STRUCTURE AND MECHANICAL BEHAVIOUR OF POLYPROPYLENE YARNS

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ABSTRACT
The possibilities of prediction of twist influence on the yarn packing density and fibers orientation in the staple polypropylene yarn are discussed. The geometrical models are compared with predicted mean orientation from measurements of packing density, yarns acoustic modulus and yarn initial tensile modulus. Increase of the polypropylene yarn twist level leads to the decrease of the yarn acoustic and initial tensile modulus and orientation of fibers as well.
Key Words: yarn packing density, fiber orientation factor, parallel fiber bundle, sonic velocity, acoustic modulus, initial modulus

1. Introduction

It is well known that fineness and twist (twist factor) have huge influence on the mechanical properties of short staple fiber yarns. It was shown that with the increasing twist the polypropylene yarn strength is reduced [1]. There exist other factors with high influence on yarn mechanical properties. One of the main factors is friction between the fibers, which is connected with the yarn packing density. Due to increasing of twist the packing density is also increased to the limit value approximately 0.7 to 0.8. Second important factor is the orientation of fibers in the yarn. The increasing twist leads to the decreasing of orientation factor and therefore yarn strength is reduced.
The main aim of this contribution is prediction of orientation factor from packing density and ratio of yarn and fiber bundle modulus. Yarn packing density is evaluated from yarn cross-section analysis. Orientation factor is computed from yarn and fiber bundle acoustic modulus and yarn and fiber bundle initial modulus. Results are compared with Gegauff [2], White et. all [3] and Pan [4], [5] model. It is shown that orientation factor measured as ratio between yarn acoustic modulus and fiber bundle acoustic modulus correlates with orientation factor calculated by Pan model. This orientation factor can be used for prediction of yarn strength

2. Theoretical part

Relative yarn strength σ_y is frequently calculated as product of relative fiber strength σ_f and correction factor ϕ_{fy} expressing utilization of fibers strength in yarn.

$$\sigma_y = \sigma_f \phi_{fy} = \sigma_b \phi_{by} = \sigma_f \phi_{fb} \phi_{by} \tag{1}$$

Utilization of fiber strength in yarn is product of fiber strength utilization in bundle ϕ_{fb} and utilization of bundle strength in yarn ϕ_{by}. The σ_b denotes bundle strength. The fiber strength distribution of Weibull two-parameter type was proposed by Pan [4], [5]. Simple approximate relation for utilization of fiber strength in bundle based on Pan result derived in work [1] has the form

$$\phi_{fb} = u^u \exp(-u) / \Gamma(1+u), \quad u = 0,909\, v_{\overline{\sigma_f}} \tag{2}$$

where the symbol Γ() is gamma function and $v_{\overline{\sigma_f}}$ is variation coefficient of fiber strength.

Utilization of bundle strength in yarn was derived by Pan [4], [5]

$$\phi_{by} = V_f n_\beta \tag{3}$$

Volume ratio (packing density) V_f and orientation factor n_β as correction factors are here used. Orientation factor η_β is function of helix angle β_D and yarn Poisson ratio η [4].

$$\eta_\beta = \frac{2\beta_D(1-\eta)+(1+\eta)\sin 2\beta_D}{4\beta_D} \tag{4}$$

Poisson ratio η has the form [4]

$$\eta = \frac{\sin^5 \beta_D}{2(1-\cos^3 \beta_D)\left(\frac{1}{2}\beta_D - \frac{1}{4}\sin 2\beta_D\right)} \tag{5}$$

Packing density μ is generally defined as ratio between fiber volume V_{fib} and whole yarn volume V_y,

$$\mu = V_{fib}/V_y = 4T/\pi D^2 \rho \tag{6}$$

where T is yarn fineness, D is yarn diameter and ρ is mass density. Packing density can be calculate by using the following relationship [6]

$$\frac{\left(\frac{\mu}{\mu_m}\right)^{5/2}}{\left[1-\left(\frac{\mu}{\mu_m}\right)^3\right]^3} = \frac{M\sqrt{\pi}}{2\mu_m^{5/2}\sqrt{\rho}}\left(ZT^{1/4}\right)^2 \tag{7}$$

where M is the material and technology parameter and μ_m is the limit packing density. A suitable value of parameter M for compact, ring, rotor and new type of cotton yarns was found in [6], [7] and [1].

Based on the careful inspection of above mentioned models the modified relation for prediction of polypropylene yarn relative strength was proposed [1]

$$\sigma_P = \sigma_f (1+\varepsilon_f)\phi_{fb}\mu\eta_\beta^* \tag{8}$$

where ε_f is fiber deformation at break and η_β^* is corrected orientation factor derived by Pan (see eqn. (4)). The so called true stress [8] involving a change in yarn geometry was incorporated to the prediction of relative yarn strength.

Let the staple yarn is composed of thin, elastic cylindrical rods with dynamic modulus E and density ρ. Let the longitudinal sonic waves propagation is investigated. The rate of these waves spread c is computed from well known relation [9]

$$c = \sqrt{(E/\rho)} \tag{9}$$

The acoustic dynamic modulus of yarns is much lower then acoustic dynamic modulus of fibers (multiple factor is in the wide range from 0.05 to 0.6). Acoustic dynamic modulus of yarns is influenced by the twist level mainly. In 1907 Gegauff [2] proposed a simple analysis to correlate the twist angle of yarn β_D with the yarn modulus E_y. Based on yarn helical model the tangents of surface fiber helix angle β_D is directly connected with number of twists Z i.e.

$$tg\beta_D = \pi DZ \tag{10}$$

Yarn acoustic modulus E_y at the twist level Z is then function of fiber modulus E_f

$$E_y = E_f \cos^2 \beta = E_f /(1+(\pi DZ)^2) \tag{11}$$

White et. all [3] proposed more complex analysis based on the continuum mechanics. Their final equation has the form

$$E_y = E_f\left(\frac{1}{4} + \frac{9F}{4} + \frac{3F}{1-F}\ln\sqrt{F}\right) \tag{12}$$

where $F = \cos^2 \beta_D$. From the acoustic dynamic modulus of yarns E_y at some twist level Z it is possible to calculate the approximate orientation factor η_β from simple relation

$$\eta_\beta = \frac{E_y}{E_b} \tag{13}$$

where E_b is the acoustic dynamic modulus of yarns without twist (i.e. fibrous bundle). The E_b is in fact replacing the fiber modulus in eqn (11) and (12). The eqn. (13) can be used for prediction of orientation from yarn initial tensile modulus.

3. Experimental part

Compact polypropylene yarns of the same fineness T = 25 tex with different twist level were spun. Yarns were produced in the pilot plant conditions with the smallest and greatest possible twist. Twist factor was varied from 30 to 100 [m^{-1} $ktex^{2/3}$]. Yarns were produced from three type's polypropylene fibers see table 1. Nominal fiber fineness was 2.2 dtex (PP 1, PP2) and 1.7 dtex (PP 3).

Table 1 Fibers properties

fiber properties	fiber type	mean value	95% conf. interval	var.coef. [%]
fineness [tex]	PP 1	0.232	0.218 - 0.243	15.93
	PP 2	0.225	0.213 - 0.236	17.66
	PP 3	0.182	0.174 – 0.190	14.46
length [mm]	PP 1	51,12	50,49 - 51,75	-
	PP 2	48,84	48,19 - 49,49	-
	PP 3	40	-	-
strength [N/tex]	PP 1	0.356	0.344 - 0.370	12.73
	PP 2	0.308	0.301 - 0.315	7.69
	PP 3	0.399	0.389 – 0.409	8.11
deformation at break [%]	PP 1	60.06	52.76 - 67.36	42.79
	PP 2	55.15	48.78 - 61.53	40.68
	PP 3	36.08	34.11 – 38.05	17.7

Polypropylene yarn packing density and diameter were measured from yarn cross-section images. The limit packing density and optimal value of material and technology parameter M for prediction of polypropylene yarns packing density based Neckar model eqn. (7) were found [6]. Influence of twist coefficient and fiber type on yarn packing density is shown in Fig.1.

The yarns sonic velocity was measured on the apparatus Dynamic Modulus Tester (Lawson Hemphill) with piezoelectric crystal transducer. The acoustic dynamical modulus was calculated as function of sonic velocity and fiber mass density. The initial tensile modulus of yarns was evaluated from smoothed stress strain curves measured on the tensile testing machine under standard conditions. The smoothing was realized by using of optimal cubic smoothing splines [10]. The acoustic dynamic modulus of parallel fiber bundle was calculated from linear dependence of yarn sonic velocity on the twist coefficient α (extrapolation to the α = 0). The initial tensile modulus of parallel fiber bundle was calculated from linear dependence of yarn initial tensile modulus on the twist coefficient, as well.

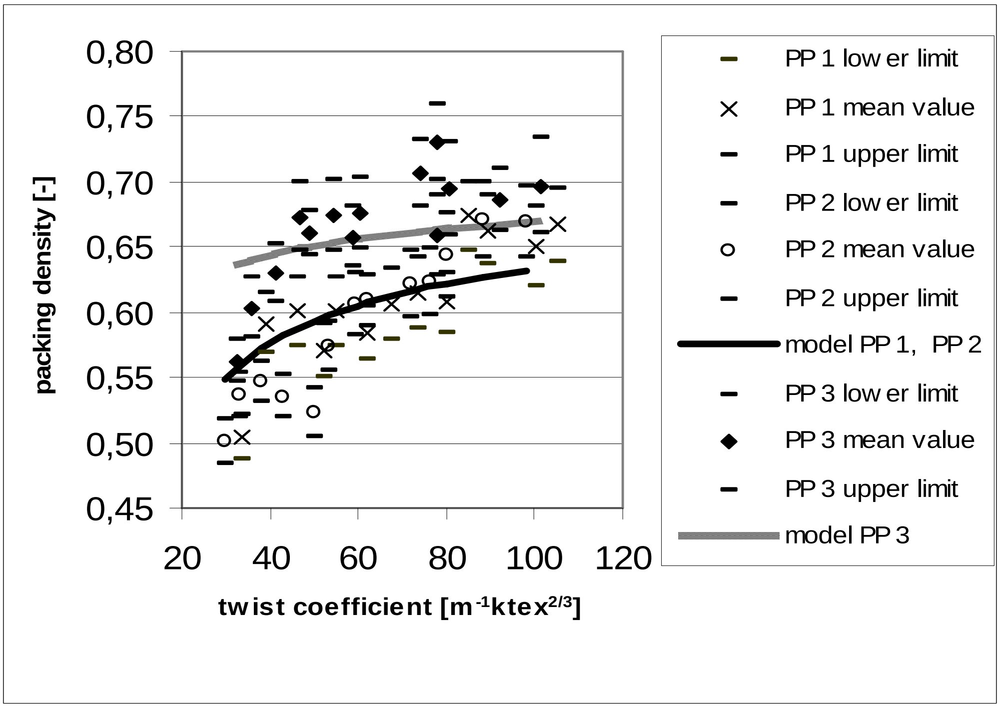

Fig. 1 Yarn packing density as function of twist coefficient

The orientation factor was calculated as ratio between yarn and parallel fiber bundle acoustic dynamic modulus and yarn and parallel fiber bundle initial tensile modulus. Results are compared with orientation factor calculated by Gegauff, White and Pan model (see Fig.2).

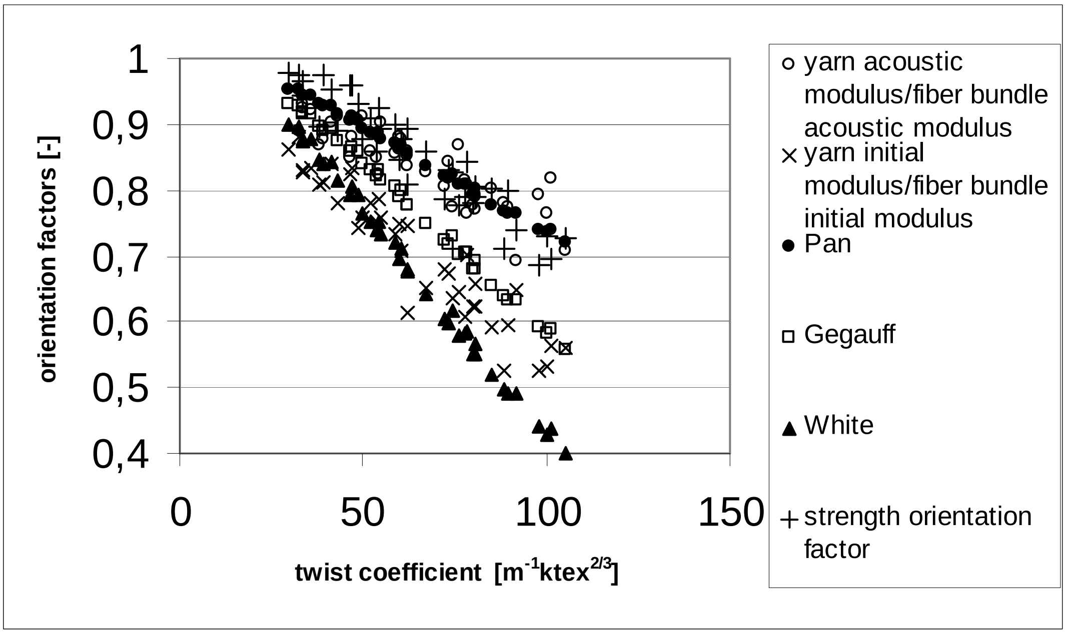

Fig. 2 Orientation factors as function of twist coefficient

Yarns strength was predicted according eqn.(8) and compared with experimental data (see. Fig. 3).

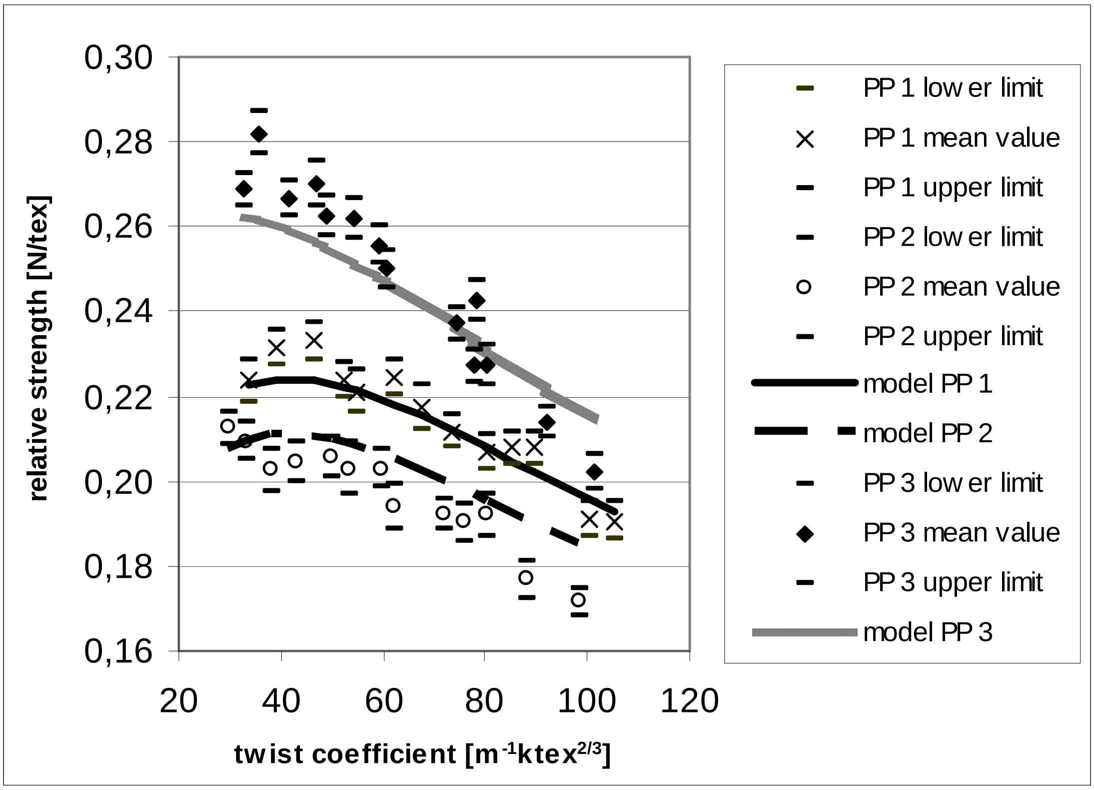

Fig. 3 Yarn strength as function of twist coefficient

4. Results and Discussion

It is shown, that yarns spun from finer fibers have higher packing density at the same twist level due to higher relative fiber surface. Higher packing density means lower yarn diameter on one side and higher number of inter-fiber contacts leading to higher utilization of fiber bundle strength in yarn on the other side. Yarns spun from fibers with the same fineness and higher strength have higher strength, but the same packing density and diameter at twist level. Packing density of polypropylene yarn is increasing function of twist coefficient to the limit value μ_m = 0.7. Polypropylene yarn diameter calculated from eqn. (6) is decreasing function of twist coefficient. For yarns spun from fiber of fineness 2.2 dtex (PP1, PP2) is optimal parameter material and technology M = 0.0919 [m] and for yarns of fiber fineness 1.7 dtex (PP3) M = 0.099 [m].
Yarns spun from finer fibers are more squeezed, packing density is higher, diameter is lower and structure is more homogeneous. This fact leads to higher sonic velocity, higher acoustic dynamical modulus and higher initial tensile modulus, too.
It was found that for prediction of orientation factor from sonic modulus the Pan model is the best and for prediction of orientation factor from initial tensile modulus the White model is the best (see fig.2). For prediction of yarn strength the Pan orientation factor is the best. This factor can be calculated from acoustic dynamic modulus.

5. Conclusion

Connection between polypropylene fiber and yarn geometrical and mechanical properties has been studied. It was shown that the strength of the yarn is influenced mainly by the fiber bundle strength, which depends on the single fiber strength and its coefficient of variation. Another important factor is the reduction of the fiber cross-section area due to the tensile deformation. This factor is representing as so called true stress calculated with using of deformation at break. Fiber fineness have influence on the another factor, i.e. the yarn packing density. An important factor is the orientation of fibers in the yarn. These factors are multiplied. With the increasing of twist the packing density is increasing and the orientation factor is decreasing.

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