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This is the accepted version of the publication Guo, Y., & Tao, X. (2018). Fiber packing density in the cross-section of low torque ring spun yarn. In Textile Research Journal (Vol. 88, Issue 2, pp. 191–202) Copyright © The Author(s) 2016. DOI: 10.1177/0040517516677225.

Fiber packing density in the cross-section of low torque ring spun yarn

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Abstract

Fiber packing density in the yarn cross-section is one of the major parameters that reflect the yarn internal structure and its final properties. Taking the novel low torque ring spun yarn as the object, this work studied the fiber packing density of low torque ring spun yarns and conventional ring spun yarns under various axial tensions. With the increase of tension, the change of fiber packing state in low torque ring spun yarns and conventional ring spun yarns was compared qualitatively. In this study, fiber distribution in the cross-section of both Tencel yarns and wool yarns was carried out. The results show that, under the same axial tension, the packing density of fibers of low torque ring spun yarn is much higher than that of conventional ring spun yarn. The axial tension has greater influence on the fiber packing density for the conventional ring spun yarn. From the experimental results, in low torque Tencel yarn, the fiber packing density nearly reaches 0.9, which is the maximum value for close-packed yarn. Due to different fiber properties and yarn structure, it is difficult to form a close packing for fibers in low torque ring wool yarns. The current results indicate that low torque ring spun yarn has a more compact structure than conventional ring spun yarn. Compared with conventional ring spun yarns with the same count and twist levels, in low torque ring spun yarns, more fibers contribute to the yarn breaking strength.

Keywords
cross-section, packing density, axial tension, low torque ring spun yarn

In recent years, a novel low torque ring spinning technique has been developed by inserting a false twister between the front rollers and yarn guide on the conventional ring frame,[1,2] as shown in Figure 1. A large number of experimental results have shown that low torque ring spun yarns have very low residual torque, less hairiness, and relatively high breaking strength even at a lower (25–40%) twist than conventional ring spun yarns. The skewness of the resultant denim fabrics and spirality of plain knitted fabrics made by low torque ring spun yarns have been greatly reduced.[3–7] Besides fiber properties and weaving parameters, the mechanical properties of yarns and the performance of the final fabrics are mainly attributed to the internal structure of the yarn. In the low torque spinning system, the incorporation of a false twister changes the fiber tension and its distribution in spinning triangle, which results in a special internal structure of the low torque yarn as compared with the conventional ring spun yarn.

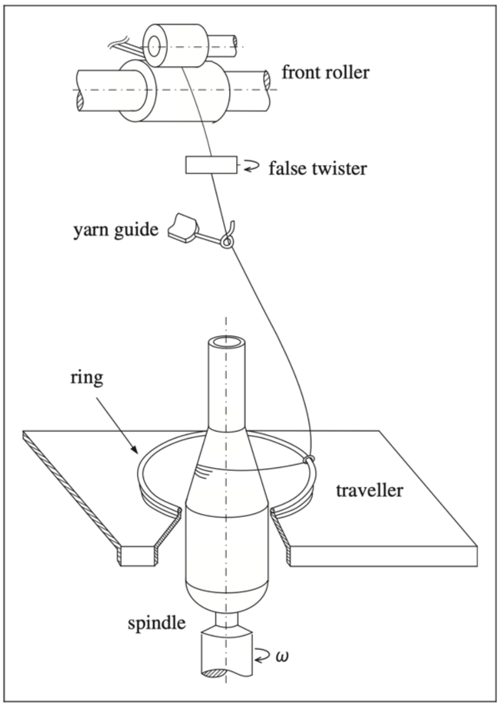

Figure 1. Schematic diagram of the low torque yarn spinning system.

The internal structure of a yarn is usually characterized from two aspects, that is, three-dimensional geometric configurations of fibers along the length of a yarn and fiber packing density in the yarn cross-section. Generally, three approaches have been used to analyze fiber packing density.[8–20] The first was proposed and developed based on the assumption that fibers are arranged into perfectly hexagonal configuration in a yarn cross-section.[8] In this way, Schwarz[8] studied a small number of fibers in a yarn cross-section. However, this method is only applicable to filaments, rather than staple yarns. It was also shown that the fibers were closely packed and could be approximated by choosing a uniform packing density in an unbulked continuous filament yarn.[9,10] However, a number of experiments revealed that the radial packing density of staple yarn is non-uniform.[13–18] Based on the assumption that fibers are arranged in the form of concentric helices in a yarn, Hearle et al.[10] introduced the second approach to analyze fiber packing density by dividing the yarn cross-section into several annular zones. As shown in Figure 2, traditionally, there are two zone-dividing methods: (a) the equal width method, that is, all annual zones have the same width,[16,20] and (b) the equal area method, that is, all annual zones have the same area.[13–15]. Considering there is a large variation in the fiber cross-sectional area, the fiber packing density is suggested to be defined as the ratio of the total cross-sectional area of the fibers in a given zone to the area of that zone in either method.[12,13] Besides the two approaches above, considering the fact that fibers are virtually arranged in the yarn cross-section neither in the form of a circular nor a hexagonal con- figuration, Grishanov et al.[19] introduced the concept of “virtual locations” by assuming fibers are distributed in the shape of a combination of a ring and a hexagonal configuration. In this case, the air gaps between fibers can be simulated, but this is not so practical for calculating the real fiber packing density.

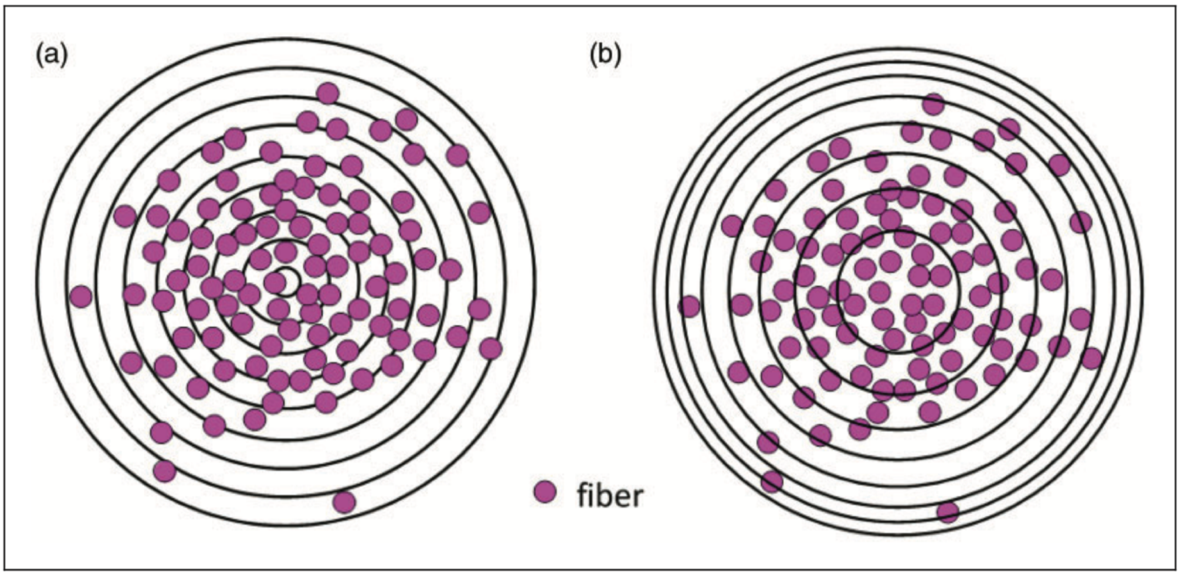

Figure 2. Schematic diagram of the zone-dividing method: (a) equal width method; (b) equal area method.

Many researchers have adopted the second approach to analyze fiber packing density because it is relatively easily implemented with satisfactory precision.[3,13–16,21] In this method, one main difficulty is to calculate the total cross-sectional area of fibers in each zone. Jiang et al.[13] introduced a relatively detailed method that was also adopted by other authors.[3] In their method, the fiber cross-section is assumed to be round and of the same shape and dimensions. The cross-sectional area of the fiber is then calculated approximately from the mean fiber fineness. In Choi's study,[21] a fiber cross- section was regarded approximately as an octagon. The cross-sectional area of a fiber was estimated approximately according to the manually measured length of each side. Mohamed and Sayed[20] introduced a segmentation method to detect the actual geometries and cross-sectional areas of fibers and the yarn.

Studies have shown that fiber packing density is mainly affected by fiber fineness, the shape of the fiber cross-section, the spinning method, and the spinning parameters, such as twist level and yarn count.[13–16] Some researchers have mentioned in their papers that their samples were prepared under fixed axial tension. However, the effect of axial tension on fiber packing density in the yarn cross-section was missed in most studies. It is obvious that yarns are not usually kept under a zero tension condition in practical applications. More importantly, the change of fiber packing density under various axial tensions can reflect the fiber cohesion during the yarn tensile process. Therefore, it is desirable to study yarn structures at different levels of tension. Unfortunately, preparing yarn samples for microtomy is a tedious and time consuming exercise, although some simple devices have been introduced.[3,13,21]

As a novel yarn type, it is important to study the internal structure of low torque ring spun yarn in depth so that to explain the unique properties of the yarn or fabric products. Based on the tracer fiber technique, which was first proposed by Morton and Yen,[22] three-dimensional configurations of fibers in the low torque ring spun yarns have been carried out in previous studies.[23,24] It was found that most fibers follow deformed non-concentric helices in the low torque ring spun yarn and the direction of orientation angles of some fiber segments is opposite to that of yarn twist. As for studies on fiber packing density, only Yang[3] has made a primary comparison on fiber packing density in low torque ring spun yarn and ring spun yarn under various twist levels. In order to provide a full understanding of low torque ring spun yarn structure and, hence, yarn mechanical properties, in this work, the difference of the fiber packing density between low torque ring spun yarn and conventional ring spun yarn under various axial tensions was studied. With the increase of tension, the change of fiber packing state for low torque ring spun yarn and conventional ring spun yarn were compared qualitatively. A sampling apparatus developed in our lab[25] was used to control the axial tension of the yarn in the sampling process. Then equal area zone dividing method was used in the fiber packing density calculation. The border was of each fiber were traced in order to obtain a more precise cross-sectional area of fiber.

Experimental details

Materials

In order to analyze the fiber packing density in cross-sections of conventional ring spun yarn and low torque ring spun yarn, which are produced by both the cotton spinning system and the wool spinning system, cotton fibers and wool fibers are preferred as raw materials. In this study, Tencel fibers were used to replace cotton fibers because, firstly, it is difficult to identify the center of cotton fiber when computing the fiber packing density due to its irregular cross-section. More precise results can be obtained if Tencel fibers with a circular cross- section are used. Secondly, in a previous study,[23] Tencel fibers were used to produce yarn samples in order to analyze fiber three-dimensional configurations along the axial of the low torque ring spun yarn by using the tracer fiber technique, so Tencel fibers are also chosen in the present research in order to ensure consistency and comparability with the previous studies.[5,23]

The Tencel fiber has a cut length of 38 mm and a diameter of 12.08 mm with a measured coefficient of variation (CV%) of 9.52%. The wool fiber has a length of 71.1 mm with a CV% of 37.4% and a diameter of 19.00 mm with a CV% of 20.00%. Fiber diameters were measured on the Projectina Microscope (Model: CH-9435 Heerburgg, Switzerland) at 100 randomly selected places. Zinser 351 (cotton spinning frame) and Zinser 451 (wool spinning frame) spinning machines were used for the production of Tencel yarns and wool yarns, respectively, on which special devices[3] were installed for low torque ring spun yarn production. The yarn count and twist are shown in Table 1.

Table 1. Specifications of yarn samples

Yarn type	Yarn count	Twist (turns/m)
Conventional ring Tencel yarn	Ne 20	440
Low torque ring Tencel yarn	Ne 20	440
Conventional ring wool yarn	Nm 24	294
Low torque ring wool yarn	Nm 24	294

Methods

Preparation of yarn cross-section microtomy. Figure 3 shows the schematic diagram of an apparatus for controlling the axial tension of the yarn in the sampling process. The main components include tubes for threading yarn specimens, upper clamps that are installed in the upper bar for fixing the sealed end of the tubes, lower clamps that are installed in the lower bar for fixing the other end of the yarn, and a tension gauge for applying and adjusting tension to the yarn.

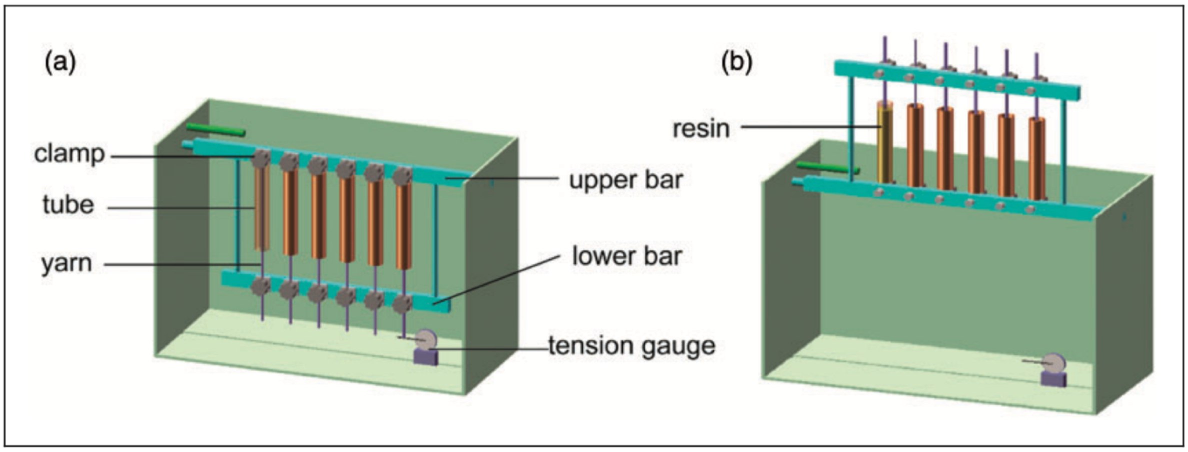

Figure 3. Schematic diagram of the apparatus: (a) sample preparation; (b) sample solidification.

In order to prepare the yarn cross-section microtomy under certain axial tension for further analysis, the following six steps were followed before cutting.

(1) Thread the conditioned yarn specimen through a tube.
(2) Seal one end of the tube by keeping the yarn position approximately at the centerline of the tube, and fix the sealed end of the tube with an upper clamp.
(3) Apply the desired tension to the yarn specimen using the tension gauge. Two aims of the present experiment are to analyze the difference in the fiber packing density between conventional ring spun yarn and low torque ring spun yarn under the same axial tension, and to compare qualitatively the change of fiber packing state with the increase of tension. Although both Tencel yarns and wool yarns were analyzed, there is no comparison of packing density between wool yarn and Tencel yarn. Tencel yarn samples were prepared under axial tensions of 0, 3, 5, and 8 g, while wool yarn samples were prepared under axial tensions of 0, 1, 2, 4, 6, and 8 g, respectively.
(4) Maintain the applied tension of the yarn and fix the other end of the yarn with the corresponding lower clamp.
(5) Flip the middle component of the apparatus vertically.
(6) Fill the tube with the prepared resin. In this study, a Leica Historesin Embedding Kit was used for making the resin. The specifications are listed in Table 2.

Table 2. Specifications of the Leica Historesin Embedding Kit

Basic resin/liquid	Activator	Hardener
(2-Hydroxyethyl) - methacrylate	Dibenzoylperoxide	Dimethyl sulfoxide

After several hours of solidification, the solidified yarn was performed into the desired thickness manually using a Leica RM 2135 microtome. The specimen thick- ness was 10 µm. Yarn cross-sectional images were examined under an optical microscope (Nikon OPTIPHOT-POL) and then were captured for further analysis.

Calculation of fiber packing density in the yarn cross-section. In this study, the packing density of fibers in the yarn cross-section was carried out according to the following steps.

(a) *Determination of the fiber center and cross-sectional area:* according to the contrast grade between fibers and the background, the gray value and scale of the image, the number of fibers, the central coordinate, and the width (X) and height (Y) of each fiber in the image were obtained firstly. Also, the cross-sectional area of each fiber, which is determined by the number of pixels occupied by the fiber, was calculated automatically with the help of Image Pro Plus software.

(b) *Determination of the yarn center and radius:* assume a yarn cross-section has n fibers, and the central coordinates of each fiber are (x_i, y_i), where $i = 1, 2, \ldots n$. Thus, the central coordinates of the yarn cross-section O_y (X, Y) can be obtained by averaging all fiber coordinates. In this study, yarn radius R_y equals the sum of the distance from the yarn center O_y to the center of the fiber O_{fi}, which is farthest from the yarn center, and the fiber radius R_{fi}, as shown in Figure 4.

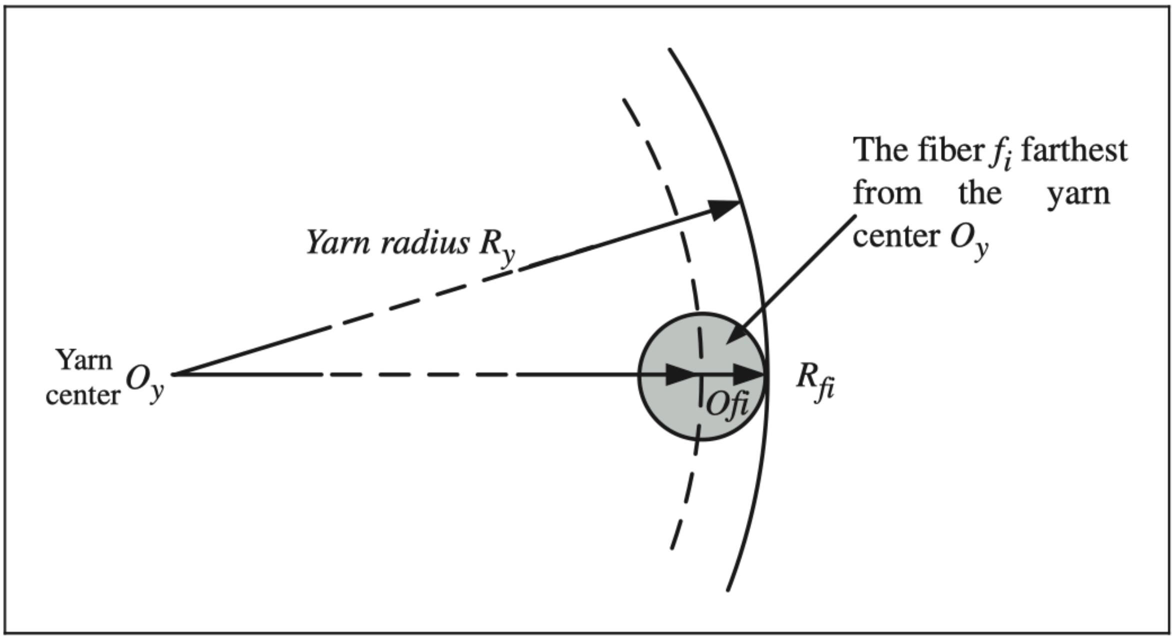

Figure 4. Schematic diagram of the calculation of yarn radius.

(c) *Division of the concentric annual zones:* in this study, fiber packing density in the yarn cross-sec- tion was determined by the equal area method. So in this step, a circle with its center at O_y (X, Y) and radius equal to R_y was drawn firstly, which was defined as the yarn cross-section. Then the circle was divided into several concentric zones with the same area, as shown in Figure 5.

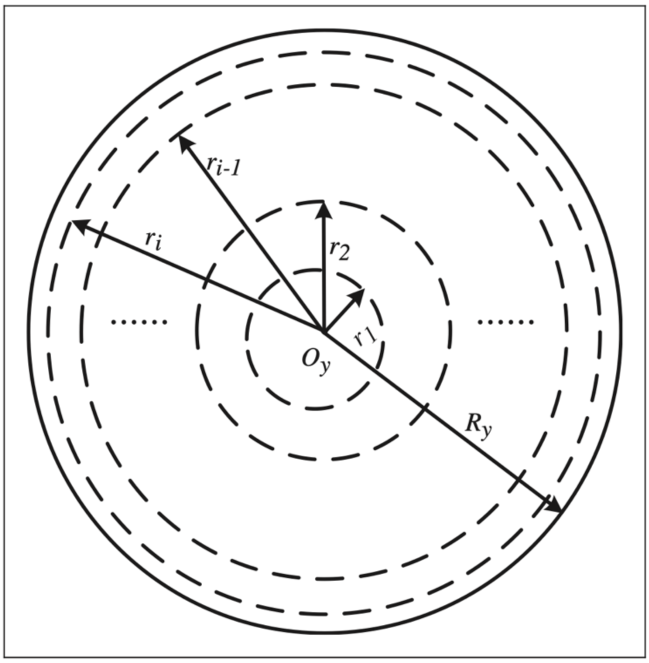

Figure 5. Division of concentric annual zones.

(d) *Calculation of the packing density:* the packing density for a given concentric zone was defined as the ratio of the total fiber cross-sectional areas in this zone to the area of this zone. Based on the central coordinate and cross-sectional area of each fiber obtained from step (a), the method provided by Jiang et al.[13] was used to calculate the cross- sectional area of a fiber in a particular annular zone. A program was developed to perform the calculation. Assuming the radius of the ith concentric zone is equal to r_i, the ratio of r_i to yarn radius R_y was defined to be radial position (r/R), which reveals the relative position of the concentric zone to the center of the yarn. Thus, the packing density of fibers in various radial positions can be plotted.

Yarn tenacity test. In previous research on low torque ring technology, the advantages of low torque ring spun yarns and fabrics have been reported.[3,4,6] One significant feature of low torque ring spun yarn is the high yarn tenacity under a low twist level. The aim of this study is to explain this unique feature from the viewpoint of fiber lateral distribution in the yarn cross-section. So, only the yarn tenacity is presented here.

All yarn samples were conditioned for at least 24 hours under standard conditions ($20 \pm 2^{\circ}$C and $65 \pm 2\%$ relative humidity (RH)) before the experiment. According to standard ASTM 2256-02, the yarn tenacity was obtained using an Uster Tensorapid 3 with a gauge length of 500 mm and testing speed of 5000 mm/min. Fifty readings were obtained for each sample.

Results and discussion

Yarn tenacity

Yarn tenacity is an important property in evaluating yarn performance. As shown in Table 3, for both Tencel and wool yarns, the low torque ring spun yarn has much higher mean tenacity and higher minimum and maximum tenacities than the conventional ring spun yarn with the same twist level. According to the previous study on fiber three-dimensional configurations along the yarn axis,[23] most fibers in the low torque ring spun yarn tend to be distributed close to the yarn center. Also, frequent changes of the fiber radial position and the irregular migration pattern increase the frictional force between fibers, thus improving the yarn breaking strength during the yarn failure process.

Table 3. Measured yarn tenacity

Yarns	Mean tenacity (cN/tex)	[CV %]	Min tenacity (cN/tex)	Max tenacity (cN/tex)
Conventional ring Tencel yarn	17.58	[10.9]	10.95	20.93
Low torque ring Tencel yarn	21.34	[6.2]	18.39	24.50
Conventional ring wool yarn	6.83	[7.3]	5.78	7.99
Low torque ring wool yarn	7.78	[7.6]	6.31	9.60

Fiber packing density in the cross-section of Tencel yarns

Figures 6-9 show the fiber distribution in the cross-section of Tencel yarns under different axial tensions. Figure 10 shows the corresponding fiber packing density curves.

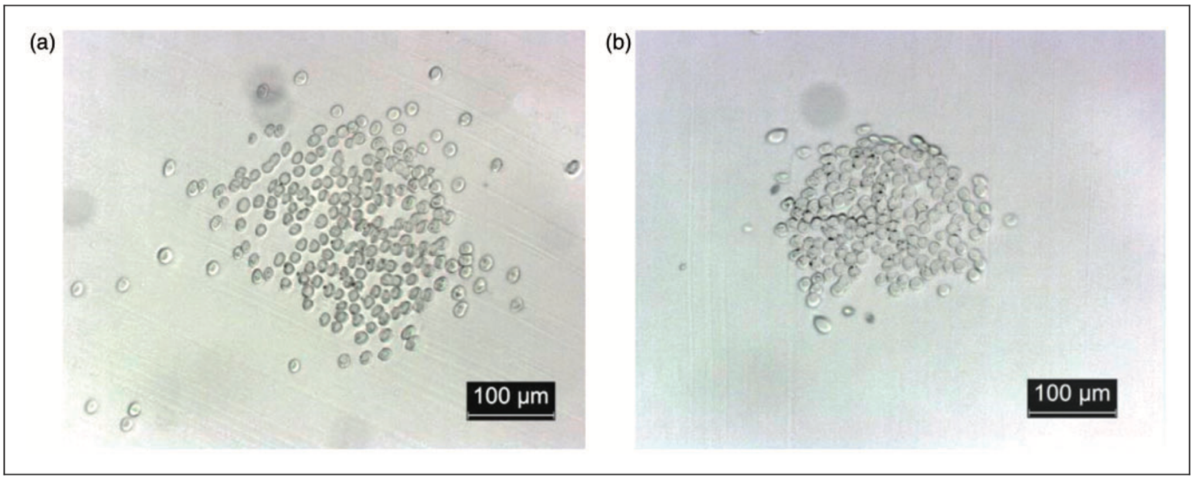

Figure 6. Typical cross-sectional images of Tencel yarn under the tension-free state: (a) conventional ring Tencel yarn; (b) low torque ring Tencel yarn.

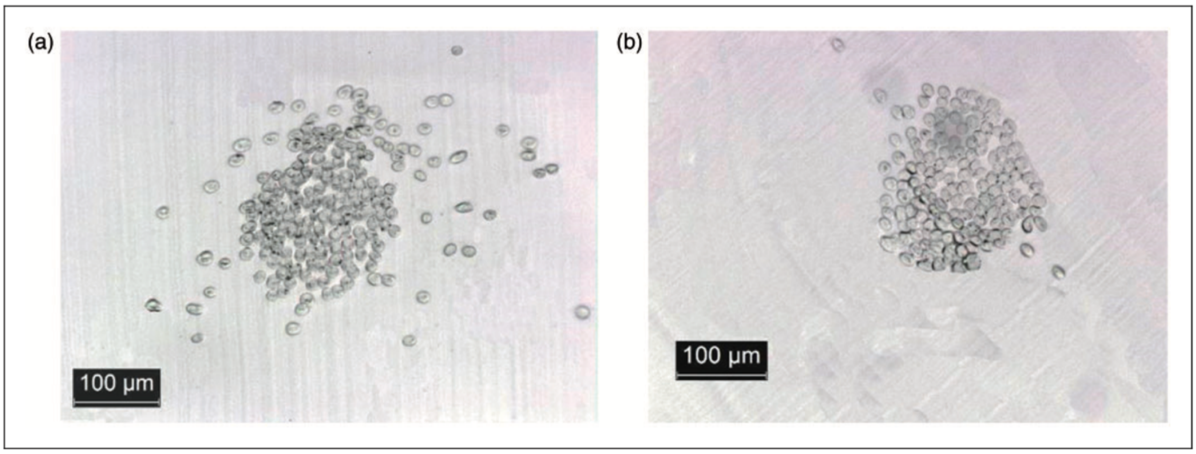

Figure 7. Typical cross-sectional images of Tencel yarn under 3 g axial tension: (a) conventional ring Tencel yarn; (b) low torque ring Tencel yarn.

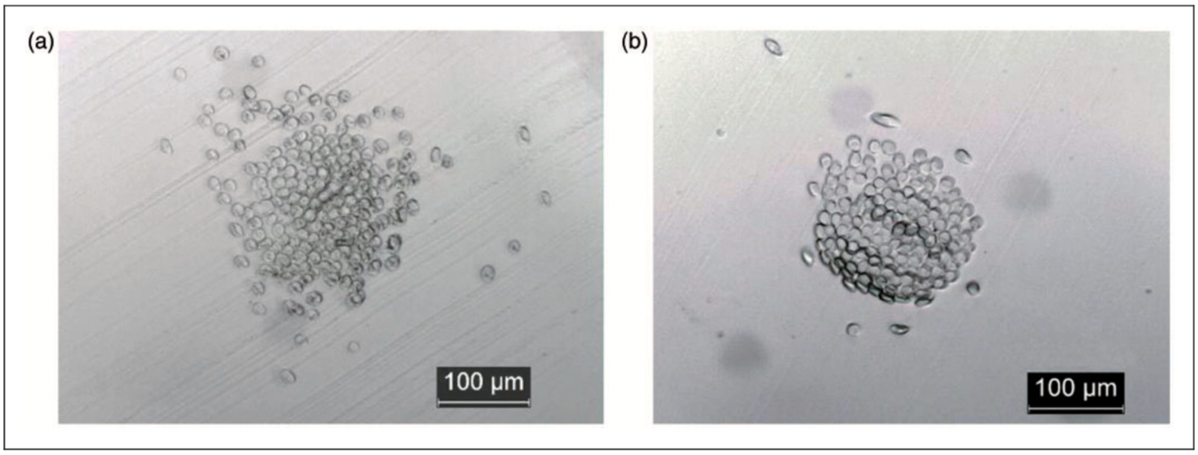

Figure 8. Typical cross-sectional images of Tencel yarn under 5 g axial tension: (a) conventional ring Tencel yarn; (b) low torque ring Tencel yarn.

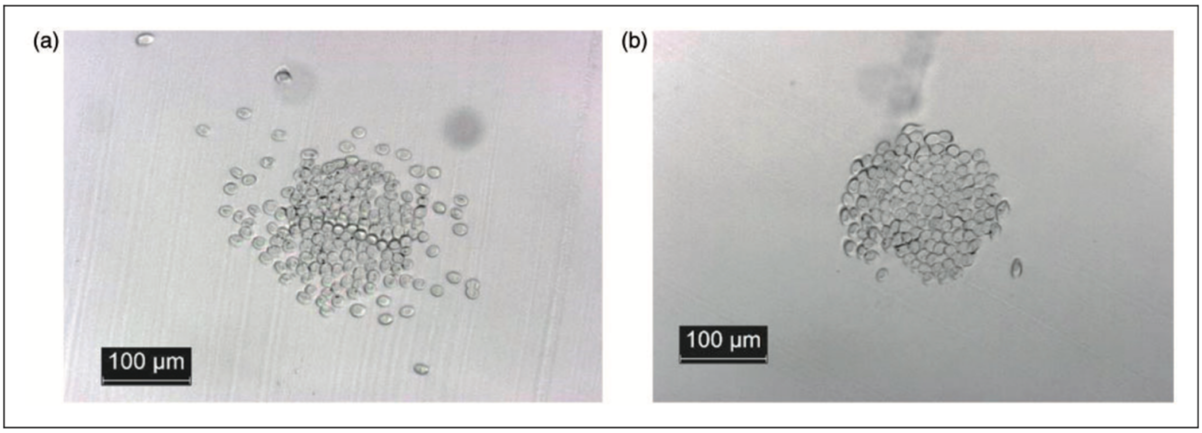

Figure 9. Typical cross-sectional images of Tencel yarn under 8 g axial tension: (a) conventional ring Tencel yarn; (b) low torque ring Tencel yarn.

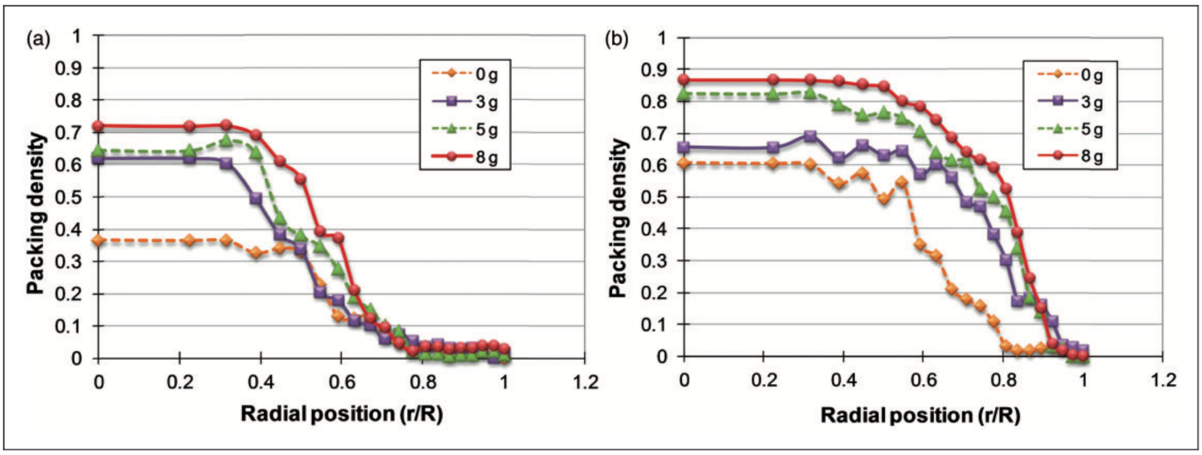

Figure 10. Fiber packing density at various radial positions in Tencel yarns: (a) conventional ring Tencel yarn; (b) low torque ring Tencel yarn.

These figures firstly show that, under a tension-free state, fibers distribute in the yarn cross-section loosely. Comparatively, the packing density of fibers in low torque ring Tencel yarn is much higher than that of conventional ring Tencel yarn. Some researchers have pointed out that, in the central yarn zone, the fiber packing density of carded ring spun yarn with normal twist is around 0.38-0.55, while that of the combed ring spun yarn is around 0.5-0.6[17] and the combed compact yarn is around 0.5-0.7.[18] From the present experimental results, under the tension-free state, the fiber packing density in the center of low torque ring Tencel yarn is over 0.6. This indicates that low torque ring Tencel yarn has a compact structure under such a low twist level.

It also can be observed from these figures that, when the yarn undergoes a very low axial tension, fibers move towards the yarn center, indicating fiber movement in the lateral direction in order to avoid being extended. With the increase of axial tension, a dense region appears gradually near the yarn center, and the fiber packing density at each radial position increases correspondingly. Furthermore, the axial tension has a greater influence on the fiber packing density of the conventional ring Tencel yarn, which demonstrates a relatively loose structure in conventional ring Tencel yarn.

According to the shortest-path hypothesis[26] and the jammed region theory,[21] under external tension, the fiber lateral movement will stop until the fibers are prevented from doing so by preoccupied fibers. In this case, the fibers can actually be divided into two states, a jammed state, which is generally located at the yarn center, and a freely moving state, which is outside of the jammed region. Fibers in the jammed state undergo tension and contribute to the yarn strength. When a fiber is in the freely moving state, its neighboring fibers do not have any interaction with it, so the fiber does not contribute to the yarn breaking strength. From these figures, even under tension as low as 8 g, almost all fibers in the low torque ring Tencel yarn are tightly packed together without any space. The fiber packing density reaches nearly 0.9, which is the maximum value for close-packed yarn.[10,27] However, in the conventional ring Tencel yarn, there are still many fibers dispersed in the outer area. The results indicate that, for yarns with the same count and twist level, under the same axial tension, the number of fibers in the jammed region of low torque ring Tencel yarn is more than that of the conventional ring Tencel yarn. That is to say, in low torque ring Tencel yarn, there are more fibers contributing to the yarn breaking strength. Combining the analysis of the fiber three-dimensional trajectory along the yarn axis[23] and the present results, the feature that low torque ring spun yarn has higher tenacity under low twist level could be explained reasonably. During the yarn rupture process, many more fibers experience the tension, reach their breaking extension, and then break almost at the same time, which means higher breaking strength of the yarn. Meanwhile, the compact structure of low torque ring spun yarn enhances the fiber-to-fiber frictional force arising from the increment of lateral pressure, and then significantly improves the fiber-to-fiber cohesion, thus minimizing the chance of fiber slippage and improving the yarn strength.

Fiber packing density in the cross-section of wool yarns

Figures 11-16 show the fiber distribution in the cross- section of wool yarns under different axial tensions. Figure 17 shows the corresponding fiber packing density curves.

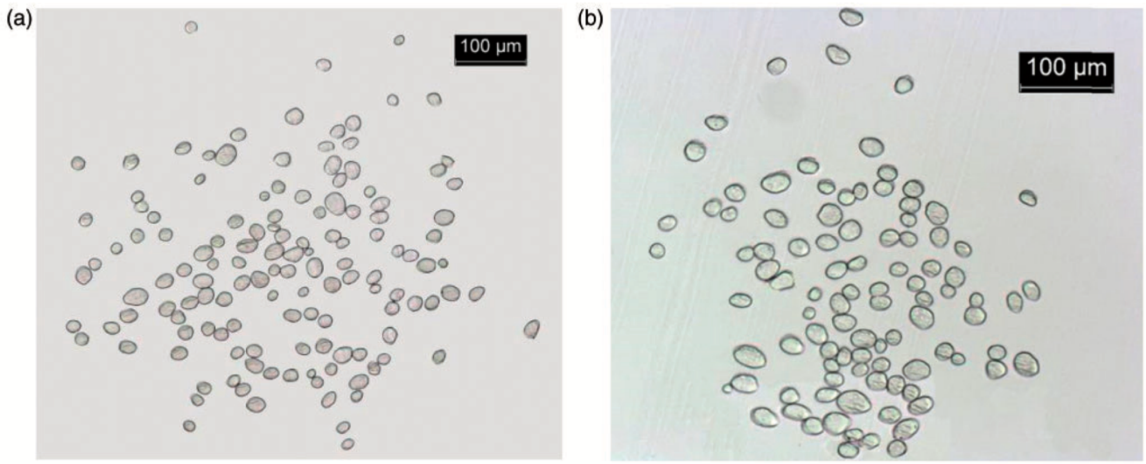

Figure 11. Typical cross-sectional images of wool yarn under the tension-free state: (a) conventional ring wool yarn; (b) low torque ring wool yarn.

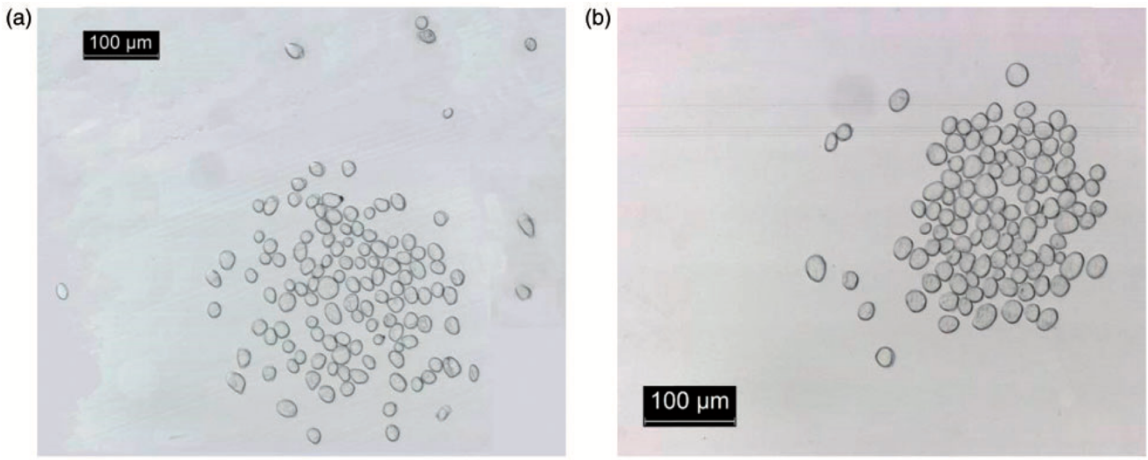

Figure 12. Typical cross-sectional images of wool yarn under 1 g axial tension: (a) conventional ring wool yarn; (b) low torque ring wool yarn.

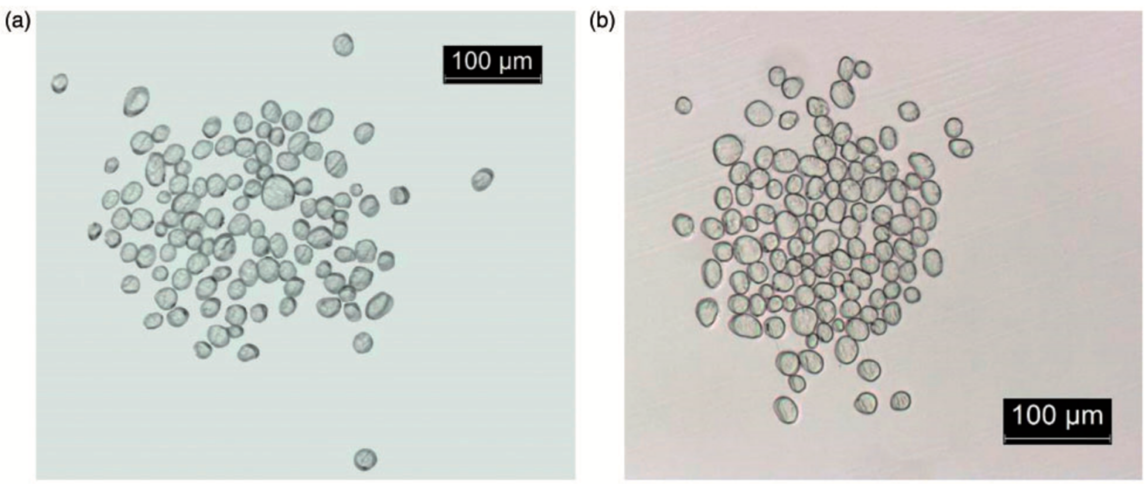

Figure 13. Typical cross-sectional images of wool yarn under 2 g axial tension: (a) conventional ring wool yarn; (b) low torque ring wool yarn.

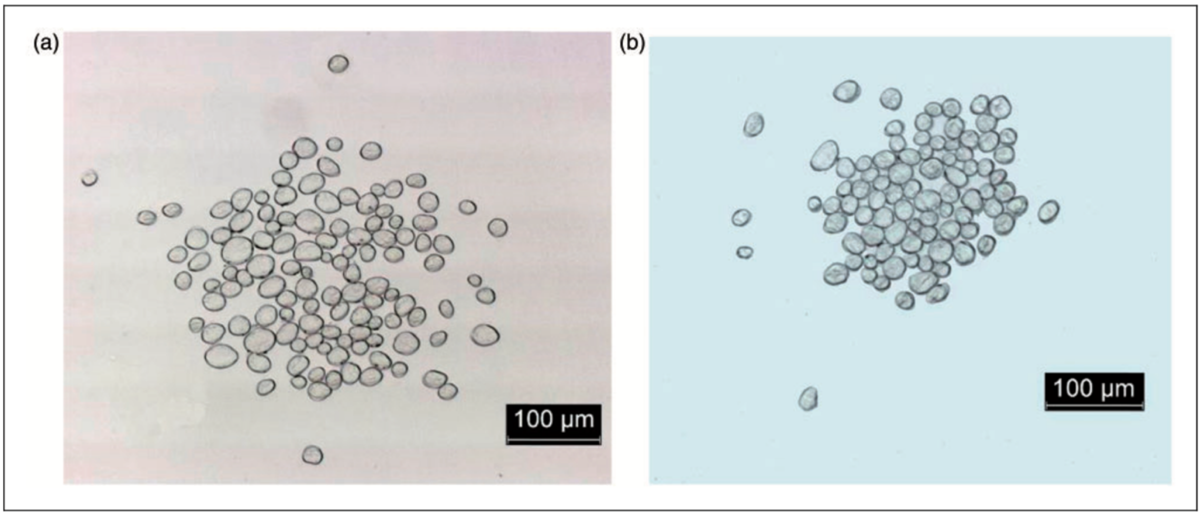

Figure 14. Typical cross-sectional images of wool yarn under 4 g axial tension: (a) conventional ring wool yarn; (b) low torque ring wool yarn.

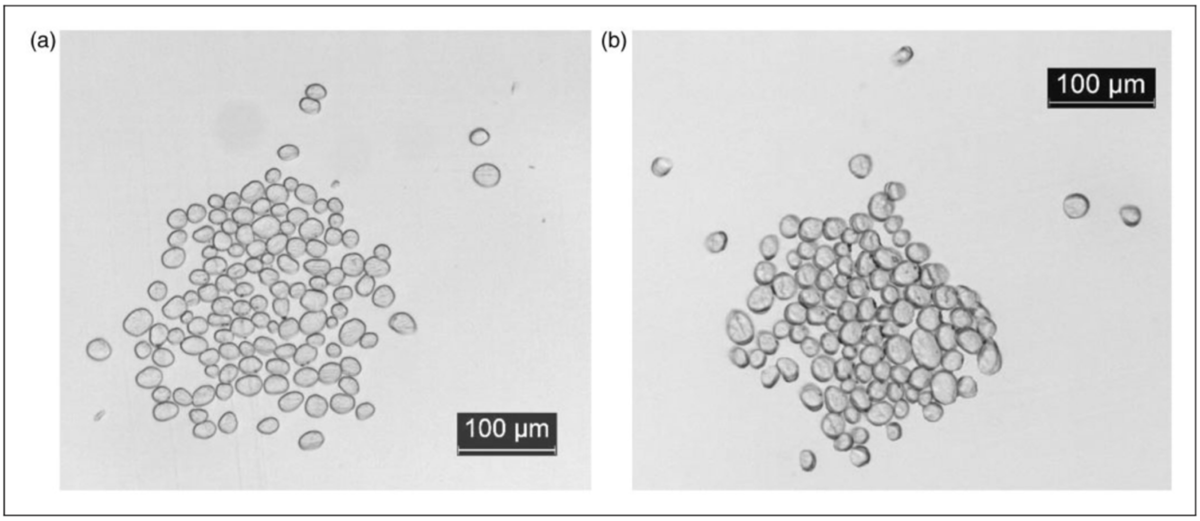

Figure 15. Typical cross-sectional images of wool yarn under 6 g axial tension: (a) conventional ring wool yarn; (b) low torque ring wool yarn.

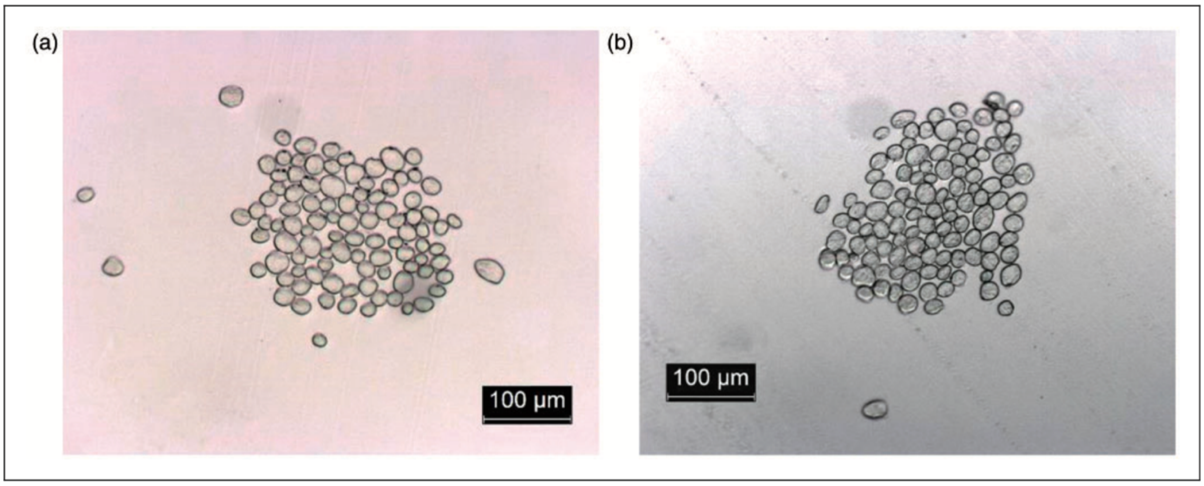

Figure 16. Typical cross-sectional images of wool yarn under 8 g axial tension: (a) conventional ring wool yarn; (b) low torque ring wool yarn.

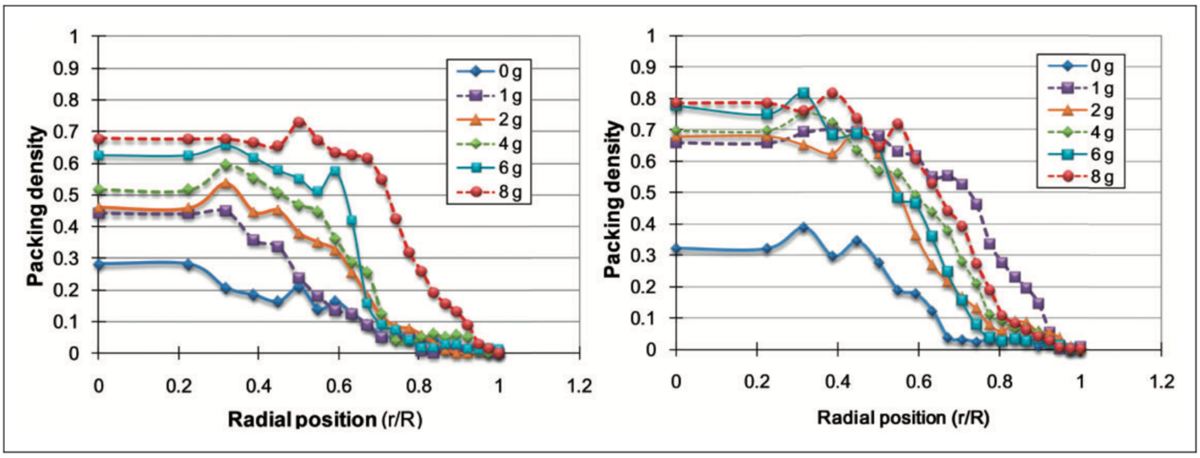

Figure 17. Fiber packing density at various radial positions in wool yarns: (a) conventional ring wool yarn (b) low torque ring wool yarn.

One obvious difference from Tencel yarns is that fibers in wool yarns distribute loosely and evenly in the cross-section with larger spaces between fibers. It can be easily found that for most cases, the relationship between fiber packing density and the radial position is nonlinear (Figures 17 and 18). However, under the tension-free state, fiber packing density in conventional ring wool yarn has a significant linear correlation with the radial position (Figure 18(c)). Meanwhile, it is also noticed that, under the same axial tension, the fiber packing density of low torque ring wool yarn is higher than that of conventional ring wool yarn in the same radial position. For both conventional ring and low torque ring wool yarns, the fiber packing state increases sharply when the yarn undergoes a slight load. However, even in such a compact state, as shown in Figure 16(b), the highest fiber packing density along the yarn radial direction is only around 0.8 (Figure 17(b)). Furthermore, in almost all packing density distribution curves, it can be observed that there is a peak in around one-quarter of the yarn radial positions (Figure 17), which coincides with a previous study.[11] In another experiment based on the equal width method,[16] it was found that the maximum packing density in wool yarn occurs at approximately one-sixth of the yarn radius from the yarn axis.[16] The difference was caused by different zone dividing methods, yarn parameters, and properties of raw material.

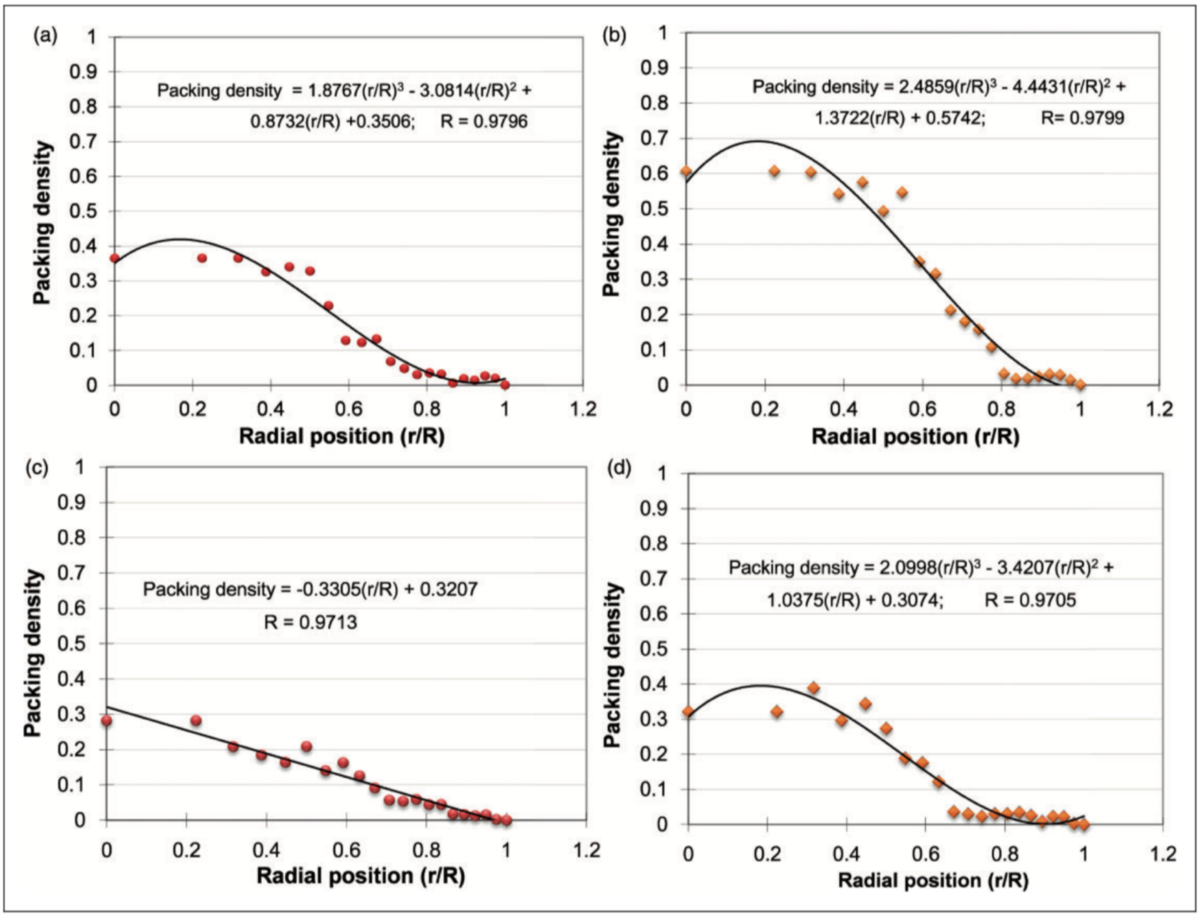

Figure 18. Curve fitting of fiber packing density under the tension-free state: (a) conventional ring Tencel yarn; (b) low torque ring Tencel yarn; (c) conventional ring wool yarn; (d) low torque ring wool yarn.

Above-side features can be explained by the yarn structure and fiber properties. Firstly, the structure of wool yarn is not as compact as Tencel yarn due to natural crimps of wool fibers, so there are more spaces between fibers in the wool yarn.

Secondly, wool fiber fineness and its coefficient of variation are very large, so it is difficult for it to form a close packing.

Conclusions

We compared fiber packing density in conventional ring spun yarn and the novel low torque ring spun yarn under a series of axial tensions. Both Tencel yarns and wool yarns were analyzed. In contrast, under the same axial tension, the packing density of fibers in low torque ring spun yarn is much higher than that of conventional ring spun yarn. Also, the axial tension has a greater influence on the fiber packing density of the conventional ring spun yarn. Under slight tension, the fiber packing density in low torque ring Tencel yarn reaches nearly 0.9, which is the maximum value for close-packed yarn. However, it is difficult for fibers in wool yarns to form close packing due to the different fiber properties and yarn structure. Under the tension-free state, the fiber packing density distribution in conventional ring wool yarn has a significant linear correlation with the radial position.

Combining the present results and the analysis on the fiber three-dimensional trajectory along the yarn axis, a comprehensive understanding of the structural characteristic of the low torque yarn was achieved. The feature that low torque ring spun yarn has higher tenacity under low twist level could be explained reasonably. During the yarn rupture process, many more fibers experience the tension, contributing their strength to the yarn breaking strength. Meanwhile, the compact structure of low torque ring spun yarn enhances the fiber-to-fiber frictional force arising from the increment of lateral pressure, and then significantly improves the fiber-to-fiber cohesion, thus minimizing the chance of fiber slippage and improving the yarn strength.

Acknowledgement

The authors would like to acknowledge the NuTorque group, Hong Kong Polytechnic University, for their help with this work.

Declaration of conflicting interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The authors disclosed receipt of the following financial sup- port for the research, authorship, and/or publication of this article: This was supported by the Applied Basic Research Project of Nantong City (GY12015006).

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