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Study of Light Sheet and Mie Scattering Theory for Detection of Powder Flow Field in Laser Remanufacturing of Robot

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Abstract In order to detect the velocity and concentration field of metal power particles in laser cladding, an optical system is built based on a 100-mW diode laser. A combined lens is designed to collimate the beam of laser, after the elliptic spot corrected by a prism into a circular one. At the last laser beam is extended into uniform sheet laser by a cylindrical mirror. Laser physical model after scattering by spherical powder particles is constructed from Mie scattering theory . Laser intensity distribution is plotted by mathematical software when it is irradiated by green and red light . The research result shows that scattering intensity of green light is two times of red's under the same condition and sub-maximum intensity of 532-nm light is appeared around 20°. So 532-nm diode laser is selected as the light source. Pictures are much better when the angle between charge coupled device (CCD) camera and incident direction is 20°. It provides the theory for a cheap and portable powder flow field detecting system.

Key words image detection; powder flow field; spot compression; reflection sheet laser; Mie scattering theory

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1 Introduction

Laser remanufacturing has been developed to an effective method for direct fabricating three-dimensional (3D) parts and repairing expensive and important parts[1]. It was widely used in many industries such as aerospace, petrochemical, electronic information, etc. Research of powder flow field has been done by scientist, but it is seldom reported in laser remanufacturing[2~7]. While repairing expensive and important parts with laser robot, the velocity and concentration field of metal power particles is essential to improve the quality of repairing. In this paper, a practical method is proposed. Low power diode lasers are selected as light sources. Large divergence angle and elliptic spot of diode laser are solved by an optical lens. The scattering intensity in different angles and wavelengths can be calculated with the Mie theory and DPIV technique.

2 Design of Optical System

2.1 Negation of Inverted Telescope Method

The physical nature of laser is the light amplification by stimulated emission of radiation. Light propagation alone z-axis must be a Gaussian beam that ever the resonator is[8]. Gaussian beam and its parameters are shown in Fig. 1.

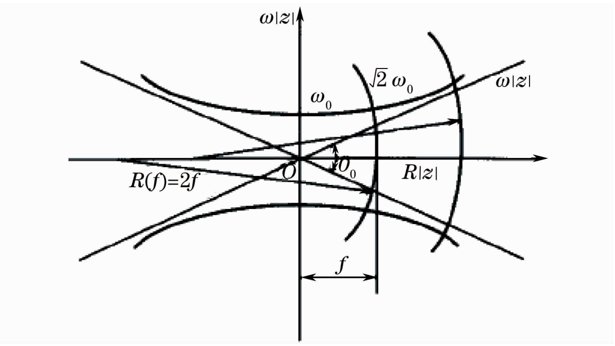

Fig. 1 Gaussian beam and its parameters

Radius of the Gaussian beam is

$$w(z) = w_0\sqrt{1+\left(\frac{z}{f}\right)} = w_0\sqrt{1+\left(\frac{\lambda z}{\pi w_0^2}\right)^2}. \quad (1)$$

The beam radius obeys hyperbolic law, ie., it reaches the minimum at $z=0$ and $w(z)=w_0$. On the plane far from the center of the resonator, $w(z\rightarrow\infty)\approx\frac{\lambda z}{\pi w_0}$, the far-field divergence angle of basic mode is

$$\theta_0 = \frac{2w(z\rightarrow\infty)}{z} = \frac{2\lambda}{\pi w_0}. \quad (2)$$

For Gaussian beam with limited w_0 far-field divergence angle could not be zero. Normal method for divergence angle compression is to invert a telescope system. It is effective for a gas laser, but unsuitable for a diode laser, because the divergence angle of the diode laser is too large. In powder flow field detection, divergence angle after collimation is required to one hundredth of

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the old one.

2.2 Collimation of Laser Beam and Correction of Elliptic Facular

The light source of the powder flow field detecting system is a common dual heterogeneous diode laser (G5320Y), whose parameters are as follows: size of light source is 0.42 mm × 0.42 mm; parallel direction of divergence angle is 10° while vertical direction is 28°; output power is 100 mW; the output wavelength is 532 nm. Emergence beam can be approximated as geometric beam as a low power diode laser is used. Optical pathway diagram of composite lens can be designed as Fig. 2.

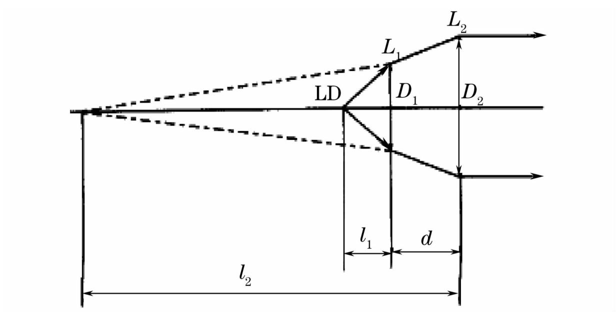

Fig. 2 Modular optical lens for collimating laser beam

The distance from the exit surface of the diode laser to the L_1 lens l_1 is −10 mm. The focus lengths of L_1 and L_2 are $f_1 = 15$ mm, $f'_1 = 35$ mm, and the distance between them is d. Calculating with the formula of lens imaging, this conclusion can be obtained. The emergent light is similar to the parallel light when d is 5 mm. The emergent light is suitably collimated by a lens system. From optical parameters and triangle relation of diode laser, the followings can be obtained: $D_1 = 4.987$ mm, $D_2 = 5.818$ mm, and $f' = 11.67$ mm, where D_1 and D_2 are the clear apertures of L_1 and L_2, respectively, and f' is focus length. The output beam of the diode laser is an elliptic Gaussian beam. But a circular beam is better than that as the area of a circular spot is smaller than an elliptic one. This can improve the irradiation power per unit area. The purpose of flare correction is equating the spot size of two direction. Figure 3 shows the spot compressed by a right angle prism .

According to the geometric relation, we can obtain

$$\delta_1 + \varphi_2 = \alpha, \quad D_1 = a\cos\varphi_1, \quad D_2 = b\cos\varphi_2. \tag{3}$$

The compression ratio of light spot T is defined as D_2/D_1. From law of refraction, there is

$$n_1 \sin\varphi_1 = n_2 \sin\delta_1, \quad n_1 \sin\delta_2 = n_2 \sin\varphi_2. \tag{4}$$

When the beam incident from the angle satisfied Eqs. (3) and (4), the spot can be compressed. In this

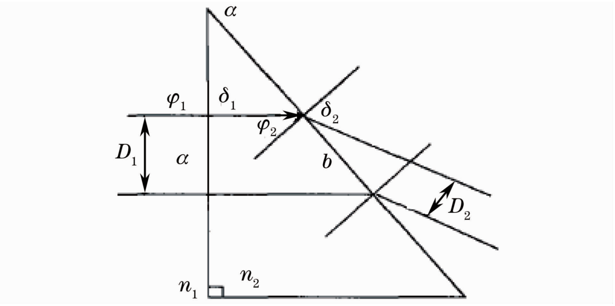

Fig. 3 Spot compression with a prism

paper the beam is vertical to the prism. Refractive index of the prism is $n_2 = 1.5$; Refractive index of air is $n_1 = 1$. Angle α must be smaller than 42° to avoid total emission. T is varying with α as

$$T = \frac{\cos\delta_2}{\cos\alpha} = \frac{\sqrt{1 - n_2^2 \sin^2\alpha / n_1^2}}{\cos\alpha}. \tag{5}$$

The curve is showed in Fig. 4. Dispersion can be ignored as monochromaticity of the laser is good.

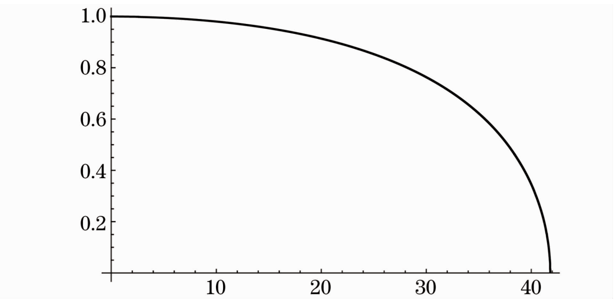

Fig. 4 Spot compression and the apex angle of prism

3 Relation between the Laser Light Sheet Formed by a Reflection of Cylindrical Lens

Laser light sheet is formed to detect powder flow field output by coaxial nozzle in laser repair with robot, and the picture is treated with digital particle image technology. How to form a light sheet, the usual way is to apply in cylindrical extension. The collimated laser beam is projected in a cylindrical lens, and then light sheet is formed by unidirectional extension. The quality of cylindrical lens on surface and uniformity of optical material will exert more influence on light intensity

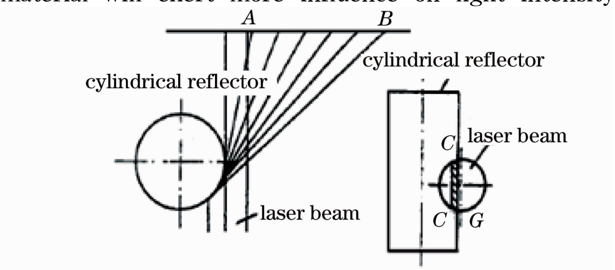

Fig. 5 Light sheet formation in cylindrical mirror

distribution in this way. So the image shooting is not clear. Focusing on those problems, we designs a new laser light sheet which makes laser beam irradiate on a cylindrical reflector of continuous variation of incident angle and the light sheet is formed by extension (Fig. 5).

Cylindrical mirror will realize the function of mirror in Fig. 6 and the light sheet is formed[8], when the laser beam shines on the side of cylindrical surfaces. During the process of cylindrical mirror, fine grinding and polishing on the material of common steel are done, and then plating a high reflector, which is more easier than processing a glass cylinder and cylindrical lens, and it can avoid the optical distribution of inhomogeneity of glass, when the light transmits the lens.

4 Mie Scattering Theory

The accurate solution can be acquired via Mie scattering theory, when the light wave is scattered by a uniformly spherical particle. The model is shown in Fig. 6.

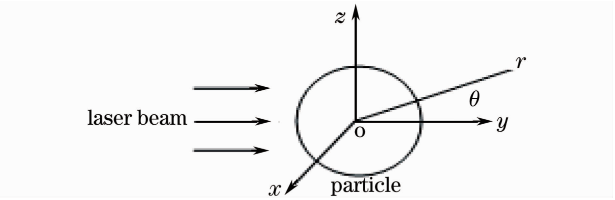

Fig. 6 Scattering model of spherical particle

The accurate solution of scattering electrical field based on the Maxwell's Equations and continuous boundary conditions can be calculated as[9]

$$\begin{cases} E_r^{(s)} = \dfrac{1}{k^{(1)2}} \dfrac{\cos\varphi}{r^2} \sum_{l=1}^{\infty} l(l+1)\,{}^{e}B_l \zeta_l^{(1)} P_l^{(1)}(\cos\theta), \\ E_\theta^{(s)} = -\dfrac{1}{k^{(1)2}} \dfrac{\cos\varphi}{r} \sum_{l=1}^{\infty} \left[{}^{e}B_l \zeta_l^{(1)\prime} P_l^{(1)\prime}(\cos\theta)\sin\theta - i\,{}^{m}B_l \zeta_l^{(1)} \dfrac{P_l^{(1)}(\cos\theta)}{\sin\theta} \right], \\ E_\varphi^{(s)} = -\dfrac{1}{k^{(1)2}} \dfrac{\sin\varphi}{r} \sum_{l=1}^{\infty} \left[{}^{e}B_l \zeta_l^{(1)\prime} \dfrac{P_l^{(1)}(\cos\theta)}{\sin\theta} - i\,{}^{m}B_l \zeta_l^{(1)} P_l^{(1)\prime}(\cos\theta)\sin\theta \right], \end{cases} \tag{6}$$

$$\begin{cases} {}^{e}B_l = i^{l+1} \dfrac{2l+1}{l(l+1)} \dfrac{n\psi_l'(q)\psi_l(nq) - \psi_l(q)\psi_l'(nq)}{n\zeta_l^{(1)\prime}(q)\psi_l(nq) - \zeta_l^{(1)}(q)\psi_l'(nq)}, \\ {}^{m}B_l = i^{l+1} \dfrac{2l+1}{l(l+1)} \dfrac{n\psi_l(q)\psi_l'(nq) - \psi_l'(q)\psi_l(nq)}{n\zeta_l^{(1)}(q)\psi_l'(nq) - \zeta_l^{(1)\prime}(q)\psi_l(nq)}, \end{cases} \tag{7}$$

$$\psi_l(x) = \sqrt{\pi x/2}\,J_{l+1/2}(x), \tag{8}$$

$$\zeta_l(x) = \sqrt{\pi x/2}\,H_{l+1/2}(x), \tag{9}$$

where $J_{l+1/2}(x)$ and $H_{l+1/2}(x)$ denote Bessel and Hankel function, respectively, n is the relative index between spherical particle and medium, q is an optical constant and its numeric value is equal to $2\pi a/\lambda$ (a is the particle radius, λ is the laser wavelength), and $P_l^{(1)}(\cos\theta)$ is a step Legendre function. An approximately effective formula derived by Debye with respect to taking the value of l, proved that partial wave amplitude attenuates quick to zero when $l+1/2$ exceeds q. So it is shown that this theorem and Huygens-Kirchhoff's Law have the same results only considering of anterior q[10]. Taking red or green light as an example, the laser scattering is simulated. The parameters of simulation are: the particle radius of spherical powder is equal to 20 μm, the spherical particle index $n = 1.25 + 0.03\mathrm{i}$. The distribution of normalized scattered intensity is calculated by a mathematical software for the spherical particle radius equaling to 20 μm, when 532- and 632.8-nm scattered by a spherical particle.

As shown in Fig. 7, the scattering intensity of red light and green light in $[0, \pi/2]$ is much larger than that in $[\pi/2, \pi]$, especially for $\pi/6$. The integral scattering intensity of green light is about two times higher than that in red light, the first secondary maximum occurs at $\pi/18$, and the second secondary maximum occurs at $\pi/9$. Considering the instrumental

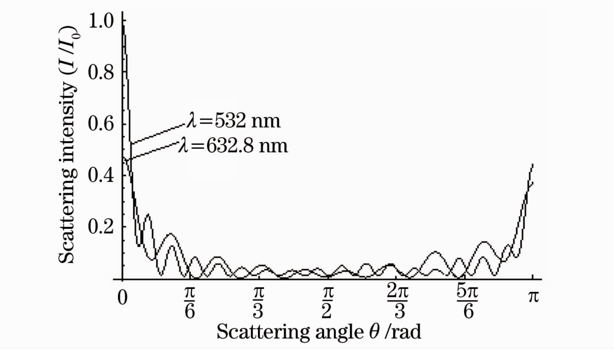

Fig. 7 Relationship between the scattering intensity and the scattering angle

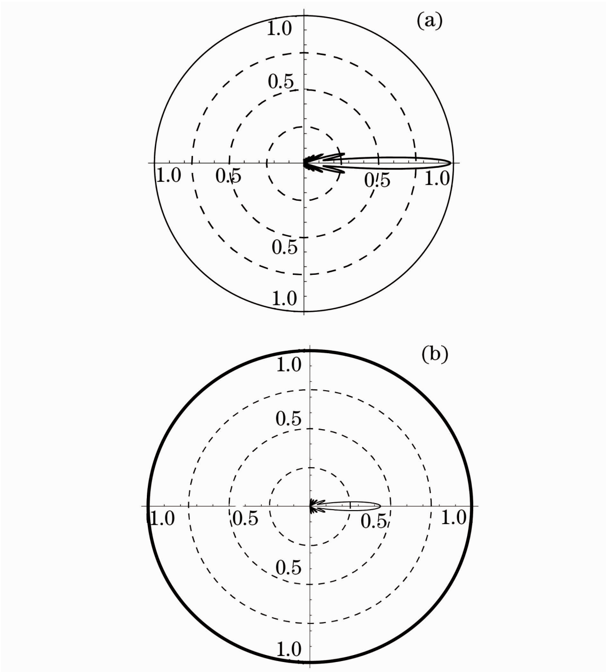

Fig. 8 Simulation of the distributions of scattering intensity. (a) λ = 532 nm, (b) λ = 632.8 nm

placement and the relation between scattering intensity and angle change, we chose 100-mW green laser for lighting source, and the angle between the charge coupled device (CCD) camera and forward scattering angle was $\pi/9$ for shooting.

5 Principle of Detection and the Picture of Experiment in Metal Powder Flow Field

The main principle of detection for powder flow field in laser remanufacturing is that the continuous laser emitted from a 100-mW and 532-nm semiconductor laser, collimated by a composite lens,

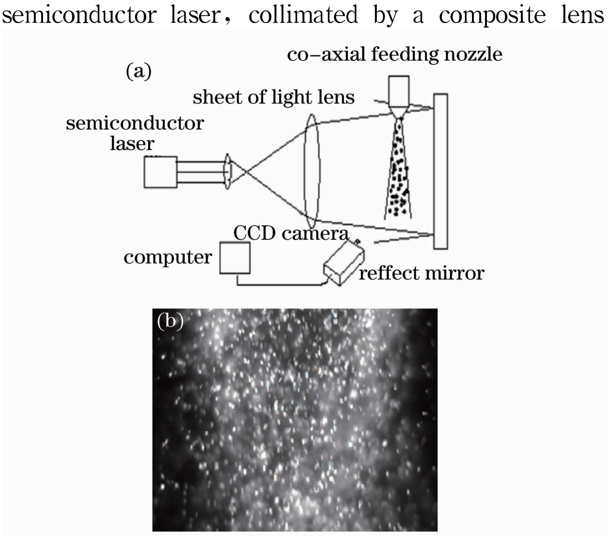

Fig. 9 (a) Principle of DPIV measurement, (b) picture of powder flow field

and then corrected by a prism, at last, a light sheet is formed in cylindrical mirror, and the gas-metal powder two flow output by coaxial nozzle laser is illuminated by the light sheet.

The picture of metal powder flow is photographed by high-speed CCD camera of spanning frame, which is input to computer by a digital image processing card, and the forward angle is $\pi/9$ between it and light sheet. There is a special image processing software, which is developed for the picture, and it is invented by the laser processing center of Tianjin Polytechnic University. The principle picture of DPIV measurement and experiment detecting for powder stream concentration field and velocity field are shown in Fig. 9.

6 Conclusions

The method to obtain a top quality laser light sheet is introduced, which is achieved by adjusting a combinative optical system, and it could reduce error of calculation because of particle coincidence. It can also get an optimum shooting angle on the basis of study of Mie scattering theory to solve the difficulty of intensity shortage. A portable and cheap detection system of powder flow field is developed and applied, and it can take a clear image to meet requirements in detecting in laser field repair for robot. So, it is important both in theories and applications.

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