Effect of Laser CO_2 Irradiation on Various Properties of Polyester Fabric: Focus on Dyeing

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ABSTRACT: In this research, the effect of CO_2 laser on various properties of polyester fabric specially dyeing was studied. Three disperse dyes of red, yellow, and blue were used and irradiation was performed before and after dyeing. To evaluate the color changes due to laser treatment, CIELAB ΔE^*_{ab} color difference values were calculated. The morphology of the irradiated surfaces was examined by scanning electron microscopy. Other properties including color fastness, bending rigidity, wettability, and crystal size were also examined. The results revealed that laser treatment had an increasing effect on the color difference value. Among the three laser parameters examined in this work, laser power had the strongest effect. While no significant color fastness improvement with low laser intensity was observed, high-intensity laser irradiation increased the light and rubbing fastness. Properties such as wettability and bending rigidity were negatively affected by an increase in laser intensity. J Appl Polym Sci 124: 342–348, 2012

Key words: laser; polyester fabric; dyeing property; fastness properties; rigidity

INTRODUCTION

Laser technology has been widely used in surface modification of polymers. Characteristic modifications of the surface morphology of polymers like polyamide and polyester can be produced by the laser irradiation.[1–4] Wong et al.[5–7] reported the modification of poly(ethylene terephthalate) by a KrF excimer laser 248 nm. It was observed that the PET surface developed a periodic roughness or ripple. Surface roughness spacing increased with laser energy. In addition, it was shown that with the appropriate laser treatment, the wettability of polyester greatly decreased. In the other work,[8] the same group reported the effect of laser treatment on dyeing rate of two commercially available high temperature dyes of red and blue on polyester. They found that laser could improve the initial rate of dyeing and equilibrium exhaustion. Kan[9–11] also studied the textile properties of polyester due to the high and low-fluence laser irradiation. He indicated that wettability and air permeability were positively affected while fiber weight and diameter, tensile strength, yarn abrasion, and bending properties were adversely affected. He confirmed that laser treatment did not influence the bulk properties of polymer due to its low penetration depth.

While most of the efforts in developing surface treatments have been made using UV laser, infra-red lasers, like CO_2 appear to be less concerning. In 1999 and 2002 infra-red lasers were used in polymeric films by Dadsetan et al.[12] and Dadbin,[13] respectively. Esteves and Alonso[14] investigated dyeability of polyester and polyamide fabrics due to the use of CO_2 pulsed laser. An increase in the surface area and dye adsorption was found as a result of certain roughness created on the fiber surface. They examined different experimental conditions to choose the most appropriate ones. In their point of view, CO_2 laser treatment can have similar results to those found by UV lasers. As infra-red radiation can cause thermal damages, selecting optimum laser parameters is very important. In this study, the influence of CO_2 laser treatment on dyeing properties of polyester fabric was examined. For this purpose irradiation was performed before and after dyeing. Different laser parameters were applied to evaluate their effects. These parameters included power level and laser speed.

EXPERIMENTAL

Materials

In this study, a 100% polyester fabric weighing 160 g/m^2 with the warp density of 60 yarn/cm and weft density of 34 yarn/cm was used. Samples were washed with 0.5 g/L nonionic detergent in 70°C for 10 min before dyeing. Samples were dyed with three

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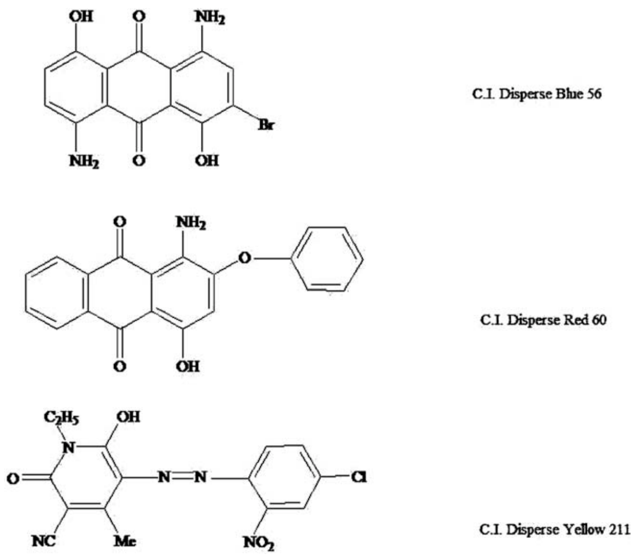


Figure 1 Chemical structure of C. I. Disperse Blue 56, C. I. Disperse Red 60, and C. I. Disperse Yellow 211.

disperse dyes: C.I Disperse Blue 56, C.I Disperse Red 60, and C.I Disperse Yellow 211. Chemical structure of applied dyes is shown in Figure 1.

Laser irradiation

Laser treatment was performed using a commercial pulsed CO_2 laser (LST TEX-100), providing wavelength of 10.6 μm. Different experimental conditions such as power, mark speed, and jump speed were applied for examining their effects on polyester properties.

Dyeing

Samples were dyed with 1% dye, 1 g/L dispersing agent, and 0.25 g/L acetic acid (pH = 4.5–5) according to the temperature-time curve shown in Figure 2.

Spectrophotometery

The amount of color changes due to the laser irradiation was determined by spectrophotometer (Color Guide). L^* a^* b^* color values of control and laser-treated samples were obtained by spectrophotometer and CIELAB ΔE^*_{ab} color difference values under illuminant D65 for 1964 standard observer were quantified according to eq. (1). (Control referred to samples that were only dyed without laser irradiation).

$$\Delta E^*_{ab} = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{0.5} \tag{1}$$

where ΔL^*, Δa^*, and Δb^* are differences between color values of control and laser-treated samples.

Moreover, reflectance values of samples (R) were used to calculate K/S based on eq. (2):

$$\frac{K}{S} = \frac{(1-R)^2}{2R} \tag{2}$$

Color fastness

Color fastness to light

Light fastness of laser irradiated samples was measured in accordance with ISO 105-B01. In this test a prepared specimen of laser irradiated fabrics was half covered and exposed to sunlight along with a scale of light sensitive blue dyed wool standards designed to fade after different time periods. Only the uncovered part of the test sample was subjected to light. Typical exposure time was 3 days. The light fastness of samples was evaluated and compared to control.

Color fastness to rubbing

Color fastness to rubbing was evaluated according to ISO 105-X12. This test was undertaken on a crock meter, whereby the fabric specimen was subjected to rubbing with a sample of standard undyed cotton fabric to check for color transfer.

Two tests were involved, one using the rubbing cloth dry, the other with the cloth wetted. The rubbing cloth was placed on the finger of the crock meter and moved back and forth across the fabric sample 10 times at a constant speed. The rubbing cloth was then evaluated using standard "Gray Scales" for staining, on which "1" signifies maximum staining and "5" no staining.

Color fastness to washing

According to ISO 105-C03 the test specimen was stitched with two pieces of test fabrics (polyester and cotton), then put into washing liquid, rotated under a certain temperature and time, the combination of specimen and test fabrics was washed with distilled water and then dried. The color change of

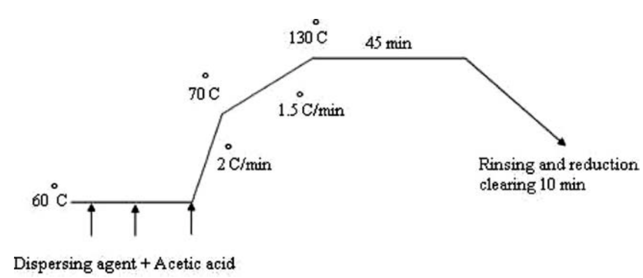


Figure 2 Dyeing temperature and time curve.

TABLE I
Experimental Conditions Used in Laser Irradiation of Polyester Fabric

Sample L	Sample D	*P* (%)	*M* (m/s)	*J* (m/s)
1L	1D	2	8.1	35.5
2L	2D	50	8.1	21.2
3L	3D	21	7.0	44.0
4L	4D	50	8.1	35.5
5L	5D	50	8.1	35.5
6L	6D	21	9.2	27.0
7L	7D	50	10.0	35.5
8L	8D	50	8.1	35.5
9L	9D	50	8.1	35.5
10L	10D	80	7.0	27.0
11L	11D	80	9.2	44.0
12L	12D	50	8.1	35.5
13L	13D	50	8.1	49.8
14L	14D	80	9.2	27.0
15L	15D	21	7.0	27.0
16L	16D	80	7.0	44.0
17L	17D	50	8.1	35.5
18L	18D	50	6.3	35.5
19L	19D	21	9.2	44.0
20L	20D	100	8.1	35.5

specimen and the staining of test fabrics were assessed with "Gray Scale."

Scanning electron microscopy

The morphology of samples was analyzed by scanning electron microscope, SEM, (Philips XL30). All samples were coated by gold before SEM examination.

Bending rigidity

Bending rigidity of samples in warp direction was measured. In this test, the fabric specimen was allowed to bend under its weight. The free length, which bended under its weight sufficiently to make its leading edge intersected a plane of 41.5° inclination, was called as bending length of the fabric *C*. Bending rigidity of samples (*G*) was calculated based on the eq. (3):

$$G = W \times C^3 \times 1000 \tag{3}$$

where *W* is the weight per area of each sample.

Wetting

Wettability of specimens was evaluated by measuring the time required for water droplet to spread on the fabric surfaces.

Crystal size

The XRD measurement was conducted by using a diffractometer (Pert MPD). The samples were exposed to the X-ray beam from an X-ray generator running at 40 KV and 40 mA.

The size of the ordered (crystalline) domains (τ) was calculated based on the Scherrer equation:

$$\tau = \frac{K\lambda}{\beta \cos \theta_\tau} \tag{4}$$

where *K* is the shape factor, λ is the X-ray wavelength, typically 1.54 A^o, β is the line broadening at half the maximum intensity (FWHM) in radians, and θ is the Bragg angle. The dimensionless shape factor has a typical value of about 0.9.

RESULTS AND DISCUSSION

Laser irradiation

Table I shows different laser parameters investigated in the laser treatment. "*P*" is a parameter relates with laser power ranging between 0 and 100 W. Mark speed "*M*" relates to the time laser beam spends on each pixel. Speed has an inverse relationship with time, therefore as "*M*" increases; the time laser beam spends on each pixel decreases. Jump speed "*J*" shows the speed which galvanometers use for moving from one pixel to the other. To evaluate the effect of laser treatment on dyeing properties of polyester fabric, laser irradiation was applied before (L) and after (*D*) dyeing.

Effect of laser parameters ("*P*", "*M*," and "*J*") on color difference between irradiated specimens and control in two conditions L and D is summarized in Tables II–IV. Values of *K*/*S* that indicate the ability

TABLE II
Effect of Laser Power on Color Difference Between Irradiated Samples and Control in Two Conditions L and D

Sample color	*P* (%)	Sample No.	Δ*E** L	Δ*E** D	*K*/*S* L	*K*/*S* D
Yellow	–	control	–		9.4	
	2	1	1.5	0.8	9.8	10.1
	50	8	11.1	3.4	26.4	19.7
	100	20	13.1	4.8	33.3	27.3
Red	–	control	–		17.1	
	2	1	0.6	1.5	17.4	18.3
	50	8	3.5	7.2	27.0	32.3
	100	20	5.7	11.6	34.0	38.0
Blue	–	control	–		32.5	
	2	1	0.2	1.2	33.5	33.5
	50	8	1.4	5.2	38.2	62.8
	100	20	2.3	9.9	46.3	79.0

In all samples mark speed and jump speed are 8.1 and 35.5 (m/s), respectively.

TABLE III
Effect of Laser Mark Speed on Color Difference Between Irradiated Samples and Control in Two Conditions L and D

Sample color	*M* (m/s)	Sample no.	Δ*E* *		*K* / *S*	
			L	*D*	*L*	*D*
Yellow	–	Control	–		9.4	
	6.3	18	12.8	4.4	29.5	26.5
	8.1	8	11.1	3.4	26.4	19.7
	10.0	7	7.4	3.1	17.6	15.8
Red	–	Control	–		17.1	
	6.3	18	4.8	9.9	30.4	36.6
	8.1	8	3.5	7.2	27.0	32.3
	10.0	7	2.3	4.9	23.8	29.5
Blue	–	Control	–		32.5	
	6.3	18	2.4	8.8	55.3	76.1
	8.1	8	1.4	5.2	38.2	62.8
	10.0	7	1.4	3.9	37.9	48.4

In all samples jump speed and power are 35.5 (m/s) and 50% respectively.

TABLE IV
Effect of Laser Jump Speed on Color Difference Between Irradiated Samples and Control in Two Conditions L and D

Sample color	*J* (m/s)	Sample no.	Δ*E**		*K* / *S*	
			L	D	L	D
Yellow	–	control	–		9.4	
	21.2	2	10.5	3.1	21.8	19.0
	35.5	8	11.1	3.4	26.4	19.7
	49.8	13	11.6	4.0	28.5	21.2
Red	–	control	–		17.1	
	21.2	2	2.9	5.6	24.6	31.3
	35.5	8	3.5	7.3	27.0	32.3
	49.8	13	3.8	7.8	28.2	34.8
Blue	–	control	–		32.5	
	21.2	2	1.4	5.1	38.1	56.3
	35.5	8	1.4	5.2	38.2	62.8
	49.8	13	1.5	5.4	38.9	64.6

In all samples mark speed and power are 8.1 (m/s) and 50% respectively.

of dye adsorption are also calculated. In each case one of the parameters was changed while the other two were constant.

It can be observed that laser power has strong effect on color difference in contrast to the other parameters. It is clear that an increase in laser power and laser jump speed leads to an increase in color difference and dye adsorption in all three dyes. Color difference values and ability of adsorption are adversely affected by increase in laser mark speed. By analyzing the influence of laser parameters in two conditions (L and *D*), it seems that while color difference in laser-treated samples after dyeing are higher for red and blue dyes, it is lower in yellow dye. Laser irradiation before dyeing results in surface morphological modification, but laser treatment after dyeing may also lead to some changes in molecular structure of dyes. In the latter case, anthraquinone dyes are more influenced by the irradiation than the azo dye. Comparing our results to those obtained by Wong et al. it was found that use of pulsed UV laser also had an improvement effect on dyeability. They believed the increment was due to the ripple structure of the modified surface.[8]

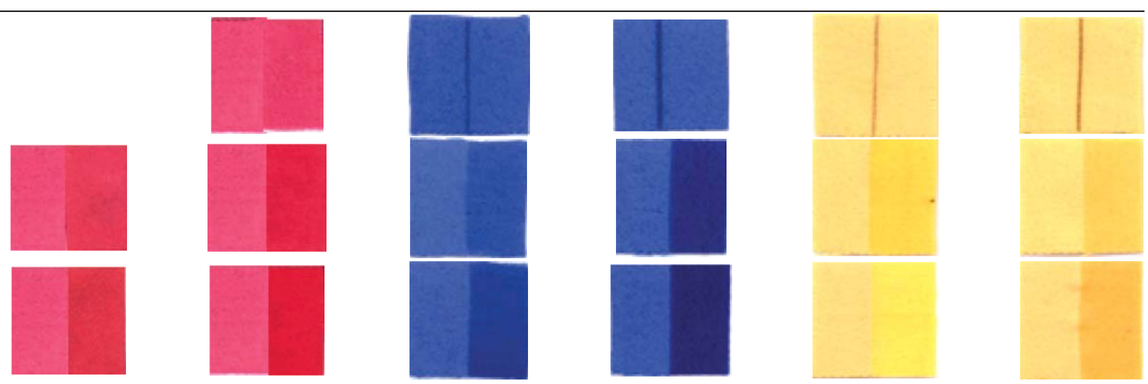
Table V shows dyeing results of laser-treated samples in conditions L and *D* considering different laser powers which also confirms the previous results.

Color fastness

Table VI shows light fastness of laser-treated fabrics. While there is no significant difference between light fastness values of irradiated specimens and control in low intensity of laser, the medium and high laser intensity significantly increase the light fastness in

TABLE V
Dyeing Results of Laser-Treated Samples in Three Different Laser Powers in Two Conditions L and D [Color table can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Sample No	L	D	L	D	L	D
1						
8						
20						



Left half of samples are control.

TABLE VI
Light Fastness of Laser-Treated Fabrics

	Blue		Yellow		Red	
Control	6-7		7		6	
Sample No.	L	D	L	D	L	D
1	6-7	6-7	7	7	6	6
2	7-8	8	7-8	8	7	7-8
3	6-7	6-7	7	7	6	6
4	7-8	8	7-8	8	7	7-8
5	7-8	8	7-8	8	7	7-8
6	6-7	6-7	7	7	6	6
7	7-8	8	7-8	8	7	7-8
8	7-8	8	7-8	8	7	7-8
9	7-8	8	7-8	8	7	7-8
10	7-8	8	7-8	8	7	7-8
11	7-8	8	7-8	8	7	7-8
12	7-8	8	7-8	8	7	7-8
13	7-8	8	7-8	8	7	7-8
14	7-8	8	7-8	8	7	7-8
15	6-7	6-7	7	7	6	6
16	7-8	8	7-8	8	7	7-8
17	7-8	8	7-8	8	7	7-8
18	7-8	8	7-8	8	7	7-8
19	6-7	6-7	7	7	6	6
20	7-8	8	7-8	8	7	7-8

comparison to the control. It can be observed that the increase is smaller in the samples treated by laser before dyeing (L).

Laser irradiation has no noticeable effect on the washing fastness of the samples. Only a small change is observed for samples irradiated after dyeing with yellow dye.

TABLE VII
Rubbing Fastness of Laser-Treated Fabrics

	Blue		Yellow		Red	
Control	4-5		4		5	
Sample No	L	D	L	D	L	D
1	4-5	4-5	4	4	5	5
2	4-5	5	4	5	5	5
3	4-5	4-5	4	4	5	5
4	4-5	5	4	5	5	5
5	4-5	5	4	5	5	5
6	4-5	4-5	4	4	5	5
7	4-5	5	4	5	5	5
8	4-5	5	4	5	5	5
9	4-5	5	4	5	5	5
10	4-5	5	4	5	5	5
11	4-5	5	4	5	5	5
12	4-5	5	4	5	5	5
13	4-5	5	4	5	5	5
14	4-5	5	4	5	5	5
15	4-5	4-5	4	4	5	5
16	4-5	5	4	5	5	5
17	4-5	5	4	5	5	5
18	4-5	5	4	5	5	5
19	4-5	4-5	4	4	5	5
20	4-5	5	4	5	5	5

Measurements are carried out in warp direction and dry condition.

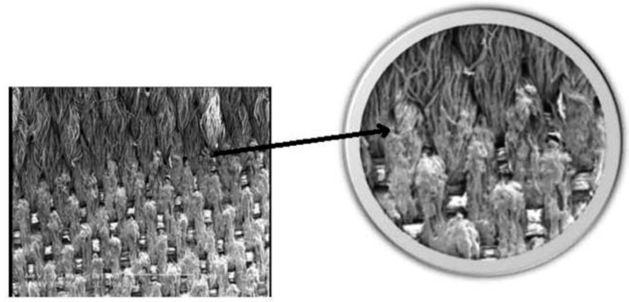


Figure 3 SEM image of difference between surface morphology of laser treated (down zone) and untreated (up zone).

Rubbing fastness of laser irradiated samples was measured in warp and weft directions for both dry and wet conditions. As the same results were obtained for two directions and two conditions, one

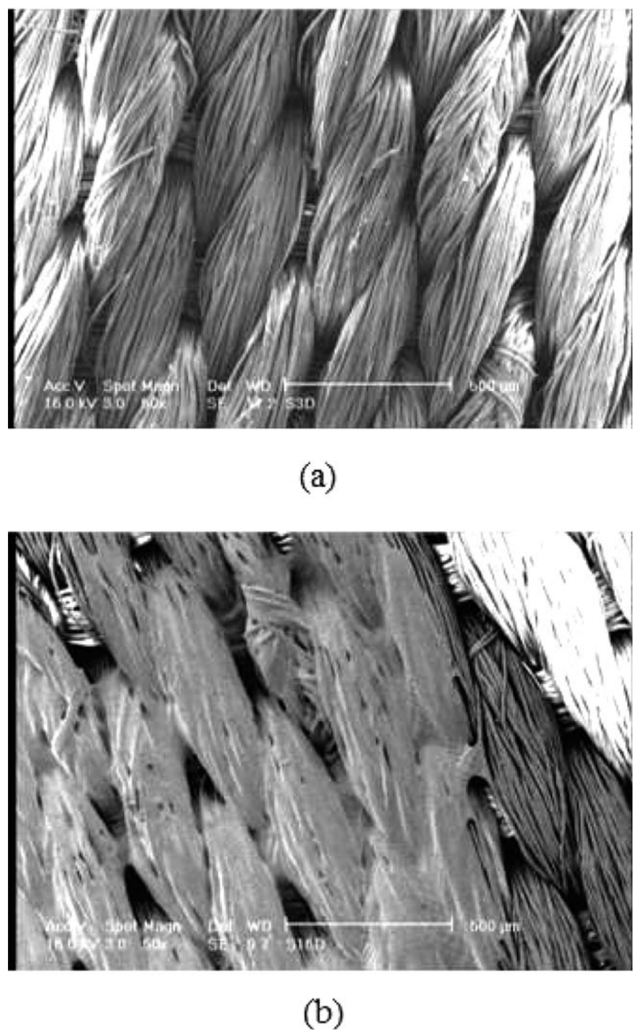


Figure 4 SEM images of the influence of laser power on surface morphology. (a) sample 3D ($P = 21\%$), (b) sample 16D ($P = 80\%$).

TABLE VIII
Bending Rigidity of Laser-Treated Fabrics Dyed with C.I. Disperse Yellow 211

Sample no.	L			D		
	C (cm)	$W \times 10^3$ (g/cm^2)	G (mg.cm)	C (cm)	$W \times 10^3$ (g/cm^2)	G (mg.cm)
Control	1.15	20.6	31.33	1.15	20.6	31.33
1	1.80	19.9	116.06	1.80	20.1	117.22
2	2.20	19.4	206.57	2.90	20.5	499.97
3	1.80	19.9	116.06	2.50	20.1	314.06
4	2.00	19.3	154.40	3.05	21.1	598.66
5	2.30	18.7	277.52	3.15	21.7	678.25
6	1.75	19.7	105.58	2.45	20.9	307.36
7	1.85	19.3	122.20	2.75	21.1	438.81
8	2.20	18.9	201.25	3.00	21.6	583.20
9	2.15	19.6	194.79	3.05	21.6	612.85
10	2.50	20.0	312.50	4.45	23.4	2062.63
11	2.05	19.6	168.86	3.20	21.1	691.40
12	1.90	19.7	135.12	3.00	21.6	583.20
13	1.90	19.6	134.44	3.05	21.3	604.34
14	2.00	19.8	158.40	3.20	20.8	681.57
15	1.75	19.6	105.04	2.70	20.7	407.47
16	2.75	20.8	432.58	4.00	23.9	1529.60
17	2.00	19.3	154.400	2.95	21.6	554.52
18	2.30	19.6	238.47	3.80	22.2	1218.16
19	1.65	18.8	84.45	2.20	20.9	222.54
20	2.20	20.5	218.28	4.10	22.9	1578.29

of the values is included in Table VII. With the low intensity of laser irradiation, no significant difference is evaluated. It is also clear that the lowest and highest values of rubbing fastness belong to yellow and red dyes, respectively.

Scanning electron microscopy

Figure 3 shows SEM image of the laser irradiated and unirradiated zones in polyester fabric. It can be seen that laser heat causes the polyester fibers to

TABLE IX
Drop Test Results of Laser-Treated Samples

Blue				Yellow				Red			
L		D		L		D		L		D	
Sample No.	Sec.	Sample No.	Sec.	Sample No.	Sec.	Sample No.	Sec.	Sample No.	Sec.	Sample No.	Sec.
control	6	control	6	control	597	control	597	control	404	control	404
1L	7	1D	7	1L	603	1D	611	1L	480	1D	509
2L	8	2D	293	2L	531	2D	673	2L	636	2D	720
3L	8	3D	102	3L	436	3D	992	3L	670	3D	790
4L	10	4D	387	4L	594	4D	805	4L	657	4D	815
5L	9	5D	410	5L	536	5D	812	5L	645	5D	833
6L	6	6D	6	6L	604	6D	934	6L	604	6D	789
7L	3	7D	65	7L	549	7D	807	7L	597	7D	700
8L	7	8D	377	8L	555	8D	892	8L	603	8D	870
9L	9	9D	420	9L	579	9D	871	9L	667	9D	852
10L	32	10D	920	10L	808	10D	1354	10L	1100	10D	1119
11L	19	11D	14	11L	487	11D	1000	11L	903	11D	1006
12L	9	12D	390	12L	517	12D	804	12L	669	12D	890
13L	5	13D	55	13L	742	13D	724	13L	580	13D	730
14L	12	14D	39	14L	750	14D	1200	14L	1009	14D	850
15L	6	15D	72	15L	420	15D	970	15L	920	15D	990
16L	13	16D	353	16L	801	16D	1384	16L	1093	16D	1150
17L	8	17D	360	17L	525	17D	847	17L	637	17D	807
18L	19	18D	590	18L	760	18D	965	18L	680	18D	1100
19L	3	19D	28	19L	390	19D	763	19L	590	19D	550
20L	21	20D	807	20L	868	20D	1284	20L	1175	20D	1100

melt and adhere to each other which results in changing porosity of the fabric surface. It should be emphasized that laser surface modification is strongly relative to the laser power. As indicated in Figure 4, there is a significant difference in surface morphology of samples 3*D* and 16*D* which irradiated by 21 and 80% laser power, respectively. It is shown that the higher laser power results in fiber adhesion.

Bending property

Bending property has an important effect on the handle performance of textiles. Bending rigidity of all specimens increases with an increase in laser intensity. As an example the values of yellow samples are shown in Table VIII. A higher increment is observed for samples irradiated after dyeing (D). Adhesion of fibers as a result of laser heating can restrict bending. Similar increase in bending properties has been reported using UV excimer laser which claimed to be due to the ripples increasing the friction between the fibers in the yarn and restricting the bending.[9–11]

Wetting

Drop test results are shown in Table IX. It is observed that the time required for water to adsorb and penetrate into the blue fabrics is less than the red and yellow ones. This may be due to the existence of more hydrophilic groups in the blue dye. In addition, the wetting time of all samples increases by an increase in the laser intensity. The increment is more significant in condition D. A reduction in the wettability of fabrics is believed to be related to the adhesion of fibers by laser heating. Fabric pores are closed by polymer melts, resulting in an increase in the wetting time. In some weak points, due to the dyeing tensions, closed pores are opened resulting in higher hydrophilicity in condition L. Lower wettability of polyester fabrics after high-fluence UV laser irradiation was also reported by Kan.[9–11]

Crystal size

Table X shows the crystal size of samples L9, L10, D10, and D15. Results reveal a trend toward a reduction in the crystal size as laser power increases. However, it seems that the trend is relative to the power and reverses in high powers. This may be due to the joining of small crystals by which bigger crystals are made. In most of literatures on laser treatment applied to polyester, no significant change in the degree of crystallinity has been reported. The penetration depth of laser energy has been believed to be limited to the surface of fabric where the bulk properties remain unchanged.[9–11]

TABLE X
Crystal Size of Four Laser-Treated Samples in Two Conditions L and D

Laser power (%)	Sample	Crystal size (A°)
–	control	100.77
50	9L	79.92
80	10L	87.25
21	15D	80.62
80	10D	86.06

CONCLUSIONS

Application of CO_2 laser on the polyester fabric and its effect on the dyeing properties was investigated. It was shown that the color difference values between laser-treated samples before and after dyeing and control was increased. This work demonstrated the importance of a careful selection of laser parameters like power and speed. For instance, it was found that the effect of laser power was more significant than the laser speed. Modification in surface morphology of samples irradiated before dyeing was part of the reason for color changes. In addition, in laser treatment after dyeing it was believed that some changes in dyes structure may be occurred.

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