

## Review Articles

# Yarn structure - properties relationship

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Yarn structure and its relationship with the properties have attracted many researchers and scientists. This has resulted in a large number of published research works scattered in many places. The importance of this subject has increased due to the need of yarn with best possible quality at optimum cost. Also, the diversification of textiles in various products, such as technical textiles, where performance is the main criteria, necessitated better yarn engineering. An attempt has been made to analyse the study reported in this subject area.

**Keywords:** Core yarn, Elongation-at-break, Mean fibre extent, Migration parameters, Packing fraction, Sheath yarn, Single yarn tenacity, Wrapper fibre, Yarn evenness, Yarn imperfections

## 1 Introduction

Yarn can be defined as a product of substantial length and relatively small cross-section consisting of fibres and/or filaments with or without twist<sup>1</sup>. It forms an important immediate stage in many methods of textile production. Despite the growing use of several forms of nonwoven fabrics (directly assembled fibres), fabrics composed of interlaced yarns will remain of predominant importance for many years. Amongst the yarns, the continuous filament yarns are the simplest in structure, but they are now being subjected to many modifying processes designed for bulkiness, texture, extensibility and other properties. Spun yarns made of staple fibres have the additional complexity of the discontinuities at the fibre ends and difference in structures due to difference in spinning technologies. The interest in the studies of yarn structure and its influence on properties is continuing from 1950s. In this paper, the work carried out on structure and properties of staple fibre yarns during the last 15-20 years has been reported.

## 2 Structural Analysis of Yarn

The tracer fibre technique introduced by Morton and Yen<sup>2</sup> is being used till date as a reliable method to study the path of the fibre in the yarn. Alagha and Oxenham<sup>3,4</sup> adopted an image processing method for analyzing the structure of friction-spun yarn, which provided several benefits over the traditional microscopic method. They obtained the data two-

dimensionally and recommended that the improvement is needed to refine the analysis procedure so it could be done automatically. Huh *et al.*<sup>5</sup> carried out the three dimensional analysis of migration and staple yarn structure.

It is observed that any single parameter cannot characterize the migration pattern in view of its statistical nature. Ishtiaque *et al.*<sup>6,7</sup> adopted the approach of cutting cross-sections of yarns and attempting to characterize the radial positioning of fibres in the yarn. They used the technique of soft cross-section for cutting the yarn samples. They used a coating of polyvinyl acetate before cutting the yarn section by microtome. After drying, the samples were embedded in a mixture of molten wax and paraffin by pouring the mixture to a receptacle, in the middle of which yarn was positioned. The thickness of the cross-section was maintained at 25  $\mu\text{m}$  and xylene was used as immersion liquid while viewing under microscope. Jiang *et al.*<sup>8</sup> also made yarn cross-sections to analyse the radial packing density. They utilized personal computers to capture and store the image from microscope. Fu *et al.*<sup>9</sup> used hi-scope video microscope to analyse the longitudinal and cross-sectional fibre arrangement in a yarn. An attempt has been made by them to simulate three dimensional view based on those observations.

Some researchers studied the yarn structure by analysing the surface appearance and structure<sup>10-13</sup>. Cybulska<sup>10</sup> and Basu<sup>11</sup> used image analysis for this purpose. A microscopic image of a yarn was registered by camera, sent to computer, and then

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processed and analysed by the software. Soe *et al.*<sup>14</sup> used a digital camera to investigate the visual assessment of the yarn surface structure.

It can be seen that the methods used by various researchers broadly followed two approaches. One group tried to study the fibre configuration inside the yarn using migration and cross-section of the yarn while the other group studied the surface structures. Both groups tried to correlate the structural parameters with yarn properties. For yarns produced by ring spinning method, the former method was followed in most of the cases, whereas for yarns spun using unconventional method the surface structure method was used predominantly.

### 2.1 Structural Features of Ring-spun Yarns

The yarn, spun by ring spinning method, is being used for longer period as compared to the yarns, spun by unconventional methods; its migration behaviour is well researched and documented. Ishtiaque<sup>15</sup> reported that the fibre packing density across the yarn cross-section is not uniform and that it is not highest at yarn core. Najar *et al.*<sup>16</sup> used wool and acrylic fibres to produce the yarns. They found that the migration index for the acrylic component is positive for all three yarns used by them. It is deduced that the acrylic fibre is preferably positioned in the outer layer and wool fibre migrates towards the inner layer of the blended yarns. The lower tensile modulus and higher denier of acrylic fibre may be responsible for its outward migration.

Anandjiwala *et al.*<sup>17</sup> compared the ring yarns made from intimate (blow room) blended and draw frame blended cottons and found that the compactness of upland (shorter and weaker) fibres is slightly higher than that of Pima (longer and stronger) fibres in the core of the yarn. They observed that the net distribution of fibre packing follows a trend. The maximum number of fibres in the centre decreases gradually to reach the minimum number of fibres at the outside periphery. This finding is similar to the findings of Goswami *et al.*<sup>18</sup>. Anandjiwala *et al.*<sup>17</sup> observed that the preferential distribution of two fibres varies with the blending method but the net distribution of fibres remains similar.

### 2.2 Structural Parameters of Unconventional Spun Yarns

The introduction of new spinning technologies during 1970s opened up a new area in yarn structural parameters. The unconventional spinning technologies used different kinds of techniques for

either drafting or twisting. As a result, the fibre distribution as well as surface structure became different as compared to ring-spun yarns. Though many new technologies appeared during that time, only four or five systems could become commercially successful. The technologies, such as rotor spinning, air-jet spinning, friction spinning, air-vortex, compact spinning, wrap spinning, have become popular within those newly introduced systems.

#### 2.2.1 Rotor-spun Yarns

Many authors have classified yarn structure based on its surface morphology. Lawrence and Finikopulos<sup>19</sup> classified rotor-spun yarn structures into seven classes based on scanning electron micrographs. Class I may be termed as ordered structure, because few, if any, outer zone fibres are present and the fibres are uniformly twisted. In Class II, the loosely wrapped fibres are superimposed on the uniform structure of yarn core. Their wrapping angles differ from the twist angle of the core fibres and vary along the yarn length. In Class III, the outer zone fibres are loosely attached to the yarn and appear entangled. They give a hairy appearance to the surface structure. Class IV may be termed as multiple wrapped, because parts of the wrapping fibres are lightly coiled around the core, whereas their remainders adopt lower wrapping angles. In Class V, the outer zone fibres have an opposing helix to the twist helix of the core fibres, and their wrap angle can be up to 75°. In the case of Class VI, the surface fibre appears tightly and closely wrapped around the core. These sections of yarn look uniform and have no protruding fibre ends or loops. The angle of warp is approximately 90°. In Class VII, one or two fibres are observed tightly wrapped around the core at an angle of 90°, forming a belt shape owing to the locally concentrated winding. Several authors have studied the mechanism of wrapper formation<sup>19-21</sup>. It is reported that the number of wrapper fibre increases with increased rotor speed, reduced rotor diameter, reduced rotor groove angle, increased yarn count and fibre fineness. The rotor speed in relation to opening roller speed influences the fibre configuration in the yarn<sup>21</sup>.

Ishtiaque *et al.*<sup>22,23</sup> used the term spinning-in coefficient to express the mean fibre extent. Spinning fibre coefficient ( $K_F$ ) has been defined as shown below:

$$K_F = \frac{\sum_{i=1}^n L_i / n}{L} = \frac{L_0}{L}$$

where  $L_i$  is the individual fibre extent;  $L_o$ , the arithmetic mean of individual length projection along the axis of the yarn;  $n$ , the number of observations; and  $L$ , the mean fibre length.

It was observed by them<sup>23</sup> that for yarn samples made of viscose fibres of 1.5 denier and 44 mm length, the spinning-in coefficient for rotor yarn is 0.46 against a value of 0.69 for ring yarn. Kumar *et al.*<sup>24</sup> also studied the effect of spinning process variables on the packing density of rotor, ring and air-jet spun yarns.

### 2.2.2 Air-jet Spun Yarns

In air-jet spinning, the yarn formation principle is different from ring and rotor spinning and accordingly it produces yarn with unique structure. Lawrence and Baqui<sup>13</sup> reported that air-jet spun yarn consisted of an untwisted core of fibres and a surface layer of fibres wrapped around the greater part of the core. They classified the yarn into three types w.r.t. its structure. How *et al.*<sup>25</sup> observed that air-jet yarns are different from other yarns. Two parts, bundle fibres and outside wrapping fibres constitute the yarn. In the bundle fibres, a majority of the fibres are inclined at an angle of 5° – 10° in 'S' and 'Z' directions; sometimes the fibres are parallel to each other or crossed together. The outside wrapping fibres are gripped on the bundle fibres in different styles, such as a 'corkscrew like' wrapping, irregular wrapping, linked wrapping, even wrapping featuring the edge free and fibres wrapped evenly on the bundles, loose wrapping and non wrapped portions. Similarly, Basu<sup>12</sup> and Oxenham<sup>26</sup> classified the yarn structure into four classes. Basu and Oxenham<sup>27</sup> observed that the average length of wrapped structure is different for yarns made with different fibres, mainly due to fibre length and other fibre properties. Bhortakke *et al.*<sup>28, 29</sup> also studied the structure of polyester/cotton air-jet spun yarns. In another study, Oxenham and Basu<sup>30</sup> studied the influence of nozzle designs on the structural parameters of air-jet spun yarn. The yarn properties can be optimized by changing the nozzle design parameters. Chasmawala *et al.*<sup>31</sup> reported that the prominent feature of air-jet spun yarn is the predominance of leading hooks. These hooks could have originated in the carding process or could be due to either air currents or the frictional resistance encountered by the fibres at the point of entry into the nozzles. In contrast, Punj *et al.*<sup>32</sup> observed that while using polyester-viscose blended yarn for analysis, there is a majority of trailing hooks as compared to

leading and both sides hooks. Viscose fibre has more hooking tendency as well as more hook extent than polyester fibre.

Ishtiaque and Khare<sup>6</sup> observed that fibre packing density for ring, rotor and air-jet blended yarns is not uniform across the yarn cross-section. Of all the three yarns, rotor yarns show maximum packing density followed by ring-spun and air-jet spun yarns in the first zone (of five equal width zones) from the core. On the other side, air-jet spun yarn shows least packing density followed by rotor- and ring-spun yarns in the outermost zone of the yarn cross-section. In air-jet spun yarn, fibres are mostly packed in the first three zones, last two zones showing least packing density in comparison with the other two. However, the total packing coefficient, calculated as the ratio of the total area of fibres in the cross-section to the yarn cross-section, is maximum for air-jet spun yarn followed by ring and rotor yarns.

Punj *et al.*<sup>33</sup> found that in air-jet spun yarn, a maximum density occurs towards the yarn centre and it gradually decreases from core to surface. The latest development in air-jet spinning technology is vortex spinning, in which yarn formation principle is different from conventional air-jet spinning<sup>34, 35</sup>. It is claimed that MVS yarn has a similar structure to ring-spun yarn. It consists of core of parallel fibres covered by the free fibres twisted over it<sup>35</sup>. Basal and Oxenham<sup>36, 37</sup> observed that vortex yarn has more ring yarn like appearance as compared to air-jet spun yarn. According to them, in air-jet spinning only the edge fibres become wrapper fibres. In vortex spinning, on the other hand, the fibre separation from the bundle occurs everywhere in the outer periphery of the bundle, resulting in yarn with much higher number of wrapper fibres as compared to air-jet spun yarns.

Artzt<sup>38</sup> opined that the amount of wrapping fibres, which is somewhat below 10% in classical air-jet spinning, has been increased considerably in air-vortex yarn. Tyagi *et al.*<sup>39</sup> reported that the vortex yarn consists of about 50-60% of core fibres and rest is wrapper or wild fibres.

### 2.3 Structural Characteristics of Friction-spun Yarns

In friction spinning technology, generally two methods are followed, namely open-end and core-sheath.

Lawrence *et al.*<sup>40</sup> observed 50% fibre extent in the yarn spun on a prototype friction spinning machine as against 90-95% in corresponding ring-spun yarn and 70-80% in rotor-spun yarns. Ibrahim<sup>41</sup> also reported

very poor fibre orientation and low fibre length utilization in polyester open-end friction-spun yarn.

According to Rust and Lord<sup>42</sup>, in the case of friction-spun yarns the mechanism that causes migration in ring yarns cannot be present since the fibres are applied more or less one at a time without the cyclic differentials in tension. The principal tension in friction spinning might occur only after the yarn structure is already formed, and the tensions acting on the fibre during assembly are likely to be very low. With the aid of the data of relative radial positions of fibres along the axial positions, they<sup>42</sup> observed that the fibres in the friction spinning process move inwards radially towards the apex of the cone as they are assembled into the yarn.

Ghosh *et al.*<sup>23</sup> observed that the OE friction-spun yarn exhibits a layer type of structure because the fibres are fed to the yarn tail at a different position along its length without tension. As a result, some fibres appear at the yarn surface and others close to the yarn centre. The average helix angle of fibres in this yarn is substantially higher than that of fibres in ring, rotor and air-jet yarns.

Similarly, Alagha and Oxenham<sup>4</sup> reported that the amplitude of migration is found to be highest for friction-spun yarns followed by rotor-spun and ring-spun yarns.

In contrast, Lawrence *et al.*<sup>40</sup> found no evidence of fibre migration from the macroscopically observations of successive cross-sections taken along the length of the yarn. They reported that the fibre paths progress from yarn surface inwards towards the yarn core. There was no crossing or intermingling of fibres to give a well-locked yarn structure.

In the case of second type of friction-spun yarn, there are distinct sheath and core components. The core consists of a filament or a bundle of staple fibres, which is false twisted<sup>43</sup>. The sheath fibres are wrapped helically over the core. Therefore, the structures of both core and sheath play important role. Some researchers reported that the core exhibits twist<sup>44-47</sup>. Merati *et al.*<sup>45</sup> analyzed false twist distribution in the filament core of a friction-spun yarn.

Tyagi *et al.*<sup>48</sup> found that the packing density in inner three zones (out of five concentric zones of equal radial distance) was found to be considerably higher and gradually decreased towards the outer surface. Ishtiaque and Agarwal<sup>49</sup> observed that twist distribution in a sheath is non-linear, i.e. the twist is

not uniformly distributed along the length of the fibres. The twist per unit length in leading end is less than that in the trailing end of the fibre. Variation in twist can be due to the sliver positioning in the feeding zone of the sheath fibres.

#### 2.4 Structure of Compact-spun Yarns

Compact spinning, which is a modified version of ring spinning, has drawn attraction of various researchers. In compact spinning, the fibre stream coming out of the drafting unit is condensed by means of pneumatic or any other mechanical compaction. As a result of this compaction, the structure of yarn changes along with its various characteristics. Due to the condensation of fibre flow, all the fibres lay close to each other and due to the absence of spinning triangle, all fibres are twisted to the yarn body<sup>50</sup>. The packing fraction calculated from the yarn diameter is higher for compact yarn as compared to that for ring yarn<sup>50-52</sup>.

According to Basal and Oxenham<sup>53</sup>, the statistical model shows that for both compact and conventional ring-spun yarns neither the twist nor the spinning system have any significant effects on the mean fibre position. However, the compact yarn has slightly smaller mean fibre position value. The mean fibre position was in the range of 0 – 5 for both types of yarns, indicating that the density is greater near the centre of the yarns. The compact spinning system produces yarn with higher mean migration index. The root mean square deviation, the amplitude of migration, is also higher for compact yarn, which indicates that the fibre migration in compact-spun yarn is deeper across the yarn cross-section in comparison with that in conventional ring-spun yarn.

In contrast, Ganesan *et al.*<sup>54, 55</sup> observed that for both pneumatic compacting and mechanical compacting systems, the compact-spun yarn has less mean fibre position, root mean square deviation and mean migration intensity, as compared to conventional ring-spun yarn.

Besides compaction during ring spinning some researchers attempted to make the yarn compact and to reduce air hairiness by using various attachments on conventional machines. Wang *et al.*<sup>56</sup> and Cheng and Li<sup>57</sup> used air-jet nozzle after front roller of the ring frame. They observed that the yarns produced by this system are much leaner with fewer long hairs on the surface due to wrapping of surface fibres by the swirling air currents in the air-jet.

### 2.5 Yarns Produced by Other Systems

The wrap spinning works on the principle of wrapping filament on a staple core yarn. With the increase in wraps per unit yarn length, the yarn becomes more compact, i.e. the fibres in the yarn pack more closely<sup>58, 59</sup>. Waviness on the yarn profile is developed during wrapping of filament around core fibre bundle due to high dynamic radial pressure exerted by the wrapping element during the spinning process<sup>60</sup>. Su *et al.*<sup>61</sup> examined the structure of elastic core-spun yarn. According to the position of spandex in the yarn, they classified the structure into four categories. Su and Leu<sup>62</sup> produced composite yarns spun from multifilament and staple fibres. Based on the study of cross-sectional structures they classified the structure into five representative classes. They observed that the size of the traveller influences yarn spinning tension, causing different fibre migrations inside the yarn structure and directly influencing the cross-sectional structure of composite yarns.

Ishtiaque *et al.*<sup>7</sup> studied the structural features of siro-spun yarn and observed that the fibre packing density is not uniform across the yarn cross-section and it is not maximum at the core. The maximum packing density occurs at  $1/3^{\text{rd}}$  of the yarn radius from the yarn axis. Siro yarns are more compact near the yarn axis as compared to ring-spun yarns. The total packing density of normal ring yarn is less than that of siro yarn. The cross-sections of siro yarns show a close resemblance to that of single ring-spun yarn compared to conventional double yarn. Study by Johari<sup>63</sup> revealed that the fibre extent of siro-spun yarn improves with increased strand spacing. The diameter of yarn also reduces with the increased strand spacing.

Lawrence and Chiu<sup>64</sup> studied the structural features of woolen yarns, spun by disc ring spinning system developed by them. They observed that as per fibre configurations, the yarn structure could be grouped into seven classes.

Zhang and Li<sup>65</sup> and Sawhney and Kimmel<sup>66</sup> studied a spinning method, which is a combination of friction and air-jet spinning. According to them the structure of friction-air-jet compound spun yarn resembles with the structure of Dref 3 friction-spun yarn except that it has a core, which is fully parallel to yarn axis and twistless as compared to the one in Dref 3 yarn, which exhibits both straight and twisted portions.

Chongwen<sup>67</sup> and Topf<sup>68</sup> reported a new spinning concept, namely open-end spinning. The structure of

the yarns, spun by their system, resembles with rotor, open-end friction or vortex-spun yarns. The open-end jet spun yarn has a true false twist structure and its appearance is closer to that of rotor-spun yarn, particularly with respect to wrappers<sup>68</sup>. The arrangement and orientation of fibres in the yarn are inferior to that of rotor-spun yarn but superior to that of friction-spun yarn.

Miao and Lui<sup>69</sup> conducted microscopic examination of self-twist (repc) yarn and found that the wrap fibres with traces of entanglement occurred in both self-twisted and zero-twisted parts.

### 3 Structure-properties Relationship

Beside the fibre properties, yarn structure is the most important factor which influences the properties. If the relationship is understood, the yarn structure can be modified for changing the yarn properties.

Anandjwala *et al.*<sup>17</sup> observed that the intimated blended (two cottons) ring yarns show better tensile strength than draw frame blended yarns, even though the high strength constituent fibres are positioned in the core of the yarn. This is because non-uniform fibre distribution resulting from blending of different fibres affects the migratory behaviour of fibres. The tensile failure of such yarns is governed by the mode of fibre breakage and fibre slippage as determined by the yarn structure, fibre distribution and migration.

Choi and Kim<sup>70</sup> used the 'surface length distribution' of fibres, i.e. the segment of fibre length which appears on the surface of the yarn to study its influence on the abrasion resistance of the yarn. They observed that the yarn abrasion resistance is inversely proportional to the average surface length with a coefficient of determination ( $R^2$ ) value of 0.948.

Lawrence *et al.*<sup>40</sup> reported that rotor-spun yarns are weaker than ring-spun yarns due to their structural difference. The tenacity value of cotton air-jet spun yarn is 55-60% of that of similar ring-spun yarn and this value is 80-85% for polyester and polyester/cotton blended yarns<sup>71</sup>. Sreenivasamurthy *et al.*<sup>72</sup> showed that single yarn tenacity of air-jet spun yarn is lower as compared to that of ring yarns but the elongation-at-break values are similar to ring yarns. It is reported<sup>73-75</sup> that in the case of polyester, viscose, acrylic or their blends with cottons, the difference in tenacity values is less.

Ghosh *et al.*<sup>23</sup> conducted a detailed study on the structure of ring, rotor, friction and air-jet spun yarns and its influence on their tensile properties. They observed that the OE friction-spun yarn is bulkier and

fibres in this yarn are most loosely packed, followed by rotor, ring and air-jet spun yarns. The interlocking of fibres due to their better migration in ring-spun yarn in comparison with others enhances the gripping of fibre bundle; hence the ring yarn is strongest at longer gauge lengths. When the gauge length is well below the fibre staple length, air-jet spun yarn displays the shortest failure zone length and its strength is even higher than ring-spun yarn. The open-end friction-spun yarn is the weakest as compared to others due to its poor fibre orientation. Realf *et al.*<sup>76</sup> and Cybulska *et al.*<sup>77</sup> reported similar findings. Soe *et al.*<sup>14</sup> observed that the difference in measured yarn properties of ring, open-end rotor and vortex-spun yarns could be explained by the difference in yarn structure.

The observations on the unevenness and imperfections of the yarns reported by various researchers<sup>71,72,78</sup> show a general trend. According to them air-jet spun yarn shows lowest unevenness, followed by friction, wrap, rotor-spun and ring-spun yarns. That is, friction-spun yarn has higher value than air-jet spun yarn, wrap-spun yarn has higher value than friction-spun yarn and so on.

It is well known by now that different yarn production systems produce yarns of different structures. Within a system also yarn structure can be modified by varying process parameters, which, in turn, changes the yarn properties. Basu<sup>11</sup> has reported that the structural parameters, such as incidence of wrappers per unit length of yarn, average length of wrapped zone and the average number of wraps per unit length of wrapped zone influence the yarn properties. They are highly correlated with yarn tensile properties.

Chasmawala<sup>31</sup> derived equations for air-jet spun yarns in which the yarn structure has been related to yarn properties. Basu<sup>79</sup> observed that the physical properties of air-jet yarns are correlated with structural parameters. Rajamanickam *et al.*<sup>80</sup> formulated a computer simulation model for the prediction of yarn strength from the various parameters, including the number of wrapper fibres, the wrapping angle and the length of structural classes. The type of wrappers also determines the strength of yarn<sup>25</sup>. Punj *et al.*<sup>81</sup> reported that for blended (polyester/viscose) and 100% polyester yarns the evenness improves with the decrease in polyester fibre denier due to increased number of fibres per cross-section. The unevenness was maximum when

100% viscose yarn was produced due to higher unwrapped proportion in the yarn.

The wrap-spun yarn contains parallel fibre core wrapped with filament or yarn. The wrapping element exerts a radial tension on the parallel fibre core, thereby providing the necessary frictional force between the individual fibres in the core<sup>60</sup>. During tensile loading along the yarn axis, structural deformation takes place before ultimate failure. The breakage of wrap-spun yarn may be catastrophic or stick-slip type depending on the physical properties of the wrapping element, wrap density, etc.<sup>82</sup> The breaking strength of wrap-spun yarn increases with the increase in wrap density up to a certain level and then decreases. Breaking elongation follows similar trend.

Park and Oh<sup>83</sup> observed that the yarn bending rigidity depends on the bending and torsional rigidity of its constituent fibres, the arrangement due to twist and the geometrical parameters such as the helix angle. They have derived the bending rigidity of yarn in theory from the tensile modulus and inertia moment of the constituent fibres.

#### 4 Conclusions

The yarn structure changes with the yarn production technology, process parameters and fibre parameters. Within a system of yarn preparation various authors have reported contradictory views. The ring yarn being in the system for so many years, many researchers considered the structure and properties of ring-spun yarn as standard. As a result they represented the structure and properties of unconventional yarns in relative to that of ring-spun yarn. For example, the yarn produced by rotor spinning is weaker than the ring yarn. This may be due to too much simplification as the usages of textile material are no longer restricted to conventional clothing material. According to end uses, the yarns produced by one of the unconventional methods may be more suitable as compared to conventional ring-spun yarn. The knowledge of the structure-properties relationship helps us in choosing ideal spinning system and parameters.

#### References

- 1 *Textile Terms and Definitions*, 10<sup>th</sup> edn, edited by J E McIntyre & P N Daniels (The Textile Institute, Manchester, U K), 1997.
- 2 Morton W E & Yen K C, *J Text Inst*, 43 (1952) T60.
- 3 Alagha M J, Oxenham W & Iype C, *J Text Inst*, 85 (1994) 383.

- 4 Alagha M J, Oxenham W & Iype C, *Text Res J*, 64 (1994) 185.
- 5 Huh Y, Kim Y R & Rye W Y, *Text Res, J*, 71(1) (2000) 81.
- 6 Ishtiaque S M & Khare S K, *Text Asia*, 24(2) (1993) 36.
- 7 Ishtiaque S M, Sharma I C & Sharma S, *Indian J Fibre Text Res*, 18 (1993) 116.
- 8 Jiang X Y, Hu J C, Cheng K P S & Postle R, *Text Res J*, 75(3) (2004) 233.
- 9 Fu P, Cheng L, Wang S, Zhou Y & Fan H, *Melliand Int*, (4) (2005) 290.
- 10 Cybulska M, *Text Res J*, 69(5) (1999) 369.
- 11 Basu A, *J Text Inst*, 91, Part I, (1) (2000) 179.
- 12 Basu A, *Influence of fibre type on properties of jet-spun yarn*, Doctoral thesis, Department of Textile Industries, University of Leeds, 1991.
- 13 Lawrence C A & Baqui M A, *Text Res J*, 61(3) (1991) 123.
- 14 Soe A K, Takahashi M, Nakajima M, Matsuo T & Matsumoto T, *Text Res J*, 74 (9) (2004) 819.
- 15 Ishtiaque S M, *Indian J Fibre Text Res*, 11 (1986) 208.
- 16 Nazar S S, Amani M & Hasani H, *J Text Inst*, 94 Part I (3, 4) (2003) 177.
- 17 Anandjiwala R D, Goswami B C, Bragg C K & Bargerion J D, *Text Res J*, 69(2) (1999) 129.
- 18 Goswami B C, Anandjiwala R D & Carmical M, Fibre properties for spinning on various systems, *J Appl Polym Sci, Appl Polym Symp.* (1991) 47, 463.
- 19 Lawrence C A & Finikopulos E, *Indian J Fibre Text Res*, 17 (1992) 201.
- 20 Kampen W, Lunenschloss J & Phoa T T, *Int Text Bull, Yarn Forming*, 3 (1997) 373.
- 21 Ishtiaque S M & Kumar P, *Indian J Fibre Text Res*, 19 (1994) 71.
- 22 Ishtiaque S M & Saxena A K, *Indian J Fibre Text Res*, 23 (1998) 141.
- 23 Ghosh A, Ishtiaque S M & Rengasamy R S, *Text Res J*, 75(10) (2005) 731.
- 24 Kumar A, Ishtiaque, S M & Salhotra K R, *Autex Res J*, 6(3) (2006) 122.
- 25 How Y L, Cheng K & Wong S, *Text Asia*, 22(11) (1991) 51.
- 26 Oxenham W, *Indian J Fibre Text Res*, 17 (1992) 194.
- 27 Basu A & Oxenham W, *Indian Text J*, 102 (11) (1992) 60.
- 28 Bhortakke M K, Nishimura T, Matsuo T, Ivone Y & Morihashi T, *Text Res J*, 67 (1997) 107.
- 29 Bhortakke M K, Nishimura T & Masico T, *Text Res J*, 69(2) (1999) 84.
- 30 Oxenham W and Basu A, *Text Res J*, 63 (11) (1993) 674.
- 31 Chasmawala R J, Hansen S M & Jayaraman S, *Text Res J*, 60(1) (1990) 61.
- 32 Punj S K, Ishtiaque S M & Dhingra L K, *Indian J Fibre Text Res*, 22(2) (1997) 73.
- 33 Punj S K, Debnath S & Chowdhury A, *Indian J Fibre Text Res*, 26 (2001) 251.
- 34 Wray G M, How M V S makes yarn? *Proceedings, EFS Seminar* (Cotton Incorporated, Raleigh, U.S.A.), 1999.
- 35 Oxenham W, *J Text Apparel Technol Mgmt*, 1 (1) (2001) 1.
- 36 Basal G & Oxenham W, *Autex Res J*, 3(3) (2003) 96.
- 37 Basal G & Oxenham W, *Text Res J*, 76(6) (2006) 492.
- 38 Artzt P, *Melliand Int*, 6 (2006) 107.
- 39 Tyagi G K, Sharma D & Salhotra K R, *Indian J Fibre Text Res*, 29(4) (2004) 419.
- 40 Lawrence C A, Foster W, Wilding M, Howard A & Kudo R, *A study of the structure and properties of friction spun yarns*, paper presented at the VI International IZMIR Textile Symposium, 1992.
- 41 Ibrahim A R B, *Indian J Fibre Text Res*, 20 (1995) 211.
- 42 Rust J P & Lord P R, *Text Res J*, 61 (1991) 645.
- 43 Gowda R V M, *New Spinning Systems* (NCUTE, India), 2006, 100.
- 44 Dharniya S, *Twist structure and quality aspects of friction spun yarns in relation to raw material and process parameters*, Doctoral thesis, Department of Textile Technology, Indian Institute of Technology, New Delhi, India, 1999.
- 45 Merati A A, Konda F, Okamura M & Maruo E, *Text Res J*, 68 (1998) 441.
- 46 Gowda R V M, *Influence of frictional characteristics of core and sheath on structure, twist and tensile properties of DREF3 friction spun yarns*, Doctoral thesis, Department of Textile Technology, Indian Institute of Technology, New Delhi, India, 2001.
- 47 Ishtiaque S M, Das A & Vishnoi P, *J Text Inst*, 96 (5) (2005) 339.
- 48 Tyagi G K, Kaushik R C D & Salhotra K R, *Indian J Fibre Text Res*, 25 (2000) 20.
- 49 Ishtiaque S M & Agarwal D, *J Text Inst*, 91, Part I (2000) 546.
- 50 Dash J R, Ishtiaque S M & Alagirusamy R, *Indian J Fibre Text Res*, 27 (2002) 362.
- 51 Subramanian S N, Venkatachalam A & Subramaniam V, *Melliand Int*, 2(2006) 107.
- 52 Artzt P, *Int Text Bull, Yarn and Fabric Forming*, (2) (1997) 41.
- 53 Basal G & Oxenham W, *Text Res J*, 76(7) (2006) 567.
- 54 Ganesan S & Ramakrishnan, *Indian J Fibre Text Res*, 31(3) (2006) 381.
- 55 Ganesan S, Venkatachalam A & Subramaniam V, *Indian J Fibre Text Res*, 32(2) (2007) 163.
- 56 Wang X, Miao M & How Y, *Text Res J*, 67 (4) (1997) 253.
- 57 Cheng K P S & Chi Li, *Text Res J*, 72 (12) (2002) 1079.
- 58 Sharma I C, Chatterjee K N, Mukhopadhyay A & Ray W C, *Indian J Fibre Text Res*, 22 (1997) 89.
- 59 Miao M & Chen R, *J China Text Univ*, 8 (1991) 1.
- 60 Roy A N & Basu G, *Indian J Fibre Text Res*, 26 (2001) 246.
- 61 Su C I, Maa M C & Yang H Y, *Text Res J*, 74 (7) (2004) 607.
- 62 Su C I & Leu C S, *Text Res J*, 68 (10) (1998) 715.
- 63 Johari M S, *The application of SIRO spun technology for processing of short staple fibres*, Doctoral thesis, Department of Textile Industries, University of Leeds, U.K., 1991.
- 64 Lawrence C A & Chiu S F, *Text Res J*, 66 (3) (1996) 158, 164.
- 65 Zhang W & Li L, *Text Asia*, June (1996) 63.
- 66 Sawhney A P S & Kimmel L B, *Text Res J*, 65 (9) (1995) 550.
- 67 Chongwen Y, *Text. Res J*, 69(7) (1999) 535.
- 68 Topf W, *Melliand Int*, 6, March (2000) 21.
- 69 Miao M & Lui K K, *Text Res J*, 67 (3) (1997) 188.
- 70 Choi K F & Kim K L, *Text Res J*, 74(7) (2004) 603.
- 71 Stalder H, *Text Asia*, 21(2) (1990) 59.
- 72 Sreenivasamurthy H V, Chattopadhyay S K, Parthasarathy M S & Srinathan B, *Feasibility of Air-jet spinning of Indian*

- cotton and their blends with polyester*, paper presented at the 49<sup>th</sup> All India Textile Conference, Bombay, India, 1993.
- 73 Kaushik R C D, Salhotra K R & Tyagi G K, *Indian J Fibre Text Res*, 17 (1992) 219.
- 74 Sengupta A K, Chattopadhyay R & Das Pal D, *Indian J Fibre Text Res*, 17 (1992) 215.
- 75 Punj S K, Mukhopadhyay A & Chakrabarty A, *Indian J Fibre Text Res*, 23 (1998) 19.
- 76 Realff M L, Se M C, Schwart P & Backer S, *Text Res J*, 61(9) (1991) 517.
- 77 Cybulska M, Goswami B C & Mac Alistar III, D, *Text Res J*, 71(12) (2001) 1087.
- 78 Punj S K, Mukhopadhyay A & Maity T, *Indian J Fibre Text Res*, 22 (1) (1997) 1.
- 79 Basu A, *Asian Text J*, (2000) 63.
- 80 Rajamanickam R, Hansen S M & Jayaraman S, *Text Res J*, 67 (1997) 223.
- 81 Punj S K, Behera B K & Sen A, *Text Asia*, 4 (1995) 38.
- 82 Khatua D P, Aditya R N, Mukherjee S, Neogi S K & Bhattacharya P K, *Proceedings, National Seminar on Jute and Allied Fibres* (Jute Technological Research Laboratory, Calcutta, India), 1989.
- 83 Park J W & Oh A G, Bending rigidity of yarns, *Text Res J*, 76 (6)(2006) 478.