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Effect of Using the New Solo-siro Spun Process on Structural and Mechanical Properties of Yarns

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Abstract
Mechanical and physical properties of spun yarns are very important for post-spinning operations as well as for determining some final fabric characteristics. These properties greatly depend on the yarn structure characterised by the geometrical arrangement of fibres in the yarn body. The geometry of the spinning triangle plays a significant role in determining the spun yarn structure. Solo-siro is a new spinning system which proposes fundamental modifications to the Solo spinning process with the aim of altering the geometry of the spinning triangle and hence the yarn structure. By comparing Solo-siro and Solo spun yarns, the present research focuses on identifying those structural differences which can be used to explain the properties of these novel yarns. Results show that Solo-siro spun yarns enjoy superior physical and mechanical properties in comparison with Solo spun yarns. This can be attributed to the higher mean fibre position, higher migration factor, greater proportion of fibres which are broken during yarn failure and lower hairiness in Solo-siro spun yarns.

Key words: *solo-siro spun yarn, solo spun yarn, migratory properties, tenacity, broken fibres.*

Introduction

In the past decades, all the new spinning systems have been designed to achieve higher production per spinning unit as well as better yarn quality. Manufacturing methods impose certain restrictions on the disposition and migration of fibres in the yarn body. Revolutionary improvements in terms of yarn quality have been achieved with the introduction of Solo and Siro spinning technologies. During the two last decades, there has been a wealth of research activity on the properties of Siro spun yarns and their advantages over conventional ring spun yarns. These researches have demonstrated that Siro spun yarns enjoy better properties in many ways (for more details see [1 - 3]). Researches on Solo spun yarns have focused on the mechanism of yarn formation and twist penetration in these yarns. These studies reported that the twist amplitude is distributed more evenly in Solo spun yarns, which results in increasing the breaking strength of these yarns by about 15% higher than that of conventional ring spun yarns [4 - 7].

The Solo-siro spinning system is a new system which can produce a distinctive yarn structure by combining Solo and Siro spun processes. In other words, the Solo-siro spinning system can be viewed as a refinement of the Siro and Solo spinning systems. Despite intensive investigations on the properties of Solo and Siro spun yarns, few investigations have been carried out on Solo-siro spun yarns. Shaikhzadeh et al. [8] conducted pioneering research on the properties of worsted Solo-siro spun yarns and reported that their hairiness is significantly less than that of both Siro spun and conventional ring spun yarns. Their findings also indicated that the tenacity of Solo-siro spun yarns is higher than that of conventional ring spun yarns. In a related study, Shaikhzadeh et al. [9] compared the physical properties of Siro spun and Solo-siro worsted spun yarns produced at different twist multipliers. They reported that the hairiness of Solo-siro spun yarns is significantly less than that of Siro spun yarns. Their findings also indicated that the evenness, count and twist of Solo-siro spun yarns change slightly in comparison with Siro spun yarns; however, the tensile strength and abrasion resistance remain almost un-changed.

In our earlier work [10, 11], we made a detailed study of the structure-property relationships of lyocell yarns spun on Solo, Siro, Compact and conventional ring spinning systems. Those results showed different yarn properties due to the different yarn structures.

Currently there is little information available on Solo-siro spinning, particularly the importance of structural parameters for the physical and mechanical properties of these yarns. Therefore this study focuses on characterising the inner structure of Solo-siro spun yarns at different twist multipliers and its comparison with Solo-spun yarns. Moreover we attempt to explain the strength properties aided by the characteristic structure of the yarns.

Experimental

Staple (38 mm, 1.77 dtex) lyocell fibres were processed to produce a drawn sliver of 2.6 Ktex. Tracer fibres were added to un-dyed lyocell fibres during the opening stage, which was followed by carding, two stages of drawing, roving and spinning. A laboratory SKF spinner was used to produce a series of 22 tex Solo and Solo-siro spun yarns containing black, green and violet tracer fibres. Using different colours facilitates the determination of the proportion of broken and slipped fibres. First of all, Solo-siro spun yarns were produced at 5 strand spacings - 0, 2, 4, 8 & 12 mm and 4 twist multipliers (α_{tex}) - 2500, 3000, 3600 & 4200. As the yarns produced at an 8 mm strand spacing exhibited the highest performance in terms of yarn tenacity and structural parameters, they were chosen for comparison with Solo spun yarns.

To analyse the inner structure of the yarns, they were pulled through a glass trough containing an immersion liquid (Methyl salicylate), which was, in turn, placed on a microscope stage. Yarn guides were used to maintain the yarn sample on a set path through the trough. Images of the tracer fibres were captured via a DINO microscope. These images were then transferred to a computer and stored. Due to the high resolution, it was impossible to obtain a complete image of one tracer fiber on a single image. Therefore an image of the tracer fibers was captured in successive 3-mm long sections of the yarns as the yarn was drawn manually [10, 12]. Afterwards, using im-

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age processing methods, the parameters of the yarn structure were calculated. Yarn migration was quantified using migration parameters such as the mean fibre position (Y), root mean square (RMS) and mean migration intensity (I) [13, 14]. These parameters were derived from ***Equations 1** - **3***, respectively.

$$\overline{Y}=\frac{1}{L}\int_{0}^{L} y\,dz=\frac{1}{n}\sum_{i=0}^{n-1} y_i \qquad (1)$$

Where L is the total yarn length observed, z the length coordinates along the yarn and n is the total number of observations. In this equation y_i is equal to $(r_i/R_i)^2$ $i = 0, 1, 2, \ldots, (n - 1)$ the sequence number of observations, R_i the yarn radius and r_i is the helix radius of the i^{th} observation.

$$D=\left[\sqrt{\frac{1}{L}\int \left(Y-\overline{Y}\right)^{2} dz}\right]= =\sqrt{\frac{1}{n}\sum_{i=0}^{n-1}\left(y_i-\overline{Y}\right)^{2}} \qquad (2)$$

Where D is the amplitude of migration, which is the deviations from the mean position represented by the root mean square deviation.

$$I=\sqrt{\frac{1}{n}\sum_{i=0}^{n-1}\frac{\left(y_{i+1}-y_i\right)^{2}}{\left(z_{i+1}-z_i\right)^{2}}} \qquad (3)$$

Moreover, the yarn migration factor was calculated by multiplying the mean migration intensity and RMS deviation values, as suggested by Huh et al. [15].

The fibre spinning-in-coefficient K_F , as defined by Kasparek, relates to the fibre length present in the yarn and is defined in ***Equation 4***.

$$K_F=\sum^{n}\frac{K_{Fi}}{n} \qquad (4)$$

Where K_{Fi} is the spinning-in-coefficient of a given fibre and n is the number of fibres tested [16].

The yarns were conditioned at 65 ± 2% RH and 24 ± 2 °C for 24 hours and subsequently tested for physical and mechanical properties. The yarns then were subjected to uniaxial loading on a CRE (constant rate of extension) tensile tester (model M10-82701-1). The standard measurement of yarn strength was executed at a 500 mm gauge length and for a 20 ± 3 second testing time. For each set of experiments 40 tests were conducted.

Yarn hairiness and evenness tests were performed on an Uster evenness tester 3 using a testing speed of 100 m/min and testing time of one minute, with 25 tests for each sample.

The method evolved by Ghosh et al. [17] was employed to calculate the proportion of broken and slipped fibres. The pair of broken ends was observed under a Projectina microscope. To calculate the proportion of broken and slipped fibres, the slide containing the broken ends is covered by another slide. By introducing an optically dissolving liquid, Methyl salicylate, between the slides, a tracer of colored fibres becomes observable in the failure zones. If both the failed segments contain the same tracer fibre, i.e., of the same color and sum of lengths of both the tracer ends of same color is equal to the original tracer length, the fibre is categorized as broken fibre. If a tracer of a particular colour exists in only one end of the broken yarn, the fibre is classified as slipped fibre [17].

To establish more reliable results, an analysis of variance (ANOVA) and Duncan test at a 95% confidence level were applied using a SPSS 16 program.

Results and discussions

Table 1 shows test results for the structural, physical and mechanical properties of Solo-siro and Solo spun yarns. To display more clearly, some of the results in this table are presented as graphs in ***Figure 1***.

Fibre configuration and spinning-in-coefficient

Referring to ***Table 1***, for all yarns, by increasing the twist multiplier (α_{tex}) from 2500 to 4200, no discernible trend in the percentage and shape of hooked fibres is observed; however, Solo spun yarns compromise the highest percentage of hooked and entangled fibres. A higher proportion of hooked and entangled fibres causes a poor fibre-to-yarn translation of tensile properties, hence lowering yarn tenacity. Generally the Solo-siro spinning system produces yarns with a higher spinning-in-coefficient and percentage of straight fibres compared to those in Solo spun yarns. Results indicate that for all yarns, by increasing the twist multiplier (α_{tex}) up to 3600, the spinning-in-coefficient increases, beyond which it decreases. By increasing the twist multiplier, the tension applied to individual fibres in the spinning triangle is increased. This leads to the straightening of fibres, thus increasing the spinning-in-coefficient. By further increasing the twist multiplier, fibres make a higher angle with the yarn axis, as a result of which the spinning-in-coefficient decreases.

Yarn migration parameters

Migration parameters i.e., the mean fibre position, RMS deviation, migration

Table 1. *Solo-siro and Solo spun yarn properties.*

Twist multipliers- α_{tex}	2500		3000		3600		4200	
Spinning system	**Solo**	**Solo-siro**	**Solo**	**Solo-siro**	**Solo**	**Solo-siro**	**Solo**	**Solo-siro**
Spinning-in-coefficient, %	69.04	74.49	70.12	77.13	72.31	78.81	64.76	72.56
Leading hooks, %	12	8	10	7	8	5	6	5
Trailing hooks, %	8	6	7	4	5	3	4	4
Middle leading hooks, %	4	3	4	2	2	1	1	1
Middle trailing hooks, %	5	3	3	1	1	--	2	2
Both end hooks, %	5	2	4	2	2	1	3	2
Other fibres	7	6	7	4	5	4	6	3
Straight fibres, %	59	72	65	80	77	86	78	83
Mean fibre position	0.277	0.301	0.307	0.343	0.350	0.381	0.374	0.402
CV of mean fibre position, %	29.77	27.84	32.71	29.15	34.24	29.74	30.19	31.55
RMS deviation	0.135	0.154	0.141	0.160	0.156	0.177	0.151	0.171
CV of RMS deviation, %	26.55	24.19	25.49	26.50	30.81	27.02	29.52	27.66
Mean migration intensity	1.661	1.762	1.840	1.993	2.428	2.619	2.512	2.711
CV of mean migration intensity, %	26.69	30.48	35.92	33.62	39.14	35.76	40.37	35.80
Migration factor	0.224	0.271	0.259	0.319	0.383	0.464	0.376	0.461
Yarn hairiness	6.86	6.31	6.53	6.04	6.27	5.67	6.03	5.52
Yarn evenness CV%	13.46	13.02	13.70	13.27	13.80	13.41	13.98	13.57
Breaking extension	9.40	10.05	10. 33	11.41	11.32	11.98	11.88	12.25
Yarn tenacity, cN/tex	12.07	12.72	12.84	13.83	13.33	14.62	13.30	14.45
Tenacity CV%	7.11	5.90	7.53	6.01	8.18	6.44	9.10	6.89

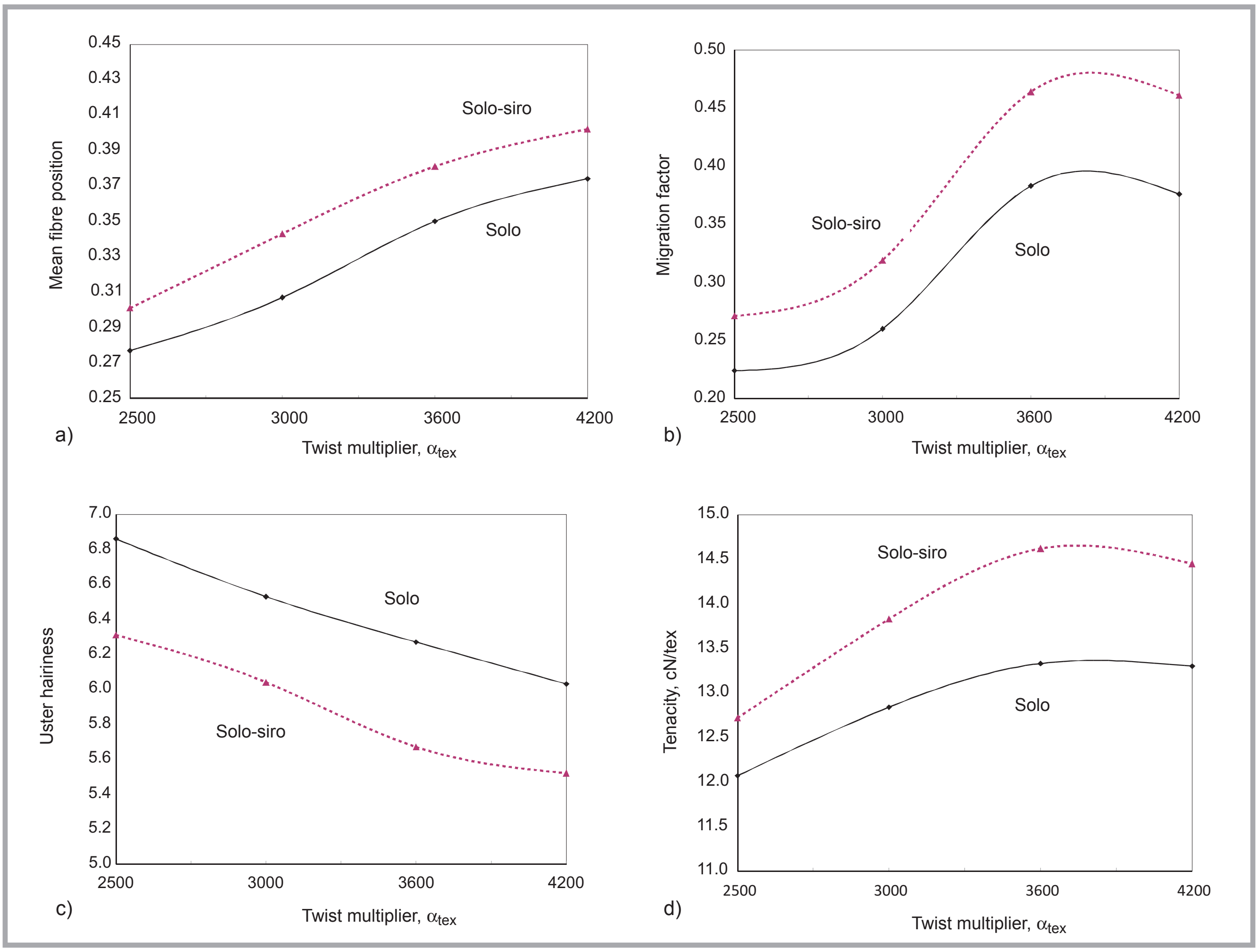

Figure 1. *Variation of: a) mean fibre position, b) migration factor, c) Uster hairiness, d) yarn tenacity with twist multiplier.*

intensity and migration factor, are fundamental in characterising spun yarn properties.

Figure 1.a reveals that at all levels of twist multiplier, Solo-siro spun yarns enjoy a higher mean fibre position. The mean fibre position value characterises the average radial position of a fibre in a yarn cross-section and shows the overall tendency of a fibre to be near the yarn surface or yarn center. A higher mean fibre position of Solo-siro spun yarns indicates that the amplitude of fibre migration is higher for them than for Solo spun yarns, which contributes to the higher tenacity of Solo-siro spun yarns. For both types of yarns the value of mean fibre position is below that of 0.5, indicating that the density is greater near the center of the yarns since the mean fibre position in a uniform yarn with complete migration would be closer to 0.5 [13].

Referring to ***Table 1***, in comparison with Solo spun yarns, Solo-siro spun yarns enjoy higher RMS deviation at all twist multipliers. The root mean square deviation is of particular interest for spun yarns since it represents the root-mean-square value of the radial deviation of the helix profile from the mean fibre position calculated from the experimental data [18]. A higher RMS deviation in Solo-siro spun yarns signifies that migration in Solo-siro spun yarns is deeper across the yarn cross section compared with Solo spun yarns. In other words, the density of these yarns is higher, and consequently the RMS deviation values are higher. A higher density would also infer higher fibre to fibre interaction and thus higher tenacity [15].

Migration intensity shows the rate of change in the radial position of a fibre and is considered to be a significant parameter when discussing the results of a migration study. Referring to ***Table 1***, at all twist multipliers Solo-siro spun yarns enjoy the highest migration intensity compared with Solo spun yarns.

The total degree of migration in a yarn is expressed by the migration factor. ***Figure 1.b*** depicts the variation in the migration factor at different twist multipliers for Solo-siro and Solo spun yarns. The results show that at all twist multipliers Solo-siro spun yarns enjoy a higher migration factor compared with conventional ring-spun yarns, which is due to the higher RMS deviation and migration intensity of these yarns.

For both yarns the effect of increasing the twist multiplier is a rise in the value of the mean fibre position and mean migration intensity. This is a well known phenomenon which has been observed in spun yarns by many researchers [1, 2, 10 and 12]. As the yarn twist increases, more tension in outer fibres is created and a more compressive force developed on the innermost fibres in the spinning triangle, which offers higher migration parameters.

The significance of differences between the mean values of migration parameters was determined by an ANOVA test. Statistically both the spinning system and twist multiplier were found to have a significant effect on yarn migration parameters.

Table 2. Effect of twist multiplier on proportion of broken fibres and length of failure zone for Solo spun yarns.

Twist multipliers- α_{tex}	2500	3000	3600	4200
Broken fibres, %	61	66	75	78
Length of failure zone, mm	4.06	3.61	2.75	2.66

Table 3. Effect of twist multiplier on proportion of broken fibres and length of failure zone for Solo-siro spun yarns.

Twist multipliers- α_{tex}	2500	3000	3600	4200
Broken fibres, %	72	80	86	87
Length of failure zone, mm	2.88	2.19	1.60	1.52

Yarn physical properties

Values of yarn hairiness and yarn evenness at different twist multipliers are given in ***Figure 1.c*** and ***Table 1***, respectively. As illustrated in ***Figure 1.c***, for both yarns hairiness decreases as the twist multiplier increases, which is due to increased fibre migration and the trapping of surface fibres. As can be observed, Solo-siro spun yarns enjoy lower hairiness in comparison with Solo spun yarns, which is due to higher migratory properties induced by the special yarn formation mechanism of Solo-siro spun yarns. Results also indicate that at all levels of twist multiplier, Solo-siro spun yarns enjoy a lower uster CV% compared with Solo spun yarns.

Yarn mechanical properties

Tables 2 and ***3*** show the percentage of broken fibres and the length of the failure zone for Solo-siro and Solo spun yarns produced at different twist multipliers. As can be seen, at all twist multipliers Solo-siro spun yarns have the shortest failure zone length and largest number of broken fibres. The interlocking of fibres provided by better migration thereof improves the gripping of the fibre bundle, as a consequence of which yarn failure is dominated by the breakage of fibres (fibre tenacity) rather than by the weakening of the structure due to the slippage of fibres [18]. Therefore the larger the proportion of broken fibres, the higher the yarn tenacity would be. Results also indicate that for both yarns, by increasing the twist multiplier, the proportion of broken fibres goes up and the yarn failure zone length decreases.

Variation in the yarn tenacity with the twist multiplier is depicted in ***Figure 1.d***. Results signify that by increasing the twist multiplier (α_{tex}), the yarn tenacity increases up to 3600, beyond which it drops slightly. The reduction in yarn strength by increasing the twist multiplier (α_{tex}) from 3600 to 4200 may be explained by a reduction in the spinning-in-coefficient, a lower migration factor and the obliquity of fibres in the yarn body.

Another finding worthy of mention is that at all levels of twist multiplier Solo-siro spun yarns enjoy an appreciably higher tenacity compared with Solo spun yarns. The superior strength of Solo-siro spun yarns lies in their structure (interlocking of fibres provided by deeper fibre migration), a higher proportion of broken fibres, a higher evenness as well as lower hairiness compared to those in Solo spun yarns. As illustrated in ***Figure 1.d***, the superiority of Solo-siro spun yarns in terms of tenacity is more pronounced at higher twist multipliers.

The significance of differences between mean values of yarn strength was determined by two way ANOVA. Statistically both the spinning system and twist multiplier were found to have a significant effect on yarn strength parameters.

Conclusions

The mechanical and physical properties of spun yarns and fabrics depend not only on the properties of constituent fibres but also on the yarn structure as characterised by the geometrical arrangement of fibres in the yarn body. We attempted to establish a structure-property relationship for Solo-siro spun yarns.

The results showed that Solo-siro spun yarns enjoy a higher mean fibre position, higher migration factor, a greater proportion of fibres which are broken during yarn failure and lower hairiness. Results showed that higher migration parameters mean the yarn forms a coherent self-locking structure in which fibre slippage is restricted. The tensile deformation of such a yarn is dominated by fibre breakage rather than by the weakening of the structure due to fibre slippage, thereby increasing yarn strength and elongation.

It is hoped that the results of this study will allow us to make the first step towards establishing a "process-structure-property" model for Solo-siro spun yarns which can be used to optimise and improve the new Solo-siro spinning technology. Thorough experimental work is under way and the results will be reported in a separate paper.

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