A New Regression Based Model for Estimation of the Process Parameters Affect for Texturing of Polyethylene Terephthalate (PET) Yarn

Kenan Yildirim, Suna Cetin, and Yusuf Ulcay

***Abstract*—This study comprises investigations of the effect of false-twist texturing process parameters onto the properties of PET (polyethylene terephthalate) yarn and performing prediction equations based on a non-linear regression mathematical model. The effect of texturing parameters on the properties of PET filaments was characterized through measurements of boiling water shrinkage, shrinkage force, crimp stability and crimp contraction. The properties of the textured yarn can be altered by changing of mainly three parameters which are D/Yratio, draw ratio and first heater temperature. Yarn samples were produced in three different levels of each of selected parameters and tested. In order to obtain empirical formulas for predicting the change of textured PET yarn properties with respect to selected production parameters, the yarns were produced in 27 different combinations. The starting point of the empirical equation is based on a completely randomized variance analyses model. The coefficients of the curves fitted were computed by means of non-linear regression analysis. R^2 values for these curves were observed to be highly reliable being about 0.85.**

***Index Terms*—PET yarn, fals-twist texturing factors, physical and performance parameters, regression-based mathematical model.**

I. Introduction

One of the main disadvantages of man-made fibers is the flat geometry and smooth surface. The fiber waviness or crimp increases volume, resilience, moisture absorption, etc. Texturing methods have been developed to overcome this problem. Texturing is a common commercial process which gives crimp to the flat yarns. Among the several texturing methods, false twist texturing is the most favored method. False-twist texturing process is composed of four main steps, heating the thermoplastic fibers above the glass transition temperature (Tg), twisting, cooling the fibers below Tg and untwisting. Heater parameters, mainly heater temperature and residence time, together with fiber thermal properties influence textured yarn properties such as tenacity, crimp rigidity, dyeability, etc. [1]-[6].

False-twist texturing process can be investigated based on three main parameters, which are called 3t: tension, twist, and temperature [2], [7]. Draw ratio, D/Y ratio, and heater temperatures are the main process parameters to change 3t. The ratio of the disk surface speed to the yarn speed is usually referred to as *D*/*Y* ratio. *D*/*Y* ratio is calculated as follows:

$$\frac{D}{Y} = \frac{\text{circumferential speed of disks (m/min)}}{\text{throughput speed of yarn (m/min)}} \quad (1)$$

If D/Y ratio is low, the yarn tension before twisting unit will be low and the tension after the twisting unit will be high [8]-[11]. This situation can cause yarn damages. Draw ratio is the ratio of center shaft speed to the input shaft speed and is calculated as follows:

$$Draw \quad Ratio = \frac{\text{center speed shaft (m/min)}}{\text{input speed shaft (m/min)}} \quad (2)$$

Yildirim K. and coworkers used regression-based mathematical model for prediction poly oriented yarn (POY) PET yarn properties according to process parameters. The equation of this model was similar to a completely randomized variance analysis model. They used this model for prediction POY PET yarn properties according to process parameters in terms of tensile strength, tensile strain, draw force, crystallinity degree, K/S, brightness and boiling water shrinkage. They claimed that R^2 and r values showed that the equations are well-suited to predicting PET POY yarn properties for selected production parameters [12].

A. Majumdar and co-workers used linear regression model for estimation of rotor spun yarn breaking elongation beside other prediction methods of neural network and neuro-fuzzy. While their model includes parameters which affect yarn breaking elongation omitting parameter interactions, the model in this work includes both influence parameters and interactions of these parameters. According to A. Majumdar and co-workers' results, all of three prediction models give reasonable results with high accuracy. However, the error term is less in regression model than the others but standard deviation is higher [13].

J. Carey and co-workers used simple regression-based model as an alternative to existing models, which are finite element analysis, fabric geometry model and modified classical laminate plate theory, to eliminate the complexity and impractical use in industrial design for open mesh braided/woven fabrics [14].

Sular and Okur used simple regression model to predict total fabric handle with a minimum number of parameters. They used objective measurement results which are tensile, bending, shear, compression and surface properties, and

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pulling through a nozzle test, to predict subjective fabric handle. They used linear and log linear equations and claimed that very good result was obtained within the R^2 =0.88 [15].

Park and co-workers used regression equation to estimate holding power and pressure sensation utilizing average pressure and pressure distribution, and constructed the regression equation to estimate Comfortable fittability index using the calculated pressure sensation. They defined comfortable fittability index and holding power to represent the subjective wearing comfort of caps. Using this model they developed a tool to measure comfort and holding power of a baseball cap from measuring the pressure inside caps [16].

TABLE I: TEXTURED PET YARN PROPERTIES [19]

First heater temperature (0C)	150								
D/Y ratio	1.5			2.0			2.5		
Draw ratio	1.55	1.60	1.65	1.55	1.60	1.65	1.55	1.60	1.65
Crimp contraction (%)	4.78	5.00	5.43	7.76	6.77	6.40	6.75	6.82	5.91
Std. Deviation	0.03	0.49	0.28	0.99	0.18	0.09	0.39	0.32	0.26
Crimp stability (%)	76.38	77.24	77.37	75.04	74.98	75.52	73.78	74.54	74.08
Std. Deviation	1.17	1.11	2.50	1.32	1.46	1.59	0.73	1.41	1.34
Boiling water shrinkage (%)	3.25	3.29	3.32	2.85	2.98	3.15	3.02	3.22	3.00
Std. Deviation	0.12	0.11	0.11	0.08	0.08	0.10	0.06	0.07	0.08
Shrinkage force (cN)	6.31	7.20	8.03	5.93	6.80	7.51	5.84	6.69	7.41
Std. Deviation	0.22	0.16	0.14	0.18	0.19	0.25	0.13	0.21	0.16
First heater temperature (^{0}C)	190								
D/Y ratio	1.5			2.0			2.5		
Draw ratio	1.55	1.60	1.65	1.55	1.60	1.65	1.55	1.60	1.65
Crimp contraction (%)	12.13	13.63	10.45	13.43	12.82	11.83	12.00	11.98	10.89
Std. Deviation	0.19	0.20	0.61	1.50	0.46	0.54	0.34	0.25	0.54
Crimp stability (%)	81.88	84.12	82.23	80.74	81.68	81.73	77.71	78.67	78.78
Std. Deviation	0.79	0.38	0.38	1.00	0.38	0.53	0.45	0.82	0.71
Boiling water shrinkage (%)	2.06	1.94	1.92	1.72	1.75	1.83	1.69	1.72	1.83
Std. Deviation	0.03	0.04	0.09	0.07	0.07	0.05	0.08	0.04	0.04
Shrinkage force (cN)	4.10	4.26	5.30	3.11	3.80	4.80	2.93	3.54	4.39
Std. Deviation	0.19	0.14	0.30	0.19	0.19	0.15	0.14	0.20	0.23
First heater temperature (^{0}C)	230								
D/Y ratio	1.5			2.0			2.5		
Draw ratio	1.55	1.60	1.65	1.55	1.60	1.65	1.55	1.60	1.65
Crimp contraction (%)	18.13	18.77	16.49	17.50	18.07	17.36	17.76	17.29	18.28
Std. Deviation	0.53	2.78	0.75	0.70	0.43	0.41	0.83	0.74	2.10
Crimp stability (%)	80.28	82.73	82.38	78.61	80.84	81.52	79.02	80.81	81.49
Std. Deviation	0.94	1.87	0.66	1.47	0.48	0.62	0.49	0.66	0.90
Boiling water shrinkage (%)	1.60	1.60	1.62	1.53	1.53	1.52	1.32	1.29	1.51
Std. Deviation	0.14	0.03	0.08	0.06	0.05	0.04	0.09	0.04	0.04
Shrinkage force (cN)	1.11	1.28	1.45	1.02	1.13	1.17	0.96	1.05	1.18
Std. Deviation	0.04	0.05	0.06	0.03	0.04	0.03	0.04	0.04	0.05

TABLE II: THE ASSESSMENT OF PREDICTION CAPACITY OF MODEL

Independent variable	Predicted value1	Actual value1	Predicted value2	Actual value2	Predicted value3	Actual value3	Predicted value4	Actual value4	Predicted value5	Actual value5
First heater temperature (^{0}C)	190		220		200		210		205	
D/Y ratio	2		2.5		2.0		1.5		1.5	
Draw ratio	1.55		1.60		1.65		1.55		1.60	
Dependent variable										
Crimp contraction (%)	12.42	13.43	16.34	16.2	13.20	13.50	15.50	15.3	14.18	16
Crimp stability (%)	78.6	80.7	80.0	80.5	80.42	82.4	81.0	82.2	81.0	84.0
Boiling water shrinkage (%)	2.11	1.72	1.42	1.30	1.98	1.69	1.87	1.78	1.96	1.70
Shrinkage force (cN)	3.43	3.11	1.63	1.60	3.74	3.90	2.41	2.58	3.17	3.10

R. G. Ovejero and co-workers used non-linear regression methods to fit the experimental results to the three kinetics models of dying kinetics of poly(tri-methylene terephthalate (PTT) yarn with C.I. Disperse Red 82. They considered that this model adaptation was correct and relatively good fit was obtained due to that regression coefficient was higher than 0.90 in all case [17].

Yildirim K. also used regression-based mathematical model for prediction seam opening behavior of woven upholstery fabrics. He used this model for prediction seam opening behavior of woven fabric according to fabric properties with respect to test condition carried out under static and dynamic loading . They concluded that R^2 which was 0,90 and r which was 0,96 values showed that the equations are well-suited to predicting seam opening behavior of woven fabric [18].

In the present study, the effect of first heater temperature, D/Y ratio and draw ratio on boiling water shrinkage, shrinkage force, crimp stability and crimp contraction of textured PET yarn has been examined. The ability of regression-based model to predict yarn properties from production parameters was investigated in this study too.

II. Material and Method

A. Materials

167 dtex, 96 filaments, semi-dull, POY PET yarn was draw-textured on the lab type Barmag AFK-M texturing machine with two heaters. Process speed was 650 m/min. The first heater length was 2.5 m. Second heater length and temperature were 1.25 m and 165 ℃, respectively. Disk-type friction texturing unit was used. The disk configuration was 1+6+1. The disk material was ceramic and the disk thickness was 9 mm

B. Methods

The simultaneous draw texturing process was carried out. All processing parameters were kept constant except first heater temperature, D/Y ratio and draw ratio. The first heater temperatures were 150 ℃, 190 ℃ and 230 ℃. The. D/Y values were 1.5, 2.0, and 2.5 and the draw ratios were 1.55, 1.60 and 1.65

C. Measurements

1) Crimp properties of the yarn

Crimp stability and crimp contraction tests were performed according to DIN 53840 standards by using Textechno Texturmat ME. Five specimens have been used for each samples.

Shrinkage force test was done using Textechno Dynafil ME. Dynafil ME was arranged for test as following: The applied pre-load was 13 cN, the heater temperature was 250 0C. The shrinkage force test was done at 90 m/min testing speed. The yarn length was 50 m.

2) Boiling water shrinkage of the yarn

Boiling water shrinkage test was carried out according to DIN 53866. Six specimens have been used for each samples. A tensioning weight of 0.125 cN/tex was applied to the yarn, which was *I* m in length, and a hank was formed. The first length in this condition was recorded as I_1, and then the load was removed. The yarn was wetted in a soap solution (*I* g of soap per I_1 of water) and left in the solution at 100 ℃ for 15 min and then dried for one hour at 60 ℃, after which the yarn was hung for *I* h on the device. Then the same weight was applied to the yarn, and the length was recorded as I_2. Boiling water shrinkage was calculated from Eq. (3):

$$\text{Boiling water shrinkage } (\%) = \left[\left(I_1 - I_2 \right) / I_1 \right] \times 100 \qquad (3)$$

D. Mathematical Model

In order to compute coefficients of the regression-based model with respect to selected production parameters, the yarns were textured with 27 different combinations and then were tested. All of the test results for these four yarn properties at different production parameters were used in the regression analysis. The advantage of using this model is to take into account the interaction effects in addition to the individual production parameters.

The regression-based mathematical model is similar to a completely randomized variance analysis model. The reason for establishing this type of model is to take into account the effects of both selected production parameters and their interactions. The model equation used in the study is

$$\begin{aligned} Yi &= a_i + b_i \times (FHT) + c_i \times (DY) + d_i \times / FHT \times DY) + \\ & e_i \times (DR) + f_i \times (FHT \times DR) + g_i \times (DY \times DR) + \\ & h_i \times (FHT \times DY \times DR) \end{aligned} \qquad (4)$$

where, Y_i are the yarn properties (i= 1, crimp stability, i=2, crimp contraction, i= 3, shrinkage force, i= 4, boiling water shrinkage), a_i, b_i, c_i, d_i, e_i, f_i, g_i and h_i are coefficients, and FHT (first heater temperature), *DY* (*D*/*Y*) and *DR* (Draw ratio) are texturing process parameters. All coefficients were found based on a non-linear regression method in terms of the established equation by using the SPSS version12 statistical program using the Levenberg–Marquardtmethod. Using these equation computer program were written by using C++ (version 6.0).

III. Results and Discussion

The non-linear regression equations relating textured yarn crimp stability, crimp contraction, shrinkage force and boiling water shrinkage, and texturing production parameters are given as follows:

$$\text{Boiling water shrinkage} = -12.41708334 + 0.093702778 \times FHT + 7.669194437 \times DY - 0.052025000 \times FHT \times DY + 11.679999994 \times DR - 0.070666667 \times FHT \times DR - 4.880833329 \times DY \times DR + 0.032250000 \times FHT \times DY \times DR \qquad (5)$$

$$\text{Shrinkage force} = -56.02423607 + 0.219178241 \times FHT + 1.675578681 \times DY - 0.007340278 \times FHT \times DY + 47.691435152 \times DR - 0.186875000 \times FHT \times DR - 1.913194431 \times DY \times DR + 0.007291667 \times FHT \times DY \times DR \qquad (6)$$

$$\text{Crimp contraction} = -234.6944723 + 1.388652778 \times FHT + 125.50825003 \times DY - 0.675741667 \times FHT \times DY + 131.89694447 \times DR - 0.753083333 \times FHT \times DR - 75.88750002 \times DY \times DR + 0.410250000 \times FHT \times DY \times DR \qquad (7)$$

$$\text{Crimp stability} = 29.951231506 + 0.227119444 \times FHT + 44.248166653 \times DY - 0.261183333 \times FHT \times DY + 29.359444424 \times DR - 0.117166667 \times FHT \times DR - 31.04083333 \times DY \times DR + 0.172250000 \times FHT \times DY \times DR \qquad (8)$$

The computer code of the program is based on calculation of unknown yarn properties which are dependent variables of known production parameters which are independent variables of the model, as given in Eq. (5)-Eq. (8). Axes of the solution space are first heater temperature, D/Y and Draw ratio while surfaces in the space belong to the yarn properties. If the surfaces generate a closed volume in the space, any point in the closed volume is a solution for the question.The actual results and their standard deviations were given in Table I. These values were obtained from the samples of textured yarn, which were tested in the laboratory by using proper test devices. These values were used to calculate model coefficients by using non-linear regression analysis with respect to model equation.

The R^2 of the non-linear regression equations relating textured yarn crimp stability, crimp contraction, shrinkage force and boiling water shrinkage properties were change in terms of yarn properties type. The R^2 of the non-linear regression equations for crimp stability was 0.68, for crimp contraction was 0.96 for shrinkage force was 0.99 and for boiling water shrinkage was 0.88. As our model includes the effects of interactions of factors, the correlation coefficients between predicted and measured values are very good. Except crimp contraction properties, the rest of three properties can be predicted by using this model due to high value of R^2.

With the help of a regression-based model, we can predict four yarn properties easily and accurately. The ability of the model to estimate the properties of textured PET yarn was tested and all measured values and predicted values given in the Table II. The correlation coefficient (r) was 0.83 for crimp stability, 0.98 for crimp contraction, 0.97 for shrinkage force and 0.90 for boiling water shrinkage. Higher correlation coefficient (r) imply us that the result obtained from computer program by using this model can be acceptable as reliable for crimp contraction, boiling water shrinkage and shrinkage force properties of textured PET yarn, but for crimp stability properties there was a inconvenience for reliability of estimation. In order to increase level of accuracy and reliability of the equations, more samples produced under more different production conditions for calculation coefficients of model equation by non-linear regression analysis.

IV. Conclusion

R^2 values for curves fitted to model equations have been observed to be highly reliable for crimp contraction and shrinkage force being about 0.98. Also the correlation coefficients between actual and predicted values for shrinkage force, crimp contraction and boiling water shrinkage were high being about 0.90. R^2 and r show that the equations are well-suited to predicting textured yarn properties for selected production parameters. This study was limited in that only three texturing parameters of PET yarns were adopted. The yarn properties could be predicted if the other factors are constant. In order to increase level of accuracy and reliability of the equations, it is very important to take into account other texturing parameters.

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