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Mechanical Properties of Ring-spun Yarn and Its Strength Prediction Model

Abstract
In this paper, the structural and mechanical properties of ring-spun yarn were studied comprehensively. Relationships between yarn count, yarn twist, and relative yarn structural and mechanical properties were obtained. Through statistical analyses of 200 pure cotton yarn count, twist and strength, with consideration of some influential factors such as being carded or combed, and the application of long-staple cotton, experimental functions of the yarn relative strength with the yarn count and twist were deduced. Considering the above mechanical properties and experimental functions, a pure cotton ring-spun yarn strength prediction model has been established based on continuous mechanics theory. The Equation is easily used with high precision of strength prediction for pure cotton yarn. The relationship between the value predicted and the test value is characterised by high linearity, and the determination ratio of the regression Equation is as high as 0.9623.

Key words: *yarn twist, yarn strength, ring-spun yarn, mechanical properties, strength prediction model.*

RESEARCH & DEVELOPMENT

Introduction

Predicting yarn strength with fibre properties and yarn design parameters is very important for reasonable use of fibre raw material, reducing cost and guaranteeing yarn quality. Since the early twentieth century, many researchers have put forward a number of idealist hypotheses on yarn structure and done some research work on fibre distribution and tension in yarn using structural and mechanics theory. Subsequently, yarn structural and mechanical properties were analysed using statistics. They have had considerable achievements with respect to the structural and mechanical properties of filament yarn and ring-spun staple fibre yarn [1 - 4] and have established a number of yarn strength prediction models [5 - 9]. However, there were some shortcomings as the models were the functions of many unobtainable parameters; hence, prediction precision was limited.

In this paper, the structural and mechanical properties of ring-spun yarn were studied comprehensively, and based on this a single ring-spun yarn strength prediction model was established.

Experiment design and material

Firstly, we made a hypothesis concerning the structure and mechanical properties of single ring-spun yarn according to literature [1, 2]. The relationships between yarn twist and selected yarn structure and mechanical factors, such as the fibre-volume fraction, yarn surface helix angle, the cohesion factor, the slippage ratio, the fibre length efficiency factor and yarn radius were deduced based on the hypothesis.

Secondly, we deduced the experimental correction function of the single ring-spun yarn strength (F) with the yarn count (N_t) and twist (T) using the statistical method. In order to obtain a universally practical function, 200 groups of data for pure cotton single ring-spun yarn (from Changchun Textile Mill and Jiangsu Xinguang Textile Company Limited) with various values of N_t, T and F were collected. The 200 representative yarn samples included all carded and combed yarns generally used and were made of Upland and Sea Island cotton with yarn counts from 5.8 tex to 58.3 tex.

Thirdly, in accordance with continuous mechanics theory, by using the yarn structure and mechanical factors as well as the experimental correction function of the yarn strength with the yarn count and twist, a yarn strength prediction model was established.

Finally, the model was verified using the yarn samples, and a regression function between the yarn strength predicted and tested was obtained. The model achieved high precision for pure cotton ring-spun yarn.

Hypothesis on the structural and mechanical properties of ring-spun yarn

With reference to the analysis of staple fibre yarn by Hearle [1] and Pan [2], the following hypotheses are proposed.

(a) Constitutive fibres have the same properties with a relatively higher elasticity and tension behaviour, in accordance with Hooke's Law. (b) The yarn cross section is circular and the linear density is uniform along the yarn axle. (c) When a yarn is being extended, the stress distribution along the yarn radial direction is uniform, and there is symmetry along the axle. (d) The trace of fibre in the yarn is a conical helix, and its axle is also that of the yarn. (e) The twist distribution along the yarn radial direction is uniform, and the cohesion is omitted when the twist is zero.

Relationship between twist, yarn structure and mechanical properties

Fibre-volume fraction versus yarn twist

Hearle [10] pointed out that the construction of fibre in yarn is in accordance with the least energy principle so as to keep their equilibrium. The fibre-volume fraction (V_f) is the ratio of fibre volume versus yarn volume, and the V_f value is influenced directly by yarn twist (T). According to data on V_f and the twist relation of Hickie et al [11], Pan [2] obtained the function of V_f and T_e (twist/inch) as ***Equation 1***.

$$V_f = 0.7 \times (1 - 0.87\times e^{-0.195T_e}) \qquad (1)$$

Converting T_e to T in twist/m, ***Equation 1*** becomes ***Equation 2***.

$$V_f = 0.7 \times (1 - 0.87\times e^{-0.004957T}) \qquad (2)$$

Equation 2 is illustrated as ***Figure 1***. When T is low, V_f increases rapidly with

T, and when T reaches a certain value, V_f levels off at its maximum - about 0.7.

Yarn surface helix angle versus yarn twist

Studying the relationship between the filament yarn surface helix angle (q) and yarn twist T, Hearle [10] proposed the following equation:

$$q = arctg\left[0.0001 \times T \times \left(\frac{40\pi}{\rho_f V_f}\right)^{1/2}\right] \quad (3)$$

where T is the yarn twist in twist/m, ρ_f - the fibre specific velocity in g/cm^3, and V_f is the fibre-volume fraction. Considering the difference between staple fibre yarn and filament fibre yarn, Pan [2] added a correction ration a_q, and when $a_q = 2.5$, ***Equation 3*** becomes as follows:

$$q = arctg\left[a_q \times 0.0001 \times T \times \left(\frac{40\pi}{\rho_f V_f}\right)^{1/2}\right] \quad (4)$$

Substituting V_f in ***Equation 4*** with equation (2), we obtain the function of q and T as follows:

$$q = \frac{180}{3.14159} \times arctg\left[0.00025 \times T \times \sqrt{\frac{40\pi}{0.7 \times \rho_f \times \left(1 - 0.78 \times e^{-0.00495T}\right)}}\right] \quad (5)$$

When we take ρ_f as 1.53 g/cm^3 [16] in ***Equation 5***, we obtain what is illustrated in ***Figure 2***, which shows that q increases nonlinearly with T.

Yarn cohesion factor versus yarn twist

Fibre in yarn will experience friction and cohesion with surrounding fibres when the yarn is drawn. The cohesion factor n is a non-dimensional factor [2], which reflects the friction and cohesion of a random fibre in yarn. The larger the T, the tighter the yarn, and the larger the action of friction and cohesion on the fibre; hence, the bigger the n value is.

According to the graph of n versus T in reference [2], we obtain the inverse exponential curve of n and T.

$$n = 0.604 \times e^{-919.4/T} \quad (6)$$

Taking the influence of fibre length and fineness into consideration, the above equation is corrected with s, which is the

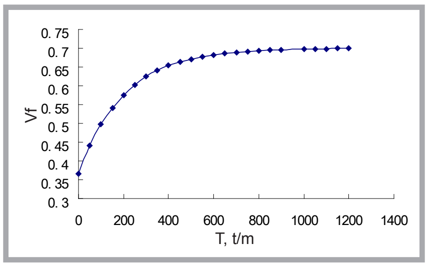

Figure 1. *Fibre-volume fraction versus yarn twist.*

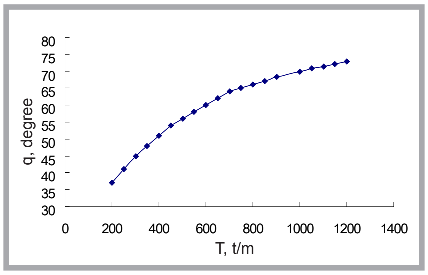

Figure 2. *Yarn surface helix angle versus yarn twist.*

ratio of fibre length to diameter, which is also a non-dimensional factor; hence ***Equation 6*** becomes ***Equation 7*** as follows:

$$n = 0.0003355 \times s \times e^{-919.4/T} \quad (7)$$

For Upland cotton, the fibre length is about 25 ~ 33 mm, the diameter - about 17 ~ 20 μm, so, and the ratio of fibre length to diameter is within the range of 1941 ~ 1250. When Sea Island cotton, with its higher length to diameter ratio, is taken into consideration, the mean value is about 1700 without dimension [17]. When $s = 1700$, ***Equation 7*** is charted as ***Figure 3***, showing that the cohesion factor n increases non-linearly with T. When T is less than 150 (t/m), $n = 0$. The practical meaning is just above that mentioned in the hypotheses, that is, the cohesion among fibres in yarn is omitted when the twist is zero.

Fibre slippage ratio versus yarn twist

When the yarn is extended to breaking point, a fraction of fibres will break, and the others will slip. The slippage ratio λ is the slippage fibre number over the total fibre number at the end of yarn breakage. In accordance with the equation in literature [3] concerning relations between λ, n and s, as ***Equation 8*** reveals, we obtain the power function of λ, s and T, as in ***Equation 9***.

$$\lambda ns\,(1 - \lambda) = tg\,h\,[ns\,(1 - \lambda)] \quad (8)$$

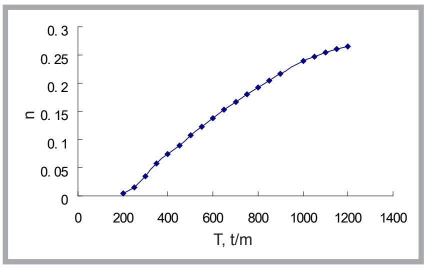

Figure 3. *Yarn cohesion factor versus yarn twist.*

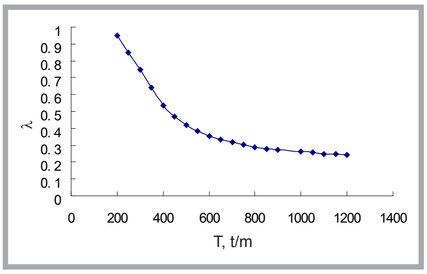

Figure 4. *Fibre slippage ratio versus yarn twist.*

$$\lambda = 266.8/s \times e^{492.1/T} \quad (9)$$

When $s = 1700$, ***Equation 9*** is illustrated as in ***Figure 4. Figure 4*** reveals that when T is low, levelling at 0, λ increases remarkably, levelling off at 1. The curve means that when T is 0, there is no cohesion among fibres, and when the yarn is drawn to breaking point, all the fibres will slip without breakage.

Fibre length efficiency factor versus yarn twist

Considering the results obtained while analysing the force acting on a random fibre in a tensioned state [12], Pan [2, 3] proposed that the length efficiency factor $\eta_{s\lambda}$ of fibres in a yarn is a function of the friction factor (μ) among fibres, the cohesion factor n, the fibre length diameter ratio s, and the slippage ratio λ. Moreover, the influence of parameters including μ, n, s, and λ on the yarn mechanical property is entirely revealed by $\eta_{s\lambda}$, as the following equation shows.

$$\eta_{s\lambda} = 1 - \lambda + \frac{tgh[ns\mu(1-\lambda)]}{2ns\mu} \cdot \frac{\left[(ns\mu\lambda)^2 - 2\right]}{\left[1 + (1-\lambda)(ns\mu\lambda)^2\right]} \quad (10)$$

When $s = 1700$, $\mu = 0.25$ and substituting n and λ in ***Equation 10*** with equation (7) and ***Equation 9***, the relationship between $\eta_{s\lambda}$ and T is plotted as in ***Figure 5***. When T is in a practical range (500 ~ 1200 t/m), $\eta_{s\lambda}$ increases with that of T. This result is just in accordance with

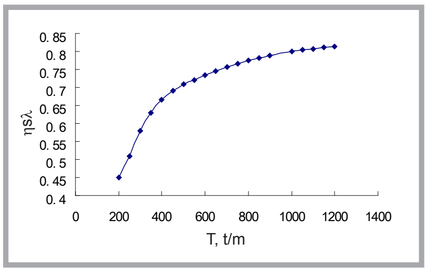

Figure 5. Fibre length efficiency factor versus yarn twist.

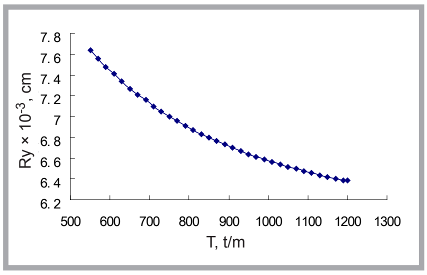

Figure 6. Yarn radius versus yarn twist.

reality i.e. the larger the T, the tighter the yarn, and consequently the greater $\eta_{s\lambda}$ is.

Yarn radius versus twist

Literature [13] proposed a diameter (D) calculation equation for pure cotton yarn as follows.

$$D = \frac{0.97}{\sqrt{N_m}}\sqrt{\frac{T^2 + 390400}{T^2 + 1525 \times N_m}} \qquad (11)$$

Where the dimension of D is in millimetres, T - twists per meter, and N_m is the metric count. Converting D into the radius(R_y), with the dimension in centimetres, and N_m into the cotton yarn count N_t in *tex*, the calculation equation of the yarn radius R_y is obtained as follows.

$$R_y = 0.001533707 \times \times N_t \cdot \sqrt{\frac{T^2 + 390400}{T^2 \cdot N_t + 1525000}} \qquad (12)$$

When the cotton yarn count is 14.6 *tex*, the non-linear relation of R_y and T is illustrated as in ***Figure 6***. It is obviously that R_y decreases non-linearly with an increase in T.

Experimental correction function for yarn strength with the cotton yarn count and twist

In order to obtain the experimental function of yarn strength F with the cotton yarn count N_t and twist T, we collected 200 groups of data of pure cotton yarn with various values of N_t, T and F from Changchun Textile Mill and Jiangsu Xinguang Textile Company Limited. A conversion was made, with the maximum F value taken as 1, the other yarn strength values were divided by the maximum F value and subsequently converted into relative strength values in the range of 0 ~ 1.

Considering the cotton yarn count N_t, carded or cobmed, and the application of long-staple cotton using statistical analyses, we obtained yarn strength correction functions - ***Equation 13*** and ***Equation 14***. These correction functions possess high precision with a determination ratio of the regression equation as high as 0.9930 and 0.9291, respectively.

$$F_{tex} = 229.28 \times (0.0151 \times N_t + 0.0363) \times N_t^{-1.2553} \qquad (13)$$
$$R^2 = 0.9930 \ (13)$$

$$F_t = 2484.703 \times T^{-1.6567} \qquad (14)$$
$$R^2 = 0.9291$$

Equation 13 and ***14*** are plotted as in ***Figures 7*** and ***8. Figure 7*** reveals that the relationship between the yarn relative strength F_{tex} and N_t is a power function. F_{tex} decreases with an increase in N_t, as low N_t yarns are generally made of a fraction of long-staple cotton or high quality Upland cotton, most of which are combed, whereas high N_t yarns are generally made of poor quality Upland cotton or sometimes blended with a fraction of reusable cotton waste, most of which are carded.

Figure 8 reveals that the relationship between the yarn relative strength F_t and N_t is also a power function. F_t decreases with an increase in T. When T increases gradually, the yarn surface helix angle increases, and the interior stress in the yarn also rises, subsequently inducing a decrease in the extention standing ability of fibres in the yarn.

Establishment of a strength prediction model for ring-spun yarn

Pan [2, 3, 14] proposed the yarn modulus E_y expression equation as follows.

$$E_y = \frac{3V_f E_f}{4} \times \eta_{s\lambda} \times \frac{(1+\cos q)^2}{(1+\cos q + \cos^2 q)} \qquad (15)$$

Where E_f is the fibre extension modulus. Platt [15] proposed the relationship between the yarn extension strain ε_y, fibre extension strain in a yarn ε_f, and the yarn surface helix angle q as in ***Equation 16***.

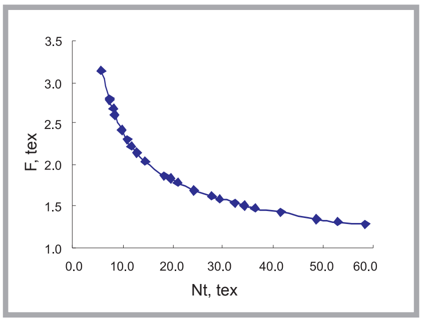

Figure 7. Relative strength versus yarn count.

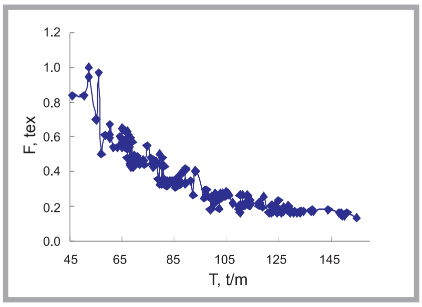

Figure 8. Relative strength versus twist.

$$\varepsilon_y = \varepsilon_f / \cos^2 q \qquad (16)$$

According to the continuous medium mechanics theory, the relationship of yarn extension stress σ_y, strain ε_y, and modulus E_y should be as follows.

$$\sigma_y = \varepsilon_y \times E_y \qquad (17)$$

Subsequently, the yarn strength prediction model is established as below.

$$F = \pi R_y^2 \times \sigma_y \qquad (18)$$

Taking the influence of N_t on yarn strength into consideration, the N_t correction function (13) should be multiplied in yarn strength prediction model ***Equation 18***.

The above-mentioned relationships between the twist T and number of structural and mechanical properties, such as V_f, q, n, λ, $\eta_{s\lambda}$, and R_y are all based on the theory that yarn strength is directly proportional to T. But in reality this is not the case – as shown in ***Figure 8***, there is also a diminishing trend of the yarn strength with an increase in yarn twist. Therefore the T correction function ***Equation 14*** should be multiplied in the yarn strength prediction model ***Equation 18***.

Combining ***Equations (12) - (17)*** with ***(18)***, the final pure cotton ring-spun yarn strength prediction model should be as follows.

$$F_y = 1345.466 \times V_f E_f \varepsilon_f \eta_{s\lambda} \times$$
$$\times \frac{(1+\cos q)^2}{(\cos^2 q + \cos^3 q + \cos^4 q)} \times {R_y}^2 \times T^{-1.6567} \times \qquad (19)$$
$$\times (15.1 \times N_t + 63.3) \times N_t^{-1.2553}$$

Verification of the yarn strength prediction model

In order to verify the prediction precision of the yarn strength prediction model, based on 200 groups of yarn strength data for pure cotton yarn, we took the mean values of the fibre properties as E_f = 78400000 cN/cm^2 [16], ε_f = 9.5%, s = 1700, μ = 0.25 and ρ_f = 1.53 g/cm^3 [17], then put all these fibre property values, the cotton yarn count N_t and twist T into the model, and 200 groups of predicted yarn strength values were obtained using calculation software.

Taking the predicted yarn strength (F_y)as an independent variable and the test yarn strength (F_s) as a dependent variable, we obtained the following linear regression equation.

$$F_s = 0.9048\ F_y + 29.118 \qquad (20)$$
$$r^2 = 0.9623$$

The regression equation reveals that the prediction precision of the pure cotton ring-spun yarn strength prediction model is very high, with a determination ratio as high as 0.9623.

Conclusions

The relationships between the twist T and a number of structural and mechanical properties, such as V_f, q, n, λ, $\eta_{s\lambda}$, and R_y are in accordance with reality. On the basis of 200 pure cotton experimental data, the N_t and T correction function obtained for yarn relative strength shows high precision. The pure cotton ring-spun yarn strength prediction model deduced shows high precision with a determination ratio of the regression equation as high as 0.9623. As for the application of the model, one simply puts the the mean value of cotton properties, such as E_f, ε_f, s, μ and ρ_y, the yarn count N_t and twist T into calculating software, and a predicted yarn strength value can be obtained. This model may provide some reference for cotton blending and a yarn quality guarantee in a textile mill.

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