Cotton Fibre-to-Yarn Engineering: A Simulated Annealing Approach

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Abstract
In this paper we undertake to engineer yarn of predefined strength by choosing suitable raw material and process parameters. In an attempt to achieve a yarn of optimal strength, the constrained optimisation problem is formulated with the relation between raw material and yarn properties. Frydrych's theoretical model of yarn strength is used for formulation of the optimisation problem. The simulated annealing (SA) method has been used to solve the optimisation problem by researching the best combination of raw material and process parameters that can bring into reality a yarn with the strength desired. The results show that SA is capable of ascertaining a set of parameters that gives the yarn strength desired.

Key words: *cotton fibre properties, Frydrych model, simulated annealing, yarn strength, yarn engineering.*

Introduction

The manufacturing of yarns with predefined quality parameters by selecting appropriate raw materials and process parameters is referred to as yarn engineering. Many works have been reported on the prediction of yarn quality in recent years. Ramesh et al. [1], Cheng and Adams [2], Pynckels et al. [3], Sette et al. [4], Shanmugam et al. [5], Guha et al. [6], Yadav and Kothari [7] and Rajamanickam et al. [8] have used a neural network model to predict yarn properties. Majumdar and Ghosh [9] proposed the modelling of ring spun cotton yarn strength using the fuzzy expert system. Sette et al. [10] proposed a model for optimisation of the fibre to yarn process using genetic algorithms (GA). Admuthe and Apte [11] developed a hybrid Neuro-Genetic and GA technique to model, simulate and predict the ring yarn spinning process and cost optimisation. They reported that the performance of the hybrid model was superior compared to current manual machine intervention.

But hitherto very few researchers, such as Das et al. [12], have actually put effort into engineered yarn design. In this paper, an attempt has been made to predict process parameters and fibre properties for the designing of engineered yarn of predefined strength using simulated annealing (SA).

Frydrych's mechanistic model [13], with its better predictive accuracy, has emerged as a potent and convincing approach in establishing the fibre-yarn esoteric interrelationship. Although the Frydrych's mechanistic model for the prediction of yarn strength was developed way back in the eighties, its applications have been limited due to the mathematical rigours involved in the computational works. But with the advent of very high computational speed and non-traditional optimisation techniques, it has now become possible to apply this model for yarn engineering.

Mechanistic model

The model used by Frydrych [13] to predict the strength of cotton yarns incorporates the migrating property of a fibre. Relevant equations for evaluating the fibre length as well as stress and strain generated in it were developed in accordance with the yarn structure described by Zurek [14]. Many equations described by Frydrych [13] owe their origin to previous works by Zurek [14] and Zurek, Frydrych and Zakrzewski [15]. The mechanistic model for yarn strength prediction developed by Frydrych is discussed below:

The metric twist factor is

$$\alpha_m = T\sqrt{\frac{Tt_y}{1000}} \tag{1}$$

where, T - twist per meter (t.p.m.) and Tt_y - yarn linear density in tex.

The density of yarn according to Barella [16] is

$$\rho_y = 560 + 2.8\alpha_m \tag{2}$$

The nominal twist parameter is

$$g = 2\pi RT = \sqrt{\frac{125.7}{\rho_y}}\left(\frac{\alpha_m}{100}\right) \tag{3}$$

where, R is the radius of yarn in meters.

The equivalent fibre diameter is

$$d_f = \sqrt{\frac{4Tt_f}{\pi\rho_f}} \tag{4}$$

where, Tt_f is the linear density of the fibre in tex and ρ_f is the fibre density in kg/m^3.

The yarn diameter in mm is

$$d_y = \sqrt{\frac{4Tt_y}{\pi\rho_y}} \tag{5}$$

The reduced twist parameter [17] is

$$g_c = 2\pi\left(R - \frac{d_f}{4}\right)T = g\left(1 - \frac{1}{2}\frac{d_f}{d_y}\right) \tag{6}$$

The contraction factor is [17]

$$s = \frac{\ln\sqrt{1+g_c^2}}{\sqrt{1+g_c^2}-1} \tag{7}$$

The coefficient of yarn diameter contraction can be calculated according to the following formula [17]:

$$u = 1.13 - \frac{0.0265}{g_c} - 0.12\sqrt[4]{100a_h} \tag{8}$$

Since a_h is unknown, it is first assumed that a_h - fibre breaking strain (a_f), and the value of u is calculated. Knowing the approximated value of u, the strain of the breaking zone of the yarn is found from the relationship

$$a_h = \sqrt{\left(\frac{1+a_h}{s}\right)^2 - u^2 g_c^2} - 1 \tag{9}$$

Then a new value of u is calculated, and again a new value of a_h is found. This process is continued until the values of u calculated do not change.

The parameter of the change in the fibre axis shape is [14]

$$k = \frac{1+a_h}{u} \tag{10}$$

The critical value of the twist parameter is

$$g_r = \frac{g}{k}\left(1 - \frac{2}{u}\frac{d_f}{d_y}\right) \tag{11}$$

The radius of the fibre axis curvature in the external layer of yarn is

$$P = \left(Ru - d_f\right)\frac{1+g_r^2}{g_r^2} \tag{12}$$

z is the parameter which represents the change in yarn strength because the fibres are constrained from moving freely in the yarn; the numerical value of z can be calculated from the formula as follows:

$$f(z) = \frac{4P}{\mu(c\eta l_f - \lambda)} = \frac{1-z}{(2z+1)\ln\left(1+\frac{1}{2z}\right)-1} \qquad (13)$$

where, μ is the coefficient of friction between fibres, c the coefficient depending on the spinning system; 1.0 for carded yarn and 1.1 for combed yarn, η is the length of fibre ends outside the yarn, l_f the mean length of fibres, and λ is the length of fibre ends outside the yarn.

The fracture zone length is

$$l_h = \frac{2P}{\mu}\ln\left(1+\frac{1}{2z}\right) \qquad (14)$$

The ratio of the specimen length (l_y) to the length of the fracture zone is

$$q = \frac{l_y}{l_h} \qquad (15)$$

Parameter C depends on the twist and change in the fibre axis shape while the yarn was being strained

$$C = \frac{2k}{g^2}\ln\frac{[1.0253g^2+1]^{0.5}+[1.0253g^2+k^2]^{0.5}}{[0.0253g^2+1]^{0.5}+[0.0253g^2+k^2]^{0.5}} \qquad (16)$$

Parameter v_{Fh} is dependent on the coefficient of variation of yarn strength, the actual mass variation of the yarn, Martindale's limit mass variation [18], fibre linear density and yarn count. The coefficient of irregularity of the yarn linear density for a combed spinning system ($\beta = 1.35$) is determined according to the relationship:

$$v_{Fh} = \beta\sqrt{\frac{Tt_y}{Tt_f}} \qquad (17)$$

where, Tt_f and Tt_y is the fibre and yarn linear density in tex, respectively.

The yarn strength at a zero gauge length Q_h was calculated from equation [13]

$$Q_h = z\,Q(\varepsilon)\,C \qquad (18)$$

where $Q(\varepsilon)$ is the breaking strength of the fibre.

The strength of a y mm long yarn sample (Q_y) was obtained using the modified Peirce's equation [13]

$$Q_y = Q_h\left[1-3.64v_{Fh}\left(1-q^{-\frac{1}{7}}\right)\right] \qquad (19)$$

where Q_h is the yarn strength at a zero gauge length, v_{Fh} is the variation coefficient of the breaking force in the length of the fracture zone.

Simulated annealing

SA was first put forward by Metropolis [19] and successfully applied for the optimisation of problems by Kirkpatrick [20]. It emulates the cooling process of molten metals through annealing with the concept of the Metropolis algorithm.

It is a point-by-point search method. The algorithm begins with an arbitrary point in the search space and a high initial temperature. A second point is created at random in the vicinity of the initial point and the difference in the function values at these two points is calculated. If the second point has a smaller function value, the point is accepted; otherwise the point is accepted with a probability. This completes one iteration of the SA procedure. In the next iteration, another point is created at random in the neighborhood of the current point and the Metropolis algorithm is used to accept or reject the point. In order to simulate the thermal equilibrium at every temperature, a number of points are usually tested at a particular temperature, before reducing the temperature at a fixed cooling rate. The algorithm is terminated when a sufficiently small temperature is obtained or a small enough change in function values is found.

Optimization model

20 tex yarn made from cotton fibre in the ring spinning system is considered in this study. The mechanistic model of yarn strength prediction developed by Frydrych [13] has been used for formulation of the optimisation problem. The twist per meter (t) as a process parameter and raw material parameters such as the cotton fibre linear density (Tt_f), elongation at break (a_f), strength ($Q(\varepsilon)$) and mean length (l_f) are used to predict the yarn strength from ***Equation 19***.

The following optimisation problem is developed for the production of cotton yarn with the target strength (T_y). In this model the value of T_y is considered as 20 cN/tex.

$$\left.\begin{array}{l} \text{Minimize: } \left(Q_y - T_y\right)^2 \\ \text{Subject to inequility constraints:} \\ t^L \le t \le t^U \\ Tt_f^L \le Tt_f \le Tt_f^U \\ a_f^L \le a_f \le a_f^U \\ Q(\varepsilon)^L \le Q(\varepsilon) \le Q(\varepsilon)^U \\ l_f^L \le l_f \le l_f^U \end{array}\right\} \qquad (20)$$

where, superscripts L and U refer to the values of lower and upper bounds, respectively. Q_y and T_y are the predicted and target yarn strength, respectively.

Results and discussion

A non traditional optimisation method such as Simulated Annealing is used to obtained the predefined cotton yarn strength by selecting the governing raw material and process parameters. The optimisation problem of ***Equation 20*** was solved using the SA algorithm with MATLAB (version 7.7) coding on a 2.6 GHz PC. The maximum number of iterations was set at 1000. The values of T, T_{min}, the cooling rate and number of iterations at each temperature for SA were set as 1000, 0.9, 10% and 30, respectively.

Table 1. *Boundary of constraints.*

Controlling parameters	Lower boundary	Upper boundary
Twist of yarn, t.p.m.	650	700
Fibre linear density, tex	0.120	0.150
Fibre elongation at break, %	6.0	7.0
Average fibre length, mm	25	33
Fibre tenacity, cN/tex	28	35

Table 2. *Optimised value of constraints.*

Controlling Parameters	Optimized values
Twist of yarn, t.p.m.	**681.5**
Fibre linear density, tex	**0.135**
Fibre elongation at break, %	**6.75**
Average fibre length, mm	**32.7**
Fibre tenacity, cN/tex	**34.3**

Table 1 shows the lower and upper bounds of inequality constraints. ***Table 2*** illustrates the optimum combination of fibre properties and twist/meter for the production of 20 tex yarns with a strength of 20 cN/tex. The value of yarn strength obtained with the optimised parameters is 19.97 cN/tex. The model is able to minimise the objective function ***Equation 20*** such that it satisfies the condition of the inequality constraints.

Conclusions

In this paper, optimum combinations of fibre properties such as fibre linear density, elongation at break, tenacity, mean length and process parameters, such as twist/m, have been predicted for the production of ring spun cotton yarn of 20 cN/tex. SA is used to research the best combination of parameters that can produce a yarn with the requisite strength by solving the constrained optimisation problem deriving from Frydrych's yarn strength equation. The SA is an efficient technique for engineering the design of a textile product since it can easily be implemented and it is computationally inexpensive as fewer parameters are involved.

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