Influence of material parameters and thermal treatment on structure and properties of polyester air-jet spun yarn

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The effect of thermal treatment (dry and wet) under slack conditions, blend ratio and fibre cross-section on the structure and properties of air-jet spun yarns has been studied. It is observed that the thermal treatment, particularly in wet condition, increases the linear density, helix angle, helix diameter, breaking extension and abrasion resistance and decreases the mean fibre extent, tenacity and flexural rigidity of the yarns. The increase in amount of coarser denier fibre exhibits higher helix diameter, mean fibre extent, yarn tenacity, breaking extension, abrasion resistance and flexural rigidity, and lower helix angle. The increase in trilobal fibre content in the blend shows increased helix diameter and mean fibre extent, and lower helix angle, yarn tenacity, breaking extension, abrasion resistance and flexural rigidity in the yarn.

Keywords: Air-jet spinning, Flexural rigidity, Helix angle, Mean fibre extent, Polyester

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1 Introduction

Among the modern high production technologies, air-jet spinning is now a well-established technology in the finer yarn count sector and can produce quality yarns for many applications. The past few years have witnessed intensive research on technological effects of material and system variables on yarn characteristics.1-3 Air-jet spun yarns are well known for being stiffer than equivalent ring and rotor-spun yarns. The high bending rigidity of air-jet spun yarn is ascribed to its structure. The straight and parallel arrangement of core fibres wrapped by helically arranged binding fibres offers very little freedom of movement to the fibres within the core when the yarn is bent, which enhances stiffness. Studies have been done to reduce the yarn rigidity by the use of lower feed ratio4 with the reduction in main draft and by lowering down the injector jet pressure.5 It stands to be logical that the use of heat also plays important role in controlling rigidity. The influence of annealing on the general properties of polyester6 and polyester-viscose blended7,8 yarns under dry conditions has also been studied. The present study aims at investigating the influence of blend variations of different fibre cross-sections and different fibre deniers, and thermal treatment (dry and wet) under slack conditions on the structure and properties of air-jet spun yarns.

2 Materials and Methods

2.1 Preparation of Yarn Samples

Three polyester (P) fibres of different linear densities and cross-sections [circular (cir) and trilobal (tbl)] were selected for the study. The specifications of fibres used are given in Table 1. Two sets of 20 tex yarns were spun with three blend ratios, as given below:

Set I—P (cir 2.0 den)/P (tbl 2.0 den) with 30/70, 50/50, 70/30 blend ratios
Set II—P (cir 2.0 den)/P (cir 1.2 den) with 30/70, 50/50, 70/30 blend ratios

Fibres were hand opened and mixed in calculated amount by simple weighing method to adjust the different blend ratios. Tracer fibres (0.8-1% by weight), disperse dyed with blue and red colours were taken in same blend ratio and blended with undyed fibres. After first toppling, an emulsion made of 2.5% water and 0.05% LV 40 was sprayed on the material uniformly and the material was kept for 24 h to render homogeneous conditioning of material. The conversion to drawn sliver was carried out by using a MMC carding machine and a Lakshmi Rieter’s draw frame DO/2S. Three draw frame passages were given

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to carded slivers. The drawn slivers were spun into yarn on Murata Air-Jet Spinner 802 MJS (200 m/min).

2.2 Thermal Treatment

All the yarns were subjected to both dry and wet thermal treatment at 160° C for 20 min in a laboratory curing setting chamber under relaxed condition. Skeins of 360 yards were prepared on a wrap reel and laced at 5 points. The lacings were kept completely loose so as not to hinder the relaxation process in yarn during shrinkage. The skeins were then hung loosely in curing-setting chamber for thermal treatment. For wet treatment, the skeins were immersed loosely inside water for 24 h, squeezed to remove excess water in laboratory hydro-extractor and then immediately placed inside the curing setting chamber for thermal treatment.9

2.3 Fibre Tests

2.3.1 Tenacity and Elongation

The polyester fibre used in the investigation was tested for tenacity and breaking elongation by using stelometer, the rate of loading being 1 kg/s. Elongation was directly read from the scale while tenacity was calculated at 1/8 inch gauge length using the following formula:

\[
\text{Tenacity (g/tex)} = \frac{\text{Breaking load (kg)} \times 1.5 \times 10}{\text{Sample weight (mg)}}
\]

No. of observations made is 10.

2.4 Yarn Tests

2.4.1 Measurements of Yarn Structural Parameters

The structural behaviour of air-jet spun yarns was measured by tracer fibre technique as suggested by Morton and Yen.10 A small quantity (0.8-1%) of polyester fibres dyed with blue (trilobal for Set I and 1.2 den for Set II) and red (circular for Set I and 2.0 den for Set II) colours (disperse dye) was added to the mixing before processing with the assumption that these fibres behave in the same way as the grey fibres during the formation of yarn.

In order to observe the path of the individual dyed fibre, the yarn under investigation was passed through a transparent glass patry dish filled with methyl salicylate solution. As the refractive index of methyl salicylate (1.536-1.538) was approximately same as that of undyed polyester staple fibres (1.537), the grey polyester fibres are optically dissolved and only the dyed fibres could be seen. The patry dish is placed on the microscope and transmitted light from below is passed through the specimen. This helps in a clear vision of the yarn on the screen of the visual display unit.

2.4.1.1 Measurement of Helix Angle and Helix Diameter

The helix angle (the angle between the fibre and the helix axis at the point where the fibre intercepts the axis) and the helix diameter (the amplitude between the successive crest and trough) as defined by Alagha et al.11 were measured for different coloured fibres by passing the yarn through methyl salicylate solution. Eighty observations were made for each yarn sample.

2.4.1.2 Measurement of Mean Fibre Extent

The mean fibre extent (mm) was measured for the coloured fibres, passing through the methyl salicylate solution, using the Leica Q500 MC. Thirty observations were made for each yarn sample.

2.4.2 Measurement of Yarn Properties

Thermal shrinkage was measured according to BSI method using the following expression:

\[
\text{Thermal shrinkage (%)} = \left[\frac{L_1 - L_2}{L_1}\right] \times 100
\]

where \(L_1\) is the length of skein before thermal treatment; and \(L_2\), the length of the skein after thermal treatment.

The Instron tensile tester (4411) was employed for the measurement of single yarn strength and breaking elongation.

The flex abrasion resistance of all the yarns was determined by the Universal wear tester according to ASTM standards.12

For measuring flexural rigidity of different yarn samples, yarn loops were prepared with the help of a circular glass tube of known diameter and by putting the reef knot for joining both ends of yarn. The tube was mounted horizontally on a stand and a strip of black paper was introduced into the tube so as to provide an opaque background for better visibility of loop. The glass tube surface was covered with thin cellophane sheet wrapped around the glass tube to allow convenient withdrawal of the loops. This way the circular loops were obtained. If at all, any loop was formed out of shape due to faulty reef knot, it was rejected. A special care was taken to keep the same tension while putting the reef knot for preparing the yarn loops. For avoiding the effect of bulk, it was
tried to keep the knot at 45° with the vertical in each test. Thirty observations from all yarn samples were made. Flexural rigidity was calculated with the help of Riding and Owen’s table\textsuperscript{13} using the following relationship:

\[ G = \frac{M g L^2}{Z} \text{ dynes–cm}^2 \]

where \( M \) is the mass of rider (g); \( Z \), the table value of non-dimensional load corresponding to value of \( d_1/L \); \( L \), the length of loop (cm); \( d_1 \), the deflection produced by the weight of the rider; and \( g \), the acceleration due to gravity (981 cm/s\(^2\)).

Following precautions were taken while performing the tests:

(i) Ring loop formed should be a perfect circle.
(ii) Loop length should be in the range of 1.00-1.75 cm and depends on the fibre denier.
(iii) Weight of rider should be chosen such that the ratio of deflection and loop length may lie between 0.05 and 0.09.

The yarn diameter was measured using ‘Leica Q500 MC’, the computerized image processing instrument. Yarn unevenness and imperfections were recorded by Uster Evenness Tester-3 (UT-3).

3 Results and Discussion

3.1 Linear Density

Table 2 shows that the linear density of yarn tends to increase after both types of thermal treatments due to fibre shrinkage. Fibre cross-section does not show any regular trend for linear density but in the other case, the increase in linear density is more as the coarser fibre content in the blends increases due to higher shrinkage potential of coarser fibre. Also, wet thermally treated yarns show more increase in linear density.

3.2 Thermal Shrinkage

It is observed from Fig. 1 that in both dry and wet thermal treatments, yarns undergo thermal shrinkage. This behaviour can be ascribed to the thermoplastic nature of polyester fibre. According to Sengupta \textit{et al.}\textsuperscript{14}, with the application of heat the bends between the molecular chains get weakened and the originally strained molecules on processing settle down to the position of least strain which results in shrinkage. The shrinkage in the case of wet treatment is more which is due to the fact that the water molecules, acting as plasticizer between the molecules, will enhance the strain relaxation of the molecules.

It is observed that the fibre cross-section doesn't affect shrinkage behaviour, whereas in the other case shrinkage increases as the coarser fibre content in the blends increases which is due to more number of polymer chains produced at a certain cross-section of the fibres as well as the yarn. This increased number of polymer chains will exhibit an increased amount of shrinkage in the fibres and consequently in the yarn.

3.3 Yarn Structural Parameters

3.3.1 Helix Angle and Helix Diameter

Figure 2 shows that in all the blends of polyester circular and trilobal fibres, trilobal fibres show lower helix angle as compared to their circular counterparts. The trilobal fibres on account to their higher bending rigidity require higher torque to bend, which results in
the formation of lower helix angle. In the blends of 1.2 den and 2.0 den polyester fibres, finer fibre shows higher value of helix angle; finer fibres being lighter and less rigid tend to wrap much better as the twist transference from core to wrapper will be better for less rigid fibres, resulting in higher helix angle. Variations in blend do not show any trend of helix angle. Figure 2 shows that helix angle increases after thermal treatment as shrinkage takes place in the yarn along the longitudinal axis which brings the consecutive helices closer to each other. The increase in helix angle is more in case of wet thermally treated yarns as a consequence of higher thermal shrinkage.

Figure 3 shows that helix diameter of trilobal fibre is more than its circular counterparts in all the blends of polyester trilobal and circular fibres. The trilobal fibres on account to their higher bending rigidity tends to form larger helix diameter. Helix diameter for both the fibres increases as trilobal content in the blends increases. In case of blends of 1.2 den and 2.0 den fibres, finer fibres exhibit lesser value of helix diameter as a consequence of lower bending rigidity of finer fibres which results in formation of more tighter wrappers, leading to lower value of helix diameter. The helix diameter values increase for both fibres, as coarser fibre content in the blends increases. The thermal treatment causes a marked increase in helix diameter which is due to increase in bending and buckling of fibre components, which, in turn, results in the loosening of structural matrix of yarn owing to decrease in cohesive forces. The increase in helix diameter is noticed more for wet thermally treated yarns due to higher shrinkage.

3.3.2 Mean Fibre Extent

Figure 4 shows that the mean fibre extent for circular fibre is lower owing to lower bending rigidity of circular fibres; its wrapping tendency is more due to which mean fibre extent of circular fibre is found to be lower. In case of blends of 1.2 den and 2.0 den fibres, finer fibres show lesser values of mean fibre extent, as these fibres are less rigid and more of such fibres will be separated. They wrap much better, giving lesser value of mean fibre extent. No particular trend is observed for mean fibre extent in relation to blend proportion. The mean fibre extent shows marked decrease as a consequence of thermal treatment. The decrease in mean fibre extent is brought about by alteration in structural matrix of fibres. The decrease in mean fibre extent is noticed more for wet thermally treated yarns.

3.4 Fibre Tenacity and Breaking Elongation

Table 1 shows an increase in yarn tenacity when circular fibre content in the blends of circular and trilobal fibre is increased. This may be due to breaking strength and lower packing density of trilobal fibre than that of circular fibre. In the case of 1.2 den and 2.0 den blends, the tenacity of the yarn increases as coarser fibre content increases. It is expected that finer fibres should produce stronger yarns but in case of air-jet spun yarns, when finer fibres are used although the number of fibres per cross-section is increased, the number of wrapper fibres remains the same and the ratio of wrapper fibres to core fibres becomes lower, which, in turn, makes the yarn weaker.
The breaking extension of the yarn decreases as the circular fibre content in the blends of circular and trilobal fibres increases which is due to lower breaking extension of circular fibre. In the other case, as the 1.2 den fibre content increases the breaking extension decreases, as finer fibres give more wrapper fibre percentage which resists the core fibres slipping against one another, resulting in low breaking extension.

It is also observed from Table 1 that the yarn tenacity decreases and breaking extension increases after both types of thermal treatments. This may be attributed to shrinkage of polyesters fibres that occurs due to molecular disorientation and chain folding, which leads to loosening of yarn matrix. These changes are more prominent in the case of wet thermally treated yarns due to more shrinkage of polyester fibres which leads to greater loosening of yarn matrix. The yarn spun with higher content of trilobal fibres shows greater decrease in yarn tenacity as loose structure is being spun from trilobal fibres which results in greater decrease in yarn tenacity.

### 3.5 Abrasion Resistance

The abrasion resistance is expressed as the number of abrading cycles required to break the specimen. Figure 5 shows that as the circular fibre content increases in the blends of circular and trilobal fibres, abrasion resistance increases. The lower fibre-to-metal friction of circular fibres decreases the intensity of transmission of frictional force from abrading surface to fibre, which decreases the rate of wear, and thus improves the abrasion resistance. It is also observed that as the coarser fibre content in the blends increases, the abrasion resistance of the yarn decreases. This is due to the presence of lesser number of fibres in the yarn cross-section.

Figure 5 shows that the abrasion resistance of yarns is improved for both types of thermal treatments. The improved abrasion resistance may be attributed to the opening up of yarn structure which leads to greater fibre mobility in the yarn body. In case of wet thermally treated yarns, greater abrasion resistance is due to more opening up of the structure and more extensibility of yarns because of the higher shrinkage which reduces the intensity of abrading action to a greater extent. However, the increase in abrasion resistance is more marked in yarn spun from higher content of coarser fibres due to higher stress relaxation.

### 3.6 Flexural Rigidity

It is observed from Fig. 6 that the flexural rigidity of the yarn increases when circular fibre content in the blends of circular and trilobal fibre increases. This can be ascribed to the higher bending rigidity of trilobal fibres and hence these fibres give less tighter wrapping than their circular counterparts. It is also observed that as the coarser fibre content in blends increases, the flexural rigidity of yarn increases. This is due to the fact that when finer fibres are used in air-jet spinning, although the number of fibres per cross-section is increased, the number of wrapping remains the same, i.e. the ratio of wrapping fibres to core fibres becomes lower which could be expected to
make the yarn less stiff and more flexible.

The flexural rigidity of air-jet spun yarn decreases after both types of thermal treatment (dry and wet). This is attributed to the opening up of the structure which favours easy inter-fibre movement during bending. Wet thermally treated yarns show greater decrease in flexural rigidity as the more shrinkage enhances the freedom of fibre movement in the yarn.

However, the yarn spun from higher content of coarser fibres shows greater decrease in flexural rigidity.

### 3.7 Yarn Diameter

Table 2 shows the diameter of experimental yarns. The yarn having greater content of trilobal fibres exhibits larger optical diameters owing to the higher bending rigidity of these fibres. The coarser and more rigid fibres resist more to bending while twisting into yarn, leading to a higher radius of curvature, which, in turn, is caused by the movement of fibres away from axis. It has also been observed that the yarn diameter increases as the coarser fibre content in the blends increases.

An increase in yarn diameter is also observed from the table as a consequence of thermal treatment. This can be attributed to the increase in bending and buckling of fibre components, which, in turn, results in the loosening of the structural matrix of yarn owing to the decrease in cohesive forces. There is a greater increase in yarn diameter in case of wet thermally treated yarn owing to the higher thermal shrinkage in this case. However, the increase in yarn diameter is more as coarser fibre content in the blends increases.

### 3.8 Mass Irregularity and Imperfections

#### Table 2 — Influence of material parameters and thermal treatment on linear density and yarn diameter of polyester air-jet spun yarns

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Blend</th>
<th>Blend ratio</th>
<th>Linear density, tex</th>
<th>Yarn diameter, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Dry Thermally treated</td>
<td>Grey Thermally treated</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Dry Wet</td>
<td>Dry Wet</td>
</tr>
<tr>
<td>1</td>
<td>Pcir/Ptbl</td>
<td>30/70</td>
<td>19.96 20.99 21.21</td>
<td>0.183 0.187 0.190</td>
</tr>
<tr>
<td>2</td>
<td>Pcir/Ptbl</td>
<td>50/50</td>
<td>20.05 21.24 21.42</td>
<td>0.176 0.180 0.182</td>
</tr>
<tr>
<td>3</td>
<td>Pcir/Ptbl</td>
<td>70/30</td>
<td>19.96 21.03 21.27</td>
<td>0.171 0.175 0.175</td>
</tr>
<tr>
<td>4</td>
<td>P2.0d/P1.2d</td>
<td>30/70</td>
<td>19.87 20.66 20.93</td>
<td>0.152 0.155 0.157</td>
</tr>
<tr>
<td>5</td>
<td>P2.0d/P1.2d</td>
<td>50/50</td>
<td>20.05 21.16 21.42</td>
<td>0.156 0.161 0.166</td>
</tr>
<tr>
<td>6</td>
<td>P2.0d/P1.2d</td>
<td>70/30</td>
<td>20.25 21.72 21.93</td>
<td>0.160 0.168 0.170</td>
</tr>
</tbody>
</table>

#### Table 3 — Influence of material parameters and thermal treatment on unevenness and imperfections of polyester air-jet spun yarns

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Un Evenness, U%</th>
<th>Imperfections/1000 m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Grey Thermally treated</td>
<td>Grey Thick Thick Neps</td>
</tr>
<tr>
<td></td>
<td>Dry Wet</td>
<td>(-50%) (+50%) (+200%)</td>
</tr>
<tr>
<td>1</td>
<td>15.64 15.92 15.87</td>
<td>44 59 132</td>
</tr>
<tr>
<td>2</td>
<td>15.06 15.37 15.51</td>
<td>39 52 118</td>
</tr>
<tr>
<td>3</td>
<td>14.71 15.02 15.12</td>
<td>33 46 103</td>
</tr>
<tr>
<td>4</td>
<td>13.32 13.67 13.54</td>
<td>23 30 67</td>
</tr>
<tr>
<td>5</td>
<td>13.87 14.12 14.19</td>
<td>29 34 64</td>
</tr>
<tr>
<td>6</td>
<td>14.25 14.54 14.69</td>
<td>34 39 69</td>
</tr>
</tbody>
</table>
Table 3 shows that the yarn evenness deteriorates as trilobal fibre content increases in the blends of circular and trilobal fibres owing to the higher stiffness of trilobal fibres. It is observed that with the increase in finer fibre content in the blends, the yarn unevenness improves due to greater number of fibres in yarn cross-section. On heat treatment, a slight increase in unevenness is noticed. This deterioration in yarn evenness occurs because heat treatment increases permittivity and dielectric constant\(^1\), which, in turn, alters the capacitance of the condenser. Therefore, the Uster evenness tester records apparently higher values of U% for thermally treated yarns. No particular trends have been observed for methods of thermal treatment.

The values of yarn imperfections, such as thin places (-50%), thick places (+50%) and neps (+200%), are given in Table 3. The yarn spun with higher content of trilobal fibres exhibits more imperfections, as higher bending rigidity of trilobal fibres is responsible for higher number of neps. It is observed that there is a slight increase in thin and thick places as the coarser fibre content in the blends increases. The yarn imperfections for thermally treated yarns appear to be high but do not reflect any specific trend.

4 Conclusions

4.1 Thermal treatment causes increase in linear density of yarn and the increase is more marked with wet thermal treatment. There is marked increase in yarn linear density as coarser fibre content in the blends increases. In the case of thermal shrinkage, wet thermally treated yarns exhibit higher relaxation shrinkage than dry thermally treated yarns; the latter, however, increases with increasing coarser fibre content in the yarn.

4.2 In the blends, trilobal fibre shows lower helix angle, higher helix diameter and greater mean fibre extent than their circular fibre counterparts. Finer denier fibres exhibit higher helix angle, lesser helix diameter and lesser mean fibre extent than their coarser denier fibre counterparts. The helix diameter increases as the trilobal fibre and coarser denier fibre content in their blends increase. After thermal treatment, helix angle and helix diameter increase whereas mean fibre extent decreases. The changes are more prominent with wet thermally treated yarns.

4.3 The yarn tenacity and breaking extension increase as circular fibre content and coarser denier fibre content in their blends increase. Thermal treatment leads to substantial increase in breaking extension but adversely affects the yarn tenacity. The changes are more prominent with wet thermal treatment. Marked decrease in tenacity has been observed in the yarns spun from higher content of trilobal fibres in their blends.

4.4 Polyester MJS yarns produced with higher content of circular fibres and coarser denier fibres in their blends exhibit higher values of abrasion resistance. Thermal treatment results in substantial increase in abrasion resistance and is more prominent with wet thermal treatment. Marked increase has been observed in the yarns spun with higher content of coarser denier fibres in their blends.

4.5 The flexural rigidity of the yarns increases as circular fibre and coarser denier fibre contents in their blends increase. Thermal treatment results in consistent decrease in flexural rigidity which is more prominent with wet thermal treatment. The yarns spun with higher content of coarser fibre exhibit marked decrease in flexural rigidity.

4.6 The yarn diameter increases as trilobal fibre and coarser denier fibre contents in their blends increase. Yarn diameter increases after thermal treatment. Marked increase has been observed as coarser denier fibre content in their blends increases.

4.7 The evenness increases and imperfections decrease as circular fibre and coarser denier fibre contents in their blends increase. There is a slight increase in unevenness and imperfections after thermal treatment.

References