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Helium/Oxygen Atmospheric Pressure Plasma Treatment on Poly(ethylene terephthalate) and Poly(trimethylene terephthalate) Knitted Fabrics: Comparison of Low-stress Mechanical/Surface Chemical Properties

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Abstract: Helium-oxygen plasma treatments were conducted to modify poly(trimethylene terephthalate) (PTT) and poly(ethylene terephthalate) (PET) warp knitted fabrics under atmospheric pressure. Lubricant and contamination removals by plasma etching effect were examined by weight loss (%) measurements and scanning electron microscopy (SEM) analysis. Surface oxidation by plasma treatments was revealed by x-ray photoelectron spectroscopy (XPS) analyses, resulting in formation of hydrophilic groups and moisture regain (%) enhancement. Low-stress mechanical properties (evaluated by Kawabata evaluation system) and bulk properties (air permeability and bust strength) were enhanced by plasma treatment. Increasing interfiber and interyarn frictions might play important roles in enhancing surface property changes by plasma etching effect, and then changing low-stress mechanical properties and bulk properties for both fabrics.

Keywords: Plasma, Etching, PTT, PET, Surface modification

Introduction

It is known that first synthesis of poly(trimethylene terephthalate) (PTT), one of polyesters, was reported by Whinfield and Dickson of the Calico Printers Ink in 1940's [1]. However, the commercialization of PTT has been delayed due to the high cost of 1,3-propanediol until Shell Chemical introduced a new method in 1995. Although poly(ethylene terephthalate) (PET) has good properties and has been used widely in textile industry, PTT has been paid remarkable attentions by textile industries as a new textile material for film, carpet, and textile applications [1,2]. Compared to *trans* molecular structure of PET, PTT has *trans-gauche-gauche-trans* sequence structure in a unit crystal cell [3], influencing thermal and mechanical properties. Its molecular structure resulted in the lower melting temperature of PTT, rendering enhanced spinning processibility [4,5], lower crystallinity [3,6,7], higher elongation [5], higher strain recovery and shrinkage [8]. In addition, it was reported that PTT had better dyeability than PET due to lower crystallinity enhancing dye absorption [9-11].

Bombardments of plasma active species induce a removal of contamination on substrate surface (cleaning effect) or incision of outmost surface (etching effect). Plasma etching effect can cause surface morphology change and micro-roughness on substrate surface physically. In plasma treatments for polymeric materials, slack molecules in amorphous region is etched more easily than rigid crystalline region; that is, etching behaviors is predominated over amorphous region preferably (a selective etching) [12]. Generally, it is known that bulk properties of substrate are not depreciated because depth of plasma treatment is hundreds of Å layers. However, it was reported that tensile strength of plasma treated fabrics was enhanced at short exposure times due to increasing interfiber and interyarn frictions, resulted from etching effect on surface [13]. Previous studies [13-15] showed that the severe plasma treatments in low-pressure plasma led to higher degradation extensively, resulting in decreasing tensile strengths of fibers and fabrics at long exposure time and high power. In atmospheric pressure plasma, active species (ions and electrons) have lower energies than low-pressure plasma due to shorter mean free lengths [16]. In our previous study [17] we found that strength of single filament increased at some conditions in helium atmospheric pressure plasma without surface morphology change. This is probably because cross-linking formation would be dominated over etching effect [18], and then tensile strength and modulus increased [17,19].

Though bulk property changes by etching effect were not consistent with plasma conditions, it has been explained clearly that low-stress mechanical properties of fabrics were affected significantly by low-pressure plasma treatments [20-22]. Increasing interfiber and interyarn frictions, resulted from an increase of fiber surface friction due to etching, played important roles in changing low-stress mechanical properties. However, there has been few study about low-stress mechanical property changes of fabrics in atmospheric pressure plasma treatment. In addition, compared to PET fabrics, very few attentions

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have been paid on low-stress mechanical properties of PTT fabrics. In this paper, the low-stress mechanical and surface chemical properties of PTT and PET warp knit fabrics were studied before and after helium/oxygen atmospheric pressure plasma treatments.

Experimental

Fabric Preparation

For this experiment, PTT and PET warp knitted fabrics were produced using two bar warp knitting machine. Both fabrics were designed with a structure of 1 × 1 double tricot (1012/1210) using same yarn specification (75/36), and their densities were 20 course/cm and 28 wale/cm. After manufacturing both knit fabrics, heat setting was conducted at 150 °C for PTT and 180 °C for PET. The density and weight of PTT fabric (22 course/cm and 33 wale/cm, 83.6 g/cm^2) was higher than PET (22 course/cm and 30 wale/cm, 75.3 g/cm^2) after heat setting. No additional finishing process was applied for both prepared fabrics.

Plasma Treatment

An atmospheric pressure plasma system in this study was designed and fabricated in North Carolina State University for textile industrial applications as shown in Figure 1. This capacitively-coupled plasma system can be operated under atmospheric pressure at audio frequency range (1-12 kHz), and the applied voltage across two electrodes was 7.5 kV_{rms}. In order to generate stable and uniform plasma under atmospheric pressure, helium was fed into the plasma chamber as an initiating gas, and then oxygen was mixed. We could obtain stable and uniform plasma at frequency, 5.0 KHz through the operation. The samples were cut into 25 × 25 cm, and then were placed in the middle of plasma chamber. Gas flow rates were 13 lpm (liter per minute) for helium and 0.15 lpm for oxygen, and plasma exposure times were 2 and 4 minutes.

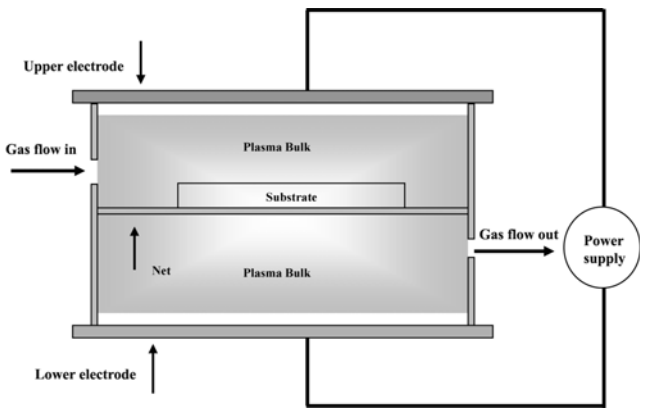

Figure 1. Schematic diagram of capacitively-coupled atmospheric pressure plasma system.

Measurement

Scanning electron microscopy (SEM) and weight loss (%) measurement were conducted to evaluate surface morphology change and etching effect of plasma. Both plasma treated fabrics were examined at magnifications of 2,500 × at 5.0 kV, using Hitachi model S-3200 after coated with gold by sputtering technique. Weight loss (%) was calculated based on weight reduction of fabrics right after plasma treatment as follow equation:

$$\textit{Weight loss (\%)} = \frac{(W_0 - W_i)}{W_0} \times 100 \quad (1)$$

where W_0 is the initial weight of the fabric and W_i is the weight of the fabric after plasma treatment. Plasma treated samples were conditioned under 20 ± 2 °C and 65 ± 2 % RH for 24 hours, and then dried in a oven at 80 °C for 24 hours. The weight difference after conditioning was estimated as moisture regain (%) as following equation:

$$\textit{Mositure regain (\%)} = WT_1 - WT_2 \quad (2)$$

where WT_1 is the weight loss (%) of the fabric right after plasma treatment and WT_2 is the weight loss (%) of the plasma treated fabric after conditioning.

Kawabata evaluation system (KES-FB) was used to estimate low-stress mechanical properties of plasma treated PTT and PET fabrics [23]. Tensile, shearing, bending, surface and compression properties, measured in warp and weft direction, were listed in Table 1. Air permeability of plasma treated fabrics was tested using air permeability tester (Model: FX3300, Texstest, AG/Switzland) according to ISO 9237 method (Textiles - Determination of the permeability of fabrics to air). The fabric testing area was 38 cm^2 with a pressure 10 Pa. Burst strength measurements were conducted according to ASTM D3787-89 (Standard Method for Bursting Strength of Knitted Goods-Constant-Rate-of-Traverse (CRT) Ball Burst Test).

Surface chemical change on fabric surface was examined using X-ray photoelectron spectroscopy(Perkin Elmer PHI 5400 XPS photospectrometer). X-ray source was Mg_α (1,253.6 eV) with take-off angle, 45 °, and scanning depth, 1-10 nm. The pressure in the XPS chamber was hold at between 10^{-9} and 10^{-10} torr. The XPS data were obtained through a RBD Enterprises model 147 controlling system in a Windows^{TM}-based environment. For peak deconvolution analyses, five carbon components assigned to binding energies of 285.0 eV (-C-C-C-), 286.2 eV (-C-O-), 286.6 eV (-COH), 288.7 eV (-C=O) and 289.3 eV (-COO-) based on PTT and PET molecular structures [24]. Also, four oxygen components were examined at binding energies assigned to 531.2 (CH=O), 532.3 eV (-C=O), 533.2 eV (C-O-C), and 533.6 eV (-C-OH).

Statistical analyses, one-way analysis of variance (ANOVA) and Turkey pair-wise multiple comparison, were performed for the results of air permeability and burst strength among different plasma treatment groups [25].

Table 1. The low-stress mechanical properties of PET and PTT fabric tested on the KES-FB system

	Properties[1]	Symbol	Definition	Units
Tensile	Linearity	LT	Linearity of the load-extension curve	-
	Tensile energy	WT	Energy in extending fabric to 500 gf/cm width	gf·cm/cm^2
	Tensile resilience	RT	Percentage energy recovery from tensile deformation	%
Shear	Shear stiffness	G	Average slope of the linear region of the shear hysteresis curve to ±2.5 ° shear angle	gf/cm · degree
	Shear hysteresis at 0.5 °	2HG	Average width of the shear hysteresis loop at ±0.5 ° shear angle	gf/cm
Bending	Bending rigidity	B	Average slope of the linear regions of the bending hysteresis curve to 1.5 cm^{-1}	gf·cm^2/cm
	Bending hysteresis	2HB	Average width of the bending hysteresis loop at 0.5 cm^{-1} curvature	gf·cm/cm
Surface	Coefficient of friction	MIU	Coefficient of friction between the fabric between the fabric surface and a standard contractor	-
	Mean deviation	MMD	Mean deviation of MIU	-
	Mean deviation of roughness	SMD	Variation in surface geometry of the fabric	μm
Compression	Linearity	LC	Linearity of compression/thickness curve	-
	Compression energy	WC	Energy in compressing fabric under 50 gf/cm^2	gf·cm/cm^2
	Compression resilience	RC	Percentage energy recovery from lateral compression deformation	%
	Thickness at 0.5 gf/cm^2	T_0	Fabric thickness at 0.5 gf/cm^2 pressure	mm
	Thickness at 50 gf/cm^2	T_m	Fabric thickness at 50 gf/cm^2 pressure	mm

[1]Tensile, shear, bending, and surface properties were measured in both weft and warp directions.

Results and Discussion

Plasma Etching Effect

The bombardments of plasma active species into substrate surface play an important role in etching effect, leading to surface morphology change and weight loss [12,15,26]. Figure 2 shows the changes of weight loss (%) and moisture regain (%) after plasma treatment. Weight loss (%) of both fabrics increased with an increase of exposure time after plasma treatment, and PTT fabrics had higher weight loss (%) than PET at all plasma conditions. Compared to PET, it was known that PTT had lower crystallinity because of has *trans-gauche-gauche-trans* sequence molecular structure [3,6]. Plasma etching behavior is a selective etching, which is predominated over amorphous region in polymers. Thus, it is expected that PTT would be more susceptible to etching effect than PET due to higher amorphous region. PTT fabrics showed higher moisture regain (%) at all plasma conditions. It seems that PTT can be oxidized more easily than PET by plasma treatment due to lower rigidity of PTT surface. Then, plasma surface oxidation would render moisture absorption to fabrics from air, resulting in weight gain for both plasma treated fabrics after conditioning. The results of increasing weight loss (%) after drying corresponded with moisture absorption behavior of plasma treated fabrics, suggesting hydrogen bonds between moisture and hydrophilic functional groups on fabric surface.

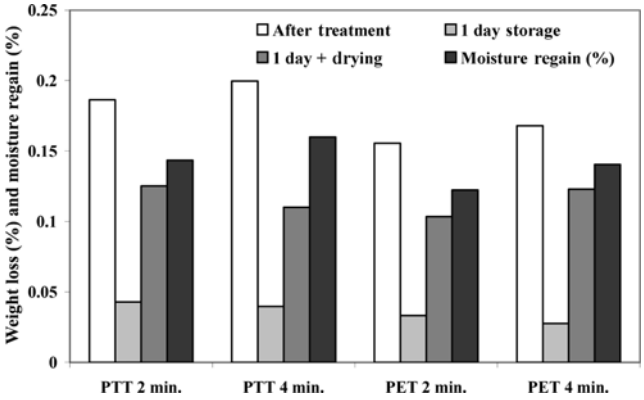

Figure 2. Weight loss (%) and moisture regain (%) of PTT and PET warp knitted fabrics after He/O_2 atmospheric pressure plasma treatment.

SEM analyses (Figure 3) showed that there was not apparent surface morphology change for both plasma treated fabrics, but contamination removals on fabric surface. Control fabrics would obtain a lubricant and contamination through knitting processes. However, plasma treatments removed some of contamination on fabric surface due to etching effect. The surface of both fabrics became cleaner with an increase of plasma exposure time.

Surface Modification by Plasma

XPS analyses were conducted to characterize surfaces of plasma treated PTT and PET fabrics. Typical XPS survey scans of PTT and PET fabrics are presented in Figures 4 and 5, respectively. Increasing oxygen intensity showed that PTT and PET fabrics were oxidized significantly by plasma treatment.

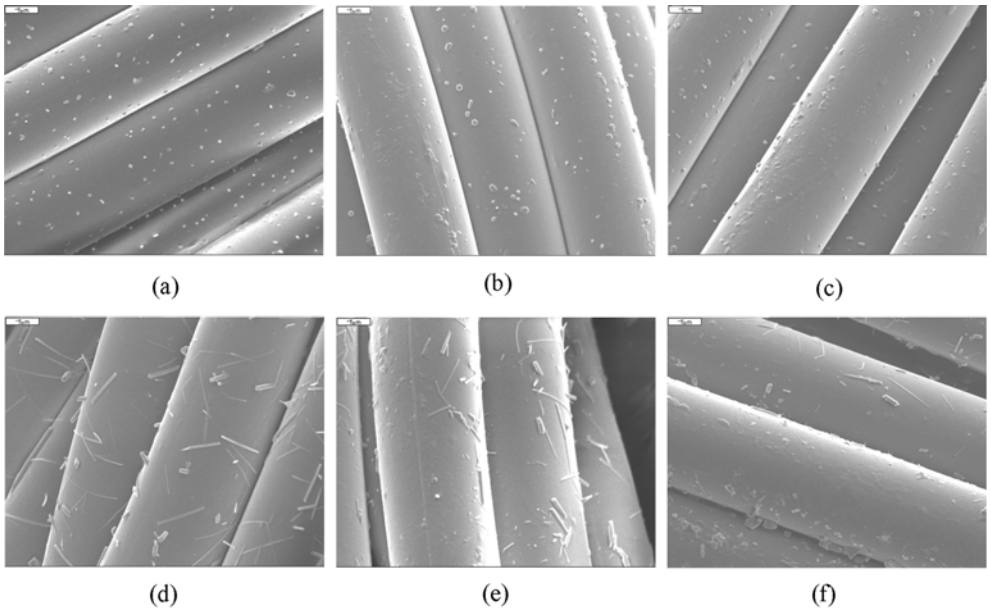

Figure 3. SEM photographs of PTT and PTT fabrics treated by He/O_2 atmospheric pressure plasma: (a) PET control, (b) PET 2 min., (c) PET 4 min., (d) PTT control, (e) PTT 2 min., (f) PTT 4 min.

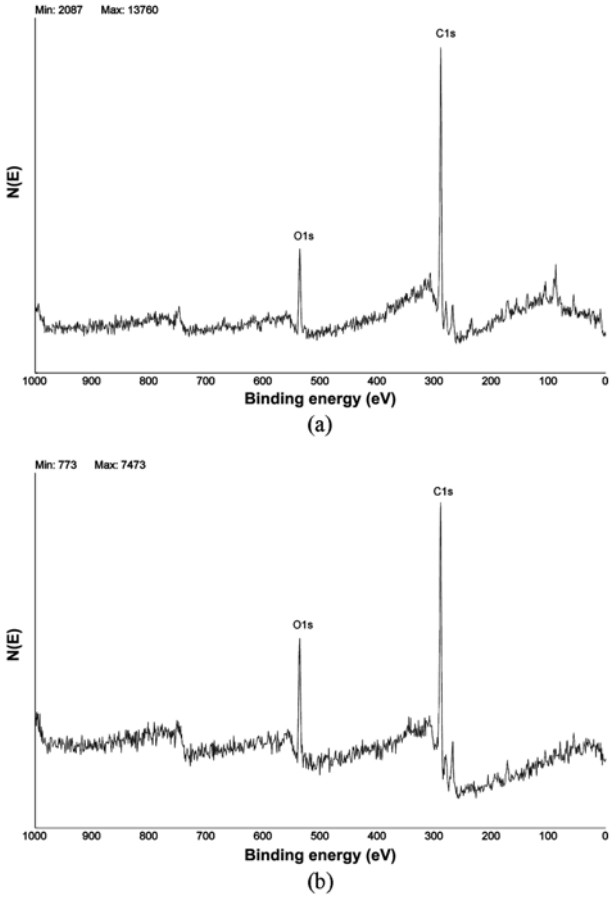

Figure 4. XPS survey scan of PET warp knitted fabrics treated by He/O_2 atmospheric pressure plasma: (a) control, (b) 2 min.

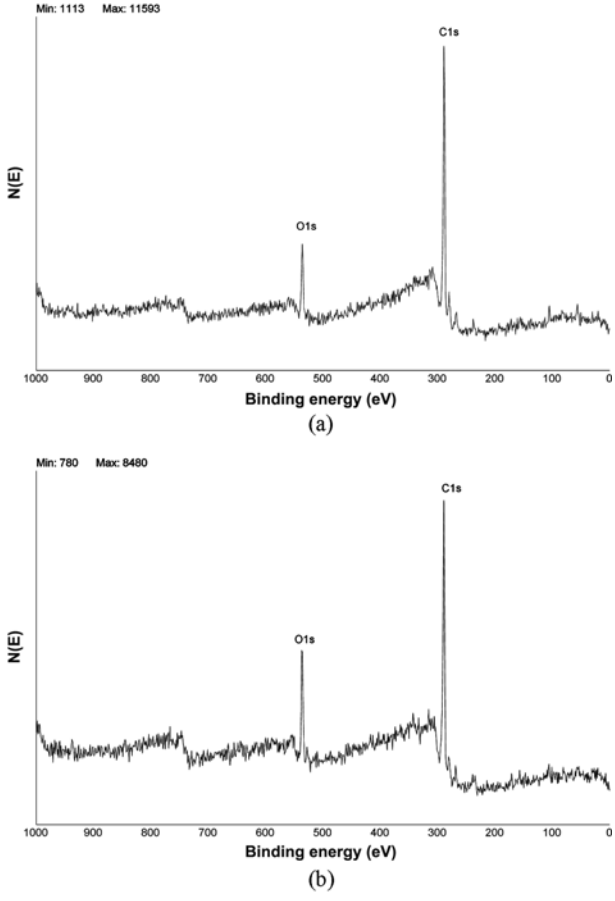

Figure 5. XPS survey scan of PTT warp knitted fabrics treated by He/O_2 atmospheric pressure plasma: (a) control, (b) 2 min.

Table 2. Relative chemical composition and atomic ratios determined by XPS for PTT and PET warp knitted fabrics untreated and treated with He/O_2 atmospheric pressure plasmas

Fabrics	Treatment	Chemical composition, %				Atomic ratio, %		
		C_{1s}	N_{1s}	O_{1s}	Si	O/C	N/C	(O+N)/C
PTT	Control	88.2	0.7	9.2	1.9	0.10	0.01	0.11
	2 min.	79.8	1.7	17.3	1.2	0.22	0.02	0.24
	4 min.	73.8	1.0	24.9	0.3	0.34	0.01	0.35
PET	Control	86.4	0.0	10.1	3.5	0.12	0.00	0.12
	2 min.	81.2	0.8	15.9	2.1	0.20	0.01	0.21
	4 min.	76.8	2.1	19.3	1.8	0.25	0.03	0.28

Table 3. C_{1s} deconvolution analysis for PTT and PET warp knitted fabrics untreated and treated with He/O_2 atmospheric pressure plasmas

Fabrics	Treatment	Relative area corresponding to different chemical bonds, %				
		C-C	C-O	C-OH	CH=O	COO
PTT	Control	77.7	13.3	3.6	0.6	4.8
	2 min.	73.7	8.3	10.7	4.2	3.1
	4 min.	72.3	6.5	13.5	5.6	2.1
PET	Control	77.7	13.4	4.8	0.9	3.2
	2 min.	74.8	9.2	10.2	2.0	3.8
	4 min.	73.4	7.6	10.9	4.6	3.5

Table 4. O_{1s} deconvolution analysis for PTT and PET warp knitted fabrics untreated and treated with He/O_2 atmospheric pressure plasmas

Fabrics	Treatment	Relative area corresponding to different chemical bonds, %			
		CH=O	C=O	C-O	C-OH
PTT	Control	24.2	45.5	20.4	9.9
	2 min.	35.5	23.8	11.7	29.0
	4 min.	40.2	15.2	6.5	38.1
PET	Control	25.5	47.3	16.6	10.6
	2 min.	32.4	31.7	12.4	23.5
	4 min.	38.6	21.5	8.8	31.1

In addition, the relative chemical compositions for both fabrics were changed significantly after plasma treatments as shown in Table 2. Oxygen contents (O_{1s}) of plasma treated fabrics increased with an increase of plasma exposure time while carbon contents (C_{1s}) decreased. Thus increasing O/C and (O+N)/C ratios showed that polymer surface became hydrophilic through plasma treatment. Increasing nitrogen content (N_{1s}) revealed the chemical interactions between surface radicals and nitrogen, existing in the chamber through plasma treatment under atmospheric pressure. It is noteworthy that reduction of silicon contents (Si_{2p3}) was related to cleaning effect on fabric surface by plasma etching. Plasma treated PTT fabrics showed higher oxygen content (O_{1s}), O/C and (O+N)/C ratios than PET fabrics at all plasma conditions. These results indicate that surface oxidation of PTT is more substantial to plasma treatment than PET. Peak deconvolution analyses (C_{1s} and O_{1s}) (Tables 3 and 4) confirmed higher susceptibility of PTT to plasma surface oxidation fabric than PET, showing higher C-OH and CH=O groups and moisture regain (%).

Low-stress Mechanical Properties of Plasma Treated Fabrics

Tables 5 and 6 show the low-stress mechanical properties of PTT and PET knitted fabrics in warp and weft directions after plasma treatments. Previous studies showed that plasma etching effect altered surface properties, influencing on other mechanical properties [7,21,22]. For both fabrics, it was observed that surface properties (surface friction (MIU), mean deviation (MMD) and surface roughness (SMD)) were changed significantly after plasma treatment. Surface friction (MIU) increased after plasma treatment for both fabrics in both directions, while mean deviation (MMD) and surface roughness (SMD) decreased. Lubricant used in knitting process could introduce oily surface into control fabrics, resulting in low surface friction. Plasma etching might increase an increase of surface friction (MIU) and reduce mean deviation (MMD) and surface roughness (SMD) simultaneously by removing a lubricant on fabric surface. Even though SEM did not observe surface morphology change on fabric surface, surface cleaning was significant, corresponding with the results of surface roughness (SMD) and mean deviation (MMD). In both directions of fabrics, it was found that plasma treatments enhanced tensile, bending, and shearing properties. Increment of tensile energy (WT), bending rigidity (B), and shear stiffness (G) was related to surface friction enhancement, resulting in increasing interfiber and interyarn friction. In addition, increasing surface friction affects fabric recoverability after tensile, bending, and shearing deformation. The results showed that tensile resilience (RT) and compression resilience (RC) decreased after plasma treatment and that bending hysteresis (2HB) and shearing hysteresis (2HG) decreased. When stress

Table 5. KES-FB results for He/O_2 plasma treated PTT and PET warp knitted fabrics in warp direction*

KES-FB parameters		Plasma exposure time, min.					
		PTT			PET		
		Control	2	4	Control	2	
Tensile	LT	0.940	0.977 (3.9%)	0.973 (3.5%)	0.663	0.680	(2.6%)
	WT (gf·cm/cm^2)	0.287	0.327 (14.0%)	0.320 (11.6%)	0.140	0.173	(23.8%)
	RT (%)	36.713	32.247 (−12.2%)	33.590 (−8.5%)	39.683	38.423	(−3.2%)
Bending	B (gf·cm^2/cm)	0.0426	0.0468 (9.9%)	0.0566 (32.9%)	0.0358	0.0419	(17.0%)
	2HB (gf·cm/cm)	0.0349	0.0368 (5.6%)	0.0421 (20.6%)	0.0162	0.0198	(21.8%)
Shear	G (gf/cm·degree)	1.970	2.197 (11.5%)	2.260 (14.7%)	2.117	2.287	(8.0%)
	2HG (gf/cm)	4.258	4.304 (1.1%)	4.463 (4.8%)	3.135	3.547	(13.1%)
Surface	MIU	0.140	0.153 (9.0%)	0.145 (3.6%)	0.155	0.184	(18.5%)
	MMD	0.015	0.011 (−27.3%)	0.008 (−43.2%)	0.008	0.008	(−4.2%)
	SMD (μm)	2.791	2.201 (−21.2%)	2.372 (−15.0%)	1.831	1.804	(−1.5%)
Compression	LC	0.698	0.721 (3.3%)	0.722 (3.5%)	0.547	0.668	(22.2%)
	WC (gf·cm/cm^2)	0.010	0.010 (0.0%)	0.010 (0.0%)	0.003	0.003	(0.0%)
	RC (%)	31.110	26.453 (−15.0%)	29.443 (−5.4%)	24.523	24.190	(−1.4%)
	T_m (mm)	0.230	0.250 (8.7%)	0.250 (8.7%)	0.222	0.227	(1.9%)
	T_o (mm)	0.253	0.280 (10.5%)	0.273 (7.9%)	0.240	0.243	(1.4%)

*Values with the parenthesis are property change (%) of plasma treated samples compared with the control sample.

Table 6. KES-FB results for He/O_2 plasma treated PTT and PET warp knitted fabrics in weft direction*

KES-FB parameters		Plasma exposure time, min.					
		PTT			PET		
		Control	2	4	Control	2	4
Tensile	LT	0.857	0.867 (1.2%)	0.869 (1.4%)	0.626	0.632 (0.9%)	0.674 (7.7%)
	WT (gf·cm/cm^2)	0.413	0.480 (16.1%)	0.433 (4.8%)	0.227	0.241 (6.5%)	0.240 (5.9%)
	RT (%)	44.577	41.410 (−7.1%)	44.563 (−2.3%)	46.240	43.333 (−6.3%)	38.177 (−17.4%)
Bending	B (gf·cm^2/cm)	0.0112	0.0130 (15.7%)	0.0149 (32.5%)	0.0125	0.0149 (19.1%)	0.0152 (21.5%)
	2HB (gf·cm/cm)	0.0102	0.0105 (2.8%)	0.0113 (11.0%)	0.0069	0.0087 (25.3%)	0.0092 (33.0%)
Shear	G (gf/cm·degree)	2.016	2.080 (3.2%)	2.093 (3.9%)	1.864	1.950 (4.6%)	2.023 (8.6%)
	2HG (gf/cm)	4.082	4.310 (5.6%)	4.967 (21.7%)	3.169	3.607 (13.8%)	3.450 (8.9%)
Surface	MIU	0.202	0.220 (8.8%)	0.219 (8.5%)	0.223	0.233 (4.2%)	0.224 (0.4%)
	MMD	0.016	0.015 (−3.5%)	0.013 (−15.9%)	0.021	0.018 (−14.5%)	0.019 (−8.1%)
	SMD (μm)	20.000	19.267 (−3.7%)	18.343 (−8.3%)	21.707	20.000 (−7.9%)	20.000 (−7.9%)

*Values with the parenthesis are property change (%) of plasma treated samples compared with the control sample.

was released, increasing surface friction might cause higher cohesive forces between yarns, and then higher resistance to extension of fabrics, compared to untreated fabrics. Thickness (T_0 and T_m) of fabrics under constant pressure increased after plasma treatment. It is suggested that increasing surface friction enhanced fabric fullness due to higher compression resistance under constant pressure.

Air Permeability and Burst Strength

Figure 6 shows air permeability of plasma treated PTT and PET fabrics. Air permeability is dependent upon space or void content of fabric, resulting from its structure. Although plasma treatment did not alter fabric structure, removing contamination on fabric surface by etching effect might increase space between yarns, decreasing air resistance to fabric. Lower air permeability of PTT fabric was due to higher density, resulting from higher shrinkage after heat setting. In addition, plasma treated PTT fabrics had higher air permeability than untreated at all plasma conditions, while an increase of air permeability of plasma treated PET fabrics was not significant, respectively. This is probably due to higher etching effect on PTT than PET, corresponding to higher weight loss (%) on

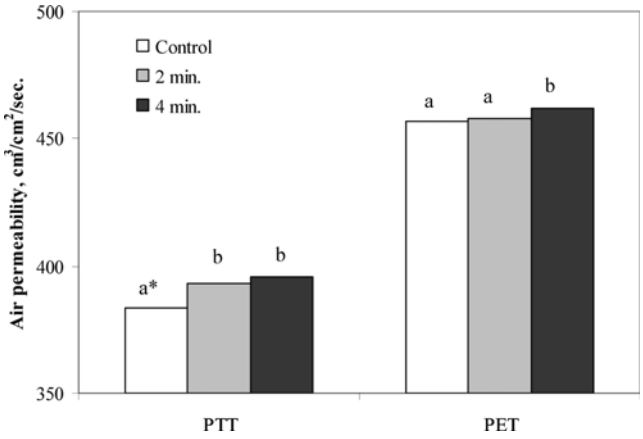

Figure 6. Air permeability of He/O_2 atmospheric plasma treated PTT and PET warp knitted fabrics (*means with different letters are statistically different at $p<0.05$ and A P-value smaller than 0.05 was considered significant).

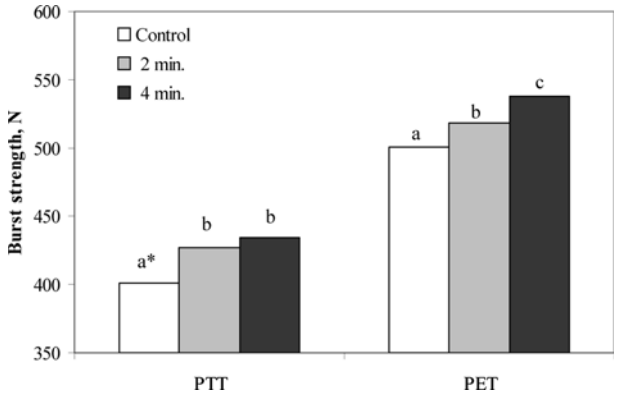

Figure 7. Burst strength of He/O_2 atmospheric plasma treated PTT and PET warp knitted fabrics (*means with different letters are statistically different at $p<0.05$ and A P-value smaller than 0.05 was considered significant).

plasma treated PTT fabrics (Figure 2). Figure 7 illustrates that burst strength of plasma treated fabrics was higher than untreated, and that burst strength increased with an increase of plasma exposure time. Despite of lower fabric density of PET fabrics, PET fabrics had higher burst strength than PTT because of higher rigidity of PET. Increasing burst strength might be related to higher resistance against fabric deformation due to increasing surface friction and cross-linking formation.

Conclusions

Change in surface morphology of both plasma treated fabrics was not observed through SEM analyses. However, it was clear that a lubricant or contamination was removed by plasma treatment. In addition, increasing weight loss (%) of fabrics revealed plasma etching effects on both fabrics. Higher portion of amorphous region in PTT might lead to higher weight loss (%) than PET because etching is predominated over amorphous region, which is a selective etching. Increasing moisture regain (%) after conditioning showed the moisture absorption from air, resulting from hydrogen bonding between hydrophilic groups and water moisture in air. Higher moisture regain (%) in plasma treated PTT fabrics than PET implied that PTT was more susceptible to plasma oxidation than PET.

Surface chemical change by plasma treatment results from radical formation by chain scission or substitution and then consecutive chemical interactions with active species in plasma. XPS analyses showed plasma treated fabrics had higher oxygen content (O_{1s}), O/C, and (O+N)/C ratios than untreated. The results of chemical composition and deconvolution analyses proved that PTT was oxidized more easily by plasma treatment than PET, corresponding to higher moisture regain (%) of PTT fabrics.

KES evaluations showed that increasing surface friction had a significant effect on other low-stress mechanical properties, such as tensile, bending, shear and compression. Changes of surface properties (friction and roughness) were strongly related to plasma etching and cleaning on fabric surfaces, resulting in an increase of surface friction (MIU) and a reduction of surface roughness (SMD). Specially, increasing surface friction (MIU) enhanced interyarn and interfiber frictions, hindering fabric stress deformation and recoverability. In addition, increasing air permeability of plasma treated fabrics might be consisted with enlarged voids (space) between fibers and yarns, resulting from contamination removal by plasma etching. This result was corresponded with increasing plasma treated fabric thickness (T_0 and T_m) under constant pressures. Burst strength of plasma treated fabrics increased with an increase of exposure time, showing that increasing surface friction (MIU) could induce a resistance against fabric deformation.

Acknowledgements

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