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Concentration model based on movement model of powder flow in coaxial laser cladding

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ABSTRACT

The structure below the coaxial nozzle is critical since the spatial distribution of metal powder particles determines the laser attenuation as well as catchment efficiency. It is difficult to simulate the powder concentration distribution, because the complex phenomena involved in the two-phase turbulence flow. In this paper, the air-powder flow is studied along with powder properties, nozzle geometries and shielding gas setting. A Gaussian model is established to quantitatively predict the powder stream concentration in order to facilitate coaxial nozzle design optimizations. An experimental setup is design to measure the powder concentration for this process. The simulated results are compared with the experimental results. This study shows that the powder concentration mode is influenced significantly by powder properties, nozzle geometries and shielding gas setting.

1. Introduction

The quality and efficiency of laser-aided direct metal deposition largely depends on the powder flow structure below the nozzle. Operating parameters such as powder properties, nozzle geometries and shielding gas setting should be optimized based on the understanding of the powder concentration distribution.

Some researches were done in this field. Model of effects of powder concentration distribution on fabrication of thin-wall parts in coaxial laser cladding was developed by Liu et al. [1]. They defined the static model of powder mass concentration distribution at cold-stream conditions in coaxial single-pass cladding with a low-power laser as a Gaussian function [2]. They also investigated formation mechanism of cross-sectional profile of a clad bead in coaxial laser cladding [3], and presented in-time adjustment in laser cladding manufacturing process as a means to improve dimensional accuracy and surface finish of the built part [4]. An experimental investigation of the influence of processing parameters on clad angle in laser cladding by powder was presented by Onwubolu et al. [5], and the movement model and thermal model of powder particle in coaxial laser cladding is proposed by Lin [6,8].

In this paper, an investigational approach is described which includes simulation method and experimental setup. This simulation methodology considers more general conditions and has the potential for optimization of powder flow for coaxial laser cladding. A precise and low-cost optical measuring system and its application are also included.

2. Movement model

The powder stream with shield gas output from the annular nozzle can be divided into three regions by AA′ and BB′. The longitudinal section of the annular nozzle and the powder stream are shown in Fig. 1, where w is the nozzle exit width, r is the nozzle inward wall radius, α is nozzle angle and ϕ is powder divergence angle. In order to establish powder particle movement model, some assumptions should be illustrated [8–11]:

(1) A powder particle is moving in a uniform gas flow, and its initial spray angle from the nozzle exit is α.
(2) The velocity of shield gas is constant in a short stand-off distance.

The velocity of particle can be solved by

$$\begin{cases} \dfrac{dv_x}{dt} = \dfrac{18\mu(1+0.15\mathrm{Re}^{0.687})(u_x - v_x)}{\rho_p d_p^2} \\ \dfrac{dv_y}{dt} = \dfrac{18\mu(1+0.15\mathrm{Re}^{0.687})(u_y - v_y)}{\rho_p d_p^2} + g \\ \mathrm{Re} = \dfrac{\rho d_p}{\mu}\sqrt{(u_x - v_x)^2 + (u_y - v_y)^2} \\ v_{x0} = v_0 \cos\alpha \\ v_{y0} = v_0 \sin\alpha \\ u_x = u_0 \cos\alpha \\ u_y = u_0 \sin\alpha \\ v(t) = \sqrt{v_x^2 + v_y^2} \end{cases} \quad (1)$$

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Nomenclature

w	nozzle exit width (m)
r	nozzle inward wall radius (m)
α	nozzle angle
ϕ	powder divergence angle
g	gravitational acceleration (m/s^2)
v	particle velocity component (m/s)
u	gas velocity component (m/s)
v_0	initial velocity of particle at nozzle exit (m/s)
u_0	initial velocity of gas at nozzle exit (m/s)
t	time (s)
μ	gas viscosity (kg/s m)
ρ	gas density (kg/m^3)
d	diameter (m)
ρ	density (kg/m^3)
Re	Reynold number
e	velocity recovery ratio
mp	powder mass flow rate (kg/s)
$f(x, y, z)$	powder particles number 3D distribution function (particles/m^3)
$m(y)$	powder particles number vertical distribution function (particles/m)
δ	Gaussian parameter (m)
N	particle number flow rate (particles/s)
R	powder stream radius

Subscripts

p	particle
g	gas
x, y, z	directions in Cartesian coordinates
A, A′	point A, A′

where v is particle velocity, u is shield gas (argon) velocity, v_0 is initial particle velocity at nozzle exit, u_0 is initial gas velocity at nozzle exit, $v(t)$ is velocity of the particle at moment t, μ and ρ are gas viscosity and density, d_p and ρ_p are particle diameter and density, Re is the Reynold number.

The spraying angle ϕ of powder flow at point A (Fig. 1) can be estimated by the collision reflect angle of two particles M and N. M comes from the outward wall exit of the nozzle's left side and N comes from the inward wall exit of nozzle's right side. Based on the constant momentum principle at the collision moment, the reflect angle of M can be used to estimate the spraying angle by

$$\phi = \arctan\left(e\frac{v_{px}}{v_{py}}\right) \tag{2}$$

Where e is velocity recovery ratio of the particles (M, N) after collision, v_{px} and v_{py} are velocity component in X- and Y-axes of M before collision. The constant parameters can be seen in Table 1.

3. Concentration model

In this paper, the powder flow concentration distribution in regions 2 and 3 is more concerned than region 1, as shown in Fig. 1, and the concentration of powder is expressed by volume fraction. We suppose that the 3D distribution of the powder particles' number in regions 2 and 3 could be expressed by the Gaussian function [12]:

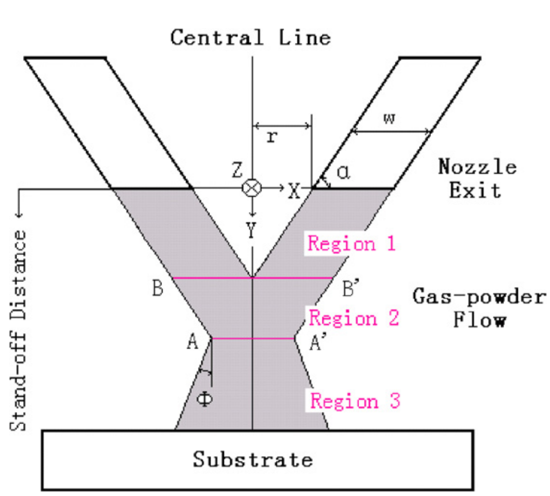

Fig. 1. The three regions of gas-powder flow.

$$f(x,y,z) = \frac{m(y)}{2\pi\delta^2}\exp\left[-\frac{x^2+z^2}{2\delta^2}\right] \tag{3}$$

where $f(x, y, z)$ is powder particles number 3D distribution function, $m(y)$ is powder particles number vertical distribution function: the number of particles in the powder stream in different cross-section along stand off distance, δ is Gaussian parameter.

The powder particles in regions 2 and 3 come from the annular nozzle, so

$$m(y) = \frac{N}{v_y} \tag{4}$$

where v_y can be solved by Eq. (1), N is the number of particles sprayed by the nozzle in one second, the relationship of N and powder mass flow rate mp is

$$N = \frac{3\text{mp}}{4\pi(d_p/2)^3\rho_p} \tag{5}$$

Based on $\pm 3\delta$ principle, more than 99% of the particles in the region $x^2+z^2+\leqslant 9\delta^2$, so the radius of powder stream can be estimated by 3δ:

$$3\delta = R(y) \tag{6}$$

where $R(y)$ is the radius of powder stream in regions 2 and 3.

Substituting Eqs. (4)–(6) with Eq. (3), the powder 3D volume fraction function is given by

$$c(x,y,z) = \frac{4}{3}\pi\cdot(d_p/2)^3\cdot f(x,y,z) = \frac{9\text{mp}}{2\pi\cdot R(y)^2\cdot v_y\cdot\rho_p}\exp\left[-\frac{9(x^2+z^2)}{2R(y)^2}\right] \tag{7}$$

In region 2,

$$R(y) = r + w - x(y) \tag{8}$$

where $x(y)$ is the horizontal displacement of the particle sprayed from the outward wall of nozzle, it could be solved by Eq. (1).

In region 3,

$$R(y) = x_{A'} + (y - y_{A'})\tan\phi \tag{9}$$

where $(x_{A'}, y_{A'})$ is the coordinate of point A′, it could be solved by Eq. (1). ϕ could be solved by Eq. (2).

When $z = 0$, the results of Eq. (7) can be shown as 2D figures from Figs. 2–5. The curve 1, 2 and 3 in Fig. 2 are, respectively, the