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Structural and mechanical characteristics of polyester dref-3 yarns in relation to fibre profile and annealing treatment

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The influence of process parameters and annealing treatment on structural parameters, tensile properties, flexural rigidity and abrasion resistance of polyester dref-3 yarns has been studied. Annealing leads to a marked increase in helix angle and helix diameter, and a decrease in mean fibre extent. The results show significant improvement in breaking extension, work of rupture and abrasion resistance, and an appreciable decrease in tenacity, hairiness and flexural rigidity on annealing. The degree of change in these characteristics is more marked in the yarns made from a circular polyester fibre and the coarse fibre denier, thicker core and higher production speed facilitate it. Compared to the yarns made from a trilobal fibre, the yarns spun from a circular fibre exhibit higher thermal shrinkage which further increases with the increase in spinning speed.

Keywords: Annealing, Core-wrapper ratio, Dref-3 yarn, Polyester yarn, Thermal shrinkage, Trilobal fibre
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1 Introduction

Friction-spun yarns have been around for over 25 years. With advances in machine designs and friction elements aimed at improving fibre alignment, friction-spun yarns are widely used in manufacturing textile products for high performance applications like automobiles, filtration, geotextiles, safety and heavy protective garments and many other industrial applications. Friction-spun yarns were studied in as early as 1981-82 by the researchers examining the effect of yarn production conditions on the characteristics of friction-spun yarns[1]. A comprehensive bibliography of the considerable literature on friction-spun yarns has been reported by Ishtiaque *et al.*[2] There are occasional references to the response of jet- and friction-spun yarns to thermal treatment in the literature.[3-6] However, no publication regarding contribution of fibre profile to friction yarn quality is available so far. As friction-spun yarns become more refined and diverse, the information with regard to the combined influence of system variables and heat treatment needs further corroboration and systematic investigation. Such a detailed knowledge is imperative for establishing processing guidelines because the textile substrates made from friction-spun yarns for some high-tech applications are subjected to high temperature. The present study aims at investigating the effects of annealing under relaxed condition on the changes in structural and mechanical characteristics of polyester dref-3 yarns in relation to fibre profile, core-wrapper ratio and production speed.

2 Materials and Methods

2.1 Preparation of Yarn Samples

Three polyester fibres of different linear densities and cross-sections were used for the study. The specifications of these fibres are given in Table 1. Each polyester fibre was hand opened and processed in opening room. The conversion to drawn sliver was carried out by using a MMC carding machine and a Lakshmi Rieters' draw frame DO/2S. Two drawing

Table 1 — Specifications of polyester fibres

Fibre profile	Length mm	Linear density dtex	Breaking strength cN/tex	Breaking extension %	Coefficient of friction	
					Fibre-to-fibre (μ_{ff})	Fibre-to-metal (μ_{fm})
Circular	44	1.66	44.05 (46.49)	36.3 (29.5)	0.449	0.188
Circular	44	2.22	42.67 (45.02)	35.9 (29.2)	0.399	0.161
Trilobal	44	2.22	38.53 (40.61)	37.0 (30.0)	0.424	0.165

Figures in parentheses indicate values for grey yarns.

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Table 2 — Spinning parameters for dref-3 yarns
[Yarn linear density, 59 tex; Friction drum speed, 4500 rpm; and Combing rollers speed, 12000 rpm]

Yarn ref. no.	Fibre profile	Fibre linear density dtex	Core/wrapper ratio	Production speed m/min	Inlet speed, m/min	
					DU -I	DU - II
S1	Circular	1.66	50/50	100/150/200	1.01/1.53/2.04	0.20/0.30/0.41
S2	Circular	1.66	60/40	100/150/200	1.22/1.83/2.44	0.16/0.24/0.33
S3	Circular	1.66	70/30	100/150/200	1.42/2.14/2.85	0.12/0.18/0.24
S4	Circular	2.22	50/50	100/150/200	1.01/1.53/2.04	0.20/0.30/0.41
S5	Circular	2.22	60/40	100/150/200	1.22/1.83/2.44	0.16/0.24/0.33
S6	Circular	2.22	70/30	100/150/200	1.42/2.14/2.85	0.12/0.18/0.24
S7	Trilobal	2.22	50/50	100/150/200	1.01/1.53/2.04	0.20/0.30/0.41
S8	Trilobal	2.22	60/40	100/150/200	1.22/1.83/2.44	0.16/0.24/0.33
S9	Trilobal	2.22	70/30	100/150/200	1.42/2.14/2.85	0.12/0.18/0.24

DU-I—Drafting unit I, and DU-II—Drafting unit II.

passages were given to carded slivers. The drawn slivers were spun into 59 tex yarns on DREF-3 spinner using the process parameter given in Table 2. In all the spinnings, the friction drum and combing roller speeds were kept constant at 4500 rpm and 12000 rpm respectively.

2.2 Annealing Treatment

All the yarns were annealed by dry heating at 160°C for 5 min in a laboratory curing-setting chamber under relaxed condition. Skeins of 300-400 m were prepared on a wrap reel and laced at 5 points. The lacings were kept loose so as not to hinder the relaxation process in yarn during shrinkage. The skeins were then hung loosely in curing-setting chamber for annealing.

2.3 Tests

Prior to processing, a small fraction of dyed fibres was added to the grey fibres during mixing and the lots were spun into yarns in a normal way. The yarns were then immersed in a fluid with the same refractive index as the fibres so that the dyed fibres could be readily observed through an image analyser. The yarn structural parameters, namely helix angle, helix diameter and mean fibre extent (Fig. 1), were then measured for dyed sheath fibres using a Leica Q500 MC image analyser. Eighty yarns with both ends shown on the screen were observed for each yarn sample. The yarns were also tested for the following properties as per ASTM standards : tenacity, breaking extension and work of rupture (Instron); flexural rigidity by ring loop method[7] (Shirley weighted ring yarn stiffness tester); abrasion resistance (CSI abrasion tester); and hairiness by Zweigles hairiness meter.

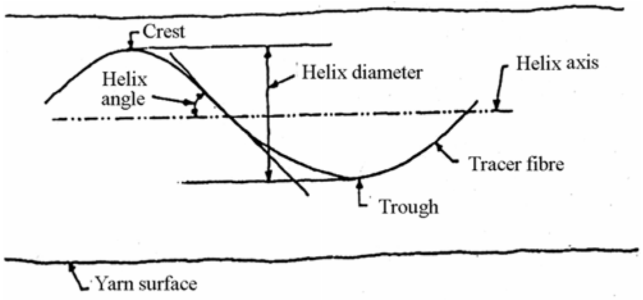

Fig. 1 — Helix diameter and helix angle of tracer fibre

3 Results and Discussion

3.1 Yarn Structural Parameters

Table 3 shows experimental results for structural parameters. It is observed that the distinct fibre cross-sections produce different helix angles and their variances depend upon the fibre linear density and spinning speed, which means that the measured results depend on the experimental conditions. Invariably, the helix angle appears larger for the yarns made from a non-circular polyester fibre but it substantially decreases as the yarn is delivered faster. This decrease could be caused by the lower amount of twist inserted by higher speed. Although no particular trend is observed for helix angle with variation in core content, the increased fibre linear density causes helix angle to decrease. On the other hand, annealing treatment causes a marked increase in helix angle at all spinning speeds. This concides with the occurrence of longitudinal shrinkage in the yarn, which, in turn, brings the consecutive helices closer to each other. The increase in helix angle of yarns spun from a trilobal fibre is significantly greater than the increase in yarns spun from a circular polyester fibre. The

Table 3 — Influence of fibre profile, fibre linear density, core content and production speed on helix angle, helix diameter and mean fibre extent of polyester dref-3 yarns

Yarn ref. no.	Helix angle, deg			Helix diameter, mm			Mean fibre extent, mm		
	100[a]	150[a]	200[a]	100[a]	150[a]	200[a]	100[a]	150[a]	200[a]
S1	54.41 (49.69)	48.72 (43.72)	43.58 (35.95)	0.336 (0.332)	0.354 (0.346)	0.375 (0.355)	4.11 (5.66)	5.89 (11.78)	7.72 (12.51)
S2	46.70 (44.58)	46.46 (43.60)	40.44 (35.57)	0.330 (0.284)	0.333 (0.293)	0.343 (0.320)	4.02 (8.74)	5.03 (9.94)	7.06 (11.70)
S3	48.00 (43.72)	44.26 (42.46)	42.82 (38.68)	0.326 (0.280)	0.333 (0.286)	0.342 (0.308)	4.57 (7.71)	5.94 (11.91)	7.44 (12.24)
S4	45.31 (42.25)	42.00 (37.63)	39.35 (33.30)	0.347 (0.341)	0.365 (0.356)	0.381 (0.367)	5.32 (7.75)	6.89 (12.34)	8.12 (12.78)
S5	43.38 (40.97)	40.43 (35.43)	40.17 (34.05)	0.337 (0.305)	0.344 (0.328)	0.361 (0.345)	5.75 (9.81)	6.61 (11.35)	8.18 (12.20)
S6	46.16 (43.27)	41.46 (38.50)	40.93 (34.80)	0.335 (0.296)	0.341 (0.316)	0.347 (0.339)	5.68 (9.16)	6.99 (12.48)	7.98 (12.94)
S7	46.44 (44.13)	42.98 (37.97)	42.57 (34.39)	0.374 (0.359)	0.390 (0.370)	0.398 (0.384)	4.28 (5.83)	5.84 (8.47)	5.88 (8.89)
S8	46.17 (42.80)	42.83 (40.32)	40.34 (35.33)	0.359 (0.336)	0.363 (0.338)	0.374 (0.348)	4.10 (6.96)	5.30 (7.08)	5.58 (7.12)
S9	47.14 (43.69)	42.71 (38.55)	41.34 (37.48)	0.345 (0.327)	0.351 (0.332)	0.367 (0.342)	4.00 (7.44)	5.03 (7.64)	5.33 (8.90)

[a] Production speed in m/min. Figures in parentheses indicate values for grey yarns.

yarns produced at 200 m/min speed, however, display smaller helix angle than those processed with 100 m/min spinning speed.

Table 3 indicates that the yarns made from a trilobal polyester fibre, in general, display larger helix diameter than the equivalent yarns spun under identical processing conditions but with a circular polyester fibre. The trilobal fibres on account of their higher bending rigidity tend to form a larger sleeve and hence a larger helix diameter. The fibre linear density and core-sheath ratio have a significant effect on helix diameter which increases as both fibre linear density and core-sheath ratio increase. The increase in helix diameter is associated with a decrease in yarn twist arising due to the formation of a larger sleeve. Further, as the spinning speed increases, helix diameter also increases due to lower yarn twist. The effect of annealing can also be observed in Table 3. Under all experimental conditions, the helix diameter steadily increases on annealing. The bending and buckling of fibrous components result in the loosening of structural matrix of yarn, thus increasing helix diameter.

The values of mean fibre extent of the polyester dref-3 yarns corresponding to different process parameters are given in Table 3. In general, the mean fibre extent is considerably lower for the yarns containing trilobal polyester fibre and it increases as the production speed increases from 100 m/min to 200 m/min. This is the result of lesser yarn twist, which contributes directly to mean fibre extent. Although no specific relationship between core-sheath ratio and mean fibre extent has been observed, the latter however reduces as the fibre linear density decreases. Finally, the mean fibre extent decreases dramatically on annealing. This is obvious consequence of the shortening of fibre length brought about by the alteration in structural matrix of fibres upon heating. However, the decrease in mean fibre extent is relatively more marked in yarns spun with 1.66 dtex polyester fibres. The finer fibres on account of their lower bending rigidity get buckled easily and form loops before they are incorporated in the yarn. Besides, buckling tendency is alleviated by the shrinkage of fibres on heating, hence reducing the mean fibre extent immensely. The influence of fibre profile on the mean fibre extent is minimal.

3.2 Tensile Properties

The influence of five experimental factors, viz. fibre linear density, fibre profile, core-wrapper ratio, production speed and annealing treatment, on the yarn properties was assessed with the help of ANOVA analysis (Table 4); the confidence level used was 99%. Table 5 shows the result of tensile tests. The data show that the annealing treatment leads to a

2.6-9.5% decrease in tenacity, a 43.4-48.2% increase in breaking extension and 32.5-43.8% increase in work of rupture of polyester dref-3 yarns, depending upon the process parameters used. The changes are obviously caused by the loosening of yarn structure, decrease in fibre tenacity and increase in breaking extension due to annealing (Table 1). Higher core content raises tenacity loss; the decrease, though always more in yarns spun from a circular polyester fibre, demonstrates a downward trend with decreasing fibre linear density. Such a trend occurs because greater compactness no longer favours the transmission of heat to axial fibres and consequently higher values of strength due to lower relaxation shrinkage. In addition to fibre profile and core-wrapper ratio, spinning speed also appears to significantly affect the tenacity loss after annealing. Higher spinning speed leads to higher tenacity loss, and the amount of yarn wist is known to have an effect on the loosening of yarn structure arising due to bending and buckling of core fibres during shrinkage.

Table 4 — ANOVA test results

Process variable	Yarn property Tenacity	Breaking extension	Work of rupture	Abrasion resistance	Flexural rigidity	Hairiness
A	s	s	s	s	s	s
B	s	s	s	s	s	s
C	s	s	s	s	s	s
D	s	s	s	s	s	s
E	s	s	s	s	s	s

s – Significant at 99% confidence level.

A – Fibre linear density, B – Fibre cross-section, C – Core-wrapper ratio, D – Spinning speed; and E –Annealing treatment.

Annealing treatment causes a marked increase in breaking extension of polyester dref-3 yarns (Table 5). The increment is the result of rearrangement of molecular structure due to yarn shrinkage and increased fibre extension. However, the increment in breaking extension is more marked in yarns spun from a circular fibre as compared to their non-circular counterparts owing to the lower yarn twist[8]. Consequently, fibres shrink more, resulting in higher extensibility. In regards to fibre linear density and core-wrapper ratio, the breaking extension shows a similar trend as for yarn tenacity. Analysis of variance for spinning speed suggests that an increased spinning speed results in greater increase in breaking extension after annealing.

As shown in Table 5, the yarns made from a trilobal fibre possess considerably lower work of rupture. The work of rupture displays a descending relationship with the increase in proportion of wrapper fibres. This behaviour is analogous to the tenacity of the yarns. Increasing production speed markedly reduces the work of rupture. Surprisingly, there is a noticeable increase in work of rupture on

Table 5 — Influence of fibre profile, fibre linear density, core content, production speed and annealing treatment on tenacity, breaking extension, work of rupture and abrasion resistance of polyester dref-3 yarns

Yarn ref. no.	Tenacity, cN/tex			Breaking extension, %			Work of rupture × 10^{-3}, g/den			Abrasion resistance, cycles		
	100^{a}	150^{a}	200^{a}	100^{a}	150^{a}	200^{a}	100^{a}	150^{a}	200^{a}	100^{a}	150^{a}	200^{a}
S1	20.57 (21.12)	20.32 (20.94)	19.89 (20.62)	15.65 (10.92)	15.50 (10.68)	15.25 (10.38)	182 (130)	176 (126)	171 (121)	4898 (4293)	4736 (4055)	4634 (3768)
S2	25.82 (26.71)	24.03 (24.96)	22.76 (23.86)	15.46 (10.72)	15.39 (10.69)	15.11 (10.31)	226 (162)	209 (149)	194 (139)	6788 (5747)	6700 (5650)	5968 (4809)
S3	26.88 (28.01)	26.26 (27.53)	24.12 (25.64)	15.23 (10.51)	15.01 (10.28)	14.55 (9.88)	231 (166)	223 (160)	198 (143)	7313 (5804)	7170 (5778)	6438 (5147)
S4	19.84 (20.85)	19.31 (20.44)	18.78 (20.00)	15.54 (10.76)	15.38 (10.56)	14.94 (10.16)	174 (127)	168 (122)	162 (115)	4791 (3864)	4623 (3708)	4566 (3641)
S5	23.54 (24.92)	22.70 (24.49)	20.52 (22.63)	15.41 (10.57)	15.24 (10.48)	14.86 (10.08)	205 (149)	195 (145)	171 (129)	5666 (4537)	5636 (4489)	5573 (4406)
S6	24.90 (26.58)	23.43 (25.61)	21.76 (24.05)	15.11 (10.34)	14.93 (10.20)	14.27 (9.63)	213 (155)	198 (147)	175 (131)	7101 (5632)	7088 (5599)	6407 (4994)
S7	19.82 (20.40)	19.00 (19.92)	18.71 (19.47)	15.50 (10.85)	15.46 (10.77)	15.19 (10.42)	173 (125)	166 (121)	160 (114)	3078 (2499)	2878 (2323)	2859 (2299)
S8	21.20 (22.00)	20.51 (21.53)	19.03 (20.38)	15.48 (10.76)	15.44 (10.66)	15.09 (10.32)	187 (130)	179 (129)	162 (119)	3392 (2736)	2982 (2383)	2952 (2351)
S9	22.29 (23.39)	21.37 (22.91)	19.76 (21.67)	15.43 (10.69)	15.22 (10.45)	14.63 (9.95)	195 (141)	184 (135)	163 (122)	3670 (2934)	3310 (2629)	3145 (2473)

^{a} Production speed in m/min. Figures in parentheses indicate values for grey yarns.

annealing. This is quite understandable and arises due to increased yarn breaking extension.

3.3 Abrasion Resistance

The results of yarn abrasion test are given in Table 5. The data show that under all experimental conditions the abrasion resistance of polyester dref-3 yarns increases remarkably after annealing, indicating the effectiveness of annealing treatment towards yarn abrasion. This is well known that the annealing causes loosening of yarn structural matrix due to bending and buckling of fibres. Consequently, the greater fibre mobility is produced by opening of yarn structure, which reduces the intensity of abrading action. However, an increase in spinning speed from 100 m/min to 200 m/min causes a greater increase in abrasion resistance. This concides with the change in yarn shrinkage at higher spinning speed. A statistical analysis of the data indicates that the fibre profile and core- wrapper ratio have significant effect on abrasion resistance with *F*-ratios of 921828.6 and 3795 respectively. This indicates that the increase in abrasion resistance with thicker core and circular profile is reasonable. With increased fibre linear density, the increase in abrasion resistance shows an increasing trend. This obviously arises due to increased stress-relaxation, which, in turn, leads to a greater fibre mobility and hence a higher abrasion resistance.

3.4 Flexural Rigidity

Table 6 shows that for polyester dref-3 yarns, heated under relaxed condition, the flexural rigidity is 4.6-13.6% lower than that for the corresponding grey yarns. The reduction in flexural rigidity is expected as a consequence of the loosening of yarn core, favouring easy inter- fibre movement during bending. The yarns produced with low spinning speed have higher flexural rigidity. On annealing, these yarns exhibit a lesser decrease in flexural rigidity. The data suggest that a lower spinning speed leads to a lesser drop in restriction on the movement of core fibres due to the compact nature of yarn because of the higher yarn twist. The decrease in flexural rigidity increases with the increase in core content on account of increased thermal shrinkage. From the figures in the foregoing, it can be observed that there is a strong influence of fibre profile on flexural rigidity of annealed yarns, the values obtained for non-circular profile are significantly higher. The higher inter-fibre cohesion and higher bending rigidity of trilobal fibre could help to explain this lesser decrease in flexural rigidity. Moreover, the decrease in flexural rigidity also increases when the fibre linear density is increased from 1.66 dtex to 2.22 dtex.

3.5 Hairiness

The hairiness results for various dref-3 yarns are given in Table 6. In general, the yarns made from a

Table 6 — Influence of fibre profile, fibre linear density, core content, production speed and annealing treatment on flexural rigidity, hairiness and thermal shrinkage of polyester dref-3 yarns

Yarn ref. no.	Flexural rigidity, dynes.cm^2			Hair/20m			Thermal shrinkage. %		
	100[a]	150[a]	200[a]	100[a]	150[a]	200[a]	100[a]	150[a]	200[a]
S1	60.8 (63.8)	44.6 (48.1)	29.2 (32.3)	16 (24)	22 (33)	33 (44)	6.8	7.1	7.5
S2	65.9 (74.3)	45.7 (51.8)	31.2 (35.4)	14 (21)	16 (30)	30 (40)	7.3	7.8	8.1
S3	67.7 (76.8)	52.1 (59.3)	35.5 (40.6)	29 (31)	25 (35)	37 (41)	7.6	8.5	9.0
S4	61.4 (68.0)	47.5 (54.1)	31.0 (35.8)	39 (58)	47 (50)	77 (87)	7.8	8.4	9.0
S5	66.7 (77.2)	52.7 (61.2)	32.0 (37.8)	44 (58)	49 (64)	81 (125)	8.2	9.0	9.7
S6	68.6 (81.8)	60.2 (72.7)	35.9 (42.7)	39 (44)	54 (69)	60 (74)	9.1	10.1	10.6
S7	71.6 (77.6)	51.4 (57.8)	34.6 (39.6)	31 (92)	68 (143)	124 (182)	7.4	8.2	8.6
S8	75.9 (87.0)	54.9 (63.3)	43.1 (50.6)	41 (55)	64 (82)	87 (193)	7.8	8.5	8.9
S9	80.3 (95.1)	66.8 (80.0)	50.8 (61.3)	40 (71)	72 (75)	160 (165)	8.5	9.02	9.6

[a] Production speed in m/min. Figures in parentheses indicate values for grey yarns.

trilobal polyester fibre are relatively more hairy than the yarns made from a fibre having circular cross-section. Hairiness decreases when fibre linear density increases, and at the same time when production speed decreases. This is because at lower production speed, the residence time of fibres in the nip of friction drums increases and hence the yarn twist,which, in turn, results in firm embedment of surface fibres in the body of the yarn. The hairiness values depict no specific trend with the change in core content. Furthermore, the annealed yarns have lesser hairiness than grey yarns regardless of fibre profile, core content and spinning speed. The reduction, however, is relatively more marked in yarns spun from 1.66 dtex fibres.

3.6 Thermal Shrinkage

Table 6 shows that the polyester dref-3 yarns spun from coarse denier fibres undergo greater thermal shrinkage on annealing. It increases further with the increase in core content.This is due to lesser restriction on the core fibres owing to the lower percentage of sheath fibres and consequently better heat transmission to the core components. The spinning speed also has a marked effect on the thermal shrinkage; higher spinning speed results in higher shrinkage. The use of circular profile further increases the thermal shrinkage.

4 Conclusions

4.1 Structural behaviour of polyester dref-3 yarns is predominantly influenced by annealing treatment. On annealing, all yarns exhibit a marked increase in helix angle and helix diameter, and a decrease in mean fibre extent. Yarns spun from a non-circular fibre, on the other hand, show larger helix angle and helix diameter, and lesser mean fibre extent. An increase both in fibre denier and production speed increases the mean fibre extent and helix diameter but decreases helix angle. The helix diameter reduces with the increase in core content.

4.2 Annealing of polyester dref-3 yarns leads to a substantial increase in breaking extension, work of rupture and abrasion resistance and decrease in tenacity, hairiness and flexural rigidity.The level of change in these yarn characteristics is more marked in the yarns spun from a circular polyester fibre and it increases when each of the fibre linear density, core content and production speed increases.

4.3 Yarns made from a circular fibre exhibit considerably higher thermal shrinkage than the equivalent yarns spun from a fibre with trilobal cross-section.The thermal shrinkage increases when both fibre linear density and production increase, the increase is more prominent in yarns spun with a thicker core.

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