(REFEREED RESEARCH)

INVESTIGATION OF AIR-JET TEXTURING OF TECHNICAL POLYESTER YARNS

TEKNİK POLİESTER İPLİKLERİN HAVA-JETLİ TEKSTÜRE İŞLEMLERİNİN İNCELENMESİ

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ABSTRACT

This paper reports an investigation of air-jet texturing of technical polyester yarns without causing important decrease in their breaking strength. The overfeed levels are kept low in order to maintain the parallel fiber alignment which is essential to maintain the yarn strength. Surface of the fibers are analyzed by scanning electron microscopy (SEM) studies. Results show rougher surfaces after air-jet texturing. Optical microscopy is used to study the yarn structure. An increased overfeed level results in more loops on the surface. Furthermore, flexural rigidity of the fibers is calculated and it is concluded that fibers with high flexural rigidities give open loop structure, whereas the fibers with low flexural rigidities result in closed loops.

Key Words: Polyester, Air-jet texturing, Mechanical properties, Flexural rigidity, Surface property.

ÖZET

Bu çalışmada teknik polyester ipliklerin, kopma mukavemetlerinde önemli bir azalmaya yol açmadan hava-jetli tekstüre edilmeleri incelenmiştir. Çalışmada kullanılan aşırı besleme oranları iplik mukavemeti için gerekli olan liflerin paralel konumlanmalarını korumak için düşük tutulmuştur. Liflerin yüzeyleri elektron tarama mikroskobu (SEM) çalışmaları ile incelenmiştir. Sonuçlar hava-jetli tekstüre sonucunda daha pürüzlü yüzeylerin elde edildiğini göstermektedir. Optik mikroskop çalışmaları iplik yapısının anlaşılması için kullanılmıştır. Aşırı besleme oranındaki artış yüzeyde daha ilmekli bir yapının elde edilmesine yol açmaktadır. Ayrıca liflerin esneklik rijitlikleri hesaplanmış ve yüksek esneklik rijitliğine sahip olan liflerin açık ilmek, düşük esneklik rijitliğine sahip olanların ise kapalı ilmek oluşturduğu sonucuna varılmıştır.

Anahtar Kelimeler: Poliester, Hava-jetli tekstüre, Mekanik özellikler, Esneklik rijitliği, Yüzey özelliği.

Received: 25.04.2010 Accepted: 28.07.2010

1. INTRODUCTION

Polyester (PES) fibers are a major type of textile raw material having high functional properties. Polyethylene terephthalate (PET) is the most common fiber-forming polymer among all the polyesters. It has an excellent capacity for physical modification. The possibility of wide variation of its physical structure, from the totally amorphous to the deeply crystallized state as a function of the temperature-deformation and time conditions of processing, leads to production of different kinds of PET fibers such as high tenacity PET (HTPET) and dimensionally stable PET (DSPET) fibers. New kinds of fibers based on different polyesters like Vectran and polyethylene naphthalate (PEN) are also being manufactured on industrial scale. Among these fibers, Vectran is very different to the other polyesters. It is fully aromatic giving a highly oriented, chain extended structure, with molecular weight increases by heating after melt spinning. All of these polyesters have a good combination of mechanical and thermal properties therefore they are widely used in industrial applications (1-4).

Air-jet texturing process is a purely mechanical method which uses a specially designed nozzle to provide typically a supersonic and turbulent air stream to entangle the continuous filaments into a voluminous (bulked) spun-like construction with loops on the surface locked in the core of the yarn. Air-jet texturing operates by mechanical interlocking and not by heat-setting. It can therefore be applied to any continuous-filament yarn including rayon, glass and the new high-performance fibers, as well as nylon, polyester and polypropylene (5, 6).

Owing to its unique properties air-jet texturing can be used to produce both conventional and technical yarns. It can be used to alter the bulk and hygroscopicity of the yarns resulting an improvement in the consumer properties of fabrics, or to blend different kinds of fibers and produce hybrid yarns. Moreover it can be used to improve the adhesion behaviour of the reinforcing filaments in the composites (7-9).

In the literature there are many works about texturing of polyester fibers as well as the effects of air-jet texturing parameters including jet designs on conventional fibers (10-15). However this work deals with air-jet texturing of technical polyester yarns and explains surface and mechanical changes related to fiber properties. The purpose of this study is to investigate the effects of air-jet texturing on different kinds of polyesters in terms of mechanical behaviour, yarn geometry and single fiber surface topography. The changes in the yarn geometry are characterized by means of optical microscopic studies, while changes in the single fiber surface are investigated by scanning electron microscopy (SEM). The mechanical behaviour of the single fibers and the yarns are analyzed by tensile measurements and the results are discussed in detail.

2. MATERIALS AND METHODS

2.1 Material Properties

In this study five different commercially available polyester filament yarns namely, conventional PET (FDYPET), DSPET, HTPET, PEN and Vectran are used. All of the yarns but FDYPET are technical polyesters. FDYPET is involved to the study in order to make a comparison to the technical ones. Properties of the yarns and the given yarn codes are presented in Table 1.

2.2 Determination of the Air-jet Texturing Parameters

Owing to large differences between the properties of the supply yarns (both mechanical and thermal), the air-jet texturing parameters are selected with great care to obtain the same texturing conditions for all the materials.

The yarns used in this study are expected to find application in the making of composites. The loops on the surface would enhance the mechanical interlocking of the yarns to the composite matrix. However increasing the intensity of loop formation is achieved at the expanse of reducing axial strength. Therefore, it is of interest to bring together the mutually conflicting demands of retaining high axial strength and increasing intensity of loop formation. It is also important to create a homogeneous yarn structure without clear separation of the core and the effect yarns. Therefore, in this study the yarns are fed to the air-jet texturing machine as single end method with low overfeed levels. FDYPET yarn which has a lower linear density is fed into the machine with three ends to keep the linear density of the supply yarns similar and obtain comparable results.

It is well known that air-jet texturing results in mechanical loss for the yarn strength. As the mechanical performance of the technical polyesters are very important due to their applications, in order to improve their mechanical properties the yarns are subjected to drawing between the heated feed rollers when being fed into the machine. The draw ratio is selected within the limitations of the texturing machine. The temperatures of the feed rollers are very important to obtain sufficient drawing effect on the internal structure of the single filament. The reorganization of the internal structure is more effective above glass transition temperatures. Therefore, in this study the temperature of the feed rollers are set at temperatures above glass transition. However as all the polyester yarns in this study show different temperature-dependent behaviour, the temperature of the feed rollers are adjusted at 15ºC above the glass transition temperature of the yarns in order to obtain a similar effect. Since Vectran shows no clear glass transition temperature and has a high melting temperature, the feed rollers are, therefore, set at maximum temperature in order to obtain sufficient molecular movement.

Air-jet pressure, production speed and mechanical stretching values are, however, kept constant throughout the tests for all the samples. Three different overfeed levels of 10, 15 and 20% are chosen in order to analyze the air-jet texturing effect on the technical polyesters. Overfeed levels are also kept low purposely as the mechanical performance of the technical yarns is crucial for end-uses.

The air-jet texturing of the filament yarns were carried out on a SSM Stähle RM3-T machine, with the following parameters: 300 m/min texturing speed, Hemajet A357 type of nozzle, 8 Bar air pressure, 210°C heat-setting temperature, 3% mechanical stretch. Details of the process are given in Table 2.

Table 1. Yarn properties and the given yarn codes

Chemical structure and type of the filaments	Yarn code	Yarn count (tex)	Number of filaments	Glass transition temp. (°C)	Melting point (°C)
Conventional PET (Fully drawn)	FDYPET	33.50	72	69	252.3
Dimensionally stable PET	DSPET	110	300	73	254.1
High tenacity PET	HTPET	110	192	123	255.5
PEN	PEN	110	200	76	272.2
Vectran	Vectran	110	200	-	323.5

Table 2. Details of the air-jet texturing process

Type of the feed yarn	Yarn code	***Overfeed Level (%)***	Draw ratio (%)	***Temp. of the feed rollers (°C)***
FDYPET	FDY10 FDY15 FDY20	10 15 20	1.30	84
DSPET	DSPET10 DSPET15 DSPET20	10 15 20	1.05	88
HTPET	HTPET10 HTPET15 HTPET20	10 15 20	1.05	138
PEN	PEN10 PEN15 PEN20	10 15 20	1.02	91
Vectran	Vectran10 Vectran15 Vectran20	10 15 20	1	200

2.3 Measuring Methods

Tensile measurements of both the fibers and the yarns have been performed on a 4301 Instron tensile tester. A gauge length of 50 mm and a crosshead speed of 50 mm/min for the fibers (16), and a gauge length of 500 mm and a crosshead speed of 300 mm/min for the yarns have been used (ASTM D 2256). Twenty samples have been tested in order to establish the overall tensile curves and the tensile parameters for both the fibers and the yarns.

The yarn geometry has been observed by means of Automatic Trinoculer Stereo Zoom Microscope (Olympus SZ6045 Model).

Surface topography of the single fibers has been investigated by means of SEM analysis, on a Jeol JSM-6335F model scanning electron microscope.

3. RESULTS AND DISCUSSION

3.1 Optical Microscopy and SEM Results

Optical microscopy images are given in Figure 1. The images show intense loop formation in textured yarns with higher overfeed levels. The images reveal that the filaments in the centre of the yarns are relatively better aligned than the filaments at the surface at lower overfeed levels. The permanent loop formation is largely restricted to the filaments that are closer to the surface of the yarn. At high overfeed levels the filaments closer to the centre are also disturbed and followed a nonlinear path due to the buckling of the filaments. When a filament is in the centre of the yarn, it is better aligned, and the filaments on the surface of the yarn form loops. The shape of the loop, however, differs according to the type of the yarn. The loops form at the exit of the nozzle and shapes-up depending on the texturing parameters and the yarn structure (i.e, material, thickness, number of filaments, linear density of each filament…) Kollu T., classified the loops formed during air-jet texturing. Figure 2 shows the types of loops formed due to air-jet texturing (17).

The shapes of the loops are affected by process parameters as well as type of the material. The filaments that can easily bent form closed loops. The bending behaviour of the filament is described as flexural rigidity (E_r) and calculated by the following formula introduced by Hearle (18):

$$E_r=(1/4\pi)(\eta ET^2/\rho)\ x10^{-3}$$

where; "η" is fiber shape factor , "*E*" isYoung's Modulus of the fiber (N/tex), "*T*" is fiber linear density (tex), "ρ" is fiber density (g/cm^{-3}).

In this study the flexural rigidity values of the single fibers are calculated by the given formula and given in Table 3. All the fibers have circular cross-section therefore their shape factor is 1 (18). PEN and Vectran filaments show high resistance against bending as they have very high flexural rigidity. Therefore they mostly form elongated, open loops. Vectran also showed kink band formation due to its highly anisotropic structure. Its fibrillar structure resulted in little fibrillation on the fiber structure. FDYPET, DSPET and HTPET filaments have lower flexural rigidity, therefore can easily form loops. They showed mostly small, closed loops especially for the high overfeed levels. HTPET filaments have higher flexural rigidity than DSPET filaments. Therefore they need higher overfeed levels to form closed loops.

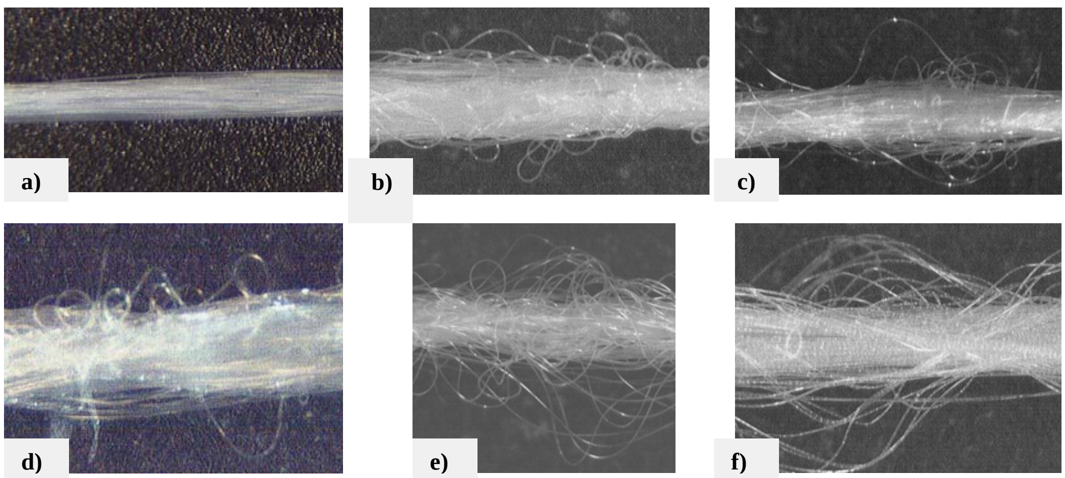

Figure 1. Optical microscopy images of the air-jet textured yarns: (a) A typical polyester yarn before air-jet texturing, (b) FDY20, (c) DSPET20, (d)HTPET20, (e) PEN20, (f) Vectran20

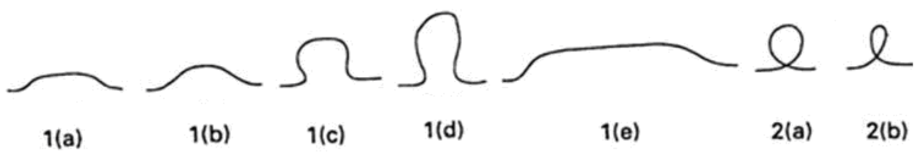

Figure 2. Classification of the loops (17)

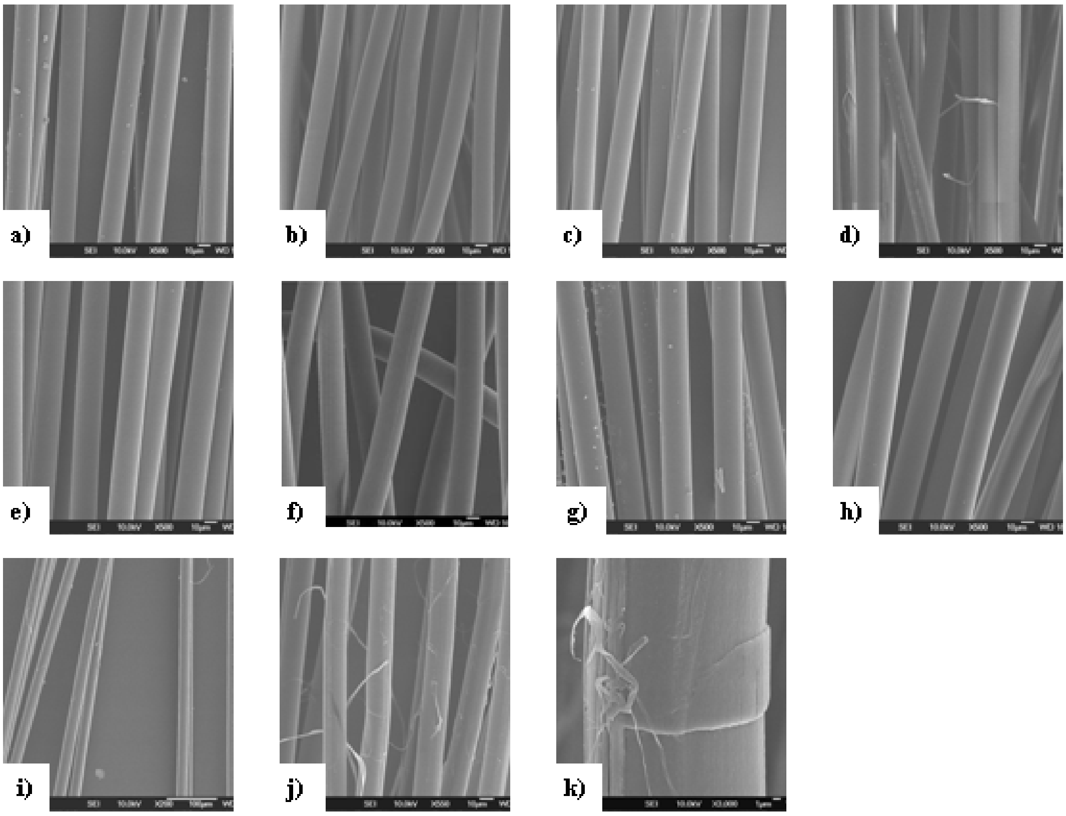

Figure 3. SEM images of the yarns before and after air-jet texturing; a)FDYPET Raw, b)FDY20, c)DSPET Raw, d)DSPET20, e) HTPET Raw, f)HTPET20, g)PEN Raw, h)PEN20, i)Vectran Raw, j)Vectran20, k)Vectran20

Table 3. Tensile results of the single fibers

Fiber Type	Fiber count (tex)	Tenacity (N/tex)	Breaking extension (%)	Young modulus (N/tex)	Fiber density (g/cm^3)	Flexural rigidity x10^{-3} (Nmm^2)
FDYPET	0.4653	0.4210	39.84	5.929	1.380	0.07406
DSPET	0.3670	0.7258	19.25	7.4680	1.386	0.05778
HTPET	0.5730	1.0040	13.66	9.546	1.390	0.17952
PEN	0.5500	0.8639	10.70	17.64	1.355	0.31354
Vectran	0.5500	2.5930	4.477	79.60	1.400	1.36937

Figure 3 shows the SEM images of the yarns before and after air-jet texturing. For all kinds of fibers after texturing clear and smooth surfaces are observed. It can be concluded that texturing has removed the impurities and the spin finish off the surfaces. Moreover air-jet texturing caused some fibrillation and peeling off the surface at some places on the filaments especially for DSPET, HTPET and Vectran. This effect is the most pronounced for Vectran fibers. They have rough and fibrillated surface even before texturing. Due to their fibrillar nature Vectran fibers show higher fibrillation rate after texturing. In addition, breaking and buckling of the stiff molecular chains cause kink bands on the surface (19) (Figure 3k).

3.2 Tensile Test Results

Table 3 shows the tensile test results and Figure 4a shows the stress-strain curves of single filaments. Vectran, liquid crystalline polyester, has the highest modulus and breaking strength with lowest breaking extension. PEN with a naphthalate ring on the molecular chain gave the second best modulus value. However has lower breaking strength than that of HTPET. HTPET fibers have high amorphous orientation than PEN fiber due to multiple post drawing process. Therefore they have better breaking strength. HTPET fibers are produced from higher molecular weight polymers and are subjected to multiple post drawing processes in order to obtain higher tenacity. Therefore they have higher orientation than DSPET fibers. On the other hand DSPET fibers are produced at higher temperatures with lower drawing values than HTPET to obtain fibers with thermal stability. Therefore they have lower modulus compared to HTPET fibers. Commercial PET, FDYPET showed the lowest modulus and the breaking strength as expected.

Table 4 shows the tensile results of the yarns before and after air-jet texturing at different overfeed levels. Analysis of the tensile properties of the textured yarns with different overfeed levels are carried out in two ways:

1-Analysis of the modulus, tenacity and breaking extension values

2-Analysis of the stress-strain curves.

Figures 4b-4f show the stress-strain curves of the yarns before and after air-jet texturing with different overfeed levels. The curves of yarns produced at different overfeed levels show very similar behaviour. All samples except FDYPET show a reduction in breaking strength and breaking extension after texturing. Molecular structure of FDYPET yarn is not stable like molecular structure of other polyesters used in this work. Therefore application of an initial drawing between the feed rollers affected FDYPET yarns in a different way, leading to an increase in their breaking strength. All the test samples also show reduction in breaking strength and an increase in breaking extension with increasing overfeed levels. The initial part of the stress-strain curves, which indicates the modulus of the yarns, appear to be affected, Overfeed determines the alignment of the filaments in the yarn. When the filaments have better alignment it results in a higher modulus and high breaking strength. The decrease in breaking tenacities of the textured yarns is also caused by the disturbance of the parallel arrangement of the single filaments.

Air-jet texturing process involves exposing yarns to a volume of supersonic, turbulent air flow which entangles the constituent filaments of the yarns, which in turn develops a final yarn structure with an entangled core and looped sheath. The air-jet textured yarns show strength reduction due to disorientation of the single filaments and fiber damage during texturing. The looped and entangled fibers also play an important role on breaking extensions. As strain increases under tensile loading entangled and looped fibers become aligned with the loading direction, thereby contributing to the load. However the fibers were not loaded evenly. The tightest fibers break at first, then the fibers that were previously slack are loaded. However some of the entangled and looped fibers can also hold each other and restrict further extension. The noticeable difference between the textured and untextured yarns is the breaking extension value. Breaking extension is reduced after texturing at different levels depending on the fiber type. For FDYPET yarn a large reduction in breaking extension after texturing is observed. The yarns are subjected to drawing between the feed rollers when being fed into the machine as explained earlier. Part of the reduction in breaking extension is considered to be affected by this initial drawing. For DSPET, HTPET and PEN breaking extension shows little decrease after texturing than that for Vectran yarn and almost no change is recorded in breaking extension after texturing.

The reduction in breaking extension after texturing is attributed to two reasons: the initial drawing of the yarns when being fed into the machine and the entangled filaments preventing further extension. For FDYPET, DSPET, HTPET and PEN both factors play important role on the breaking extension reduction. However, for Vectran both factors are not as effective because it is already fully-drawn and show no entanglement of the filaments due to high flexural rigidity. This yarn structure of Vectran affects fiber slippage from loops giving intermittent extension and uneven sharing of load giving lower strength.

However, increased overfeed level cause increase in breaking extension due to opening up of the looped and entangled filaments. The looped, entangled fibers are unevenly loaded allowing for additional extension but lower load bearing, therefore a decrease in breaking tenacity is recorded for all type of the yarns after texturing and with increased overfeed level.

Table 4. Tensile results of the yarns before and after air-jet texturing

Yarn code	Yarn count (tex)	Tenacity (N/tex)	Change in the tenacity (%)	Breaking extension (%)
FDYPET Raw	33.50	0.3316	--	32.90
FDY10	83.28	0.4571	+37.85	8.220
FDY15	86.83	0.3536	+6.634	8.154
FDY20	89.95	0.2859	-13.78	8.369
DSPET Raw	110.00	0.5998	--	12.92
DSPET10	115.81	0.4054	-32.41	8.740
DSPET15	119.97	0.3987	-33.53	9.102
DSPET20	124.49	0.3246	-45.88	9.235
HTPET Raw	110.00	0.7112	--	13.830
HTPET10	115.54	0.5567	-21.72	11.39
HTPET15	121.34	0.4982	-29.95	12.53
HTPET20	121.83	0.4138	-41.82	12.47
PEN Raw	110.00	0.7330	--	15.88
PEN10	124.34	0.4086	-44.26	14.98
PEN15	125.87	0.3244	-55.74	17.06
PEN20	128.28	0.3080	-57.98	20.99
Vectran Raw	110.00	2.2390	--	6.188
Vectran10	116.47	0.9526	-57.45	6.877
Vectran15	119.42	0.8832	-60.55	11.171
Vectran20	122.05	0.8137	-63.66	13.589

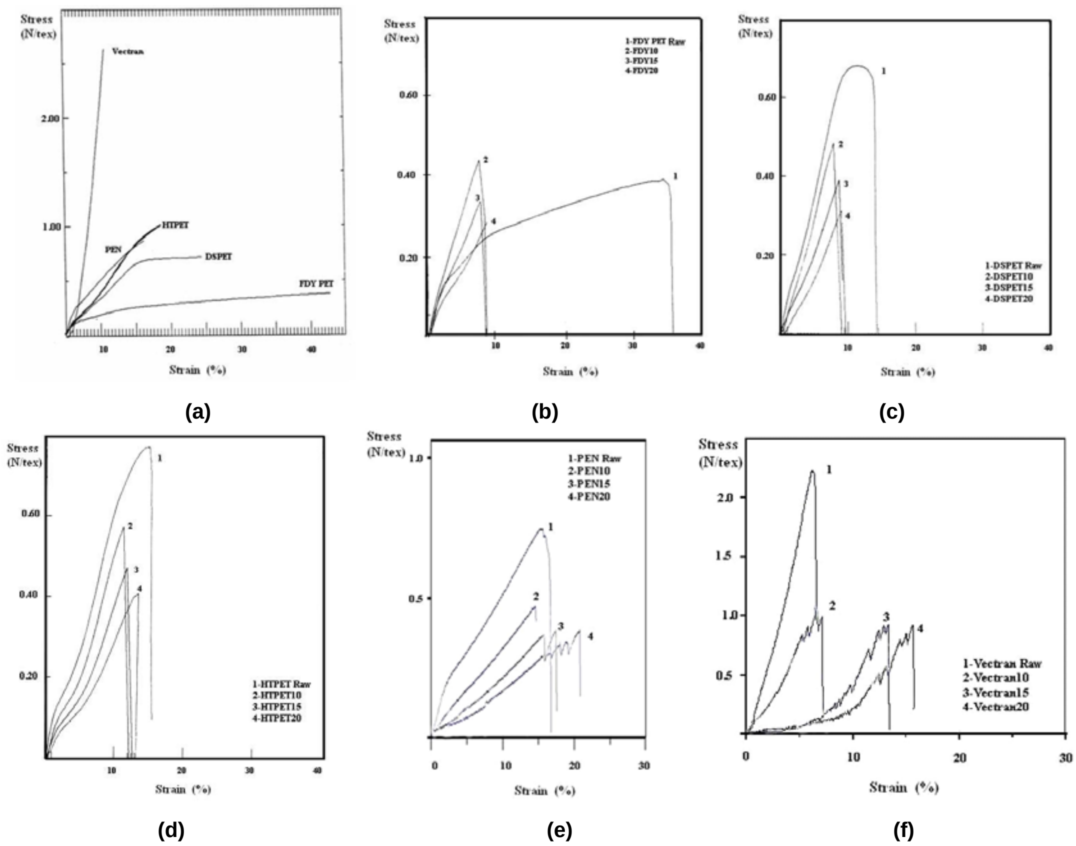

Figure 4. Stress-strain curves; a)Single filaments, b)FDYPET, c)DSPET, d)HTPET, e)PEN, f)Vectran

3.3 Discussion

Air-jet texturing causes different degrees of changes to the fiber surface and produces yarns with different characteristics depending on the fiber type. Fiber surface characteristics such as fibrillation tendency, roughness and the bending behaviour play an important role on the effect of air-jet texturing of fibers.

Air-jet texturing alters the mechanical behaviour of the yarns such as breaking extension, breaking strength and the modulus. It also affects the surface of the fibers. It can clean the surface of the fiber by removing spin finish from the surface, hence creating rougher surfaces. Air-jet texturing also causes kink bands on the surface or peeling off the surface depending on the fiber type.

Air-jet texturing reduces the breaking strength of the yarn due to disorientation of the individual filaments within the yarn and fiber damage during texturing. Breaking extension is noticeably reduced after texturing when the filaments are entangled and formed into loops. However increased overfeed level results in an increase in the breaking extension due to opening of the loops and entangled filaments.

4. CONCLUSIONS

Air-jet texturing can be recommended as a technique to affect the fiber surface as well as the bulkiness of the yarn. The SEM analysis show fibrillation, peeling off and kink bands on the fiber surface as well as removal of the spin finish after texturing. The filaments form different type of loops depending on the material characteristics and the process parameters. The bending behaviour of the filaments plays an important role on the shape of the loops.

Although air-jet texturing causes a reduction in strength and higher overfeed levels are known to result in higher breaking extension, the research reported in this paper lead to the conclusion that such yarns can be air-jet textured without causing large reduction in the breaking strength of the yarn when low overfeed levels are applied. Air-jet texturing of technical fibers can be designed to produce yarns with rougher fiber surfaces and higher bulk, rendering them more suitable for use in composites, because of their better adhesion characteristics (9).

ACKNOWLEDGEMENTS

The authors would like to thank KordSA, Turkey; Korteks, Turkey, for their support and valuable information. This work was supported by The Scientific and Technological Research Council of Turkey, the project number is 106M131.

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Bu araştırma, Bilim Kurulumuz tarafından incelendikten sonra, oylama ile saptanan iki hakemin görüşüne sunulmuştur. Her iki hakem yaptıkları incelemeler sonucunda araştırmanın bilimselliği ve sunumu olarak ***"Hakem Onaylı Araştırma"*** *vasfıyla yayımlanabileceğine karar vermişlerdir.*