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Effect of air-jet texturing on adhesion behaviour of polyester yarns to rubber

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ABSTRACT

Air-jet texturing of conventional poly(ethylene terephthalate) (PET) yarns, having the same chemical structure with high modulus and tenacity PET yarns, are studied in order to improve their adhesion to rubber. Air-jet texturing of these yarns is performed without any visible loop formation in order to minimize the mechanical loss, and an improvement in the adhesion to rubber of conventional PET yarns is achieved. This improvement is investigated by means of surface changes of single filaments and yarn geometry changes due to air-jet texturing. Changes of the cross-sectional structure of the yarns after air-jet texturing and therefore a higher surface area is found to be the main reason for this improvement.

1. Introduction

Composites based on fiber and rubber materials such as pneumatic tires, conveyor belts, hoses, etc., have the widest application. Because of their severe service conditions, these composites require a very high level of adhesion. The polarity and high modulus of fibers are very different from nonpolar nature and low modulus of rubber. Therefore, in most recent applications a cord–adhesive rubber system is used. The resorcinol–formaldehyde–latex (RFL) adhesive system developed in the early 1940s is still in use throughout the rubber industry. The latex component makes the adhesive layer flexible and is mixed with rubber layer through secondary bond and co-vulcanization, while RF component react with the hydrogen bonding groups [1].

The properties of the fiber used for composites also play an important role on the performance and adhesion behaviour. Textile fibers like nylon 6, nylon 66 and poly(ethylene terephthalate) (PET) are the most widely used rubber reinforcing materials. Among these materials, PET is especially preferred because it has a good combination of strength, dimensional stability and cost. However, its hydrophobic nature inhibits its potential. As a result of this hydrophobic nature, the normal RFL treatment is not satisfactory for use. Various methods have been proposed for improving the adhesion of PET fibers to rubber [1,2]. However, most of these techniques are either very expensive, difficult or not very environmentally friendly.

The air-jet texturing process produces spun-like yarns by modifying the uniform arrangement of the synthetic continuous multi-filament yarns and entangling them using a supersonic air stream delivered by a texturing nozzle designed for this purpose [3]. The basis of this method is that yarn is overfed into the compressed air-jet-stream, so that loops are forced out of the yarn [4]. Supply yarns can be fed into the air-jet in three ways: a single supply yarn or, two or more yarns of the same or different types, can be textured at the same speed (parallel end texturing), or can be co-textured at different speeds (core and effect texturing) [5]. Disturbance of the originally parallel arrangement of the filaments to the yarn axis and formation of surface loops anchored in the yarn core, adversely affect the mechanical properties, fatigue and as well as adhesion behaviour of the air-jet textured yarn. In most of the rubber reinforcement applications, mechanical properties and fatigue behaviour are very important. However, air-jet texturing is an inexpensive and fully mechanical process, with great potential to lead to the development of fiber-reinforced composites with

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Table 1
Properties of the feed yarn

Yarn count (dtex)	551
Number of filaments	72
Tenacity (cN/dtex)	2.18
Elongation at break (%)	214.15

good adhesion properties. Because of this reason, we propose to develop an air-jet texturing process to produce textured yarns using high performance filament yarns with as little disturbance as possible to the parallel arrangement of the filaments, as it is very important for fatigue and mechanical performance, and with as few surface loop formation as possible. By this way we expect to obtain tangible improvement in their adhesion properties.

In this paper we report the preliminary work performed by using conventional PET yarns as they have the same chemical structure with high modulus and tenacity PET yarns. The aim of this work is to determine the air-jet texturing parameters to keep the parallel structure of the filaments as much as possible without causing significant mechanical loss and to understand the effects of air-jet texturing on adhesion behaviour of conventional PET to rubber.

2. Experimental

2.1. Materials

In this study commercially produced partially oriented PET yarns, which were supplied by Korteks, Turkey were used. Their properties are given in Table 1.

RFL, used for dipping of the yarns and the rubber compound used for adhesion tests were provided by KordSA. An example formulation for the RFL solution is given in Table 2.

2.2. Air-jet texturing studies

In this work, core-and-effect texturing of four supply yarns was performed. In each step the number of core and effect components and their overfeed levels were changed to determine the suitable air-jet texturing parameters in order to keep the parallel structure of the filaments as much as possible with no significant mechanical loss. In air-jet texturing, changing the core yarn overfeed has a direct influence on the strength of the textured yarn while the effect yarn overfeed determines the size of the loops. Core and effect yarn overfeeds usually range from 2 to 15% and 15 to 150%, respectively [4]. A typical air-jet textured yarn for conventional textiles application is shown in Fig. 1.

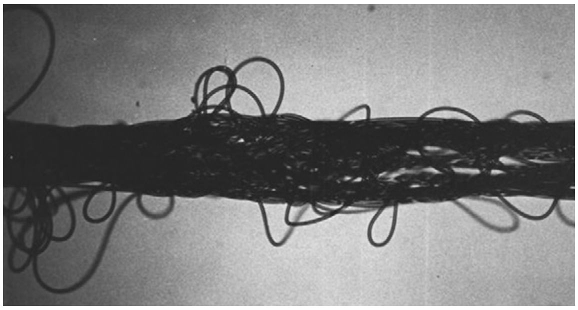

Fig. 1. A typical air-jet textured yarn for conventional textiles application [7].

To obtain these desired yarn properties the overfeed levels were kept low. Only the core component was wetted prior to texturing and the pressure of the air jet was 1.05 MPa. The yarn codes and the production parameters are given in Table 3.

All the air-jet texturing studies were carried out in the Laboratories of Korteks, Turkey on a SSM Stähle RM3T machine with the following parameters: 500 m/min texturing speed, 200 °C heater temperature, Hemajet T341 type of nozzle.

Table 2
Typical one stage RFL adhesive formulation [6][a]

	Dry part (g)	Wet part (g)
RF solution		
Resorcinol	11.0	11.0
Formaldehyde	6.0	16.2
Sodium hydroxide	0.3	3.0
Soft water	–	235.8
Maturation: 25 °C, 6 h	17.3	266.0
Final dip solution		
RF solution	17.3	266.0
Latex	100	250.0
Ammonium hydroxide	–	11.3
Soft water	–	59.2
Maturation: 25 °C, 20 h	117.3	586.5

[a] Usually adhesion promoter is applied to this formulation.

Drawing and air-jet texturing of the feed yarns were performed in one step. The draw ratio was 2.15, and the temperatures of the drawpins were 55 and 75 °C, respectively.

The yarn with a code of 4CR was produced as a reference yarn by only drawing of four ends of core yarns without air-jet texturing with the same production parameters.

2.3. Tensile measurements

Tensile measurements were performed on a Textechno Statimat ME tensile tester at a gauge length of 500 mm and crosshead speed of 300 mm/min.

2.4. Optical microscopic studies

The arrangement of the filaments in the yarns was observed by means of Automatic Trinocüler Stereo Zoom Microscope (Olympus SZ6045 Model).

2.5. Scanning electron microscopy (SEM)

Scanning electron microscopy studies were carried out in order to analyze the effects of air-jet texturing on surface topography of single fibers and also on the yarn geometry. The equipment used was a Jeol JSM-6335F model scanning electron microscope.

Table 3
Yarn codes and the process parameters of the textured yarns

Yarn code	Feed yarns used	Overfeed of the core (%)	Overfeed of the effect (%)
4CR (reference yarn)	4 core	–	–
C3ED	1 core+3 effect	10	15
2C2ED	2 core+2 effect	10	15
4CC	4 core	10	–

2.6. Atomic force microscopy (AFM)

Atomic force microscopy belongs to a series of scanning probe microscopes invented in 1980s [8]. It allows imaging the topography of both conducting and insulating surfaces in atomic resolution. Therefore, it is a very useful technique for investigation of surface morphologies of the textile materials without any surface treatment such as coating. In this study a Benyuan CSPM4000 model AFM, in the Laboratories of Jiangnan University of China was used. Scanning was carried out in contact mode AFM and the fibers were immobilized on magnetic AFM sample stubs by the help of a double-sided tape. All the samples were scanned at ambient conditions.

2.7. Dynamic contact angle measurements and dynamic adsorption tests

Contact angle is the quantitative measurement of wettability for a solid surface being wetted by a liquid. The direct measurement of contact angle for small-diameter fibers is difficult and two methods are commonly employed: static drop micro-observation and dynamic testing method. However, the first method has many disadvantages as it can only acquire static contact angles [9]. Therefore, in this study the dynamic testing method based on the Wilhelmy technique, where a solid sample was immersed and withdrawn into and out from a liquid while simultaneously measuring the force acting on the solid sample [10] was used.

In addition to these dynamic contact angle measurements of the single fibers, wettability of textured yarns were also measured by means of dynamic adsorption tests.

Dynamic contact angle measurements and dynamic adsorption tests were performed on the same machine; CDCA-100F produced by Camtel Ltd., UK.

2.8. H-adhesion tests

After dipping of the air-textured polyester yarns by using a dipping simulator, they were impregnated H shaped rubber test specimens and were tested by measuring pull-out force in a Instron 4502 at a crosshead speed of 300 mm/min, ASTM D4776.

3. Results and discussion

Results of the tensile measurements are given in Table 4. As it is expected, tensile results show a decrease in tenacity due to air-jet texturing process. The air-jet texturing turbulence in the nozzle disorientates the filaments, resulting a decrease in tenacity of the textured yarn. In addition to this, an excess yarn length due to yarn overfeed the individual filaments can form loops [11] and therefore can be disorientated more easily.

In the case of core-and-effect air-jet textured yarns, filaments of the core components have less overfeed than filaments of the effect components. This gives a higher orientation to core filaments than the effect filaments with respect to the textured yarn axis. If the differences between the overfeed of core-and-effect filaments are large, then core filaments mainly take up the load and effect filaments contribute very little to tensile strength [12]. However, in this study, both of the overfeed levels were kept low and similar in order to achieve desired yarn properties, so both components contribute to tensile strength.

Table 4
Tensile results

Yarn code	Yarn count (dtex)	Tenacity (cN/dtex)	Elongation at break (%)
4CR	1156	4.84	12.65
C3ED	1250	3.09	13.75
2C2ED	1227	3.32	13.29
4CC	1172	3.74	12.25

Table 5
H-adhesion test results

Yarn code	Adhesion force (N)
4CR	27.53 ± 3.31
C3ED	42.63 ± 4.41
2C2ED	43.84 ± 4.30
4CC	27.36 ± 5.92

Extension behaviour of a textured yarn can be attributed to extension behaviour of the individual filaments and yarn packing. The originally parallel arrangement of the filaments to the yarn axis and their locations are altered due to air-jet texturing process. Filament entanglements and surface loops anchored in the yarn core are occurred, affecting the extension behaviour of the final yarn. In this study, an increase in breaking extension values of C3ED and 2C2ED was observed while a decrease was observed for 4CC. The increase in breaking extension values of C3ED and 2C2ED can be attributed to the looped structure of the textured yarns. While in case of 4CC there is no effect component to form loops. In addition to this, filaments were tangled slightly due to the production parameters resulting a decrease in extension values of 4CC.

When all the tensile measurements are concerned, as a result of the similar and low overfeed levels of the ends, it can be seen that both of the components play role in the tensile behaviour of the air-jet textured yarn. However, it is also seen that behaviour of the final yarn is mainly governed by the dominant component.

Table 5 shows the maximum pull-out forces of the H-adhesion tests. The results show an improvement in the adhesion to rubber after air-jet texturing process.

Yarn to rubber adhesion development can occur by mechanical entanglement (interlocking), primary chemical bond formation, specific physicochemical interactions such as hydrogen bonding, or molecular interfusion [13]. Since air-jet texturing is a fully mechanical process no change of the type of the bonds between rubber and yarn is expected. Therefore, the improvement of the adhesion has been attributed to two reasons below:

1. Changes on the fiber surface due to air-jet texturing.
2. Changes of the yarn geometry due to air-jet texturing.

The surface changes of the individual fibers firstly investigated by SEM analysis. Fig. 2 shows the SEM images of the fibers before and after air jet texturing. Comparing all the images no distinct surface change was observed due to air-jet texturing. However, because of the mechanical performance issues, in this work overfeed levels were kept low to maintain the parallel filament arrangement within the textured yarn. Therefore, effect of the air-jet texturing on the filament surface could be very little and due to coating of the filaments for SEM studies these changes could be hidden.

In order to have better understanding of the surfaces, AFM studies have also been carried out. Fig. 3 shows the AFM images of the filaments taken from the yarns before and after texturing. From these AFM images, some changes were observed in contrast to SEM images. However, no clear relationship between the surface changes and the texturing parameters could be established. Therefore, dynamic contact angle measurements of the filaments were also performed and the results were analyzed together with the AFM studies.

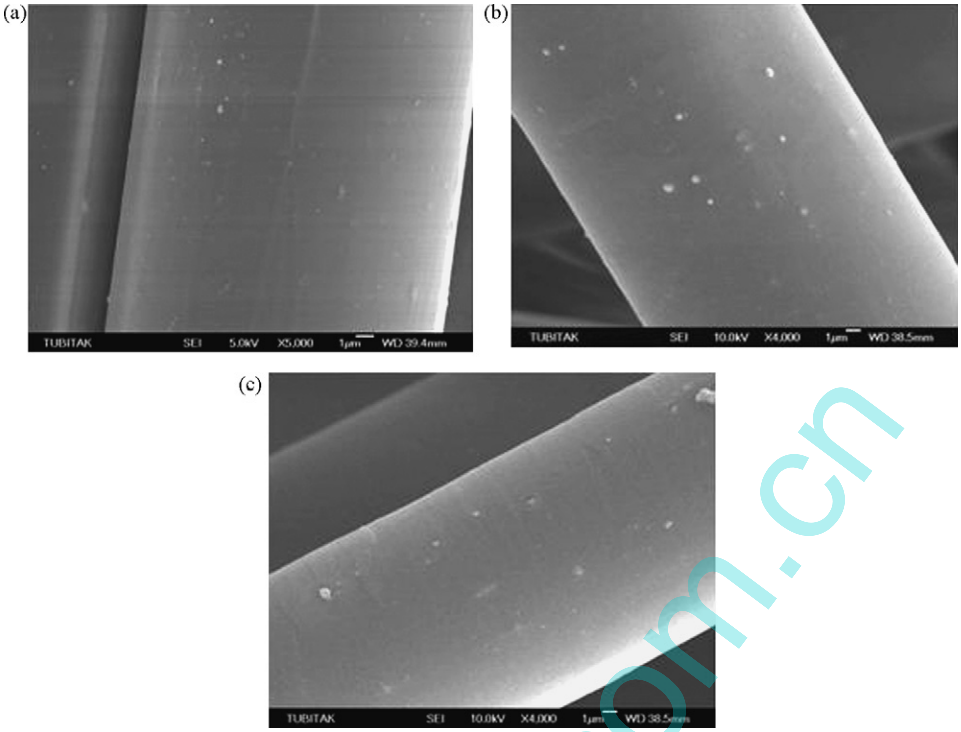

Fig. 2. SEM images of single filaments: (a) 4CR, (b) C3ED and (c) 4CC.

Table 6 shows the recorded advancing contact angle (Q_a), receding contact angle (Q_r), and hysteresis (H), values of the single fibers. All of these values represent the wettability of the fibers, however, it is declared that surface roughness have much more influence on receding contact angle while advancing contact is more related to the surface properties [9]. A decrease in Q_a and Q_r values for fibers taken from 2C2ED and 4CC yarns has been observed. This indicates changes in surface roughness. This result is in good agreement with AFM images. However, an increase in both Q_a and Q_r values were recorded for fibers taken from C3ED yarns. In texturing process the bulkiness of the yarn is obtained by the intermingling of the effect yarns by the air pressure. Therefore, fibers in the effect yarn move randomly during texturing. It is thought that as the number of the filaments in the effect component is the highest for C3ED sample, the filaments in the effect component behave as bundles rather than as individuals. Therefore, the effect of air pressure on the individual fiber surface can be minimal. This can also be seen in AFM image of C3ED (Fig. 3b).

Both the AFM images and the dynamic contact angle measurements conclude some surface changes on the filaments due to air-jet texturing. However, it is well known that yarn

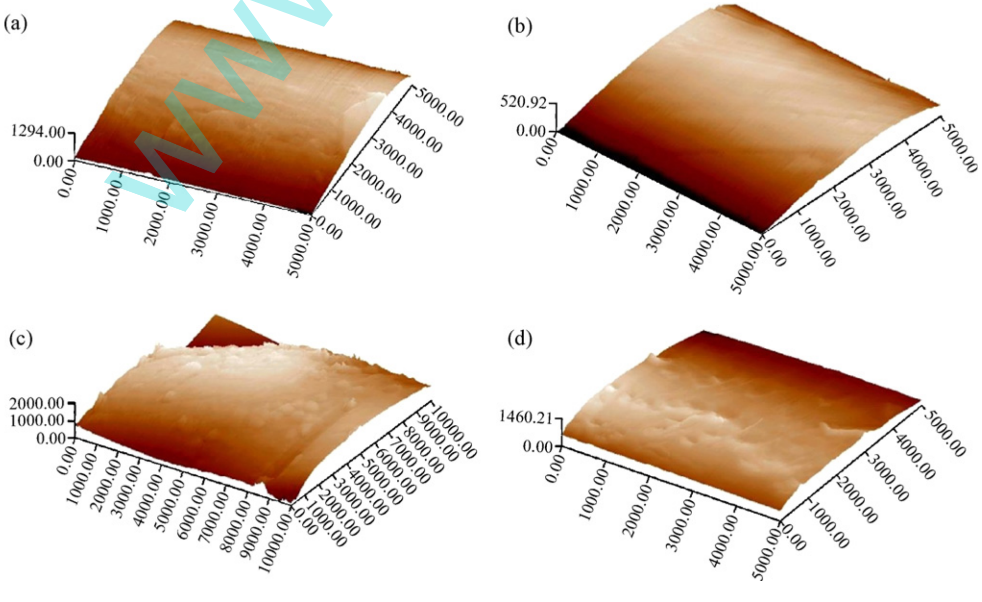

Fig. 3. AFM images of single filaments: (a) 4CR, (b) C3ED, (c) 2C2ED and (d) 4CC.

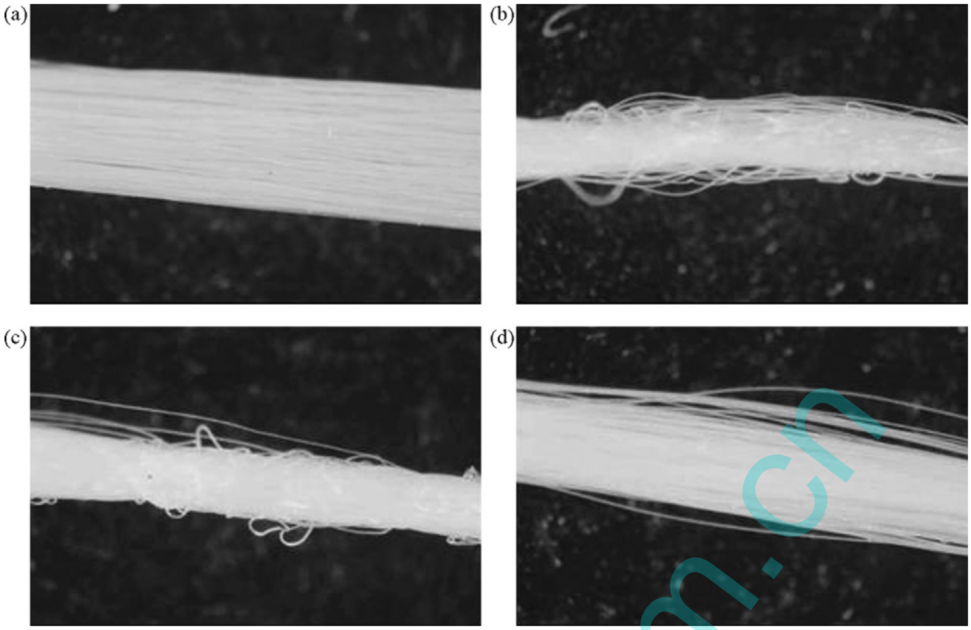

Fig. 4. Optical microscopic pictures of the textured yarns: (a) 4CR, (b) C3ED, (c) 2C2ED and (d) 4CC.

geometry is also very important on adhesion. Therefore, optical microscopic studies, SEM analysis and dynamic adsorption tests of the air-jet textured yarns have also been carried out.

Optical microscopic images of the yarns are given in Fig. 4. From these images, it can be seen that disorientation of the filaments increases due to the increase in overfeed levels and number of effect yarns. Disorientation of the filaments and loop formation is more distinctly observed in yarns composed of more number of effect components (C3ED), while the least disorientation is observed in 4CC yarn, which is composed of only four core ends. Although a looped structure is observed for both C3ED and 2C2ED yarns, size of the loops are still smaller than typical air-jet textured yarns (Fig. 1) due to the low overfeed levels.

Dynamic adsorption tests give information about the amount of liquid uptake in a certain period. Higher water uptake means higher wettability. Table 7 shows results of the dynamic adsorption tests. From these results it can be seen that air-jet texturing improves adsorption behaviour of the final yarns.

The SEM images of the cross-sectional shape of the textured yarns have been analyzed in terms of the yarn geometry and the dip penetration (Figs. 5 and 6). When the dip penetration is concerned, for all the yarns, an RFL penetration of two to four filaments has been observed indicating no increase in the penetration dept. It is known that an RFL penetration of two to three filaments is necessary for good adhesion. Deeper penetration does not contribute to adhesion [14].

Moreover, after air-jet texturing, a distinctive yarn geometry change, which may play a more important role on the improvement of adhesion, was seen. The textured yarns have “lobed” cross-sectional shape depending on the number of components in the yarn while the un-textured yarn (4CR) showed circular cross-section with no “lobes”. This change in the yarn geometry increases the contact area between the yarn and RFL and this improves the adhesion to rubber.

Table 6
Dynamic contact angle measurement results

Yarn code	Advancing contact angle (°)	Receding contact angle (°)	Hysteresis (°)
4CR	85	50	35
C3ED	86	63	23
2C2ED	74	44	30
4CC	71	46	25

Table 7
Dynamic adsorption test results

Yarn code	Water uptake in 120 sn (mg)
4CR	13
2C2ED	17
C3ED	16.5
4CC	19

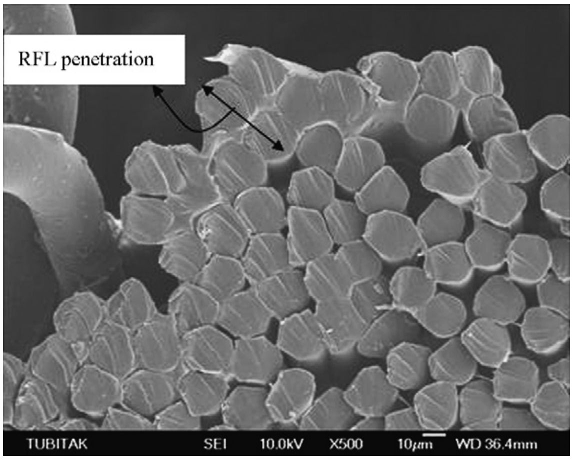

Fig. 5. RFL penetration: cross-sectional view of 2C2ED yarn.

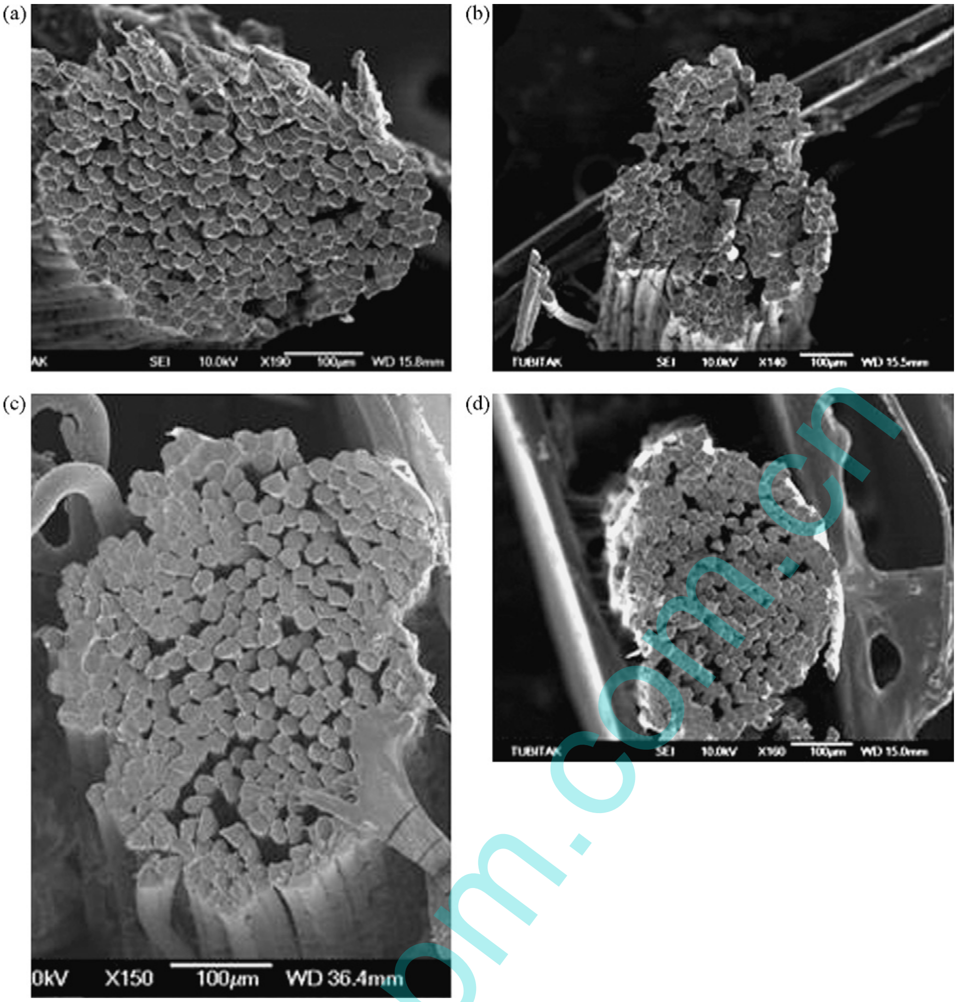

Fig. 6. Cross-sectional views of the yarns: (a) 4CR, (b) C3ED, (c) 2C2ED and (d) 4CC.

4. Conclusion

In this study we aim to improve adhesion to rubber behaviour of PET without introducing expensive and difficult methods where the fiber properties can also be altered. Air-jet texturing of conventional PET yarns was performed without any visible loop formation by keeping the overfeed levels for both core and effect yarns low and an improvement in the adhesion to rubber of conventional PET yarns was achieved. Even though the overfeed parameters were kept very low, in order not to disturb the filament orientation within the textured yarns so that the strength reduction could be minimal, still strength reductions were recorded. Therefore, in the second part of this study, some of the air-jet texturing parameters such as drawing and thermal setting would be investigated to improve the mechanical performance as well. Although no clear change of the surface topography on the single fibers was observed by SEM due to air-jet texturing, some surface changes were seen by the help of both AFM and dynamic contact angle measurements. This surface changes, however were minimum due to low overfeed levels. Therefore, the improvement of adhesion behaviour of conventional PET yarns was mainly attributed to change in the cross-sectional shape of the yarns after air-jet texturing. Since the objective of our main project is to improve the adhesion of high modulus and tenacity PET to rubber by using air-jet texturing, as this study has concluded that air-jet texturing is an inexpensive, fully mechanical and environmentally friendly method to improve the adhesion behaviour of PET to rubber, we continue our studies considering the results of this preliminary work.

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