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Yarn structure and properties from different spinning techniques

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Abstract: This chapter presents a systematic and comprehensive study of unconventional staple yarns, their structural features, properties, factors influencing their properties, structure–property relationships, applications, and the possibilities for future developments. The quality aspects of ring, rotor, air-jet and friction spun plied yarns are also discussed.

Key words: air-jet spinning, Dref-3 friction spun yarn, plied yarns, rotor spun yarn, wrapper fibres, wrap spinning.

5.1 Introduction

The textile industry has witnessed many exciting technological innovations in spinning machines since the late 1960s. Machinery manufacturers looked for alternatives to ring spinning which seemed to have reached a plateau in regard to maximum production speeds. Ring spinning offered little scope for further development and impeded all efforts directed towards automation of the whole spinning process. The power consumption was also seen to be disproportionately high at faster spindle speeds. These disadvantages laid the foundation for the development of alternative methods of spinning, particularly for higher production speeds. As a result, various new spinning technologies based on radically different principles of fibre consolidation appeared. Among the new spinning technologies introduced in the late sixties and early seventies, only rotor spinning established itself on a significant scale in comparison to ring spinning, going on to claim a major share of coarse yarn production. This was achieved mainly on the basis of its lower cost of production and amenability to automation. Despite these positive aspects, there was a growing realization that rotor spun yarns would have limited end uses, particularly as these yarns impart a harsh feel to the fabric. These constraints therefore restricted rotor spinning to coarse and medium counts.

Research and development of other high production technologies for finer counts resulted in three prominent systems: air-jet, friction and wrap spinning. All three have met with varying degrees of acceptability. The air-jet

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system appeared to offer real promise of commercial success because of its technological superiority to conventional systems over the finer yarn count range of 7.5 tex to 12 tex. Friction spinning, on the other hand, produced yarns of more acceptable quality due to their pliability imparted by real twist. This system offers greater scope in production of high-tech yarns for technical fabrics, filters and other applications. Wrap spinning, which appeared in commercial form earlier than air-jet and friction spinning, has become important for certain specific applications where the use of a filament binder is not objectionable. Further studies into spinning technologies brought out the drawbacks in these new yarns and led to the current practice of engineering yarns for producing specific textile substrates. There is a consensus that each of these technologies produces different structural features depending mainly on the properties of the constituent fibres and the inherent characteristics of the processing system. These differences in internal structure are reflected in different performance characteristics.

The following sections are intended to deepen understanding of structure, properties and influencing parameters, structure–property relationships, quality control and end uses of the yarns spun by ring and new spinning technologies.

5.2 Ring spun yarns

5.2.1 Structural features of ring spun yarns

Surface structure

Most yarns made from staple fibres are ring spun yarns. The twist that provides the final entanglement is built up from the outside to the inside. Although a high quality ring yarn first appears to be as uniform as a filament, closer microscopic examination would reveal a uniform helical arrangement of fibres at the surface, as shown in Fig. 5.1. Also noticeable would be an outer fringe of fibres known as the fuzz-zone caused by protruding fibre ends. The twist is the same across the yarn cross-section (Chattopadhyay, 1993). Consequently, if twist is removed by untwisting on a twist tester, one may observe a parallel bundle of fibres at some point of time, indicating complete removal of twist. Fibres can be highly packed in the yarn and thereby produce a compact structure. The packing coefficient generally ranges between 0.5 and 0.6. The closed packing is caused by the high level of tension acting on the fibres at the yarn formation point.

Migration

The term fibre migration is used to describe the relative movement of a fibre with respect to neighbouring fibres during the process of twist insertion into

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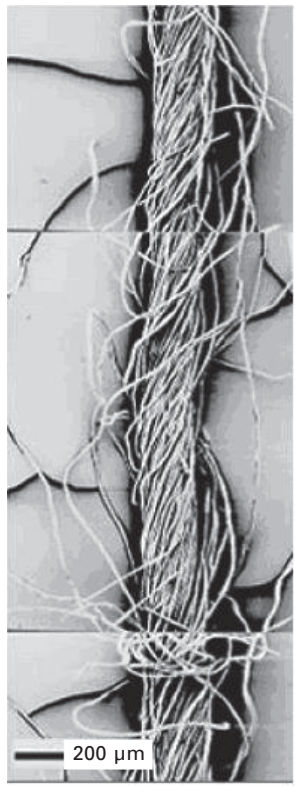

5.1 Ring spun yarn surface structure.

the fibre assembly and the ultimate position of the fibre in the final yarn structure. The phenomenon of fibre migration in the processing of fibres, filaments and blends has been studied by many since the earlier work of Morton and Yen (1952). A very thorough treatment of fibre migration in yarn structure is found in structural mechanics of fibres, yarns and fabrics by Hearle *et al*. (1969).

Fibre migration, which is expressed by various parameters and indices, depends on fibre properties, the characteristics of the fibre assembly, and the processing conditions. The fibre properties include length, degree of elasticity, stiffness and fineness. Short, coarse and stiffer fibres move out of the core towards the sheath, while long, fine and flexible fibres move towards the core. Strongly crimped fibres are also found predominantly in the sheath. In blends of fibres with substantially different processing characteristics, preferential radial migration occurs; one component of the blend is found primarily in the core and the other component mostly near the surface.

Fibre migration is caused largely by the existence of varying fibre tensions at the point where the strand is twisted. Fibres at high tension try to relieve

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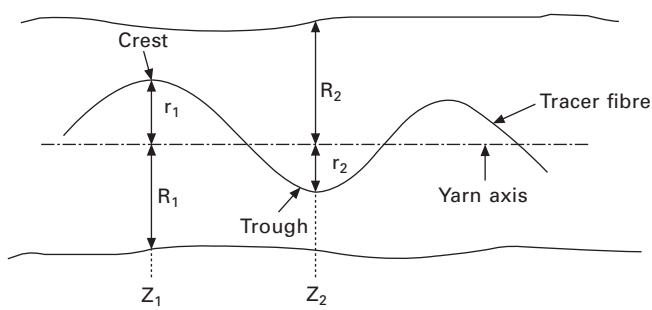
their tensions by migrating to the core. Relatively slack ones are displaced outwards. In ring spinning, the fibre tensions are generated in the delta zone where the fibres leave the nip of the front drafting rollers and pass into the twisted yarn.

Table 5.1 shows the typical values of migration parameters for ring spun viscose rayon yarns. The mean fibre position has a value ranging between 0.33 and 0.38, implying greater packing density near the centre of the yarn with increasing twist. Migration takes place from the sheath to the core and vice versa. Root-mean-square deviation values are almost half of the value expected for ideal migration. The ideal migration pattern is essentially one in which the fibre migrates regularly and uniformly from the outside to the centre of the yarn and then back to the outside, in such a way that the density of packing of fibres in the yarn is constant throughout the yarn. The mean migration intensity values, which indicate the mean rate of change of radial position, range between 0.12 and 0.49 depending upon the level of twist (Hearle *et al.*, 1969). Figure 5.2 illustrates the cyclic path migration of the fibres moving from one cylindrical layer to another.

Table 5.1 Migration parameters in a spun rayon yarn

	Twist factor			Value for complete ideal migration
	2.1	3.0	6.0	
Mean fibre position	0.33	0.36	0.38	0.5
CV%	39	32	22	
RMS deviation	0.17	0.16	0.21	0.29
CV%	28	20	12	
Mean migration intensity (cm^{-1})	0.12	0.17	0.49	–
CV%	32	24	22	
Equivalent migration frequency (cm^{-1})	0.10	0.16	0.34	–
CV%	25	23	19	

Source: Hearle *et al.* (1969).



5.2 Tracer fibre path in ring spun yarn structure.

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5.2.2 Properties of ring spun yarns

Tensile properties

Breaking strength and elongation are two prime quality attributes of any spun yarn. The strength and elongation of a yarn are important to the processability of the yarn in the downstream processing and operational life of the substrate made with the yarn. The strength of a staple yarn is determined by various fibre properties, the yarn structural geometry and the spinning parameters. It is known that yarn strength increases first to a maximum value with increase in twist and then falls with further increases in twist. One traditional explanation of this change in strength with twist is based on the combination of slippage and breakage of fibres. At low twist factors, the initial increase in yarn strength is determined by the resistance of fibres to slippage. At high twist factors, the contribution from resistance to slippage reaches a steady maximum. However, as the twist factor becomes high, the effect of fibre obliquity comes into play, and this has a tendency to cause a decrease in yarn strength. The twist–strength relationship is therefore the result of the combined influence of these two factors. The twist at which yarn strength is highest is called the optimum twist. This optimum value of twist is largely determined by the fibre length, fibre fineness, fibre strength and the fibre coefficient of friction, in addition to the count of the yarn being spun.

Mass irregularity and imperfections

Another important quality parameter of the yarn is its mass unevenness along its length. This unevenness is the result of the variation in the number of fibre ends per unit length. Martindale (1945) showed that a random distribution of fibre ends would give the lowest unevenness, termed the ideal unevenness. The random distribution of fibre ends is based on the premise that each fibre is separate from the others and can move independently. The unevenness or irregularity increases as the fibre dynamics move away from this situation, which is the case for current spinning systems. For example, in ring spinning, roller drafting does not give a random distribution of fibres in the cross-section but a quasi-periodic variation due to the phenomenon of drafting wave formation in the drafted ribbon of fibres. Thus, when the ribbon is twisted to form the yarn, the drafting wave adds to the ideal unevenness, thereby increasing the irregularity of the spun yarn.

The important measures that can reduce yarn irregularity and associated imperfections are (1) individualization of fibres, (2) minimization of inter-fibre contact by greater fibre parallelization, and (3) control on the movement of short fibres. The first requirement puts greater demands on the carding operation, whereas the second requirement necessitates maximum parallelization during drawing, roving production and ring spinning. The control of the movement

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of short fibres depends on the sophistication of the drafting system as well as the fibre characteristics, especially fibre friction and the short fibre content. The inter-fibre cohesion too has marked influence on the mass irregularity. The cohesion which is influenced by inter-fibre friction can be controlled through roving twist, spacer and the draft.

Short, small, thick, or thin places may sometimes be caused by excessive amplitude of the drafting wave at the spinning machine. Their origin is in the drafting elements, most likely of the spinning machine. Carding at high speeds can increase their frequency. Neps are often caused in carding, and the phenomenon is more pronounced with finer and immature fibres.

Hairiness

Hairiness is a property which indicates the amount and length of fibre ends and loops protruding from the body of the yarn. It is a desirable property in certain situations and undesirable in other circumstances, depending upon the type of end-use and application of the resultant fabric. The hand and thermal insulation of textiles call for the most hairy yarn. On the other hand, high-speed knitting and weaving machines require a yarn structure in which protruding fibres are suppressed. An important consequence of the hairiness is the pilling of fabrics (Barella *et al.*, 1991). Yarn hairiness also influences the abrasion resistance of fabrics. Barella (1999) observed that the level of yarn hairiness depended on the number of fibres at the outer layer of the yarn that were not directly adhered to the body of the yarn. According to Wang *et al.* (1999), the looped hairs originate mainly from poorly aligned fibres, fibres with a U-shape or a large hook in the fibres, and the dynamic snap-back of fibres when during spinning they are suddenly released from the front roller nip of the drafting system. Mohamed *et al.* (1975) stated that fibre migration is responsible for the formation of looped hairs. Reducing the spinning triangle by increasing spinning tension may, however, reduce yarn hairiness (Stalder, 1991).

5.2.3 Factors affecting yarn properties

Fibre factors

Although several experimental investigations concerning the strength and elongation of staple yarns have been reported in the literature, it is important to know the order in which the fibre and other parameters affect yarn strength, so that appropriate attention may be paid to these factors during the selection of the raw materials and processing parameters. As the yarn is composed of fibres, it is evident that the tenacity and elongation of fibres will have a pronounced effect on yarn strength and elongation. Stronger fibres will therefore always lead to a stronger yarn. Usually the strength translation efficiency

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from fibre to yarn is 40–65%. The yarn elongation also depends upon fibre elongation. The yarn strength can be changed by altering the staple length of the fibres or by altering the fibre fineness. Increased fibre length leads to greater resistance to fibre slippage during yarn rupture, primarily because of longer overlapping lengths of fibres, and this causes an increase in strength. Finer fibres also increase the frictional resistance to slippage. The optimum twist level is reduced and the maximum strength is increased by increasing the staple length or the fibre fineness. This explains why a premium is placed on the longer staple fibres and why fine fibres are preferred for spinning. When fibres of similar nature are to be blended, their properties should be compatible especially in terms of length, fineness and elongation.

Yarn hairiness is another important quality attribute affected by the fibre parameters. Fibre fineness has the maximum influence on the hairiness, and is followed by fibre length. However, with cotton, maturity contributes very little towards hairiness. Using a heavier linear density increases the torsional stiffness of the fibre and makes it less likely that fibres will bend along with twist, resulting in increased hairiness.

Yarn factors

As the linear density of a yarn is reduced, the yarn strength is also reduced because of the lower number of fibres in the yarn cross-section. As explained earlier, high variations in the mass per unit length of slivers or rovings cause irregularities in the spun yarn and result in large variations in yarn strength. Proper selection of speeds of machine elements and adjustment of settings between various rotating parts and the optimization of twist will therefore ensure smooth processing and production of a good quality yarn.

Machine factors

Yarn hairiness can be regulated by selecting the ring frame draft and spindle speed. For a constant yarn count, hairiness increases with increase in these two factors. Increased spinning tension also increases yarn hairiness. High-production carding, chemical processing of fibres prior to spinning, poor ring frame conditions due to traveller flutter, and high levels of humidity can also cause excessive hairiness.

5.2.4 End uses of ring spun yarns

The ring spinning system can be used to produce very coarse to extremely fine yarns with a very large range of twist density from various types of fibres and their blends. Ring spun yarns can therefore be engineered to impart the desired hand, e.g. crispness or softness, to a fabric according to requirements.

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Ring spun yarns are widely used for shirts, trousers, nightwear, blouses, overalls, suits, skirts, sheeting, curtaining and other industrial textiles.

5.3 Rotor spun yarns

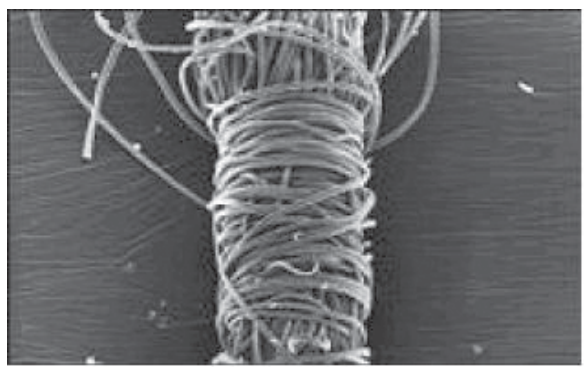
5.3.1 Structural features of rotor spun yarns

Surface structure

Figure 5.3 depicts the surface structure of a rotor spun yarn. As can be seen, a rotor spun yarn consists essentially of a three-part structure, namely, a densely packed core of fibres that are substantially aligned with the axis of the yarn, an outer zone of more loosely packed fibres which occurs irregularly along the core length, and the fibres that are wrapped around the outside of the yarn to form wrapper fibres of very small inclination (Nield, 1975). A detailed study of the surface structure of rotor spun yarns (Lawrence and Finikopulos, 1992) shows that the variation of surface appearance along the yarn length may be classified as indicated in Fig. 5.4. The number of wrapper fibres increases with rotor speed, reduced rotor diameter, reduced rotor groove angle, increased yarn count, fibre length and fibre linear density. The length of the yarn formation zone has a decisive effect on the incidence of wrapper fibres; the longer the zone, the greater is the incidence. Wrapper fibres improve yarn abrasion resistance but reduce the wicking property of the yarn. For both short and long staple yarns, an increase in wrapper fibres results in deterioration in yarn strength and yarn density in general.

Migration

In rotor spinning, fibre migration is partially caused by the twist in the rotor groove and the manner in which the fibres are deposited on the forming



5.3 Rotor spun yarn surface structure.

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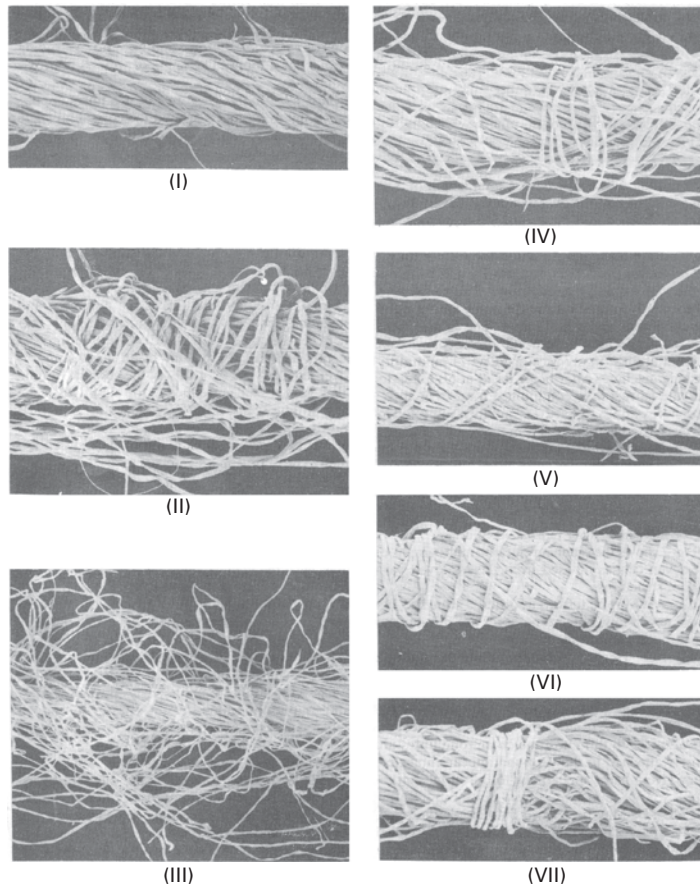

5.4 Scanning electron micrographs of rotor spun yarn surface structure: (I) ordered; (II) loosely wrapped; (III) hairy; (IV) multiple wrapped; (V) opposingly wrapped; (VI) tightly wrapped; and (VII) belt wrapped (Lawrence and Finikopulos, 1992).

yarn in the groove of the rotor. The fibre tensions in the rotor groove are much lower than those encountered in the delta zone of ring spinning. The result is that fibre migration is more local, as may be reflected by the lower values of the root-mean-square deviation. The root-mean-square deviation for a typical ring yarn is about 0.54, whereas it is only 0.44 for rotor yarn. If one looks at the mean fibre position in ring and rotor spun yarns, it would be seen that most of the migrating fibres in rotor yarn lie in the core. The preferential arrangement of fibre components in a blend is also lower for rotor than for ring spun yarns.

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Twist deviation

The twist of rotor spun yarns is in principle built up from the inside to the outside. Unlike for ring yarns, the measured twist values are lower than the machine twist values for rotor spun yarns, thus indicating that there is indeed fibre slippage during yarn formation within the rotor. This is an inevitable consequence of the system of yarn formation and is one of the reasons for the high machine twist setting requirements of rotor spun yarns. The difference between rotor and ring spun yarn can therefore be reduced only within certain limits by keeping the twist deviation as low as possible. The twist deviation is known to depend upon the rotor speed, the draw-off nozzle profile, and the speed of the opening roller (Manich *et al.*, 1986). These factors can be varied to avoid the danger of over-twisting. Yarn count, twist and blend level play a significant role in determining the amount of fibre slippage and, in consequence, the twist deviation. The heavier the yarn, or the greater the twist or the greater the polyester content, the greater the twist deviation (Lord and Grady, 1976). The fibre factors influencing twist deviation include fibre length, fineness, stiffness, finish and cross-sectional shape (Tyagi *et al.*, 2001).

5.3.2 Properties of rotor spun yarns

Rotor spun yarns appear to be no different from ring spun yarns on the surface. However, there exist some rather important differences in the internal structures of the yarns, especially in fibre contiguity. These differences in internal structures are reflected in different performance characteristics. Rotor spun yarns tend to be more uniform in appearance and in linear density than ring spun yarns. It is conceivable that the better short-term evenness of rotor spun yarn is an obvious result of the suppression of the drafting wave and the large packages formed in rotor spinning. Also, rotor spun yarns are known to be somewhat more extensible, fuller, softer and less hairy. The main disadvantage is that rotor spun yarns are not as strong as ring spun yarns, and the maximum tenacity of rotor spun yarns is at least 10–30%, and in some cases even up to 40%, lower than that of ring spun yarns. It is pointed out that although significant differences exist between rotor and ring spun yarns, various fibre factors and spinning conditions could greatly alter the properties of rotor spun yarns.

5.3.3 Factors affecting yarn properties

Fibre parameters

The choice of raw material plays a dominant role in controlling yarn quality in rotor spinning. There is a general consensus of opinion that the

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raw material properties must be ranked in a different order of importance for rotor spinning than for ring spinning. The first significant raw material parameter controlling the characteristics of a rotor spun yarn is fibre fineness. Use of finer fibres for spinning rotor yarns provides several advantages such as increased spinning limit, more even yarn and lower optimum twist. Consequently, finer fibres should be preferred for rotor spinning than for ring spinning, the increase in the number of fibres in the yarn cross-section reducing strength loss due to poor fibre parallelization (Simpson and Murray, 1978). Another major parameter influencing rotor yarn quality is fibre strength. As expected, a stronger fibre yields a stronger yarn and therefore reduces the strength deficiency.

Fibre length characteristics, particularly length uniformity, play only a minor role in rotor spinning, and long fibres offer no advantage. Longer fibres can adversely affect yarn strength and evenness due to the greater incidence of wrapper fibres and poor fibre orientation (Kaushik *et al.*, 1987a).

Sliver quality

The quality of feed sliver in terms of cleanliness, uniformity and orientation of fibres has a profound influence on end breaks in rotor spinning and consequently on the rotor yarn properties such as strength and irregularity. The requirements in so far as trash is concerned depend upon whether or not trash removal facilities are available on the rotor machine. Part of the trash left in the sliver reaches the rotor groove and accumulates there, leading to short-term irregularity and strength variation of the yarn and ultimately to end breakage. This accumulation rate obviously depends upon residual trash content in the sliver. Reportedly, the level of trash in the feed sliver should not exceed 0.2% (Hunter, 1978).

Sliver variations cause an uneven flow of fibres through the transport duct and their subsequent deposition in the rotor groove, which, in turn, results in yarn count variation and poor spinning performance. It needs to be mentioned that rotor spinning can compensate for inherent very short mass variation in the sliver due to the layered deposition of fibres in the rotor groove. The Uster CV% should be maintained between 2.5 and 3, for a 3 ktex sliver count, which is widely used in the spinning of rotor yarns.

It is important to maintain high fibre orientation in the drafted sliver, since this leads to a more ordered arrangement of fibres in the rotor groove, which facilitates easy flow of twist along the rotor periphery and improves spinning stability and yarn strength. Two drafting passages are therefore recommended to ensure fairly uniform sliver with adequate fibre parallelization (Tyagi *et al.*, 1999).

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Rotor machine variables

While producing thick sliver, the question of high total draft inevitably crops up. Draft, referring to the ratio of input sliver linear density to that of the yarn, affects fibre orientation. Overall draft ratios between 160 and 170 are suitable under many of the conditions encountered in practice. Increasing total spinning draft leads to an increased end-breakage rate and deterioration in the tenacity, breaking elongation and uniformity of the spun yarn.

The opening roller is a key parameter influencing rotor spun yarn characteristics. It individualizes the fibres and thereby assists in feeding them to the rotor. There is a practical limit to the opening roller speed for each type of opening roller covering and fibre type. Too low a speed results in inadequate fibre separation, whereas too high a speed leads to excessive fibre breakage and a decrease in yarn strength and breaking elongation (Hunter, 1978). The use of an opening roller covering with too severe an action can also cause a significant reduction in yarn tenacity as a result of fibre breakage.

The rotor diameter is normally chosen in relation to the length of fibres to be spun. Smaller diameter rotors result in lower power consumption and lower yarn tension, but impair yarn formation and lead to yarn irregularity and end-breakages. The width of the rotor groove has a marked influence on the strength of rotor spun yarns, and a large, open and self-cleaning rotor groove is preferable for coarse yarns. The maximum attainable rotor speed on a particular rotor spinning machine is a function of the design and diameter of the rotor, the yarn strength and its variability. With increasing rotor speed, throughput rate increases, which in turn affects fibre separation by the opening roller, leading to poor fibre orientation and high short-term yarn variability. High rotor speeds demand high twist coefficients to maintain spinning stability, resulting in a yarn of higher stiffness.

In discussing the structure and properties of rotor yarns, particularly with regard to the wrapper-fibre surface structure, it is appropriate to consider the influences of the doffing tube navel design on the frequency of wrapper fibres and on other yarn characteristics. It is generally agreed that a grooved doffing tube enables lower twists to be used, but such doffing tubes often adversely affect the yarn characteristics and give a rougher yarn surface. Studies have shown that changes in doffing tube design effect changes in the frequency of certain classes of wrapped structures and in a number of the measured parameters defining the handle of knitted fabrics (Lawrence and Finikopulos, 1992). The details of the doffing tube navels and the measured yarn properties are shown in Tables 5.2 and 5.3 respectively. The tensile properties of the yarns and the number of thick places, thin places and neps remained unaffected by the doffing tube navels. However, the irregularity and hairiness increased as the navel became more grooved (Lawrence and Finikopulos, 1992).

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Table 5.2 Changes in doffing tube parameters

Nozzle type	*D* (mm)	*d* (mm)	*R* (mm)	*H* (mm)	*x* (deg)	Features
Ceramic						
CSMO	17.0	2.5	6.2	4.0	30	Smooth
CSPI	16.5	2.5	7.0	3.9	30	Spiral
C4NO	15.4	2.5	7.0	4.0	30	4 notches
C6NO	16.5	2.5	7.0	3.9	30	6 notches
Steel						
SSMO	17.0	2.5	7.0	4.0	30	Smooth
S4NO	17.0	2.5	3.5	4.0	30	4 notches
S6NO	17.0	2.5	3.5	4.0	30	6 notches

D = outer diameter, *d* = bore; *R* = base radius; *H* = flange thickness, *x* = inclination of groove.
Source: Lawrence and Finikopulos (1992).

Table 5.3 Measured yarn properties

	Doffing tube						
Property	CSMO	CSPI	C4NO	C6NO	SSMO	S4NO	S6NO
Irregularity (U%)	8.8	9.5	10.1	10.9	9.0	9.8	10.6
Neps (+280%)	0	0	0	1.0	0	0	1.0
Thin places (–50%)	0	0	0	0	1.0	0	1.0
Thick places (+50%)	3.0	3.0	2.0	2.0	3.0	3.0	2.0
Hairiness							
H (Uster value)	4.0	4.5	4.8	5.0	4.5	5.1	5.6
CV% (Uster value)	1.1	1.2	1.2	1.2	1.2	1.3	1.5
Tenacity (cN/tex)	12.7	12.4	12.6	12.5	12.6	12.5	12.4
CV%	5.2	5.1	5.2	5.1	5.3	5.3	5.2
Extension (%)	6.6	6.5	6.4	6.6	6.7	6.5	6.4

Source: Lawrence and Finikopulos (1992).

5.3.4 Rotor spinning of synthetic fibres and blends

The choice of raw material

The major fibre properties that influence yarn quality in rotor spinning are fibre tenacity, fineness and length. High tenacity fibres should normally be preferred so as to reduce the strength deficiency of rotor spun yarns, end-breakages and fibrous rotor deposits attributable to the aggressive action of the opening roller. Fibre linear density affects the number of fibres in the yarn cross-section. The use of finer fibres for spinning rotor yarns offers considerable advantages in respect of spinning limit and yarn regularity. Further advantages are the ability to reduce yarn twist and increase breaking tenacity. However, as fine fibres are more prone to damage, the optimum

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fibre linear density per filament for rotor spinning seems to be 1.67 dtex, and the optimum fibre length has been found to be 32 mm for man-made fibres (Salhotra, 1992). Shorter fibres not only favour higher rotor speeds due to the smaller rotor required, but also improve yarn strength and evenness due to a distinct decrease in the number of wrappers.

The fibre cross-sectional shape is also an important variable. Technically speaking, modification of the cross-section of the fibre allows engineering of the surface properties of yarns and fabrics. However, in rotor spinning, the use of non-circular fibres offers no technical advantage as far as yarn quality is concerned. Published data have shown that yarns produced with a trilobal polyester fibre perform no better than yarns made from a circular fibre in respect of twist deviation, tensile properties and mass irregularity (Tyagi *et al.*, 2002).

Mechanical crimping has been found to be useful to facilitate processing of man-made fibres during various stages of spinning. The crimp introduced, however, is lost in the ensuing processing stages prior to spinning due to lack of durability. Higher crimp also has a deleterious effect on yarn quality. The fibre crimp, therefore, needs to be examined for its level and permanence. A lower fibre crimp yields better results. The arcs per centimetre should lie between 3.5 and 5 for polyester fibre (Salhotra, 1992).

Another important aspect of synthetic fibre characteristics, which is of direct relevance to spinners, is surface finish. Fibres generally spin better with the right finish than without any finish. It is now recognized that spin finish can lead to incomplete opening if the fibre contains a high lubricant level. However, fibres with too low a lubricant level also cause trouble with rotor deposits. It should be pointed out that polyester fibre with a lubricant level slightly lower than that often required for ring spinning performs well during spinning on rotor spinning machines. Generally, an addition of 0.05–0.1% antistatic agent is recommended for rotor spinning (Ishtiaque, 1992).

Rotor spinning appears to be more restrictive than ring spinning with regard to the inclusion of inorganic pigments in synthetic fibres as they cause severe wear of rotors and opening rollers. The delustrant TiO_2 added to fibres meant for rotor spinning should be less than that normally used for ring spinning and a value of 0.1% seems to be the optimum.

Sliver requirements

The important issue here is the yarn blend. With blended yarns, although the uniformity of fibre proportions along the yarn is one of the blend's important features, the homogeneity of the blend constituents is equally important. Homogeneous blending needs a randomized distribution of fibres in a cross-section through careful mixing and an optimized number of doublings in the drafting passages. Blending techniques form an important basis for rotor yarn

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characteristics. Both flock-blending and draft-sliver blending can be used for blending, say, polyester and cotton fibres; the choice of blending technique depends on whether the cotton component used is carded or combed. There is sufficient experimental evidence to suggest that use of combed cotton instead of carded cotton does not improve yarn strength, clearing doubt as to whether the carded cotton can be used in general as a replacement for combed cotton. However, in the case of draft-sliver blending, an autolevelling at card is to be followed by two or three stages of drawing.

The choice of rotor machine variables

Many investigations into the influence of processing parameters on yarn quality, when rotor spinning of man-made fibres and their blends has been carried out, and a comprehensive review can be found in the publication by Lawrence and Chen (1984). The main problem in spinning synthetic fibres and their blends is to separate the fibres without creating hooks on the fibres or damaging them. There is an optimum opening roller speed for each roller covering and fibre. Opening roller speeds are kept somewhat higher for synthetic fibres than for cotton but excessively high speeds can damage the fibres. The widely recommended opening roller speeds for synthetic fibres and blends vary from 6000 to 7000 revolutions per minute.

The type of opening roller used is responsible for spinning performance and the resulting yarn properties. Most synthetic fibres are best processed with an opening-wire front angle between 90° and 100°, and a relatively lower density of 5–9 teeth per square centimetre. The opening-wire front angle on the opening roller for acrylic and viscose fibres is adequate when close to 90°, and a roller with 99° front angle gives good separation for polyester fibre (Vigo and Barella, 1981).

Higher rotor speeds are necessary to make the rotor operation more economically attractive, but this introduces its own technical complications. The essential criterion for the level of speed to be used is the thread tension, which is largely governed by the rotation of the thread-end in the rotor; its absolute value is dependent upon the yarn fineness as the mass has a linear influence on the centrifugal force. It is therefore useful to express the thread tension as a specific value in relation to the yarn linear density. An absolute spinning limit is considered to be approximately 2 cN per tex (Artzt *et al.*, 1992). In practice, it is recommended to use smaller rotors for spinning yarns at higher rotor speeds. However, experiments have shown that the zone with optimum spinning stability is not the zone for best possible yarn quality. Every rotor diameter must therefore be assessed separately with respect to its speed zones.

Another factor relevant to rotor spinning is that the rotor diameter must be in a certain ratio to the fibre length. The stability of the spinning process

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as well as the yarn structure is dependent on this ratio. The ratio of rotor diameter to fibre length should be 0.9–1.0 (Artzt *et al*., 1992).

Yarn formation and quality are greatly influenced by the design of the doffing tube and the twist index. In general, smooth doffing tubes are preferred for spinning man-made fibres on rotor spinning machines. It may be noted, however, that the selection of twist is based more on the criterion of spinning stability rather than producing a strong yarn. Invariably, low twist factors are recommended for man-made fibre rotor spun yarns than for all-cotton yarns of equivalent linear density (Barella *et al*., 1980), and the values of twist close to 140 (turns per metre)tex$^{1/2}$ have been found to be optimum for polyester fibre yarns, about 120 for acrylic fibres and below 120 for viscose yarns (Barella and Vigo, 1980).

5.3.5 End uses of rotor spun yarns

Rotor spinning can be employed to spin good quality yarns of 18–200 tex from cotton, polyester blends, viscose rayon and acrylic fibres. From microfibres, it is now quite possible to spin yarns down to 10 tex (Ernst, 1993). The products for which rotor spun yarns are considered particularly suitable include dress materials, denim and jeans, sheeting, leisure wear, industrial wear, interlining, towels, furnishings and warp knits.

5.4 Air-jet spun yarns

5.4.1 Structural features of air-jet spun yarns

Classification

The air-jet spun yarn, also termed a fasciated yarn, is composed of a central core of essentially parallel fibres bound together by wrappers, and has many distinctive recurring features in wrapping along the yarn length. Several different classification systems have been applied to air-jet spun yarns but the system suggested by Basu (1991) has been greatly acknowledged. The classification which was used to quantify the various structural components along the yarn length was as follows:

- Class 1: those parts of the yarn which have a regular helical wrapping and in which the core is crimped
- Class 2: those parts which have no wrapping fibres and possess the appearance of a low-twisted yarn
- Class 3: those parts of the yarn which have a straight yarn core regularly bound with wrapper fibres
- Class 4: those parts of the yarn which have a straight yarn core bound by irregular wrapper fibres.

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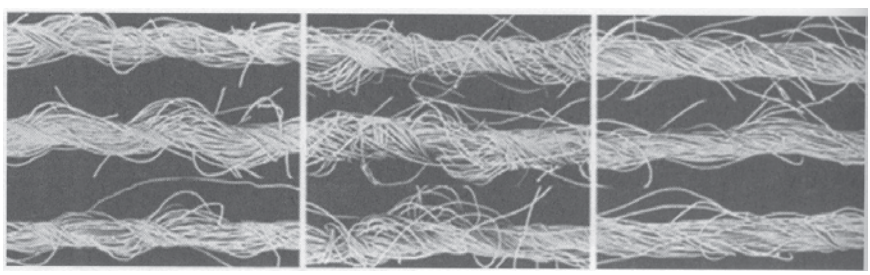
The average length of the wrapped structure was found to be different for different yarns made from different materials. In another study, Lawrence and Baqui (1991) classified the yarn structure into three groups, as orderly wrapped, randomly wrapped and unwrapped section (Fig. 5.5). Chasmawala *et al.* (1990) described the yarn structure as essentially that of a comparatively straight central core of fibres held together by taught surface fibres wound helically onto the central core. They reported five different configurations of fibres in the yarn, namely core, wrappers, wild, core–wild and wrapper–wild.

Migration

In air-jet spinning, there is considerable variability in wrapper fibre configuration, with some wrapper fibres wrapping in both the S and Z directions. The homogeneity of the structure and the interlocking of individual fibres through migration is absent in air-jet spun yarns, and this is partly responsible for their lower strength. The fibre packing density is non-uniform throughout the yarn cross-section, with fibres mostly packed nearer the yarn core (Ishtiaque and Khare, 1993). Attempts have been made to relate yarn properties to yarn internal structure in terms of the fibre extent (Punj *et al.*, 1997). The extent of short wrappers, long wrappers and migrated core fibres in viscose air-jet yarns may be dependent on fibre type as these structural characteristics were found to be more prevalent than in polyester air-jet yarns. The fibre extent varies with second nozzle pressure and production speed. Alteration in yarn structural properties occurs with changes in fibre type, and therefore with composition of the fibre blends and production speed (Tyagi and Doshi, 2006). Under all experimental conditions reported, polyester–viscose yarns exhibited more wrappers and wraps per centimetre, larger helix angles and larger helix diameters than polyester–cotton yarns. For both blends, each of these parameters showed an ascending relationship when both the polyester content and the spinning speed increased.



5.5 Air-jet spun yarn surface structure (Lawrence and Baqui, 1991).

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5.4.2 Properties of air-jet spun yarns

There are many marked differences between the properties of air-jet spun yarns and those of ring spun yarns owing to differences in fibre configuration within the yarn and the yarn structure. Air-jet spun yarn strength ranges from weaker to much weaker than ring spun yarn strength, depending upon the fibre used. The tenacity value of cotton air-jet spun yarn is 50–60% of that of similar ring spun yarn; this increases to 80–85% for polyester or polyester-cotton blended yarn (Stalder, 1990). In comparison with ring spun yarns, air-jet spun yarns have higher bending rigidity, are less hairy, more even, have fewer neps, slubs and thick and thin places, and have lower abrasion resistance: see Table 5.4. Air-jet spun yarns produced with polyester fibre in blends with either viscose or cotton fibres possess better structural integrity, lower compression energy and better compression resilience than the corresponding ring spun yarns from the same fibe types (Tyagi *et al.*, 2007).

5.4.3 Factors influencing the properties of air-jet spun yarns

Fibre parameters

The fibre properties that are thought to have a marked influence on the properties and performance characteristics of air-jet spun yarns are (1) fineness, (2) fibre length, (3) strength, and (4) inter-fibre friction. As the number of fibres in the cross-section of an air-jet spun yarn has to be greater than that for the corresponding ring spun yarn, finer fibres should be preferred. Air-jet spun yarns produced from fine fibres have considerably higher strength, lower rigidity and higher elastic recovery (Kaushik *et al.*, 1993). It may be noted, however, that using fine polyester fibre in a polyester–cotton blend enables increased production speeds without significant loss in yarn strength and unevenness, but may cause considerable deterioration in yarn imperfections and hairiness (Bhortakke *et al.*, 1997). Fine fibres are prone to nep generation, therefore the most suitable fibre linear density for air-jet spinning appears to be 1.3 dtex.

The fact that strong fibres produce strong yarn also holds true for air-jet spun yarns. Nevertheless, in the case of polyester, fibre tenacities beyond 7 grams per denier offer no additional advantage for yarn strength. Such high strength fibres have lower elongation, and wrappers formed by less extensible fibres cannot hold the core fibres with a tight grip for a longer period when the yarn goes through stress. Hence, fibre strength should always be considered along with fibre elongation which should be high enough to generate wrapping-compression (Salhotra, 1992).

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Table 5.4 Influence of fibre profile and spinning speed on performance properties of polyester–viscose and polyester–cotton ring and MJS yarns

	Fibre profile	% Decay				Compressional energy (%)				Compressional resiliency (%)			
		Ring yarn	MJS yarn			Ring yarn	MJS yarn			Ring yarn	MJS yarn		
			160[a]	180[a]	200[a]		160[a]	180[a]	200[a]		160[a]	180[a]	200[a]
Polyester–viscose (65:35)	Circular	48.1	37.8	36.6	33.5	1.27	1.24	1.22	1.12	56.1	57.6	60.2	65.0
	Trilobal	49.7	41.5	40.9	39.0	1.29	1.26	1.24	1.18	51.0	53.2	54.4	63.8
Polyester–viscose (48:52)	Circular	50.8	42.7	40.8	38.9	1.24	1.21	1.19	1.14	58.2	59.3	61.0	68.5
	Trilobal	52.0	43.6	42.5	40.6	1.28	1.23	1.21	1.16	54.1	55.2	57.2	66.5
Polyester–cotton (65:35)	Circular	54.3	42.0	40.6	38.9	1.30	1.29	1.26	1.18	44.5	47.0	47.2	64.2
	Trilobal	56.1	43.5	41.5	40.1	1.34	1.30	1.28	1.20	43.0	44.2	45.8	62.8
Polyester–cotton (48:52)	Circular	55.1	43.8	41.9	40.8	1.26	1.25	1.22	1.15	45.5	46.8	48.6	64.7
	Trilobal	57.0	44.9	43.2	42.0	1.30	1.27	1.25	1.18	42.4	43.2	45.0	63.8

[a] Production speed, m/min.
Source: Tyagi *et al*. (2007).

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Fibre length is very important to the properties of fasciated yarns, more so than for twisted yarns (Santjer, 1991). Longer fibres can be wound around the yarn core a greater number of times with the same angle of wrap, and thus can securely hold the fibre bundle. However, looking at the problems encountered in processing long fibres at the card, it is preferable to use fibres of 38 mm for polyester–cotton blends, whereas for polyester–viscose blends the staple length should be about 44 mm.

Air-jet spun yarn strength depends very much on inter-fibre friction. Higher inter-fibre cohesion results in reduced end breaks and improved yarn strength. With synthetic fibres, particularly polyester, it is essential that the fibre has a non-depositing finish because such fibre finishes cause undesirable nozzle deposits. Sliver fed to the air-jet spinner should not contain fibre aggregate, particularly cotton fibres, as these would hinder the rotation of forming yarn in the narrower tube of the air jets and lead to interruption in twist insertion.

Process parameters

In order to produce a sufficiently strong yarn, it is important for the highest number of wrapper fibres to be available in the yarn structure. The first nozzle pressure has great influence in this respect. With a twin-jet system, an increase in the first nozzle pressure, up to a critical value, was found to improve the tenacity and breaking elongation for polyester–viscose blended yarns (Punj *et al.*, 1997). The same effect was seen for the flexural rigidity, but the evenness of the yarn was distinctly reduced. Beyond the critical value, an increase in first nozzle pressure decreases the yarn tenacity. Similar studies by Tyagi and Salhotra (1996a) showed this critical value for the first nozzle to be above 3 kilograms per square centimetre. An increase in second nozzle pressure increases the yarn tenacity, breaking elongation and flexural rigidity and results in an increase in the percentage of tight wrappers and wrapper extent (Punj *et al.*, 1997). With regard to yarn tenacity there is an interaction between first nozzle and second nozzle pressures (Rajamanickam *et al.*, 1998). This is because for a given first nozzle pressure the total number of wrapper fibres in a given yarn section and the length of the wrappings depend on the level of second nozzle pressure, and vice versa. Thus, the optimum number of wrapper fibres and wrapping lengths can be obtained with various combinations of nozzle pressures.

Production speed is another parameter influencing air-jet spinning. As this is increased, the yarn strength goes up but the number of thick places and neps becomes higher (Lawrence and Baqui, 1991). In fact, increased air flow at high speed causes the edge fibres to move away from the fibrous strand and assists these fibres to become long wrappings. However, in another study (Wang, 1987), the yarn strength improved with increase in production

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speed up to certain level, after which it deteriorated. It can therefore be said that the optimum speed does not yield the best value for all the yarn characteristics.

In air-jet spinning, the main draft is a highly significant factor for breaking load, breaking elongation and hairiness. Draft affects fibre orientation and its influence is greater at high production speeds. The preliminary draft and main draft also depend on the amount of draft. Higher main drafts give higher strength, higher breaking elongation, abrasion resistance and flexural rigidity. The number of thick places and neps rises sharply with an increase in main draft. It is claimed that a main draft of about 35 is applicable to many of the process requirements encountered in practice (Tyagi *et al.*, 2003).

The size of the condenser controls the width of the sliver in the main drafting zone. In one study (Tyagi and Salhotra, 1996a), the most significant difference found between yarns spun with 3 and 5 mm condensers was the number of wrapper fibres. The wider condenser produced a yarn that was less uniform and more rigid, had better strength and breaking elongation, and had higher imperfection indices than the narrower condenser. In contrast, Kampl and Leitner (1989) suggested that minor improvement of the yarn tensile properties can be achieved by using a narrower condenser.

Tyagi and Salhotra (1996b) studied the quality aspects of increasing the feed ratio and the distance between the first nozzle and the nip of the front roller on an air-jet spinning machine. It appears that, in general, increasing the feed ratio causes an improvement in yarn breaking strength, breaking elongation, uniformity and the frequency of imperfections. The flexural rigidity also increases dramatically at high feed ratios. Surprisingly, however, changing the distance between the first nozzle and the nip of the front roller hardly affects the yarn tenacity and breaking elongation, although a wider gap between the first nozzle and the nip of the front roller results in enhanced uniformity and flexural rigidity (Table 5.5). The implications of differences in the feed ratio on the structural and characteristic variations of acrylic air-jet spun yarns have also been considered by Lawrence and Baqui (1991). With increase in feed ratio, the frequency and average length of loosely wrapped portions and unwrapped portions reduce, whereas the frequency and average length of tightly wrapped portions increase. The yarn tenacity and elongation showed marginal increases.

5.4.4 End uses of air-jet spun yarns

Air-jet spun yarns are used extensively for bed linens, shirting, overcoat fabrics, dress materials, knitted goods, home furnishings and some industrial applications.

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Table 5.5 Characteristic variations in jet-spun yarns

Feed ratio	Ribbon width (mm)	Tenacity (mN/tex)		Breaking extension (%)		Unevenness (U%)		Flexural rigidity × 10^3(g.cm^2)	
		38[a]	41[a]	38[a]	41[a]	38[a]	41[a]	38[a]	41[a]
0.96	3	146.8	151.1	12.8	13.5	11.9	11.4	10.5	11.6
0.97	3	152.9	158.3	13.4	13.8	11.2	10.5	11.0	12.1
0.98	3	159.7	165.4	13.8	14.1	10.7	10.2	11.6	12.6
0.96	4	151.6	157.2	13.4	13.8	12.5	12.0	10.8	12.1
0.97	4	157.6	163.6	13.7	14.2	11.8	11.5	11.2	12.5
0.98	4	164.4	170.2	14.2	14.6	11.6	10.3	11.8	13.0

[a]Distance between the first nozzle and the nip of the front roller.
Source: Tyagi and Salhotra (1996b).

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5.5 Friction spun yarns

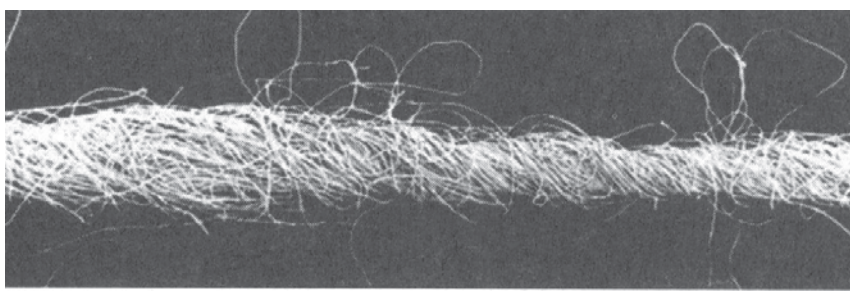
5.5.1 Structural features of friction spun yarns

Surface structure

A friction spun yarn visually appears to be more like a ring spun yarn than an open-end rotor spun yarn but its internal structure differs from both, as can be seen from Fig. 5.6. It is characterized by inferior fibre orientation, buckled and folded fibre configurations and loose packing of fibres. A Dref-3 friction spun yarn consists of a two-part structure, namely a densely packed core containing both straight and twisted fibres that are randomly distributed along the yarn length, and the fibres that are wrapped helically over the core to form a sheath and that exhibit Z-twist (Gowda, 2001). Several fibres have their leading end hooked, whereas the trailing end is almost free from any hook. The average fibre extent for core fibres is about 32 mm for Dref-3 spun yarns produced from 38 mm and 1.65 dtex acrylic fibres, the figure being 19 mm for the sheath fibres. The packing density is highest at the core and decreases towards the surface (Tyagi *et al.*, 2000).

Migration

In friction spinning, the fibres are applied more or less one at a time without the required cyclic differentials in tension. Also, the principal tension occurs only after the yarn structure is already produced, and the tensions acting on the fibres during assembly are likely to be extremely low. These small tension variations may result in some fibre migration, but only to a small degree. As the fibres are fed to the yarn tail without tension and lie along the yarn tail at necessarily different radial positions, they occupy different radial positions, exhibiting a layered structure (Fig. 5.7). However, many technologists have different opinions about the occurrence of migration in friction spun yarns. Rust and Lord (1991) showed that the fibres in the friction spinning process



5.6 Dref-2 friction spun yarn surface structure.

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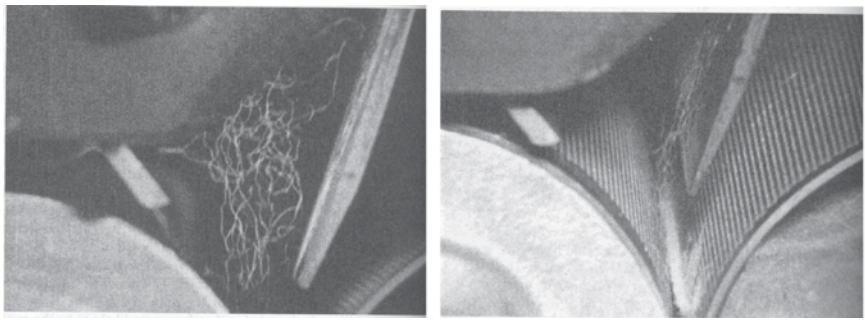

(a) (b)

5.7 Yarn formation on Dref-2 friction spinner: (a) fibre movement from the opening roller to the friction drums; (b) fibre lending and twisting.

move inwards radially towards the apex of the cone as they are assembled into the yarn. In another study by Alagha *et al*. (1994), the amplitude of migration was found to be highest for friction spun yarns, followed by rotor- and ring spun yarns. On the other hand, Lunenschloss *et al*. (1986) found a stronger migration friction spun yarns than for ring spun yarns.

Twist structure

When a fibre is wrapped about the core with a constant yarn axial velocity and constant rotational speed, the pitch remains constant, but the fibre helix angle increases as a function of the radial position. In fact, because the diameter of the yarn tail along the yarn axis varies in the yarn-forming zone, each point of the yarn turns with a different rotational speed, which is faster in the nip of the yarn tail. This produces a differential twist distribution in the inner and outer layers, and the twist in the yarn centre is 2–2.5 times higher than the twist in the surface (Rust and Lord, 1991). With some friction spinning systems several slivers are fed together, side-by-side, to the friction twisting zone. Fibres are therefore fed from different feed positions, and their location in the multiple sliver feed determines their subsequent location in the yarn structure. For example, it was found that in staple-core Dref-3 friction spun yarns with a core–sheath ratio of 70:30, the helix angle and helix diameter of sheath fibres reduced progressively from the position nearest to the delivery end to that farthest from the delivery end. However, the twist remained essentially the same irrespective of the sliver position (Gowda, 2001). On the other hand, in continuous-filament core Dref-2 yarns spun with a core–sheath ratio of 30:70, the structural parameters of the sheath fibres from the different sliver positions are different, indicating that the surface character of the core influences the wrapping of sheath fibres.

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5.5.2 Properties of friction spun yarns

Many studies concerning the properties of yarns made by different spinning systems have appeared in the literature in the past few years. However, their findings cannot be generalized as these studies differed in terms of raw material characteristics, machine versions and spinning conditions used. In general, friction spun yarns have 60–75% strength, 60–90% unevenness, 100–140% bulk and require 75–100% of the minimum number of fibres in the yarn cross-section as compared with the corresponding ring spun yarns (Deussen, 1989). In respect of yarn-to-metal friction, ring spun yarns exhibit the highest friction, followed by rotor and friction spun yarns for cotton and viscose fibres. However, with polyester fibres, friction spun yarns show the highest value, followed by rotor and ring spun yarns (Chattopadhyay and Banerjee, 1997). Also, friction spun yarns are inferior in terms of strength variability, imperfections and hairiness. Nevertheless, the best yarn appearance is obtained for Dref-3 yarns followed by ring and rotor spun yarns (Louis *et al*., 1985).

5.5.3 Factors affecting yarn properties

Machine parameters

There appears to be general agreement concerning the functioning of the opening roller. Problems involved here include fibre damage, fibre doffing, and preservation of consistent yarn quality due to larger tuft size. Most opening rollers are covered with garnet-wire or needle-pins to cope with the high throughput, and it is claimed that spiral winding of the clothing on the opening roller results in excellent opening of fibres. The opening roller design and the opening roller speed greatly affect the spinning performance. Many researchers have investigated the effect of opening roller speed on yarn properties using different raw materials, spinning conditions and ranges of speed. The results of these studies, however, led to contradictory conclusions. Saad and Sherouf (1989) found an increase in yarn specific tension and breaking elongation for cotton and polyester–cotton yarns but no change in yarn tenacity with the opening roller speed increasing from 3500–5000 rev min^{-1}. According to Ulku *et al*. (1995), an increase in opening roller speed has no effect on the fibre tenacity and elongation at break. However, a high level of fibre damage, differing from one sort of material to another, is caused by the high opening roller speeds, which leads to a deterioration in yarn quality, mainly in terms of tenacity, elongation, unevenness and imperfections.

The quality of friction spun yarns depends essentially on the arrangement for feeding fibre to the twisting element. Generally, a direct comber-roller feed results in a greater fibre extent and therefore a higher yarn tenacity and

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elongation than the indirect feed method in which the fibres are first accumulated on the ingoing roll and then transferred to the nip (Rust and Lord, 1991). With regard to the transport-duct angle, a 30° angle produces the strongest yarn, and an increase in the angle of inclination leads to a decrease in yarn strength. The position of the mouth of the duct relative to the friction drum is also important. Increasing the distance between the duct and the solid friction drum increases the amount of air passing against the yarn end. As a result, air force acting on the fibre assembly owing to air flow increase, which, in turn, raises the level of yarn tension (Stalder and Soliman, 1987).

Process parameters

The speed of the spinning drums is one of the key process variables that influence the yarn twist. For a given friction ratio, a higher spinning speed causes greater fibre buckling and a deterioration in yarn properties, particularly in irregularity and tenacity (Tyagi *et al*., 1995). In case of Dref-3 cotton yarns, the tenacity increases with an increase in the speed of the friction drum from 3000 to 5000 rev min^{-1}, although other yarn properties remain virtually unchanged (Padmanabhan and Ramakrishnan, 1993).

Importantly, the twist in friction spun yarns is controlled by the friction ratio, and the ratio of the friction drum surface speed to the yarn delivery rate has to be adjusted according to the fibre and mode of yarn formation used. It was found that for polyester spun by the Dref-3 system, an increase in the friction ratio resulted in a large increase in tenacity, breaking elongation, flexural rigidity, abrasion resistance and packing density of polyester Dref-3 yarns (Tyagi *et al*., 2000). Friction spinning has a large potential for increasing delivery rate. However, higher delivery speeds are detrimental to the mechanical properties of polyester Dref-3 friction spun yarns (Tyagi and Khanna, 2005).

Suction pressure is another factor influencing friction spinning. A high air suction gives a high restraining force on the fibre assembly so that it will be pressed more firmly against the surface of the friction drums. This leads to increased friction between the two and an increased amount of torque acting on the surface of the fibre assembly. Consequently, yarn twist, tension and twisting efficiency tend to increase. An increase in suction pressure is also accompanied by an increase in airflow and therefore in mean fibre speeds in the fibre transport tube. This facilitates fibre orientation inside the tube and thus improves yarn tenacity, appearance and evenness and reduces the yarn diameter (Konda *et al*., 1996).

The core–sheath ratio has a considerable influence on the properties of polyester friction spun yarns. Generally, yarns produced with a thicker core are significantly stronger and less extensible, and have a higher work of rupture and higher abrasion resistance than the equivalent yarns produced

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with the thinner core. This critical core content depends on the fibre fineness and profile (Tyagi and Khanna, 2005). For 100% cotton, it is comparatively difficult to produce Dref-3 yarns with a 50:50 core–sheath ratio (Louis *et al.*, 1985). The maximum strength is achieved with 70% core fibres and 30% sheath fibres (Padmanabhan and Ramakrishnan, 1993).

Another system-dependent parameter is spinning tension. A higher spinning tension results in a compact structure. A lower tension, on the other hand, reduces the end-breakage rate but results in lower yarn strength owing to insufficient friction between the fibres. As mentioned earlier, the tension is relatively low in friction spinning, and depends on the size of the force on the yarn tail generated by the air flow, as well as the friction coefficients of the spinning drums, the yarn diameter and the yarn tail diameter. In the case of filament-core yarns, the pretensioning of the filament core is an important factor. The level of pretension affects the configuration of the filament in the core and the other structural elements and consequently the mechanical properties of the spun yarns.

Fibre factors

The twisting rate in friction spinning is largely dependent upon the friction between the fibres and the drum surface. Therefore, a high friction between the fibres and the friction drum surface is desirable. The inter-fibre friction should also be high as the parallel-fibre core needs to be properly bound to resist slippage. Thermoplastic fibres are produced with a spin finish applied to their surface to make them amenable to further processing. It is believed that spin finishes, or generally lubricating additives, affect the deformability of fibres during twisting because of decreased friction between the fibres. An increase in the level of spin finish would cause low frictional resistance between the fibres and the friction drum, and thus would prevent them from being twisted as desired. This could then result in decreased yarn strength, abrasion resistance and structural integrity (Sengupta *et al.*, 1992).

The properties of the constituent fibres would also affect such factors as fibre-strength utilization, the propensity to fibre damage and the twist insertion during friction spinning. It has been reported (Louis *et al.*, 1985) that about 74% of the strength of 74 tex cotton Dref-3 yarn is accounted for by fibre length, strength, elongation and micronaire, as against 94% in ring spun yarns. The number of fibres in a given yarn cross-section depends on the individual fibre denier. As the minimum number of fibres required in friction spinning is higher than for ring spinning, fine denier fibres are required for the medium to fine count range. The yarn twist increases directly with fibre fineness. This is because the depositing fibres are pressed more firmly into the wedge of the friction drums, resulting in a smaller sleeve. Thus the use of finer fibres offers considerable advantage in friction spinning in respect of

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yarn strength, breaking elongation, abrasion resistance and rigidity. However, fine fibres are more prone to damage during opening and carding.

The fibre length requirement in friction spinning is similar to that in rotor spinning, in that yarns spun from longer fibres are stronger and more extensible (Louis *et al.*, 1985). However, longer fibres are more susceptible to damage, and have a tendency to lap around the opening roller.

Synthetic fibres can be produced with various cross-sectional shapes, such as circular, trilobal and triangular. Trilobal fibres are not regarded as suitable for friction spinning (Tyagi and Khanna, 2005). In general, trilobal fibre yarns exhibit lower strength, lower abrasion resistance and higher flexural rigidity than the equivalent yarns made from a circular fibre (Table 5.6).

5.5.4 End uses of friction yarns

Generally, friction spinning can be used to spin yarns from cotton, polyester, acrylic, most fibre blends and recycled fibres. The yarns can be used for knitted goods, terry towel, weft and pile yarns, velvet and blankets. Some other applications include carpet backings, warping cloths, outer door textiles, protective textiles and filters.

5.6 Wrap spun yarns

5.6.1 Properties of wrap spun yarns

The wrap spinning process produces yarns which are structurally somewhat similar to air-jet yarns (Fig. 5.8). The important difference is that the wrapping of the core fibres is by a filament yarn and not by staple fibres as in the air-jet spinning process. Wrap spinning technology, therefore, offers many advantages such as higher productivity, higher yarn tenacity and uniformity, less hairiness, the possibility of using coarse fibres for finer yarns, and greater covering ability in woven and knitted fabric structures.

Table 5.6 Structural and mechanical parameters of polyester Dref-3 yarns

Core-wrapper ratio	50/50[a]	60/40[a]	70/30[a]
Helix diameter (1/100 mm)	36.7 (38.4)	34.5 (34.8)	33.9 (34.2)
Helix angle (degrees)	33.3 (34.3)	34.0 (35.3)	34.8 (37.4)
Twist (turns/m)	308 (354)	222 (294)	172 (255)
Fibre extent (mm)	12.7 (8.8)	12.2 (7.1)	12.9 (8.9)
Tenacity (cN/tex)	20.0 (19.4)	22.6 (20.3)	24.0 (21.6)
Breaking elongation (%)	10.1 (10.4)	10.0 (10.3)	9.6 (9.9)
Abrasion resistance (cycles)	3641 (2299)	4406 (2351)	4994 (2473)
Flexural rigidity (dynes-cm^2)	35.8 (39.6)	37.8 (50.6)	42.7 (61.3)

[a]Figures in parentheses indicate values for trilobal polyester fibre.
Source: Tyagi and Khanna (2005).

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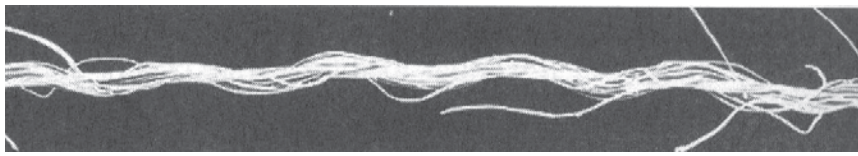

5.8 Wrap spun yarn surface structure.

5.6.2 Factors affecting wrap yarn characteristics

The properties of wrap spun yarns strongly depend on the properties of the wrapper filament, and the choice of the filament must always take into account the linear density and the end use requirements of the yarn (Taub, 1980). The uniformity of the wrapper filament affects the evenness of the composite yarn. Of equal importance is the need to ensure optimal radial pressure on the core by the wrapping filament. Yarn strength is greatly influenced by the filament modulus and the wrap density. A coarse filament is generally recommended for sewing threads and industrial yarns (Taub, 1980). A monofilament will wrap round the core fibres like a wire spring, whereas a multifilament gives a ribbon wrap structure (Steiner, 1983).

The distance between the front roller and the hollow spindle significantly influences the resulting yarn properties. Increasing this distance will adversely affect the orientation of the core fibres, and produce yarns with lower strengths and elongations. The tenacity and elongation of wrap spun yarn is determined not only by wrapping density, but also by the linear density and tensile properties of the wrapping filament yarn (Behery and Nunes, 1986). This is because the tensile properties of the filament yarn generate the bending tension and, together with the linear density of the filament yarn and the amount of wraps per unit length, produce the geometrical configuration of the fibrous core and the inter-fibre frictional forces within the core and between the surface of the core and the filament itself.

5.6.3 End uses of wrap spun yarns

Wrap spun yarns are suitable for weaving and knitting. These yarns find applications in carpets, knitted outerwear, blankets, towels and furnishings.

5.7 Structure–property relationships of staple spun yarns

5.7.1 Tenacity

The properties of staple spun yarns are strongly related to their structural characteristics. This can be best understood by comparing the distinctive

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structural differences of the yarns produced by the four staple spinning systems of most commercial importance: ring, rotor, friction and air-jet spinning.

Ring yarns provide a unique combination of structural features that contribute to a consistently higher yarn tenacity that is not possible with any other yarn structure. This unique combination of structural features is made up of the greatest proportion of straight and parallel fibres, a high level of migration, and a reasonably high packing density. These structural features permit the greatest translation of fibre-to-yarn strength (i.e. fibre strength utilization).

Rotor and friction spun yarn strengths range from weaker to much weaker than that of ring spun yarn, depending on the fibre and processing parameters used. The yarn structural features responsible for lower yarn strength are as follows: in the case of rotor spun yarns, disoriented and folded fibres in the core, lower fibre packing, non-load-sharing wrapper fibres, and a low level of migration; and in the case of friction spun yarns, the presence of highly disoriented and folded sheath fibres as well as a low degree of fibre packing in the yarn core.

As described earlier, air-jet yarns have surface fibres tightly wrapped around a core of parallel and straight fibres which generate sufficient radial pressure on the core fibres to give a better translation of fibre-to-yarn strength than in rotor or friction spun yarns. Changes in yarn properties with various process parameters have therefore been explained by the changes in the structural parameters (Lawrence and Baqui, 1991).

5.7.2 Breaking elongation

Air-jet yarns are least extensible due to an untwisted core of straight and parallel fibres comprising 90% of the population. In comparison with ring spun yarns, rotor spun yarns have a higher breaking elongation, though it is lower than that of friction spun yarns. The large proportion of hooked and disordered fibres in the sheath and the low tension used during friction spinning tend to make the structure less dense and more extensible. The unique combination of yarn structural features responsible for the higher breaking elongation of rotor spun yarns is a higher incidence of hooked and disoriented fibres in the structure and a low level of spinning tension.

5.7.3 Abrasion resistance

Abrasion resistance is often considerably higher for rotor spun yarns than for ring spun yarns, presumably due to surface fibre configurations. However, comparing air-jet and ring spun yarns, the former is inferior in terms of abrasion resistance. The reason is that with air-jet yarns, the wrapper fibres do not adequately shield the yarn core, and consequently this leads to its

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early exposure to abrasion. Ring spun yarns, on the other hand, are spun under the highest level of spinning tension, and there are no hooked fibres in the structure, but the helical arrangement of fibres is a highly significant factor in determining yarn breaking elongation during abrasion.

5.7.4 Bending rigidity

It is generally recognized that air-jet spun yarns display higher bending rigidity (i.e. specific rigidity) than the equivalent yarns spun on other spinning systems. The clustering effect of core fibres due to the parallel arrangement and tightly wound binding fibres restricts the freedom of fibre movement during bending. Rotor spun and friction spun yarns are more rigid structures than ring spun yarns because of their compact core and large diameters. In the case of ring spun yarns, the helical fibre arrangement is a contributing factor to the lower bending rigidity.

5.8 The plying of staple fibre yarns

5.8.1 Ring spun yarns

Generally, when staple fibre yarns do not meet the property requirements for certain applications it becomes necessary to ply two or more of the same yarn to form a plied yarn with improved characteristics. Most plied yarns throughout the world are produced from ring spun yarns because of their specific structure and their suitability to plying. Ply-twisting ring yarns in the direction opposite to the spin twist results in a fully balanced yarn that is more even and less hairy, has higher tenacity and breaking extension, has higher abrasion resistance and fewer imperfections than the component single yarns. Plied yarns are also produced by ply-twisting in the same direction, i.e. twist-over-twist. Such yarns generally have more compactness and retain some twist-liveliness. The level of ply-twist used is usually determined by the number of single components folded together, the yarn linear density and spin twist. The direction of ply-twist in yarns depends on their intended use.

5.8.2 Rotor spun yarns

Rotor spun yarns are generally superior in breaking extension and short-term regularity and have fewer imperfections compared to ring spun yarns, but lack the quality characteristics of plied ring spun yarns. Consequently, there has been a considerable increase in the production of plied rotor yarns in the recent years. However, a simple substitution of plied rotor yarns for plied ring spun yarns has been possible only for selective applications. Plied rotor spun yarns have much higher tenacity and breaking elongation compared

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with singles rotor yarn of the equivalent count as a result of plying (Kaushik *et al*., 1987b). The improvement in tenacity is more marked for twist-over-twist yarns plied from low-twist singles yarn and consistently decreases with increase in singles' twist factor. The explanation for this is as follows. The improvement in tenacity results from the fact that binding single yarns together increases the binding of the fibres within each individual yarn and leads to a higher inter-fibre cohesion. However, because the number of wrapper fibres increases with increased singles' twist factor, they restrict the tightness of the binding by the ply twist. Hence the tenacities of plied rotor yarns prepared from highly twisted singles are lower than those from low-twisted singles.

5.8.3 Air-jet spun yarns

Ply-twisting has a beneficial effect on the tensile characteristics of air-jet spun yarns and it is only necessary to use 60–70% of the ply-twist which would be needed for ring spun yarns of equivalent counts. Tenacity increases and rigidity decreases for ply-twist when twisting is in the opposite direction to wrapping of the surface fibres (Chattopadhyay, 1997). Studies with viscose air- jet spun yarns (Tyagi and Dhamija, 2000) have shown that improvement in yarn properties depends upon the feed ratio, the second jet pressure, and the level and direction of ply-twist. Z-ply yarns were more rigid than S-ply yarns, but the flexural rigidity of Z-ply yarns consistently decreases as the ply-twist factor increases. S-ply yarns twisted with a higher twist factor were less rigid than single yarns of equivalent count and the rigidity of the plied yarns further decreased with decreasing feed ratio and second jet pressure.

5.8.4 Friction spun yarns

Although friction spun yarns are usually weaker than other yarns, their strengths can be improved through ply-twisting (Lord and Radhakrishniah, 1987). Chattopadhyay and Chakrabarti (1998) have also reported a substantial rise in friction spun yarn tenacity as a result of plying. Cotton yarns in particular derived maximum benefit in terms of gain in tenacity and breaking elongation. The level of ply-twist was found to have little effect on the yarn tenacity, whereas the direction of ply-twist was important; friction spun yarns should generally be plied in the same direction as their wrapping sheath fibres.

5.9 Future trends

The future trends in staple fibre spinning can be predicted by a careful scrutiny of current developments and extrapolation of various scientific innovations. The starting point is a basic assumption, quite familiar to every

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spinner, that staple fibre yarns, irrespective of the spinning system, must meet ever-increasing demands in quality. Effectively, ring spun yarn has been dominant due to its unique yarn characteristics and unmatched versatility. However, for some time now rotor spun yarn has occupied the undisputed domain of coarse count yarns owing to the high productivity of the process and their superior evenness.

Over the past 27 years, air-jet spinning has become the most favoured method of spinning fine staple yarns on an economic basis. Development activities during recent years have concentrated on improving yarn quality through design modifications, and such work has led to the recognized need to optimize product specifications. However, some undesirable features and sectorial applicability of the yarns spun on these spinning systems have restricted their suitability for some commercially important applications, in particular for knitted fabrics where yarns are required with a low twist for a soft handle. A viable commercial friction machine to spin good quality fine yarns still remains a shimmering dream. There seems to be a pressing necessity to improve the quality of yarns spun on these non-traditional spinning systems and, in particular, to solve the problem of the harsh feel of air-jet yarn fabric through suitable design and process modifications. Such steps would no doubt make these new technologies more attractive.

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