An Investigation into the Fatigue Behavior of Core-Spun Yarns under Cyclic Tensile Loading

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ABSTRACT

In this research, the effects of different production parameters and number of tensile fatigue cyclic loads on the breaking strength of core-spun yarns before and after tensile fatigue cyclic loads were studied using Taguchi's experimental design. A custom-built instrument for evaluating the tensile fatigue of fibrous materials under cyclic loads was used in this study. Based on the Taguchi method 18 samples were manufactured. Polyester and nylon multifilament yarn and three kinds of sheath material, namely, polyester/cotton (80/20), polyester, and viscose fiber were used. Fatigue behavior of core-spun yarns was evaluated after 100, 500 and 1000 cyclic loads. English twist factors (α_e) 3.2, 3.5, and 3.8 were applied to core-spun yarns and core pre-tensions of 0, 30, and 60g.were used. Experimental results show a reduction and, in some cases, an increase in breaking strength after cyclic loading. A microtome technique was used to evaluate the cross-section of the yarns. Twist factor was found to be the dominant effect on the fatigue value of core-spun yarns after cyclic loads. The results also show that the ranking of effective parameters on breaking strength vary before and after cyclic loads.

INTRODUCTION

Core-spun yarns are structures consisting of two component fibers, one of which forms the core of the yarn, and the other sheath or covering. Mostly, the core is a continuous monofilament or multifilament yarn, while staple fibers are used for the sheath of the yarn [1]. Core-spun yarns have been produced successfully by many spinning systems such as ring, rotor, friction, and air-jet. These yarns have been used to improve the strength, aesthetic, durability and functional properties of fabrics [1]. The application of core-spun yarns in the textile industry is very versatile. In these yarns, the sheath part causes surface physical and aesthetic properties, while the core part affects the mechanical properties of yarn and improves yarn strength and permits the use of lower twist levels [1, 2].

Many studies were managed to optimize and evaluate the physical and mechanical properties of core spun yarns and fabrics. In Some research, physical and mechanical properties of cotton-covered nylon core spun yarns and fabrics were studied [3-5]. Ruppenicker et al. [6] compared physical and mechanical properties of Cotton/Polyester Core and Staple Blend Yarns and Fabrics. Ghareaghaji et al. [7] proposed an artificial neural network model to predict the tensile properties of cotton-covered nylon core spun yarns. Pourahmad et al. [8] tried to reduce the slip-back phenomenon of core-spun yarns by presenting a three-strand modified method, which employed three strands of sheath fibers and three core filaments on a modified ring spinning frame. The influence of spinning parameters on sheath slippage of core-spun yarn was studied by Miao et al. [2]. Properties of cotton covered-polyester core-spun yarns and fabrics were compared with all-cotton and intimate staple blended yarns and fabrics by Harper et al. [9]. Physical and mechanical properties of cotton covered polypropylene core-spun yarns and fabrics were evaluated by Ziaee et al. [10].

Fatigue may be defined as the failure of material after repeated stressing at a level less than that needed to cause failure in a single application of stress. Three models of cyclic tensile loading that are used for textile materials have been proposed by Hearle et al. [11]. Yarns are often required to support tensile cyclic loads during different applications. This repeated loading affects the mechanical properties of the yarns, which may cause decay or even fail. Fatigue research allows measuring the strength properties of prepared specimens or of final goods related to the impact of loads originating in repeated changeable forces. Thus, this phenomenon is important during applications of textile yarns.

Lyons and Dusan studied fatigue behavior of fibers and fibrous materials in different conditions [12-15]. Hearle and Wong [16] studied fatigue properties of nylon 6.6, polyester, and polypropylene fibers. The fatigue life of open-end, ring spun, and siro spun yarns using the technique of biaxial rotation over a pin were studied by Subramaniam et al. [17]. Fatigue behavior of warp yarn under cyclical elongation accompanied by abrasion action was studied by Anandjiwala et al. [18] on the basis of failure, damage rate, and visual appearance. The fatigue behavior of technical polyamide 66 fibers was studied by Nasri and Lallam [19]. They studied the structural and viscoelastic properties and loading criteria for fatigue failure was identified. Asayesh et al. [20] modeled fatigue behavior of textured polyester woven fabrics.

This paper focuses on the effect of different production parameters and the number of tensile fatigue cyclic loads on the breaking strength of core-spun yarns after cyclic tensile fatigue loads. Taguchi's experimental design was used to analyze the effect core and sheath composition, core pre-tension, twist, and number of cyclic loads on breaking strength. The optimum spinning conditions were determined through the experimental design. To evaluate this phenomenon precisely, the Taguchi's experimental design was also applied on breaking the strength of core spun yarns before cyclic loading. A microtome technique was used to asses the cross-section of the core-spun yarns.

MATERIALS AND METODS

Core-Spun Yarn Production Method

The method proposed by Sawhney et al. [3] was used to produce core-spun yarns. A schematic illustration of spinning process is shown in *Figure 1*. A conventional ring spinning frame with a double apron drafting system was modified to accommodate packages of core yarns. The 100/36f den polyester and nylon multifilament yarns, which were used as core part, were fed from the cone through an adjustable tensioning device to the front rolls of the drafting system. Polyester/cotton (80/20), polyester, and viscose fiber rovings were used to form the sheath part of 12Ne count. Mechanical properties of three fibers used are presented in *Table I*. The cut length of polyester and viscose fiber was 38mm and the mean length of cotton fiber was 23.21mm. *Table II* shows production parameters of core-spun yarns. According to *Table II*, the twist values of core-spun yarns and pre-tension on core part were selected in three levels.

TABLE I. Physical properties of used fiber as sheath part.

	Fineness (dtex)	Tenacity (g/den)	Strain (%)
Polyester	1.60	4.80	25.2
Viscose	1.60	2.70	20.4
Cotton	1.69	2.90	7.1

Fatigue Test Setup

A custom-built instrument for evaluating tensile fatigue of fibrous materials under cyclic loads was used in this study. The structure of this instrument is shown in *Figure 2*. This apparatus was designed in a way that can control the number of cyclic loads, the rate of elongation, and the loading frequency. It had been designed for fatiguing samples in accordance with the first and second method of cyclic loading proposed by Hearle et al. [11]. The schematic design of instrument is presented in *Figure 3*.

The inverter (4) which controls the speed of motor (5) determines the frequency of cyclic loading. Each sample is clamped by two jaws, one fixed (clamp (1)) and the other movable (clamp (2)). The rate of elongation, which is accordance to the rate of movement of the movable clamp, is controlled by position sensor (3-a), and the initial length of samples is determined by the position sensor (3-b). In other words, these sensors control the cyclic motion of movable clamp in such a way that when it reaches each sensor, the direction of movement is reversed. The movable and fix clamps are mounted on two parallel rail bars [21].

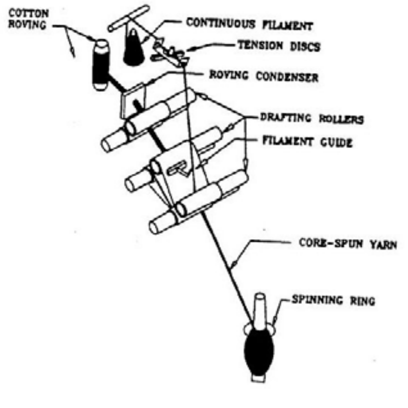


FIGURE 1. Spinning process of core-spun yarn [4].

The number of tensile fatigue cyclic loads was studied at values of 100, 500 and 1000. The samples length was 25cm,, based on the first method proposed by Hearl et al. [11], Each sample was loaded up to 90% of its breaking elongation. A 10 Hz cyclic loading frequency was used.

TABLE II. Spinning parameters of core-spun yarns

Parameter	Value
Spindle Speed (rpm)	7940
Roving Count. (Hank)	Polyester/Cotton(0.95) Polyester (1.074) Viscose (0.72)
Sheath Count (Ne)	12
Core Count(den)	100
English Twist Factor(α_e)	3.2, 3.5, 3.8
Pre-tension (g)	0, 30, 60
Ring dia. (mm)	60

Taguchi Methodology

In order to estimate the optimum process conditions and examine the individual effects of each of the controllable factors on a particular response, Taguchi's experimental design was used. This experimental design involves using orthogonal arrays to organize the factors affecting the process and the levels at which they should be varied [22]. The controllable factors, which were considered in this research, were sheath material, core material, yarn twist factor, core pre-tension, and number of tensile fatigue cyclic loads on core-spun yarns. We chose the orthogonal array L_{18} shown in *Table III*, because it required only eighteen runs for combinations of one factor (core material) varied at two levels and other controllable factors varied at three levels. The percentage of variation in breaking strength of core-spun yarns before and after tensile fatigue cyclic loads was considered as response.

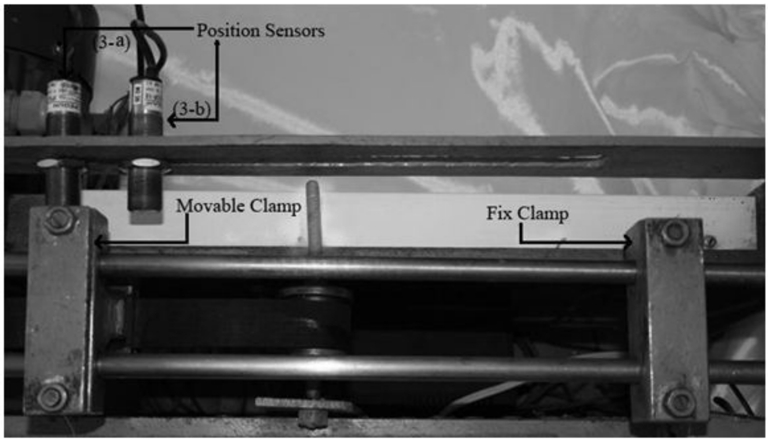


FIGURE 2. Illustration of apparatus used for tensile fatigue cyclic loads [21]

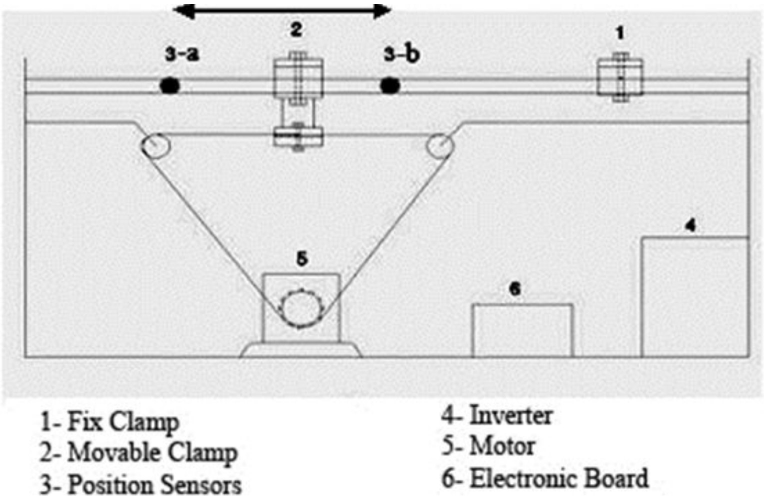


FIGURE 3. The schematic of apparatus used for cyclic loads [21]

Experimental

With reference to ASTM D2256[23], yarn tensile properties were measured before and after tensile fatigue cyclic loads by using a Zwick tensile tester, which works based on a constant rate of elongation (CRE) method. Each sample was tested 15 times and the average value was considered. The fatigue value of core spun yarn was determined using Eq. (1).

A microtome technique was used to assess the structure and position of the core structure.

$$\text{F.V (\%)} = \frac{\text{Breaking strength before cyclic loads - Breaking strength after cyclic loads}}{\text{Breaking strength before cyclic loads}} \times 100 \qquad (1)$$

Statistical Evaluation

Minitab software was used to the experimental results based. Taguchi method SPSS14 software was used for the analysis of variance.

RESULTS AND DISCUSSION

Effect of Cyclic Loads on Fatigue Behavior of Multifilament Core Yarns

Tensile properties of the multifilament core yarns before and after tensile fatigue cyclic loads are presented in *Table IV*. Data in parenthesis are coefficient of variation of measurements.

The findings show the decrease of tensile properties of multifilament yarns after cyclic loads. Maximum reductions in tenacity and breaking elongation of nylon multifilament core yarns of 17.6% and 30.92% occurred after 500 cyclic loads. For polyester core yarn, 23.76% and 41.32% decreases in tenacity and breaking elongation were observed after 100 cyclic loads. This means that polyester multifilament yarns showed higher fatigue than multifilament nylon yarn, even under lower cyclic loading. This trend was confirmed by the results of Nosraty et. al [24]. Analysis of variance results showed that there was a significant difference between the tensile properties of multifilament polyester and nylon yarns before and after cyclic loads at the 95% confidence level**.** This means that the cyclic loads had a significant effect on crack and defect formations as well as deterioration of yarn quality.

TABLE III. Taguchi orthogonal array for fatigue test.

Sample Code	Core material	Sheath material	Pre-tension (g)	English Twist Factor(α_e)	Number of cyclic loads
1	Polyester	Polyester/cotton	0	3.2	100
2	Polyester	Polyester	30	3.2	500
3	Polyester	Viscose	60	3.2	1000
4	Polyester	Polyester/cotton	0	3.5	500
5	Polyester	Polyester	30	3.5	1000
6	Polyester	Viscose	60	3.5	100
7	Polyester	Polyester/cotton	0	3.8	100
8	Polyester	Viscose	30	3.8	500
9	Polyester	Polyester/cotton	60	3.8	1000
10	Nylon	Viscose	0	3.2	1000
11	Nylon	Polyester/cotton	30	3.2	100
12	Nylon	Polyester	60	3.2	500
13	Nylon	Polyester	0	3.5	1000
14	Nylon	Viscose	30	3.5	100
15	Nylon	Polyester/cotton	60	3.5	500
16	Nylon	Viscose	0	3.8	500
17	Nylon	Polyester/cotton	30	3.8	1000
18	Nylon	Polyester	60	3.8	100

TABLE IV. Tensile properties of multifilament yarns used as core part, before and after cyclic loads.

Core Material	Nylon				Polyester			
	Before loads	Number of cyclic loads			Before loads	Number of cyclic loads		
		100	500	1000		100	500	1000
Tenacity (cN/tex)	37.98 (4.44)	32.40 (17.04)	31.50 (31.03)	33.75 (18.84)	25.38 (3.85)	19.35 (22.69)	21.06 (17.35)	20.16 (17.80)
Breaking Elongation (%)	11.74 (14.31)	9.16 (28.64)	8.11 (27.41)	9.13 (39.02)	9.10 (21.68)	5.34 (43.83)	5.95 (28.76)	5.70 (27.31)

*Data in parenthesis are Coefficient of Variation (CV%)

Effect of Process Parameters on Breaking Strength of Core-Spun Yarns before Cyclic Loads

To compare the most effective parameters on breaking strength of core-spun yarns before and after cyclic loads, Taguchi analysis was made on the yarn breaking strength before cyclic loads. A level average analysis was adopted to interpret the results. This analysis is based on combining the data associated with each level for each factor. The difference in the average results for the highest and lowest average response was the measure of the effect of that factor [22]. The greatest value of this difference was related to the largest effects of that particular factor. *Table V* shows the results of this analysis. It is clear that sheath part followed by twist factor were the most effective parameters affecting the breaking strength of core-spun yarns. Pre-tension on the core part showed the least effect on the breaking strength of core-spun yarns.

TABLE V. Response table of breaking strength of core-spun yarns before tensile cyclic loads.

Level	Core Material	English Twist Factor (α_e)	Pre-Tension (g)	Sheath Material
1	61.92	62.49	62.20	61.73
2	62.48	61.81	62.35	65.03
3	-	62.30	62.24	59.84
Delta	0.57	0.68	0.24	5.19
Rank	3	2	4	1

Effect of Cyclic Loads on Fatigue Behavior of Core-Spun Yarns

Breaking strength data of core-spun yarns after tensile fatigue cyclic loads is shown in *Table VI.* The obtained results show that in most cases, the breaking strength was reduced. Also, in some cases the increase of breaking strength was observed. To evaluate this trend, cross sections of core-spun yarns were studied. The cross-sections of samples 17 and 12 before and after determined number of cyclic loads are shown in *Figure 4*.

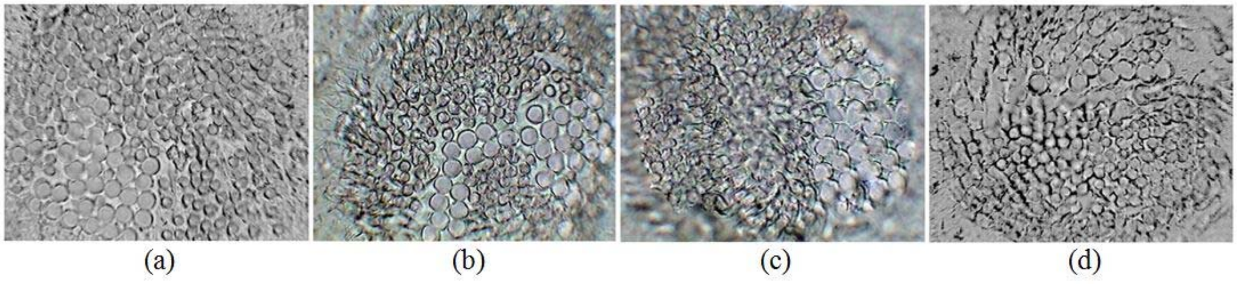


FIGURE 4. Cross-section of samples 17 and 12 before and after cyclic loads, a)sample17,before cyclic loads, b)sample17,after cyclic loads, c)sample12,before cyclic loads, and d)sample12,after cyclic loads.

It is clear from *Figure 4a & 4b* that the position of the multifilament cores changed and are distributed within the sheath fibers, after cycle loading. Based on the literature [25], this could be due to the breaking strength of core-spun yarns. Tensile fatigue cyclic loading can cause damage to fiber structure, so this could have caused the reduction of yarn breaking strength, as can be seen in *Table IV*. Therefore, we can say that the effect of strand displacement was greater than fiber damage due to tensile fatigue loading. The obtained results show that the samples with 1000 cyclic loads were more affected by this trend. This trend was not observed in *Figure 4c & 4d***,** which belong to sample 12. Therefore, the reduction of breaking strength is thought to have occurred after cyclic loading. Besides the damage of fiber structure, the deterioration of yarn structure and the less integrity because of cyclic loads could be other reasons for the decrease in breaking strength (*Figure 5*). This phenomenon is dominant in samples produced with the lower values of English twist factor of 3.2 and 3.5.

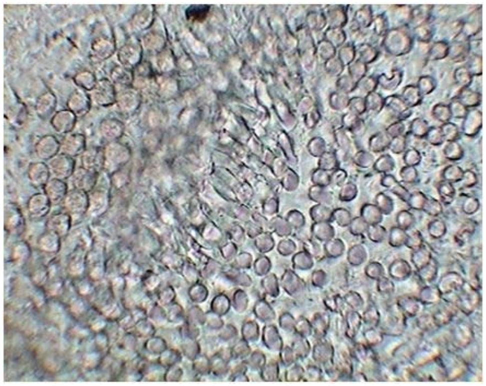


FIGURE 5. Cross-section of sample 2 after tensile fatigue cyclic loads.

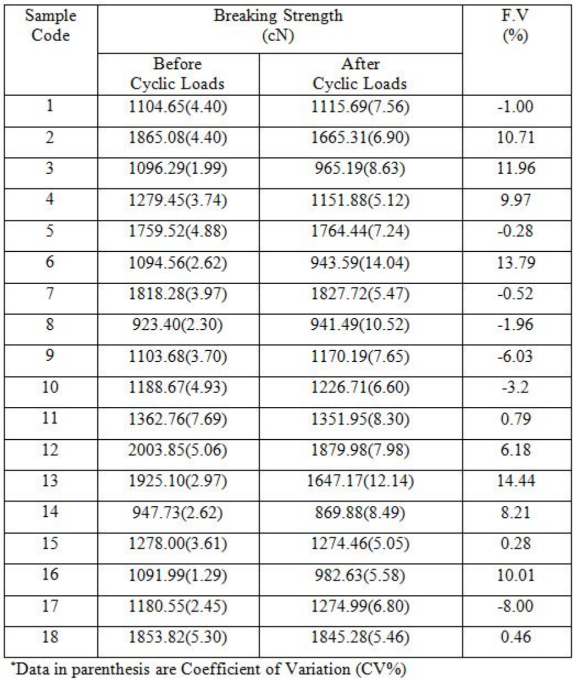
According to the level average analysis (*Table VII*) of core-spun yarns, twist factor showed the dominant effect on breaking strength after cyclic loading. Sheath material was the second effective parameter and was followed by number of cyclic loads, pre-tension on the core, and core material. Although the breaking strength of core yarns was reduced after cyclic loading, it showed the least effect on the breaking strength of core-spun yarns, because of the unique structure of core-spun yarns and interaction between these two components.

Figure 6 shows the optimum level of each controllable factor. Accordingly, a core spun yarn produced from nylon multifilament as core, polyester/cotton fiber as sheath, highest twist factor (3.8) and 30g pre-tension on the core resulted in the least reduction on the breaking strength of core-spun yarn after cyclic loading. The fatigue value of this yarn after 1000 cyclic loads was -8.00%.

Generally speaking, the fibers placed in the yarn core undergo the maximum stress during tensile loading. In core-spun yarns, since the core filaments are located straight and parallel to yarn axis, it was expected that the core fibers were broken before the sheath part. Because the core fibers had no twist, the fracture mechanism of the core filaments was based on fracture of individual fibers. This means that using the stronger multifilament yields higher yarn strength. Thus, the yarn spun from nylon multifilament as the core yielded stronger core spun yarn than that of a polyester core.

In addition, this figure show that the highest number of cyclic loads resulted in the highest breaking strength of core spun yarn. This could be confirmed by our explanation on the cross-section of yarns (*Figure 4*) after cyclic loading. Besides, up to 500 cyclic loads the decrease in breaking strength that was observed could be because of fiber damage and less integrity of yarn structure. *Figure 6* indicates that there was a margin difference between the effectiveness of these two kinds of core yarns up to 1000 tensile cyclic loads.

TABLE VI. Breaking strength of core spun yarns before and after cyclic loads.



Sample Code	Breaking Strength (cN)		F.V (%)
	Before Cyclic Loads	After Cyclic Loads	
1	1104.65(4.40)	1115.69(7.56)	-1.00
2	1865.08(4.40)	1665.31(6.90)	10.71
3	1096.29(1.99)	965.19(8.63)	11.96
4	1279.45(3.74)	1151.88(5.12)	9.97
5	1759.52(4.88)	1764.44(7.24)	-0.28
6	1094.56(2.62)	943.59(14.04)	13.79
7	1818.28(3.97)	1827.72(5.47)	-0.52
8	923.40(2.30)	941.49(10.52)	-1.96
9	1103.68(3.70)	1170.19(7.65)	-6.03
10	1188.67(4.93)	1226.71(6.60)	-3.2
11	1362.76(7.69)	1351.95(8.30)	0.79
12	2003.85(5.06)	1879.98(7.98)	6.18
13	1925.10(2.97)	1647.17(12.14)	14.44
14	947.73(2.62)	869.88(8.49)	8.21
15	1278.00(3.61)	1274.46(5.05)	0.28
16	1091.99(1.29)	982.63(5.58)	10.01
17	1180.55(2.45)	1274.99(6.80)	-8.00
18	1853.82(5.30)	1845.28(5.46)	0.46

*Data in parenthesis are Coefficient of Variation (CV%)

TABLE VII. Response table of F.V% of core-spun yarns.

Level	Core Material	English Twist Factor (α_e)	Pre-Tension (g)	Sheath Material	Number of cyclic loads
1	-21.68	-22.29	-22.51	-17.33	-22.07
2	-20.79	-24.42	-19.34	-22.99	-23.48
3		-17.01	-21.86	-23.39	-18.17
Delta	0.89	7.41	3.17	6.06	5.31
Rank	5	1	4	2	3

The analysis of variance at the α=0.05 significance level was made on calculated SN-ratios of the breaking strength of core-spun yarns. The obtained results are presented in *Table VIII.* Our finding shows that twist factor, pre-tension on core part, number of cyclic loads and sheath materials had significant effect, but core material did not have significant effect on the breaking strength of core-spun yarns after tensile fatigue cyclic loading. *Figure 6* confirms this result.

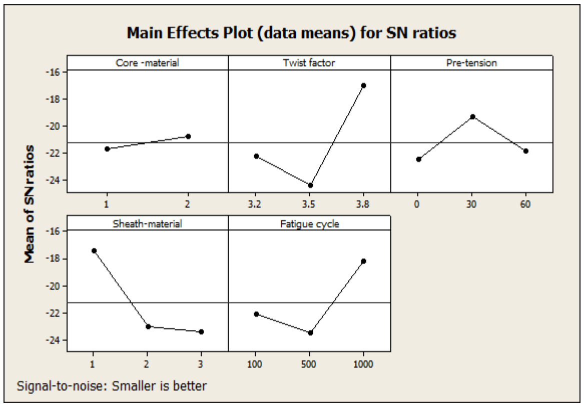


FIGURE 6. The Main Effects Plot for SN ratios of F.V%.

Yarn twist obviously determines the integrity, compactness of yarn structure, and fiber-to-fiber cohesion. So we could expect that cyclic loads which cause buckling of fiber in the yarn structure have less effect on samples produced with higher values of twist. This explanation is confirmed by the cross-section of sample 4 (*Figure 5*). Sheath material also showed more effect than pre-tension on the core and core yarn type, which may be explained as follows: The kind of sheath part, which determines the surface characteristics of the fiber, had an effect on fiber-to-fiber friction of core and sheath parts; and this influence the failure mechanism of core-spun yarns.

30g pre-tension on core was found as optimum values on the fatigue behavior of core-spun yarns. It was confirmed [5] that pre-tension up to a specific level determines and controls the position of core part in core-spun yarn structures, gives the best properties of core-spun yarns. The less effectiveness of 60g pre-tension compared with 30g pre-tension on the core could be explained by the damage of the core-part during the production process.

Comparing the Effective Parameters Before and After Tensile Cyclic Loads

If we compare the effective parameters before and after cyclic loads, we see that the ranking of the first two effective parameters on breaking strength changed. During cyclic loading, micro-cracks were formed on the sheath fibers. In addition, according to *Figure 5*, the cyclic loading caused reduction of yarn compactness as well as fiber-to-fiber cohesion. So, the fiber sliding played an important role on the fracture mechanism of the sheath material. Thus, it could be logic that yarn twist, which was one of the main effective parameters on yarn structure, and packing density had more effect on the yarn breaking strength after cyclic loading compared with the type of sheath material.

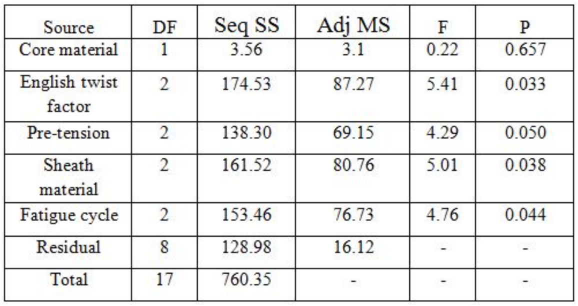
Also, the pre-tension on the core part showed more effect than core yarn type on breaking strength after cyclic loading. As mentioned, pre-tension on the core part determines and controls the position of the core part in the yarn structure and therefore could be a parameter which effected the core strand displacement during cyclic loading.

Finally, the variation of each independent parameter showed a lesser effect on breaking strength before cyclic loading, but this trend was more dominant after cyclic loads. This means that the behavior of each independent parameter after cyclic loading was different compared with before cyclic loading and the sensitivity of each parameter was more visible after cyclic loads.

CONCLUSION

Taguchi's experimental design was used to analyze the effects of core and sheath part, pre-tension on core part, twist values, and number of cyclic loads on the breaking strength of core-spun yarns after tensile fatigue cyclic loads. The optimum spinning conditions were determined through the experimental design. Accordingly, a core spun yarn produced from nylon multifilament yarn as the core part, cotton-polyester fiber as sheath material, 3.8 twist factor, and 30g core pre-tension resulted in minimum values of fatigue. This interesting research was an introduction for our next work on fatigue behavior of core-spun yarns. Studying the fatigue behavior of woven and knitted fabrics, made from core-spun yarns, the effect of fiber blending on fatigue behavior of core-spun yarns, and failure mechanism of core-spun yarns after cyclic loads on microscopy scale will be another area of our future research.

TABLE VIII. Analysis of variance for calculated SN-ratios of F.V% at 95% significant level.



Source	DF	Seq SS	Adj MS	F	P
Core material	1	3.56	3.1	0.22	0.657
English twist factor	2	174.53	87.27	5.41	0.033
Pre-tension	2	138.30	69.15	4.29	0.050
Sheath material	2	161.52	80.76	5.01	0.038
Fatigue cycle	2	153.46	76.73	4.76	0.044
Residual	8	128.98	16.12	-	-
Total	17	760.35	-	-	-

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