Adhesion improvement at polyester fabric-silicone rubber interface by plasmas of argon and air to obtain conveyor belt

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ABSTRACT – REZUMAT

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Conveyor belt production requires good adhesion between coating layer and fabrics. Adhesion is important for good mechanical properties of belts. Silicone rubber has gained importance in food carrying because it is harmless when being in contact with food materials. The aim of this study is to enhance the problematic adhesion properties between polyester fabrics and silicone rubber coating by plasma treatment. The fabrics are modified by air or argon RF plasmas under different power and time conditions. Influence of plasma parameters was investigated by adhesion strength tests. To investigate changes on adhesion, wettability measurements, X-ray photoelectron spectrometry (XPS), Atomic Force Microscopy (AFM), scanning electron microscopy (SEM) were performed untreated and plasma treated polyester fabrics. After plasma treatments, the coating adhesion between fabric and coating polymer was increased approximately for 4.6 times for argon and 4.3 times for air plasmas.

Keywords: *adhesion; plasma; polyester; silicone; fabric.*

Îmbunătățirea aderenței la interfața dintre țesătura de poliester și stratul de cauciuc siliconic, prin tratarea cu plasmă de argon și aer pentru obținerea benzilor transportoare

Realizarea benzilor transportoare necesită o bună aderență între stratul de acoperire și materialele textile. Aderența este importantă pentru proprietățile mecanice ale acestora. Cauciucul siliconic a câștigat importanță în transportul alimentelor, deoarece este inofensiv atunci când intră în contact cu produsele alimentare. Scopul acestui studiu este de a îmbunătăți proprietățile de aderență între țesăturile de poliester și stratul de cauciuc siliconic, prin tratamentul cu plasmă. Țesăturile sunt tratate cu plasme de aer sau argon RF în diferite condiții de putere și timp. Influența parametrilor tratamentului cu plasmă a fost analizată, prin teste de rezistență la aderență. Pentru a analiza modificările de aderență au fost realizate determinări ale capacității de umezire, spectrometrie fotoelectronică cu raze X (XPS), microscopie de forță atomică (AFM), microscopie electronică de scanare (SEM), pe țesături din poliester netratate și țesături tratate cu plasmă. După tratamentele cu plasmă, aderența dintre țesătură și polimerul de acoperire a fost crescută de aproximativ 4,6 ori pentru argon și de 4,3 ori pentru plasmele de aer.

Cuvinte-cheie*: aderență, plasmă, poliester, silicon, material textil*

INTRODUCTION

Conveyor belts are usually produced by one or more layers of coated fabric products. These products need high strength because they are used strained to carry materials. Polyester is the most used textile material for the production of conveyor belts. Polyester fibers have inert chemical structure and smooth surfaces so the adhesion between polyester and coating polymers is difficult to obtain [1–3]. Adhesive chemicals are used in the coating recipes to be able to overcome this difficulty. However, the chemical process is not a complete solution and in order to increase the adhesion, an adhesive is used at the interface. When coating with silicone rubber, the adhesion strength is too low to be used as a conveyor belt. Therefore, there are researches for alternative methods of enhancing adhesion [4–6].

Adhesion is sticking two different materials to each other by mutual interactions and formation of chemical bonds with a product and important to many materials; such as coating or composite structures [2, 7–10]. The cause of high strength of conveyor belts is the adhesion strength between coating polymer and fabric. The highest adhesion strength between two polymers is obtained when covalent bonds are formed. Adhesion properties are influenced by two properties of polymers (here fiber-coating polymer) simultaneously: surface energy and macromolecular mobility. There are four fundamental mechanisms that contribute to the total adhesion between two polymer materials: mechanical interlocking, interdiffusion of chains, electrical interactions and chemical interactions [3, 7–8, 11–13]. Two different solutions can be regarded to increase the adhesion between coating polymer and the fabric. The polymer side, a high molecular weight polymer having good mechanical properties can be used and for substrate side, surface roughness and surface energy can be increased by different treatments (like plasma) to enhance entanglement [13]. Surface energy gives an idea about the hydrophilic and hydrophobic nature of the material. For instance, hydrophilic materials have

high surface energy with low contact angle and good wettability. These properties are related to adhesion strength [4, 14]. Air plasma treatments of polymer surfaces improve the adhesion strength by increasing both the surface roughness and surface energy of the material. The polar groups creation at the polymer surface and increasing the surface roughness could enchance coating layer adhesion. There are forces of physical and chemical adsorption on the polymer surface which is modified by different treatment methods to for polar groups. The formation of polar groups results in the formation of covalent bonds which are primarily responsible for adhesion [6, 13, 15–17].

Plasma technology is one of the proper methods to improve adhesion properties by changing surface properties of materials with its superficial effects up to 100 Aº. Surface properties are changed and surface becomes suitable to adhesion by plasma processing. Additionally, plasma treatments do not harm the mechanical properties of the product like the other processes do. Plasma processing is a dry and environmentally-friendly technique, which does not call for a vast supply of water, heating or drying, and requires only little amounts of chemicals to reach the desired functionality. Investigating literature, it is seen that plasma treatment about polyester materials are focused on wettability, dyeability and yield in wet treatment [3, 12, 18–24]. Applying plasma technology, it is possible to obtain or increase the number of chemical groups at the interface that enhance binding between polymer and fiber. In addition, the adhesion surface area between polymer and fiber is increased. As a result of this, the adhesion of the fabric and the polymer was improved. Plasma treatment is used also to improve the adhesion of other polymers such as polyethylene fibers with epoxy resin [25], aramide fibers with epoxy resin [26–28]. It is seen that in order to obtain enhancement in adhesion properties, many researches are applied plasma treatments to various polyester materials e.g. polyester with rubber, polyester film with silicone film [5, 6], polyester fabrics with polyurethane, fluoropolymers and also for lamination [3–4, 11, 29–33].

The aim of this study is to enhance the problematic adhesion properties between polyester fabrics and silicone rubber coating. Motivation for this research was the good results of our preliminary work [34]. In order to solve the problem of adhesion, low-pressure plasma technology was used. This type of plasma has more homogenous effects than atmospheric plasmas and can penetrate deeper than atmospheric plasmas [17, 35]. Air and argon gases, different discharge powers and time in plasma processes were applied to polyester fabrics. To observe the effect of plasma treatments on surfaces, X-Ray Photoelectron Spectrometry (XPS) analysis were performed. After that plasma treated fabrics were coated by silicone rubber. Then adhesion properties of the plasma were examined by adhesion strength measurements.

EXPERIMENTAL

Materials

300 g/m^2 plain weave (1:1) 100% polyester fabric was used. The settings in both warp and weft direction and linear densities of warp and weft yarns were 13 cm^{-1}, 9 cm^{-1}, Nm 6 and Nm 11, respectively. Fabrics were supplied by Rultrans Transmisyon A.S. Fabrics were used as received.

Plasma treatments

Plasma polymerization treatments were carried out in PICO RF (radio frequency 13.56 MHz) Plasma Polymerization System (Diener electronic GmbH + Co. KG, Germany). After placing the fabric inside reactor was evacuated to 30 Pa and air and argon was allowed to flow through the reactor. Polyester fabrics were modified in air and argon gases and various plasma polymerization conditions (discharge power: 20–80 W and exposure time: 1–30 min). At the end of the process, the generator was turned off and argon gas was allowed to flow for 10 min to deactivate free radicals. Effects of plasma were characterized on the fabrics by X-ray photoelectron spectrometry (XPS) analysis, hydrophilicity and Scanning Electron Microscopy (SEM) analysis.

Coating

Untreated and plasma treated polyester fabrics were coated with silicone rubber. The recipe is given below:

– 90 wt% DC M-RTV Mould Making Silicone Curing Agent (Dow Corning Corp.)
– 10 wt% M-RTV Base Mould Making Silicone Curing Agent (Dow Corning Corp.)

Coating recipe was applied with a knife at 1 mm coating gap and cured for 2 minute at a curing temperature of 180 ºC.

Adhesion tests

The adhesion between the silicone rubber and polyester fabrics was measured and evaluated according to TS EN ISO 252 and TS ISO 6133, respectively. For measurements Instron 4411 Universal Testing Machine was used. Six strips 25 mm wide and 200 mm long were prepared from each coated fabric sample. The peeling speed was 100 mm/min.

Hydrophilicity measurements

Hydrophilicity of treated and untreated fabrics was measured by means of capillary rise measurement. For the capillary rise test, three samples of each coated fabrics were prepared as 20×2 cm^2 strips parallel to the warp direction. The strips were mounted in parallel to a millimeter scale and the lower ends of the strips were partly immersed into a diluted (1 wt%) potassium chromate aqueous solution. Height readings were made at the 10th, 30th, and 60th seconds of the first minute and at time intervals of 30 s in the following 4 min.

X-Ray Photoelectron Spectroscopy (XPS)

XPS measurements of untreated and plasma treated polyester fabrics were recorded on a PHI 5000 Versa Probe in METU Central Laboratory. This device is equipped with monochromatized aluminum X-ray source having a pass energy of 187.85 eV. Spectra were taken at 45°. Curve fitting of the C1s peak was done using XPSpeak 4.1 software. Because of the surface charging of non-conductive polymers (in our case polyesters), shifting of spectra occured. Shifted spectra were corrected to compensate for this effect using reference value of peak of C–C/C–H bonds as 285.0 eV [36].

Scanning Electron Microscopy (SEM)

Scanning electron microscopy (SEM) was utilized to observe and evaluate the change in surface morphology of polyester fabrics before and after plasma treatment. Samples were coated with Au-Pd prior to imaging. SEM observations were performed by Quanta 400F Field Emission scanning electron microscope in METU Central Laboratory. Magnifications were set at 250×, 1000× and 10000×.

Atomic Force Microscopy (AFM)

The topography of the polyester fabrics was investigated by means of atomic force microscopy by Veeco Multi Mode V in METU Central Laboratory. Measurements were carried out in tapping mode. Scan area was 5×5 μm^2. Samples were measured in air.

RESULTS AND DISCUSSIONS

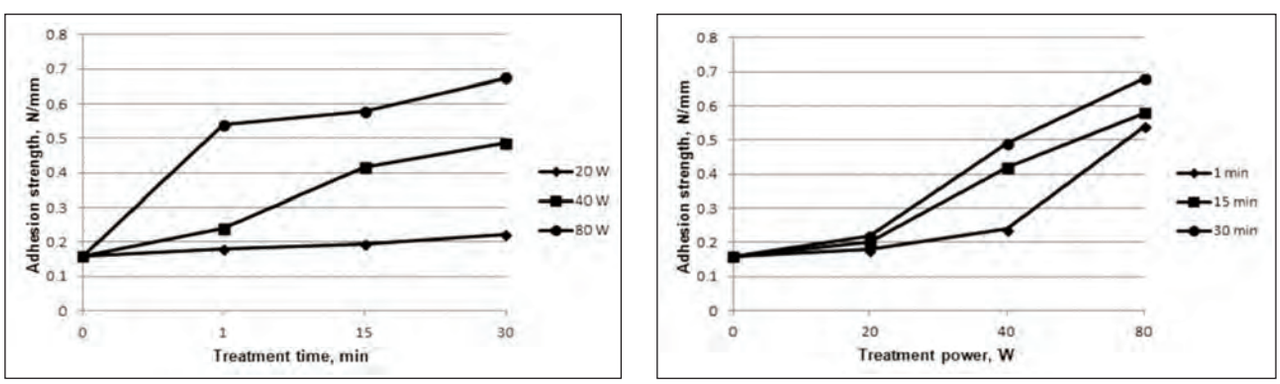
Effects of plasma modification on adhesion strength

Adhesion strengths of untreated and plasma treated coated fabrics were given in figures 1 and 2. As seen in figures, low pressure plasma treatments improved adhesion between polyester fabric and silicone rubber coating.

The adhesion strength value of untreated polyester fabric is 0.16 N/mm. As can be seen from the figures, there was almost no change in adhesion strength for 20 W/1 min plasma treated samples for both plasma gases. This adhesion strength value was the lowest among all air and argon plasma treatments.

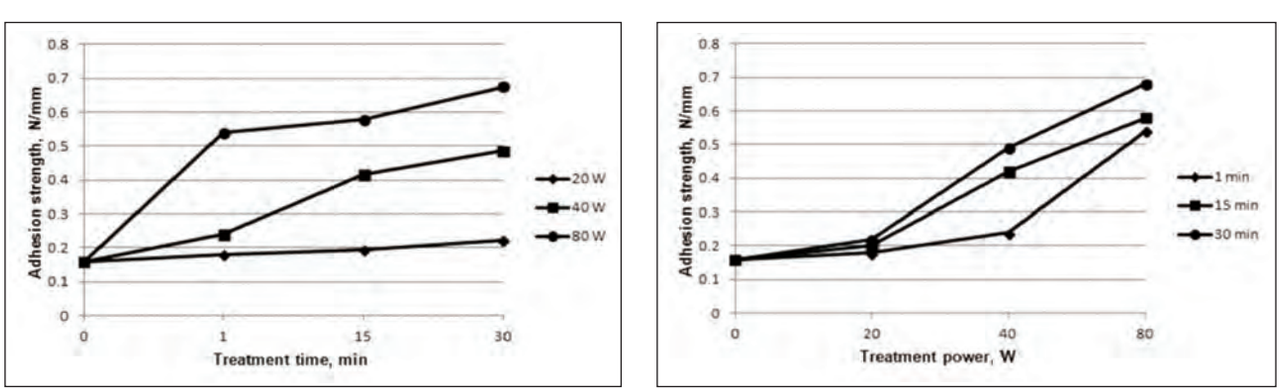
For air plasma treatments, at low power conditions (20 W), the duration of plasma treatment has almost no effect on adhesion strength (figure 1, *a*). However, increasing the power, the effect of air plasma time can be seen clearly. The adhesion strength at 40 W/30 min is 104% higher than the adhesion strength at 40 W/1 min.

In figure 1, *b*, the effect of air plasma power on adhesion strength at different plasma times can be seen.



a *b*

Fig. 1. *a* – the effect of air plasma power on adhesion strength at different plasma treatment times, *b* – the effect of air plasma treatment time on adhesion strength at different plasma treatment powers



a *b*

Fig. 2. *a* – the effect of argon plasma power on adhesion strength at different plasma treatment times, *b* – the effect of argon plasma treatment time on adhesion strength at different plasma treatment powers

In this figure, the biggest change in increase in adhesion strength was obtained between 40 W/1 min and 40 W/15 min plasma conditions for air plasma. For all time conditions, the adhesion strength values at 80 W plasma power are approximately three times higher than the values at 20 W plasma power. The highest adhesion strength was obtained at the condition of 80 W/30 min as 0.68 N/mm. This value is quadruple of the value of untreated fabric.

In figure 2, *a* and *b*, the effects of argon plasma power and argon plasma time on adhesion strengths are shown. It can be seen that 20 W argon plasma conditions are highly effective on adhesion strength of polyester fabrics contrary to air plasma, except 20 W/ 1 min. For example, while the adhesion strength value after 20 W/30 min air plasma was 0.22 N/mm, the adhesion strength value after 20 W/ 30 min argon plasma was 0.37 N/mm.

Regarding the effects of argon plasma time (figure 2, *a*), the biggest difference obtained at 20 W from 1 min to 30 min. The increase rates of adhesion strength values from 1 min to 30 min are 110%, 15%, 21% for 20 W, 40 W, 80 W, respectively. The highest adhesion strength was obtained at the condition of 80 W/30 min as 0.73 N/mm. Regarding the effects of argon plasma power (figure 2, *b*), the adhesion strength at 40 W/1 min is approximately three times higher than at 20 W/1 min.

For air and argon plasma treatments, increasing plasma power and time caused an increase in adhesion strength and the highest coating adhesion value was obtained at 80 W/30 min plasma condition. However, it can be seen from the results that power is more effective than time as plasma condition. In addition, according to the results, argon plasma treatments are found to be more effective than air plasma treatments.

Hydrophilicity of fabrics

The effects of discharge power and exposure time parameters on the hydrophilicity of untreated and plasma treated polyester fabrics were evaluated and presented graphically in figures 3 and 4.

All plasma treatments seem to enhance the hydrophilic character of polyester fabrics. Even at initial rises at 10 s, this effect can be seen for all plasma conditions. This capillary values are 1.3 cm, 1.8 cm, 2.1 cm, 3.0 cm, 1.9 cm, 2.3 cm, 3.2 cm for untreated and 40 W/30 min air, 80 W/1 min air, 80 W/ 30 min air, 40 W/30 min argon, 80 W/1 min argon and 80 W/30 min argon plasma treated fabrics, respectively (figure 3, *a*).

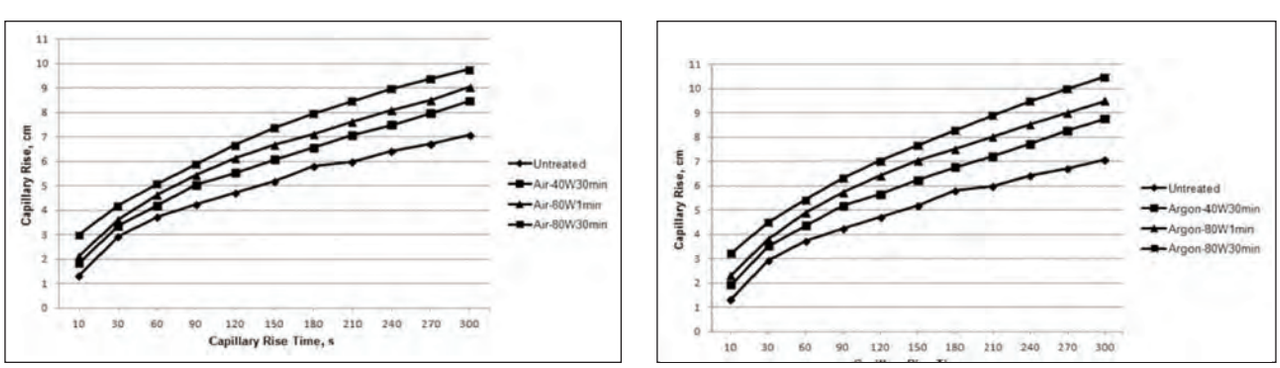
As can be seen from the figures and the values, argon plasma treatments enhance hydrophilicity more than air plasma treatments. As stated in literature, increase in wettability is caused by argon plasma due to surface oxidation. Even argon plasma has no oxygen atoms, oxidation reactions occur at the carbon radicals after finishing plasma discharge [37]. The capillary rise value at 300 s for air and argon plasma at 80 W/30 min is 15%, 20% higher than the rise at 40 W/30 min, respectively. Additionally, the capillary rise values at 300 s for air and argon plasma at 80 W/30 min were 8% and 11% higher than the values at 80 W/1 min, respectively. These results show that the RF plasma power is more effective than RF plasma duration time. Furthermore, these results support the results of adhesion strength measurements (figure 3, *b*).

XPS measurement

In order to detect the effects of plasma treatments on the chemical composition of the surfaces, XPS analysis was applied. XPS spectra of untreated, air plasma and argon plasma treated polyester fabrics are shown in figure 4. In this XPS wide survey spectra, the main photoelectrons of carbon, oxygen and nitrogen can be seen.

All survey spectra show photoelectron peaks at binding energies of ~532 eV, ~400 eV, ~285 eV, and ~164eV, which can be attributed to the O1s, N1s, C1s, and S2p, respectively [20]. Additionally, Si2p peak is observed (at ~102 eV) in one spectrum as seen in table 1. The reason for this can be the contamination from the silicone coating paste. Atomic percentages of carbon, oxygen, nitrogen and the other atoms found in the surface of untreated and treated polyester fabrics are given in table 1.

The atomic concentrations of carbon and oxygen of the untreated polyester fabric was 84.4 % and 15.6 %, respectively. The best adhesion obtained at 80 W/ 30 min in argon plasma. For that fabric sample, the atomic concentration of carbon was decreased



a *b*

Fig. 3. The effect of: *a* – air and *b* – argon plasma treatments on capillary rise (cm) of polyester fabrics

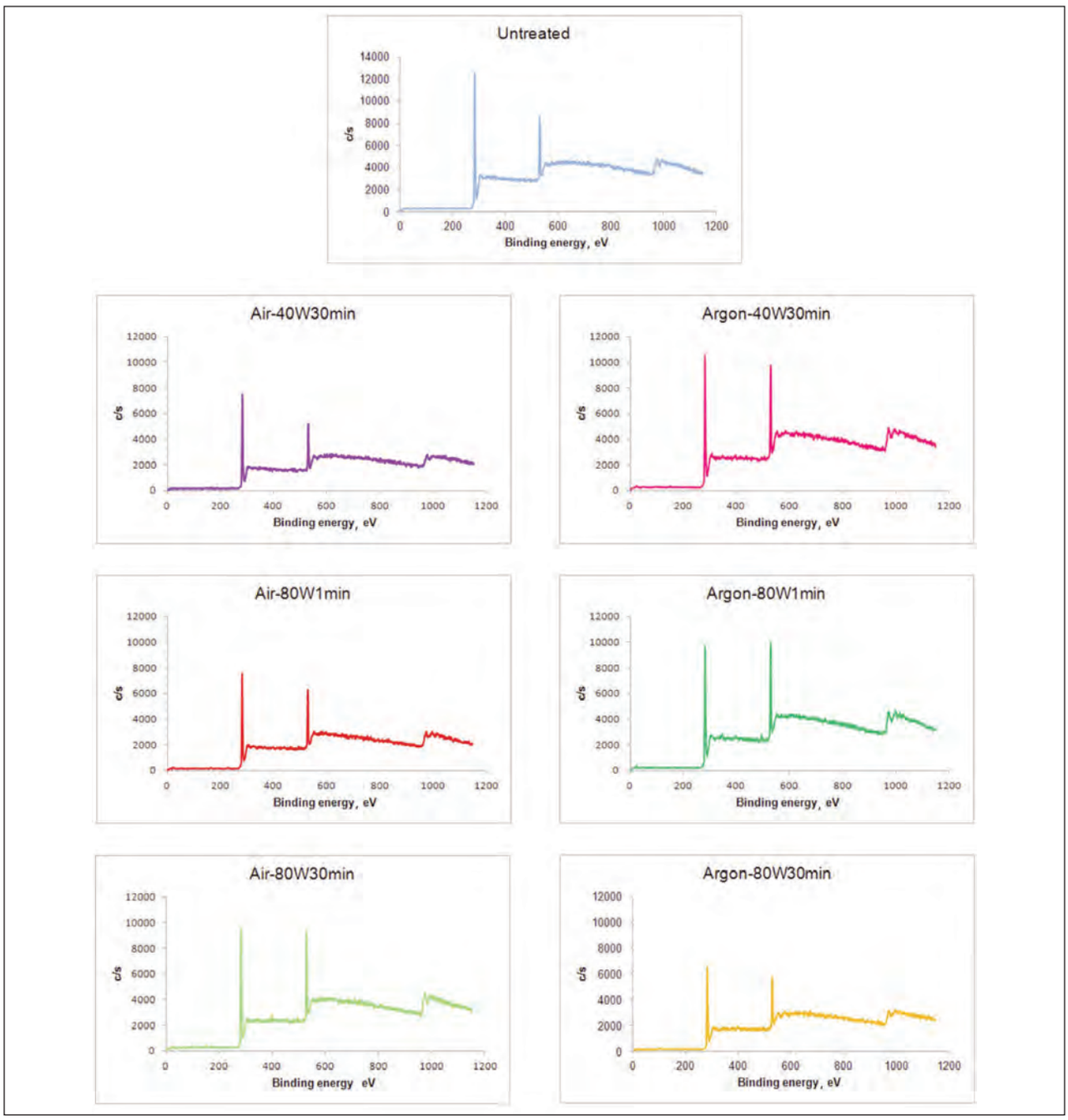


Fig. 4. XPS results of untreated and treated polyester fabrics

Table 1

CHEMICAL COMPOSITIONS AND O/C ATOMIC RATIOS FOR UNTREATED AND PLASMA TREATED POLYESTER SURFACES

Fabrics	Surface chemical composition (%)					Atomic ratio O/C
	C	O	N	S	Si	
Untreated	84.4	15.6	-	-	-	0.19
Air-40 W/30 min	81.9	18.1	-	-	-	0.22
Argon-40 W/30 min	77.1	22.3	0.7	-	-	0.29
Air-80 W/1 min	79.8	20.2	-	-	-	0.25
Argon-80 W/1 min	77.1	22.2	0.7	-	-	0.29
Air-80 W/30 min	73.9	22.7	2.0	0.2	1.1	0.31
Argon-80 W/30 min	75.1	23.7	1.2	-	-	0.32

(75.1 %). Contrary to carbon, oxygen showed an increase in a concentration as 23.7 %. Incorporated oxygen atoms after plasma treatments were increased by time and power conditions. Argon plasma is known to lead to cross-linking in combination with surface oxidation. If cross-linking is dominant, it inhibits surface oxidation resulting in lower oxygen functionalities [38–40]. However, in this research, oxygen functionalities increased after treatments which shows that cross-linking has not dominate yet in these conditions. As seen in table 1, O/C atomic ratios were increased for all plasma treated samples compared to untreated one (0.19). For 80 W/30 min air and argon plasma treated samples,

O/C ratios were found as 0.31, 0.32, respectively. Regarding these increased ratios, it can be concluded that oxygen-containing functional groups are formed on the polyester fabric surface after air or argon plasma and these may be the reason of increase hydrophilicity [5, 40–41]. Additionally, very small amounts of nitrogen and sulphur were found on polyester surfaces after all argon plasma treatments and 80 W/30 min air plasma treatment. This may confirm the deposition of reactive species on plasma treated active surfaces [42].

Peak fitting of C1s peaks of XPS spectra for untreated and plasma treated fabrics were realized to get detailed information about the altered species on the polyester surfaces. C1s high resolution spectra were fitted to investigate the functional groups formed after air and argon plasma treatments (figure 5). Percentage ratios of plotted areas of peaks are given in table 2.

C1s core level spectrum of untreated polyester fabric is shown in figure 5, *a*. The peaks of C1s spectrum for untreated polyester at 285.0 eV, 286.4 eV and 289.0

Table 2

RESULTS OF DECONVOLUTION OF C1s PEAKS

Fabrics	Ratios of C1s components (%)			
	–C–C– 285.0 eV	**–C–O– 286.4 eV**	**O=C–O 289.0**	**–C=O 288.0 eV**
Untreated	65.21	29.03	5.76	-
Air-40 W/30 min	64.71	28.36	6.93	-
Argon-40 W/30 min	64.12	25.81	10.07	-
Air-80 W/1 min	63.47	29.78	6.75	-
Argon-80 W/1 min	61.71	28.08	9.62	0.58
Air-80 W/30 min	61.36	29.33	9.31	-
Argon-80 W/30 min	47.73	33.81	13.47	4.99

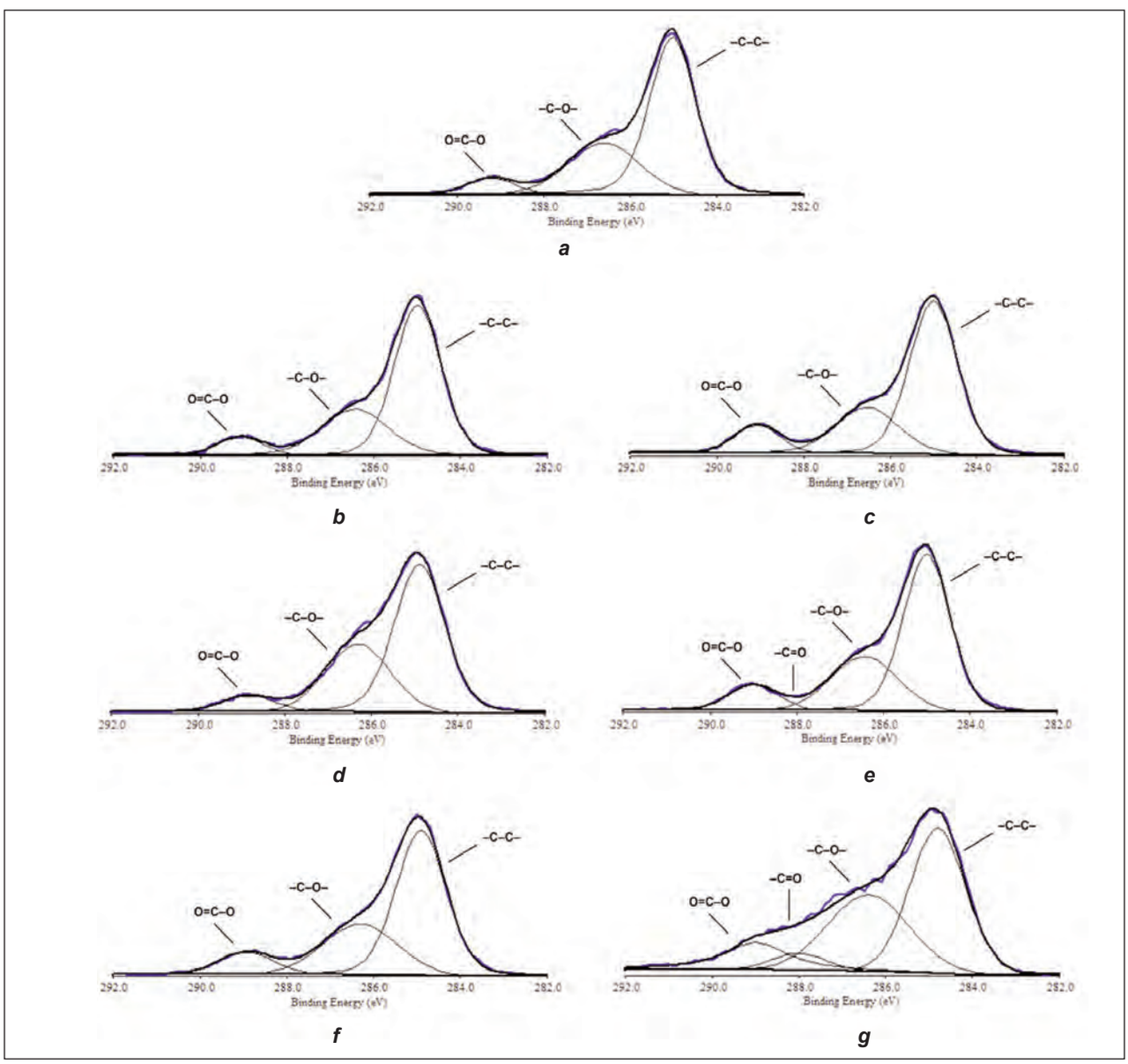


Fig. 5. C1s spectra of polyester fabrics: *a* – untreated, *b* – air-40 W/30 min, *c* – argon-40 W/30 min, *d* – air-80 W/1 min, *e* – argon-80 W/1 min, *f* – air-80 W/30 min, *g* – argon-80 W/30 min

eV may be identified as –C–C–, –C–O– and O=C–O, respectively [38, 42–44]. The plasma treatments, as shown in figure 5, *b, c, d, e, f, g*, led to obvious changes in the C1s spectra. In 80 W/1 min and 80 W/30 min argon plasma conditions, a new peak at 288.0 eV was detected and it may be attributed to –C=O bond. As seen from the figure 5, oxidation on the surfaces was significant by the increase in the intensities of the –C–O– and O=C–O peaks compared to the intensities of the –C–C– peak [43]. These results indicate that some of the –C–C– bonds in polymer surface may be broken by the bombardment by the active species in plasma medium. Increase in the hydrophilicity of polyester fabrics may be due to the increase in the polar groups [42]. The highest alteration in C1s peaks was obtained from 80 W/30 min argon plasma treated polyester fabric. These alterations are observed as decrease in –C–C– peak and increases in peaks of oxygen containing groups on the polyester surface. Besides, radicals are produced on the polymer surface by plasma treatments via polymer chain scission or hydrogen abstraction. Possible combination of these radical species with atmospheric gas atoms, contribute the increase in the amount of polar groups on the treated polymer surfaces [44]. This combination can be the reason for nitrogen and sulphur atoms were detected in XPS wide survey spectra.

SEM

SEM image of untreated fabric is given in figure 6.

As seen in figure 6 and as known, surface of polyester fibers is quite smooth. However, in this figure small particles are seen on the surface. To identify which elements are present in these particles, SEM-EDX (energy dispersive X-ray microanalysis) was conducted. Figure 7, *a* and *b* shows SEM image of a particle and its EDX spectrum, respectively. The particle was identified as NaCl crystal. The reason for having these particles on the fiber surfaces can be the insufficient removal of fiber/fabric production chemicals.

SEM images of plasma treated fabrics are presented in figure 8.

In figures 6 and 8, it is seen that there has not been a lot of changes in the fiber morphology. Only change is the increase in the amount of particles on the fabric surface, parallel to the increase in plasma power and time. Figure 8, *e* and *f* shows the SEM images of the polyester fabrics after air-80 W/30 min and argon-80 W/30 min plasma treatments, respectively. Especially in extended plasma treatments, accumulation can be seen on the polyester fiber surfaces. SEM-EDX analysis was conducted to investigate this accumulation for 80 W/30 min air plasma treated fabric (figure 9, *a, b*). Results of his SEM-EDX showed that this deposited matter was composed of mostly C and O atoms. Therefore, we can conclude that these particles were

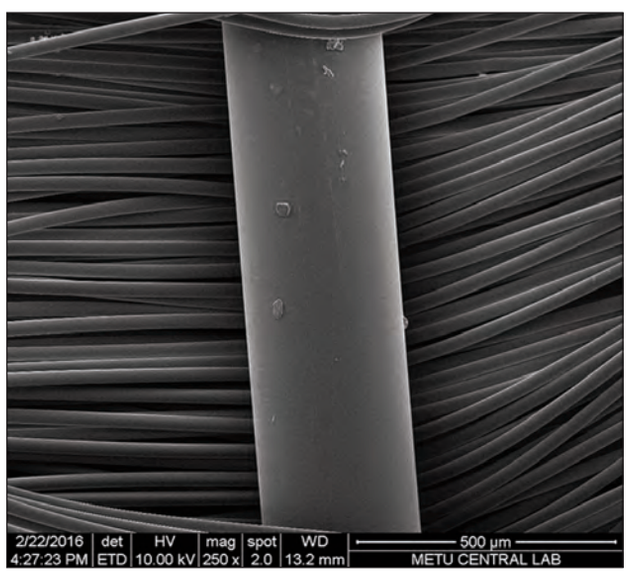
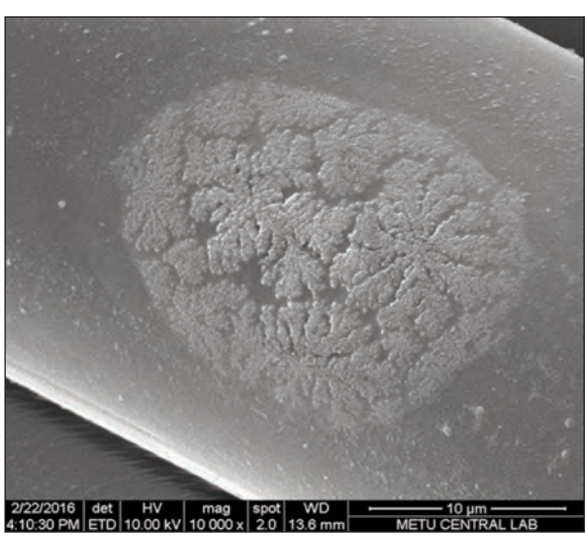
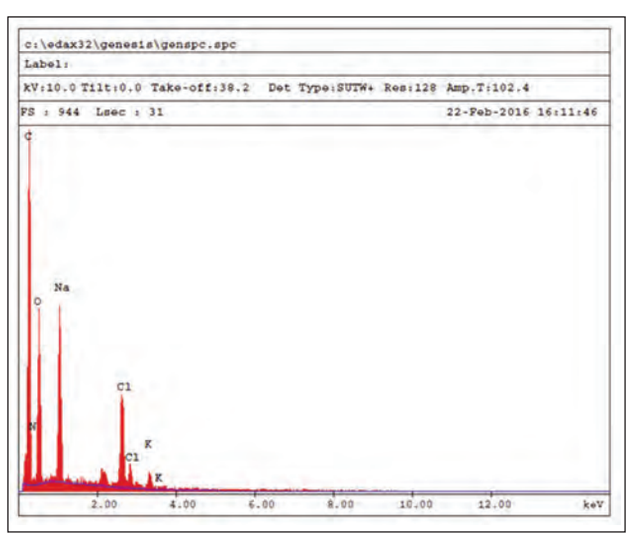


Fig. 6. SEM image of untreated polyester fabric



a



b

Fig. 7. *a* – SEM image of argon-80 W/1 min plasma treatment, *b* – EDX analysis of argon-80 W/1 min plasma treatment

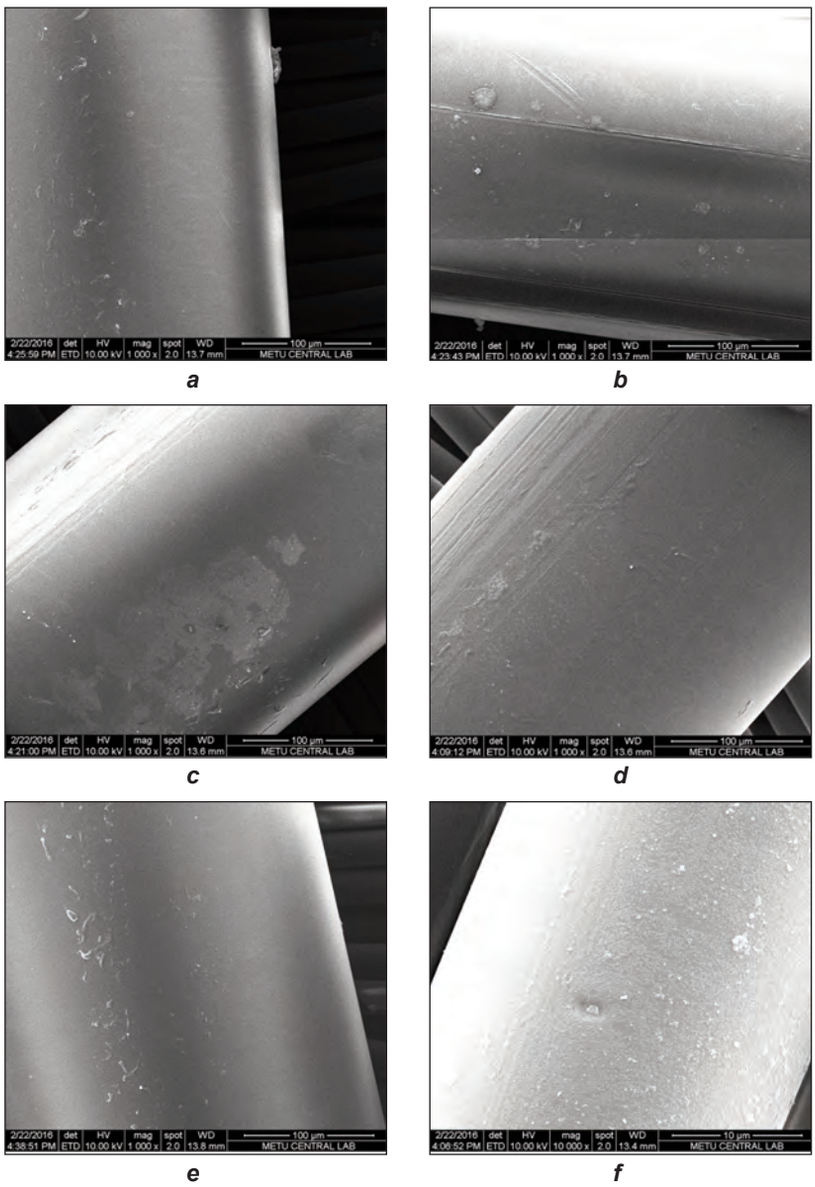


Fig. 8. SEM images of plasma treated polyester fabrics: *a* – air-40 W/30 min, *b* – argon-40 W/30 min, *c* – air-80 W/1 min, *d* – argon-80 W/1 min, *e* – air-80 W/30 min, *f* – argon-80 W/30 min

coming from polyester fibers, which were destroyed and deposited on the fiber surfaces because of the collisions occurred in the discharge medium [40].

As can be seen from the figures, SEM images did not indicate significant difference between untreated and plasma treated polyester fabrics. Because, scanning electron microscopy has limited depth resolution, morphological changes below micrometer size are difficult to detect. For this reason, atomic force microscopy was applied to obtain more detailed morphological information about the fiber surfaces [44, 45].

AFM

To investigate topography of the polyester fabric surfaces, AFM images (figure 10) were taken from untreated and plasma treated polyester fabrics. In addition, surface roughness data was collected from samples. The root mean square roughness (R_q) values are seen in table 3.

Untreated polyester fabric had smooth and uniform surface. However, the surfaces became rough after air and argon plasma treatments [43]. This suggested that effects of air and argon plasmas showed effective etching processes. Argon plasma caused more roughness than air plasma. Poletti et al. explained the reason for this, as the difference between average

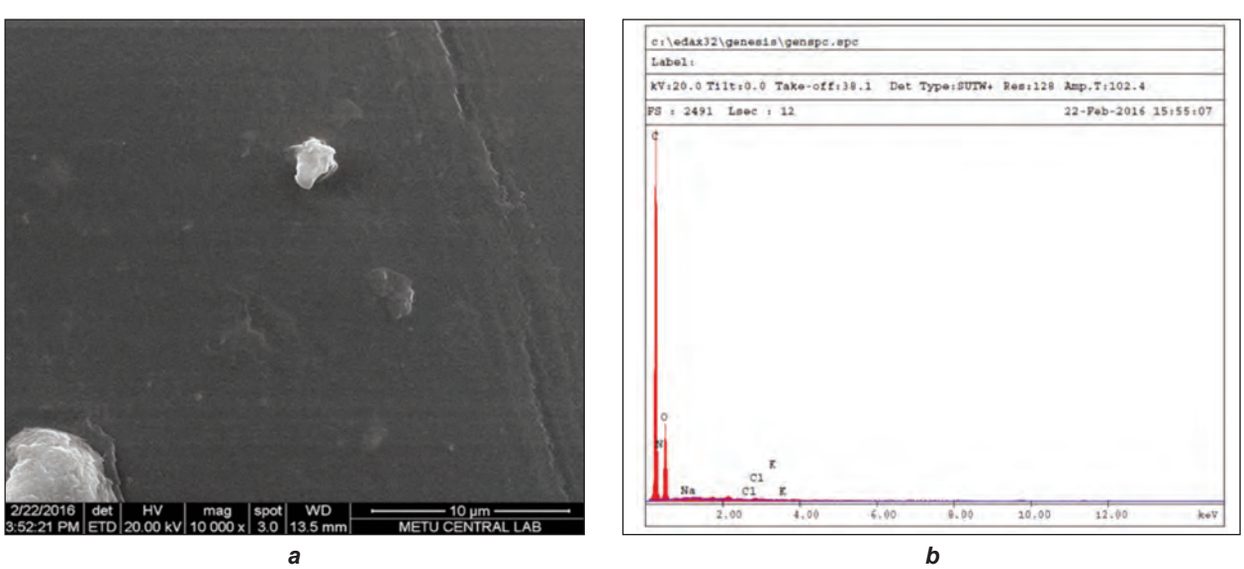


Fig. 9. *a* – SEM image of air-80 W/30 min plasma treatment, *b* – EDX analysis of air-80 W/30 min plasma treatment

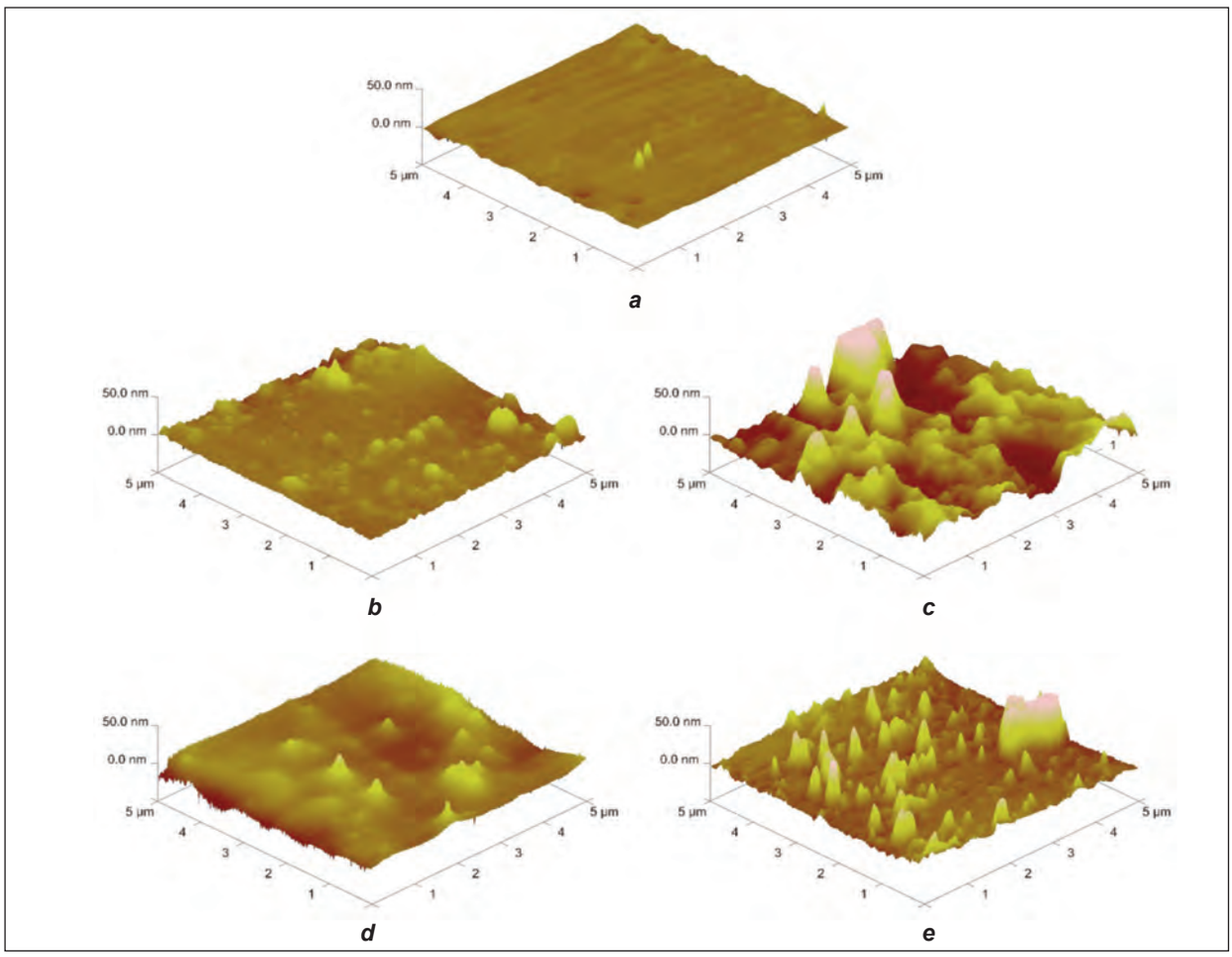


Fig. 10. AFM images of untreated and plasma treated polyester surfaces: *a* – untreated, *b* – air-80 W/1 min, *c* – argon-80 W/1 min, *d* – air-80 W/30 min, *e* – argon-80 W/30 min

Table 3

THE ROOT MEAN SQUARE ROUGHNESS (R_q) VALUES OF UNTREATED AND PLASMA TREATED POLYESTER FABRICS

Fabrics	R_q (nm)
Untreated	1.39
Air-80 W/1 min	3.86
Argon-80 W/1 min	9.45
Air-80 W/30 min	5.23
Argon-80 W/30 min	9.71

dimensions of the bombarding ions, i.e. argon ions are bigger than the ions in air. This could be also attributed the significant etching effect of the noble gases [45]. In addition, increase in air and argon plasma times increased the surface roughness of polyester fabrics. These results are convenient with literature. As can be seen from the results of AFM and XPS analyses, the increase in hydrophilicity can be attributed to both the roughened surface and the incorporation of polar atoms [39, 42–43, 45]. The results of AFM analysis also confirmed that argon plasma is superior to air plasma for improvement of adhesion.

CONCLUSION

In this article, at various plasma conditions (different plasma powers and plasma times) of polyester fabrics with air and argon gases are modified, these fabrics coated by silicone rubber and then adhesion strengths were measured. It was showed that plasma pretreatments have led to an increase in adhesion strength of problematic coating between the polyester fabric and silicone rubber coating by both air and argon plasmas. Comparing influences of the plasma parameters, plasma power was found to be superior to plasma time. Capillary rise measurements confirmed these findings. Oxygen containing functional groups are increased by increasing power and time of plasma treatments. The best adhesion strength obtained at 80 W/30 min treatment condition in argon plasma. All plasma treatments increased the wettability and adhesion strength. However, the roughness of the polyester fabrics was increased by the increase in plasma treatment time. As indicated by the analyses and test performed, the adhesion strength was enhanced mainly due to an increased surface roughness and presence of oxygen containing groups on the plasma treated polyester surface.

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