New Materials, Compounds and Applications
Vol.4, No.2, 2020, pp.117-125

INFLUENCE OF FIBER SURFACE MORPHOLOGY ON THE DYEING PERFORMANCE OF POLYESTER YARN

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Abstract. The effects of fiber morphology such as fiber fineness and cross-sectional shape on the dyeing mechanism of polyester filaments were analyzed. Round shaped 50d (1.38 denier per filament or dpf) polyester filament yarn, scalloped oval shaped 75d (2.5 dpf) polyester filament yarn and cruciform shaped 100d (4.7 dpf) polyester filament yarn was studied for this research. The color difference, darkness-lightness variation, color fastness to wash and visual assessment of residual dye bath liquor were investigated. The difference in cross-sectional shape and fiber fineness caused the difference in color and shade, darkness-lightness variation, difference in color fastness to wash as well as residual dye bath concentration. The results showed that 50d filament yarn having round shape showed higher dye uptake (hence lower dye bath residual), lower color difference from the standard and more similarity to standard's shade in comparison with polyester filament yarns made of 75d (scalloped oval shape cross-section) and 100d (with cruciform shape cross-section).

Keywords: *polyester yarn, fiber fineness, fiber cross-section, dyeing performance, surface morphology.*

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Received: *04 June 2020;* ***Accepted:*** *21 July 2020;* ***Published:*** *25 August 2020.*

1. Introduction

Polyester fibers, poly (ethylene terephthalate) (PET)) fibers, dominate the world synthetic fibers industry. A polyester fiber is composed of long-chain synthetic polymer including at least 85 wt. % of an ester of a dihydric alcohol (HOROH) and terephthalic acid (p-OOCC$_6$H$_4$COOH) (Abou Nassif, 2012). Polyethylene terephthalate (PET) and polybutylene terephthalate (PBT) have been produced commercially for more than 50 years. Amongst other uses, PET has been used worldwide for the production of synthetic fibers due to its good physical properties (Pang *et al.*, 2006). For comparison, microfibers are half the diameter of a silk fiber, one-third the diameter of cotton fiber, one-quarter the diameter of fine wool fiber and one hundred times finer than human hair. In order to be called a microfiber, a fiber must be less than one denier, which is the weight in grams of a 9000 m length of fiber or yarn. Many microfibers from 0.5 to 0.6 denier are used for making man made fibers (Burkinshaw, 1995; Christmann *et al.*, 1994). Asahi, Kanebo, Kuraray, Mitsubishi, Rayon, Teijin, Toray, Toyobo and Unitika are the Japanese companies that produce microfibers, filament and staple fibers (Kiang, & Cuculo, 1992). Fig.1 shows different types of cross-section of polyester fiber such as round, scalloped oval and cruciform (Bueno *et al.*, 2004). Today, round fiber cross section is the most common shape manufactured by synthetic fiber producers. Other shapes are beginning to emerge for a variety of reasons—performance, comfort, pilling propensity bulkiness, tenacity, processing etc. (Morris, 1989; Okamoto & Kajiwara, 1995; Wada, 1992).

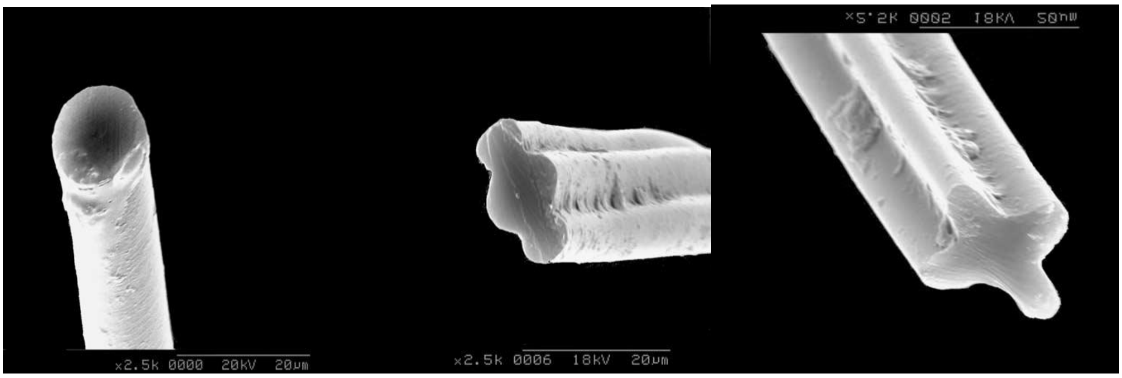

Figure 1. Fiber Shapes Photograph (Kim *et al.*, 2019)

Dyeing can be carried out as a continuous or batch process (Moore & Ausley, 2004). The most appropriate process to use depends on several factors, such as type of material (fiber, yarn, fabric, fabric construction, and garment), generic type of fiber, size of dye batch and quality requirements for the dyed fabric, but batch processes are more commonly used to dye textile materials. Polyester has been dyed in batch process (Perkins, 1991). The dyeing of polyester is limited to only disperse dyes. Dyeing of polyester fibers requires special conditions such as high temperature (130ºC), dry heat (190 – 220ºC), or using carrier in the dye bath (Trotman, 1984). One important aspect of dyeing with disperse dyes is the state of dye in the dye bath during dyeing, the finely divided dispersion of dye particles works as a dye reservoir. The solubility of disperse dyes, though small, is also a very important factor. In addition, the stability of the dye dispersion, the equilibrium between dye dispersion and dye in true solution in the dye bath, and the rate of dyeing are all affected by the type and concentration of the dispersing agents. It has been shown experimentally that dispersing agent can also diffuse into polyester substrates (Odvarka & Schejbalova, 1994; Al-Etaibi *et al.,* 2016). Some of the dispersing agents present in the dye bath are derived from the commercial dye powder, but often more is added to the dye bath to help maintain dispersion stability under dyeing conditions and to assist level dyeing. The rate of dissolution of dye in the dye bath affects the instantaneous concentration of dye that can be to adsorb at the fiber surface, and subsequently diffuse into the fiber (Odvárka & Huňková, 1983; McDowell & Weingarten, 1969). In the present study, the effect of the number of filaments on physical and mechanical properties of polyester woven fabrics was investigated. The physical and mechanical characteristics of five different 150 denier polyester filament yarns containing different number of filaments were studied with respect to fabric thickness, fabric strength, breaking elongation, air permeability, tearing strength, crease recovery and abrasion resistance (AL-Ansary, 2012). But the influence of fiber fineness and cross-sectional area on the dyeing performance of polyester filament was not investigated before. So, the prime aim of this study is to investigate all of these parameters.

2. Experimental Section

2.1 Materials & Methods

2.1.1 Filaments yarn and Chemicals

100% polyester filaments used for the investigation of fiber fineness in dyeing performance, were collected from a polyester filament manufacturing plant. The specifications of different filament yarn are given in Table 1. Trade names and types of all the commercial grades of chemicals for dyeing are listed in Table 2.

Table 1. Filament yarn specifications

Yarn Count (Denier)	Respective Cross-Sectional Shape	No. of Filament in Cross-Sectional Area	Denier per Filament
50d	Round	37	1.38
75d	Scalloped oval	30	2.50
100d	Cruciform	22	4.70

Table 2. Trade names and types of chemicals and auxiliaries used

SL. No.	Chemicals (Trade name)	Types
1.	FORON G-Yellow S-WF	Dyestuff
2.	Dyetech-VSB	Levelling agent
3.	Textaux Sequester K-9907	Sequestering agent
4.	Textaux Carrier K-9323	Carrier
5.	Acetic Acid	Acid

2.2. Application of Dyestuff in Carrier Method

The bath set up is given below in Table 3.

Table 3. Dyestuff Application bath

Dyeing bath set-up		Amount
Chemicals	Disperse dye [%]	2 owf
	Dispersing agent [gm/L]	1
	Carrier [gm/L]	2
	Acetic acid	As required
Application parameters	Material: liquor	1:30
	Temperature [°C]	100
	Time [min]	45

2.3. Application of chemicals for wash fastness test

ISO 105C03 method was used to carry out wash fastness test of the dyed sample. The name of the chemicals and application parameter is listed below for wash fastness test in Table. 4.

2.4. Dye Uptake measurement

The dyeing behavior of polyester yarn was studied based on the measurement of dye uptake%. Dye uptake can be measured as a percentage of dye absorption by the fiber from dye bath during dying process (Kim *et al.*, 2019; Muralidharan & Laya, 2011). Spectrophotometer Spectro 20D Plus RS-232C was used to measure the dye uptake percentage by measuring the dye concentration used for polyester dyeing process.

Table 4. Wash fastness chemical application bath

Wash fastness bath set-up		**Amount**
Chemicals	Standard soap [gm/L]	5
	Soda ash [gm/L]	2
Application parameters	Material: liquor	1:50
	Temperature [°C]	60
	Time [min]	30

Therefore, dye uptake percentage can be defined as the difference in dye concentration before and after dyeing, which can be shown in the following equation 1 (Nguyen *et al.,* 2018).

$$Conc_f\% = 100 \times (Abs_i - Abs_f)/Abs_i \quad (1)$$

Here, $Conc_f\%$ indicates the dye uptake percentages, Abs_i indicates the initial dye concentration and Abs_f indicates the dye concentration of the dye liquor after dyeing.

2.5. Fourier Transform Infrared (FTIR) Analysis

Fourier Transform Infrared (FTIR) analysis is used to explore if there any structural change and introduction or alteration of any functional groups due to treatment of materials with dyes or chemicals (Muralidharan & Laya, 2011; Biswaset *et al.*, 2020; Ibrahim *et al.,* 2019). The structural analysis of fibers was investigated on the Shimadzu FTIR IRTracer-100 using 64 scans and 4 cm-1 spectral resolutions. FTIR spectra in the 400-4000 cm^{-1} range were recorded for dyed and un-dyed yarns with built-in spectrum matching software. The un-dyed fibers of PET yarn were analyzed first. Then the individual fibers separated from the dyed and dried yarns were used and mounted on to the instrument to record the IR spectrum of the yarns.

3. Result and Discussion

3.1. Dyeing Behavior of PET Yarn Measurement from Dye Uptake%

The dye uptake percentages (%) was measured and recorded to study the dyeing behavior of PET fibers. Fig. 2 presents the dye uptake (%) results for three different yarns. The highest dye uptake percentage was recorded from 50d yarn at the specified dyeing temperature, which was about 60%. The other two verities 75d (scalloped oval shape cross-section) and 100d (with cruciform shape cross-section) yarns had dye uptake of 55% and 50% respectively, which were lower than that of 50d yarn. Thus, it shows that dye absoprtion of polyester fiber changes with the change of its fineness and cross-sectional shape.

This test was further extended based on the visual evaluation of residual dye liquor in the dye bath after dyeing (by assessing the difference in initial dye bath and final dye bath concentration). The outcome of this test or observations of residual dye bath liquor after dyeing lead us to a result that the dye uptake of finer polyester yarn is higher than that of coarser polyester yarn. Thus, the result it proves that dye absorption of polyester fiber changes with the change of its fineness and cross-sectional shape.

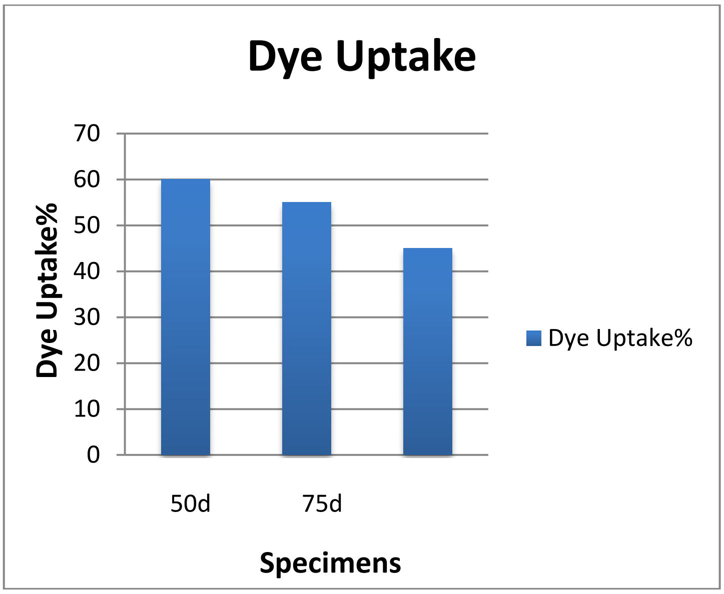

Figure 2. Dye uptake (%) of polyester fibers having different count

3.2. Fourier Transform Infrared (FTIR) Analysis

Spectroscopy was used to investigate changes in the vibrational chemistry of these fibers before and after dyeing shown in Fig. 3. From the quintessential IR peaks of carbonyl groups, it was observed that the peak patterns are almost identical of dyed or treated and un-dyed or untreated samples. There are no additional peaks are found in the treated samples. However, it is worth mentioning that the characteristic peak of carbonyl of ester groups (C=O) for untreated polyester was found at 1730 cm^{-1}, which was slightly towards higher wavenumber of 1750 cm^{-1} for dyed PET yarns. It is also noticing that the peak width reduced slightly indicating the interaction of dye molecule with yarn. A small peak at around 721 cm^{-1} also can be accounted for out-of-plane bending of aromatic ring of the polymer matrix. The result presented in Fig.3 (I, II & III) shows that there is no structural change and introduction or alteration of any functional groups due to dyeing of PET fibers with disperse dyes.

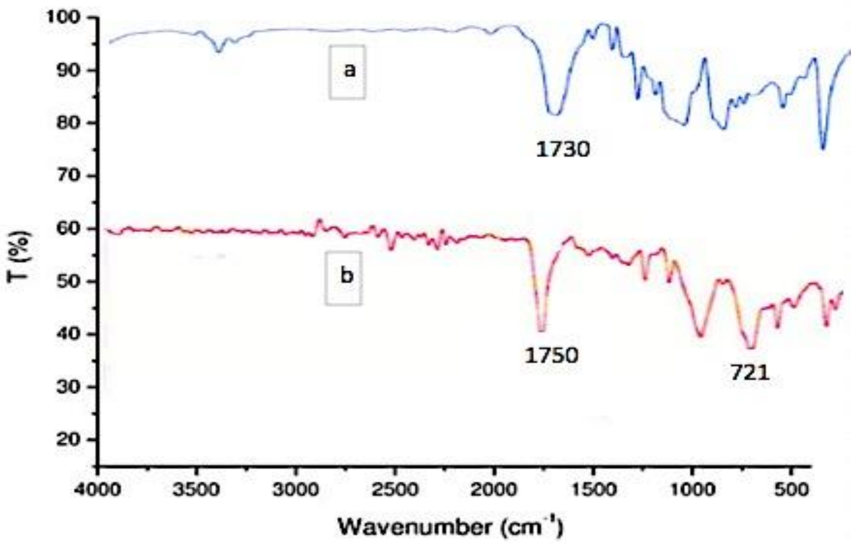

Figure 3(I). FTIR spectra and transmittance (T%) for (a) un-dyed vs. (b) 50d dyed polyester yarn

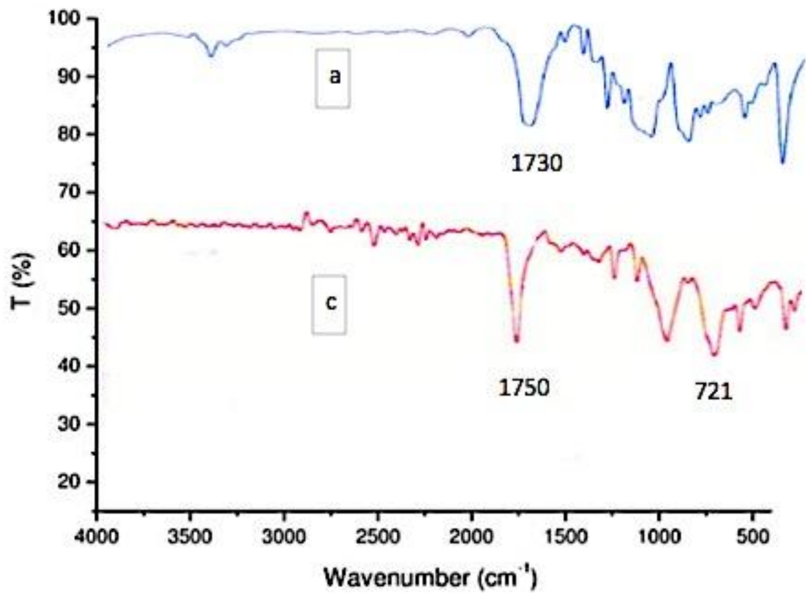

Figure 3(II). FTIR spectra and transmittance (T%) for (a) un-dyed vs. (c) 75d dyed polyester yarn

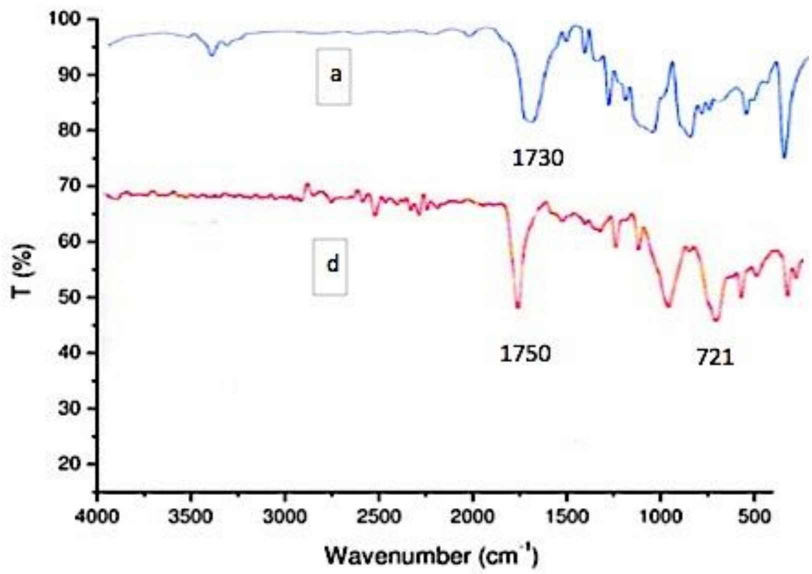

Figure 3(III). FTIR spectra and transmittance (T%) for (a) un-dyed vs. (d) 100d dyed polyester yarn

However, interestingly it has been found that the transmittance percentage (T%) change with the change of the cross-sectional shape. The 50d fiber with round shape has the lowest transmittance value as shown in Fig. 3(I), than that 75d (scalloped oval shape cross-section) and 100d (with cruciform shape cross-section) yarns. 75d yarn has a transmittance value higher than 50d but lower than 100d as shown in Fig. 3(II) and 100d the highest transmittance value as shown in fig. 3(III). This indicates the difference in dye absorption among polyester fibers of different cross-sectional shape.

3.3. Color Difference Evaluation

2 individual tests were conducted in order to test the hypothesis. The results for first (color difference) and second (lightness-darkness variation) tests were based on the color difference value DE* and lightness (+DL*) and darkness (-DL*) values respectively, indicated in CIELAB color space and projected by data color spectrophotometer.

3.3.1. Color Difference Evaluation

Table 5. Color difference and lightness-darkness variation among 50d (round) and 75d (scalloped oval) Yellow dyed polyester filament

lll/Obs	Decision	DE*	DL*	Da*	Db*	DC*	DH*
D65 10 deg	Fail	1.40	1.00	0.40	0.90	0.98	-0.09
TL83 10 deg	Fail	1.53	1.08	0.32	1.03	1.07	-0.06
A 10 deg	Fail	1.55	1.08	0.35	1.05	1.11	0.00

Table 6. Color difference and lightness-darkness variation among 50d (round) and 100d (cruciform) Yellow dyed polyester filament

lll/Obs	Decision	DE*	DL*	Da*	Db*	DC*	DH*
D65 10 deg	Fail	5.42	3.10	-1.93	-4.00	-4.40	0.62
TL83 10 deg	Fail	5.50	2.86	-1.64	-4.41	-4.67	0.56
A 10 deg	Fail	5.51	2.79	-1.79	-4.40	-4.74	0.31

The data shown in Table 5 specifies the color difference between 50d standard sample of dyed polyester filament and batches of 75d and table 6 compares the standard sample with the batch of 100d dyed filament. According to the observations of D65 10 deg, TL 83 10 deg and A 10 deg, there existed a little color difference (score of color difference DE*=+1) between 50d standard and 75d dyed filament, whereas the color difference was remarkable (score of color difference DE*=+4) between 50d standard and 100d filament yarn. Therefore, it can be stated that coarser polyester filament yarn belongs to a different color of the spectrum in comparison with finer polyester filament yarn. It can be also inferred that the color reflection of dyed polyester filament largely vary from each other based on their fineness or denier per filament. It also supports that our hypothesis that color difference of polyester filament vary with the change of cross-sectional shape of polyester fiber.

3.3.2. Lightness and Darkness Evaluation

The assessment of lightness-darkness variation was also conducted based on the aforementioned observations. The result depicted from this test (shown in Table 5& 6) indicates that the shade of the trial batch of 100d filament is lighter and more saturated than another trial batch of 75d as well as the standard batch of 50d polyester yarn. Similarly, the shade of trail batch of 75d yarn is lighter and more saturated than standard batch of 50d polyester filament but deeper and less saturated than the trail batch of 100d filament yarn. Although the 50d standard sample and the other two batches of 75d and 100d filament yarns were dyed with Yellow disperse dye, the 75d batch was found redder and the batch of 100d was found yellower than the standard. So, it can be deducted that as the number of filament per yarn increases, the area of fiber cross-section per yarn increases, which causes more dye absorption and a little desorption. Thus, both of the results supported our hypothesis that lightness and darkness property of polyester filament with the change of its fiber's fineness as well as with the change of cross-sectional shape of polyester fiber.

3.4. Color Fastness Test

For this test color fading and color staining of polyester dyed filament was investigated. The gray scale measurement for color fading showed that 50d filament yarn had a color fastness of 3-4, whereas 75d and 100d filament yarn had a resistance to color fading of 4. Moreover, as per the grey scale for staining the 50d filament yarn showed a score of 3 on Acetate, 4-5 on cotton, 3-4 on nylon, 3 on polyester, 4 on acrylic and 3-4 on wool. On the other hand, for 75d and 100d filament yarn the scores were 3-4 on acetate, 4-5 on cotton and 4 on nylon, polyester, acrylic and wool respectively. The data provided in table 3 indicated that 50d filament yarn with round cross-sectional shape had a poor resistance to color fading and staining compared to 75d filament yarn scalloped oval cross-sectional area. Moreover, the result also showed that 75d filament yarn and 100d filament yarn had a similar resistance to color fading and staining.

4. Conclusion

Dyeing solution containing disperse dyes and other chemicals such as dispersing agent, carrier and acetic acid was used for this experiment. Results were established based on the data found from dye uptake, FTIR analysis by spectrophotometer, color difference evaluation and color fastness test. All of these tests produced almost similar results. From these experiments it was deducted that fiber fineness and cross-sectional shape possessed effect on the dyeing mechanism of polyester filament yarn. With the increase of fineness and change of the cross-section color difference increases as what happened when we compare 50d filament yarn with 75d and 100d polyester. Moreover, the level of yarn darkness changes with the change of the yarn count and cross-section. The dye absorption property was found to be better for 50d round shaped yarn compared to 75d scalloped oval shaped and 100d cruciform shaped yarns. Although there was a little difference among the filament yarns in terms of color fastness to wash, it established that color fastness to wash changed with the change of the fiber fineness and cross-sectional area. However, future researchers can investigate whether some other factors such as hue (Da) and saturation (Db) have any direct impact on color difference among the polyester filaments of various counts. Furthermore, they can also conduct this experiment using multiple dyeing temperature and time.

Acknowledgement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflicts of Interest

The authors declare no competing financial interest.

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