INTERNATIONAL JOURNAL OF APPLIED RESEARCH ON TEXTILE
URL: http://atctex.org/ijartex
Volume 3, Issue 2, pp 49-59, December 2015

NUMERICAL SIMULATION OF YARN BENDING: STATISTICAL OPTIMIZATION

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Received 11 April 2015, Accepted 15 December 2015

ABSTRACT:

During yarn formation by spinning, polyamide filaments are bent into approximately helical shapes and tension is created. Polyamide yarn undergone bending to compensate different stresses applied on filaments during the twist test.

In this study, polyamide filaments of different linear density and circular cross-sectional shapes have been numerical simulated at different twist and tension levels. The twist behaviour of the multifilament has been simulated by using the ABAQUS finite element package and modelling the yarns as 3D continuum elements.

The target of the research is to establish dependency relationships between certain factors (such as tension value, twist value and filament number) and the yarn bending expressed by the spatial orientation angle of the central filament.

Statistical experiment design is used to optimize polyamide yarn bending phenomenon during spinning for a series of models varying in the tension value, twist value and filament number. Results indicate that the twist value and the yarn count are the most influential variables that control yarn bending. With a good choice of tension and twist values, yarn bending during spinning can be avoided.

KEYWORDS:

Polypropylene filaments assembly, yarn bending, numerical simulation, spinning parameters, Statistical Optimization.

1. INTRODUCTION

The prediction of the macro-mechanical behavior of textile structure should be achieved according to the yarn structure and the consisting filament's properties. This necessitates carrying out a3D numerical modeling of twisted yarn.

Twist is essential to provide a certain minimum coherence between filaments (Treloar, 1964).When twisting filaments parallel to the yarn axis, they incline over a defined angle and turn around the yarn axis. This happens at an effective tensile force because of the torsion moment, the filament's rotation around the yarn axis and the compression forces on the filaments towards the yarn core. Filaments become closer. The adhesion between filaments in the yarn increases and yarn fineness decreases. The different layers are

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going to exercise one on the other inwards a controlled pressure, so that it creates new friction strength between the layers (Maâtouk et al., 2010).

The movement of filaments during deformation and their final positions after deformation are determined by their need to minimize tensile strain, which is the so-called the shortest-path hypothesis (Liu et al., 2007).

In a previous paper concerning migration and pressure phenomenon (Maâtouk et al., 2014), we have remarked that polyamide yarn undergone bending to compensate different stresses applied on filaments during the twist test.

Literature reveals that researchers have been interested to the yarn structure (Sriprateep et al., 2009) (migration phenomenon) and not to the yarn bending during spinning; so far, no work has been published.

This necessitates carrying out a research work on yarn bending phenomenon by using a numerical simulation with finite element technique.

This study deals with the influence of spinning parameters on the linearity of polyamide multifilament yarn using a statistical experiment design.

The application of Design of Experiment technique on the optimization of an industrial process is frequently used (Kumar and Ishtiaque, 2009; Halimi et al, 2009). Design of Experiment (DOE) is an experimental or analytical method that is commonly used to statistically signify the relationship between input parameters to output responses, where by a systematic way of planning of experiments, collection and analysis of data is executed (Rahman Khan et al., 2015)

Several textile problems have also been studied by means of these techniques. Taguchi method can be a useful technique for optimizing textile processes (Salhotra et al., 2006; Webb et al., 2007). Taguchi method can be also used to optimize a textile process, where the product quality is highly variable and dependent on the combination of number of processes as well as on machine parameters

Thus, our goal is to establish dependency relationships between some factors (such as tension value, twist value and filament number) and the yarn bending, expressed by the spatial orientation angle of the central filament. This study should predict maximum accuracy a response from a minimum number of tests.

2. MATERIALS AND METHODS

2.1. Yarn specifications

To define the geometry of a single yarn, the model which is usually adopted is that of an ideal physical form with length of 10 mm. All the filaments are identical and uniform along their length with a circular cross-section of a uniform specific volume.

The stress–strain properties of the filaments in the yarn are assumed to be the same. The interactions between filaments within a yarn are processed because they have a significant role in its mechanical properties.

The 3D numerical modeling of filaments assemblies has been developed, thanks to 3D finite element simulation which is based on C3D8R continuum element. The 3D continuum model is considered adequate to describe yarn deformations.

To obtain the twist, the model must be embedded from one side and twisted from the other.

The geometrical models for 7 and 19 filaments are presented in Figure 1.

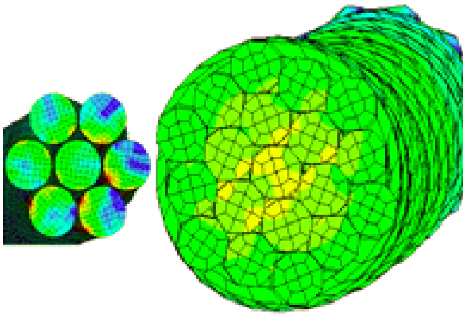


Figure 1: Geometrical models for yarns consisting of 7 and 19 filaments.

For the twist simulation test, the one end of the model is considered clamped, on the other end a rotation (R) and a tensile load (F) are imposed (Figure 2).

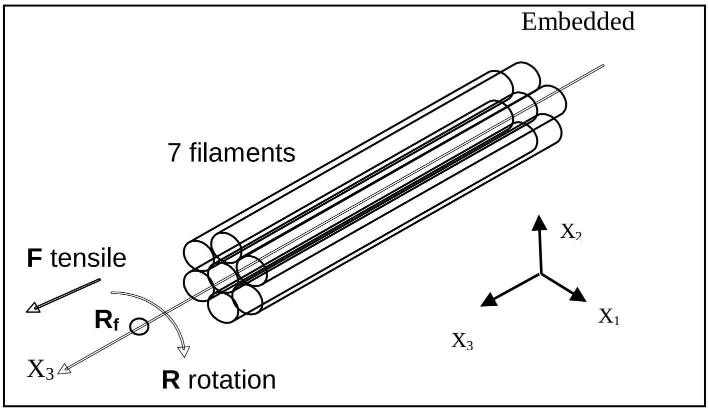


Figure 2: Boundary conditions of model

2.2. Behaviour law

The studied model was a polyamide yarn. The law behavior is visco-elastic. It is a simple law, identified by the load-extension curve resulted from the tensile test and the relaxation test. These tests are then numerically simulated in ABAQUS.

The main filament characteristics that are needed by the packager ABAQUS, as input parameters, to simulate twist test are evaluated. Young's modulus of filaments is determined from tensile curves. The Poisson's ratio of the yarns is equal to 0.3. This value has been considered by many researchers in the literature (Huh et al., 2001).

Table 1 gives the details of the filament characteristics.

Table 1: Physical properties of filament

Filament	Type	Radius (µm)	Young's modulus (MPa)	Linear density (Tex)
PA1	polyamide	11	2210	0.456
PA2	Polyamide	13	2788.99	0.64
PA3	Polyamide	17	3074.63	1.09

For the numerical simulation, we have used polyamide filaments with various counts. A microscopic study of filaments morphology shows that the section is circular.

For every type of filament, a set of continuous filament twisted yarns were simulated using 7 and 19 filaments with different twist level.

2.3. Numerical model

First, we tried to simulate the torsion textile linear structure operation using ABAQUS Standard but numerous problems were encountered because of the stern contact. For that, we have used a non-linear finite element method with an explicit dynamic process (ABAQUS explicit) to solve the quasi-static problem involving complex contact conditions.

The 3D numerical modeling of filaments assemblies has been developed, thanks to 3D finite element simulation which is based on C3D8R continuum element. The FEM using 3D continuum elements is implemented for the analysis of the multifilament twisted yarns. The 3D continuum model is considered adequate to describe yarn deformations. However, the modeling with volumic elements represents a disadvantage regarding the liberty degrees; all 3D continuum elements have only translational liberty degrees. To resolve this problem, we used a kinematic coupling constraint with a reference point of an analytical rigid body which has six liberty degrees.

During this study, we considered linear visco-elastic 3D elements to model filaments in yarn. The constitutive equation for an isotropic visco-elastic material, as it is implemented on ABAQUS and given in an integral form, can be written as follows (Hibbitt, Karlsson, & Sorensen, 2001):

$$\sigma(t) = \int_0^t 2G(\tau-\tau')\dot{e}\,d\tau' + I\int_0^t K(\tau-\tau')\dot{\phi}\,d\tau' \qquad (1)$$

With e: deviatoric strain tensor;

ϕ : volumetric strain;

G: shear modulus;

τ: reduced time (function of the time t and the glass transition temperature);

K: bulk modulus;

I: unit matrix.

Given that the effect of glass transition temperature is not studied, the reduced time τ is assumed to be equal to the time t.

During the torsion textile linear structure operation, we assume that the volumetric strain is purely elastic. K is assumed to have a constant value.

The relaxation function G (t) is defined individually in terms of a series of exponentials known as the Prony series.

For ABAQUS/CAE, in order to define the visco-elastic material, it is not necessary to calculate the terms of Prony series. Indeed, it is only required to input the dimensionless relaxation test results and the terms of Prony series are evaluated.

2.4. The spatial orientation angle

The spatial orientation angle θ (Huh et al., 2001), defined as the spatial angle between the yarn axis and the filament segment and calculated in accordance with Equation (2). This spatial angle contains the information on the change in radial position and it reflects the obliqueness of the filament arrangement to the yarn axis.

$$\theta = \tan^{-1}\left[\frac{\sqrt{((x_{i+1}-x_i))^2+\left(y_{i+1}-y_i\right)^2}}{(z_{i+1}-z_i)}\right] \tag{2}$$

Where: x_i, y_i, z_i , given by ABAQUS finite element package, are the coordinates of each ith node on the location of the filament axis.

The spatial orientation angle can be used as an important parameter to describe the yarn structure. Furthermore, it is an important parameter which can inform us about the migration phenomenon (Maâtouk, 2011).

3. RESULTS AND DISCUSSIONS

3.1. Bending optimization for a yarn of PA1 filaments

During spinning, the yarn bending is influenced by several parameters and it is represented by the spatial orientation angle for the central filament.

The study is designed on the base of Taguchi experiment which consists of three factors using MINITAB program Design of Experiments (DOE). The selected three factors for the optimization of yarn linearity are: twist value, tension value and filament number per section.

For each variable, we have chosen two levels and were designed Tr, Te and Ns respectively as shown in table 2.

Table 2: Level and range of chosen variables

Factor	Variable	Level and range of coded values	
		(-1)	(+1)
Tr	Twist (tr/m)	318	796
Te	Tension (N)	1	5
Ns	Filament's Number per section	7	19

The output parameter Teta is the average value of the spatial orientation angle calculated for the central filament along the yarn length.

A set of continuous filament twisted yarns were numerical simulated using 7 and 19 PA1 filaments with different twist level.

The experimental data was then analyzed statistically; the response variable can be approximated by the following regression equation:

$$Teta = 0{,}1145 + 0{,}0515 \times Tr - 0{,}0458 \times Te + 0{,}1051 \times Ns - 0{,}0034 \times Tr \times Te + 0{,}0447 \times Tr \times Ns - 0{,}0393 \times Te \times Ns \tag{3}$$

The principal effects of each studied parameter on yarn bending are depicted in figure 3. It can be observed that the number of filament per section is the most significant factor on the yarn bending during spinning and the factor "twist value" is prominent. However, the "tension value" has a negative effect.

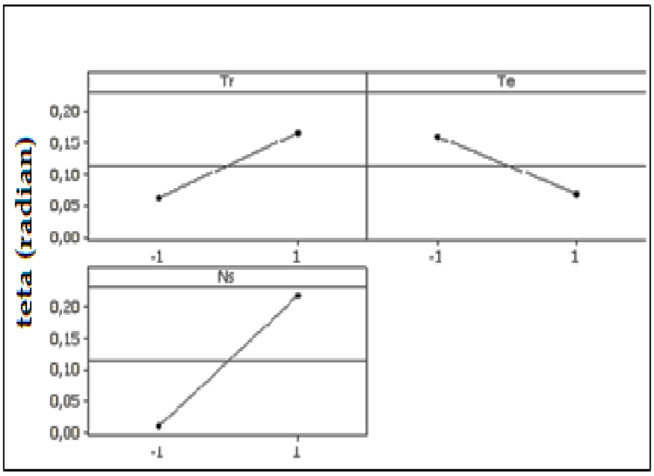


Figure 3: The effect of filament's number per section, twist and tension value on yarn bending

In figure 4, we monitor the combined interactions between these factors. We notice that, during spinning, yarn bending tends to increase with the increase in filament's number per section, whatever the twist and tension value.

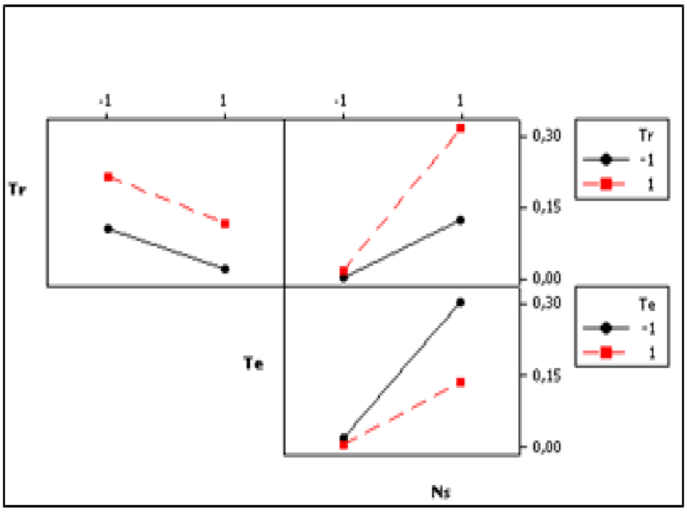


Figure 4: The effect of interactions

To understand the pattern of interaction and to envision synergistic and antagonistic effects between test variables, the student's t–test and P values were listed in Table 3. The larger the magnitude of t-test and smaller the P-value, the more significant is the corresponding coefficient (Liu et al., 2011).

Student's t–test was employed to determine the knowledge of the error mean square that is essential in testing the significance of the estimated coefficient of the regression equation. The student's t–test value can be obtained by dividing each coefficient by its standard error. A large 't' value implies that the coefficient is much greater than its standard error.

Table 3: Significance test for main and interaction effects

Variable	Estimated Coefficients	e_i^2	t-value	P-value
Constant	0.1145	3.677E-06	59.7260	0.0053
Tr	0.0515	3.677E-06	26.8610	0.0118
Te	-0.0454	3.677E-06	-23,7088	0.9866
Ns	0.1051	3.677E-06	54.8161	0.0058
Tr.Te	- 0.0034	3.677E-06	-1.7901	0.8378
Tr.Ns	0.0447	3.677E-06	23.2960	0.0136
Te.Ns	- 0.0393	3.677E-06	-20.4968	0.9844

Table reveals that the effect of filament number by section (P = 0.0058) has a major edge over other interaction and main effects. Therefore, the filament number by section has a strong positive linear effect on the yarn linearity as it has the largest coefficient followed by the twist value.

However the values of "t" and their sign imply the impact of their effects on the PA yarn linearity.

The effect of twist value increase the yarn bending (t = 26,86), while the effect of tension value (t value of – 23,7088) decrease the yarn bending.

However, the interaction effects between twist and tension value with low t-value and high P-value is found to be insignificant.

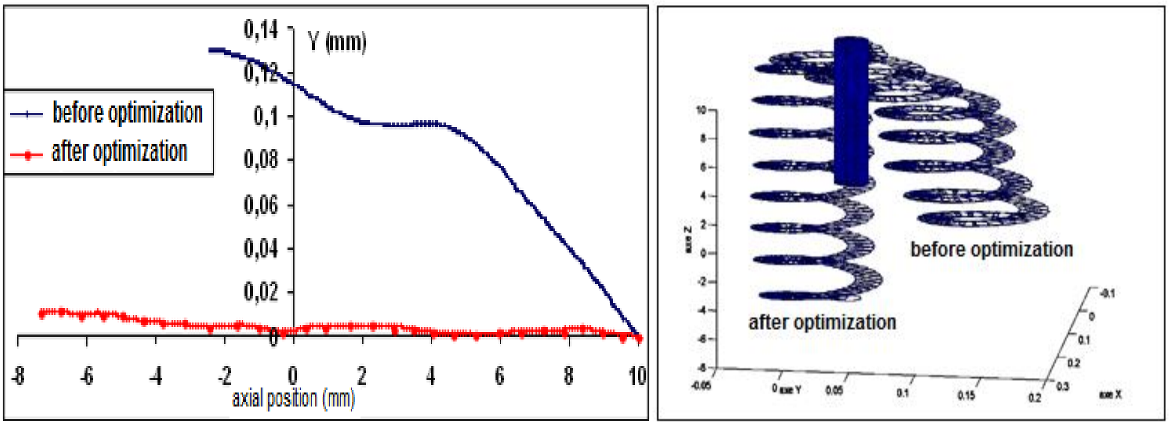
The polynomial model for yarn linearity (Teta= 0) was regressed by mainly considering the significant terms and was expressed by Equation 4.

$$\mathrm{Teta} = 0.1145 + 0.0515 \times \mathrm{Tr} - 0{,}0458 \times \mathrm{Te} + 0{,}1051 \times \mathrm{Ns} + 0{,}0447 \times \mathrm{Tr} \times \mathrm{Ns} - 0{,}0393 \times \mathrm{Te} \times \mathrm{Ns} \quad (4)$$

The experimental data obtained by the Taguchi Method must be processed by numerical simulation to achieve a complete result.

A numerical simulation was carried out to verify the availability and accuracy of the model (Equation 4). Hence, we calculate the necessary tension value (9.412 N) for an assembly of 19 filaments with twist equal to 796 turns/m.

Thereafter, we compare the trajectory of the external and the central filament before and after optimization (figure 5).



(a) (b)

Figure 5: Filament trajectory comparison before and after optimization: (a): central filament, (b): external filament

A comparison of the results before and after implementation of the optimal condition in PA yarn spinning reveals that twisted yarn is more linear compared to the non-optimized twisted yarn which suggesting that our model is very effective for yarn bending optimization.

3.2. Bending optimization for a polyamide yarn

Statistical methodology can be a powerful and a simple tool to effectively optimize the yarn bending during spinning.

Therefore, in this part, we intend to optimize the yarn linearity during spinning for a series of polyamide yarns, we selected three factors: twist value, tension value and filament diameter.

For each variable, we have chosen three levels and were designed Tr, Te and Diam respectively as shown in table 4.

Table 4: Level and range of chosen variables

Factor	**Variable**	**Level and range of coded values**		
		1	2	3
Tr	Twist (tr/m)	318	477	796
Te	Tension (N)	1	2	3
Diam	Filament's Diameter (mm)	0.022	0.026	0.034

Numerical simulation of twist for an assembly of 7 filaments (PA1, PA2 and PA3) was carried out to calculate the output parameter (the spatial orientation angle (Teta)) and results are illustrated in table 5.

The experimental data was then analyzed statistically to obtain the following regression equation:

$$\mathrm{Teta} = -0.0207 + 0,.0222 \times \mathrm{Tr} - 0.0061 \times \mathrm{Te} + 0.012 \times \mathrm{Diam} – 0.0046 \times \mathrm{Tr}^2 + 0.001 \times \mathrm{Te}^2 - 0.0025 \times \mathrm{Diam}^2 - 0.0004 \times \mathrm{Tr} \times \mathrm{Te} + 0.0017 \times \mathrm{Tr} \times \mathrm{Diam} – 0.0002 \times \mathrm{Te} \times \mathrm{Diam} \quad (5)$$

Figure 6 shows the principal effects of each studied parameter. It can be observed that twist value is the most significant factor followed by filament diameter. However, the tension value has a negative effect.

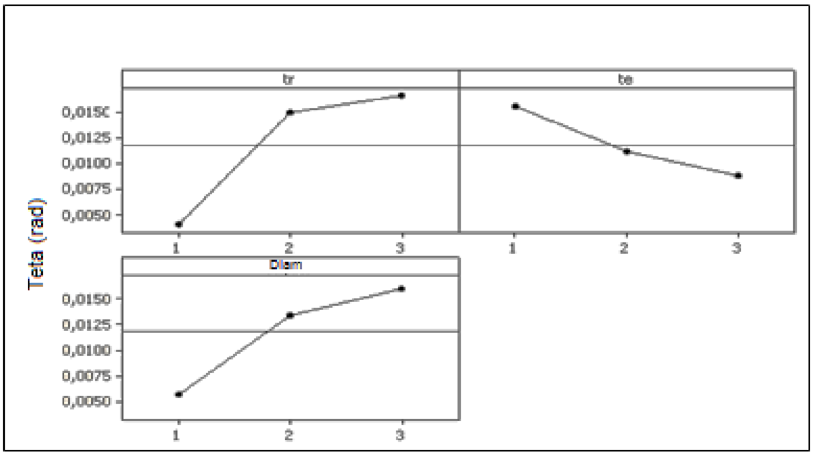


Figure 6: The effect of filament diameter, twist and tension value on yarn bending

Table 5: Experimental data

Experiment number	Variable			Output
	Tr	Te	Diam	Téta
1	1	1	1	0.00359
2	1	1	2	0.00539
3	1	1	3	0.00906
4	1	2	1	0.00144
5	1	2	2	0.00371
6	1	2	3	0.00419
7	1	3	1	0.00064
8	1	3	2	0.00142
9	1	3	3	0.00647
10	2	1	1	0.01058
11	2	1	2	0.02701
12	2	1	3	0.02920
13	2	2	1	0.00326
14	2	2	2	0.01694
15	2	2	3	0.01790
16	2	3	1	0.00295
17	2	3	2	0.01172
18	2	3	3	0.01439
19	3	1	1	0.01333
20	3	1	2	0.01976
21	3	1	3	0.02199
22	3	2	1	0.00982
23	3	2	2	0.01965
24	3	2	3	0.02326
25	3	3	1	0.00624
26	3	3	2	0.01591
27	3	3	3	0.01864

In figure 7, we monitor the combined interactions between these factors. We notice that with increased the filament diameter there is an increase in the yarn bending during spinning whatever the twist and tension value.

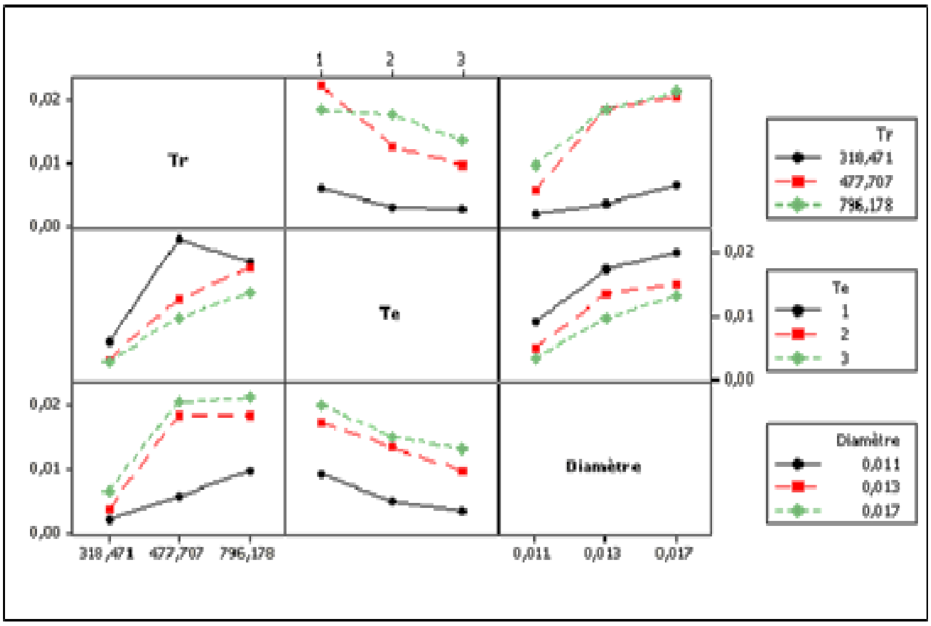


Figure 7: The effect of interactions

The study of the combined interactions between the three studied factors shows that there are interactions by second order which have no effect on the response.

Similar to the first part, in order to understand the pattern of interaction and to envision synergistic and antagonistic effects between test variables, the student's t–test and P values were tabulated as shown in Table 6.

Table 6: Significance test for main and interaction effects

Variable	Estimated Coefficients	t-value	P-value
Constant	-0.0207	-1.818	0.087
Tr	0.0222	3.388	0.003
Te	-0.0061	-0.931	0.365
Diam	0.0125	1.913	0.073
Tr^2	-0.0046	-3.192	0.005
Te^2	0.001	0.687	0.501
$Diam^2$	-0.0025	-1.764	0.096
Tr×Te	-0.0004	-0.389	0.702
Tr×Diam	0.001706	1.661	0.115
Te×Diam	-0.00025	-0.25	0.805

Table 6 reveals that the twist value has a strong positive linear effect on the yarn linearity as it has the largest magnitude of t-test and the smaller P-value (t=3.388; p=0.003), followed by the filament diameter. On the other hand, tension value shows negative effect on the yarn linearity.

The squared effects of twist (P 0.005 and T 3.192) have a major edge over other interaction and main effects. This leads to the fact that yarns bending increases during spinning with increased twist level. However, the interaction effects between filament diameter and tension value with low t-value and high P-value found to be insignificant.

The polynomial model for yarn linearity (eq. 5) is expressed by mainly considering the significant terms and we obtain the following regression equation:

$$\mathrm{Teta} = -0{,}0207 + 0{,}0222 \times \mathrm{Tr} - 0{,}0061 \times \mathrm{Te} + 0{,}012 \times \mathrm{Diam} - 0{,}0046 \times \mathrm{Tr}^2 + 0{,}001 \times \mathrm{Te}^2 - 0{,}0025 \times \mathrm{Diam}^2 + 0{,}0017 \times \mathrm{Tr} \times \mathrm{Diam} \quad (6)$$

4. CONCLUSION

In this paper, our study deals with the problem of predicting a statistical model permitted to determine optimal values for significant factors that affect the yarn bending during spinning.

It is clear from the results presented in this study that the twist value and the yarn density are the most influential variables that control yarn bending. As the twist increases, filaments appear to compensate these pressures strain while bending. These findings are in accordance with the previous research which has shown that filaments buckle or migrate in order to minimize tensile strain and it is the so-called the shortest-path hypothesis [Liu et al., 2007].

The prediction equation obtained can be used as a guide in further simulation to evaluate the necessary tension value which minimizes the phenomenon of polyamide yarn bending during spinning.

Although, this equation is valid only for the particular studied material, we can expand our study for other kind of filament. Nevertheless, the number of filaments that can be modeled in a yarn is limited by the computational requirements.

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