Variance Tolerancing and Decomposition in Short-Staple Spinning Processes

Part II: Simulations and Applications to Ring and OE Spun Yarns

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ABSTRACT

The variance tolerancing and decomposition method developed in Part I of this paper is applied to a large amount of fiber and yarn test data obtained from a spinning mill during a three-year period. The variabilities of single-end strengths found in six different ring spun and open-end yarns are successfully decomposed into random and process-induced variance components by tolerancing the variances of the matching fiber length and tensile properties. A total of 43,080 single-end yarn strength tests, 4,200,000 AFIS® fiber lengths, and over 70,000 Mantis® single-fiber tensile tests are performed for the required parameter estimation, simulation, and model validation. The results confirm that variance tolerancing through "effective gauge length" and other intrinsic components is effective for variance estimation and decomposition. Most significant is that the process-induced variances account for 69–82% of the total yarn strength variations, signifying the importance of and challenges in controlling and reducing process variances in spun yarn manufacturing.

General Concept for Model Validation

In Part I [4], we described spun yarn as a continuous chain of length $S = rL$ consisting of r twisted parallel fiber bundles, each with an effective gauge length L within which the average number of fibers is known. We then defined the strength of a yarn as the strength of the weakest bundle of length L among r, matching the bundle strength obtainable from the smallest number of continuous fibers within L. In this model, the mean and variance of the yarn strength were derived based on such intrinsic components as the mean and variance of fiber strength, the smallest number of continuous fibers to be found within the effective gauge length L, and the fiber length distribution.

The key to model verification and variance tolerancing is to obtain the optimum effective gauge length $L = L_0$ under which the yarn strength theoretically computed by the model is almost identical to the actual average yarn strength from the single-end tests. As we will show, this objective is accomplished by a large number of computer simulations. Further details on the simulations are also presented.

Experimental Data for Model Validation

A large amount of yarn test data was collected for three years in a spinning mill under a carefully controlled sample collection, preparation, and test scheme. The cotton fibers consumed during the same period were sampled and tested for their single fiber length and tensile properties. For each yarn, the matching fiber properties were toleranced onto the variance of the yarn strength.

Over 70,000 single fibers were randomly selected from five cottons and tested for their tensile properties with a Mantis®. These cottons were grown in California and Texas. In Mantis testing, 1000 pairs of load and extension values were generated for each fiber to draw the entire load-extension diagram to the failure point. In addition, single fibers from slivers were randomly sampled from card slivers and tested on an AFIS® for their lengths. The data were used for variance tolerancing as input variances due to raw material properties.

For the three-year period, the cotton bales were processed to produce three open-end (OE) yarns with sizes of 94.4 tex (6.3/1 Ne), 41.7 tex (14.25/1 Ne), 29.7 tex (20/1 Ne), one 29.7 tex (20/1 Ne) ring spun carded (RSK) yarn, and two ring spun combed (RSC) yarns with sizes of 29.7 tex (20/1 Ne) and 14.9 tex (40/1 Ne), all at an identical twist multiplier (TM) of 4.75. The California cottons were used to spin 14.9 tex (40/1 Ne) RSC yarn and the Texas cottons for the other yarns. All yarns were tested for single-end strength on a Tensorapid®: twice a week, ten packages per test for the 94.4 tex OE yarns, and once a week, eight packages per test, all ten times per package

TABLE I. Summary of actual yarn tensile strengths for six different yarns.

Yarn count, Ne	Spinning method	No. of packages	Total no. of tests	Average, gf	SD, gf	CV_T, %
94.4 tex (6.3/1)	OE	3266	32,600	1240.00	103.42	8.34
41.7 tex (14.25/1)	OE	120	1,200	500.58	51.11	10.21
29.7 tex (20/1)	OE	88	880	359.22	44.36	12.35
	RSK	384	3,840	444.52	54.28	12.21
	RSC	216	2,160	476.43	49.02	10.29
14.9 tex (40/1)	RSC	240	2,400	279.71	39.24	14.03

for other yarns. Table I shows the summary statistics for the six yarns. We used these data to validate the theoretical models.

Variance Tolerancing in Spun Yarn Strength

We applied the variance tolerancing technique to the six yarns based on the fiber properties and effective gauge length L through the geometric and probabilistic model of yarn tensile strength. In this section, we estimate the mean and variance of yarn tensile strength through variance tolerancing. The computational scheme shown in Figure 1 is described next.

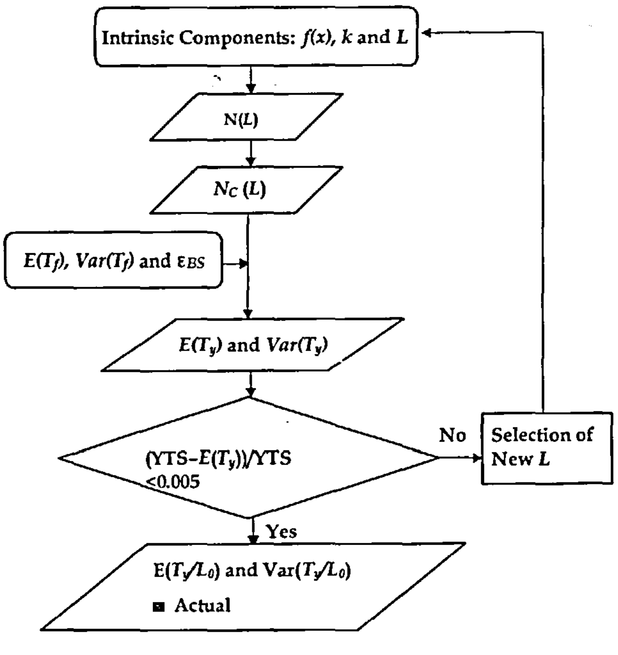

FIGURE 1. Simulation and model validation.

DISTRIBUTION OF NUMBER OF CONTINUOUS FIBERS WITHIN L

We calculated the mean and variance of the number of continuous fibers within L using the Maple® program based on fiber length distribution, effective gauge length L, and the average number of fibers per yarn cross section (k), which we calculated by dividing the yarn count (tex) by the average micronaire of the fibers (3.80 μg/inch).

Based on Equation 1 [4], the number of continuous fibers within L was assumed to follow a Poisson distribution with intensity parameter λp to be estimated from the fiber length distribution. For the simulations in this study, it was necessary to assume a length distribution for the cotton fiber length measured by the AFIS.

Several studies [5–8] have shown that the observed distributions of cotton fiber lengths are positively skewed and become more so after processing. For simulation purposes, we tried a truncated gamma distribution ($0'' \leq x \leq 1.5''$) with nine different combinations of means and standard deviations (mean = 2.54, 2.64, and 2.79 cm, standard deviation = 1.016, 1.143, and 1.270 cm) to assess the effects of different means and standard deviations on the effective gauge length and the resulting simulated yarn strengths. We chose these combinations based on AFIS data, truncating to match the range of actual cotton fiber lengths and to simplify the computational process. We computed the average number of continuous fibers to be found within L for all the combinations by using the equation

$$E[N_C(L)] = \frac{k}{E[S(L)]} \int_L^{\infty} \frac{x - L}{x + L} f(x)dx \quad , \qquad (1)$$

where $S(L)$ is the length of a fiber segment contained within L and

$$E[S(L)] = \mathop{E}_{x}\left[\frac{Lx}{x + L}\right] \quad .$$

We used the Maple program for the numerical integrations.

MEAN AND VARIANCE OF SMALLEST NUMBER OF CONTINUOUS FIBERS WITHIN L

Next, we derived $E(Y_1)$ and Var (Y_1), the exact mean and variance of the bundle that contains the smallest

TABLE II. The smallest number of continuous fibers within L: $E(Y_1)$ and Var (Y_1): (a) 94.4 and 41.7 tex yarns), and (b) (29.7 and 14.9 tex yarns).

(a) Fiber length, inch		94.4 tex (6.3/1 Ne, k = 657)				41.7 tex (14.25/1 Ne, k = 282)			
		L = 0.76 cm (0.30 inch)		L = 0.89 cm (0.35 inch)		L = 0.76 cm (0.30 inch)		L = 0.89 cm (0.35 inch)	
Mean	STD	Mean	Var	Mean	Var	Mean	Var	Mean	Var
	1.02 (0.40)	387	101	352	96	153	41	139	39
2.54 cm (1.00)	1.14 (0.45)	379	99	343	94	149	40	135	38
	1.27 (0.50)	367	94	331	90	145	38	130	36
	1.02 (0.40)	400	104	366	100	157	42	144	40
2.64 (1.04)	1.14 (0.45)	384	100	349	95	151	40	137	38
	1.27 (0.50)	372	97	336	92	146	39	132	37
	1.02 (0.40)	407	106	374	102	161	43	147	41
2.79 cm (1.10)	1.14 (0.45)	401	104	367	102	158	42	144	40
	1.27 (0.50)	391	102	357	97	155	41	141	39

(b) Fiber length, inch		29.7 tex (20/1 Ne, k = 197)				14.9 tex (40/1 Ne, k = 99)			
		L = 0.38 cm (0.15 inch)		L = 0.51 cm (0.20 inch)		L = 0.18 cm (0.07 inch)		L = 0.25 cm (0.10 inch)	
Mean	STD	Mean	Var	Mean	Var	Mean	Var	Mean	Var
	1.02 (0.40)	133	31	123	29	68	13	66	14
2.54 cm (1.00)	1.14 (0.45)	131	30	121	29	68	13	65	14
	1.27 (0.50)	128	29	118	29	67	13	65	14
	1.02 (0.40)	135	30	125	30	68	13	66	14
2.64 cm (1.04)	1.14 (0.45)	132	30	121	29	68	13	65	14
	1.27 (0.50)	129	29	119	29	67	13	65	14
	1.02 (0.40)	136	31	127	31	69	14	67	14
2.79 cm (1.10)	1.14 (0.45)	134	30	125	30	68	13	66	14
	1.27 (0.50)	133	30	123	30	68	13	66	14

number of continuous fibers within L, by generating the order statistics [2] from the distribution of the number of continuous fibers within L. In order to simplify the computation, we chose the maximum number of continuous fibers within L to be equal to the average number of fibers per yarn cross section (k). We calculated the values of $E(Y_1)$ and Var (Y_1) for 94.4 tex (6.3/1 Ne), 41.7 tex (14.25/1 Ne), 29.7 tex (20/1 Ne), and 14.9 tex (40/1 Ne) yarns using Equations 2 and 3 [4]. For the simulations, the values of L were allowed to vary from 0.127 to 1.270 cm by 0.127-cm increments. The basic equations [4] we used for this were

$$E[Y_1] = \sum_{n=1}^{k} n g_{Y_1}(n) \quad , \tag{2}$$

$$E[Y_1^2] = \sum_{n=1}^{k} n^2 g_{Y_1}(n) \quad ,$$

$$\mathrm{Var}[Y_1] = E[Y_1^2] - [E[Y_1]]^2 \quad , \tag{3}$$

where

$$g_{Y_1}(n) = \left[1 - \sum_{i=1}^{n-1} \frac{e^{-\lambda p}(\lambda p)^i}{i!}\right]^r - \left[1 - \sum_{i=1}^{n} \frac{e^{-\lambda p}(\lambda p)^i}{i!}\right]^r \quad .$$

The computed values of the smallest number of continuous fibers within L are given in Table II for two selected L values out of many we used in the search for L_0, the optimal L value. These two values were chosen at near L_0 (see Table III) merely to show the sensitivity of the response variables $E(Y_1)$ and Var (Y_1).

TABLE III. Best effective gauge length L_0 for six different yarns.

Yarn count (Ne)	Spinning method	Best effective gauge length L_0, inches
94.4 tex (6.3/1)	OE	0.76–0.89 cm (0.30"–0.35")
41.7 tex (14.25/1)	OE	0.76–0.89 cm (0.30"–0.35")
29.7 tex (20/1)	OE	0.64–0.76 cm (0.25"–0.30")
	RSK	0.38–0.51 cm (0.15"–0.20")
	RSC	0.25–0.38 cm (0.10"–0.15")
14.9 tex (40/1)	RSC	0.18–0.25 cm (0.07"–0.10")

Table II shows the effects of fiber length distribution and effective gauge length on $E(Y_1)$, the smallest number of continuous fibers within L among r bundles making up the test gauge. As we expected, $E(Y_1)$ is greater for a longer mean fiber length, a smaller standard deviation of fiber length, and a smaller value of L. However, it is striking to note that the effects of the fiber length parameters are rather small, especially for the finer yarns. This implies that the conclusions drawn from this study do not depend on the choice of fiber length distributions made for the study. Based on Var (Y_1), $CV(Y_1)$ ranges from 2.5–5.7%, and the higher $CV(\%)$ values for the finer yarn counts match the same trends (Table I) found in the $CV(\%)$ of the single-end strengths. Based on the values of $E(Y_1)$ and Var (Y_1), we have simulated the yarn strengths and compared them with the actual test averages as follows.

MEAN AND VARIANCE OF SPUN YARN STRENGTH

We calculated the means and variances of spun yarn strength (T_y) for the six yarns using Equations 4 and 5 [4] with selected means and variances of single fiber strength (T_f) and bundle strength efficiency ε_{BS}. We determined the bundle strength efficiency by the range of the smallest number of continuous fibers within L based on the earlier study by Cui [1]. Based on Cui's study, we applied $\varepsilon_{BS} = 0.59$ to 41.7, 29.7, and 14.9 tex yarns and $\varepsilon_{BS} = 0.58$ to the rest. We obtained the mean and variance of yarn strength, $E(T_y)$ and Var (T_y), as follows, as a function of mean fiber strength $E(T_f)$, variance of fiber strength Var(T_f), and $E(Y_1)$ and Var (Y_1):

$$E[T_y] = \varepsilon_{BS} E[T_f] E[Y_1] \quad , \tag{4}$$

$$\mathrm{Var}[T_y] = \varepsilon_{BS}^2 \{\mathrm{Var}[T_f] E[Y_1] + (E[T_f])^2 \,\mathrm{Var}[Y_1]\} \quad . \tag{5}$$

As shown in Table IV, the effects of fiber length and strength on yarn tensile strength are similar to each other for all six yarns, and hence are shown only for the 94.4 tex (6.3/1 Ne) OE yarns in Figures 2 and 3 for fixed values of other parameters arbitrarily selected. Here, we see that the yarn tensile strength increases as fiber length or fiber strength (T_f) increases. In addition, yarn tensile strength decreases as the standard deviation of fiber length increases, but the effects appear to be much smaller for the finer yarns.

We studied the effects of $CV\%$ of fiber strength and of length versus $CV\%$ of the resulting yarn tensile strengths for the 94.4 tex (6.3/1 Ne) OE yarn. The results, not shown in this paper for brevity, confirm that a higher $CV\%$ of fiber strength translates into a higher $CV\%$ of yarn tensile strength. The effects of $CV\%$ of fiber length, on the other hand, were small and less consistent.

TABLE IV. Simulated means and variances of spun yarn strengths under L_0.

Yarn count (Ne)	$E(X)$, cm	$STD(X)$, cm	$E(T_f)$, gf	$STD(T_f)$, gf	$E(T_y)$, gf	$SD(T_y)$, gf
94.5 tex OE (6.3/1)	2.54–2.79	1.016–1.27	5.5–6.2	2.0–3.0	1233.4–1245.4	39.4–47.7
41.7 tex OE (14.25/1)	2.54–2.79	1.016–1.27	5.5–6.3	2.0–3.0	499.1–503.0	25.3–30.8
29.8 tex OE (20/1)	2.54–2.79	1.016–1.27	5.5–6.2	2.0–3.0	358.5–360.2	21.1–25.7
29.8 tex RSK (20/1)	2.54–2.79	1.016–1.27	5.6–6.3	2.0–3.0	442.3–446.0	22.7–27.8
29.8 tex RSC (20/1)	2.54–2.79	1.016–1.27	5.6–6.3	2.0–3.0	474.4–477.9	23.0–28.6
14.1 tex RSC (40/1)	2.54–2.79	1.016–1.27	7.0–7.2	2.0–3.0	280.8–281.4	18.0–21.7

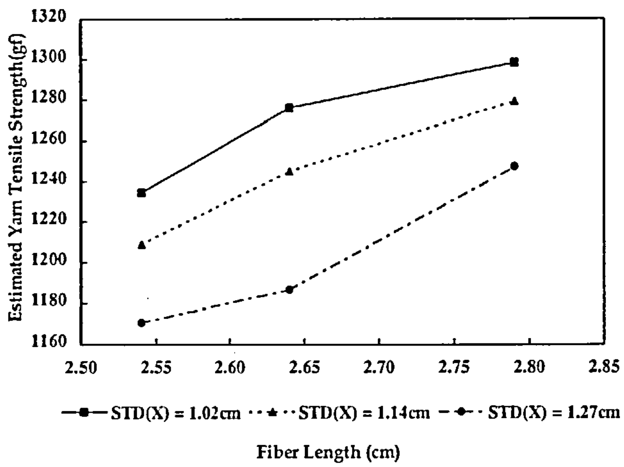

FIGURE 2. Effects of fiber length on estimated yarn tensile strength (94.4 tex OE spun yarn, L = 0.76 cm, T_f = 5.5 gf).

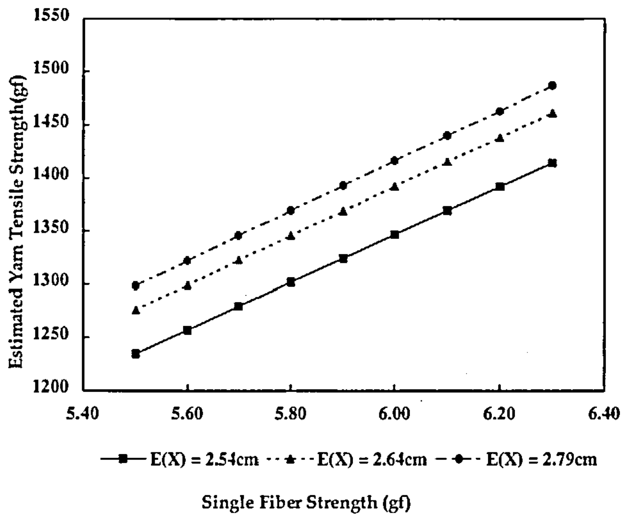

FIGURE 3. Effects of single fiber strength on yarn tensile strength (94.4 tex OE spun yarn, L = 0.76 cm, $STD(X)$ = 1.016 cm).

SIMULATION FOR ESTIMATING BEST EFFECTIVE GAUGE LENGTH L_0

As we noted previously, the strength of a spun yarn given by Equation 4 is a function of $E(Y_1)$, which in turn, is a function of L and $f(x)$, as shown in Equations 1–3. By varying the values of L through computer simulations, we determined the optimal effective gauge length L_0 such that the expected values of yarn tensile strengths under L closely match (within around 0.5%) the actual average tensile strength of the yarns tested on the Tensorapid. We estimated the best effective gauge length L_0 for each of the six yarns by using different fiber length and strength parameters to reflect the actual data ranges obtained during the three-year period. The mean and standard deviation of fiber length, fiber strength, and the resulting yarn strength by using Equations 13 and 14 of Part I [4] at L_0 are shown in Table IV. We computed the values of $E(T_y/L_0)$ and Var (T_y/L_0) as functions of $E(T_f)$, Var (T_f), $E(Y_1)$, and Var (Y_1) evaluated at $L = L_0$ and the selected values of bundle strength efficiency ε_{BS} for the ranges of L_0 shown in Table III. In the following section, we use these estimated variances of yarn tensile strength under L_0 to estimate the variance component originating from the raw material properties.

Observing the best effective gauge length L_0 in Table III, it is obvious that the value becomes smaller for finer yarns or as the number of twists per inch increases. While L_0 is clearly related to the twist pitch (1/twists per inch), the exact relationship has yet to be studied in depth along with other physical parameters of the fibers. Of particular interest here is a possible relationship between L_0 and the "short fiber contents" (SFC) in staple yarn spinning. The SFC, defined as the weight of shorter than ½-inch fibers in percent of the total, has been regarded as a key indicator by spinners in both reducing ends-down and improving yarn strength. Recognizing that fibers shorter than L_0 are not expected to be continuous within L_0, we expect a higher SFC will increase the fraction of those fibers shorter than L_0 as well. In Table III, the range of L_0 for all OE yarns is 0.25″ − 0.35″; that is, for a fiber to be continuous within this range, it must be at least as long or longer than 0.35″, or roughly 0.5″ in all OE yarns. For finer ring spun yarns, however, the range is 0.07″ − 0.20″. If we are to ignore the distance between the front and back rollers, therefore, the SFC is apparently not as critical to finer ring spun yarns as to coarse OE yarns. In terms of yarn strength, therefore, the current definition of SFC may have to be modified, perhaps placing variable cut-off limits when computing the weight ratios instead of applying the ½-inch threshold to all yarn counts and types.

Variance Decomposition of Yarn Tensile Strength

In general, variabilities in tensile strengths of yarns are attributed to variabilities in raw material properties and processing conditions. Decomposition of experimentally observed variances in Table I is accomplished by variance tolerancing of the random components and by estimating the process-induced variances from the residuals based on the total observed variances. In this section, the total variance of yarn tensile strength will be decomposed into subcomponents by tolerancing the variances of the raw material properties using the intrinsic components.

The total variance of observed yarn tensile strength (σ_T^2) decomposed into between-package variance (σ_{bp}^2) and within-package variance (σ_{wp}^2). We estimated these two components from the actual single-end test data using the SAS® VARCOMP procedure. We assumed the between-package variance (σ_{bp}^2) to be entirely due to variations among processing machines accrued at different stages of spinning.

The within-package variance, in turn, decomposed into two subcomponents—random (σ_r^2) and nonrandom (σ_{nr}^2). The random subcomponent consists of variances arising from variations in fiber properties and random arrangements of constituent fibers. The nonrandom component includes variations of fiber mass, or draft waves, caused by the processing and material handling systems. The total process-induced variance (σ_p^2) is then the sum of the between-package variance (σ_{bp}^2) and the nonrandom component (σ_{nr}^2). Decomposition of the within-package variance is accomplished by subtracting σ_r^2 from σ_{wp}^2 and by assuming that the residual is equivalent to σ_{nr}^2. In order to simplify the evaluation of various variance components, the variance components are expressed as a percent of the total variance of yarn tensile strength as follows:

$F_{bp/T}$ = between-package variance ratio (%)

$$= \frac{\sigma_{bp}^2}{\sigma_T^2} \times 100 \quad ,$$

$F_{wp/T}$ = within-package variance ratio (%)

$$= \frac{\sigma_{wp}^2}{\sigma_T^2} \times 100 \quad ,$$

$F_{r/T}$ = random within-package variance ratio (%)

$$= \frac{\sigma_r^2}{\sigma_T^2} \times 100 \quad ,$$

$F_{nr/T}$ = nonrandom within-package variance ratio (%)

$$= \frac{\sigma_{nr}^2}{\sigma_T^2} \times 100 \quad ,$$

$F_{p/T}$ = process-induced variance ratio (%)

$$= F_{bp/T} + F_{nr/T} \quad ,$$

$$F_{bp/T} + F_{wp/T} + F_{r/T} + F_{nr/T} = 100$$

The results of variance tolerancing and decomposition are summarized in Table V for the six yarns studied. Graphically, only the results for 29.7 tex RSK yarn are shown in Figure 4. All other yarns show more or less the same results.

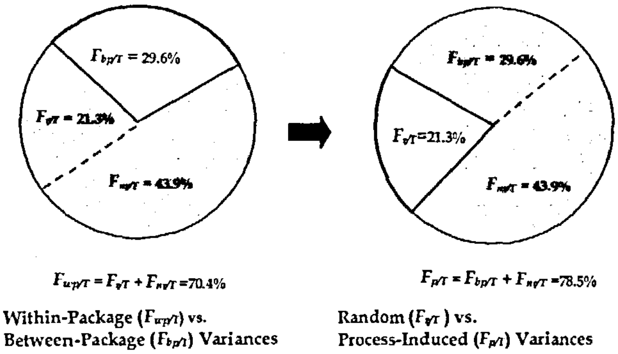

FIGURE 4. Variance decomposition of yarn tensile strength (29.8 tex RSK).

The variance ratios (%) for the six yarns are summarized in Table V. Of utmost significance are the magnitudes of $F_{p/T}$ shown in the last column. The total process-induced variance of single-end yarn strength is shown to be 69–82%, whereas only 18–31% is due to

TABLE V. Variance decomposition of yarn tensile strength.

Yarn count (Ne)	Spinning method	$F_{bp/T}$, %	$F_{wp/T}$, %	L_0, cm	$F_{r/T}$, %	$F_{nr/T}$, %	$F_{p/T}$, %
				0.76	17.6	58.5	82.2
94.4 tex (6.3/1 Ne)	OE	23.7	76.30	0.89	18.3	57.9	81.6
				0.76	29.5	44.2	70.1
41.7 tex (14.25/1 Ne)	OE	25.9	74.10	0.89	31.1	43.1	69.0
	OE	35.4	64.60	0.64	27.3	36.9	72.3
				0.76	28.7	35.8	71.2
				0.38	21.3	43.9	78.5
29.7 tex (20/1 Ne)	RSK	29.6	70.44	0.51	22.7	47.8	77.4
	RSC	28.7	71.25	0.25	27.0	43.9	72.6
				0.38	28.5	42.8	71.5
				0.18	24.6	63.9	75.1
14.9 tex (40/1 Ne)	RSC	11.2	88.80	0.25	26.4	62.4	73.6

variations in fiber properties and the random arrangements within the yarns.

Needless to say, the large proportion of process-induced variance has to be the focal point of textile quality control and improvement. Under the wide range of yarn counts and types studied, the process-induced variance has proven to be consistently high. While this has been speculated in the past without scientific verification, our study proves it to be the case for the first time. In addition, the newly developed method facilitates estimation of the process-induced or "controllable" variance components with a large amount of fiber and yarn test data.

Conclusions

A new method for combining the random features of fibers and yarns into a manageable number of intrinsic components provides a means of separating and estimating the process-induced variances from the total variance observed in single-end strength tests. The variance tolerancing and decomposition methods use a very large amount of fiber and yarn test data obtained in a spinning plant during a three-year period. The results indicate that the process-induced variances account for 69–82% of the total observed variance based on the six ring spun and open-end yarns we examined. The relatively large proportion of process-induced variance confirms the general belief that textile processes are indeed highly variable, and warrants a stronger measure for statistical quality and process control in all textile operations.

While the theoretical models we have developed are primarily for variance tolerancing and decomposition, such intrinsic components as the effective gauge length and the weakest sub-bundle within a test gauge length provide significant insights into improving spun yarn strength based on yarn count, twist, short fiber content, and single fiber length and tensile behavior. Although we have designed this experimental study for single-end strengths of spun yarns, the same modeling concept can be applied to evenness of spun yarns, the tensile or tear strength of woven fabrics, and other physical properties of textile structures. In all cases, it is important to isolate and quantify the process variances by sources for various quality control and improvement objectives.

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