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KES-F Analysis of Low Temperature Plasma Treated Wool Fabric

Abstract
Low temperature plasma (LTP) treatment was applied to wool fabric with the use of a non-polymerising gas, namely oxygen. After the LTP treatment, the fabric mechanical properties, including low-stress mechanical properties, air permeability and thermal properties were evaluated. The low-stress mechanical properties were evaluated by means of the Kawabata Evaluation System for 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 closely related to the inter-fibre 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 the increase in the fabric thickness and a change in the morphology of the fabric surface, which was confirmed by Scanning Electron Microscopy micrographs. 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 fibres. This study suggested that LTP treatment can influence the final properties of wool fabric.

Key words: *etching, oxidation, fibres, surfaces, plasma treatment, textiles.*

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 chemicals are used [1-3]. LTP is an ionic gas whose compounds and characteristics are different from normal gas, and the technique of using LTP can then be used for modifying textile materials with different features, such as a change in hydrophilicity [3].

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

Experimental

Wool fabric

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 the Soxhlet extraction method. The solvent scoured wool fabrics were then rinsed twice with 98% ethanol (A.R. Grade) and washed twice with deionised water, respectively. The cleaned fabrics were dried in an oven at 50 °C for 4 hours. Finally, the fabrics were cut to the dimension of 20 cm × 20 cm and conditioned at 25 °C at a relative humidity of 65% for 24 hours prior to further evaluation.

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-polymerising 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 the LTP treatment was 5, 10, 20 and 30 minutes. Five specimens were prepared for each duration of the

Table 1. *The tensile, shearing, bending, compression and surface properties as measured by KES-F.*

Properties	Symbol	Definition	Unit
Tensile energy	WT	Energy in extending fabric to 500 cN/cm width	cN.cm/cm^2
Tensile resilience	RT	Percentage energy recovery from tensile deformation	%
Extensibility	EMT	Percentage extension at the maximum applied load of 500 cN/cm specimen width	%
Shear rigidity	G	Average slope of the linear regions of the shear hysteresis curve to ± 2.5° shear angle	cN/cm.degree
Shear stress at 0.5°	2HG	Average width of the shear hysteresis loop at ± 0.5° shear angle	cN /cm
Shear stress at 5°	2HG5	Average width of the shear hysteresis loop at ± 5° shear angle	cN /cm
Bending rigidity	B	Average slope of the linear regions of the bending hysteresis curve to 1.5 cm^{-1}	cN .cm^2/cm
Bending moment	2HB	Average width of the bending hysteresis loop at 0.5 cm^{-1} curvature	cN .cm/cm
Fabric thickness at 0.5 cN/cm^2 pressure	T_o	Fabric thickness at 0.5 cN /cm^2 pressure	mm
Fabric thickness at 50 cN/cm^2 pressure	T_m	Fabric thickness at 50 cN /cm^2 pressure	mm
Compressional energy	WC	Energy in compressing fabric under 50 cN /cm^2	cN .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 cN /cm^2 to 50 cN /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

treatment. After the LTP treatment, the fabrics were conditioned at 25 °C with/at a relative humidity of 65% for 24 hours before being evaluated.

Morphological study

The morphology of the 5 minute-LTP-treated wool fabrics was observed using a scanning electron microscope (SEM) (Lecia Stereoscan 440). The samples were gold-coated before the SEM examination was conducted.

Low-stress mechanical properties

The Kawabata Evaluation System for 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 evaluation of the air permeability, expressed as air resistance (R), was recorded in 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 using a KES-F Thermo Labo II. The heat loss per unit area under the condition of 10°C temperature difference was measured by the warm/cool feeling (q_{max}) in W/cm^2.

Results and discussion

Morphological study

SEM micrographs of the untreated and LTP-treated wool fabrics are shown in Figures 1 and 2, respectively. It can be seen that after 5 minutes of LTP treatment with oxygen, some continuous cracks appear that are located parallel to the direction of the wool fibre axis, and the scale edges are slightly eroded and rounded. Therefore, it can be stated that LTP treatment increases the surface roughness, voids and spaces in wool fibre.

Tensile properties

Tensile properties are 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.

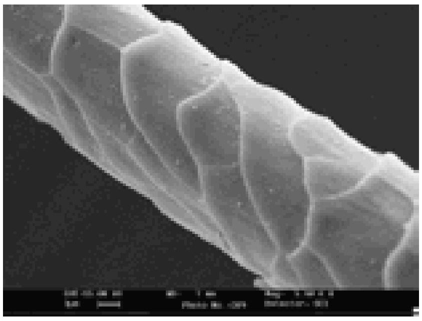

Figure 1. *SEM micrograph of untreated wool fibre.*

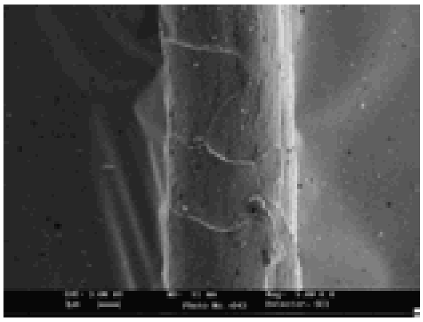

Figure 2. *SEM micrograph of LTP-treated wool fibre.*

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

Generally speaking, the tensile strength of fabrics depends on a lot of factors such as fabric structure, yarn twist and yarn count. Since identical fabrics were used, the major factor affecting the WT of the fabric would be the fabric structure. However, 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 fibre surface [9, 11]. Such a roughening effect might impart more contact points within the fibres microscopical and within yarns macroscopically scale [11, 12]. Increment at a number of contact points would have resulted in the enhancing of the inter-yarn and inter-fibre friction, where a larger cohesive force would have developed during the application of tensile stress. The increases in the value of WT were probably due to the larger cohesive force being developed during the extension period, therefore a larger amount of energy was required for extending the fabrics.

Tensile resilience (RT) refers to the ability of fabric to recover after applying tensile stress. The reduced fabric RT value indicates that the fabric is having difficulty recovering its original shape after the removal the tensile stress applied. After the LTP treatment, the overall RT decreased, and went down even more with prolonged treatment time. The reduction in the value of RT after LTP treatment could be explained by the increment of the cohesive force between the fibres and between the yarns. If the extension load had been removed, the frictional restraint would have been created simultaneously by the increase in cohesive force, which would have hindered the extended fabrics from recovering their original position. The

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

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 had difficulty recovering the original shape after the removal of the tensile stress applied. However, when prolonging the treatment time from 5 to 30 minutes, the decrease in value of RT was not so great.

Extensibility (EMT) is another interesting factor associated with the tensile properties of fibre. It is thepercentage 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 the elongation of the fabric under a known applied stress is. Under the influence of the LTP treatment, the fabrics showed a reduced EMT value, and the reduction was further enhanced with prolonged treatment time. This phenomenon could be due to the increase in the interaction force between the fibres and yarns, which reduced the relative movement of the fibres and yarns during the extension period and also restricted the elongation of the fabrics. As far as shaping and sewing are concerned, the decrease in the fabric extensibility could adversely affect the tailorability. However, a high level of EMT could have caused 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 are summarised in Table 2. The shearing properties consisted of shear rigidity (G), a shear stress of 0.5° (2HG) and 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 slightly enhanced with prolonged treatment time.

The fabric recovery ability after applying the shearing stress can be reflected by the shear stress value of 0.5° and 5° shear angle. The greater the values of shear stress, the worse the recovery ability of the fabric is. It was observed that after the LTP treatment, a significant increase in 2HG and 2HG5 values (by more than 200% when compared with the untreated fabric) were obtained. However, the LTP treatment showed a similar effect on the shear stress properties with *t* prolonged treatment time.

Shear is an important determinant of the handle and drape of fabrics. Shear rigidity reflects the subjective handle of fabric, i.e. increasing shear rigidity will enhance the subjective stiffness of fabric. After the LTP treatment, there was a very large increase in the shear rigidity and shear stress of the fabric. The high shear rigidity indicated that draping and three dimensional forming, as required in tailoring, of 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 interaction will normally increase shear rigidity. The increased value of G of the LTP-treated fabrics implied that inter-yarn friction in the wool fabrics 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 are 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 include the bending rigidity (B) and bending moment (2HB). The overall values of B of the LTP-treated fabrics rose as the duration of the treatment time increased. However, further increment after 5 minutes of treatment time was not so even as that 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 a 115% increase. The bending moment (2HB) reflects the recovery ability of the fabric after bending. The smaller the values of 2HB, the better the fabric bending recovery ability will be. In comparison, as the treatment time increased, the value of 2HB increased correspondingly.

An 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 the compression properties of the LTP-treated fabric are shown in Table 2, which includes the fabric thickness at a pressure of 0.5 cN/cm^2 (T_o), and 50 cN/cm^2 (T_m), compressional energy (WC), compressional resilience (RC) and compressibility (EMC). It was obvious that, after the LTP treatment, the fabric thicknesses both values (T_o and T_m) increased and the degree of increment was enhanced with the prolonged treatment time, but the results were quite similar. The increased fabric thickness reflected the fact that the LTP treated 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 increased to a similar extent.
On the other hand, the surface raising effect caused by the LTP treatment resulted in no significant change in the value of WC. The WC value implies a fluffy feeling of the fabric. When the values of WC increase, 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 compression deformation. When the value is small, the retention ability of deformation after compression will be good. After the LTP treatment, there was a remarkable reduction in the compressional resilience of the fabric. Such a reduction in compressional resilience could be associated with the increased cohesive forces between the yarns due to the roughening effect imparted by the LTP treatment within the yarns and hence blocked the recovery of the extended fabrics. As the treatment time prolonged, the values of RC decreased gradually but not significantly.

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, are summarised 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 prolonged treatment time. The increment in the MIU value 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 even the fabric surface will be. The LTP treatment in this study obviously increases the surface evenness of wool fabric, and the prolonged treatment time also played an important role in enhancing the evenness of the wool fabric. It was evident that upon the LTP reaction, the plasma species would bombard the fabric surface resulting in an etching effect which could cause changes in the evenness of the fabric surface, as shown in Figure 2, and hence alter the surface properties of the fabric [11, 12].

Air permeability

In this study, the air permeability of the LTP-treated fabrics expressed as air resistance (R) was investigated and the results are summarised in Table 3. The LTP treatment increased the R value of the fabric with treatment time. The air permeability depends on the construction characteristics of the yarn or fibre, 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 does not have an 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], as shown in Figure 2, on the fabric surface, which increases the fabric thickness and changes the fabric surface characteristics. These changes act as a boundary to hinder the air flow through the fabric, thus resulting in a reduction in the air permeability of 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

Thermal properties

Table 4 shows the thermal properties of fabric expressed as the warm/cool feeling (q_{max}) of the fabrics with variation in 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 surface, which will provide a cooler feeling. It can be observed that the q_{max} value of the LTP-treated fabric shows a reduction with prolonged treatment time. This implies that LTP-treated fabric has better warmth-retention properties when compared with untreated fabric. The thermal properties of a textile fabric depends, to a great extent, on the air trapped within it. As mentioned before, LTP treatment provides an etching effect on the fibre surface, and this increases the roughness, voids and space of the fabric surface, as shown in Figure 2, which may increase the amount of air trapped between the yarns and fibres [13]. In addition, the air permeability results indicate that LTP-treated fabrics have poorer air permeability, therefore, the air trapped inside the fabric will not escape easily. The air thus trapped inside the fabric can act as a good insulation medium and help to prevent heat loss in the fabric.

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

Conclusions

The low-stress mechanical properties, air permeability and thermal properties of LTP-treated wool fabrics were investigated. 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 could be explained by the inter-yarn and inter-fibre frictional force imparted by the LTP etching action. The change in the air permeability of the LTP-treated fabrics was found, which was 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 air trapped between the yarns. Although the LTP treatment showed a significant influence on the properties of the wool fabric, the prolonged exposure time in the LTP treatment did not further affect the mechanical properties, air permeability and thermal properties of the LTP-treated wool fabrics very much. To conclude, the LPT treatment for modification of wool fabric has high industrial potential as it is an environmentally friendly dry process, which does not involve any of the solvents and reagents of the wet chemical process.

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Received 16.05.2006 Reviewed 11.04.2007