BEHAVIOR OF TWO AND THREE-FOLD TWISTED MULTIFILAMENT YARNS

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Abstract: *This work deals with analysis of the behavior of two and three-fold twisted multifilament yarn in dependence on twist level. The structure and consequently various parameters and properties of filament fibers bundle are changed due to twisting. For experiment, two and three-fold twisted polyamide and polyester multifilament yarns were used. Selected properties such as tenacity, breaking elongation, twist take-up and structural parameters (multifilament yarn diameter and packing density) were observed and evaluated. The experiment showed that with increasing twist coefficient the twisted multifilament yarn twist take-up increases, whereas the yarn diameter decreases and the packing density increases-up to the value of twist coefficient of 60 - 70 ktex$^{1/2}$m^{-1}. Tenacity showed decreasing tendency with increasing twist coefficient from the level approximately equal to 50 ktex$^{1/2}$m^{-1} (which corresponds to the angle of peripheral fiber inclination of β_D = 12°) due to lower coefficient of fiber stress utilization in the twisted multifilament yarn. The behavior of the two and three-fold twisted multifilament yarns in terms of utilization of fiber tenacity and yarn breaking elongation was predicted using theoretical models. The significant correlation coefficients between experimental and predicted breaking elongation verified the validity of the corresponding theoretical model. The comparison between the two and three-fold twisted multifilament yarns of the same raw material at the same twist coefficient showed that observed number of single multifilament yarns in the twisted yarn has not any influence on analyzed properties except tenacity and yarn diameter. Moreover, saturated twist of multifilament yarn was discussed.*

Keywords: *multifilament yarn, twist, tenacity, breaking elongation, utilization of fibre tenacity, twist take-up, packing density.*

1 INTRODUCTION

Currently, multifilament yarns are becoming increasingly widespread not only in the field of technical or household textiles, but also in the clothing industry. Twisting multifilament yarns means either twisting raw single-end multifilament yarn, to increase yarn cohesion, or assembling and twisting of two or more multifilament yarns together to achieve the required multifilament thickness, increase cohesion, luster, handle, abrasion resistance, or improve their mechanical and physical properties to a certain extent. The process, where two or more strands of twist-less multifilament yarn are twisted in two-step operation is called also cabling.

One of the important factors which influence multifilament yarn properties is the angle of slope of the fiber to the yarn axis (called a twist angle) [1]. This angle changes with the level of multifilament yarn twist. By increasing number of twists, the diameter of multifilament yarns reduces, the individual fibrils come closer, and the elongation of multifilament yarn increases [2]. However, unlike staple yarn, twisting of multifilament yarn reduces their strength [1-3] which is an important factor in terms of their end use, and this become increasingly important particularly in the case of multifilament yarn for technical applications.

Structure and properties of twisted multifilament yarns were studied in number of works, for example, [1-10]. Huang et al. [4] derived a mathematical model for prediction of ply-yarn strength in relation to the twist coefficient using the single yarn radius, the twist angle, the tensile strain, the cohesion coefficient, the tensile modulus and shear modulus of the single yarn. The model is based on continuum mechanics theory and geometrical analysis of plied yarn. Zimliki et al. [5] predicted the mechanical properties of parallel filament bundles, twisted single-end multifilament yarns and the two-ply multifilament from single-multifilament yarn data. They derived a model for ply-yarn failure based on the statistical distribution of single filament breaks including average filament strength and coefficient of its variation. Kilby [6] discussed and theoretically studied the effect of the equalization of filament tensions on the initial modulus, tenacity, and breaking extension of mechanical properties of twisted single-end multifilament yarn. Treloar [7] theoretically modeled tensile properties (a stress-strain curve) of twisted single-end multifilament yarn based on its geometrical structure and properties of individual fibrils. His analysis was realized based on strain-energy of the system. He compared his model with experimental results and concluded their good agreement with theoretical curve except the region of small extension and high twist. He also applied his "energy-method" for derivation of the stress-strain curve of ply multifilament yarn [8] using theory of geometry of the ply fibers strand [9].

Hearle et al. [1] published, among others, experimental values of relative strength in dependence of inclination of peripheral fibers for single multifilament yarns of various raw material and count. These data was used by Neckar [2]. He verified theoretical model enabling calculation of utilization of fiber stress in yarn tenacity. Hearle [1] and later Neckar [2] also predicted twisted single-end multifilament yarn tenacity using geometrical helical model of yarn.

There is a lack of experimental works focused on two and three-fold twisted multifilament yarn behavior in relation to the yarn twist. Jones et al. [10] experimentally investigated tensile behavior of glass plied multifilament yarn in relation to yarn twist. They compared the results with the theoretical model of Hearle and Bosse [11] based on wrapped-ribbon twist geometry and also with mentioned Treloar's model. Thus, it is necessary to study properties and structural characteristic of twisted (plied) multifilament yarns made from various material and construction in relation to the twist level. Various theoretical models which were derived in last decades are very sophisticated and complicated. A lot of them are not suitable for use in practice. In this work we present models (described below) which seems to be easier to apply. It is necessary to verify its validity for two and three-fold twisted multifilament yarn and compare the models with experimental data. The knowledge of the relation between properties and structure is required also for modeling of behavior of plied multifilament yarns during next downstream manufacturing processes.

The aim of this work was to analyze the effect of number of twists on selected properties of two and three-fold multifilament yarns. These properties were observed: multifilament yarn twist take-up as a factor influencing yarn consumption; diameter and packing density of multifilament yarn which influence weaveability and bending rigidity of multifilament yarn. Simultaneously, tenacity and breaking elongation was analyzed. Based on experimental measurements, a model of utilization of fiber tenacity in the multifilament yarn was constructed and compared with the current theoretical model. The axial strain of fiber bundle was also predicted based on measured values of breaking strain of single-end multifilament yarn and values of angle of peripheral fibers. This work is based on work [3], where authors observed the influence of twist of single-end multifilament yarns on multifilament tenacity, breaking elongation, coefficient of fiber stress utilization in the yarn, angle of peripheral fibers and packing density. For experiment authors used polypropylene and polyester single-end multifilament yarns of count 10 tex and 17 tex. Author verified the known model relationships, derived decades ago based on the helical model, by comparing them with experimentally obtained data.

Moreover, this work contributes to the knowledge about behavior of twisted multifilament yarns particularly two and three-fold yarn used in the technical textile field.

2 SHORT THEORETICAL BACKGROUND

By twisting the fibrous bundle, individual fibers take the helix shape. This geometrical arrangement is possible to be described by concentric helices model [1, 2]. The helical model is the best known theoretical concept in the internal yarn geometry. This ideal helical model assumes that the axes of all fibers have the shape of a helix with the same direction of rotation; helices of all fibers have one common axis which is a multifilament yarn axis; the height of one coil of each helix is the same, and the packing density is the same at all places inside the multifilament yarn. Inside the textile fibrous assembly, there are fibers of volume V. When we mark the total volume of this body as V_c, the compactness of this body can be characterized by the ratio between these two volumes (V/V_c) and it is known as the fiber packing density μ. Evidently, the fiber packing density value must lie in the range from 0 to 1. The packing density in our case is compactness of fibers in the multifilament yarn.

In this work, twisting multifilament yarns means twisting several (two or three) single-end multifilament yarns together, where each of which is provided with only a protective twist or interlaced. We assume that during multifilament yarn twisting, a “doubly-wound” helix is not created. It means that a helix is wound around a helical axis as in the case of staple spun yarn or cabled multifilament yarn, but it is only one wound concentric helix.

From the model of concentric helix, generally known equation (1) results:

$$\tan \beta_D = \pi D Z = \frac{2\sqrt{\pi}\,\alpha}{\sqrt{\mu \rho}} \tag{1}$$

where β_D denotes angle of slope of the peripheral fiber to the linear axis of twisted fiber bundle; D is diameter of cylindrical helix of peripheral fibers axis; Z is twist (strictly speaking: number of turns per unit length of twisted fiber bundle); α is Koechlin's twist coefficient; ρ is fiber density and μ is packing density of fiber bundle.

The relationship between twist Z and fineness T of twisted fiber bundle was derived by Koechlin, as shown in equation (2):

$$Z = \frac{\alpha}{\sqrt{T}} \tag{2}$$

Due to twisting, the length of fiber bundle is contracted. Here, this shortening is expressed by the so called yarn retraction δ (or also yarn twist take-up) as a fractional reduction in length due to twisting [12] as shown in equation (3):

$$\delta = \frac{\Delta l}{l + \Delta l}.100 \tag{3}$$

where Δl is increment of length after untwisting of twisted multifilament yarn [mm]; l is length of twisted multifilament yarn (clamping length) [mm] and δ is yarn twist take-up [%].

Based on the ideal helical model, the yarn twist take-up δ can be derived using Koechlin´s twist coefficient α, packing density μ and fiber density ρ [2], as shown in equation (4):

$$\delta = \frac{\sqrt{1+4\pi\alpha^2/(\mu\rho)}-1}{\sqrt{1+4\pi\alpha^2/(\mu\rho)}+1} \tag{4}$$

Using formula (4) and suitable mathematical adjustment, we can express the packing density (i.e. the degree of compactness of fibrils in the multifilament yarn) depending on the Koechlin's twist coefficient [3] as shown in equation (5):

$$\mu = \frac{\pi\,\alpha^2}{\rho}\frac{(1-\delta)^2}{\delta} \tag{5}$$

Based on the knowledge of yarn retraction δ, we can predict the angle of peripheral fiber β_D by equation (6), which Braschler derived. This equation was presented, for example, in work [2] and [3].

$$\delta = \tan^2\left(\frac{\beta_D}{2}\right) \tag{6}$$

On the basis of ideal helical model and other assumptions, the relation between tensile force utilization coefficient in the twisted multifilament φ and angle of peripheral fiber β_D is valid as shown in equation (7).

The other assumptions of this model are: individual fibrils are straight; there is no interaction between individual fibers during fiber bundle tension; stress-strain curves of fiber are linear, small deformation is assumed and the contraction ratio η is constant. More general solution of this problematic is mentioned in [13].

$$\varphi = (1+\eta)\cos^2\beta_D + \eta\frac{\ln\cos^2\beta_D}{\tan^2\beta_D} \tag{7}$$

where η is Poisson's contraction ratio [-].

In the case that no image analysis is available to measure the angle of inclination of the fibers, it is possible to derive the relation between yarn twist take-up δ and tensile force utilization coefficient φ using equation (1), (6) and (7).

3 EXPERIMENTAL PART

Two types of single-end flat multifilament yarns were used for experiment: polyester (PES) and polyamide 6 (PA) multifilament yarns. Their specification is mentioned in Table 1. PES multifilament yarn was slightly twisted, whereas PA multifilament yarn was interlaced. Thereinafter, these multifilament yarns are called single multifilament yarns. Multifilament yarn cross-sections are presented in Figure 1a and 1b, longitudinal view are mentioned in Figure 2a and 2b. Cross-sections were made by a method of soft slices according to the internal standard [14].

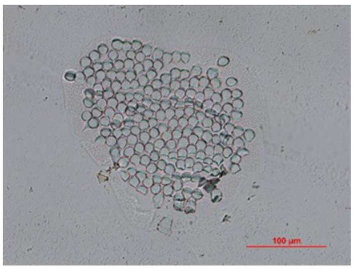

Figure 1a PES single multifilament yarn cross-section

Figure 1b PA single multifilament yarn cross-section

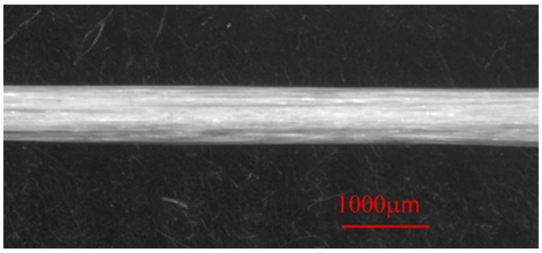

Figure 2a PES single multifilament yarn

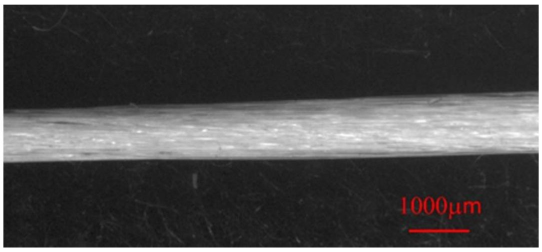

Figure 2b PA single multifilament yarn

Table 1 Parameters of multifilament yarns used for experiment

Parameter	Multifilament yarn	
	100% PES	100% PA
Nominal multifilament yarn count [dtex]	1100	1880
Number of fibrils	192	280
Fibre density [kg.m^{-3}]	1360	1140
Twist [m^{-1}]	60	-
Number of entanglements [m^{-1}]	-	17

Each type of single multifilament yarns was assembled and then twisted in Z direction using the ring twisting machine Twistec. Two folded and three folded twisted multifilament yarns with the various twist level were produced (see Table 2a and 2b). The range of twist level was selected based on the technical possibilities of twisting machine.

Actual yarn count was verified using gravimetrical method. Actual level of plied multifilament yarn twist and length of untwisted multifilament yarn were measured using a twist tester with clamping length 0.5m.

Table 2a and 2b display the nominal number of twists Z_n of twisted multifilament yarns together with values of actual number of twist Z, actual twisted yarn counts T, calculated Koechlin's twist coefficient α, and respective yarn twist take-up δ calculated according to formula (3). Only average values of observed parameters and properties are shown in Table 2a and 2b for their clarity. Differences between nominal and actual yarn twist are caused by spindle slips.

Twisted multifilament yarn diameter was measured using images analysis Nis Elements software according to the internal standard [15]. From each sample of multifilament yarn, 50 measurements were recorded. Figure 3 and Figure 4 demonstrate longitudinal views of the twisted multifilament yarns and their cross-sections. Geometrical arrangement of fibers in Figure 3 and Figure 4 verified the assumption that single multifilament yarns form flat ribbons of fibrils that are twisted around each other. Twisted multifilament yarns strength and breaking extension were measured using the tensile tester Instron under these conditions: clamping length 500 mm, cross-beam speed 500 mm/min and pre-tension 0.5 cN/tex. For each level of twist, 50 measurements were carried out. The strength and breaking extension of individual fibrils in multifilament yarns as well as single multifilament yarns were measured too. These measurements were performed under the same conditions as measurements of twisted multifilament yarns. The results are shown in Table 3. For clarification, only average values of observed parameters and properties are shown in the table.

Table 2a PES twisted multifilament yarn - results of observed parameters and measurement

Nominal twist Z_n [m^{-1}]	Twisted multifilament yarn 2 x 1100 dtex				Twisted multifilament yarn 3 x 1100 dtex			
	Actual twist Z [m^{-1}]	Actual count [dtex]	Koechlin's twist coefficient α [ktex$^{1/2}$.m^{-1}]	Yarn twist take-up δ [%]	Actual twist Z [m^{-1}]	Actual count [dtex]	Koechlin's twist coefficient α [ktex$^{1/2}$.m^{-1}]	Yarn twist take-up δ [%]
20	20	2230	9	0.120	20	3340	11	0.123
40	38	2240	18	0.292	38	3360	22	0.464
60	59	2240	28	0.388	59	3380	35	0.497
80	81	2250	39	0.573	84	3410	49	0.846
100	100	2260	47	0.794	105	3440	62	1.270
120	120	2260	57	1.081	125	3450	73	1.762
140	134	2260	64	1.309	138	3460	81	2.095
160	152	2270	72	1.768	156	3480	92	2.717
200	197	2290	94	2.723	207	3520	123	4.605
250	251	2330	121	4.213	269	3570	161	7.526

Table 2b PA twisted multifilament yarn - results of observed parameters and measurement

Nominal twist Z_n [m^{-1}]	Twisted multifilament yarn 2 x 1880 dtex				Twisted multifilament yarn 3 x 1880 dtex			
	Actual twist Z [m^{-1}]	Actual count [dtex]	Koechlin's twist coefficient α [ktex$^{1/2}$.m^{-1}]	Yarn twist take-up δ [%]	Actual twist Z [m^{-1}]	Actual count [dtex]	Koechlin's twist coefficient α [ktex$^{1/2}$.m^{-1}]	Yarn twist take-up δ [%]
20	18	3760	11	0.213	21	5650	16	0.312
40	35	3790	22	0.253	38	5680	29	0.718
60	54	3800	33	0.570	52	5700	39	0.783
80	76	3810	47	1.147	76	5760	58	1.600
100	95	3850	59	1.639	95	5790	73	2.520
120	115	3900	72	2.466	114	5810	87	3.619
140	129	3928	81	3.025	129	5880	99	4.519
160	150	3952	94	3.987	147	5940	114	5.811
200	196	4080	125	6.522	192	6250	152	8.749
250	255	4264	167	9.863	266	6570	216	15.858


a) b)

Figure 3 Twisted PA multifilament yarn 2x1880 dtex, Z = 160 m^{-1}; a) longitudinal view; b) cross-section


a) b)

Figure 4 Twisted PES multifilament yarn 2x1110 dtex, Z = 160 m^{-1}; a) longitudinal view; b) cross-section

Table 3 PES twisted multifilament yarn and PA twisted multifilament yarn - results of measurement

Nominal twist Z_n [m^{-1}]	PES twisted multifilament yarn 2 x 1100 dtex		PES twisted multifilament yarn 3 x 1100 dtex		PA twisted multifilament yarn 2 x 1880 dtex		PA twisted multifilament yarn 3 x 1880 dtex	
	Tenacity [cN/tex]	Breaking elongation [%]	Tenacity [cN/tex]	Breaking elongation [%]	Tenacity [cN/tex]	Breaking elongation [%]	Tenacity [cN/tex]	Breaking elongation [%]
0**	81.688	12.125			90.851	24.090		
0*	81.636	10.720			80.500	20.404		
20	79.262	10.964	74.092	10.712	77.202	19.982	79.812	20.130
40	79.720	11.590	73.960	10.858	77.586	21.376	80.076	20.784
60	79.738	11.752	75.272	11.657	77.296	21.531	79.506	20.938
80	80.414	11.929	75.208	11.959	77.486	21.752	78.286	21.618
100	80.648	12.502	75.657	12.514	77.759	22.654	77.174	22.540
120	80.330	12.598	74.344	12.332	75.855	23.118	74.772	23.718
140	79.900	12.466	73.748	12.618	76.082	23.706	70.518	25.045
160	79.022	12.692	72.831	12.864	74.684	24.134	69.535	25.886
200	77.856	13.812	70.542	13.552	71.564	26.439	63.862	30.414
250	73.832	13.808	63.384	12.872	67.049	30.262	56.630	33.482

Note: 0** - results of individual fibrils measurements; 0* - results of single multifilament yarn measurements

4 DISCUSSION OF RESULTS

4.1 Twisted multifilament yarn twist take-up

The dependence of the twisted multifilament yarn twist take-up on the twist coefficient is shown in Figure 5. The average values with relevant 95% confidence limit are plotted, however, the limits are not visible in the graph because they are so narrow to show up. From the results it is obvious that the yarn twist take-up increases by increasing twist coefficient. This phenomenon is logical, because the yarn gets shortened during twisting. There is not any difference in the yarn twist take-up behavior when comparing two-fold and three-fold multifilament yarns of the same raw material. This can be explained by the fact that when the twisted yarns have the same twist coefficient, they have also the same or nearly the same angle of slope of single multifilament to the twisted yarn axis, and thus the same twist take-up [3].

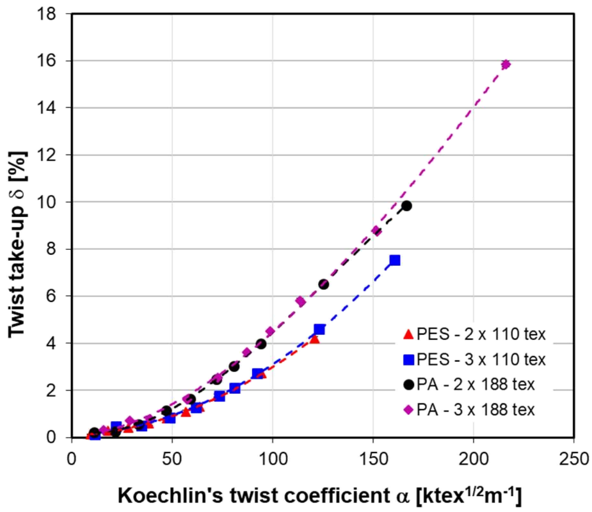

Figure 5 Influence of Koechlin's twist take-up coefficient on twisted multifilament yarn twist take-up

But when comparing PES and PA twisted multifilament yarns, the effect of raw material and structure of multifilament yarn can be observed from Figure 5. Polyamide 6 twisted multifilament yarns show higher twist take-up. It could be caused by raw material as well as the different structure of single multifilament yarn (here fibrils are mutually interlaced).

4.2 Twisted multifilament yarn diameter

By twisting, the individual filaments in the multifilament yarn get closer to each other and thus the multifilament yarn diameter decreases. Results of yarn diameter measurement confirmed this phenomenon. Figure 6 shows the dependence of average values of yarn diameter (with relevant confidence intervals with the confidence level 95%) on Koechlin's twist coefficient. Measurements of three-fold PA twisted multifilament yarns diameter at Koechlin's twist coefficient α = 216 ktex$^{1/2}$.m^{-1} were not possible to carry out by used method because of high snarling tendency of this yarn.

From the course it is obvious that the relationship is polynomial. The most decrease in diameter is visible up to the value of twist coefficient of approx. 60 ktex$^{1/2}$m^{-1}. Although the diameter has decreasing tendency, there were not recorded any statistically significant differences among average yarn diameters in the range of the twist coefficient 70-170 ktex$^{1/2}$ m^{-1} at the level of confidence 95% (according to one-way Anova).

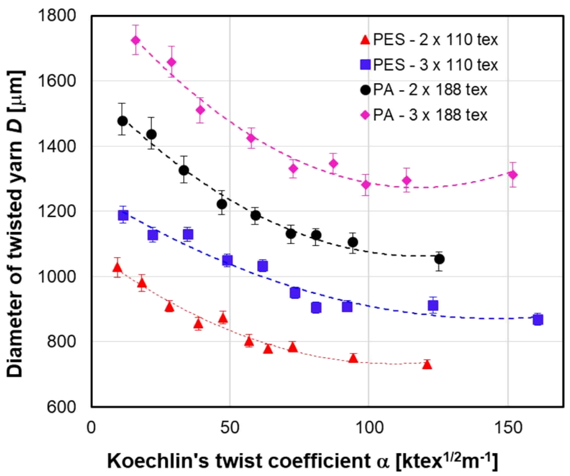

Figure 6 Influence of Koechlin's twist coefficient on twisted multifilament yarn diameter

After exceeding twist coefficient 60 ktex$^{1/2}$.m^{-1}, individual fibrils in the twisted multifilament yarn are very close to each other. During further twisting they can only mutually change their position (i.e. migrate and/or regroup between each other). That can lead to the insignificant change of yarn diameter. Insignificant fluctuation in diameter in this twist range may be also caused by small deviations in the tension of single multifilament yarns during assembling of these yarns on the twisting machine. PA6 twisted multifilament yarns have higher yarn diameter due to their higher number of fibrils in the yarn cross-section and higher diameter of fibril compared to PES twisted yarns.

4.3 Twisted multifilament yarn packing density

The dependence of twisted multifilament yarn packing density on Koechlin's twist coefficient is presented in Figure 7.

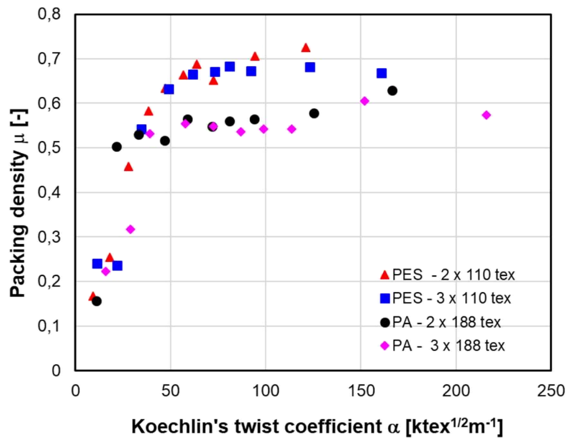

Figure 7 Dependence of twisted multifilament yarn packing density on Koechlin's twist coefficient

We can see that the multifilament yarn packing density increases with increasing Koechlin's twist coefficient because individual filaments get closer to each other during twisting. But when twist coefficient crosses the value of approx. α = 60 ktex$^{1/2}$.m^{-1}, the values of multifilament yarn packing density get stabilized. Thus, at higher twist coefficients, the packing density values are almost equal and independent of the multiplier. Fibrils can no longer be closer to each other. When being nearly constant, the level of packing density takes the value about μ = 0.68 in the case of the PES multifilament yarn and μ = 0.55 in the case of the PA multifilament yarn. The difference can be caused by internal structure of multifilament yarns. Individual fibrils in the PA single multifilament yarn are interlaced, it means that parallel arrangement of individual fibrils is worse compared to the fibrils in the PES single multifilament yarn, which has a low protective twist. The value of PES twisted multifilament yarn packing density corresponds to values of packing density of single multifilament yarn presented in [3] as well as in [2].

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4.4 Twisted multifilament yarn tenacity

Average values of twisted PES multifilament yarn tenacity depending on Koechlin's twist coefficient are plotted in Figure 8a. From this figure, we can see that when twist coefficient increases (i.e. twist level is higher), the value of tenacity decreases from the twist coefficient value approximately equal to 50 $ktex^{1/2}.m^{-1}$. Up to this value, the negligible increase in tenacity can be seen. In the range of small twist multipliers, the relationship between twisted multifilament yarn tenacity and the twist factor may be influenced by crimping of individual fibers and friction between individual fibers in consequence of twist increase. At the range of twist coefficient higher than 50 $ktex^{1/2}.m^{-1}$, the fiber arrangement become not parallel to the yarn axis, thus strength of individual fibrils is less utilized in yarn and tenacity of multifilament yarn decreases with increasing twist level. Tenacity of single multifilament PES yarn is higher than tenacity of two or three folded twisted multifilament yarn. This tendency was expected. Probably, the reason is the decomposition of tensile force in the filaments in consequence of twist because individual fibrils are not arranged in parallel to the multifilament yarn axis due to the ply twist. In the field of folded staple spun yarns, it is known that tenacity of two-ply yarn is higher than tenacity of single staple spun yarn, because plying (due to the effect of doubling) equalizes the single strand mass irregularity and compensates yarn faults (i.e. thin places, thick places). However, this relation isn't valid in the field of twisted multifilament yarn, and the tendency is different.

The dependence of PA twisted multifilament yarn tenacity on Koechlin's twist multiplier is presented in Figure 8b. We can see that behavior of two-fold PA multifilament yarns is similar to PES multifilament yarns. The three-fold PA multifilament yarns have higher values of tenacity than two-fold yarns at low multipliers, up to the twist coefficient value of approximately 70 $ktex^{1/2}.m^{-1}$. The difference can be caused by internal structure of these yarns. Individual fibrils in the PA single multifilament yarn are not slightly twisted as in the case of PES single multifilament yarn but entangled in some places. Thus, inner friction forces between individual PA fibrils probably varies more in yarn length. This phenomenon in connection with higher friction forces given by higher number of fibrils in twisted multifilament yarn cross-section may be a reason of higher tenacity of three-fold PA multifilament yarn in the small range of twist coefficient.

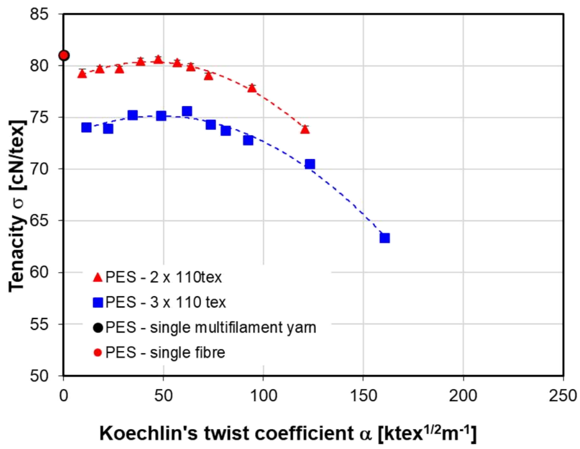

Figure 8a Dependence of PES twisted multifilament yarn tenacity on Koechlin's twist multiplier

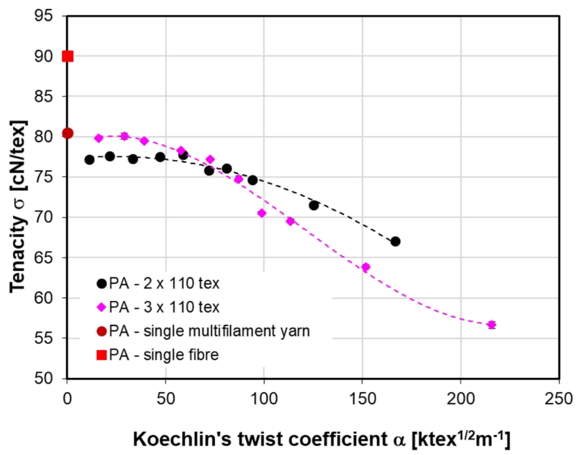

Figure 8b Dependence of PA twisted multifilament yarn tenacity on Koechlin's twist multiplier

4.5 Utilization of fibres tenacity in multifilament yarn

Low utilization of tensile forces of individual fibers causes the decreasing in the tenacity of both multifilament yarns. The coefficient of fiber stress utilization in the multifilament yarn decreases with increasing twist factor value due to higher slope of fibers to the multifilament axis. We can calculate the coefficient of fiber stress utilization in the multifilament yarn (fiber bundle) φ_{exp} based on the experimental values according to equation (8). Also, the theoretical coefficient of fiber stress utilization in the multifilament yarn can be calculated based on the helical model predicting equation (7). This model was derived by Gégauff [16] and then modified by Neckář [2].

$$\varphi_{exp} = \frac{\sigma}{\sigma^*} \tag{8}$$

where σ is tenacity of twisted fiber bundle and σ^* is tenacity of individual fibers.

It is necessary to know the value of Poisson's ratio for the evaluation of predicted coefficient of fiber stress utilization. But it is problematic to determine this constant. In the case that the value is unknown, it is generally set to η = 0.5. The multifilament yarn volume is not changed by this ratio value during small tension deformations [2].

The coefficients of fiber stress utilization in the multifilament yarn calculated according to equations (7) and (8) are presented in Figure 9.

The dependence of experimental and theoretical coefficient of fiber stress utilization in the multifilament yarn on the angle of peripheral fiber (see Figure 9) corresponds to results presented in works [1] and [2]. From Figure 9 it is seen that the experimentally determined coefficient of fiber stress utilization of PA fibers is lower than the predicted one and it has increasing tendency in the range of small angles (up to β_D = 20°).

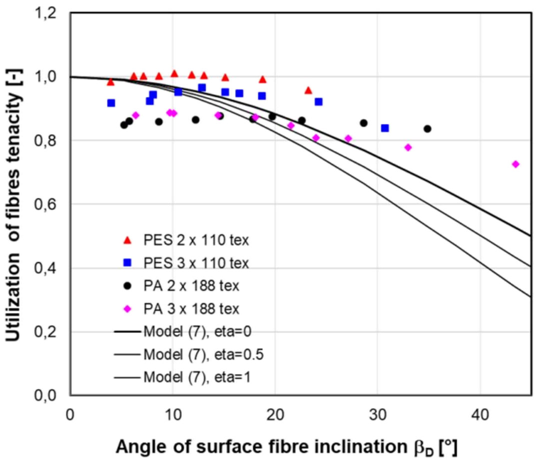

Figure 9 Dependence of coefficient of fiber stress utilization in multifilament yarn on angle of fiber inclination

The experimentally determined coefficient of stress utilization of PES fibers has increasing tendency with growing angle in the range of small angles up to β_D = 12°. The reason of this phenomenon is connected probably with different properties of individual fibers – crimping of fibers, variability of elongation at break. Thus, the average value of individual fiber tenacity is higher than tenacity of fiber bundle (the multifilament yarn), see Figure 8a and 8b. The crimping of fibers given by production technology are not identical, consequently initial lengths of individual fibers are not identical. All fibers in the fiber bundle (multifilament yarn) are loaded non-uniformly. This fact can be a cause of reduction of fiber stress utilization in the multifilament yarn. The twisting of multifilament yarn is processed under stress. Crimped fibers are straightened and interacted during this process in the range of small angles of peripheral fibers. It can lead to the increase in cohesive forces and to the increase in coefficient of fiber stress utilization in the multifilament yarn. Other reason can be the clamping (initial) length too [17], or a modification of multifilament diameter during twisting.

4.6 Twisted multifilament yarn breaking elongation

We can predict the axial strain of fiber bundle based on measured values of breaking strain of non-twisted fiber bundle (single-end multifilament yarn) and values of angle of peripheral fibers using Gégauff model [16]. This model was modified by Neckář [2] for different values of Poisson's ratio, see equation (9). The simplified assumption of this model is: all fibers have helical structure in the same direction of rotation in the fiber bundle; no deformation occurs due to twist and there is no migration of fibers.

$$\varepsilon_l = \varepsilon_a\left(\cos^2\beta - \eta\sin^2\beta\right) \tag{9}$$

where ε_a denotes relative breaking elongation of twisted fiber bundle and ε_l is the relative breaking elongation of non-twisted fiber bundle.

Average values of breaking elongation ε along with their 95% confidence level depending on Koechlin's twist multiplier are plotted in Figure 10. It can be seen that breaking elongation increases with increasing twist. The level of breaking elongation values certainly depends on twist multiplier and probably is affected by raw material and internal structure of single multifilament yarn. The PES multifilament yarn shows lower values of breaking elongation. They also exhibit lower differences between yarn tenacity at minimum and maximum observed twist coefficients compared to PA yarns.

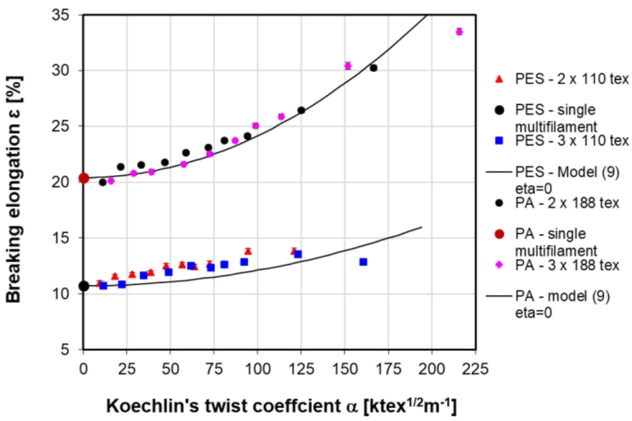

Figure 10 Dependence of PES and PA twisted multifilament yarn breaking elongation on Koechlin's twist multiplier

The comparison of experimental and predicted values of breaking elongation of twisted multifilament yarns depending on the twist coefficient is visible in Figure 10. Theoretical values of breaking elongation were calculated with Poisson's ratio η = 0. The theoretical model supposes that the dependence between the breaking strain and the twist multiplier is increasing which is evident from the diagram in Figure 10. Values of correlation coefficients, presented in Table 4, also validate this hypothesis. All correlation coefficients are statistically significant.

Table 4 Correlation coefficient between experimental and theoretical breaking elongation of multifilament yarn

Multifilament yarn	Correlation coefficient R
PA 2x 188 tex	0.989
PA 3 x188 tex	0.959
PES 2x 110 tex	0.904
PES 3 x110 tex	0.690

4.7 Saturated twist

Generally, it is possible to insert a limited number of coils into a given length of multifilament yarn. Inserting a twist higher than limited turns leads to destruction of fiber bundle and the so called twist of second order is formed [2]. Thus the optimal twist level is limited. This limit case is called saturated twist.

Based on the assumptions of helical model, the equation for calculation of twist take-up as a function of latent twist multiplier α_0 was derived [2]:

$$\delta = \frac{1}{2} - \frac{1}{2}\sqrt{1 - \frac{4\pi}{\mu}\frac{\alpha_0^2}{\rho}} \qquad (10)$$

The latent twist coefficient α_0 is defined as:

$$\alpha_0 = Z_0 \sqrt{T_0}\,. \qquad (10a)$$

where T_0 is initial fineness of non-twisted fiber bundle, Z_0 is latent twist of fiber bundle expressed as number of turns per input length of non-twisted fiber bundle (before twisting).

It is obvious from equation (10), that the value of twist coefficient is also limited. This relation is valid only when formula (11) holds.

$$\frac{\alpha_0}{\sqrt{\mu\rho}} \le \frac{1}{\sqrt{4\pi}}\,. \qquad (11)$$

In the case that $\frac{\alpha_0}{\sqrt{\mu\rho}} = \frac{1}{\sqrt{4\pi}} = 0.281$, then the theoretical twist take-up is equal to δ = 0.5 and angle of peripheral fiber is β_D = 70.5°. This is in the limit case (is referred to as saturated twist).

Figure 11 shows the course of function in equation (10) with packing density μ = 0.6; polyamide raw material was considered for the construction of the function.

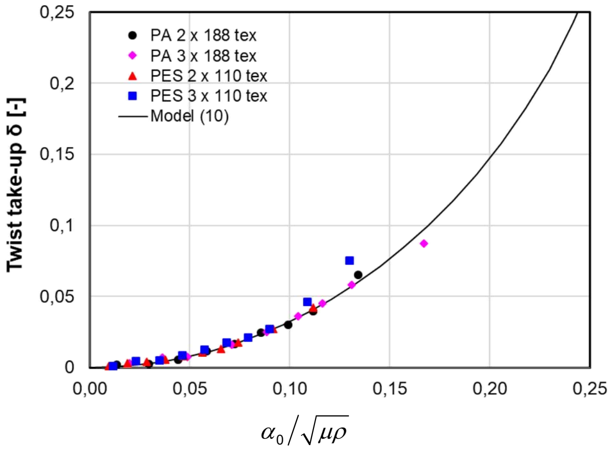

Figure 11 Dependence of twist take-up on latent twist coefficient

Such course is really observed experimentally, but for a smaller value of latent twist. Usually, the saturated twist is observed in the case of yarn twist take-up δ = 0.42, value of angle β_D lies in the range from 45° to 55° in case of multifilament yarns, or the expression $\alpha_0/\sqrt{\mu\rho}$ is approximately equal to 0.22 instead of theoretical value 0.28. Axial asymmetry of twisted yarn is the probable reason of this phenomenon [2] and [3]. If we insert a twist higher than the saturated twist to the yarn, the yarn will not able to absorb it "inside" its structure and then some turns will be placed "outside", such as the coils of the twist of second order.

5 CONCLUSION

The influence of Koechlin´s twist coefficient on selected mechanical-physical properties (tenacity and breaking elongation), yarn twist take-up, and structural characteristics (yarn diameter, packing density) of two and three-fold twisted multifilament yarns were analyzed.

The results confirmed that twisted multifilament yarn twist take-up increases with increasing twist coefficient. The relationship is polynomial. In our case, the numerical coefficients of this polynomial function probably depend on raw material (PES, PA 6) and structure of single multifilament yarn. From our experiment it results that these numerical coefficients are higher in the case of PA twisted multifilament yarn made of single-end multifilament yarns with interlaced fibrils compared to PES twisted multifilament yarn made of single-end multifilament yarns with protective twist.

The diameter of twisted multifilament yarn is influenced by number of fibrils in the cross-section, size and shape of cross-section of individual fibrils, and number of twists. In our case, the twisted multifilament yarn diameter decreases polynomially with increasing twist coefficient up to the value of twist coefficient 60 - 70 ktex$^{1/2}$.m^{-1}. After this value, the decrease in the yarn diameter is not significant. This phenomenon is in agreement with the course of packing density. Their values fluctuate non-significantly from the level of twist coefficient of 60 $ktex^{1/2}.m^{-1}$ up to higher values. The internal structure of single multifilament yarn (protective twist, interlacing) probably influences the value of maximum packing density recorded in this experiment.

The tenacity of twisted multifilament yarn showed negligible increasing tendency with increasing Koechlin's twist coefficient up to the level approximately equal to α = 50 $ktex^{1/2}.m^{-1}$. From this level, increasing twist coefficient leads to a decrease in yarn tenacity due to higher slope of individual fibers to the multifilament axis. The relationship between coefficient of fiber stress utilization and the angle of peripheral fiber inclination, predicted experimentally as well as theoretically, shows that tenacity decreases from the value of angle β_D = 12°. This phenomenon confirmed previously obtained results [3].

The significant correlation coefficient between experimentally and predicted breaking elongation verified validity of Gégauff's and Neckar's model enabling calculation of breaking elongation of twisted fiber bundle based on the breaking elongation of non-twisted fiber bundle and angle of peripheral fibers to the yarn axis.

We can conclude that observed number of single multifilament yarns in the twisted yarn has not any influence on analyzed properties except tenacity and yarn diameter. When the twisted yarns made of the same raw material have the same twist coefficient, they have also the same or nearly the same angle of slope of single multifilament to the twisted yarn axis and thus the same twist take-up, packing density and breaking elongation.

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