Design optimization and experimental study of coaxial powder-feeding nozzle in the laser cladding process

H Ju, Z J Zhang, C X Lin*, Z J Liu and H L Jiang

College of Naval Architecture and Ocean Engineering, Dalian Maritime University, Dalian 116026, China

* E-mail: lchxin@dlmu.edu.cn

Abstract. To improve the powder convergence and cladding layer quality, the three-dimensional axisymmetrical powder flow through a coaxial feeding nozzle was simulated by the Eulerian-Eulerian two-fluid model. With the composite design via the response surface method, the significance between the main geometric dimensions of nozzle and fluidization characteristics of powder flow was analyzed and regression-fitted. Moreover, a mathematical model was constructed to optimize the nozzle structure, and the optimal nozzle was used in laser cladding experiments. The results show that appropriate powder flow can be obtained in the condition of the carrier gas more than 9 l/min, and the powder sending rate less than 7.5 g/min. The structural parameters of the optimized nozzle are as follows: nozzle angle of 62.94°, outlet width of 1.0mm, exit radius of 5.83mm, and flow separation angle of 3.00°. With the optimized nozzle, the waist diameter and focus depth of the original powder flow decrease by 39.4 and 46.4%, respectively, and the discrepancy between the experimental and simulation results was less than 9%. With the appropriate technological parameters, a layer with good geometry morphology and appropriate dilution rate can be prepared in the laser cladding process with a coaxial feeding nozzle.

1. Introduction

Laser cladding, as a rapidly developing surface modification technology, has unique advantages of high energy, rapid solidification velocity, and quick cooling rate. Besides, the laser alloyed coatings displayed fine microstructure, excellent solid metallurgical bonding and small intermixing with the substrate [1-2]. It has been widely used in many practical applications such as surface metallization, component-repairing and 3D rapid prototyping [3-5]. The powder-feeding method is the crucial technological parameter in the laser cladding process and the coaxial feeding nozzles which allow the powder flow to flow coaxially with the laser beam provides the capability of precise deposition. Thus, the coaxial laser cladding has gained extensive application and much more feasibility in automatic manufacturing [6]. Considering the morphology and quality of the cladding is directly influenced by the powder flow, the feeding powder flow and the powder nozzle are always studied.

The research on the powder flow and structural design of the powder-feeding nozzle have been performed by domestic and foreign scholars [7-9]. However, since most studies were related to the powder flow rule of the two-dimensional nozzle model, no obvious improvement of the powder-feeding effect was obtained. Meanwhile, most nozzles have such deficiencies as poor powder convergence, deep focal position, large focus diameter, and low powder-usage efficiency.
In this paper, a three-dimensional coaxial feeding nozzle model was established to obtain the three-dimensional flow field by the Eulerian-Eulerian two-fluid models. And the influencing factor of nozzle structure on powder flow is multiple-square regressive analyzed by the response surface analysis. And the response model of nozzle structure and powder-feeding performance is obtained to study the influence of structural parameter on the powder flow. Moreover, the layer with good geometry morphology and appropriate dilution rate can be prepared in the laser cladding process with the coaxial feeding nozzle after a single-factor experiment of processing technologies.

2. Simulation of the powder flow stream

2.1. Simulation of the powder flow stream

The powder flow of coaxial feeding belongs to gas-solid two-phase flow, and the Eulerian-Eulerian two-fluid models are chosen to simulate the powder-gas two-phase flows. The ANSYS Fluent software is used to simulate the flow stream of the coaxial nozzle, and the simulation conditions are set as follows:

(1) The governing equation:

Based on the law of mass conservation, energy conservation, and momentum conservation, the Euler-type conservation equations are obtained.

(2) Three-dimensional model and mesh generation:

Figures 1 (a) and 1 (b) depict the 3D structure and 2D segmentation images, respectively, while the main dimensions of the nozzle model refer to the existing nozzle structure, as shown in table 1. There, the main influence factors on the nozzle flow stream are nozzle angle (θ), outlet width (w), exit radius (r). To increase the simulation speed, a quarter of three-dimensional nozzle model with main structure parameters are adopted, and the different flow field (I, II, III) is respectively meshed with different meshing size (2, 0.4, and 1 mm) as is shown in figure 1 (c).

| Parameter | θ(°) | w(mm) | r(mm) | λ(°) | α(°) | e(mm) | g(mm) | a(mm) | h(mm) | b(mm) |
|-----------|------|-------|-------|------|------|-------|-------|-------|-------|-------|
| Size      | 67   | 2.2   | 5.00  | 5.0  | 37   | 60    | 7     | 25    | 50    | 30    |

(a) 3D model; (b) sketch of a cross-section; (c) regions and their meshing

Figure 1. Three-dimensional model and meshing of the nozzle.

(3) Material properties

The carrier gas is argon, whose viscosity and density are 2.125×10⁻⁵ kg/(m·s) and 1.623 kg/m³, respectively. The powder density and particle sizes are 7.5×10³ kg/m³ and 35 μm, respectively.

(4) Boundary conditions
The inlet of carrier gas stream and powder flow is set as speed type, and the outlet of powder flow is configured as outflow type. The gravitational acceleration is $9.8 \text{ m/s}^2$, and the ambient gas pressure is $1.013 \times 10^5 \text{ Pa}$. The wall and two sides of the model are set as standard boundary and periodicity boundary conditions, respectively.

2.2. Simulation results of powder flow

The carrier gas flow and powder-feeding rate possess great influence on the characteristic and converge morphology of the powder flow field, and they are the significant parameters in the process of coaxial powder-feeding. To confirm proper feeding process parameters, the effect of a single factor (carrier gas flow and powder-feeding rate) on the volume concentration distribution is researched by the post-processing of the Fluent software.

Under the specific powder-feeding rate (5 g/min), figure 2 shows the volume concentration and flow velocity of powder with different carrier gas flow. As shown in figure 2 (a), when the carrier gas flow is minimum, the gathered position of powder is nearest to the nozzle bottom, and its powder volume concentration is maximum (about 8%). With the increment of carrier gas rate, the focal position of the powder flow gradually declines. It can be seen in figure 2 (b) that the axisymmetric powder flow rate increases with the carrier gas flow.

![Figure 2](attachment:image2.png)

Figure 2. Powder flow characteristic under different carrier gas flow: (a) Concentration; (b) Velocity.

To study the effect of powder-feeding rate on the powder flow, the distribution of powder flow under different powder-feeding rate and specific gas carrier rate (9 l/min) is shown in figure 3. It can be seen in figure 3 (a) that the powder-feeding rate has a prominent influence on powder volume concentration. That is the powder concentration of the entire nozzle model increases with the powder-feeding rate, and the maximum powder concentration can reach 20%. Figure 3 (b) shows that the velocity gradually reduces when the powder-feeding rate arises from 2.5 to 12.5 g/min, and the value remains unchanged until the level of 7.5 g/min is reached.

![Figure 3](attachment:image3.png)

Figure 3. Powder flow characteristics at different feeding rates (a) volume concentration; (b) powder velocity
Based on the above analysis, to avoid blocking the outlet by melting powder spatters, the focal position of powder flow should not be too close to the nozzle outlet. Meanwhile, to enhance the utilization efficiency of the powder and decrease the laser attenuation by the powder flow, the focal position and volume concentration of powder flow could not be too large. Thus, the carrier gas rate should not be lower than 9 l/min, and the powder-feeding rate should not exceed 7.5 g/min for a better feeding effect.

3. Structure optimization of coaxial nozzle

3.1. Regression model between nozzle structure and stream characteristic

The response surface method [10] was used to establish the regression model between feeding nozzle structure and powder flow characteristics. The center composite design [11] was adopted to study the effect of nozzle major structural parameters (nozzle angle (θ), outlet width (w), exit radius (r) and shrinkage angle (λ)) on the powder-feeding characteristics. The five levels (high-level, low-level, zero-level and two alpha levels) set in the center composite design, and the value ranges of nozzle angle, outlet width, exit radius, shrinkage angle were chosen as 55–65°, 1–2 mm, 4–6 mm, and 3–9°, respectively, according to available literature and nozzles. The design scheme included 30 points (16 comprehensive test points, 8 axial test points, and 6 central test points). The simulated tests and response values are obtained under the conditions that carrier gas flow of 9 l/min and the powder-feeding rate of 5 g/min. The Design Expert software was used to process the experimental data by the variance analysis and regression fitting, and the non-significant factor is removed by the stepwise selecting method to obtain more precise response surface regression model.

It can be seen from the variance analysis of the flow waist diameter that its F-value in the regression model is 33.82, which proves the model efficiency. The P-value is less than 0.0001, thus the difference is almost impossibly caused by the sampling error. And the phenomenon that F-value of unfitting degree is greater than 0.05 shows the fitting degree of regression model is better. Through the above analysis, three test values indicate that the regression model is prominent, and the significant items include first-order terms θ, w, r, interaction items θ × w, θ × r and second-order term θ². By removing the non-significant item, the regression model of flow waist diameter is described by equation (1):

\[d=19.151-0.570θ-0.935w+0.193r-0.543λ+0.030θw+0.009θλ+0.004θ^2\]  

In the same way, the regression model of the focal distance and depth also can be obtained. By the regression fit and significance analysis, the models always possess significance and reliability. The regression models about powder flow focal distance and depth are shown as equations. (2) and (3), respectively.

\[f=-7.478+0.099θ+2.442w-2.438r+1.381λ+0.076θr-0.020θλ-0.026λ^2\]  

\[l=-33.105+1.244θ-0.179w-2.835r+0.268λ+0.046θr+0.538wr-0.011θ^2-0.027λ^2\]  

3.2. Structural optimization of coaxial feeding nozzle

Depending on the response-surface model, the multiple-response desirability function approach is used to optimize the nozzle structure. The optimal objective is to select the minimum of waist diameter and focal depth. Meanwhile, the focal distance should not be lower than 15 mm. And the structure parameters of the optimized nozzle are shown in table 2.

| Table 2. The nozzle structural parameters. |
|-------------------------------------------|
| Parameter | θ(deg) | w(mm) | r(mm) | λ(deg) | α(deg) | φ(mm) | e(mm) | g(mm) | a(mm) |
| Size | | | | | | | | | |
| non-optimized | 67.0 | 2.2 | 5.00 | 5.0 | 37.0 | 5.0 | 60 | 7.0 | 40 |
| optimized | 62.9 | 1.0 | 5.83 | 3.0 | 37.0 | 5.0 | 30 | 4.0 | 25 |
The flow field characteristics of non-optimized and optimized nozzles are shown in table 3, which indicates that the primary powder flow characteristics are improved to a certain extent. That is, the waist diameter and focal depth are reduced by 39.4 and 46.4%, respectively. Although the focal length of powder flow is decreased by 27.6%, it is still larger than 15 mm, to avoid the nozzle bearing the excessive temperature in the laser beam vicinity.

Moreover, the actual and simulative powder flows were comparatively analyzed, and the morphologies and data obtained are presented in figure 4 and table 4.

### Table 3. The comparison of experimental data between before and after optimization.

| Nozzle angle (°) | Width (mm) | Radius (mm) | Shrinkage angle (°) | Diameter (mm) | Focal distance (mm) | Focal depth (mm) |
|------------------|------------|-------------|---------------------|---------------|---------------------|------------------|
| un-optimized     | 67.00      | 2.2         | 5.00                | 5.02          | 21.0                | 12.5             |
| optimized        | 62.94      | 1.0         | 5.83                | 3.04          | 15.2                | 6.7              |
| variation ratio | -6.1%      | -54.2%      | 16.7%               | -40.0%        | -39.4%              | -46.4%           |

![Figure 4](image)

**Figure 4.** The experimental (a) and simulation (b) powder flows.

### Table 4. The comparison between experimental and simulated data.

| Nozzle angle (°) | Width (mm) | Radius (mm) | Shrinkage angle (°) | Diameter (mm) | Focal distance (mm) | Focal depth (mm) |
|------------------|------------|-------------|---------------------|---------------|---------------------|------------------|
| Simulation       | 62.94      | 1.0         | 5.83                | 3.0           | 2.80                | 14.8             |
| Experimental     | 62.94      | 1.0         | 5.83                | 3.0           | 3.04                | 15.2             |
| Error            | 0          | 0           | 0                   | 0             | 8.6%                | 2.7%             |

The discrepancies between simulated and experimental data on the powder flow waist diameter, focal distance, and focal depth are 8.6, 2.7, and 4.7%, respectively. Since these values are less than 9%, the proposed simulation model possesses high reliability.

4. Laser cladding process with the coaxial feeding nozzle

To evaluate the performance of optimized nozzle and select the appropriate process parameters, the cladding powder is 304 stainless steel powders; powder size (-400 mesh), powder density (2.6-3.5 g/cm3), fluidity (25-35S/ 50g) and compressibility (greater than 6.55 g/cm3) in this experiment, and the cladding substrate is also 304 stainless steel plates. A DL-LPM-V CO2 laser with a wavelength of 10.6 μm and maximum power of 5 kW was used for the material processing. According to the practical tests, the main influencing factors of the cladding layer quality are carrier gas flow rate, scanning speed, powder flow defocusing distance, and powder-feeding rate. Meanwhile, the values of the laser power and laser focal distance were fixed at 2.4 kW and 30 mm, respectively.
4.1 Effect of process parameters on cladding layer quality

To study the influence of carrier gas flow rate on the cladding quality, the scanning speed, powder flow defocusing distance and powder-feeding rate were fixed at 600 mm/min, 0 mm and 3.6 g/min, respectively. By measuring the morphology features of a single layer with the metallographic, the effect of carrier gas flow on the cladding layer quality is illustrated by figure 5.

Similarly, to study the influence of scanning speed, powder flow defocusing distance, powder-feeding rate on the cladding layer quality, each factor’s effect on the cladding layer quality was plotted in figure 6.

![Figure 5. Effect of carrier gas flow on cladding layer: (a) size; (b) dilution rate](image_url)

![Figure 6. Revealed relationships: (a) scanning speed vs. cladding layer (CL) size; (b) scanning speed vs. dilution rate (η); (c) powder flow defocusing distance (Δf₂) vs. CL size; (d) distance (Δf₂) vs. dilution rate (η); (e) powder-feeding rate (M) vs. CL size; (f) powder-feeding rate (M) vs. dilution rate (η).](image_url)

4.2. Optimal technological parameters in signal laser cladding

Considering the well geometrical morphology and the appropriate dilution rate, the technological parameters are selected as follows: 2.4 kW (laser power), 30 mm (laser defocusing distance), 15 l/min (carrier gas flow), 800 mm/min (scanning speed), 0 mm (powder flow defocusing distance) and 3.6 g/min (powder-feeding rate).
Figure 7. The macro- (a) and cross-sectional morphology (b) of single pass laser cladding layer.

The macro-morphology of a single-pass laser cladding layer is shown in figure 7, which proves that the layer surface is smooth and contains no beads, bubbles, cracks or any other macroscopic defects. Meanwhile, to analyze the layer quality in more detail, the metallographic microscope was used to observe the cross-sectional morphology (figure 7 (b)). The calculated dilution rate (η) was 11.1%. So, the layer possesses a proper geometrical morphology and the appropriate dilution rate under the optimal technology. In general, the optimized coaxial feeding nozzle can be used for the laser cladding layer preparation with excellent cladding quality.

5. Conclusions
Based on the Fluent analysis software and the response surface method, the following main conclusions can be drawn:

✓ The powder flow of three-dimensional coaxial feeding nozzle is simulated by Eulerian-Eulerian two-fluid models, and the reasonable range of powder-feeding technology is obtained. They are shown as follows: carrier gas flow should exceed 9 l/min, and the powder-feeding rate should be less than 7.5 g/min.

✓ Based on the central composite design of the response surface method, the regressive mathematical model between nozzle geometric parameters and powder flow fluidization characteristics is established. The optimal parameters of the nozzle are: nozzle angle of 62.95°, outlet width of 1 mm, exit radius of 5.83 mm, and shrinkage angle of 3.00°.

✓ Comparing the powder convergence effect of the un-optimized feeding nozzle with the optimized feeding nozzle, the latter waist diameter and focal depth are reduced by 39.4 and 46.4%, respectively. The error between the simulative and experimental powder flow characteristics is small, and the results indicate that the simulation model and optimized result possess reliability.

✓ The effect of the technological parameter on the quality and dilution rate of the laser cladding layer was explored by a single-factor experiment. Then, the appropriate technological parameters were selected as follows: 2.4 kW (laser power), 30 mm (laser defocusing distance), 15 l/min (carrier gas flow), 800 mm/min (scanning speed), 0 mm (powder flow defocusing distance) and 3.6 g/min (powder-feeding rate). These parameters can guarantee a proper geometrical morphology and appropriate dilution rate of the laser cladding layer.

Acknowledgments
This work was support by the Fundamental Research Funds for the Central Universities of China (No. 3232016354).

References
[1] Ye X Y, Ma M X, Cao Y X, et al. 2011 Phys. Procedia 12 303-12
[2] Zeng C, Tian W, Liao W H, et al. 2016 s Surf. Coat.Tech. 294 122-30
[3] Smurov I, Doubenskaia M and Zaitsev A 2013 Surf. Coat. Tech. 220 112-21
[4] Baldridge T, Poling G, Foroozmehr E, et al. 2013 Opt. Laser Eng. 50 180-4
[5] Calleja A, Taberner I, Fernandez A et al. 2014 Opt. Laser Eng. 56 113-20
[6] Chew Y, Pang J H L, Bi G, et al. 2015 J. Mater. Process. Tech. 224 89-101
[7] Lu Q P, Zhang A F, Li D C, et al. 2010 Chinese J. Lasers 37 3162-6
[8] Liu H, He X L, Yu G, et al. 2015 Sci. China Phys. Mech. 58 1-10
[9] Balu P, Leggett P and Kovacevic R 2012 J. Mater. Process. Tech. 212 1598-610
[10] Wang H X, Shi C, Wang C S, et al. 2010 Trans. China Welding Inst. 31 69-72
[11] Box G E P and Wilson K B 1951 J. Royal Stat. Soci. 13 1-45