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EVALUATION OF ILLUMINATION INTENSITY OF PLASTIC OPTICAL FIBRES WITH TIO_2 PARTICLES BY LASER TREATMENT

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Abstract:

CO_2 laser treatment can increase the surface roughness of plastic optical fibres (POFs) with the diameter of 0.5 mm and enhance the input intensity and attenuation coefficient accordingly, which is supposed to weaken the side emission of POFs in long distance above 375 mm. TiO_2 particles were applied to improve the increasing optical loss of POFs by laser treatment. POFs were first modified with fine TiO_2 particles and then treated by CO_2 laser with the pixel time from 30 to 120 μs. The surface morphology was observed by scanning electron microscopy to investigate the changes of micro-structure before and after laser treatment and the distribution of TiO_2 particles. The illumination intensity and attenuation coefficient were calculated and compared in two methods. It is visible that the evaluation by model LLF2 with two parts is more suitable for the fitting of experimental data and shows higher input intensity and lower attenuation than that by standard power function. Both the evaluation methods exhibit that the utilization of TiO_2 particles could play an active role in the enhancement of side emission of POFs treated by CO_2 laser.

Keywords:

plastic optical fibres, illumination intensity, attenuation, TiO2 particles, surface roughness, laser treatment.

1. Introduction

Soft light textiles with plastic optical fibres (POFs) [1-4] have been catching more attention nowadays due to light emitting effect and special lighting images. The side emitting POFs can be woven, knitted and braided in to fabrics, or used as floatings in structures. While there is a challenge for manufacturers to produce the fine POFs that can be woven with textile fibres, surface modification has been widely applied to increase the surface roughness of POFs for side emitting effect. Surface abrasion and solvent etching are combined for the evaluation of side illumination of POFs [5], which display the improvement of side illumination intensity and decrease the mechanical properties. Notches are created on the surface of POFs to let the light escape [6]. Radiation scattering particles (like ZnO and Al_2O_3) are embedded into cladding of POFs to enhance the side illumination intensity [7,8].

CO_2 laser is utilized extensively due to its high laser efficiency, great beam size, low cost, easy operation and no pollution to the environment. Creation of microstructure for polymethylmethacrylate (PMMA) [9], surface modifications for LDPE film [10] and glass fibres mat [11] have been successfully achieved by CO_2 laser treatment.

In this study, the surface of POFs was covered with TiO_2 fine particles and then treated by CO_2 laser under different pixel time. The surface morphologies of POFs with and without TiO_2 particles after CO_2 laser treatment were investigated by scanning electronic microscopy and the illumination intensity of POFs was tested by a semi-automatic device. Both input intensity and attenuation coefficient were evaluated and compared by two methods (standard power function and model LLF2).

2. Experimental

2.1 Materials

The fundamental characterizations of POFs with 0.5-mm diameter brought from Grace POF Co., Ltd. are provided in Table 1.

2.2 Preparation of specimens

The basic characterizations of TiO_2 fine powder utilized for surface modification of POFs are exhibited in Table 2. The solid and liquid mixture was prepared by dispersing 2 g TiO_2 particles into 200 ml isopropyl alcohol at 20°C and 65% relative humidity. The mixture with 10 g/L solid concentration was obtained after stirring by ultrasound Bandelin SONOPULS mini20 ultrasonic homogenizer with 50% power for 1 minute.

Table 1. Basic properties of plastic optical fibres.

Basic properties	Values
Core material	PMMA
Cladding material	PMMA/Teflon
Diameter (mm)	0.5
Core refraction index	1.49
Cladding refraction index	1.42
Numerical aperture	0.44
Acceptance angle (°)	52.2
Storage temperature (°C)	-20 to +70
Specific gravity (g/cm^3)	1.19
Wavelength (nm)	400–780
Limit of bending radius	8 × fibre diameter

Table 2. Typical physical and chemical properties.

	PK-20
TiO_2 content (%)	>92.5
Crystal modification	Anatase
Specific surface area (m^2/g) BET (5 points)	70–110

One end of the POF with 500-mm length was dipped into the mixture slowly and bought out vertically until another end of the fibre was covered with the mixture. The POF modified with fine TiO_2 particles was prepared after dried in the air at 20°C and 65% relative humidity for 30 seconds, as shown in Figure 1.

The POFs with or without TiO_2 particles were arranged parallelly with gluing tapes in a self-made hard thick paper frame on a flat base (Figure 2), and the height of the holder between base and paper frame was about 30 mm. The distance between each neighbouring sample was at least 20 mm to minimize the influence of CO_2 laser treatment for adjacent samples.

2.3 Laser treatment

The samples were conducted by Easy Laser Marcatex Flexi CO_2 laser (Marcatex 150/250 flexi) with a carbon dioxide laser beam under 50% duty cycles. The wavelength of laser beam was 10.6 µm and the output power was 100 W. The pixel time for laser treatment was set as 30, 50, 70, 90 and 120 µs. Both front and back sides of all the samples were treated by CO_2 laser. The CO_2 laser scans in rows and the scanning direction were parallel to the fibre axis, as shown in Figure 2.

2.4 Surface morphology

The surface images of samples after gold coating were taken by scanning electron microscopy (SEM) VEGA TS 5130, at 20 kV acceleration voltage.

2.5 Intensity of side illumination

The semi-automatic instrument for tests of side illumination intensity of optical fibres is displayed in Figure 3 [12]. The sample polished with abrasive papers and diamond powder in the elongated state was connected with the light source (13) through two sets of rollers (4 and 5); the head roller (4) was controlled by the stepper motor MSHC 100B41 Sankyo (9), and the side illumination intensity of sample was tested by the light intensity sensor THOR LABS PM 100 USB (15) that was connected with the PC. The conditions for testing the illumination intensity are designed in Table 3. All measurements must be carried out in a dark background. The diameter of roller is 45 mm and the distance between light source and sensor is approximately 175 mm.

Table 3. Testing conditions of illumination intensity for samples.

Parameters	Values
Step size (mm)	5
Length measured (mm)	200
Fibre length (mm)	500

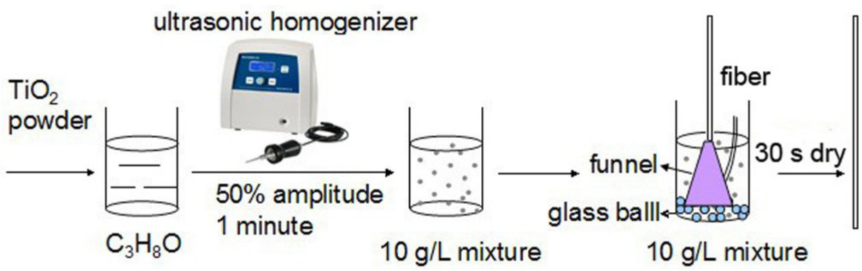

Figure 1. Preparation of POFs modified with TiO_2 fine particles.

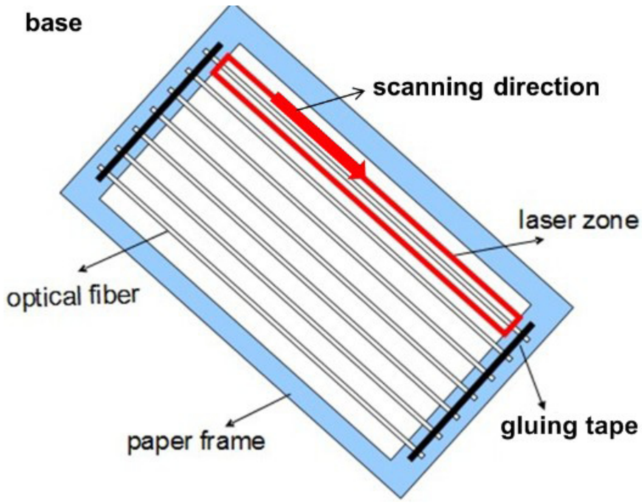

Figure 2. Preparation of samples for laser treatment.

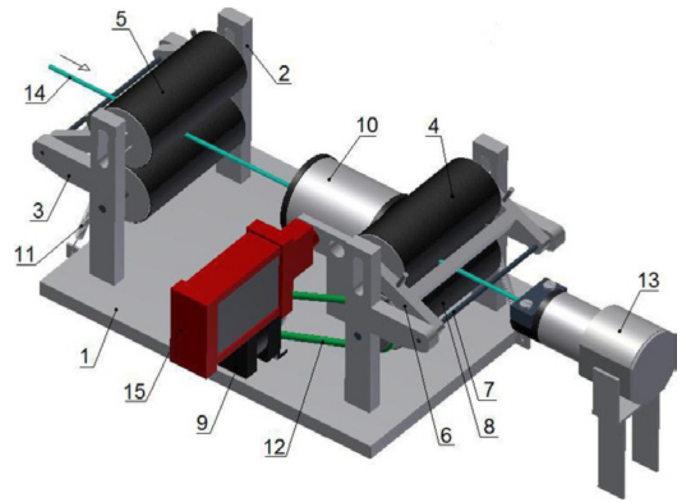

Figure 3. The device for measurement of intensity of illumination of optical fibres: 1 – motherboard, 2 – spacers (4´), 3 – console, 4 – tow roller, 5 – rollers to guide the sample, 6 – pressing lever roller, 7 – storing the lever, 8 – driven exhaust roller, 9 – stepper motor, 10 – measuring tunnel, 11 – tension springs, 12 – drive belt, 13 – lighting equipment, 14 – optical fibre, 15 – light intensity sensor.

2.6 Principle of evaluation

The attenuation coefficient *a* in decibel per unit length is usually determined by the input (transmitted) optical power into the fibre *P(0)* and the output (received) optical power *P(z)* [7,13,14],

$$az = 10 \log_{10} [P(0)/P(z)] \quad (1)$$

$$\log_{10} P(z) = -az/10 + \log_{10} P(0) \quad (2)$$

$$y = kx + q \quad (3)$$

where *z* is the distance from light source. The transformation equation (2) of Equation (1) is related to the linear fitting curve of logarithm of output power versus measured distance, as given in Equation (3) and Figure 4, the input power *P(0)* and attenuation coefficient *a* are described as,

$$P(0) = 10^{q} \quad (4)$$

$$a = -10\,k \quad (5)$$

where *k* and *q* are two parameters (slope and intercept, respectively) of the linear fitting curve. The intensity of side illumination can be calculated from Equation (1) and is a standard power function,

$$P(z) = P(0)10^{-az/10} \quad (6)$$

Form Figure 4, it is found that the estimation of parameters *P(0)* and *a* are not precise enough since there is no perfect linear fit for our experimental data. Another model named LLF2 [15] is applied to evaluate the results. LLF2 model made of two straight lines, as shown in Equation (7), is based on the widely accepted assumption that the illumination intensity decreases markedly in the short distance from the light source and then drops slowly to a constant,

$$P(z) = P_{cor}(0) + a_1 z + a_2(z-z_c) \quad (7)$$

where $P_{cor}(0)$ is the corrected input intensity that is the intercept for the first straight line, a_1 and a_2 are the sensitivity coefficients that are the slope parameters for the two straight lines and *zc* is the critical point that departs the model into two parts.

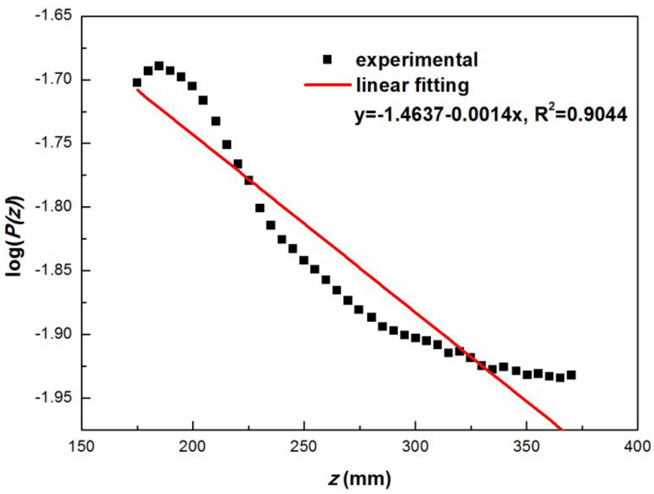

Figure 4. Linear fitting cure of log(*P(z)*) versus distance from the source for POFs without TiO_2 particles by laser treatment.

3 Results and discussion

3.1 Surface morphology

From Figure 5, the POFs modified with TiO_2 particles (d) are not full of TiO_2 particles on the surface. The smooth surface of untreated POF (a) can merely carry a part of TiO_2 particles properly by the Van der Waals force. It is obvious that the CO_2 laser treatment has a different effect on the fibre surface according to various pixel time. Without TiO_2 particles, the higher the pixel time, the deeper the holes and rougher the fibre surface, as shown in (b) and (c). With TiO_2 particles, the surface damage is not enhanced evidently with high pixel time, as given in (e) and (f). The TiO_2 particles might improve the thermal damage of POFs.

During the experiments of laser treatment, when the pixel time was up to 150 μs, the POFs became obscure. When the pixel time was about 200 μs, there were visible “neck” points along

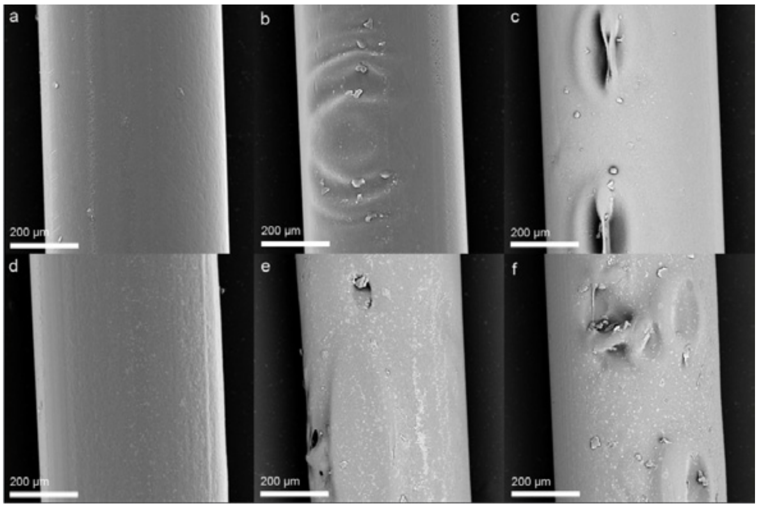

Figure 5. Surface SEM images of POFs after CO_2 laser treatment [16]. (a) 0 μs pixel time without TiO_2 particles; (b) 100 μs pixel time without TiO_2 particles; (c) 150 μs pixel time without TiO_2 particles; (d) 0 μs pixel time with TiO_2 particles; (e) 100 μs pixel time with TiO_2 particles and (f) 150 μs pixel time with TiO_2 particles.

the fibre length. The thermal damage is a significant factor that might weaken the optical properties and other properties (such as mechanical properties). In present work, the maximum pixel time was chosen as 120 μs.

3.2 Illumination of intensity

In the case of surface modification without CO_2 laser treatment, it is visible from Table 4 that both two calculation methods (standard power function and model LLF2) exhibit the enhancement of side illumination of POFs with TiO_2 particles during 375-mm distance from the light source. The differences between the values of *P(0)* and *P(z=375 mm)* for POFs with TiO_2 particles are evidently higher than that for POFs without TiO_2 particles. It is indicated that the TiO_2 particles play a positive role in side emitting effect of POFs and increase the optical loss in this distance at the same time.

Most fitting values of input intensity from model LLF2 are greater than those from standard power function, as shown in Figure 6. Figure 7 shows that the model LLF2 gives a better fit for the experimental data due to the special optical properties for optical fibres, the exponential relationship (standard power function) between light transmission and transmitting distance in POFs might not be perfect for evaluation of POFs in present work due to the short distance.

From Figure 6, it is found that the values of input intensity rise up according to the increment of pixel time during CO_2 laser treatment due to the increasing surface roughness in both methods. When the pixel time reaches to 90 μs, the input intensity of POFs starts to decline except the raising value of POFs with TiO_2 particles obtained from the standards power function, which is indicated that the thermal damage caused by high energy and treating time weakens the optical properties while the TiO_2 particles could alleviate this damage during laser treatment.

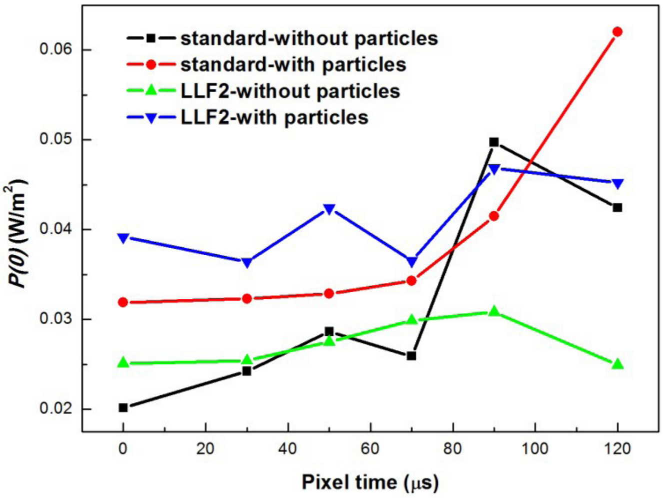

Figure 6. Dependence of input intensity on pixel time of CO_2 laser treatment.

When it comes to the optical properties, the attenuation is an inevitable parameter. From the method with standard power function in Figure 8, it is very interesting that there is a “valley” for the relation between attenuation coefficient and pixel time for POFs with TiO_2 particles. Generally, high pixel time leads to great attenuation, as shown in the curve for POFs without TiO_2 particles in Figure 8. The attenuation coefficient decreases to the minimum at 70 μs pixel time and then increases as the pixel

Table 4. Light transmission properties between POFs with and without TiO_2 particles before CO_2 laser treatment.

Fibre state	Standard power function		Model LLF2	
	P(0) (W/m²)	*P(z=375 mm)* (W/m²)	*Pcor(0)* (W/m²)	*P(z=375 mm)* (W/m²)
Without TiO_2 particles	0.0201	0.0055	0.0251	0.0057
With TiO_2 particles	0.0318	0.0057	0.0392	0.0071

time increases. It is shown that the combination of TiO_2 particles and CO_2 laser treatment might enhance the optical properties when the pixel time is in the range from 30 to 70 μs; meanwhile, when the pixel time is above this range, the thermal damage of POFs from laser treatment could not be neglected and have a severely negative influence on the side illumination of POFs. The reaction among CO_2 laser treatment, TiO_2 particles and POFs is complicated and should be discussed further.

It implies that the combination of TiO_2 particles and CO_2 laser treatment might improve the side illumination for POFs. Only CO_2 laser treatment would aggravate the side emission. The best condition of laser treatment for the enhancement of side emission of POFs with TiO_2 particles in the present work is 70 μs pixel time from the method with standard power function.

Compared with the slopes of fitting curves with model LLF2, it is obvious that the fist slope *a1* of fitting curves for POFs without TiO_2 particles is lower than that for POFs with TiO_2 particles. The similar trend is observed in the second slope *a2*. Meanwhile, the values of slope *a1* for the fitting curves for POFs with and without TiO_2 particles are greater than those of slope *a2*.

That is to say, there is a zone near to the light source with the significant optical loss, which is followed by a relatively flat light transmission with slight optical loss. During the treatment by CO_2 laser, the TiO_2 particles might contribute to the side emitting effect of POFs due to the higher input intensity (Figure 9) and smaller attenuation. The best condition of laser treatment for the enhancement of side emission of POFs with TiO_2 particles with the calculation method of model LLF2 is 90 μs pixel time.

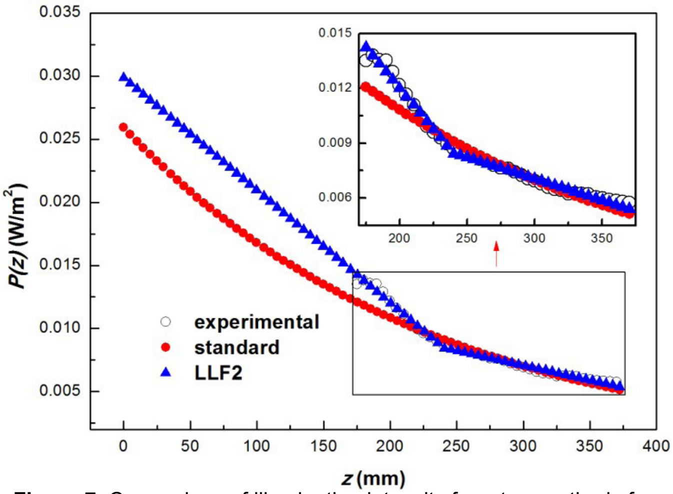

Figure 7. Comparison of illumination intensity from two methods for POFs without TiO_2 particles by CO_2 laser treatment at 70 μs pixel time.

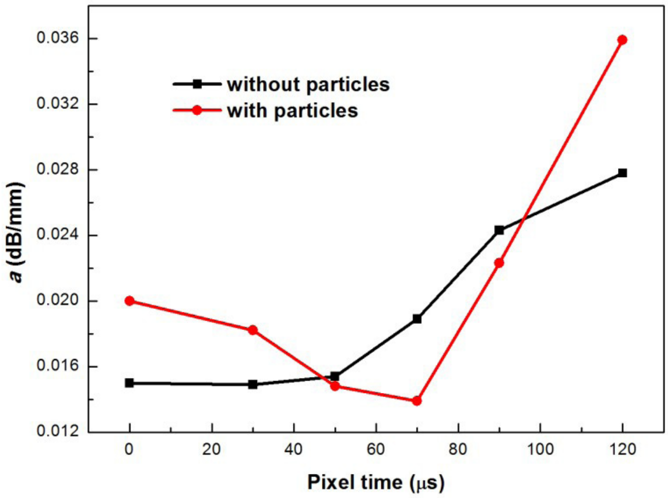

Figure 8. Dependence of attenuation coefficient on pixel time with the calculation method by standard power function.

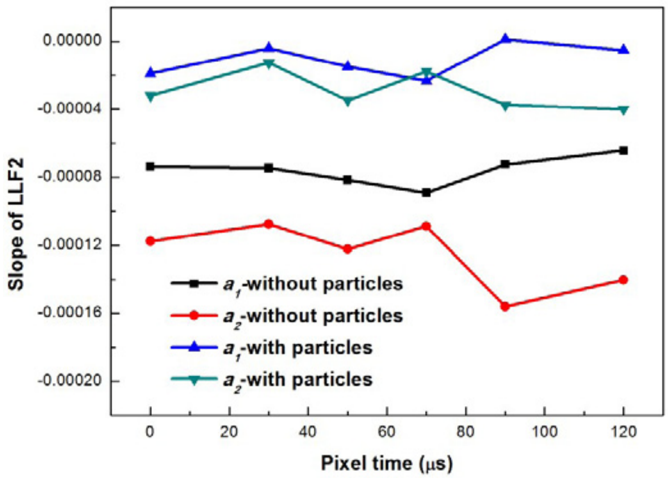

Figure 9. Dependence of slopes on pixel time with the calculation method by model LLF2.

4 Conclusions

POFs with 0.5-mm diameter were modified with TiO_2 particles and CO_2 laser treatment; the illumination intensity of POFs was measured by a self-automatic device and then calculated by two methods. It is concluded that:

The method with model LLF2 shows better fit for most of the experimental data and gives the greater input intensity for the major POFs than the method with standard power function in present investigation. The two fitting parts in model LLF2 aptly describes the zone with evident attenuation near to light source and the zone with slow attenuation far to light source.

It is seen from the results evaluated by both the calculation methods that the combination of TiO_2 particles and CO_2 laser treatment has a positive effect of side emission of POFs in some cases rather than only CO_2 laser treatment. The best conditions of laser treatment for the enhancement of side emission of POFs with TiO_2 particles for the methods with standard power function and model LLF2 are 70 and 90 μs pixel time, respectively.

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