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Blending quality of co-air-textured yarn: Optimization parameters of Kevlar/polypropylene applicable for thermoplastic composites

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Abstract

Nowadays, hybrid yarns, which consist of at least one-component thermoplastic fibers, are used in thermoplastic textile composites. The uniformity of the fibers in hybrid yarns is a key factor that directly influences the composite properties. Accordingly, one of the main aims of the present research was to optimize the air texturing parameters to achieve the uniform blending of Kevlar/polypropylene fibers. To evaluate the blending uniformity of yarns, the radial, lateral and angular distribution of fibers, based on the position of the pixels of the constituent fibers, was evaluated using the image processing data of yarn cross sections. According to this method, the production parameters, namely, blend ratio, delivery speed, feed rate and air pressure, were optimized simultaneously via the response surface method to obtain the blending uniformity of the fibers. The uniform blending distribution could be achieved by a higher blend ratio of Kevlar/PP (1:6), a lower production speed (300 m/min), a higher feed rate (500 m/min), and a higher air pressure (10 bar). Eventually, it was confirmed that there was a good correlation between the blending quality of the real samples and the predicted quality of the response surface method model.

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Keywords: Fiber distribution, blending quality, air texturing parameters, lateral distribution, hybrid yarns

1. Introduction

One of the most successful methods to produce a thermoplastic composite is to prepare the thermoplastic matrix in the shape of a fiber and then mixing it with the reinforcing fibers.[1] In this way, the possibility of wetting the reinforcement agent can be increased, while the uniformity of blending is achieved too.[2,3] Due to the advantages of the hybrid yarns production method, some researchers have recently used this method to develop a new generation of composites, such as bio-composites or eco-composites.[4–6] Several studies have been applying the hybrid yarns textile thermoplastic (HYTT) to produce lightweight and flexible composites. Moreover, some studies have presented the effect of variable parameters such as fiber content, chemical modification, and process conditions on the dynamic, mechanical, transport, microstructure, and fracture behavior properties of HYTT.[7–10]

Hybrid yarns contain two or three different filament yarns enhancing the potential of textile composites in high-performance applications. In order to prepare the hybrid yarns, different methods have been applied, such as friction spinning, co-wrapping and commingling, showing that the best and uniform blending could be obtained through the use of an air jet.[11,12] The parameters affecting the properties and structure of air jet commingled yarns can be put in raw material parameters, process parameters and nozzle design groups. It has been reported that yarn production factors and raw material parameters are among the most effective factors determining the properties of the commingled yarn.[12]

The effects of the process parameters (air pressure, degree of overfeeding, and production speed) and the number of applied filament bundles on the fiber distributions, as well as the

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blending quality of the cross-sectional components of commingled yarns used for manufacturing thermoplastic composite parts, have been investigated by Kravaev et al.[12,13] The effect of the processing parameters of glass/polypropylene on the hybrid yarns parameters has also been studied by Mankodi and Patel.[14] They concluded that the yarn linear density value was significantly affected by air pressure and overfeeding, leading to the high breakage and the poor quality of the yarn. It has been confirmed that the best mixing of glass and polypropylene can be achieved by the commingling method, as compared with other manufacturing methods. It has also been reported that the high air pressure and the low take-up speed with the average overfeed value (1%) are the optimum process factors in terms of blending uniformity.[14] The fibers blending quality and the uniform distributions of a bi-component yarn (PET/Rayon) have previously been studied by Chiu et al.,[15,16] who introduced three indexes including radial, lateral, and angular distribution indexes. In their image-processing techniques, single fiber positions were observed on the image with mask processing.

The mechanical properties of Kevlar blending with other fibers are reported in some investigations such as rami/Kevlar and kenaf/Kevlar.[17,18] Nevertheless, based on the previous studies, no research has yet been reported on the blending quality of Kevlar and polypropylene (PP) fibers. The PP fibers can be considered as a matrix due to their lower melting temperature in comparison with Kevlar fibers. The sintering of PP fibers can result in the flexibility of Kevlar fibers reinforcing a composite by the restriction of Kevlar fiber movements. The characteristic mentioned above can be achieved by the uniform distribution of PP fibers around Kevlar fibers. Accordingly, the effects of process factors on the uniformity of fiber blending were addressed in this study by considering all indexes of fiber distribution, as previously explored by Chiu et al.[15] However, there is no report examining the correlation between these indexes and evaluating the overall uniformity of the blended fibers. Indeed, these indexes are

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considered as the responses in the response surface method (RSM) to optimize the process factors of air texture.

2. Materials and methods

2.1. Materials

The fibers used in this study for mixing were in the form of multifilament strands. The specifications of the utilized fibers are presented in Table 1.

Table 1. Fiber specifications.

Material	Company	Number of filaments	Strand linear density [den]	Filament linear density [den]	Bulk density [g/cm^3]	Shape of cross section
Kevlar roving	DUPONT (USA)	1000	1500	1.5	1.44	Circular
Polypropylene filament yarn	BEHKOSH (Iran)	72	350	4.9	0.91	Circular

2.2. Production of blended yarns

To produce the yarn with the blended fibers, SSM (SCHARER, SCHWEITER And METTLER Companies) air texture machine was applied. The schematic path of the yarn used in this machine is represented in Figure 1.

In this study, blending ratio, production speed, feed rate and air pressure were considered as air texture parameters affecting the blending uniformity of the fibers.

To statistically control the production factors and design experiments, the RSM[1] methodology was applied at the level of 0.95 as the confidence interval. In this investigation, the four mentioned factors were considered at three levels of possible values (maximum, middle, minimum). The values of the considered factors and their levels are presented in Table 2. The designs of the experiments and sample codes are presented in Table 3. In this table, the samples with the codes 26–36 are the repetitive specimens for the central point.

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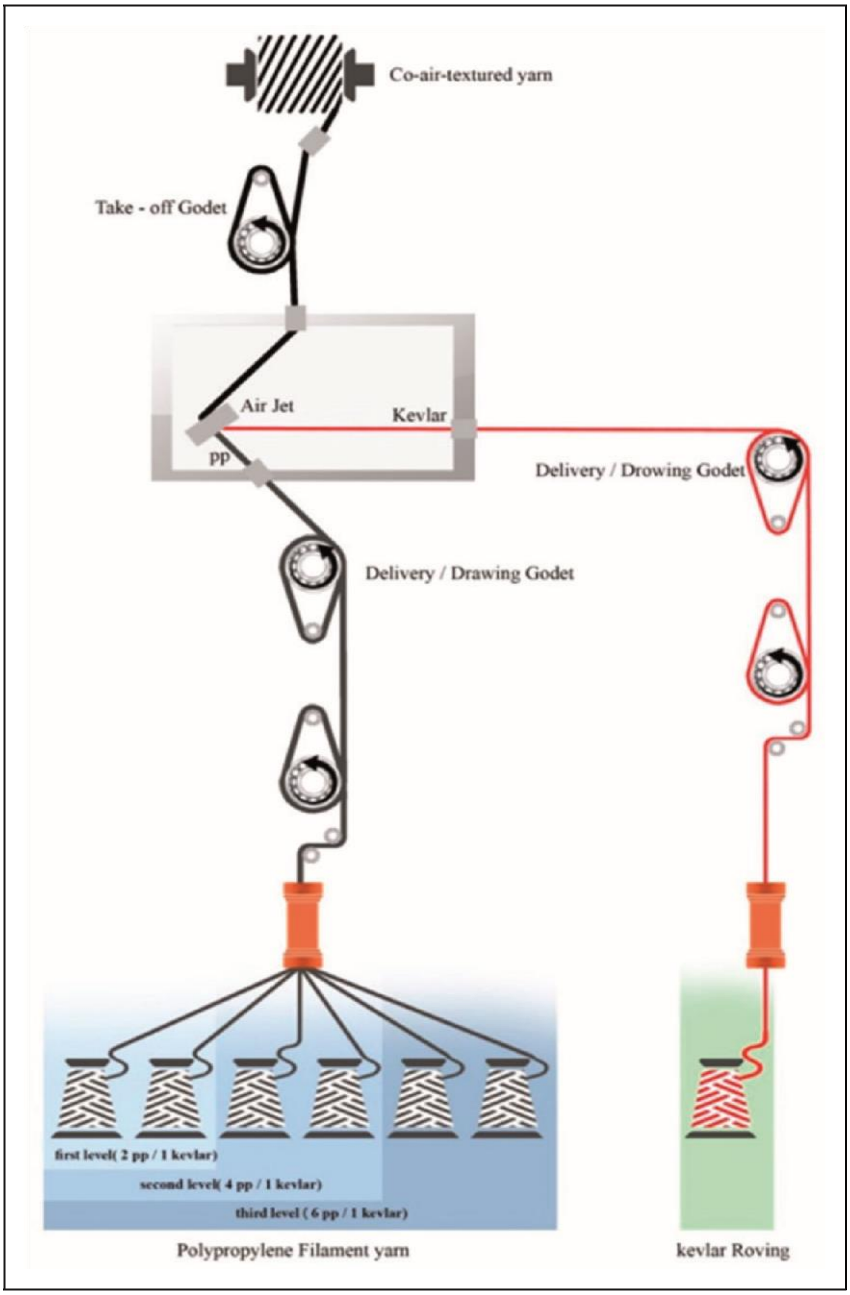

Figure 1. The schematic path of yarns in SSM machine.

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Table 2. Variables and their corresponding values.

Variable Levels	x_1: Blend ratio [Kevlar: PP]		x_3: feed rate [m/min]	x_2: production speed [m/min]	x_4: Air pressure [bar]
	Strand ratio	Volume ratio			
Low (-1)	1:2	%57:%43	300	300	3
Medium (0)	1:4	%41:%59	400	400	6
High (1)	1:6	%31:%69	500	500	10

Table 3. Samples description and the process parameters considered in this study.

Samples category	x_1: Blend ratio [Kevlar: PP]	x_2: production speed [m/min]	x_3: feed rate [m/min]	x_4: Air pressure [bar]
1	1:2	300	300	3
2	1:2	300	300	10
3	1:2	300	500	3
4	1:2	300	500	10
5	1:2	500	300	3
6	1:2	500	300	10
7	1:2	500	500	3
8	1:2	500	500	10
9	1:6	300	300	3
10	1:6	300	300	10
11	1:6	300	500	3
12	1:6	300	500	10
13	1:6	500	300	3
14	1:6	500	300	10
15	1:6	500	500	3
16	1:6	500	500	10
17	1:6	400	400	6
18	1:6	500	400	6
19	1:4	300	400	6

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20	1:4	500	400	6
21	1:4	400	300	6
22	1:4	400	500	6
23	1:4	400	400	3
24	1:4	400	400	10
25–36[a]	1:4	400	400	6

[a] Central samples with 12 repetitions

2.3. Blending parameters

The blending parameters have been pioneered by Chiu et al.[15] to reveal the blending fibers' uniformity. Three factors, namely, radial distribution, lateral distance and angular distribution, were considered to evaluate the blending fibers' uniformity. These distribution indexes were also considered in this study with some modifications. Chiu et al.,[15] as well as some other researchers, considered these indexes only for one component; however, it could be demonstrated that there is not always a correlation between these indexes for the blended fibers. For example, increasing the angular distribution of a component does not lead to an increase in the angular distribution of another component, as will be discussed later.

Radial distribution. The radial distribution indexes (R_{dk} and R_{dp}) are defined as a proportion of the radius average of one part of fibers to the overall average of the fiber radius (equations (1) to (5)).[15]

$$R_{dk} = \frac{R_k}{R_a} \tag{1}$$

$$R_{dp} = \frac{R_p}{R_a} \tag{2}$$

where R_k and R_p refer to the average distance of Kevlar pixels and PP pixels from the central gravity of yarn, and R_a is the average distance of all fiber pixels from the central gravity of the

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yarn. R_a can be computed by equation (5). The uniform distribution of a component leads to the radial distribution as a unit. The migration of fibers from the cross-section of yarns results in a radial distribution higher than unit and vice versa.

$$R_k = \frac{\sum_{i=1}^{N_k} \sqrt{[X_k(i) - C_x]^2 + [Y_k(i) - C_y]^2}}{N_k} \tag{3}$$

$$R_p = \frac{\sum_{i=1}^{N_p} \sqrt{[X_p(i) - C_x]^2 + [Y_p(i) - C_y]^2}}{N_p} \tag{4}$$

$$R_a = \frac{\sum_{i=1}^{N_k} \sqrt{[X_k(i) - C_x]^2 + [Y_k(i) - C_y]^2}}{N_k + N_p} + \frac{\sum_{i=1}^{N_p} \sqrt{[X_p(i) - C_x]^2 + [Y_p(i) - C_y]^2}}{N_k + N_p} \tag{5}$$

where R_p is the average distance of the PP pixels from the central gravity of PP fibers, *X(i)* and *Y(i)* with the subscripts *K* or *P* indicate the coordinates of the *i*th -recognized pixel of Kevlar or PP fiber, respectively, N_k and N_p represent the number of Kevlar and PP pixels in the cross-section, and C_x and C_y are the central coordinates of yarns.

Lateral distance. The lateral distance indicates the situation of the central gravities of the two components of fibers in contrast with the central gravity of the yarn. Central gravities of fibers and yarns can be computed using equations (6) to (11)

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$$C_{xk} = \frac{\sum_{i=1}^{N_k} X_k(i)}{N_k} \tag{6}$$

$$C_{yk} = \frac{\sum_{i=1}^{N_k} Y_k(i)}{N_k} \tag{7}$$

$$C_{xp} = \frac{\sum_{i=1}^{N_p} X_p(i)}{N_p} \tag{8}$$

$$C_{yp} = \frac{\sum_{i=1}^{N_p} Y_p(i)}{N_p} \tag{9}$$

$$C_x = \frac{C_{xk} + C_{xp}}{2} \tag{10}$$

$$C_y = \frac{C_{yk} + C_{yp}}{2} \tag{11}$$

where C_x and C_y with the subscripts K or P indicate the central coordinates of the fibers. Afterwards, lateral distribution factors (L_{tk} and L_{tp}) could be calculated by equations (12) and (13) to indicate the overall uniformity of each series of components.

$$L_{tk} = \frac{\sqrt{[C_{xk} - C_x]^2 + [C_{yk} - C_y]^2}}{R_a} \tag{12}$$

$$L_{tp} = \frac{\sqrt{[C_{xp} - C_x]^2 + [C_{yp} - C_y]^2}}{R_a} \tag{13}$$

Angular distribution index. The variation in the angular position of fibers can be detected by this factor. For this purpose, the average and variation of the angular position of each component could be computed to calculate an angular distribution index. To evaluate the blending quality, as mentioned before, Chiu et al.[15] and other authors have considered only distribution indexes for one component (Figure 2).

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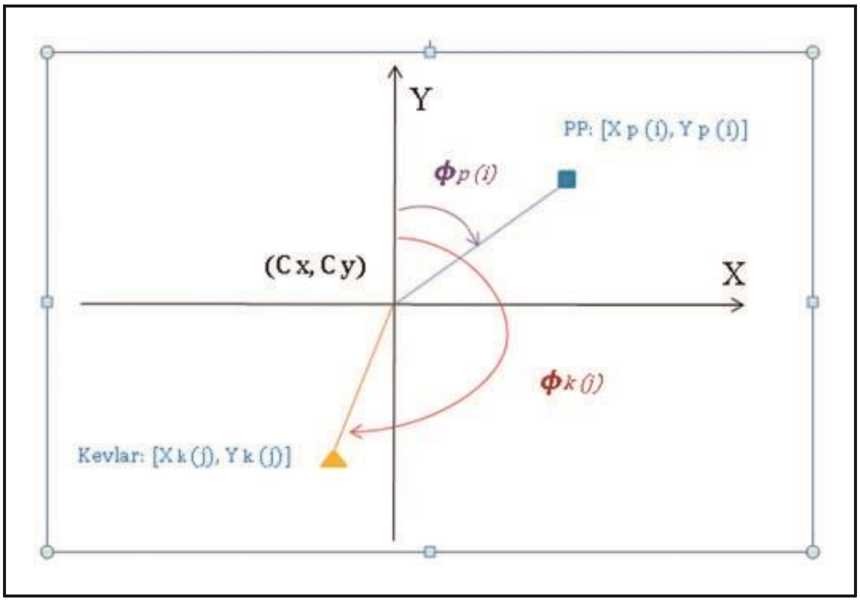

Figure 2. Geometric definition of fibers on the X-Y plane.[15].

It could be demonstrated (see the results section) that there is comparatively a positive correlation between the radial and lateral indexes of each component of fibers (Kevlar and PP). However, a negative correlation has been observed between the angular distributions of components. It means that the angular distribution of one component is not sufficient to evaluate the blending quality and quantity. Therefore, the relative angular distribution was defined for this report to reveal the variation of both components of fibers as a proportional index. Equations (14) to (19) were used to calculate the angular distribution of Kevlar and PP fibers; however, the proportion of the angular distribution of components (equation (20)) was suggested in this study to measure the total angular distribution index (ADI). The unit value of ADI could be attributed to the uniform angular distribution of both components

$$\emptyset_{AV} = \frac{\sum_{i=1}^{Np} \emptyset p(i) + \sum_{j=1}^{Nk} \emptyset k(j)}{Np + Nk} \quad (14)$$

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$$P_{\emptyset p} = \sqrt{\frac{\sum_{i=1}^{Np}\left[\emptyset p(i) - \emptyset_{AV}\right]^2}{Np}} \tag{15}$$

$$P_{\emptyset k} = \sqrt{\frac{\sum_{i=1}^{Nk}\left[\emptyset k(j) - \emptyset_{AV}\right]^2}{Nk}} \tag{16}$$

$$T_{\emptyset} = \sqrt{\frac{\sum_{i=1}^{Np}\left[\emptyset p(i) - \emptyset_{AV}\right]^2}{Np + Nk}} + \sqrt{\frac{\sum_{j=1}^{Nkp}\left[\emptyset k(j) - \emptyset_{AV}\right]^2}{Np + Nk}} \tag{17}$$

$$ADI_k = \frac{P_{\emptyset k}}{T_{\emptyset}} \tag{18}$$

$$ADI_p = \frac{P_{\emptyset p}}{T_{\emptyset}} \tag{19}$$

$$ADI = \frac{ADI_k}{ADI_p} \tag{20}$$

where $\emptyset_{AV}$ is the mean value of all $\emptyset$, $P_{\emptyset p}$ is the standard deviation of $\emptyset_p$ for the pp filament, $P_{\emptyset k}$ is the standard deviation of $\emptyset_k$ for the Kevlar filament, $T_{\emptyset}$ is the standard deviation of $\emptyset$ for all fibers, ADI_k and ADI_p are the angular distribution index for Kevlar and PP filaments, respectively, and ADI is the ratio of ADI_k to ADI_p.

Optimization method of variable parameters affecting ADI. Kravaev et al.[12] considered the radial distribution and lateral distance indexes of only one component as a blending quality, such that a minimum value of K_B (equation (21)) could be attributed to the uniform blending.

$$K_B = |1 - R_d|.L_t \tag{21}$$

To reveal the overall blending quality, this method could be useful; however, the angular distribution index is not considered in this method. Moreover, it seems that multiplying the factors cannot indicate the real changes in both indexes; also, the indexes are considered only

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for one of the components. Accordingly, five defined indexes, namely, radial distribution, lateral distance of both Kevlar and PP fibers and the angular distribution index of fibers, were considered as the response of the samples to obtain the optimum process factors using RSM. For this purpose, the radial distributions of both components were targeted as a unit, and both lateral distances of the two sets (components) of fibers were targeted as zero; the angular distribution index was considered as a unit. Table 4 indicates the optimum goals of its values. The importance and weight of the responses were considered as the unit for all factors (responses).

Table 4. The optimization setup of five responses.

Response	Goal	Lower	Target	Upper	Weight	Importance
R_{dk}	Target	0.7	1	1.3	1	1
R_{dp}	Target	0.7	1	1.3	1	1
L_{tk}	Minimize	–	0.2[a]	0.4	1	1
L_{tp}	Minimize	–	0.2[a]	0.4	1	1
ADI	Target	0.7	1	1.3	1	1

[a] This is the minimum value that leads to acceptable positive results for L_{tk}.

2.4. Preparing the cross-section of yarn samples

To analyze the filaments in the yarn, the Internal Standard Technical University of Liberec (TUL)[2] No. 46-108-01/01[19] was considered as the basic methodology. Accordingly, the yarn samples were passed through soft resin and clamped to a special frame until fixation was achieved. Afterwards, the fixed yarn samples were covered with a mixture of bee's wax and paraffin; as a result, the sample yarn was embedded in the middle of a paraffin block. In order to obtain the soft sections, it was essential to freeze the block. The cross-sections of the samples were cut by a microtome (Leica RM2255) with the approximate thickness of 10mm. The

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number of trials was six cross-sections for each sample in this test (a total of 216 cross-sections for 36 samples).

Image processing of the blended yarn cross-section. The cross-section of the blended yarns was subjected to study by using the CX31 Olympus optical microscope. The micrographs of each sample were captured using a DC338P Sony digital camera. Then, image processing was carried out for the reliable recognition of the filament position by MATLAB software. A simple method was employed to distinguish the Kevlar fibers with yellow color from the PP fibers and background. Indeed, the pixels of a Kevlar fiber were detected when the value of the red color was higher than blue in MATLAB. The pixels in the PP fibers with white color were distinguished from the background. The central gravity of the pixels of Kevlar, polypropylene and both of them as the yarn was calculated. Then, the distances between each central gravity of fiber (Kevlar and PP) components from the total central gravity of the yarn were calculated. The image processing sequence is summarized in the flowchart of Figure 3.

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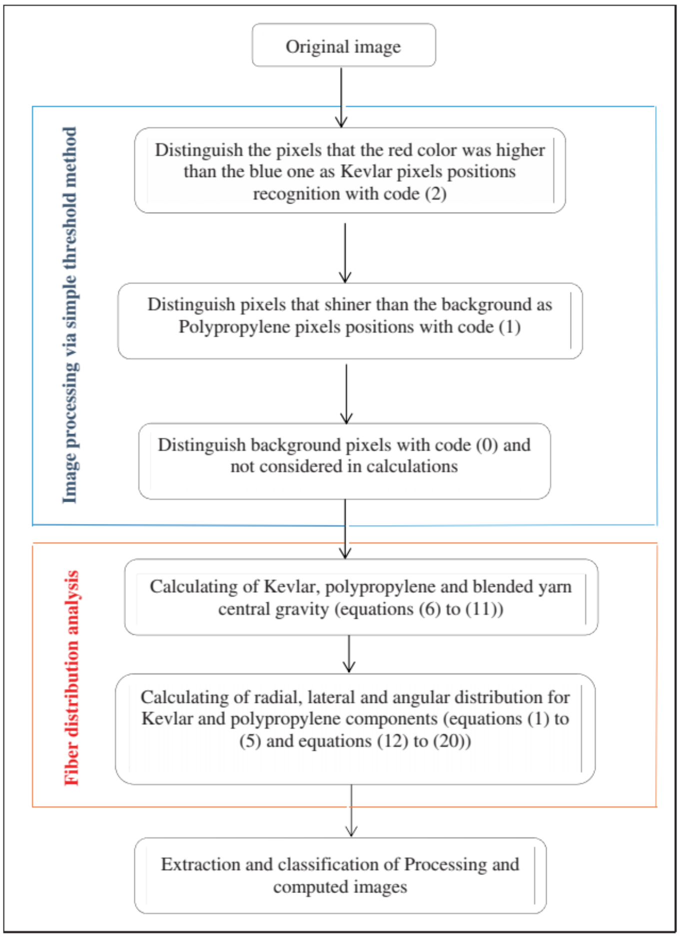

Figure 3. Procedure of the image processing using MATLAB.

An optical micrograph of the cross-section of the blended Kevlar/PP yarn is typically shown in Figure 4(a). The recognized pixels for each fiber in cross-section are depicted in Figure 4(b).

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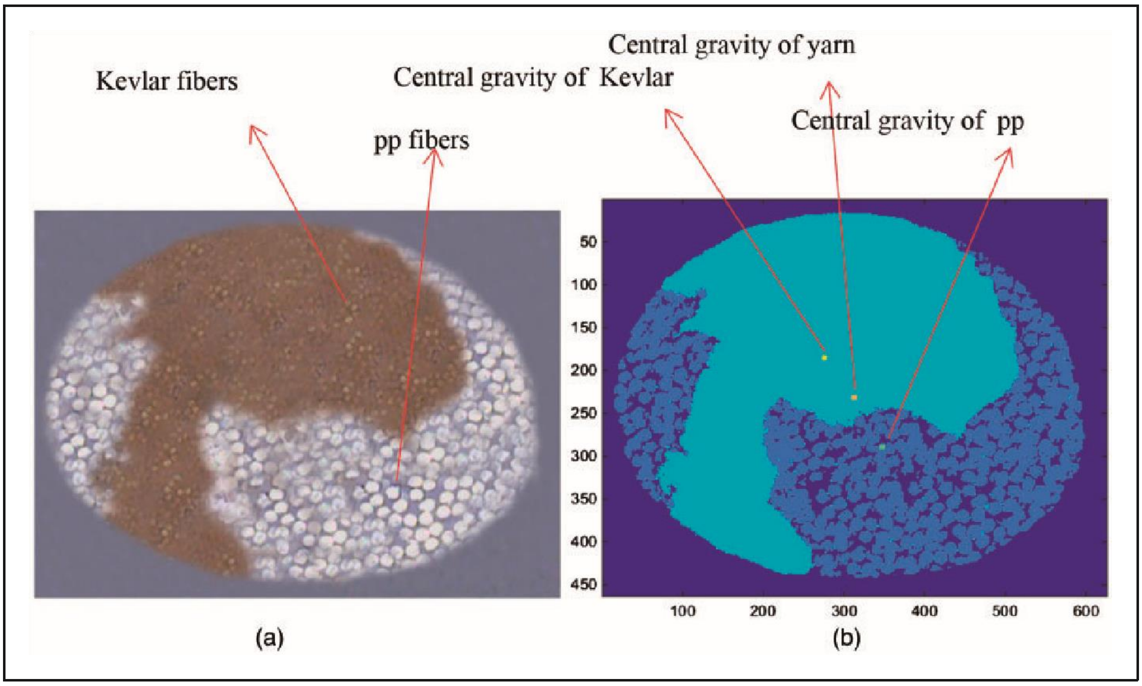

Figure 4. Cross-section of blended yarn before (a) and after (b) image processing.

3. Results and discussion

The results of the radial distribution, lateral distance and angular distribution indexes of the blended yarn with different process factors of air texture are summarized in Table 5.

3.1. Relationship between blending indexes

Linear regressions between blending indexes are depicted in Figures 5 to 7 for all pairs of components (Kevlar/PP) after the image mining of the blended yarn cross-section. According to the equations and R-square values in these regressions, one could conclude that there were relatively poor correlations between the radial and lateral indexes of components. Moreover, the angular distributions of both components showed a high level of correlation. However, a negative relationship could be observed between them. The correlations between the blending indexes of the components have not yet been reported at the level of 216 cross-sections of

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blended yarns. Therefore, it seems that considering Chiu's indexes[15] for one component is not sufficient to make a reliable decision on the blending quality.

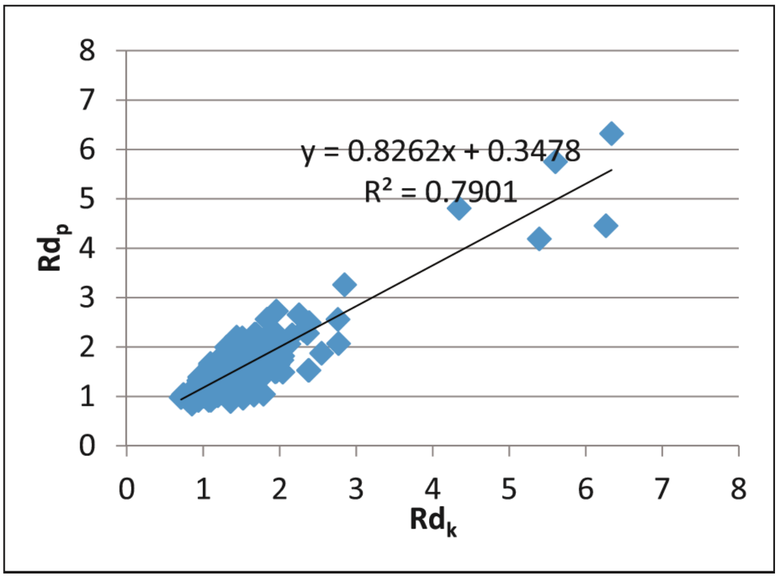

Figure 5. Correlation between R_{dk} and R_{dp} (216 data from cross-section of yarns in all categories).

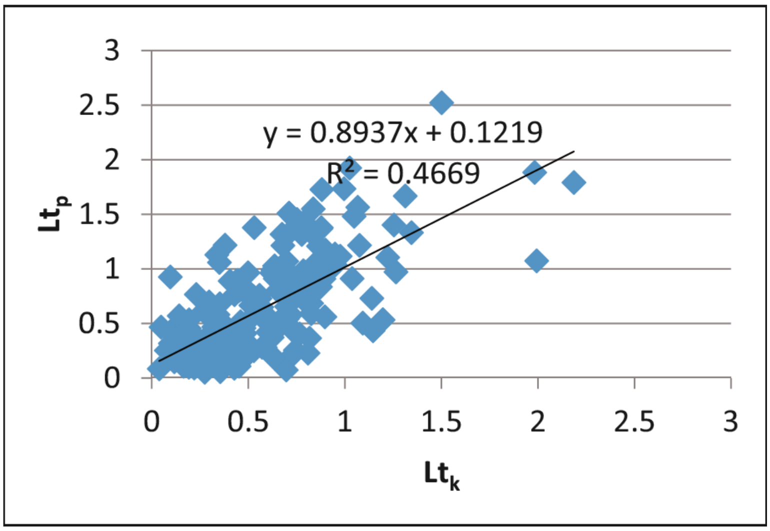

Figure 6. Correlation between L_{tk} and L_{tp} (216 data from cross-section of yarns in all categories).

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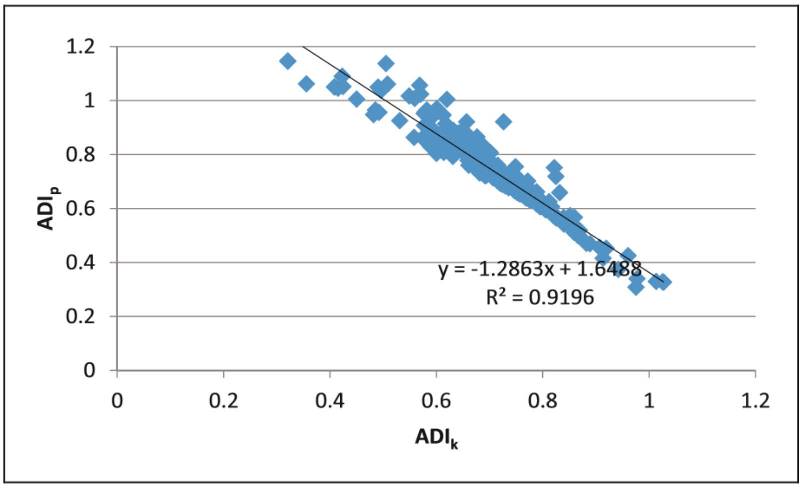

Figure 7. Correlation between ADI_k and ADI_p (216 data from cross-section of yarns in all categories).

3.2. The effect of process parameters on the blending parameters

Based on the optimization of RSM on the input data, the best process of air texture factors which corresponded to the optimum responses was evaluated. Accordingly, Figure 8 shows the influence of the process factors (X_1: blend ratio-X_2: production speed-X_3: feed rate-X_4: air pressure) on five quality indexes.

According to the results which are summarized in Figure 8, the optimum production can be achieved by controlling the process factors with desirability such as 0.63. The optimum factors are the blend strand ratio (Kevlar: PP) of 1:6 ($x_1 = 16$), the production speed at 300m/min ($x_2 = 300$), the feed rate at 500m/min ($x_3 = 500$), and the air pressure at 10 bars ($x_4 = 10$). These factors are corresponded with the production factors of category 12 (Table 3). The radial distribution and lateral distance of constituent fibers of this production obviously revealed the uniform blending, as highlighted in Table 5. The cross-sections of the optimum production are represented after image processing and the angular distribution of both components is indicated

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in Figure 9. The figures show that the angular distribution of Kevlar and PP was relatively uniform.

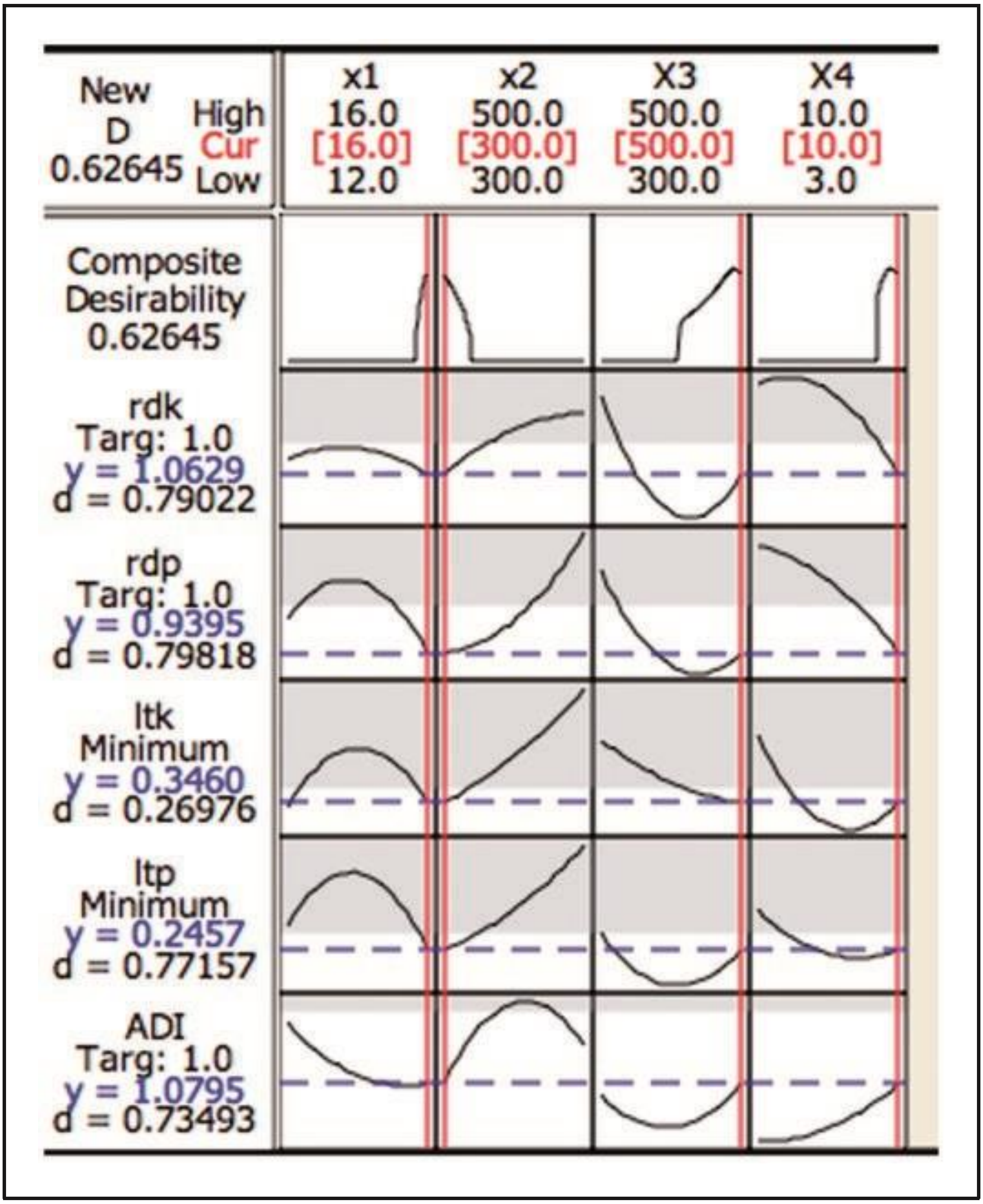

Figure 8. Optimized process parameters (X_1: blend ratio-X_2: production speed-X_3: feed rate-X_4: air pressure) for Radial, Lateral and Angular distribution.

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Table 5. Average of the radial distribution, lateral distance, and angular distribution index of blended yarn cross section.

Sample category	Radial distribution [Kevlar] [PP]		Lateral distance [Kevlar] [PP]		Angular distribution index [*ADI*]
	[R_{dk}]	[R_{dp}]	[L_{tk}]	[L_{tp}]	
1	1.8821 (0.52)[a]	2.1381 (0.27)	0.8047 (0.19)	1.3134 (0.46)	0.9363 (0.40)
2	1.2675 (0.27)	1.4137 (0.22)	0.4545 (0.14)	0.7505 (0.32)	1.1324 (0.45)
3	1.8358 (0.43)	2.0220 (0.35)	0.6119 (0.57)	0.7600 (0.43)	0.8247 (0.22)
4	1.1349 (0.23)	1.1219 (0.16)	0.3311 (0.10)	0.3017 (0.15)	1.3473 (0.15)
5	1.2536 (0.15)	1.1314 (0.23)	0.5886 (0.17)	0.2726 (0.10)	0.9719 (0.17)
6	1.4048 (0.11)	1.5112 (0.04)	0.3103 (0.11)	0.4871 (0.13)	0.9657 (0.15)
7	1.0230 (0.20)	1.2875 (0.18)	0.3220 (0.12)	0.2570 (0.11)	0.8918 (0.17)
8	1.5137 (0.49)	1.5704 (0.37)	0.2142 (0.10)	0.1499 (0.09)	1.0507 (0.14)
9	3.4063 (2.31)	3.5432 (2.35)	0.9472 (0.87)	0.7567 (0.68)	1.0497 (0.14)
10	1.1489 (0.12)	1.0975 (0.10)	0.4985 (0.20)	0.2666 (0.08)	1.1203 (0.30)
11	1.3723 (0.32)	1.2704 (0.15)	0.6175 (0.12)	0.5373 (0.28)	0.9810 (0.53)
12[b]	1.4075 (0.31)	1.2172 (0.15)	0.2845 (0.14)	0.3613 (0.23)	0.9223 (0.16)
13	1.3822 (0.41)	1.4584 (0.39)	0.7650 (0.28)	1.0505 (0.38)	1.3584 (1.35)
14	1.6295 (0.46)	1.6282 (0.50)	0.9241 (0.18)	1.1053 (0.41)	1.0071 (1.05)
15	1.3051 (0.25)	1.6265 (0.26)	0.7288 (0.14)	1.0220 (0.32)	1.1398 (0.81)
16	1.3684 (0.27)	1.8510 (0.19)	0.6101 (0.37)	0.8845 (0.38)	1.4132 (0.56)
17	1.5822 (0.35)	1.3660 (0.46)	0.5210 (0.20)	0.3520 (0.20)	1.0776 (0.37)
18	1.5442 (0.28)	1.3986 (0.13)	0.6178 (0.09)	0.3984 (0.20)	0.9164 (0.26)
19	1.6365 (0.37)	2.1429 (0.39)	0.4935 (0.11)	0.7011 (0.33)	0.9942 (0.22)
20	1.5202 (0.31)	1.7315 (0.22)	0.9029 (0.19)	0.9862 (0.23)	0.7081 (0.06)
21	3.3012 (2.01)	2.5598 (1.38)	0.6963 (0.76)	0.9584 (0.55)	1.2248 (0.47)
22	1.4571 (0.22)	1.7408 (0.31)	0.7544 (0.06)	1.1312 (0.38)	0.9694 (0.55)
23	1.3590 (0.35)	1.3684 (0.32)	0.5997 (0.38)	0.5834 (0.33)	1.0456 (0.64)
24	1.7412 (0.56)	1.7919 (0.80)	1.0327 (0.28)	1.1689 (0.77)	1.0329 (1.03)

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25–36[c]	1.5328 (0.38)	1.6217 (0.41)	0.4560 (0.27)	0.4892 (0.37)	1.0288 (0.39)

[a] Parentheses values are standard deviation
[b] Uniform category (discussed in ''The effect of process parameters on the blending parameters'' section)
[c] Central samples with 12 repetitions

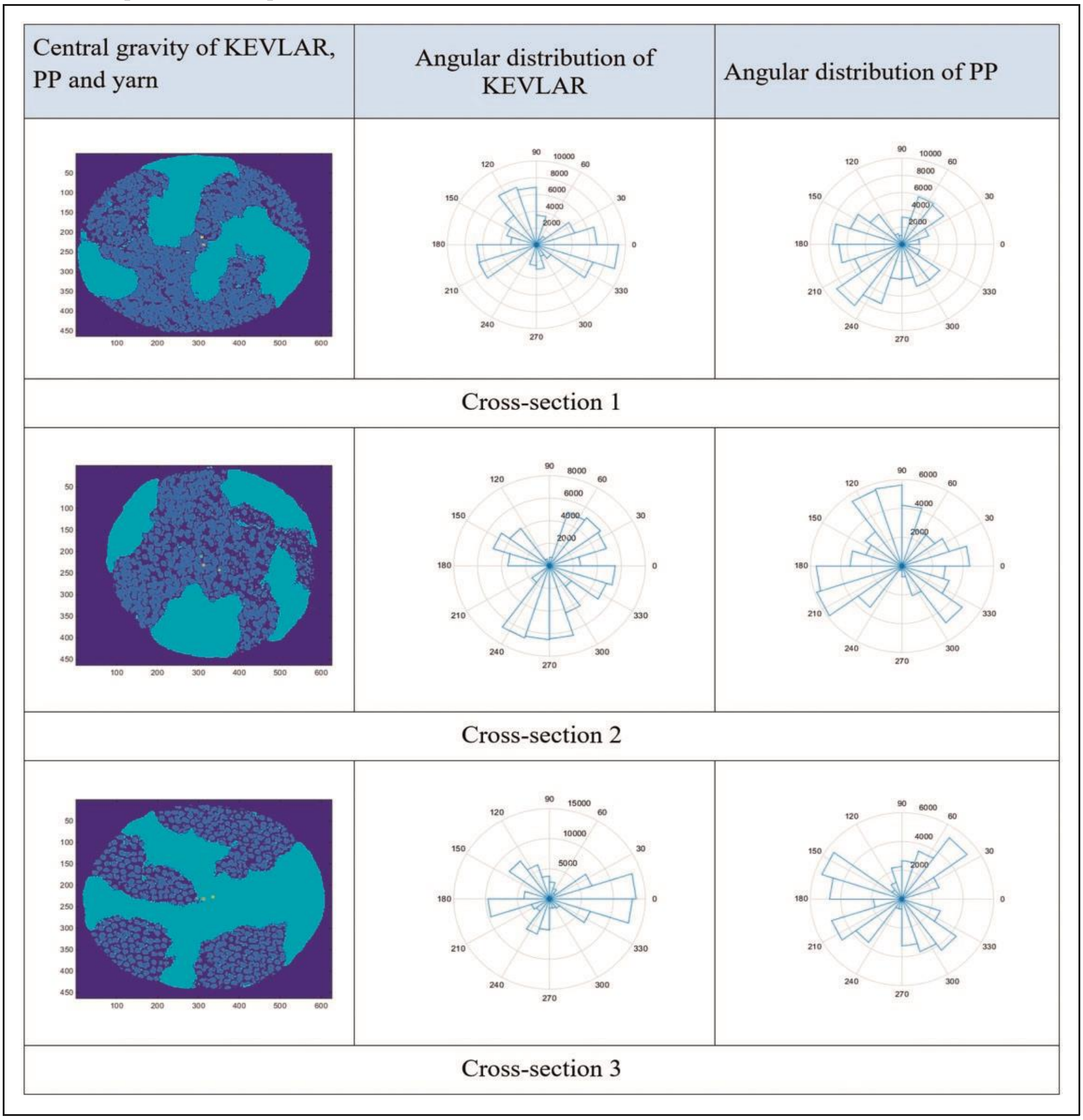

Figure 9. Central gravity and angular distribution for PP and Kevlar component of optimized sample in six cross-sections.

The Kevlar fibers are relatively finer than that of the PP fibers. Moreover, the number of fibers per strand is extremely high for Kevlar fibers in contrast with PP. Therefore, using

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maximum blend ratio of Kevlar:PP (1:6) conducts to better blending quality. The lower production speed can lead to the considerable migration of the filaments in the yarn cross-section with constant jet pressure. Fiber migration at yarn cross-section can be reduced by raising production speed, due to higher dynamic inertial of fibers. Consequently, lower production speed (300 m/min) provided better blending quality in this study. Obviously, feed rate has been shown to have a direct relationship with the degree of freedom of each filament. It can be seen that a higher value of feed rate leads to loose filament bundles which can be easily spread and blended using an air jet. This is such that with the rise of the feed rate, the availability of the free length of filament for forming loops is promoted; in fact, with the rise of the feed rate, the texturing efficiency and yarn linear density are increased as well. The higher feed rate of the yarn through the mingling jet can decrease the yarn tension, causing the yarn to move out of the potential action of air. Accordingly, the maximum feed rate (500 m/min) was suggested by RSM in this research. The air pressure is one of the other important parameters. It is related to the degree of filament and the nip formation. Air flow determines the opening up of the filaments, making it possible for them to be entangled with each other. This is such that with the increase in air pressure, flow velocity is also raised. The non-uniformity and turbulence of the air flow can also be promoted by the rise of the air pressure. The maximum air pressure (10 bars) was addressed in RSM to obtain the optimum blending quality. This could be due to the fact that all four variable parameters were interdepended, such that with increasing one component in the blended yarn, more filaments were exposed in the applied air pressure. Therefore, the filament-free movement through the yarn structure could be restricted. In this situation, with lowering the production speed, bundles of filaments had enough time to get affected by the air jet applied and blended with each other in the texturing zone. On the other hand, with regard to the deceased production speed, a higher feed rate made

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looser filament bundles with low tension that were affected by the air jet applied. In this condition, a higher air pressure improved filament migration; this, in turn, improved radial distribution, lateral distance and angular distribution.

Table 6 summarizes the experimental values of blending indexes and the values estimated by the model, as well as the corresponding errors. According to the low amount of model errors, it could be concluded that the model values were trustworthy. Furthermore, radial distribution, lateral distance and angular distribution blending are responsible to demonstrate the quality of blending using RSM in this study.

Table 6. The average value of blending quality factors for experimental, model and the error of model.

Responses	Experimental	Model	Error (%)
Rdk	1.6004	1.5591	4.13
Rdp	1.6644	1.6612	0.32
Ltk	0.6035	0.5860	1.75
Ltp	0.6818	0.6693	1.25
ADI	1.0444	1.0494	0.5

4. Conclusion

A mixture of Kevlar and PP fibers was introduced as a blended yarn for the potential thermoplastic applications. In this study, the effect of the air texture process parameters of the Kevlar/PP blended yarn, such as fiber's ratio, production speed, feed rate and air pressure, on the radial, lateral and angular fiber distribution indexes was introduced and discussed for both components. The correlation between the index pairs of components (Kevlar and PP) revealed that considering one component, as done by the previous works applying the one-component index, was not sufficient to evaluate the blending quality. Accordingly, all responses of fiber

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distribution indexes of both components were considered to estimate the blending quality and uniformity of blending fibers in this study by using the statistical RSM. Therefore, it seems that the proposed method could be regarded as a reliable way to optimize the air texture process in order to obtain the uniform distribution of fiber in terms of radial distribution, lateral distance, and angular distribution.

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