$\eta_{STB} = -10\log(\sum y^2/n)$$

where η_{LTB} is the SN ratios of strength, η_{STB} - the SN ratios of unevenness, y - the value of experimental observations, and n is the number of experiments. Based on ***Table 1***, selected control factors and level grades are used in $L_9(3^4)$ orthogonal arrays as the experimental base. Then according to the orthogonal arrays planned, experiments were carried out for nine groups, five times per group. Experimental data were collected to compute the SN ratio, the results of which are shown in ***Table 2***.

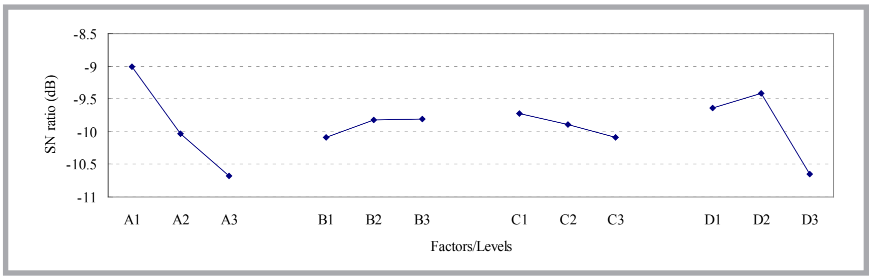

Figure 2. *Response graph for optimum strength.*

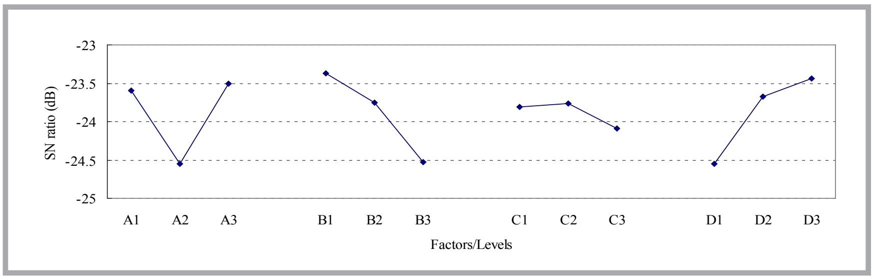

Figure 3. *Response graph for optimum unevenness.*

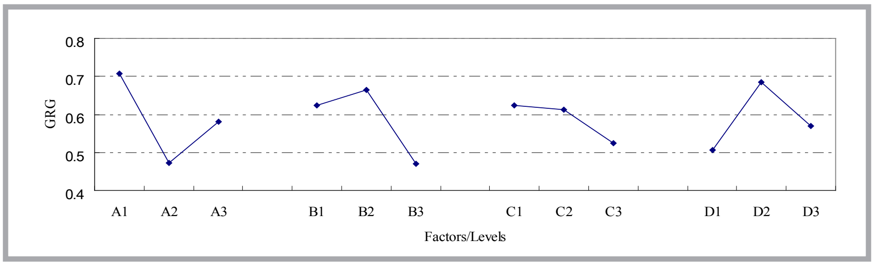

Figure 4. *Response graph for mean grey relational grades.*

By employing the SN ratio in ***Table 2***, we can compute the main effect grades in accordance with equations (1) and (2) of the main effect analysis and make a response graph thereon, as shown in ***Figures 2*** and ***3***. The optimal sets of process parameters for the strength of combed yarns are A1, B3, C1, and D2, i.e. a rotor speed of 55,000 r.p.m., an output speed of 90 m/min, a drafting roller speed of 85 m/min, and a feeding speed of 0.4 m/min. The optimal sets of process parameters for the unevenness of combed yarns are A3, B1, C2, and D3., i.e. a rotor speed of 65,000 r.p.m., an output speed of 80 m/min, a drafting roller speed of 90 m/min, and a feeding speed of 0.5 m/min.

In addition, the ANOVA analytic table obtained using the SN ratio in ***Table 2*** is shown in ***Table 3. Table 3*** indicates that factors B and C impact the strength of combed yarns less, therefore they are listed as pooled errors; however, as the resalts of the F-test of control factors A and D is larger than 4 which indicatesa larger effect thereof, the factors considered can be accepted as significant factors. The significant factors of the unevenness of combed yarns are B and D; that is, the control over preceding significant factors represents valid control over the strength and unevenness of combed yarns.

Owing to concerns regarding the strength and unevenness of combed yarns, this study employs grey relational analysis to conduct an analysis of optimal sets of this process parameter. ***Table 2*** indicates the maximal grade of the strength and the minimal grade of the unevenness of combed yarns as the reference array; that is, $X_0 = (0.379, 13.865)$. ***Table 4*** indicates different arrays of reference and orthogonal arrays, the grey relational coefficient and relational computing results. Then a response graph of the grey relational analysis is obtained by main effect analytic computation, as shown in ***Figure 4***. The response graph indicates the optimal factorial sets: A1, B2, C1, and D2., i.e. a rotor speed of 55,000 r.p.m., an output speed of 85 m/min, a drafting roller speed of 85 m/min, and a feeding speed of 0.4 m/min.

After optimal sets of process parameters for combed yarns had been obtained by grey relational analysis, confirmation experiments were conducted. According to equations (8), (9) and (10), the 95%

*Table 3. ANOVA of strength/unevenness for the $L_9(3^4)$ design in Table 2; * The pool-up terms.*

Factors	Degrees of freedom	Sum of squares	Variance	F-test
A	2/2	4.223/2.041*	2.112/-	23.620/-
B	2/2	0.156*/2.111	-/1.056	-/1.893
C	2/2	0.202*/0.190*	-/-	-/-
D	2/2	2.614/2.068	1.307/1.034	14.623/1.854
Pooled error	4/4	0.358/2.231	0.089/0.558	
Total	8/8	7.196/6.410		

Table 4. Differential sequences, grey relational coefficients and grades.

No.	$\Delta_{0,i}(1)$	$\Delta_{0,i}(2)$	$\gamma_{0,i}(1)$	$\gamma_{0,i}(2)$	$\gamma_{0,i}$
1	0.0369	0.1003	0.8017	0.5978	0.6997
2	0	0.0335	1	0.8166	0.9083
3	0.1398	0.1428	0.5157	0.5104	0.5130
4	0.2507	0.0746	0.3723	0.6664	0.5194
5	0.1478	0.3260	0.5019	0.3131	0.4075
6	0.0897	0.2701	0.6243	0.3550	0.4896
7	0.2164	0.0162	0.4074	0.9021	0.6547
8	0.2665	0	0.3581	1	0.6790
9	0.1953	0.2373	0.4324	0.3852	0.4088

Table 5. Comparison of performances at three different conditions.

Performances	Conditions		
	Optimum strength A1B3C1D2	Optimum unevenness A1B1C1D3	Grey-Taguchi Method A1B1C1D1
Strength, N	0.0397	0.0354	0.0411
Unevenness, %	13.85	13.19	12.51

confidence intervals for the strength and unevenness of combed yarns are

$$-9.213 \le \mu_{confirmation} \le -7.823 \text{ and}$$

$$-27.230 \le \mu_{confirmation} \le -20.540,$$

respectively. Through five confirmation experiments, the SN ratio means of the strength and unevenness of combed yarns obtained were -8.963 dB and -21.945 dB, respectively, both within the confidence interval, indicating the reproducibility of the factorial effect and the reliability of the results of the experiments. Moreover, the strength per OE yarn spun in this study is much better than the assessment standard for combed yarns - CNS-6379. Finally, the optimal sets of process parameters obtained, ***Figures 2*** to ***4***, are compared. ***Table 5*** demonstrates that the single quality characteristic obtained by the Taguchi Method merely renders either better strength or less unevenness; nonetheless, the optimal sets of process parameters obtained by the grey-Taguchi method do render a robustness to both the strength and unevenness thereof.

Conclusions

This study integrates grey relational analysis and the Taguchi Method to find optimal conditions for the process parameters of combed yarns with minimal experimental frequency. The response graph obtained by grey relational analysis indicates optimal process conditions for OE rotor spinning as follows: a rotor speed of 55,000 r.p.m., an output speed of 85 m/min, a drafting roller speed of 85 m/min, and a feeding speed of 0.4 m/min. ***Table 3*** demonstrates that the significant factors impacting the strength of combed yarns are the rotor speed and feeding speed, whereas the significant factors affecting the unevenness of combed yarns are the drafting roller speed and feeding speed. After five confirmation experiments, it can be stated that the experimental means of the strength and unevenness of combed yarns are within the 95% confidence interval, proving the experimental results are reproducible, the significant factorial selection is adequate, and the experiments are reliable. This study proves that the employment of grey relational analysis and the Taguchi Method is able to successfully obtain optimal process conditions for combed yarns in OE rotor spinning. Likewise, the integration of grey relational analysis and the Taguchi Method is applicable for the optimisation of process parameters in other processes, helping to improve process efficiency.

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