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A Study of Laser Treatment on Polyester Substrates

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Abstract: In this paper, modifications of textile properties of polyester due to laser irradiation were studied. Properties included fibre weight and diameter, tensile strength and elongation, yarn abrasion, bending, surface luster, wetting, air permeability as well as crystallinity. Some properties were affected significantly while others were found unchanged. Besides, some properties were positively affected and some were adversely changed. Generally speaking, laser irradiation could not affect the bulk property of polymer due to its low penetration depth, and hence, the effect of the laser irradiation on the bulk and structural properties was limited. However, the performance and comfort properties of the laser irradiated polyester could be largely affected by laser irradiation as these properties could have been changed considerably if the surface was modified.

Keywords: Polyester, Surface, Laser, Textile

Introduction

The laser irradiation on highly absorbing polymers such as polyester can generate characteristic modifications of the surface morphology [1-3]. The physical and chemical properties are also affected after laser irradiation [4-6]. Hence, it is reasonable to believe that such surface modification on polymer may have an important impact on its textile properties [7-9]. In order to find out which property of the polyester is positively or adversely affected by laser irradiation, different experiments and testing instruments were used to characterize the treated samples.

In this paper, the influence of laser irradiation against some of the important textile properties of polyester was studied. These properties include fibre weight and diameter, tensile strength and elongation, yarn abrasion, bending, surface lustre, wetting, air permeability as well as crystallinity.

Experimental

Material

Commercially available polyester fibre (continuous filament with linear density of 2.8 dtex), yarn (yarn count of 19.30 tex) and fabric (plain woven fabric, fabric weight=1.55 g/m^2; warp density=30 end/cm, weft density=52 picks/cm; yarn count of warp and weft yarns are 20 tex) from China were used for the study. All samples were conditioned for at least 24 hours prior to experiment under the standard conditions at 20 ^{o}C and 65 % relative humidity.

Laser Irradiation

Both high fluence and low fluence laser irradiations were conducted. Irradiation was performed by a commercial pulsed UV excimer laser (Lambda Physik COMP EX 205) under atmospheric condition. In high fluence laser irradiation, samples were irradiated directly from the laser beam without using any special photomask nor a focusing lens. The laser energies in terms of applied fluence and number of pulses were varied among experiments. The irradiation energies used were 50 and 150 mJ/cm^2 and the number of pulses varied between 0 to 200. In low fluence laser irradiation, only the highly polarization beam method was employed and the fluence was controlled to 2000 pulses at 6 mJ/cm^2. For the fibre and yarn samples, the samples were made parallel and mounted in a sample holder before laser irradiation. While for the fabric sample, the samples were directly irradiated with the laser.

Bulk and Structural Properties

The degree of crystallinity is determined by integrating the peak area of a differential scanning calorimetry curve. This method is based on a thermodynamic definition of order and it requires the absolute value of the heat of fusion of the ideal polymer crystal (ΔH of melting peak of ideal polyester crystal=119.8 J/g) [10,11]. The heat of fusion obtained from this is directly proportional to the crystallinity. The measurement was conducted by using a Mettler DSC Model 25 under thermally controlled conditions with a heat rate of 10 ^{o}C/min in a nitrogen atmosphere. The scanning ranges from 30 ^{o}C to 300 ^{o}C. The degree of crystallinity was calculated based on the following equation [10,11]:

$$\textit{degree of crystallinity} = \frac{\Delta H \textit{ of melting peak}}{\Delta H \textit{ of melting peak for ideal polyester crystal}} \times 100\ \%$$

Weight and Fibre Diameter Change

The sample weight and fibre diameter were measured directly before and after laser irradiation; the percentage change of the sample weight and fibre diameter could be obtained. The fibre diameter was obtained from direct microscopic measurement.

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Performance Properties

The tensile strength and elongation-at-break of the fibres were measured in accordance with ASTM D2101 using an Instron Tensile Tester 4466. The yarn abrasion of the fibres was examined by a Shirley Yarn Abrasion Tester with a silicon carbide waterproof abrasive paper 100 (etectro coated) for the creation of abrasion against the specimen. KES-F (Kawabata Evaluation System for Fabrics) Bending Tester was employed for measuring both bending rigidity, B, and hysteresis, 2HB, of the yarn samples. Specimen each comprised of 82 ends were tested. The glossiness of fabric samples were measured by a Goniophotometer (Model VG-ID, Nippon Denshoku Kogyo Co. Ltd.) designed according to Japanese Industrial Standard 28741. During the experiment, the incident angle of light was always fixed at 60 ^{o} while the receiving angle varied from 0 ^{o} to 85 ^{o} at interval of 5 ^{o}. This measurement method is widely used since its mechanism is able to simulate the subjective evaluation in which the incident light and the fabric sample are both fixed while the position of the observer is varied. The glossiness index expressed in percentage term was measured in both warp and weft directions.

Comfort Properties

The vertical drop test of fabrics was measured in accordance with BS 4554. A drop of distilled water is allowed to fall onto the fabric sample and the time for which the liquid was required to sink into the fabric completely, i.e. the liquid is no longer visible from the surface of the fabric, was recorded. The shorter the time, the more wettable is the fabric. A Shirley air permeability tester was employed to measure the air permeability of the fabric samples based on BS 5636.

Results and Discussion

Degree of Crystallinity

Table 1 shows the degree of crystallinity of laser irradiated polyester. The change of crystallinity of polyester resulted by laser irradiation was 2 % for high fluence and no change was observed under low fluence irradiation. It seems that the overall change is insignificant. The relatively small difference in the degree of crystallinity between the laser irradiated and untreated polyester are expected and explainable, although it is reasonably believed that the surface of the high fluence irradiated polyester would become highly amorphous due to ablation.

The small change may be due to the nature of laser irradiation as it generated only surface morphological modification where the bulk property of polymer remains unchanged. In fact, the penetration depth of laser energy was limited to a few microns under high fluence irradiation and even less for the low fluence counterpart, while crystallinity is a bulk internal property of polymer.

Table 1. Degree of crystallinity of laser irradiated PET fibre

Sample	Degree of crystallinity (%)	% Changes over control
Untreated	44	–
High fluence irradiated	43	↓2
Low fluence irradiated	44	–

High fluence=100 pulses at 50 mJ/cm^2 and low fluence=2000 pulses at 6 mJ/cm^2.

Weight and Fibre Diameter Change

The weight change of polyester followed by high fluence laser irradiation is shown in Figure 1. It can be observed that the weight change correlated well with laser fluence and number of pulses applied during laser irradiation, i.e. an increasing fluence and number of pulses will result in an increasing level of weight loss. In the first few pulses, the weight loss is insignificant. Increasing the pulse counts will further increase the weight loss. In fact, no saturation of weight loss was seen against the present pulse count. The reduction in weight with increased laser irradiation may be due to the etching effect induced by the high fluence ablation as the polyester fibre was etched pulse-by-pulse during fluence above the ablation threshold. Parts of the material were etched away and ejected from the surface into the atmosphere during ablation. Whereas for low fluence irradiation, no weight change was recorded. The energy involved in low fluence treatment is limited to a very low level and hence no ablation could have resulted. No material would be removed or etched from the polyester surface under such irradiation [12].

Fibre diameter measurement is shown in Figure 2 for high fluence irradiated samples only as no change was recorded for low fluence counterparts. This is similar to the weight loss study. In the high fluence irradiation, a positive relationship exists: an increase in the number of pulses will result in an increase in diameter reduction. For the first 10 pulses, the reduction is almost insignificant. But once the pulse count went beyond 20, the reduction became more severe.

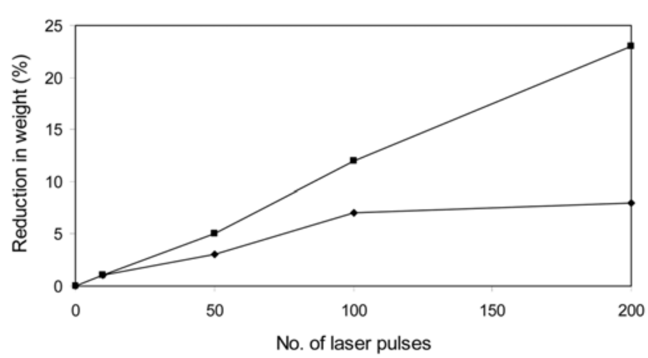

Figure 1. Weight reduction of polyester after laser irradiation; (♦) 50 mJ/cm^2 and (■) 150 mJ/cm^2.

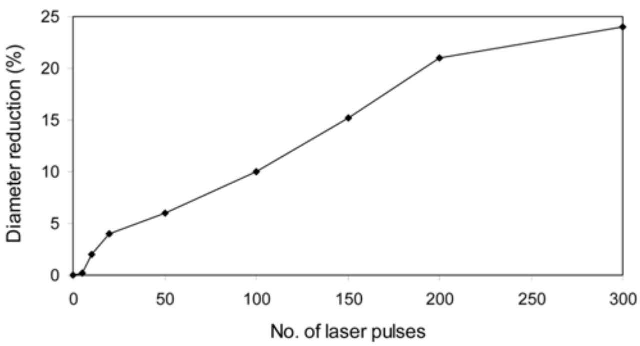

Figure 2. Fibre diameter change after laser irradiation at 50 mJ/cm^2.

Table 2. The breaking load and elongation-at-break of laser irradiated PET fibre

Sample	Breaking load (N)	Percentage of elongation-at-break (%)
Untreated	0.106	11.67
High fluence irradiated	0.094 (↓11 %)	10.40 (↓11 %)
Low fluence irradiated	0.103 (↓3 %)	11.30 (↓3 %)

The percentages in the parentheses indicate the increase/decrease in value of irradiated samples compared with the untreated sample.
High fluence=100 pulses at 50 mJ/cm^2 and low fluence=2000 pulses at 6 mJ/cm^2.

Tensile Strength and Elongation

The results of the breaking load and elongation-at-break of the polyester samples with and without laser irradiation are listed in Table 2. After low fluence irradiation, no significant change was found. The small reduction in the breaking load and elongation-at-break of the irradiated sample has little statistical meaning. It may be argued that the ripple induced by irradiation will result in more weak points to the fibre, hence the tensile strength should be reduced [7]. However, bearing in mind that the depth of ripple is in the range of sub-micron level, the weakening effect to the strength and elongation should be very little.

Under the high fluence laser irradiation, results revealed that irradiation could reduce both breaking load and elongation of the sample. The rate of reduction for both properties is similar in term of percentage, which are roughly 10 %. The reduction could be due to the fact that the induced high fluence ripples on the surface created more weak points to the fibre and eventually reduced both strength and extensibility. Another reason may be due to the deposition of debris as the debris could give a harder surface to polyester making it more rigid and thus result in lower strength and elongation.

Yarn Abrasion

Table 3 showed the yarn abrasion result and reductions of approximately 13 and 10 percent for high fluence and low fluence irradiated polyester yarn was recorded respectively. The yarn abrasion tester employs the principle of using a rotary rod wrapped with abrasive paper creating abrasion against the yarn specimen. Hence, laser irradiated yarn would obviously have a lower abrasion resistance since it is full of periodical ripple structures and these structures would largely increase the contact areas between the abrasive paper and the yarn itself [8]. These laser-developed structures induced also more weak points to the yarn sample resulting in lower yarn abrasion resistance.

Table 3. Yarn abrasion of laser irradiated PET yarn

Sample	Mean revolutions	% Changes over control
Untreated	68	–
High fluence irradiated	58	↓15
Low fluence irradiated	61	↓10

High fluence=100 pulses at 50 mJ/cm^2 and low fluence=2000 pulses at 6 mJ/cm^2.

Bending Property

The bending properties have important effects on both handle and tailoring performance of textile materials. Table 4 shows the bending properties of the laser irradiated polyester yarn including bending rigidity and bending hysteresis. Both figures in Table 4 were also increased for both types of laser irradiations. A higher increment was observed for high fluence irradiated sample as the bending rigidity and bending hysteresis were increased by 26.7 % and 50 % respectively. Under low fluence irradiation, the increment is relatively small. The bending rigidity and bending hysteresis were increased by 7 % and 25 % respectively.

The increase in bending properties may result in difficulty in manufacturing especially for the dramatic increase in bending hysteresis. Generally speaking, the smaller the values of the bending hysteresis, the better will be the fabric bending recovery ability. The tremendous increase in bending properties of the laser irradiated yarn may finally decrease the fabric flexibility and elastic recovery from bending action [13], which in turn may affect the fabric tailorability, draping quality and wear. Highly skill operators may therefore be needed to deal with the problem and thus may increase the cost of manufacturing.

Table 4. The bending properties of laser irradiated PET yarn

Sample	Bending rigidity, B (gfcm^2/cm)	Bending hysteresis, 2HB (gfcm/cm)
Untreated	0.0015	0.0004
High fluence irradiated	0.0019 (↑26.7 %)	0.0006 (↑50 %)
Low fluence irradiated	0.0016 (↑7 %)	0.0005 (↑25 %)

The percentages in the parentheses indicate the increase/decrease in value of irradiated samples compared with the untreated sample.
High fluence=100 pulses at 50 mJ/cm^2 and low fluence=2000 pulses at 6 mJ/cm^2.

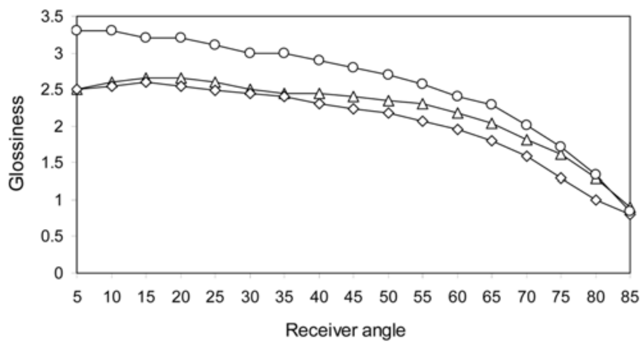

Figure 3. The glossiness distribution curve (warp direction) of laser irradiated polyester; (△) control, (◊) 100 pulses at 50 mJ/cm^2, and (○) 2000 pulses at 6 mJ/cm^2.

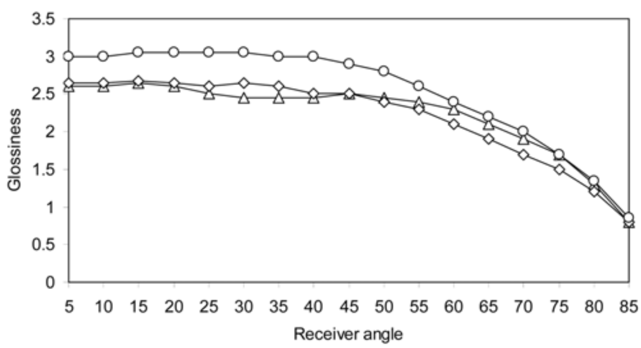

Figure 4. The glossiness distribution curve (weft direction) of laser irradiated polyester; (△) control, (◊) 100 pulses at 50 mJ/cm^2, and (○) 2000 pulses at 6 mJ/cm^2.

Surface Lustre

Surface lustre is the term generally accepted to describe the glossiness of a textile material and is defined as the intensity of directionally reflected light from a surface. The glossiness indexes of the polyester fabrics before and after laser irradiations were measured in both warp and weft directions as respectively shown in Figures 3 and 4. Results show that the glossiness distribution curves in warp and weft directions produced similar trends for the sample tested. No prominent peak value appeared in either direction where the glossiness in warp was slightly higher than that of the weft.

The change in the glossiness index between the untreated and laser irradiated sample was small and figures did show an interesting result. High fluence irradiated sample would have a lower level of glossiness index, whereas low fluence irradiated counterparts would increase the overall glossiness index. Laser irradiation is claimed to largely lower the glossiness index of textile material with sharp peaks thus making the material more silk-like [14]. It is because the surface of laser irradiated area would diffuse the incident light more evenly and eventually reduce the specular reflection. However, it is not known that why there would have an overall increase in glossiness index for low fluence irradiated sample. At the present stage, the most possible explanation would be the fact that the process of low fluence irradiation could be able to clean up the surface of the irradiated part such as removing the dust particles and minimizing the manufacturing defect by smoothening the surface. Such effects would eventually increase the glossiness index.

Table 5. Results of vertical drop test of laser irradiated PET fabric

Sample	Seconds	% Changes over control
Untreated	470s	–
High fluence irradiated	> 900s	Immeasurable
Low fluence irradiated	330s	30

high fluence=100 pulses at 50 mJ/cm^2 and low fluence=2000 pulses at 6 mJ/cm^2.

Wetting

Table 5 shows the vertical drop test result for both high and low fluence irradiated samples. It is observed that high fluence laser irradiation greatly increases the wetting time of the polyester fabric from 470s to>900s (exceeding 900s). The large increment in wetting time is believed to be closely related with the ripple structure. Ripples have increased the roughness of the surface and this kind of increased roughness enhances the unwettability of the fabric, resulting in an increase in the wetting time.

Researchers, have experimentally proved that surface roughness decreases the wettability of a hydrophobic material [15-17]. Many models have also been proposed in explaining this phenomenon. Besides, if the surface is sufficiently rough, a liquid with a large contact angle may not completely wet the surface. This incompletely wetted surface provides room for air to be trapped between the liquid and solid interface (Figure 5), resulting in a so-called composite interface [18]. This composite interface prevents water penetration and this mechanism has already been adopted by some Japanese manufacturers in producing high-tech water repellent textile materials [19].

In addition, high fluence laser irradiation always creates a thin carbonaceous layer on fibre surface and this layer may induce a hydrophobic character to the surface [20,21]. In addition, the reduced surface oxygen content may also be part of the reason for the increased wetting time.

A reduced wetting time was observed for the low fluence irradiated sample, which is completely opposite to the high

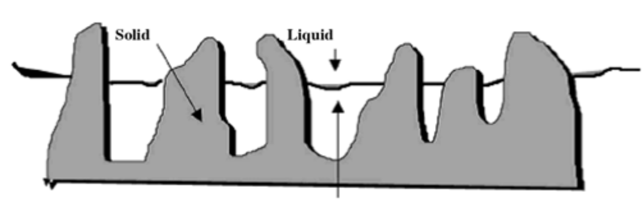

Figure 5. The effect of surface roughness on wetting.

Table 6. Air permeability of laser irradiated PET fabric

Sample	m*l*/(cm^{2}s)	% Changes over control
Untreated	19.6	–
High fluence irradiated	20.5	↑4.6
Low fluence irradiated	21.1	↑7.7

High fluence=100 pulses at 50 mJ/cm^2 and low fluence=2000 pulses at 6 mJ/cm^2.

fluence result. It means that the wettability of low fluence irradiated sample has increased (hydrophilicity increased). The ripple induced by low fluence is in the range of sub-micron level and it is reasonable to believe that air would not be able be trapped inside the gaps between ripples due to size constraints. Hence, the effect of a composite interface could not take place. On the chemical side, the increased surface oxygen content and the reduced contact angle measurement which would help in reducing the time for the droplet of water to sink into the sample. This is because the polar radicals of the low fluence irradiated polyester have increased. This increased polarity will lead to increase in an attraction force between the modified surface and the polar water molecules.

Air Permeability

Air permeability is one of the major properties of textile materials and is governed by factors like the fabric structure, density, thickness and surface characteristics etc. Table 6 indicates that both laser irradiations could increase the air permeability of the fabric samples. It is believed that the contributing factor to the increased air permeability of the irradiated sample is the surface modification of the fibres. This is because laser irradiation has induced ripple structures on the surface of the fibres, which eventual1y provide more air space between fibres and fabric. It is therefore possible for more air to pass through the fabric resulting in better air permeabi1ity.

Conclusion

In this paper, some common textiles properties of polyester were studied after both high and low fluence laser surface morphological treatment. Some properties have been affected significantly where the others were found unchanged. Furthermore, results also revealed that some properties were positively affected and some were adversely changed. In fact, depending on the end-uses of the materials, for example, increased wettability of polyester may be good for ordinary textile functions but bad for water resistant functional garments. It is therefore suggested that the correct selection of surface treatment parameters is of prime importance. In general, laser irradiation could not affect the bulk property of a polymer due to its low penetration depth, and hence, the effect of the treatment on the bulk and structural properties are limited. However, the performance and comfort properties of the irradiated polyester could be largely affected by laser irradiation as these properties could have been changed considerably if the surface is modified.

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