Fibers and Polymers 2015, Vol.16, No.12, 2670-2681
DOI 10.1007/s12221-015-5627-9

ISSN 1229-9197 (print version)
ISSN 1875-0052 (electronic version)

Combining Taguchi Method with Fuzzy Inference on Process Optimization for Fiber Manufacturing

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(Received August 20, 2015; Revised November 18, 2015; Accepted November 22, 2015)

Abstract: Lack of natural textile resources, the present textile industry in Taiwan usually uses pre-oriented yarn (POY), kind of artificial fibers, to make yarns. The POY is wound from continuous spinning of esterification and superposition of plastic pure terephthalic acid (PTA) and ethylene glycol (EG). According to yarn assessment indicators, yarn breakage of POY is crucial. And the broken filament and toughness are the most two important indicators causing yarn breakage during quality measurement. This study applies Taguchi Method to jointly consolidate broken filament degradation rate and toughness elongation percentage to establish a proper orthogonal array. The experimental control factors includes knotting device type, winding tension (CN), oil rate (%), and knotting pressure (kg/cm^2), and a $L_{18}(2^1\times3^7)$ orthogonal array is established. The key parameter design of control factors can be found by Taguchi experiment. The fuzzy inference is combined with Taguchi multiple quality characteristics to construct the process parameter module to effectively increase product yield.

Keywords: Taguchi method, Pre oriented yarn, Multiple quality characteristics index

Introduction

Taiwan's textile industry has developed with changes in industrial structures for over 50 years. Taiwan's textile industry shall implement resource integration and develop towards deepening textile technology and increasing added value of textiles [1]. This study uses Taguchi method to analyze the physical properties of pre-oriented yarn (POY), including broken filament and toughness. The parameter combination of control factors aim to reduce broken filament and increase the toughness. The control factors include knotting device type, winding tension (CN), oil rate (%), and knotting pressure (kg/cm^2). One two-level factor and three three-level factors are set for this study, and a L_{18} $(2^1\times3^7)$ orthogonal array is used to reduce the number of experiments. The optimal level combination of control factors can be determined from the model constructed by the signal to noise (S/N) ratios of broken filaments (Smaller-the-Better) and toughness (Nominal-the-Best). Unlike previous related literature aimed at single quality characteristic through Taguchi method, this study combines Taguchi method and fuzzy theory to consolidate two quality characteristics for analysis.

Taguchi quality engineering was developed and advocated by Dr. Taguchi Genichi in 1950. The orthogonal array experiment design and analysis of variance (ANOVA) were used for the analysis with a limited experimental data to effectively improve product quality. Taguchi method was rapidly popularized in Japan's industrial circle, called quality engineering [1]. The major characteristic of Taguchi method is to obtain useful information with fewer experimental combinations. Not similar to the full factorial design, Taguchi quality engineering cannot determine the exact optimum parameter combinations. However, with efficiency and effectiveness, Taguchi method is more feasible than the full factorial design. Parameter design is the most popular procedure in Taguchi method. It is used to determine the optimal level combination to render the process insensitive to signal interference, and is divided into designs of experiments, implementation and analysis of experiment, and confirmation of experimental results.

Fuzzy inference is also known as multiple logics, and the earliest literature can be traced to Quantum Philosopher, Max Black, in 1937, which inter-element condition was described by vagueness at that time. Prof. Zadeh of the University of California Berkeley published the fuzzy set theory in 1965 for quantizing the fuzzy concept, and fuzzy mathematics was developed rapidly to become a new learning of mathematics [2]. In 2000, Tarng *et al.* used fuzzy logic to convert optimal multiple quality characteristics into a single performance index, combining fuzzy logic with the S/N ratio of the Taguchi method to solve optimization problems with multiple performance characteristics [3]. This method is characterized by using fuzzy logic to convert the S/N ratio into a membership function, which replaces general normalization as the membership function between 0 and 1, and comparisons will not fail because the units of the factors are different [4-7]. This study consolidates Nominal-the-Best and Smaller-the-Better quality characteristics of yarn and proposes a multiple quality characteristics index (MQCI) for solving multiple quality characteristic problems.

Experiment Materials

Pre Oriented Yarn (POY)

Yarn is a continuous compound yarn, formed of a group of fibers bonded together. Some textile materials, such as felt

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*Corresponding author: huangml@ncut.edu.tw fabric and nonwoven fabric, are directly made of fiber; however, most fabrics are made of yarn. Yarns are classified into machine spun yarn and filament yarn, where the difference is fiber length. Machine spun yarn is spun of short fibers, and filament yarn is spun of long fibers. Lack of natural resources, Taiwan does not produce cotton, wool, or silk. The other disadvantage is high labor costs that hinder the development of short fibers. However, with the great artificial fiber throughput and complete industry integration of textile, the long fiber industry in Taiwan is invigorated. Silk is the most representative among natural long fibers, and is applicable to clothing for its good hand feeling, strength, and brightness. It is widely enjoyed and collected, and is the first objective in the long-term study of imitation natural fibers [8].

In 1941, British inventor Whinfield invented polyester fiber, and then European countries and the U.S. began to develop direct spinning machines over 70 years. At present, there are many new technologies for spinning artificial fibers, and the common method in Taiwan is continuous tow conversion, where pure terephthalic acid (PTA) and ethylene glycol (EG) plastic particles are heated, esterified, and superposed, according to customer requirements. Mixed esterified liquid flows through a 48-orifice spinneret, and the continuous long fiber tow is spun directly into yarn by drafting and stretching. It is extended in the draft zone, the tow is elongated by roller, and the traveler burns long fiber tow into yarn. Finally, it is wound by machine as POY. The manufacturing processes of continuous tow conversion are as shown in Figure 1.

Quality Characteristics

The broken filaments and toughness are the most two important indicators causing yarn breakage during quality measurement. The inspection of broken filaments relies on manual appearance inspection. It is inefficient, labor-intensive and expensive. And the major drawback is unlikely to detect broken filaments immediately at high speed production. The online broken filament detection system (FrayteeMv) has been developed for the textile industry to instantly reflect the quality of yarns. The 48 POYs are wound into yarn, and further wound into a spinning cake. The 48 filaments are likely to break during winding process. The broken filaments protruding from the side of the finished spinning cake cause poor product quality. The detection speed of the broken filament detection system is 10ms, and the winding speed is 2000 m/min. The detection length per 10 ms is 0.33 m. This range is detected by infrared, where 4 broken filaments represent Class A, 5-7 broken filaments represent Class B, and more than 8 broken filaments represents defective.

The second important indicator measuring the quality of POY is toughness. The present requirement of POY manufacturers for elasticity of toughness is 4.6±0.3 (g/d). The broken filament degradation rate and toughness elongation percentage are considered to increase product yield for POY filament in this study. The control factors influencing the broken filaments and toughness are determined. They are knotting device type, winding tension (CN), oil rate (%), and knotting pressure (kg/cm^2). This study determines the parameter combination and consolidates two quality characteristics to establish a robust process parameter module to enhance the product quality on POY.

Research Methods

Taguchi Method

The number of experiments increases significantly with the increase of experiment factor in full factorial experiment. The Taguchi method uses an orthogonal array to obtain reliable factorial effect estimates with fewer experiments to simplify the number of experiments. It has been extensively applied in numerous industries. The orthogonal array plays an important role in robust experimental design, and is one of the important tools for engineers to evaluate product performance and process designs. Taguchi method utilizes orthogonal arrays from design of experiments theory to

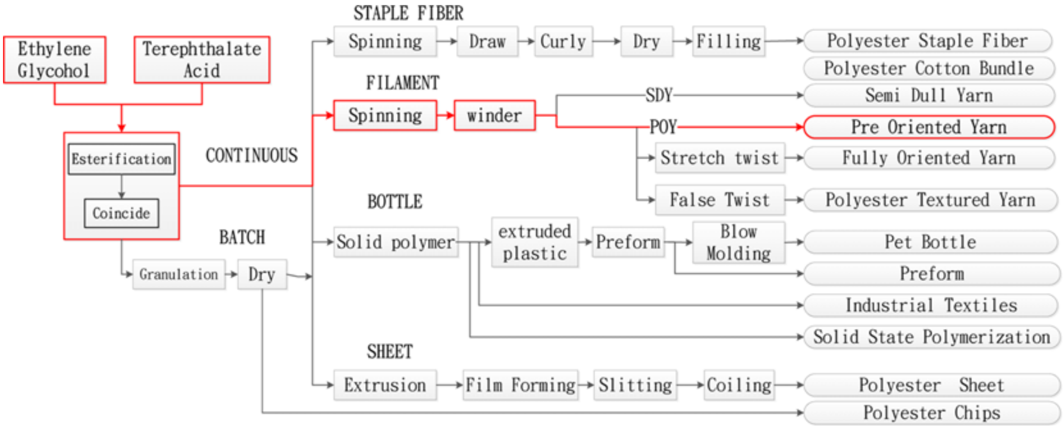

Figure 1. The manufacturing processes of continuous tow conversion.

study a large number of variables with a small number of experiments. It significantly reduces the number of experimental configurations to be studied. Furthermore, the conclusions drawn from small scale experiments are valid over the entire experimental region spanned by the control factors and their settings [9].

Taguchi advocates that quality loss at its minimum when the quality characteristic is consistent with the corresponding target value, and less quality loss represents higher product quality. The relationship between quality loss and quality characteristics shall be discovered to quantize quality loss. Taguchi participated in many communication quality improvement projects in early stages. The signal to noise (S/N) ratio provides a measure of the impact of noise factors on performance. The larger the S/N ratio, the more robust the product is against noise. Parameter design can use S/N ratio to design the optimum combination of factor levels, as well as simultaneous judgment of indicators considers mean value and variance. S/N ratio is designed as three types, Nominal-the-best (NTB), Smaller-the-better (STB), and Larger-the-better (LTB) with respect to quality characteristics.

The production approaches the target is desired, when a target value is given. The ideal production of product quality for NTB quality characteristic is on target. And the formula for NTB quality characteristic is as follows.

$$SN_{NTB} = 10\cdot\log_{10}\left(\frac{\bar{y}^2}{S^2}\right) \tag{1}$$

The smaller response value the better describes the quality for STB quality characteristic. The ideal value for STB is zero, and the formula of S/N ratio is expressed as below.

$$SN_{STB} = -10\cdot\log_{10}(MSD) = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \tag{2}$$

where MSD is mean square deviation.

On the contrary to STB, the larger response value the better describes the quality for LTB quality characteristic. The ideal value for LTB is infinity, and the formula of S/N ratio is described as below.

$$SN_{LTB} = -10\cdot\log_{10}(MSD) = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \tag{3}$$

Analysis of Variance (ANOVA) is applied to evaluate the experimental result. The interaction effect was treated as partial experimental errors in Taguchi method. When factor effect is statistically different to experimental error, this factor is treated as significant or vital in the experiment. The significant level of each factor effect is calculated based on experimental error, and those statistically significant factor effects will be selected to predict the best response of quality characteristic. Moreover, *F*-test is used to investigate the significant level of each factor effect in ANOVA. Larger *F*-value represents higher factor effect as compared to experimental error or interaction effect. An important step in Taguchi's optimization technique is to conduct confirmation experiments for validating the predicted results. Thus a 95 % confidence interval (CI_1) for the best prediction of S/N ratio and a 95 % confidence interval (CI_2) for the expected estimate of confirmation experiment are shown as [10]:

$$CI_1 = \pm\sqrt{F_{\alpha;1,v_2}\times V_e\times\frac{1}{n_{eff}}} \tag{4}$$

$$CI_2 = \sqrt{F_{\alpha;1,12}\times V_e\times\left[\frac{1}{n_{eff}}+\frac{1}{r}\right]} \tag{5}$$

where $F_{\alpha;1,v_2}$ is the F value from the F table for factor DOF and error DOF at the confidence level desired, V_e the variance of the error term (ANOVA), n_{eff} is the effective number of replications, and r is number of replications for confirmation experiment.

Fuzzy Theory

The fuzzy theory has been extensively used for uncertain or inaccurate data in many scientific and engineering domains for solving complex problems. The first step is to build a model and use it to analyze problems and forecast the response. There are two types of modeling methods: (1) if the problem can be known from physical characteristics, relevant physical equations can be used for modeling; (2) if some problems are too complex to be expressed as physical equations, the black box can be used for modeling, as shown in Figure 2. In other words, the data are collected first, and then the appropriate model is selected from the given specific mathematical models according to the approximate characteristics of the problem, and relevant parameters are estimated using system identification technology [11].

The fuzzy theory is generally established according to expertise or training samples, where each "IF~THEN" control law describes a condition statement. "IF" is a precondition, which is used for judging whether or not this statement is tenable in the condition; "THEN" is the conclusion part, which presents a matched condition result. The fuzzy inference rule base is described as follows [12]:

"**IF** (x is A_i and y is B_i) **Then**(z is C_i)" (6)

In a crisp set, the relationships of elements in the domain

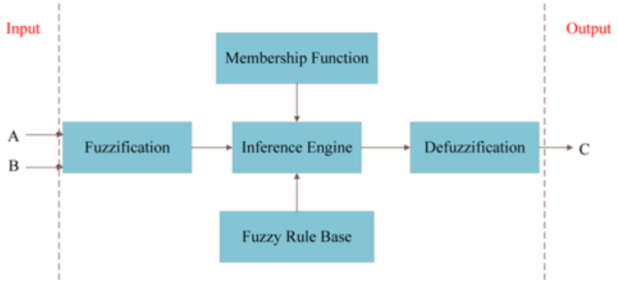

Figure 2. Fuzzy inference system.

to a set are merely "belong to" and "not belong to", i.e.:

$$\lambda_A(x) = \begin{cases} 0, & x \notin A \\ 1, & x \in A \end{cases} \tag{7}$$

There is no specific boundary in a fuzzy set, as the relationship of elements to the set is given by the membership grade value according to the similarity. The fuzzy set range is 0 to 1, and is defined, as follows:

$$\tilde{A} = \{[x, \mu_{\tilde{A}}(x)] | x \in X\} \tag{8}$$

Generally, the membership functions are divided into Gaussian types, also known as bell-shaped membership function, trapezoidal membership function, and triangular membership function. The surface of the bell-shaped membership function is smooth, and with better nonlinear characteristics. The triangular membership function and trapezoidal membership function require less amounts of computer calculation, and is applicable to real-time system responses. The triangular membership function is widely used, and the fuzzy set is defined, as follows:

$$\mu_{\tilde{A}}(x) = \begin{cases} 0, & x < a \\ \dfrac{x-a}{b-a}, & a \le x \le b \\ \dfrac{c-x}{c-b}, & b \le x \le c \\ 0, & x > c \end{cases} \tag{9}$$

The triangular curve is a function of a vector, *x*, and depends on three scalar parameters *a*, *b*, and *c*, where the parameters a and c locate the "feet" of the triangle and the parameter b locates the peak.

Defuzzification is the process of converting the conclusion from the fuzzy inference of a fuzzy set into a definite value. Defuzzification is divided into center of gravity defuzzifier and mean of maximum, where the common method is the center of gravity defuzzifier. When the domain is continuous, and the domain of the output membership function is within intervals of *a* to *b*, the center of gravity defuzzifier can be expressed, as follows:

$$y_{coa} = \frac{\int_a^b C(y) y dy}{\int_a^b C(y) dy} \tag{10}$$

For a discrete domain, if the domain of the output membership function lies in intervals (y_L, y_R), and the interval is divided into *q* parts, the center of gravity defuzzifier can be expressed as follows.

$$y_{coa} = \frac{\sum_{j=1}^{q} y_j C(y_j)}{\sum_{j=1}^{q} C(y_j)} \tag{11}$$

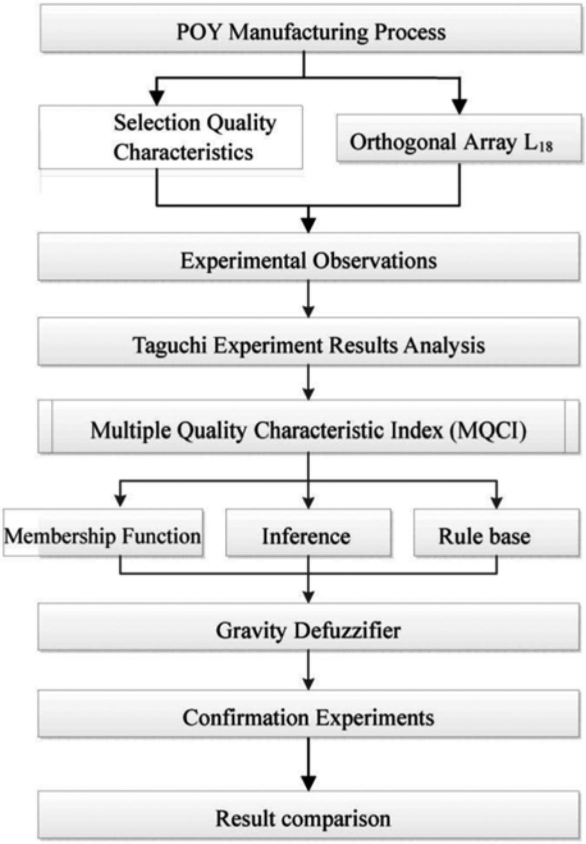

Figure 3. Research framework.

The Research Framework

The POY manufacturing data are collected to realize the quality level of the present process. Select one product type with the lowest product quality, and determine the essential control factors effecting product quality for the product. Decide factor levels and choose a proper orthogonal array for experiment. Collect experimental observations and perform data analysis for single quality characteristics. Combine the S/N ratios for all quality characteristics, and redo the data analysis. In addition, apply fuzzy inference on the treatment of multiple quality characteristics. Evaluate the parameter settings through confirmation experiments. The research framework and experiment process are shown in Figure 3.

Taguchi Experiment Planning

The studied POY manufacturing company is located in Taiwan, and it produces several types of POY. This study optimizes a robust parameter design for POY to improve quality and increase productivity. Product type FP6163X was selected as the first priority to be improved since the yield was the lowest among the all. Four control factors are set according to the process, including one 2-level factor and

Table 1. Production settings for control factors

	Factors	Level 1	Level 2	Level 3
T	Knotting device type	A	B	-
W	Winding tension (CN)	18	20	22
O	Oil rate (%)	0.6	0.8	1
P	Knotting pressure (kg/cm^2)	0.8	1.2	1.6

three 3-level factors. The sample control factors and levels are as shown in Table 1. A $\boldsymbol{L}_{18}(2^1\times3^9)$ orthogonal array is used with three replication for each parameter combination. The 54 experimental results of broken filament and toughness data of POY are collected in Table 2.

Taguchi Experimental Results

The Taguchi parameter design converts experimental observations into S/N ratio. The ideal quality for POY is without any broken filament, and the STB characteristic of Eq. (2) is adopted. The MINITAB 16 computer software is used to calculate experimental response and S/N ratio, as shown in Table 2.

$$SN_{STB} = -10\cdot\log_{10}(MSD) = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right)$$

$$= -10\cdot\log_{10}\frac{1}{3}\times[11^2+10^2+7^2] \cong -19.5424$$

The main factor effect, ANOVA and response figure are displayed in Table 3, 4, and Figure 4. The main effect for factor W (winding tension), for example, at level 1, 2 and 3 are -15.77, -14.22 and -12.96, respectively. The effect from control factor O (Oil rate) is the largest as compared to the rest of the control factors (shown in Table 3). A plot of the S/N average results would be easier for level selection. From Figure 4, the best combination of control factors would become $T_1W_3O_3P_2$, namely, T_1=A (type), W_3=22(CN), O_3= 1 (%) and P_2=1.2 (kg/cm^2).

ANOVA is applied to realize the significance and percent contribution of each control factor. From Table 4, obviously, factor T (Knotting device type) and O (oil rate) are significant and the percent contributions are 15.178 % and 61.251 %, respectively.

The final step of Taguchi method is to conduct the confirmation experiment, and this is the key step among the whole process. The purpose of confirmation experiment is to

Table 3. Average S/N ratios of each level of control factors for broken filament

Level	T	W	O	P
1	-12.68	-15.77	-19.7	-14.3
2	-16.46	-14.22	-12.97	-13.76
3		-12.96	-11.03	-15.64
Difference	3.78	2.06	8.67	1.87
Rank	2	3	1	4

Table 2. Experiment responses and S/N ratios for broken filament

No.	Factors				Broken filament			S/N ratio
	Knotting type	Winding tension (CN)	Oil rate (%)	Knotting pressure (kg/cm^2)	1	2	3	
1	A	18	0.6	0.8	11	10	7	-19.5424
2	A	18	0.8	1.2	5	4	4	-11.7609
3	A	18	1	1.6	5	5	3	-12.9373
4	A	20	0.6	0.8	11	9	8	-19.4776
5	A	20	0.8	1.2	3	2	2	-7.53328
6	A	20	1	1.6	3	2	2	-7.53328
7	A	22	0.6	1.2	8	5	6	-16.1979
8	A	22	0.8	1.6	5	3	3	-11.5635
9	A	22	1	0.8	2	2	3	-7.53328
10	B	18	0.6	1.6	11	12	9	-20.6195
11	B	18	0.8	0.8	7	4	4	-14.3136
12	B	18	1	1.2	8	5	4	-15.4407
13	B	20	0.6	1.2	11	10	10	-20.2938
14	B	20	0.8	1.6	6	12	8	-19.1027
15	B	20	1	0.8	4	4	3	-11.3566
16	B	22	0.6	1.6	12	13	13	-22.0593
17	B	22	0.8	0.8	6	4	4	-13.5539
18	B	22	1	1.2	3	4	4	-11.3566

Table 4. ANOVA including percent contribution for broken filament

Source	V	SS	MS	F	SS’	ρ(%)
T	1	64.290	64.290	11.947*	58.909	15.178
W	2	13.810	6.905	-	-	-
O	2	248.49	124.245	23.088*	237.727	61.251
P	2	11.170	5.585	-	-	-
Residual error	10	50.360	5.036	-	-	-
Pooled error	(14)	(75.34)	(5.381)		91.484	23.571
Total	17	388.12			388.12	100.00

*Significant at 95 % confidence interval.

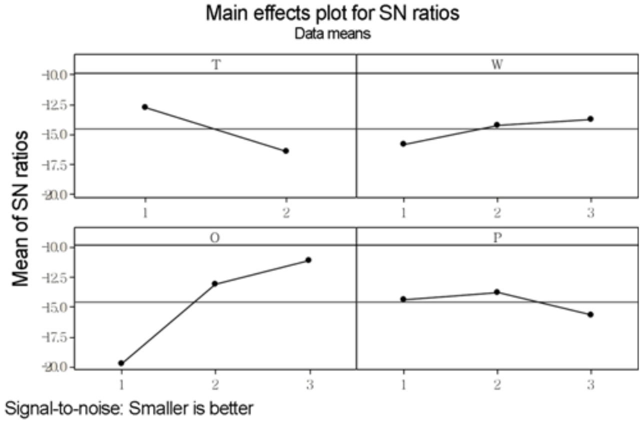

Figure 4. Response plots for control factors.

verify the feasibility from the experimental results. The experiment fails when confirmation experiment observations are apart from expectation. The confidence intervals are constructed to effectively evaluate observations.

The average S/N ratio for 18 experimental results is $\overline{\eta}$= -14.565, and the estimated average results when the two significant control factors T (Knotting device type) and O (Oil rate) are at their best levels is

$$\hat{\eta} = \overline{\eta} + (\overline{T}_1 - \overline{\eta}_1) + (\overline{O}_3 - \overline{\eta}) = -14.565 + (1.885) + (3.535)$$
$$-9.145$$

The upper and lower limits of estimated performance at the optimum condition at the 95 % confident interval are found as follows:

Table 5. The responses and S/N ratios for toughness

No.	Factors				Toughness observation			S/N ratio
	Knotting type	Winding tension (CN)	Oil rate (%)	Knotting pressure (kg/cm^2)	1	2	3	
1	A	18	0.6	0.8	4.9	5.1	4.5	23.985
2	A	18	0.8	1.2	5.2	5.3	4.9	27.840
3	A	18	1	1.6	4.7	4.8	4.4	26.950
4	A	20	0.6	0.8	4.3	4.1	3.9	26.235
5	A	20	0.8	1.2	3.9	3.7	3.9	30.422
6	A	20	1	1.6	4.6	4.2	4.4	26.848
7	A	22	0.6	1.2	4.9	4.8	4	19.330
8	A	22	0.8	1.6	5.1	5.4	5.6	26.578
9	A	22	1	0.8	4.5	4.6	4.1	24.418
10	B	18	0.6	1.6	3.5	3.7	3.6	31.126
11	B	18	0.8	0.8	4.7	4.9	5	30.065
12	B	18	1	1.2	5.8	5.5	5.2	25.265
13	B	20	0.6	1.2	5.4	5.5	4.9	24.288
14	B	20	0.8	1.6	3.6	3.9	4.2	22.279
15	B	20	1	0.8	4.3	4.5	4.7	27.044
16	B	22	0.6	1.6	4.9	4.8	5.1	30.183
17	B	22	0.8	0.8	4.6	4.9	5.1	25.728
18	B	22	1	1.2	3.9	4	4.2	28.434

$$[\hat{\eta} \pm CI_1] = \left[-9.145 \pm \sqrt{4.60 \times 5.381 \times \frac{4}{18}}\right]$$
$$= [-9.145 \pm 2.345] = [-11.490, -6.800]$$

$$[\hat{\eta} \pm CI_2] = \left[-9.145 \pm \sqrt{4.60 \times 5.381 \times \left(\frac{4}{18} + \frac{1}{3}\right)}\right]$$
$$= [-9.145 \pm 3.708] = [-12.952, -5.338]$$

The 2nd stage of this study is to improve the toughness elongation for POY, and the nominal value for toughness is set at 4.6±0.3. The average and standard deviation are 4.833 and 0.306, respectively, based on $\boldsymbol{L}_{18}(2^1 \times 3^3)$ experiment. These results are shown in Table 5. And the S/N ratios are calculated as follows.

$$SN_{STB} = -10 \cdot \log_{10}\left(\frac{\overline{Y}^2}{S^2}\right) = -10 \cdot \log_{10}\left[\frac{4.833^2}{0.306^2}\right] \cong 23.985$$

The main effect is listed in Table 6, and the largest main effect is from control factor W (winding tension). The response plot is as shown in Figure 5.

Table 6. Average S/N ratios for each level of factor for toughness

Level	T	W	O	P
1	25.85	27.54	25.86	26.25
2	27.16	26.19	27.15	25.93
3	-	25.78	26.49	27.33
Difference	1.31	1.76	1.29	1.4
Rank	3	1	4	2

The best combination for this experiment is $T_2W_1O_2P_3$, which is T_2=B (type), W_1=18 (CN), O_2=0.8 (%) and P_3=1.6 (kg/cm^2). The average of 18 S/N ratios is $\overline{\eta}$=26.501, and the best prediction value is $\hat{\eta} = \overline{\eta} + (\overline{T}_2 - \overline{\eta}) + (\overline{W}_1 - \overline{\eta}) + (\overline{P}_3 - \overline{\eta})$ =28.435. Considering the significant control factors T, W, and P, the best predicted value for toughness will be 28.435, and the corresponding confidence interval becomes [26.9456, 29.9244]. The 95 % confidence interval for the confirmation experiment is [26.329, 30.541]. From Table 7, obviously, factor T (Knotting device type) and W (Winding Tension) are significant and the percent contributions are 15.39 % and 17.919 %, respectively.

When single quality characteristic is considered, the best combinations for broken filament and toughness are $T_1W_3O_3P_2$

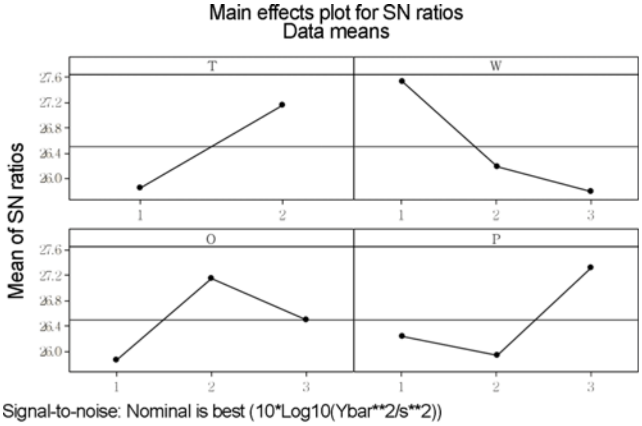

Figure 5. Main effects for S/N ratio of toughness quality characteristic.

Table 7. ANOVA for toughness quality characteristic

Source	V	SS	MS	F	SS'	ρ(%)
T	1	7.743	7.743	5.527*	6.342	15.400
W	2	10.183	5.092	3.635*	7.380	17.918
O	2	5.026	2.513	-	-	-
P	2	6.445	3.223	2.300	3.642	8.843
Residual error	10	11.790	1.179	-	-	-
Pooled error	(12)	(16.816)	(1.401)		23.823	57.841
Total	17	41.187			41.187	100.00

*Significant at 95 % confidence interval.

Table 8. Optimum values of factors and their levels for broken filament and toughness

Factors			Broken filament	Toughness
Quality characteristic			STB	NTB
Selection of experiment factors	T	Knotting type	A (TYPE)	B (TYPE)
	W	Winding tension	22 (CN)	18 (CN)
	O	Oil rate	1 (%)	0.8 (%)
	P	Knotting pressure	1.2 (kg/cm^2)	1.6 (kg/cm^2)
Impact			O>T>W>P	W>P>T>O

Table 9. Merged S/N ratios for broken filament and toughness

NO.	Observations								Merged
	Broken filament				Toughness				
	1	2	3	SN	1	2	3	SN	
1	11	10	7	-19.54	4.9	5.1	4.5	23.985	4.44
2	5	4	2	-11.76	5.2	5.3	4.9	27.840	16.08
3	5	5	3	-12.94	4.7	4.8	4.4	26.950	14.01
4	11	9	8	-19.48	4.3	4.1	3.9	26.235	6.76
5	3	2	2	-7.53	3.9	3.7	3.9	30.422	22.89
6	3	2	2	-7.53	4.6	4.2	4.4	26.848	19.32
7	8	5	6	-16.20	4.9	4.8	4.0	19.330	3.13
8	5	3	3	-11.56	5.1	5.4	5.6	26.578	15.01
9	2	2	3	-7.53	4.5	4.6	4.1	24.418	16.88
10	11	12	9	-20.62	3.5	3.7	3.6	31.126	10.51
11	7	4	4	-14.31	4.7	4.9	5.0	30.065	15.75
12	8	5	4	-15.44	5.8	5.5	5.2	25.265	9.82
13	11	10	10	-20.29	5.4	5.5	4.9	24.288	3.99
14	6	12	8	-19.10	3.6	3.9	4.2	22.279	3.18
15	4	4	3	-11.36	4.3	4.5	4.7	27.044	15.69
16	12	13	13	-22.06	4.9	4.8	5.1	30.183	8.12
17	6	4	4	-13.55	4.6	4.9	5.1	25.728	12.17
18	3	4	4	-11.36	3.9	4.0	4.2	28.424	17.08

Table 10. Average merged S/N ratios of each factor

Level	T	W	O	P
1	-0.02	-1.71	-6.93	-1.28
2	-2.49	-0.72	0.88	-1.24
3		-1.33	2.29	-1.23
Difference	2.47	1.00	9.23	0.04
Rank	2	3	1	4

and $T_2W_1O_2P_3$, respectively (shown in Table 8). Apparently, they are inconsistent. The best combination for simultaneously considering both broken filament and toughness will become $T_1W_2O_3P_3$ (shown in Table 9-11, Figure 6), namely, T_1=A (type), W_2=20 (CN), O_3=1 (%) and P_3=1.6 (kg/cm^2).

Two effective control factors T (Knotting device type) and O (Oil rate) are considered, and the best predicted S/N ratio is 16.704. The 95 % confidence interval for the best prediction of S/N ratio will be [16.704±4.470]=[12.234, 21.174].

$$CI_1 = \sqrt{F_{\alpha;1,14} \times V_e \times \left[\frac{1}{n_{eff}}\right]} = \sqrt{4.60 \times 19.546 \times \frac{4}{18}} = 4.470$$

And the 95 % confidence interval for the confirmation experiment will become [16.704±7.068]=[9.64, 23.771].

$$CI_2 = \sqrt{F_{\alpha;1,14} \times V_e \times \left[\frac{1}{n_{eff}} + \frac{1}{r}\right]} = \sqrt{4.60 \times 19.546 \times \left[\frac{4}{18} + \frac{1}{3}\right]}$$

$=7.068$

Table 11. ANOVA for multiple characteristics

Source	V	SS	MS	F	SS'	ρ (%)
T	1	27.408	27.408	1.404	7.882	1.30
W	2	0.278	0.139	-	-	-
O	2	305.241	152.620	7.816*	266.189	43.90
P	2	0.677	0.339	-	-	-
Residual error	10	272.689	27.269	-	-	-
Pooled error	(14)	(273.644)	(19.546)		332.282	54.81
Total	17	606.293			606.293	100.00

*Significant at 95 % confidence interval.

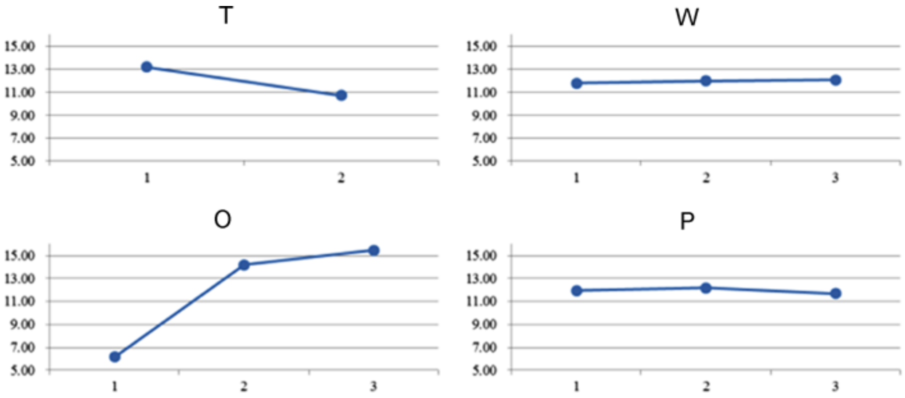

Figure 6. Main Effects for S/N ratio of multiple characteristics.

Table 12. Confirmation experiments

No.	T	W	O	P	Broken filament				Toughness				Merged
					1	2	3	SN	1	2	3	SN	
1	1	2	3	3	3	1	2	-6.6901	4.8	4.2	4.5	23.5218	16.8317
2	1	2	3	3	1	2	1	-3.0103	4.6	4.8	4.5	26.9500	23.9397
3	1	2	3	3	2	2	1	-4.7712	4.3	4.6	4.2	26.4335	21.6623
Average of SN					-4.824				25.635				20.811

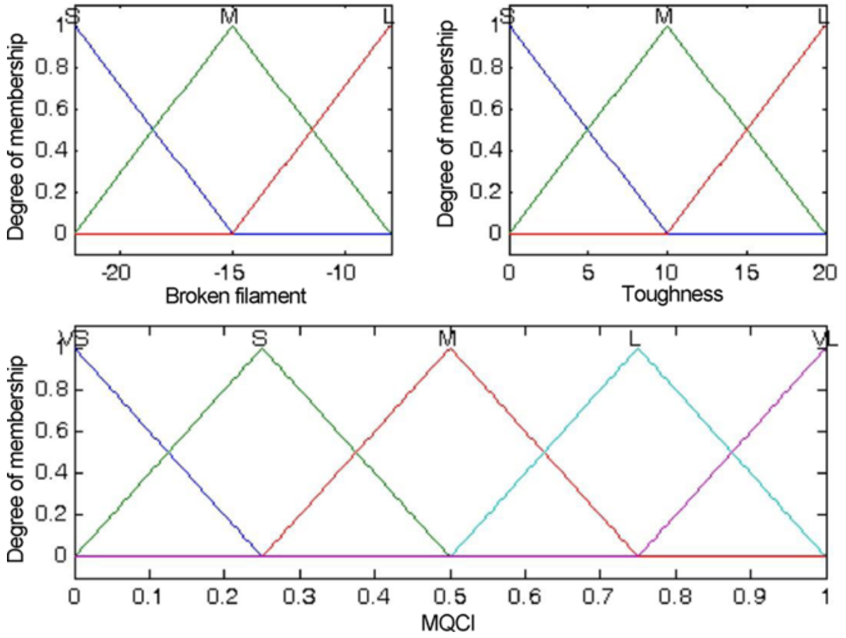

Figure 7. Membership functions for broken filament, toughness and MQCI.

The 95 % confidence intervals of the confirmation experiment for broken filament, toughness, and multi-characteristic are [-12.952, -5.338], [26.329, 30.541], and [9.640, 23.774], respectively. Three confirmation experiments are conducted in this study. All the experimental results are within the confidence intervals for broken filament and toughness as shown in Table 12.

Fuzzy Inference Experiment

In the process of fuzzy inference, the S/N ratios of various experimental combinations are used as input, the membership function is fuzzified as an appropriate semantic value, and the fuzzy rule base and fuzzy inference engine are used for synthetic operations. Finally, the fuzzy inference result is converted into a specific output value, called a multiple quality characteristic index (MQCI).

The function of a fuzzifier is to convert specific external input data into appropriate semantic fuzzy information. This study uses S/N ratios of broken filaments and toughness as the input variables of the fuzzy logic system, and generates MQCI value as the output variable (Figure 7). The triangular membership function is used for semantic fuzzy segmentation of input variables, as shown in Figure 7. The two input variables are equally divided into three fuzzy levels, large (L), medium (M), and small (S), respectively.

The theory of fuzzy logic is based upon the notion of relative graded membership and so are the functions of mentation and cognitive processes. Fuzzy sets form the building blocks for fuzzy IF-THEN rules which have the general form “IF X is A THEN Y is B” , where A and B are fuzzy sets. The most important two types of fuzzy inference method are Mamdani’s fuzzy inference method, which is the most commonly seen inference method. Fuzzy rule base is composed of IF-Then fuzzy rules, representing the logic relationship between input and output. For example,

Rule 1: **IF** (x is A_1 and y is B_1) **THEN** z is C_1
Rule 2: **IF** (x is A_2 and y is B_2) **THEN** z is C_2

The triangular membership function is used again for semantic fuzzy segmentation of output variables, and the output variables are equally divided into five fuzzy levels, very large (VL), large (L), medium (M), small (S), and very small (VS), respectively. Nine fuzzy rules are proposed to equally consider broken filament and toughness as listed in Table 13.

Table 13. Nine fuzzy rules based on multi-characteristic POY

MQCI		S/N of toughness		
		S	M	L
S/N of broken filament	S	VS	S	M
	M	S	M	L
	L	M	L	VL

Table 14. Multiple quality characteristic indices

No.	Broken filament	Toughness	MQCI
1	0.391	0.488	0.322
2	0.543	0.549	0.605
3	0.517	0.522	0.569
4	0.394	0.508	0.382
5	0.837	0.727	0.844
6	0.837	0.512	0.752
7	0.49	0.163	0.243
8	0.549	0.514	0.551
9	0.837	0.495	0.678
10	0.323	0.836	0.558
11	0.501	0.688	0.615
12	0.498	0.5	0.393
13	0.347	0.493	0.298
14	0.412	0.438	0.333
15	0.555	0.524	0.618
16	0.163	0.7	0.365
17	0.508	0.502	0.49
18	0.555	0.574	0.645

Table 15. Average S/N Ratios for each level of factor for MQCI

Level	T	W	O	P
1	0.534	0.51	0.361	0.518
2	0.624	0.538	0.573	0.504
3	-	0.495	0.609	0.521
Difference	0.09	0.043	0.248	0.017
Rank	3	2	1	4

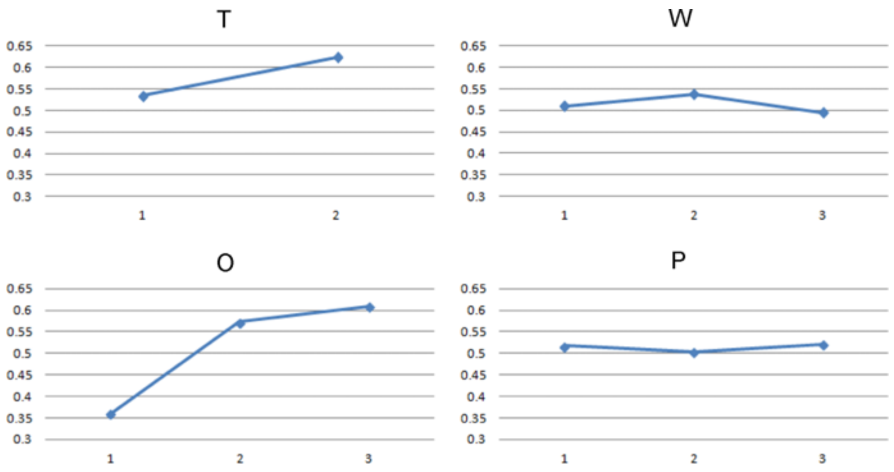

Figure 8. The main effect plots of MQCI.

The multiple quality characteristic indices calculated through Eq. (11) in Sec. Fuzzy Theory were listed in Table 14.

Table 15 and Figure 8 display the effects of control factors for MQCI, and results show that the most significant effect comes from factor O (oil rate). The analysis of variance (ANOVA) is also performed to study the relative significance of the process parameters. Table 16 shows the computed results of the ANOVA with 95 % confidence.

The best parameter combination of MQCI is $T_2W_2O_3P_3$, and the average for MQCI is $\bar{\eta} = 0.5145$. The two significant factors T (Knotting device type) and O (Oil rate) are used to estimate the expected S/N ratios for broken filament, toughness, and MPCI as $\hat{\eta}_{BrokenFilament}=-12.925$, $\hat{\eta}_{Toughness}=27.149$, and $\hat{\eta}_{MPCI}=0.6325$. The 95 % confidence interval for the confirmation experiment will be [0.419, 0.847]. These results are shown in Table 17.

The MQCI combines broken filament (STB type) and toughness (NTB type), and results show that the best parameter setting is $T_2W_2O_3P_3$, which is T_2=B (type), W_2=20 (CN), O_3=1 (%), and P_3=1.6 (kg/cm^2). Three confirmation experiments were performed to verify the feasibility of the finding parameter settings. All of the three MQCI from confirmation experiments are with the confidence interval, which means that the experiment is successful. The parameter combination is robust in this study.

Table 18 summaries the S/N ratios of quality performances from original setting, Taguchi method, and fuzzy inference for single and multiple quality characteristics. (1) The S/N ratios for single quality characteristics broken filament and toughness are -19.542 and 23.985 with the original parameter combination $T_1W_1O_1P_1$. (2) The best prediction of S/N ratios for single quality characteristics broken filament and toughness are -7.515 (parameter combination $T_1W_3O_3P_2$) and 28.435 (parameter combination $T_2W_1O_2P_3$), respectively, from Taguchi method. (3) Combining the two quality characteristics, the best S/N ratios are -4.824, 25.635, and 20.811 for broken filament, toughness, and multiple characteristics with parameter setting T_1 $W_2O_3P_3$ from Taguchi method. (4) The best results of the S/N ratios dominating the all are -2.007, 28.397, and 26.391 for broken filament, toughness, and multiple characteristics with parameter setting $T_2W_2O_3P_3$ when combining Taguchi method and fuzzy inference. The larger S/N ratio means the better product quality. The optimal parameter combination is $T_2W_2O_3P_3$, which is T_2 =B (type), W_2 =20 (CN), O_3 =1 (%), and P_3 =1.6 (kg/cm^2).

Table 16. ANOVA of MQCI

Source	V	SS	MS	F	SS'	ρ (%)
T	1	0.022	0.022	1.236	0.004	0.862
W	2	0.005	0.002	-	-	-
O	2	0.212	0.106	5.933*	0.177	36.057
P	2	-0.002	-0.001	-	-	-
Residual error	10	0.253	0.025	-	-	-
Pooled error	(14)	(0.251)	(0.018)		0.309	63.082
Total	17	0.490			0.490	100.00

*Significant at 95 % confidence interval.

Table 17. Confirmation experiments for MQCI

No.	T	W	O	P	Broken filament				Toughness				MQCI
					1	2	3	SN	1	2	3	SN	
1	2	2	3	3	2	2	1	-4.7712	4.5	4.8	4.8	28.671	0.429
2	2	2	3	3	1	2	1	-3.0103	4.9	4.6	4.6	27.0111	0.507
3	2	2	3	3	1	1	0	1.7609	4.6	4.7	4.4	29.5102	0.787
Average of SN					-2.007				28.397				0.574

Table 18. Result comparison

	Optimal combination	SN of broken filament	SN of toughness	MQCI
Initial combination	$T_1W_1O_1P_1$	-19.542	23.985	-
Taguchi: Broken filament	$T_1W_3O_3P_2$	-9.145	-	-
Taguchi: Toughness	$T_2W_1O_2P_3$	-	28.435	-
Taguchi: MQCI	$T_1W_2O_3P_3$	-4.824	25.635	20.811
Taguchi-Fuzzy: MQCI	$T_2W_2O_3P_3$	-2.007	28.397	26.391

Conclusion

The quality performances of parameter combination from (1) the original setting, (2) Taguchi method, and (3) Taguchi with fuzzy inference for single and multiple quality characteristics of pre-oriented yarn FP6163X are discussed in this study. Taguchi method consolidates four control factors including knotting device type, winding tension (CN), oil rate (%), and knotting pressure (kg/cm^2), and a $L_{18}(2^1\times3^7)$ orthogonal array is established to dramatically reduce the number of experiments. The combination of Taguchi method and fuzzy theory is proven to optimize the S/N ratio of process parameter combinations for pre-oriented yarn FP6163X. The methodology used in this research demonstrates a good example for manufacturer to effectively and efficiently improve product quality, and could be further applied on other product.

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