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Effect of Low Temperature Plasma Treatment on Wool Fabric Properties

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Abstract: Low temperature plasma (LTP) treatment was applied to wool fabric with the use of a non-polymerizing gas, namely oxygen. After the LTP treatment, the fabric properties including low-stress mechanical properties, air permeability and thermal properties, were evaluated. The low-stress mechanical properties were evaluated by means of Kawabata Evaluation System Fabric (KES-F) revealing that the tensile, shearing, bending, compression and surface properties were altered after the LTP treatment. The changes in these properties are believed to be related closely to the inter-fiber and inter-yarn frictional force induced by the LTP. The decrease in the air permeability of the LTP-treated wool fabric was found to be probably due to the plasma action effect on increasing in the fabric thickness and a change in fabric surface morphology. The change in the thermal properties of the LTP-treated wool fabric was in good agreement with the above findings and can be attributed to the amount of air trapped between the yarns and fibers. This study suggested that the LTP treatment can influence the final properties of the wool fabric.

Keywords: Low temperature plasma (LTP), Wool, Low-stress mechanical properties, Air permeability and thermal properties

Introduction

The low temperature plasma (LTP) technique is widely used for modifying textile materials and it is regarded as an environmentally friendly process because no chemical is used [1-3]. LTP is an ionic gas whose compounds and characteristics are different from the normal gas. The LTP technique can then be used for modifying textile materials with special features [3].

The action of LTP is mainly interactive (sputtering or etching) on the surface of the textile material, hence the surface properties of the textile material together with those associated with the surface characteristics will also be changed. As for the application of LTP treatment in wool fiber, most of the discussions were focused on applying this technique to improve the surface wettability [4-6] and shrink resistance [7-10]. However, little discussion has been made on the mechanical properties, thermal properties and the air permeability. This paper was so concerned mainly with the assessment for LTP modification of those properties of the wool fabric induced by LTP with a non-polymerizing gas.

Experimental

Material

100% pure 2/1 twill wool fabrics (41 ends/cm, 31 tex; 36 picks/cm, 36 tex; 180 g/m^2) were scoured with dichloromethane (A.R. Grade) for 4 hours by Soxhlet extraction method. The solvent scoured wool fabrics were then rinsed twice with 98% ethanol (A.R. Grade) and washed twice with deionized water respectively. The cleaned fabrics were dried in an oven at 50 °C for 4 hours. The fabrics were finally cut to the dimension of 20 cm × 20 cm and conditioned according to ASTM Designation: D1776 prior to further treatment.

Low Temperature Plasma (LTP) Treatment

A glow discharge generator (Showa Co., Ltd., Japan) was used for the LTP treatment of the wool fabrics. The glow discharge apparatus was a radio-frequency etching system operating at 13.56 MHz and using an aluminium chamber with an internal diameter of 200 mm. The chamber diameter was 380 mm with a height of 180 mm. A non-polymerizing gas, namely oxygen, with a flow of 20 cc/minute was used. The discharge power and system pressure were set at 80 W and 10 Pa respectively. The duration of LTP treatment was 5, 10, 20 and 30 minutes. After LTP treatment, the fabrics were conditioned before used.

Low-stress Mechanical Properties

The Kawabata Evaluation System Fabric (KES-F) was used for measuring the low-stress mechanical properties of the LTP-treated fabrics which include the tensile, shearing, bending, compression and surface properties. The parameters obtained for these hysteresis curves are defined in Table 1.

Air Permeability

The air permeability of the wool fabrics was obtained by the use of a KES-F8-AP-1 air permeability tester. The result of air permeability expressed as air resistance (R) was recorded in term of kPa s/m in which a larger value of R indicates poorer air permeability of the fabric and vice versa.

Thermal Properties

The thermal properties were studied by the use of a KES-F Thermo Labo II. The heat loss per unit area under the condition of 10 °C temperature difference was measured by

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Table 1. The tensile, shearing, bending, compression and surface properties obtained from the hysteresis curves

Properties	Symbol	Definition	Unit
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	%
Extensibility	EMT	Percentage extension at the maximum applied load of 500 gf/cm specimen width	%
Shear rigidity	G	Average slope of the linear regions of the shear hysteresis curve to ± 2.5 ° shear angle	gf/cm.degree
Shear stress at 0.5 °	2HG	Average width of the shear hysteresis loop at ± 0.5 ° shear angle	gf/cm
Shear stress at 5 °	2HG5	Average width of the shear hysteresis loop at ± 5 ° shear angle	gf/cm
Bending rigidity	B	Average slope of the linear regions of the bending hysteresis curve to 1.5 cm^{-1}	gf.cm^2/cm
Bending Moment	2HB	Average width of the bending hysteresis loop at 0.5 cm^{-1} curvature	gf.cm/cm
Fabric thickness at 0.5 gf/cm^2 pressure	T_o	Fabric thickness at 0.5 gf/cm^2 pressure	mm
Fabric thickness at 50 gf/cm^2 pressure	T_m	Fabric thickness at 50 gf/cm^2 pressure	mm
Compressional energy	WC	Energy in compressing fabric under 50 gf/cm^2	gf.cm/cm^2
Compressional resilience	RC	Percentage energy recovery from lateral compression deformation	%
Compressibility	EMC	Percentage reduction in fabric thickness resulting from an increase in lateral pressure from 0.5 gf/cm^2 to 50 gf/cm^2	%
Coefficient of friction	MIU	Coefficient of friction between the fabric surface and a standard contactor	-
Geometrical roughness	SMD	Variation in surface geometry of the fabric	micron

the warm/cool feeling (q_{max}) in term of W/cm^2.

Results and Discussion

Tensile Properties

The tensile properties composed of tensile energy (WT), tensile resilience (RT) and extensibility (EMT). The different tensile properties of the LTP-treated fabrics as measured by KES-F system are shown in Table 2.

The tensile energy (WT) is defined as the energy required for extending the fabric which reflects the ability of the fabric to withstand external stress during extension. The larger the value of WT implicates a better tensile strength of the fabric. After the LTP treatment, it was noted that the WT were increased steadily with the prolonged treatment time. However, the increment was not so great when compared with the untreated fabric.

Generally speaking, the tensile strength of the fabric depends

Table 2. Low-stress mechanical properties of LTP-treated wool fabric

KES-F properties		Plasma treatment time (minutes)				
		0	5	10	20	30
Tensile	WT	11.61	12.72	12.75	12.79	12.84
	RT	64.07	59.59	59.39	59.15	58.97
	EMT	9.54	8.39	8.34	8.28	8.20
Shearing	G	0.71	1.30	1.32	1.35	1.38
	2HG	0.60	2.00	2.05	2.06	2.08
	2HG5	1.75	5.55	5.58	5.60	5.63
Bending	B	0.111	0.139	0.140	0.143	0.146
	2HB	0.038	0.083	0.087	0.089	0.095
Compression	T_o	0.659	0.709	0.712	0.716	0.718
	T_m	0.531	0.557	0.559	0.563	0.568
	WC	0.08	0.08	0.08	0.09	0.09
	RC	46.63	19.21	19.16	19.08	19.02
	EMC	19.42	21.44	21.48	21.52	21.55
Surface	MIU	0.213	0.369	0.372	0.375	0.380
	SMD	3.88	4.20	4.32	4.43	4.53

on a lot of factors such as fabric structure, yarn twist and yarn count. Since identical fabrics were used, thus the major factor that affecting the WT of the fabric would be due to the fabric structure. The LTP treatment could not alter the fabric structure as it is only a surface treatment method causing an etching action resulting in a roughening effect on the fiber surface consequently [9,11]. Such roughening effect might impart more contact points within the fibers microscopically and within yarns macroscopically [11,12]. The increment in number of contact points would result in enhancing the inter-yarns and inter-fibers friction where a larger cohesive force would be developed during the application of tensile stress. The increases in value of WT were probably due to the larger cohesive force being developed during the extension period so that a larger amount of energy was required for extending the fabrics.

Tensile resilience (RT) refers to the ability of fabric recovery after applying the tensile stress. The reduced fabric RT value indicates that the fabric becoming very difficult to recover the original shape after removing the applied tensile stress. After the LTP treatment, the overall RT was decreased which was further decreased with the prolonged treatment time. The reduction in value of RT after LTP treatment could be explained by the increment of cohesive force between fibers and between yarns. When the extension load was removed, the frictional restraint would be created simultaneously by those increased cohesive force which would hinder the extended fabrics to recover their original position. The recovery ability of the extended fabric was finally lowered resulting in a reduced value of RT. It was therefore concluded that the LTP-treated fabrics were difficult to recover the original shape after removing the applied tensile stress. However, with the prolonged treatment time from 5 minutes to 30 minutes, the decrease of value of RT was not so great.

Extensibility (EMT) is another interesting factor associated with the tensile properties of the fiber. It is the percentage of the extended length after applying a known tensile stress to the fabric when compared with the initial length. The greater the value of EMT, the larger will be the elongation of the fabric under a known applied stress. Under the influence of the LTP treatment, the fabrics showed a reduced EMT value and the reduction further enhanced with prolonged treatment time. This phenomenon could be due to the increasing of interaction force between the fibers and yarns which reduced the relative movement of the fibers and yarns during the extension period and also restricted the elongation of the fabrics. From the view point of shaping and sewing, the decrease in the fabric extensibility could adversely affect the tailorability. However, a high level of EMT could cause an excessive hygral expansion of the wool fabric leading to puckering problems in the tailored garment at various ambient relative humidity conditions. On the whole, the EMT of the LTP-treated fabric was still acceptable in the laying-up process.

Shearing Properties

The shearing properties of the LTP-treated wool fabric were summarized in Table 2. The shearing properties consisted of shear rigidity (G), shear stress at 0.5 ° (2HG) and at 5 ° (2HG5) shear angle respectively. The shear rigidity (G) reflects the ability of the fabric to resist shear stress. After the LTP-treatment, there was a significant increase in the value of G of the wool fabrics but the increment was enhanced slightly with the prolonged treatment time.

The fabric recovery ability after applying the shearing stress can be reflected by the shear stress values at 0.5 ° and 5 ° shear angle. The greater values of the shear stress, the worse will be the recovery ability of the fabric. It was observed that after the LTP treatment, a significant increase in 2HG and 2HG values (more than 200 % increased when compared with the untreated fabric) were obtained. However, the LTP-treatment showed similar effect on the shear stress properties with the prolonged treatment time.

Shear is an important determinant of the handle and drape of fabrics. The shear rigidity reflects the subjective handle of the fabric, i.e. increasing the shearing rigidity will enhance the subjective stiffness of the fabric. After the LTP-treatment, there was a very large increase in fabric shear rigidity and shear stress. The high shear rigidity indicated that draping and three dimensional forming as required in tailoring for the LTP-treated fabric would be very difficult. On the other hand, the LTP-treated fabric exhibited a higher degree of inelasticity in shear as indicated by the extremely large values of shear stress. The shear rigidity of the fabric primarily depends on yarn interaction, i.e. an increase in yarn interactions will normally increase shear rigidity. The increased value of G of the LTP-treated fabrics implied that the inter-yarn friction in wool fabrics was increased after the LTP treatment. In order to overcome the rigid effect caused by the LTP treatment, finishing process such as softening should be applied to eliminate this deficiency.

Bending Properties

The results of the bending properties of the LTP-treated fabrics were summarized in Table 2. The bending properties have important effects on both the handle and tailoring performance of the fabric. In Table 2, the bending properties of the LTP-treated fabric studied included the bending rigidity (B) and bending moment (2HB). The overall values of B of the LTP-treated fabrics increased as the duration of treatment time increased. However, the increment was not so much even at the longest treatment time, i.e. 30 minutes, in this study.

The LTP-treated fabrics had a dramatic increase in the values of 2HB, i.e. more than 115 % increase. The bending moment (2HB) reflects the recovery ability of the fabric after bending. The smaller the values of the 2HB, the better will be the fabric bending recovery ability. In comparison, as the treatment time increases, the value of 2HB increased correspondingly.

The tremendous increase in the values of B and 2HB of the LTP-treated fabric will greatly reduce the fabric flexibility and elastic recovery from bending which in turn affects the fabric tailoring, draping and wear.

Compression Properties

The results of compression properties of the LTP-treated fabric are shown in Table 2 which includes the fabric thickness at 0.5 (T_o) and 50 (T_m) gf/cm^2 pressure, compressional energy (WC), compressional resilience (RC) and compressibility (EMC). It was obvious that, after the LTP treatment, the fabric thickness (T_o and T_m) were increased and the degree of increment enhanced with the prolonged treatment time but the results were quite similar. The increased fabric thickness reflected the LTP-treatment fabrics would be fuller than the untreated fabric in fabric handle.

Generally speaking, the compressibility (EMC) indicates the change in the thickness of the LTP-treated fabrics when the EMC value increases, the fabric handle will become fuller. After the LTP treatment, the EMC values of the LTP-treated fabric with different treatment durations were increased to a similar extent.

On the other hand, the surface raising effect caused by the LTP treatment was resulted in no significant change in the value of WC. The WC value implies the fluffy feeling of the fabric. When the values of WC are increased, the fabric will appear fluffier. In the present study, the WC values did not show significant change after the LTP treatment.

Another important property obtained from the compressional hysteresis curve is the compressional resilience (RC). This property can help to determine the recoverability of the fabric after the compression deformation. When the value is small, the retention ability of deformation after compression will be good. After the LTP treatment, there is a remarkably reduction in the fabric compressional resilience. Such a reduction in compressional resilience could be probably associate with the increased cohesive forces between the yarns due to the roughening effect imparted by the LTP treatment within yarns and hence blocked the recovery of the extended fabrics. As the treatment time prolonged, the values of RC decrease gradually but not significant.

Surface Properties

The results of the surface properties of the LTP-treated fabrics including the coefficient of friction (MIU) and geometrical roughness (SMD) of the fabric surface were summarized in Table 2.

The MIU reflects the fabric smoothness, roughness and crispness. After the LTP treatment, the values of MIU increased significantly and the increment was further enhanced with the prolonged treatment time. The increment in value of MIU indicated that the LTP-treated fabric surface became less smooth and rougher.

On the other hand, the SMD shows the evenness characteristics of the fabric surface. The greater the SMD value, the less evenness will be the fabric surface. LTP treatment in this study obviously reduces the surface evenness of wool fabric and the prolonged treatment time also played an important role to alter the evenness of the wool fabric. It was evident that upon the LTP reaction, the plasma species would bombard on the fabric surface resulting in etching effect which could cause the changes in the evenness of the fabric surface and hence altering the surface properties of the fabric [11,12].

Air Permeability

In this study, air permeability of the LTP-treated fabrics expressed as air resistance (R) was investigated and the results were summarized in Table 3. The LTP treatment increases the R value of the fabric with treatment time. The air permeability depends on the construction characteristics of the yarns and fibers in which a large proportion is occupied by air space. There are some factors affecting the air permeability of the fabric, e.g. the fabric structure, thickness and surface characteristics, etc. It is known that LTP treatment do not have influence on the fabric structure, therefore the change in R values is regarded as being closely related to the fabric thickness and surface characteristics. As discussed before, LTP treatment increases the fabric thickness and alters the surface morphology. It is possible to say that LTP treatment induces a certain degree of roughness [9,11] on the fabric surface where increases the fabric thickness and changes the fabric surface characteristics. These changes act as a boundary to hinder the air flow through the fabric, this resulting in a reduction of the air permeability of the fabrics.

Thermal Properties

Table 4 shows the thermal properties of fabric expressed as warm/cool feeling (q_{max}) of the fabrics with the variation of treatment time. The value of the q_{max} indicates the heat loss per unit area under the condition of 10 °C temperature difference. It reflects the instantaneous warm/cool feeling sensed when there is an initial contact of the fabric with the surface of the skin. A higher value of q_{max} denotes that there is a more rapid movement of heat from the skin to the fabric

Table 3. Air permeability of LTP-treated wool fabric

Properties		Plasma treatment time (minutes)				
		0	5	10	20	30
Air permeability	R (kPa s/m)	6.79	7.70	7.75	7.82	7.90

Table 4. Warm/cool feeling of LTP-treated wool fabric

Properties		Plasma treatment time (minutes)				
		0	5	10	20	30
Warm/cool feeling	q_{max} (W/cm^2)	0.155	0.128	0.124	0.120	0.113

surface which will provide a cooler feeling. It can be observed that the q_{max} value of the LTP-treated fabric show a reduction in this value with the prolonged treatment time. This implies that the LTP-treated fabric have a warmer-touch when compared with the untreated fabric. The thermal properties of a textile fabric depends a great extent on the air trapped within it. As mentioned before, the LTP treatment provides an etching effect on the fiber surface and such etching effect increases fabric surface roughness, voids and space which may increase the amount of the air trapped between the yarns and fibers [13]. In addition, the air permeability results indicates that the LTP-treated fabrics have poorer air permeability, therefore, the air trapped inside the fabric will not escape easily. The air so trapped inside the fabric can act as a good insulation medium and help to prevent the heat loss of the fabrics.

Conclusion

The low-stress mechanical properties, air permeability and thermal properties of LTP-treated wool fabrics had been investigated quantitatively. It was revealed that the LTP treatment could influence not only the mechanical properties but also affect the air permeability and thermal properties of the wool fabrics. The changes in the mechanical properties of the wool fabric were closely related to the inter-yarns and inter-fibers frictional force imparted by the LTP etching action. The change in the air permeability of the LTP-treated fabrics was found which is probably due to the plasma action increasing the fabric thickness and changing the fabric surface morphology. In addition, the change in the thermal properties of the LTP-treated fabrics was in good agreement with the above findings and could be attributed to the amount of trapped air between the yarns. Although the LTP treatment showed significant influence on the properties of the wool fabric, the prolonged exposure time in the LTP treatment did not much further affect the mechanical properties, air permeability and thermal properties of the LTP-treated wool fabrics. As a conclusion, the LTP treatment for modification of wool fabric has a high industrial potential as it is an environmentally friendly dry process, which does not involve any of the solvents and reagents for the wet chemical process.

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