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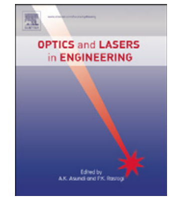

Investigation of CO_2 laser beam modulation by rotating polygon

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ABSTRACT

A beam-modulating system based on the rotating polygon has been proposed in a previous experimental work [14]. The aim was to improve the quality and efficiency of CO_2 laser surface texturing. Based on the generalized *ABCD* law, the focusing characteristics of a real beam through the modulating system are investigated in this paper. By introducing a precise defocusing, the velocity synchronization between the focal spot and the workpiece can be realized. Micro-dimples of nearly circular shape can be achieved on the surface. Surface texturing of mill roll has been performed. The experimental and theoretical results are in good agreement.

1. Introduction

Laser surface texturing is a recently developed technique to produce micro-dimples of uniform size and optimum geometric shape on a mill roll. A high energy, high beam quality and high repetition rate pulsed laser is the ideal tool for such an application. In the past two decades, many laser beam modulated by a rotating mechanical chopper have been investigated and developed for high-power cw CO_2 laser beams [1–4]. However, in the chopper method, the beam is repeatedly shielded by the chopper disk and a certain amount of the laser power is not utilized [5].

With high scanning speed, high-speed stability and large scanning range, the rotary polygon mirror has been used in many applications including optical scanning [6,7], optical coherence microscopy [8], laser heat treatment [9], laser cladding [10], laser drilling [11], and laser perforating [12,13], etc. Conventionally, in the optical-chopping polygon method, a continuous laser beam is chopped into discrete wavelets by a high-speed rotating polygon mirror. The wavelets are focused on the material surface by a multitude of lenses. Since the spot formed by any discrete wavelet is stationary as the material moves, elliptically shaped holes will be produced on the material surface. In a previous experiment [14], a beam-modulating system with rotating polygon has been proposed for improving the quality and efficiency of CO_2 laser surface texturing. Based on the generalized *ABCD* law, the focusing characteristics of a real beam through the beam-modulating system are investigated in this paper. The results show that the synchronization between focal spot shift and workpiece motion can be achieved by introducing a precise defocusing. Micro-dimples of circular shape were obtained on the workpiece surface. Theoretical considerations are presented.

2. Set-up of the beam modulation

In Fig. 1 the set-up is outlined. The incident laser beam of a high-power cw CO_2 laser is focused onto a reflecting facet of the rotating polygon. During the rotation of the polygon, the reflected beam will scan a certain angular range. When the next facet becomes effective, the reflected beam jumps back and scans again the same angular range. In every scan the reflected beam will successively sweep through the tightly arranged multi-focusing heads. A single short laser pulse is generated when the beam sweeps through each one of the focusing heads. During repeated scanning, a sequence of high peak power laser pulses will be generated for each one of the focusing heads. The cw–laser beam is transformed into multiple pulsed laser beams with a certain time sequence and a high repetition rate.

With this arrangement the texturing efficiency is greatly improved. Compared with the traditional mechanical chopping method, the energy-efficiency is significantly enhanced by applying a high-speed optical-chopping polygon.

3. Focusing characteristics of a real beam

The beam focusing characteristics (e.g., focus radius, focal depth, etc.) have great influence on the quality of the laser material processing techniques [15]. In order to guarantee the

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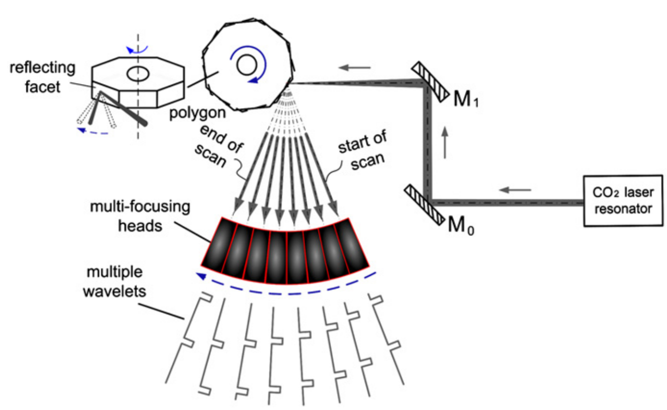

Fig. 1. Schematic diagram of laser beam modulation system with rotating polygon.

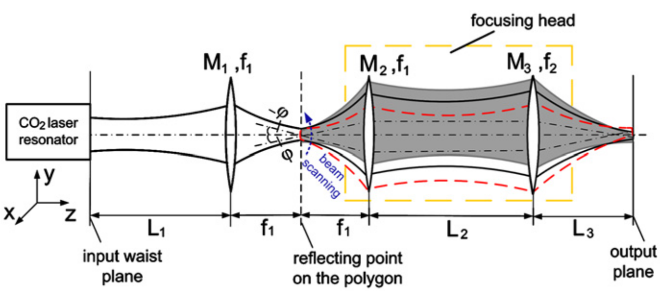

Fig. 2. Thin lens equivalence of the reflected scanning beam propagation through one of the focusing heads.

stability of the processing quality, a proper beam delivery system is essential. Therefore the focusing characteristics of a real beam through the beam modulation system should be taken into account correctly.

As a result of the radial symmetry arrangement for the multi-focusing heads, the reflected scanning beam propagation through each one of the focusing heads is equivalent.

Fig. 2 illustrates the thin lens equivalence of the reflected scanning beam propagation through one of the multi-focusing heads. All the deflecting mirrors and the rotating polygon have been omitted for greater clarity. The reflected beam is collimated by lenses M_1 and M_2, and then focused by lens M_3 slightly below the surface of the workpiece to be textured.

3.1. Second-moment-based spot size of the real beam

High-power CO_2 laser beams used in laser material processing are generally multimode beams [15]. These beams can be characterized by their six second-order intensity moments: $\langle w^2\rangle_{x,y}$, $\langle \theta^2\rangle_{x,y}$, $\langle R\rangle_{x,y}$.$\langle w^2\rangle_x$ and $\langle w^2\rangle_y$ are the beam radii in x and y directions, $\langle \theta^2\rangle_x$ and $\langle \theta^2\rangle_y$ are the far-field divergences in x and y directions, and $\langle R\rangle_x$ and $\langle R\rangle_y$ correspond to the effective radii of curvature.

The six second-order intensity moments are defined as [16,17]

$$\langle w^2\rangle_x = \frac{4}{P}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} x^2 |E(x,y)|^2\,dx\,dy$$
$$\langle w^2\rangle_y = \frac{4}{P}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} y^2 |E(x,y)|^2\,dx\,dy \quad (1)$$

$$\langle \theta^2\rangle_x = \frac{\lambda^2}{\pi^2 P}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} \left|\frac{\partial E(x,y)}{\partial x}\right|^2 dx\,dy$$

$$\langle \theta^2\rangle_y = \frac{\lambda^2}{\pi^2 P}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} \left|\frac{\partial E(x,y)}{\partial y}\right|^2 dx\,dy \quad (2)$$

$$\langle 1/R\rangle_x = \frac{\langle w\theta\rangle_x}{\langle w^2\rangle_x}, \quad \langle 1/R\rangle_y = \frac{\langle w\theta\rangle_y}{\langle w^2\rangle_y} \quad (3)$$

with P the total power in the beam; $\langle w\theta\rangle_{x,y}$ the mixed second-order moments related to the effective radii of curvature $\langle R\rangle_{x,y}$.

For the propagation of a real beam in first-order optical systems the generalized $ABCD$ law holds [16]

$$\langle w_2^2\rangle_{x,y} = A^2\langle w_1^2\rangle_{x,y} + 2AB\langle w_1\theta_1\rangle_{x,y} + B^2\langle \theta_1^2\rangle_{x,y} \quad (4)$$

$$\langle \theta_2^2\rangle_{x,y} = C^2\langle w_1^2\rangle_{x,y} + 2CD\langle w_1\theta_1\rangle_{x,y} + D^2\langle \theta_1^2\rangle_{x,y} \quad (5)$$

$$\langle w_2\theta_2\rangle_{x,y} = AC\langle w_1^2\rangle_{x,y} + (AD+BC)\langle w_1\theta_1\rangle_{x,y} + BD\langle \theta_1^2\rangle_{x,y} \quad (6)$$

where $ABCD$ are the elements of the ray transfer matrix between plane 1 and plane 2. It can be different in x and y directions.

In Fig. 2 the ray transfer matrix from the input waist plane to the reflecting point on the polygon reads for rotational symmetry

$$\begin{bmatrix} A_1 & B_1 \\ C_1 & D_1 \end{bmatrix} = \begin{bmatrix} 1 & f_1 \\ 0 & 1 \end{bmatrix}\begin{bmatrix} 1 & 0 \\ -1/f_1 & 1 \end{bmatrix}\begin{bmatrix} 1 & L_1 \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} 0 & f_1 \\ -1/f_1 & 1-L_1/f_1 \end{bmatrix} \quad (7)$$

where f_1 is the focal length of lens M_1; L_1 is the distance from the input beam waist to lens M_1.

The propagation starts at waist with $\langle w_1\theta_1\rangle_{x,y}=0$ and $\langle w_1^2\rangle_{x,y} = \langle w_{01}^2\rangle_{x,y}$. Eqs. (4)–(6) then reduce to

$$\langle w_2^2\rangle_{x,y} = A^2\langle w_{01}^2\rangle_{x,y} + B^2\langle \theta_1^2\rangle_{x,y} \quad (8)$$

$$\langle \theta_2^2\rangle_{x,y} = C^2\langle w_{01}^2\rangle_{x,y} + D^2\langle \theta_1^2\rangle_{x,y} \quad (9)$$

$$\langle w_2\theta_2\rangle_{x,y} = AC\langle w_{01}^2\rangle_{x,y} + BD\langle \theta_1^2\rangle_{x,y} \quad (10)$$

with $\sqrt{\langle w_{01}^2\rangle_{x,y}}$ the waist radii of the input beam and $\sqrt{\langle \theta_1^2\rangle_{x,y}}$ the far-field divergences of the input beam.

Substitution of Eq. (7) into Eqs. (8)–(10), the transformed beam radii $\sqrt{\langle w_{ref}^2\rangle_{x,y}}$, far-field divergences $\sqrt{\langle \theta_{ref}^2\rangle_{x,y}}$, and the effective radii of curvature $\langle 1/R_{ref}\rangle_{x,y}$ on the polygon surface are obtained, respectively:

$$\langle w_{ref}^2\rangle_{x,y} = f_1^2\langle \theta_1^2\rangle_{x,y} \quad (11)$$

$$\langle \theta_{ref}^2\rangle_{x,y} = (-1/f_1)^2\langle w_{01}^2\rangle_{x,y} + (1-L_1/f_1)^2\langle \theta_1^2\rangle_{x,y} \quad (12)$$

$$\langle 1/R_{ref}\rangle_{x,y} = \frac{\langle w_{ref}\theta_{ref}\rangle_{x,y}}{\langle w_{ref}^2\rangle_{x,y}} = \frac{f_1-L_1}{f_1^2} \quad (13)$$

The parameters of the reflected beam after propagation through one of the focusing heads are different in x, y and are obtained from Eq. (4)

$$\langle w_{out}^2\rangle_x = A_2^2\langle w_{ref}^2\rangle_x + 2A_2B_2\langle w_{ref}\theta_{ref}\rangle_x + B_2^2\langle \theta_{ref}^2\rangle_x \quad (14)$$

$$\langle w_{out}^2\rangle_y = \frac{A_2^2}{\cos^2\varphi}\langle w_{ref}^2\rangle_y + 2A_2B_2\langle w_{ref}\theta_{ref}\rangle_y + \cos^2\varphi B_2^2\langle \theta_{ref}^2\rangle_y \quad (15)$$

with $A_2B_2C_2D_2$ the ray transfer matrix from the polygon surface to the output plane; φ is the time-dependent angle between the axis of the scanning beam propagation and the optical axis of the focusing head.