Manufacturing a ring spun slub yarn using multi-channel drafting technique

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Abstract
In this paper, we propose a novel method for manufacturing a ring-spun slub yarn through multi-channel drafting using a computer numerically controlled (CNC) ring spinning frame. Through controlling the speeds of the feeding rollers, the apron rollers and the spindle, we can manipulate the blending ratio, linear density and twist of the spun yarn online, offering more degrees of freedom to configure fibers in the spun yarn. Furthermore, we develop a digital control system in conjunction with a CNC ring spinning machine, in which each CNC ring spinning machine serves as a drone machine that receives commands from a central computer. A self-developed management platform is designed to help the client manage these drone machines via online regulation. At last, a series of experiments are conducted to examine the impact of manufacturing parameters on the structures and properties of slub yarn. We found that the descriptive parameters that affect the breaking force of the slub yarn samples are the slub length, slub distance, slub multiplier, and roving ratio. The parameters that affect the breaking elongation are obtained as the slub length, slub distance, slub multiplier, and twist coefficient.

Keywords
Linear fiber assembly, CNC ring spinning, linear density, three-channel spinning, multifunctional textiles

Introduction
The fiber configuration is critical for the properties of composite yarn, such as color appearance. As such, the manufacturing methods are expected to provide more flexibility to configure the fibers in composite yarns. Ring spinning and rotor spinning are the two most widely used methods for manufacturing yarns. However, the blending ratio and linear density of the yarn are conventionally fixed in both methods, making them less useful for fabricating color blended spun yarns. Recently, progress has been achieved in rotor spinning and ring spinning by incorporating computer numerically controlled (CNC) systems into spinning machines,1–3 thereby increasing the flexibility of yarn production. However, extensive experimental and analytical studies on CNC ring spinning machines, especially regarding the relationship between the manufacturing parameters and the yarn properties, have not been carried out yet.

Slub yarn is a type of fancy yarn by periodically changing yarn’s linear density during the spinning process,4 which brings the attractive appearance and aesthetic characteristics into fabrics due to intentionally induced irregular physical characteristics.5–7 The slub length plays a
crucial role in yarn twist and is therefore important to the mechanical strength and physical properties of the slub yarn. In addition, the twist distribution of slub yarn is inversely proportional to the square of the linear density of slub yarn. Furthermore, the slub yarn’s appearance is controlled by the structural parameters, in which the slub length is associated with the yarn count, the slub thickness and the performance of servomotor. However, in the conventional approach, the base yarn and slubs share the same drafting channel, which greatly limits the aesthetic characteristics of slub yarn. The emergence of a multi-channel ring spinning approach has opened up a new path for manufacturing fancy yarn by employing three independent feeding rollers which can regulate not only the yarn’s linear density but also the color blending effect in different sections of slub yarn, enhancing the attractiveness and appearance of the fabric.

In this study, we developed a prototype CNC ring spinning system to control the speeds of the feeding rollers. Currently, we have three US patents, including No. 10,316,434 B2, No. 10,316,435 B2, and No. 10,316,436 B2, issued on this invention. Through numerical technology, the speeds of the feeding, middle, and apron rollers and the spindle can be adjusted by a programmable logic controller (PLC) to tune the linear density, blending ratio and twist of slub yarns online. In particular, we fabricated slub yarns with controllable slub and base yarn lengths as well as their colors. Then, we carried out a series of experiments to study the relationship between the manufacturing parameters and yarn properties. Our work offers a new way of producing ring-spun slub yarns that can be used for eco-friendly multi-colored textiles.

**Formulation and manufacturing process of ring-spun slub yarn**

**CNC system**

The as-developed seven-axis CNC ring spinning machine can realize variable drafting by the uneven feeds of rovings regulated by the five independent servomotors. By changing the drafting ratios of three rovings, it can manipulate the linear density and blending ratio of yarns. The drive system comprises five servomotors designed as a nested structure, as shown in Figure 1. Servo motor drives the apron roller, and servo motor drives the middle roller. Servo motors drive the three feeding rollers. The five servomotors are independent of each other, and therefore, the rovings are fed to the three feeding rollers and their drafting ratios can be manipulated separately in various ways. The system response time is 0.001 s. When compared to older drive systems that rely on cams, ratchet mechanisms, twist change wheels, gears of changing winding density and drafts to feed and draft the rovings, the new drive system offers several advantages, such as dynamic regulation of the blending ratio and linear density of yarns given by five independently controlled servomotors.

After receiving the parameter information, the PLC executes commands to control the operational speeds of the apron, middle, and feeding rollers. The servomotor rotates according to a set of user-specified rules, and the photoelectric encoder sends the real-time running parameters to the PLC. The PLC compares the measured rotor speed with the preset speed. If the deviation exceeds a fixed threshold value, the system sends the modified
frequency to the frequency converter according to the PID algorithm\textsuperscript{9,10} to adjust the rotor speeds to realize precise rotor motion.

A CNC ring spinning system can be further integrated into the digital control system, in which each CNC ring spinning system serves as a drone node that receives commands from a remote control or a local control system. A photograph and schematic diagram of the CNC ring spinning system are provided in Figure 2(b) to (d). We also built a miniature version of a digital factory in our lab, which combines a CNC ring spinning system with a digital control system, as shown in Figure 2(a). A central industrial computer is used to control each drone machine PLC. The operation information of each drone is collected, and the data are subsequently uploaded to a cloud server. A self-developed management platform provides an interface for the client to access the cloud server. By logging into the central industrial computer, the client can set up the initial parameters for the CNC spinning ring machine and manage the system by collecting real-time operating parameters and analyzing the operational status, which enables the client to control and manage the cost, thus offering a competitive advantage to the products. Screenshots of the self-developed management platform are provided in Figure 3(a) and (b). Such a combination of the servo motor, frequency converter, photoelectric encoder, PLC, cloud server, and management platform forms a closed-loop system, enabling on-the-fly control of

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{(a) A schematic of the digital factory that combines a CNC ring spinning system with a digital control system. (b) and (c) A photograph and a schematic, respectively, of the three-channel CNC ring spinning device. 1–3: rovings; 4–6: feeding rollers; 7: middle roller; 8: rubbing apron; 9: apron roller; 10: delivery roller; 11: condenser. \( V_f \) and \( V_m \) denote the feeding speeds of the apron and middle rollers, respectively, and \( V_{b1}, V_{b2}, \) and \( V_{b3} \) denote the speeds of the three feeding rollers. (d) Illustrates the formation of a spun yarn using a three-channel CNC ring spinning system.}
\end{figure}
Table 1. Production modes of the three-channel CNC ring spinning machine. M (magenta), Y (yellow), and C (cyan) represent the different colored cotton rovings that are fed into feeding rollers.

| Combination of channels | Number of production modes |
|-------------------------|-----------------------------|
| M, Y, C                 | 3                           |
| M + Y, M + C, C + Y     | 3                           |
| M + Y + C               | 1                           |

each roller and spindle and access to the operational parameter values. When a fault occurs, it is immediately identified by an alarm signal, and the faulty operation condition is automatically detected, thereby significantly improving production efficiency, product quality, and productivity.

Control of yarn structures

Three rovings of linear densities $\rho_{b1}$, $\rho_{b2}$, and $\rho_{b3}$ are fed into three feeding rollers with speeds $V_{b1}$, $V_{b2}$, and $V_{b3}$. The rovings form the spun yarn after going through drafting, gathering, twisting, and winding steps. The three-channel ring-spinning machine relies on the differences in speeds between the feeding rollers and the apron roller to form three independent drafting channels to control the blending ratio, linear density, and twist of the yarn. We can choose one feeding roller or two feeding rollers or three feeding rollers to feed the rovings. As such, there are seven production modes based on the combination of drafting channels, as listed in Table 1.

The feeding speeds of the middle and apron rollers are assumed to be $V_m$ and $V_f$, respectively. The yarn linear density can be expressed as

$$\rho = \frac{\sum_{i=1}^{3} \rho_{bi} e_i}{\sum_{i=1}^{3} V_{bi}} = \frac{\sum_{i=1}^{3} V_{bi} \times \rho_{bi}}{V_f}$$  \hspace{1cm} (1)

$$e_i = \frac{V_f}{V_{bi}}$$  \hspace{1cm} (2)

where $e_1$, $e_2$, and $e_3$ are the total drafting ratios for the three rovings.

The blending percentage of the roving is

$$k_r = \frac{\rho V_{bi}}{\sum_{i=1}^{3} \rho_{vi} V_{bi}}$$  \hspace{1cm} (3)

It can be seen from equations (1)–(3) that changing the speeds of the feeding and apron rollers changes the linear density of the spun yarn and the blending and drafting ratios of the rovings.

The yarn twist can be written as
Figure 4. Schematic drawings of the color blended slub yarns with (a) Single-component slubs and base yarns. (b) Two-component slubs composed of alterable segments. (c) Two-component slubs and base yarns composed of alterable segments. (d) Three-component slubs composed of alterable segments. (e) Three-component slubs and base yarns composed of alterable segments. (f) Three-component slubs composed of alterable segments and variable compositions. (g) Shows a photograph of a color blended slub yarn with the schematic of the structure demonstrated in (b). The upper panel shows an enlarged view of the slubs and base yarns. The bottom panel shows a zoomed-out view of the overall look of the color blended slub yarn. The photographs of other structures are provided in Supplemental Materials.

Manufacturing process of the ring-spun slub yarn

Figure 4 shows photographs and schematic drawings of slub yarns made out of the 100% combed cotton blends of different colors. The uniformity ratio, length, and strength of cotton fiber are 45.2%, 27.1 mm and 22.3 cN/tex. The raw cotton was transformed into roving by going through the conventional opening, blending and combing.\(^\text{13}\) The unevenness CV\(_m\) of the roving was obtained as 3.19%.

To realize the variable linear densities along the yarn axis, the speeds of the feeding rollers are adjusted to a certain extent, that is, \(V_1' = V_1 + \Delta V_1\), periodically. The linear density of a slub yarn can be written as

\[
\rho' = \rho_{\text{roving}} + \Delta \rho = \frac{\sum_{i=1}^{3} \frac{\rho V_f}{V_{bi} + \Delta V_{bi}}}{V_d}
\]  

(5)

where \(\rho'\) is the linear density of the slub yarn; \(\rho\) is the linear density of roving, and in this study we use the same linear densities for the three rovings; \(\rho_{\text{roving}}\) is the linear density of the base yarn; \(\Delta \rho\) is the yarn linear density variation.

For manufacturing the double-component slub yarn, the rovings are fed into two of the three feeding rollers and subjected to two different drafting ratios. The linear density of slub yarn is written as

\[
\rho' = \frac{\rho V_f}{V_{b1} + \Delta V_{b1}} + \frac{\rho V_f}{V_{b2} + \Delta V_{b2}} + \frac{\rho V_f}{V_{b3} + \Delta V_{b3}}
\]  

(6)

If \(V_{b3}\) is zero, the yarn structure shown in Figure 4(b) is produced. If none of \(V_{b1}, V_{b2}, \Delta V_{b1}\) and \(\Delta V_{b2}\) is zero, the yarn structure shown in Figure 4(c) is produced.

For manufacturing the three-component slub yarn, the rovings are fed into the three feeding rollers and subjected to three different drafting ratios. The linear density of slub yarn is written as

\[
\rho' = \frac{\rho V_f}{V_{b1} + \Delta V_{b1}} + \frac{\rho V_f}{V_{b2} + \Delta V_{b2}} + \frac{\rho V_f}{V_{b3} + \Delta V_{b3}}
\]  

(7)

If both \(V_{b1}\) and \(V_{b2}\) are zero, the yarn structure shown in Figure 4(d) is produced. If none of \(V_{b1}, V_{b2}, \Delta V_{b1}\) and \(\Delta V_{b2}\) is zero, the yarn structure shown in Figure 4(e) is produced.

The climate conditions were 23°C to 30°C and 53% to 58% Rh. throughout the production of slub yarn. The base yarn count is 19.4 tex. The spindle speed is 7020 r/min. The slub yarn samples were produced by using a ring spinning frame with 396 spindles, which were modified based on FA506 ring spinning frame.\(^\text{12,14}\)

Materials and method

Measurements and mechanical tests

A YG068C fully automatic single yarn strength tester (su zhou changfeng textile mechanical and electrical technology co., LTD, China) was used to measure the strength and breaking elongation of the yarn according to GB/T14344. For our experiment, the clamp length was 500 mm. The stretching speed was set as 500 mm/min. The pretension was set as 0.5 cN/tex. Eight cops were took as measuring samples. For each cop, the strength and breaking elongation of yarn were measured 20 times, and the average breaking strength and breaking elongation for all samples were obtained. All samples were placed under the standard room condition (65 ± 2% RH and 20 ± 2°C) for at least 48 h before the test.

The slub length and slub distance were measured with a Codman\(^\text{®}\) disposable 20 cm ruler to an accuracy of 0.1 cm. A yarn sample was placed on a black surface without tension. The beginning and endpoints of the slubs can be easily recognized due to the distinct colors of slubs and base
yarns. The lengths were measured by the ruler. We used eight cops to collect samples. For each cop, the slub length and slub distance were measured twenty times, and the average slub length and slub distance for all samples were obtained. To obtain the twist of slub yarn, a section of slub yarn, including the slub and the base yarn, was selected for measurement, in which the base yarn length was set to be 30, 25, and 20 cm, respectively, and the yarn twist was measured for each case. A conventional twist tester was used to determine yarn twist by the untwist/re-twist method, and the average yarn twist for all samples was obtained.

Due to the dramatic difference in the linear densities between the slub and the base yarn, the manufacturing parameters that are the most important to the formation of slub yarns are the slub length, the slub distance, which is the length from the end of a previous slub to the start of the subsequent slub, and the slub multiplier, which is defined as

\[ R = \rho_{\text{slub}} / \rho_{\text{base yarn}} \]  

(8)

where \( \rho_{\text{slub}} \) and \( \rho_{\text{base yarn}} \) are the linear densities of the slub and the base yarn, respectively.

We used the manual method to determine the slub multiplier. A total of 160 different samples from eight cops were collected, and the slub and base yarn sections excluding ramp sections were cut into many parts. The total length of parts for any sample is over 1 m. A precision balance with a 0.01 mg sensitivity was used to measure the weights of slubs and base yarns, and the average counts for slubs and base yarns of all samples were obtained. Finally, the slub multiplier was calculated according to equation (8). For measuring the yarn count, 10 skeins from each sample were wrapped by a wrapping reel. The skeins were weighted by a precision balance with a 0.01 mg sensitivity, and then the average counts of all samples were obtained.

The roving ratio, that is, the ratio between different colored rovings, is defined as

\[ R' = k_i / k_j \]  

(9)

where \( k_i \) and \( k_j \) are the blending percentages of two different colored rovings. In our case, the samples were prepared by feeding rovings via three drafting channels. The ratio between the three rovings was \( k_1:k_2:k_3 \) \( (k_1=k_2) \), and the third roving (yellow) was used to generate slubs, whereas the first and second rovings (cyan) were used to generate the base yarns. The schematic and photograph of the as-prepared slub yarn are shown in Figure 4(b) and (g). In the following sections, we adopt a simpler way of representing the base yarn part, in which the two rovings of the base yarn are treated as the same one; therefore, \( k_i:k_2:k_3 \) can be simplified as \( (k_1+k_2):k_3 \). It is reasonable to adopt such representation since the two rovings of the base yarn are made out of the same cotton. In addition, the two drafting channels for producing the base yarn part possess the same drafting and blending percentages; therefore, there is no difference between the two rovings during the production of base yarns.

**Experimental design**

In order to examine the manufacturing performance of the three-channel CNC ring-spinning frame, we measured the slub length, slub distance, and slub multiplier and estimated their deviations from the theoretical values. Tables 2 and 3 summarize the manufacturing parameters and the measured values used in this study, respectively. Furthermore, we analyzed the relationship between the manufacturing parameters and the mechanical properties, that is, breaking force and breaking elongation, of the yarn. Table 4 summarizes the theoretical values of five manufacturing parameters that may affect the mechanical properties of slub yarn. These descriptive parameters are independent variables, whereas the breaking force and breaking elongation are dependent variables as shown in Table 5. The analysis was conducted by repeatedly varying one manufacturing parameter at a time while holding the others fixed. The set of fixed values described here correspond to the serial no. 3 in Table 4. Furthermore, analysis of variance (ANOVA) was performed to evaluate the statistical significance of the yarn parameters on the mechanical properties of yarn, based on 2\(^6\) full factorial design method using the Design Expert 12 software. Each factor has two levels. There are 32 combinations of parameter values in the design matrix. Accordingly, 32 different samples of slub yarn were produced. Besides this, the flat yarn samples (19.4 tex) were produced to compare with the slub yarn samples.

**Results and discussion**

**Slub length, slub distance, and slub multiplier**

The actual slub lengths are larger and the actual slub distances are smaller than the theoretical values, as shown in Tables 2 and 3 possibly because at the end of each slub production cycle, it took more time to stop the movement of fiber strands held by the nip of the apron rollers due to the inertia of the fibers, which produced longer-than-usual slubs in the slub yarn. In the measurement, the average slub length deviation was obtained as 4.2% at the lower level and 13% at the higher level of the slub distance. The average slub distance deviation was obtained as 1% at the lower level and 2% at the higher level of the slub distance. In the literature, it has been concluded that a deviation of about 10 mm is normal for the slub distance and slub length. Therefore, we concluded that there is no problem with the deviation levels.

The slub length approached the theoretical value when it became longer because the drafting ratio decreased as slub length increased; consequently, the fiber bundles experienced fewer drafting forces in the main drafting
Table 2. Theoretical values of manufacturing parameters for the color blended slub yarns.

| Serial no | Time periods for one production cycle of slubs (s) | Slub length (cm) | Slub distance (cm) | Slub multiplier | Spindle speed (r/min) | Twist (TPI) |
|-----------|--------------------------------------------------|-----------------|-------------------|-----------------|-----------------------|-------------|
| 1         | 0.5                                              | 5.1             |                   |                 |                       |             |
| 2         | 0.7                                              | 7.2             | 41.1              | 1.5             | 7020                  | 1.65        |
| 3         | 0.9                                              | 9.3             |                   |                 |                       |             |
| 4         | 0.5                                              | 5.1             |                   |                 |                       |             |
| 5         | 0.7                                              | 7.2             | 41.1              | 2.0             | 7020                  | 1.65        |
| 6         | 0.9                                              | 9.3             |                   |                 |                       |             |
| 7         | 0.5                                              | 5.1             |                   |                 |                       |             |
| 8         | 0.7                                              | 7.2             | 41.1              | 2.5             | 7020                  | 1.65        |
| 9         | 0.9                                              | 9.3             |                   |                 |                       |             |
| 10        | 0.5                                              | 5.1             |                   |                 |                       |             |
| 11        | 0.7                                              | 7.2             | 41.1              | 3.0             | 7020                  | 1.65        |
| 12        | 0.9                                              | 9.3             |                   |                 |                       |             |

Table 3. Actual manufacturing parameters and the deviations from their theoretical values.

| Serial no | Time periods for one production cycle of slubs (s) | Slub length (cm) | Slub length deviation (%) | Slub distance (cm) | Slub distance deviation (%) | Slub multiplier | Slub multiplier deviation (%) |
|-----------|--------------------------------------------------|-----------------|---------------------------|-------------------|----------------------------|-----------------|-------------------------------|
| 1         | 0.5                                              | 5.91            | +13.0                     | 40.33             | -2.0                       |                 |                               |
| 2         | 0.7                                              | 7.92            | +9.2                      | 40.43             | -1.8                       | 1.40            | -7.1                          |
| 3         | 0.9                                              | 9.99            | +7.4                      | 40.39             | -1.9                       |                 |                               |
| 4         | 0.5                                              | 5.82            | +12.0                     | 40.49             | -1.6                       |                 |                               |
| 5         | 0.7                                              | 7.83            | +8.2                      | 40.50             | -1.6                       | 1.88            | -6.4                          |
| 6         | 0.9                                              | 9.90            | +6.6                      | 40.45             | -1.7                       |                 |                               |
| 7         | 0.5                                              | 5.76            | +11.0                     | 40.55             | -1.5                       |                 |                               |
| 8         | 0.7                                              | 7.82            | +8.1                      | 40.50             | -1.6                       | 2.36            | -5.9                          |
| 9         | 0.9                                              | 9.87            | +6.3                      | 40.51             | -1.6                       |                 |                               |
| 10        | 0.5                                              | 5.54            | +7.2                      | 40.77             | -0.9                       |                 |                               |
| 11        | 0.7                                              | 7.57            | +5.0                      | 40.74             | -1.0                       | 2.85            | -5.3                          |
| 12        | 0.9                                              | 9.66            | +4.2                      | 40.70             | -1.1                       |                 |                               |

Table 4. Theoretical values of manufacturing parameters in the mechanical testing experiments.

| Serial no | Twist coefficient | Roving ratio | Slub multiplier | Slub length (cm) | Base yarn length (cm) | Total draft | First roving | Second roving | Third roving | Main draft |
|-----------|-------------------|--------------|----------------|------------------|-----------------------|-------------|--------------|---------------|--------------|------------|
| 1         | 300               | 70 (35:35):30| 1.5            | 3                | 10                    | Base yarn   | 57.73        | 57.73         | 24.74        | 22.49      |
| 2         | 320               | 60 (30+30):40| 2.0            | 6                | 20                    | Base yarn   | 43.29        | 43.29         | 24.74        | 22.49      |
| 3         | 340               | 50 (25+25):50| 2.5            | 9                | 30                    | Base yarn   | 34.63        | 34.63         | 24.74        | 22.49      |
| 4         | 360               | 40 (20+20):60| 3.0            | 12               | 40                    | Base yarn   | 28.86        | 28.86         | 24.74        | 22.49      |
| 5         | 380               | 30 (15+15):70| 3.5            | 15               | 50                    | Base yarn   | 24.74        | 24.74         | 24.74        | 22.49      |

zone, thereby reducing the number of fibers that fed into the apron roller. Under the same slub multiplier, the increase in slub length did not affect the slub distance significantly because the amount of fibers that fed into the apron roller is proportional to the drafting ratio, and as such, increasing the slub length reduced the drafting ratio,
as mentioned above, which accordingly reduced the number of fibers that fed into the apron roller.

The actual slub multiplier is smaller than the theoretical value because a ramp section is generated during the slub production, as shown in Figure 4(a). Consequently, the actual length of the slub is less than expected, which decreases the actual linear density of the slub. In addition, the average count deviation is obtained as 4.3% for the color blended slub yarn, while it is 1.1% for the flat yarn samples, which is consistent with the previous work.\textsuperscript{15} The means of the twist deviations are 3.4 TPI for slub yarns and 18.1 TPI for flat yarns.

**Relationship between manufacturing parameters and mechanical properties**

**Effect of slub multiplier on mechanical properties of slub yarn.** Figure 5(a) and (b) show that both the breaking force and the breaking elongation increase with an increase in the slub multiplier. However, they evolve significantly slower once the slub multiplier is greater than 3. An increase of the slub multiplier causes twist transfer from the slubs to the base yarn.\textsuperscript{17} The twist transfer enhances the mechanical strength of the ramp section between the base yarns and the slubs. However, it also weakens the intertwining of the fiber strands in the slubs, which compromises the yarn strength.\textsuperscript{17} Moreover, when the base yarn reaches the critical twist level, the increased twist leads to a decrease in yarn strength.\textsuperscript{18} Figure 5(c) shows that the relationships between the slub multiplier and the deviations of slub and base yarn lengths are arbitrary. Figure 5(d) shows that the slub multiplier moves away from its theoretical value when it gets larger due to twist transfer.

**Effect of slub and base yarn lengths on mechanical properties of slub yarn.** Figure 6(a) and (b) show that both the breaking force

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**Table 5.** Selected independent and dependent variables with level values.

| Variable qualification | Symbol | Variables          | Unit  | Levels (low-high) |
|------------------------|--------|--------------------|-------|-------------------|
| Dependent              | –      | Breaking force     | N     | –                 |
|                        | –      | Breaking elongation| %     | –                 |
| Independent            | A      | Twist coefficient  | –     | 300–380           |
|                        | B      | Roving ratio       | –     | 70:30–30:70       |
|                        | C      | Slub multiplier    | –     | 1.47–3.49         |
|                        | D      | Slub length        | cm    | 3.6–16.9          |
|                        | E      | Slub distance (base yarn length) | cm | 9.4–49.9 |

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![Figure 5.](image-url)
force and the breaking elongation increase with an increase in the slub length because increasing the slub length stabilizes the twist distribution, thus improving the intertwining of the fibers. In contrast, both the breaking force and the breaking elongation decrease with an increase in the base yarn length, as shown in Figure 7(a) and (b), since increasing the base yarn length reduces the proportion of the slub count to base yarn count, decreasing the yarn strength. The
slub length approaches its theoretical value when it gets longer, as shown in Figure 6(c); however, we did not find a similar effect by increasing the base yarn length, as shown in Figure 7(c). Furthermore, the slub multipliers approach the theoretical values as the slub and base yarn lengths increase, as shown in Figures 6(d) and 7(d).

Effect of roving ratio on mechanical properties of slub yarn. Figure 8(a) and (b) show that initially, both the breaking force and the breaking elongation decrease with an increase in the roving ratio and then increase over the roving ratio. This phenomenon occurs because, initially, the slub yarn contains a much larger ratio of base yarn count to the slub count; therefore, the yarn strength is dominated by the base yarn. As such, the increase of the roving ratio reduces the ratio of base yarn count to slub count, compromising the yarn strength. However, when the roving ratio is increased to a certain point, the yarn strength is alternatively dominated by the slub. As such, a further increase of the roving ratio increases the yarn strength. Figure 8(c) shows that the base yarn and slub lengths approach the theoretical values as the roving ratio increases. This phenomenon occurs because the three rovings get closer to equal mixing as the roving ratio increases, which benefits the interactions between the fibers and thus prevents fiber slip. Consequently, it reduces the overfeeding of the apron rollers. Figure 8(d) shows that no regular relationship can be found between the slub multiplier and the roving ratio.

Effect of twist coefficient on mechanical properties. Figure 9(a) and (b) show that initially, the breaking force increases with the increase of twist coefficient and then decreases over the twist coefficient, and the breaking elongation maintains an approximately increasing trend. This process can be explained as follows: increasing the twist makes a more compact yarn structure, which increases the overall strength of the slub yarn. In addition, the base yarn strength is increased due to the twist transfer from the slub to the base yarn. However, the tensile strength projected onto the yarn axial direction is decreased against the twist, which compromises the yarn strength after passing a certain level of twist. Besides, the increased twist may lead to the critical twist level of base yarn, as mentioned previously, which reduces the yarn strength. Figure 9(c) shows that the variation of the slub length deviation is arbitrary, and the base yarn length deviation decreases against the twist, because, on the one hand, increasing the twist increases the overall compactness of the base yarn, and on the other hand, it compromises the slub structure due to twist transfer. The two factors compete with each other, leading to an uncertain relationship between the twist and the slub length deviation. Figure 9(d) shows that the slub multiplier deviation decreases along with the increase of the twist because increasing the twist increases the compactness of the yarn structure.

Statistical analysis. Table 6 shows the variance analysis results for the breaking force. The regression model is statistically significant at $p$-value of 0.05. $p$-values less than 0.0500 indicate model terms are significant. $p$-values greater than 0.1000 indicate the model terms are not significant. In this case, A (twist coefficient), B (roving ratio),
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C (slub multiplier), D (slub length), and E (slub distance) are significant model terms. In addition, the two-body interaction terms AC, CD and BE have a statistically significant effect on the breaking force. The adequacy checking of the model does not indicate any problem; therefore, this model can be used to navigate the design space. The ANOVA analysis indicates that the model is significant at \( p \)-value of 0.05. The coefficient of determination \( R_{\text{prediction}}^2 \) is obtained as 0.9936 and \( R_{\text{adj}}^2 \) as 0.9959. The model equation with the actual factors is written as:

\[
\text{breaking force} = 1.35667 \times A + 0.068421 \times B + 0.654155 \times C + 0.00026 \times D - 0.002623 \times E - 0.000531 \times A \times C - 0.002813 \times C \times D - 0.000658 \times B \times E
\] (10)

Table 7 shows the variance analysis results for the breaking elongation. The A, C, D, E are significant model

![Figure 9. (a) Breaking force. (b) Breaking elongation of yarn with respect to the twist coefficient. (c) Length deviations. (d) Slub multiplier deviation with respect to the twist coefficient.](image)

**Table 6. Results of the ANOVA for the breaking force.**

| Source of variance | Sum of squares | Degrees of freedom | Mean squares | F ratio | p ratio Comment |
|-------------------|---------------|--------------------|--------------|---------|----------------|
| Model             | 7.64          | 10                 | 0.7645       | 755.49  | <0.0001 Significant |
| A                 | 0.0666        | 1                  | 0.0666       | 65.83   | <0.0001 Significant |
| B                 | 0.0105        | 1                  | 0.0105       | 10.39   | 0.0041 Significant |
| C                 | 7.45          | 1                  | 7.45         | 7362.16 | <0.0001 Significant |
| D                 | 0.0613        | 1                  | 0.0613       | 60.53   | <0.0001 Significant |
| E                 | 0.0200        | 1                  | 0.0200       | 19.76   | 0.0002 Significant |
| AC                | 0.0145        | 1                  | 0.0145       | 14.28   | 0.0011 Significant |
| AE                | 0.0040        | 1                  | 0.0040       | 4.00    | 0.0585 Insignificant |
| BC                | 0.0040        | 1                  | 0.0040       | 4.00    | 0.0585 Insignificant |
| BE                | 0.0050        | 1                  | 0.0050       | 4.94    | 0.0373 Significant |
| CD                | 0.0091        | 1                  | 0.0091       | 9.01    | 0.0068 Significant |
| Residual          | 0.0325        | 19                 | 0.0017       |         |                |
| Cor total         | 7.18          | 31                 |              |         |                |
terms at \( p \)-value of 0.05. Factor B (roving ratio) does not have an individually significant effect on the breaking elongation. The two-body interaction terms AD, AE, CD, have a statistically significant effect on the breaking elongation. Three-body interaction terms, such as BCD and CDE, have a statistically significant effect on the breaking elongation. The adequacy check does not indicate any problem. The ANOVA analysis indicates that the model is significant at a \( p \)-value of 0.05. The coefficient of determination \( R^2_{\text{prediction}} \) is obtained as 0.9911 and \( R^2_{\text{adj}} \) as 0.9933. The model equation with the actual factors is written as:

\[
\text{breaking elongation} = 5.92412 - 0.004758 \times A + 0.616175 \times C + 0.000144
\times D - 0.003566 \times E + 0.000168 \times A \times D + 0.000073 \times A \times E

\times 0.016159 \times C \times D - 0.006086 \times B \times C \times D + 0.000445 \times C \times D \times E
\]

**Conclusion**

In this study, a prototyped CNC ring spinning device in conjunction with a digital control system was developed to manufacture ring-spun slub yarns, and the system has more controllability of fibers than conventional ring spinning machines do. The as-prepared slub yarn possesses a complex structure with a tunable blending ratio, linear density and twist. The slub length is typically longer than its theoretical value due to the overfeeding of the apron roller at the end of each slub-production cycle, whereas the base yarn length is typically shorter than its theoretical value, which can be addressed by increasing the twist and the slub multiplier.

Increasing the slub multiplier increases the breaking force and the breaking elongation of the yarn due to the twist transfer from the slub to the base yarn. The increase of the slub length stabilizes the twist distribution and thus increases the breaking force and breaking elongation of the yarn. On the contrary, the increase of the base yarn length decreases the breaking force and the breaking elongation of the yarn.

Even though the increase in the twist makes the yarn more compact, which increases its strength, the projection of tensile strength along the yarn axis is reduced and the twist level of base yarn tends to reach the critical level, which reduces the yarn strength after a certain level of twist. On the contrary, increasing the roving ratio changes the ratio of base yarn count to slub count, which increases the yarn strength after a certain roving ratio. When the three rovings tend to be evenly blended, the interaction between fibers is improved, which improves the manufacturing accuracy of ring-spun slub yarn.

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References
1. Yang RH, Xue Y and Gao WD. Structure and performance of color blended rotor spun yarn produced by a novel frame with asynchronous feed rollers. Text Res J 2019; 89(3): 411–421.
2. Guo M, Sun F, Wang L, et al. Analysis of the appearance of two-color cotton yarn by the double-channel spinning system. Text Res J 2019; 89(9): 1712–1724.
3. Guo M, Sun F and Gao W. Theoretical and experimental study of color-alternation fancy yarns produced by a double-channel compact spinning machine. Text Res J 2019; 89(14): 2741–2753.
4. Souid H, Babay A, Sahnou M, et al. A comparative quality optimization between ring spun and slub yarns by using desirability function. AUTEX Res J 2008; 8(3): 72–76.
5. Petrylė SJMS. Complex structure fancy yarns: theoretical and experimental analysis. Medziagotyra 2003; 9(1): 120–123.
6. Kwasniak J. Application of a pressurized-air method of fancy-yarn formation to industrial rotor-spinning machines. J Text Inst 1997; 88(3): 185–197.
7. Kwasniak J and Peterson E. The formation and structure of fancy yarns produced by a pressurized-air method. J Text Inst 1997; 88(3): 174–184.
8. Wang J and Huang XJ. Parameters of rotor spun slub yarn. Text Res J 2002; 72(1): 12–16.
9. Alagoz BB, Ates A and Yeroglu CJM. Auto-tuning of PID controller according to fractional-order reference model approximation for DC rotor control. Mechatronics 2013; 23(7): 789–797.
10. Liu J, Xie Z, Gao W, et al. Automatic determination of slub yarn geometrical parameters based on an amended similarity-based clustering method. Text Res J 2010; 80(11): 1075–1082.
11. Fraser W. On the theory of ring spinning. Philos Trans R Soc Lond A Phys Eng Sci 1993; 342(1665): 439–468.
12. Tieshan L and Zhongqi Y. FA506 spinning frame designed draft multiple configuration analysis. Cotton Text Tech 2013; 10: 6.
13. Hooda A, Nanda A, Jain M, et al. Optimization and evaluation of gastroretentive ranitidine HCl microspheres by using design expert software. Int J Biol Macromol 2012; 51(5): 691–700.
14. Liu J, Li Z, Lu Y, et al. Visualisation and determination of the geometrical parameters of slub yarn. Fibres Text East Eur 2010; 18: 78.
15. Ilhan I, Babaarslan O and Vuruskan D. Effect of descriptive parameters of slub yarn on strength and elongation properties. Fibres Text East Eur 2012; 3(9): 33–38.
16. Khuri AI and Mukhopadhyay S. Response surface methodology. Wiley Interdiscip Rev Comput Stat 2010; 2(2): 128–149.
17. Lu Y, Gao W and Wang H. A model for the twist distribution in the slub-yarn. Int J Cloth Sci Tech 2007; 19(1): 36–42.
18. Hajiani F, Jeddi AA and Gharehaghaji A. An investigation on the effects of twist on geometry of the electrospinning triangle and polyamide 66 nanofiber yarn strength. Fiber Polym 2012; 13(2): 244–252.

Appendix

| Symbol | Description                              |
|--------|------------------------------------------|
| $\rho$ | yarn linear density (tex)                |
| $\rho_{bi}(i=1, 2$ or $3)$ | linear density of roving (tex)          |
| $e_i(i=1, 2$ or $3)$ | total drafting ratio of roving          |
| $V_f$  | apron-roller speed (m/min)               |
| $V_m$  | middle-roller speed (m/min)              |
| $V_{bi}(i=1, 2$ or $3)$ | feeding-roller speed (m/min)            |
| $\Delta V_{bi}(i=1, 2$ or $3)$ | the increment in feeding roller speed (m/min) |
| $k_i(i=1, 2$ or $3)$ | blending percentage of roving          |
| $T_w$  | yarn twist (TPI)                         |
| $V_{pindle}$ | pindle speed (r/min)                  |
| $V_d$  | yarn delivery speed (m/min)              |
| $R$    | slub multiplier                          |
| $R'$   | roving ratio                             |