Optimal design of structure parameters of coaxial powder feeding nozzle for laser cladding

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Abstract. Aiming at the problems of large powder gathering diameter, low powder utilization rate, easy clogging of the nozzle, poor cooling water system effect and unstable powder feeding effect existing in the existing nozzles, an improved laser cladding coaxial powder feeding nozzle with external shielding gas structure is optimally designed. The response surface method and the BP neural network optimized by genetic algorithm are used to optimize the nozzle structure parameter combination. After the nozzle structure parameter combination is determined, the external shielding gas structure parameter range is determined according to the nozzle structure parameter combination. The unsupported laser cladding coaxial powder feeding nozzle is made of photosensitive resin material, and the powder feeding effect is verified. The optimized nozzle is measured for the powder converging point, powder converging diameter and powder utilization rate, which verifies the validity of the simulation results.

1. Introduction
With the continuous development of science and technology, laser cladding technology has emerged as a multidisciplinary product [1-2]. Laser cladding technology can realize the processing and manufacturing of complex parts and repairing some parts with high processing and manufacturing costs that cannot be accomplished by ordinary mechanical processing methods [3]. In the laser cladding technology, the quality of the cladding layer depends on the concentration, speed, continuity, uniformity and other parameters of the powder feeding. As the key component that determines these parameters, the laser cladding powder feeding nozzle has caused extensive research by domestic and foreign experts and scholars. However, the existing nozzles all have problems such as easy clogging of the nozzle outlet, unstable powder feeding, and low powder utilization rate. In order to solve these problems, this paper explores the influence of nozzle structure parameters on the powder feeding effect and optimizes the design of the existing nozzle structure.

2. Optimized design of powder feeding nozzle structure
In order to effectively improve the quality of laser cladding, the optimally designed nozzle should meet the following requirements. (1) The powder feeding from the nozzle is stable and uniform, and the powder utilization rate is high. (2) The powder has good convergence, and the convergence radius is 3 ~ 4 mm. The convergence distance of powder is appropriate to ensure that the powder at the nozzle outlet will not melt and block the nozzle due to heat radiation. Powder will not block the laser light path, resulting in laser scattering phenomenon [4]. (3) The powder cavity should not be too narrow to prevent the powder from being blocked in the powder cavity, and the powder concentration...
at the powder gathering place will not be insufficient due to the small gap of the powder cavity. (4) With effective cooling water circulation, the nozzle will not be damaged in high temperature environment. (5) In order to avoid particle contamination of the focusing lens in the laser channel, there should be shielding gas in the laser channel [5]. (6) To prevent the powder particles from being oxidized in a high temperature environment, the powder particles should always move in an environment full of shielding gas atmosphere after leaving the nozzle.

Figure 1. Structure diagram of coaxial powder feeding nozzle.

Figure 1 shows the nozzle structure. The external shielding gas duct is added to improve the concentration of the powder and make the powder particles less likely to be oxidized. The inner and outer walls of the external shielding gas duct have a certain inclination angle, so that the protective air flow can be sprayed with better stiffness. The small inclination angle at the outlet ensures that the external shielding gas will not interfere with the powder flow prematurely, so as to avoid the phenomenon of premature gathering of the powder. The newly added external shielding gas duct can effectively improve the phenomenon of powder oxidation and uneven powder aggregation in a high-temperature environment and increase the powder utilization rate. In addition, when the external shielding gas acts on the powder between the upper focal length and the lower focal length, it also has the effect of reducing the powder focal radius. A spiral tube-shaped cooling water circulation system is designed which has no gaps and will not cause problems such as nozzle blockage due to the moisture of powder caused by water vapour generated by the cooling water heating.

3. Optimization of nozzle structure parameters
It is found from the research that the convergence effect of the laser cladding coaxial powder feeding nozzle is mainly determined by the powder cavity gap, the powder cavity inclination angle, the powder cavity radius and the external shielding gas structure size parameters. Since the parameter selection range of the external shielding gas outlet radius and inclination angle is very relevant to the internal structure of the nozzle, it is necessary to optimize the internal structure parameters of the nozzle before optimizing the external shielding gas structure. Due to the large number of structural parameter variables, there will be many combinations. If the orthogonal experimental design is adopted, although fewer trials can be used to obtain the optimal parameters, the parameters obtained are limited to the given level value.

The response surface method can overcome the shortcomings of orthogonal experimental design, and obtain the optimal value within a given size limit by fitting the fitting equation of the response function. It can get the fitting equation and verify its accuracy. It can generate a large number of training samples through the fitting equation. The BP neural network algorithm optimized by genetic algorithm is used to optimize the nozzle structure parameters. After the optimal solution is obtained, the external shielding gas structure parameters are determined by orthogonal experimental design.
3.1. CCD experimental design and data processing

The range of powder cavity radius, powder cavity gap and powder cavity inclination angle are determined by CCD experiment. The levels in the experimental design are shown in Table 1.

Table 1. CCD experiment design factor level.

| Level         | Powder cavity radius $r$ (mm) | Powder cavity gap $w$ (mm) | Powder cavity inclination $\alpha$ (°) |
|---------------|--------------------------------|----------------------------|---------------------------------------|
| -alpha level (-α) | 3.98                          | 0.20                      | 15.27                                 |
| Low level (-1)   | 5                             | 0.4                        | 18                                    |
| Zero level (0)    | 6.5                           | 0.7                        | 22                                    |
| High level (+1)   | 8                             | 1                          | 26                                    |
| +alpha level (+α) | 9.02                          | 1.20                      | 28.73                                 |

As shown in Table 1, the experimental design has three factors and five levels, including -α level and +α level. Simulation analysis can determine the value range of the powder cavity radius is 5~8mm, the value range of the powder cavity gap is 0.4~1mm, and the inclination angle of powder cavity is 18°~26°. The powder convergence focal length and powder convergence diameter are used as response quantities to fit the regression model, which can intuitively reflect the quality of the powder convergence effect.

According to the CCD experiment design scheme, 20 groups of experiments are designed, including 8 groups of comprehensive experiments, 6 groups of axial experiments and 6 groups of central experiments. Because the nozzle is difficult to manufacture and the cost is high, fluent simulation is used instead of the real test. The parameters used in the simulation are shown as follows. Internal shielding gas velocity is 3m/s, powder feeding gas velocity is 1.81 m/s, powder mass flow rate is $8\times10^{-0.5}$ kg/s, the coefficient of elastic recovery is 0.93, and the diameter of the powder feeding nozzle is 0.0042 m. The powder is 316L stainless steel powder, which is regarded as a spherical particle with a particle size of 100 μm regardless of its spherical coefficient.

According to the factor level designed in Table 1, the nozzle structure parameter combinations and simulation results of 20 sets of tests generated by Design Expert software are shown in Table 2. Through the simulation results, it can be found that if the size and combination of the powder cavity inclination, the powder cavity gap and the powder cavity radius are changed, the powder convergence diameter and focal length have a great change.

According to previous studies, it is known that the best focus distance of powder is 8mm~12mm, so the best value of powder focus is 10mm. It is better that the value of the powder concentration diameter is smaller, which can improve the quality of the cladding layer. Generally, the laser spot diameter is about 3mm, so the powder concentration diameter should not be greater than 3mm.

Design Expert is used to predict the optimal values of RSM for powder cavity radius, powder cavity gap and powder cavity inclination angle. The optimal values obtained are the powder cavity radius of 5.39mm, the powder cavity inclination angle of 18° and the outlet gap of 0.44mm. The satisfaction degree is close to 1, which meets the requirements of optimization.

Table 2. CCD experimental design scheme and experimental data.

| std run | Powder cavity inclination $\alpha$ (°) | Powder cavity radius $r$ (mm) | Powder cavity gap $w$ (mm) | Focal length $h$ (mm) | Converging diameter $d$ (mm) |
|---------|---------------------------------------|--------------------------------|---------------------------|----------------------|-----------------------------|
| 19 1    | 22.00                                 | 6.50                          | 0.70                      | 10.01                | 3.97                        |
| 18 2    | 22.00                                 | 6.50                          | 0.70                      | 10.16                | 4.33                        |
| 8 3     | 26.00                                 | 8.00                          | 1.00                      | 11.22                | 4.57                        |
| 3 4     | 18.00                                 | 8.00                          | 0.40                      | 14.53                | 3.89                        |
| 4 5     | 26.00                                 | 8.00                          | 0.40                      | 11.22                | 3.52                        |
| 6 6     | 26.00                                 | 5.00                          | 1.00                      | 7.18                 | 3.57                        |
| 13 7    | 22.00                                 | 6.50                          | 0.20                      | 10.06                | 2.18                        |
| 17 8    | 22.00                                 | 6.50                          | 0.70                      | 10.20                | 3.96                        |
3.2. Structural parameter optimization based on BP neural network algorithm

Due to the complex nonlinear relationship between the laser cladding coaxial powder feeding nozzle structure parameters and the powder feeding effect evaluation parameters, in order to further optimize the structure parameters of the laser cladding coaxial powder feeding nozzle, the BP neural network is used to establish a model with genetic algorithm to optimize the nozzle structure parameters to get a better powder feeding effect [6].

BP neural network keeps the powder feeding effect to the optimal value by continuously changing its weight, and finally obtains the best parameter combination of powder feeding effect [7-8]. The neural network selected in this paper has 3 layers, 3 nodes in the input layer, 12 nodes in the hidden layer, 2 nodes in the output layer, linear functions for the input and output layer transfer functions, Log-Sigmoid function for the hidden layer transfer functions and LM algorithm for network training [9]. Among them, the input layer nodes are the powder cavity inclination angle, the powder cavity gap and the powder cavity radius, while the output layer nodes are the powder convergence diameter and the powder convergence focal distance. In order to save time and cost, the maximum number of iterations is set to 200, the population size is set to 50, the crossover probability is set to 0.7, and the mutation probability is set to 0.01. The specific algorithm flow chart is shown in Figure 2 [10].
The regression model obtained from the experimental data of the designed CCD experiment is used to randomly generate 3980 sets of data as training data to train the network. 20 sets of data in the sample data is selected to verify the network. Table 3 shows the analysis of neural network prediction values and training sample errors.

Table 3. Neural network prediction value and training sample error analysis.

| run | Focal length (actual) | Focal length (predicted) | Focal length (absolute) | Convergent diameter (actual) | Convergent diameter (predicted) | Convergent diameter (absolute) |
|-----|----------------------|-------------------------|-------------------------|-----------------------------|--------------------------------|-------------------------------|
| 1   | 11.31                | 11.26765                | -0.04235                | 2.987                       | 3.129297                      | 0.142297                      |
| 2   | 10.06                | 10.08939                | 0.029391                | 3.756                       | 3.786184                      | 0.030184                      |
| 3   | 14.58                | 14.2129                 | -0.3671                 | 5.794                       | 5.658434                      | -0.13557                      |
| 4   | 8.32                 | 8.571888                | 0.251888                | 4.61                        | 4.582836                      | -0.02716                      |
| 5   | 9.37                 | 9.503007                | 0.13007                 | 5.732                       | 5.592854                      | -0.13915                      |
| 6   | 13.71                | 13.4228                 | -0.2872                 | 3.811                       | 3.836718                      | 0.025718                      |
| 7   | 10.54                | 10.56921                | 0.029206                | 3.825                       | 3.872397                      | 0.047397                      |
| 8   | 9                    | 9.128281                | 0.128281                | 3.142                       | 3.226999                      | 0.084999                      |
| 9   | 9.33                 | 9.403594                | 0.073594                | 5.116                       | 5.012051                      | -0.10395                      |
| 10  | 9.28                 | 9.42196                 | 0.14196                 | 3.074                       | 3.186562                      | 0.112562                      |
| 11  | 11.83                | 11.69555                | -0.13445                | 3.268                       | 3.35763                       | 0.08963                       |
| 12  | 10.73                | 10.66807                | -0.06193                | 4.816                       | 4.753734                      | -0.06227                      |
| 13  | 12.52                | 12.32813                | -0.19187                | 5.432                       | 5.329173                      | -0.10283                      |
| 14  | 14.24                | 13.85813                | -0.35487                | 4.881                       | 4.833723                      | -0.04728                      |
| 15  | 10.16                | 1020091                 | 0.04091                 | 3.649                       | 3.726809                      | 0.077809                      |
| 16  | 6.85                 | 7.260955                | 0.410955                | 3.12                        | 3.269117                      | 0.149117                      |
| 17  | 8.88                 | 9.090036                | 0.210036                | 5.639                       | 5.519511                      | -0.11949                      |
| 18  | 7.72                 | 7.989319                | 0.269319                | 3.1                         | 3.219786                      | 0.119786                      |
| 19  | 6.68                 | 7.031249                | 0.351249                | 3.673                       | 3.719927                      | 0.046927                      |
| 20  | 11.52                | 11.38547                | -0.13453                | 5.44                        | 5.314785                      | -0.12521                      |

According to the previous analysis, when the powder converging diameter of the laser cladding coaxial powder feeding nozzle is within 3mm, and the powder converging focal distance is 10mm, the laser cladding effect achieves the best. Therefore, the BP neural network algorithm is used to find the most suitable combination of structural parameters. The required powder convergence focal distance is set to be 10~12mm, and the powder convergence diameter is less than 3mm. This paper uses BP neural network to generate 20 sets of structural parameter combinations that meet the screening conditions.

Table 4 shows the combination of structural parameters that meet the optimization conditions obtained by using BP neural network. Considering that in the actual processing environment, an excessively large inclination angle of the powder cavity will cause serious powder dispersion and reduce powder utilization. An excessively large powder cavity radius will cause the powder converging diameter to increase, and the powder concentration distribution in the converging plane is uneven. A small gap in the powder cavity will cause the powder in the powder cavity easy to block, and the pressure at the exit of the powder cavity will increase, resulting in the divergence of the powder at the exit due to the sudden change in pressure. After comprehensive consideration, the structural parameter combination of powder cavity inclination of 18.94°, powder cavity radius of 6.27mm and powder cavity clearance of 0.6mm is selected as the structural parameters of the nozzle.

Table 4. Optimal parameter combination of BP neural network.

| run | Powder cavity inclination angle (mm) | Powder cavity radius (mm) | Powder cavity gap (mm) | Focal length (mm) | Focal point diameter (mm) |
|-----|-------------------------------------|---------------------------|------------------------|------------------|--------------------------|
| 1   | 26.72                               | 4.93                      | 1.1                    | 11.38            | 2.835                    |
| 2   | 25.46                               | 8.72                      | 1.1                    | 11.8             | 2.812                    |
| 3   | 24.15                               | 8.16                      | 0.5                    | 10.51            | 2.864                    |
| 4   | 19.75                               | 5.6                       | 0.3                    | 10.21            | 2.875                    |
3.3. Optimization of the external shielding gas structure of the laser cladding coaxial powder feeding nozzle

The external shielding gas structure parameters of the nozzle mainly include shielding gas radius, external shielding gas inclination, external shielding gas flow rate, and external shielding gas outlet gap. Since the external shielding gas outlet gap does not have a great influence on the powder concentration effect, the research results of the predecessors are cited and the external shielding gas outlet gap is selected as 0.5mm. The inclination angle and the radius of the external shielding gas are closely related to the inclination angle and the radius of the powder cavity of the nozzle. Therefore, the structural parameters of the external shielding gas are optimized after the structure parameters of the nozzle are determined. Here we choose to use the orthogonal experiment method to optimize the external protective gas structure parameters [11].

It is analyzed that the external shielding gas radius, the external shielding gas inclination angle and the external shielding gas flow velocity are the main factors affecting the powder accumulation effect. Among them, the external shielding gas radius is selected as the level of 7mm, 8mm, and 9mm based on previous experience and the limitation of nozzle structure parameters. The external shielding gas inclination angle selects 30°, 35° and 40° as the level. The external shielding gas flow velocity selects 0.5m/s, 1.0m/s and 1.5m/s as the level. Choosing the right orthogonal table can get the best test effect with the least experiments. According to the selection of factors and levels, L9 (3^4) orthogonal table [12] is used.

Table 5. Experiment plan and result analysis.

| External shielding gas radius (mm) | External shielding gas inclination (°) | External shielding gas flow velocity (m/s) | Powder pooling diameter (mm) |
|-----------------------------------|--------------------------------------|------------------------------------------|-----------------------------|
| 1 7 30                              | 0.5                                  | 2.9476                                   |
| 2 7 35                              | 1.0                                  | 2.8576                                   |
| 3 7 40                              | 1.5                                  | 3.2005                                   |
| 4 8 30                              | 1.0                                  | 2.8976                                   |
| 5 8 35                              | 1.5                                  | 2.7501                                   |
| 6 8 40                              | 0.5                                  | 2.9767                                   |
| 7 9 30                              | 1.5                                  | 3.1335                                   |
| 8 9 35                              | 0.5                                  | 3.3239                                   |
| 9 9 40                              | 1.0                                  | 3.3375                                   |
| K1 3.0019                           | 2.9929                               | 3.0827                                   |
| K2 2.8748                           | 2.9772                               | 3.0309                                   |
| K3 3.2649                           | 3.1716                               | 3.0280                                   |
The first to ninth lines of Table 5 are the simulation test results, and the powder concentration diameter is used as an evaluation index to judge the quality of the structure. Range analysis is used to process test data. When analyzing the influence of the external shielding gas radius on the powder concentration effect, it is found that the external shielding gas inclination angle and the external shielding gas flow velocity only appear once and there is no interaction between the external shielding gas inclination angle and the external shielding gas flow velocity. It is considered that there is no interaction between various factors, and the extreme difference of the level of each factor is calculated to determine which factor is the key factor affecting the powder aggregation effect. The calculation formula is shown in formula (1).

\[ K_i = \frac{k_i}{n_i} \]  

In the formula, \( k_i \) is the average value of the test indicators, and \( n_i \) is the number of times the level \( i \) quoted in the table. For example, when the external shielding gas inclination is 30°, the corresponding \( k_1 = 3.0019 \), when the external shielding gas inclination is 35°, the corresponding \( k_2 = 2.8748 \), and when the external shielding gas inclination is 40°, the corresponding \( k_3 = 3.2649 \). The values of \( k_1, k_2 \) and \( k_3 \) reflect the influence of varying levels of the external shielding gas radius on the powder concentration effect. The smaller the value of \( k \), the better will be the powder aggregation effect at this level. For the powder external shielding gas inclination angle, since \( k_2 < k_1 < k_3 \), it can be judged that the external shielding gas inclination angle of 35° is the best level of the external shielding gas inclination angle. According to this example, the inclination angle and the flow rate of the external shielding gas are calculated, and the best external shielding gas radius is 8mm, and the best external shielding gas flow velocity is 1.5m/s.

\( R \) in Table 5 represents the extremely poor powder aggregation effect at each level of each factor. It reflects the degree of influence of various factors on the powder aggregation effect. It can be seen from Table 5 that the external shielding gas radius has the most significant influence on the powder aggregation effect, and the external shielding gas flow velocity has a weaker influence on the powder aggregation effect.

### 4. Experimental research on nozzle powder feeding performance

Because the structure of the laser cladding coaxial powder feeding nozzle designed in this article is complex, and some structures manufactured by traditional machining methods cost high, therefore, this article uses photosensitive resin material to print and manufacture the designed nozzle.

Figure 3 shows the laser cladding coaxial powder feeding nozzle printed with photosensitive resin material. This nozzle uses 3D printing technology to print as a whole without any spare parts. Therefore, there will be no problems such as damp or clogging of powder due to gas leakage or cooling water leakage. M5 copper internal threads are inlaid at the powder inlet, external shielding gas inlet, inner shielding gas inlet and cooling water inlet to facilitate the connection of pneumatic pipe joints.

Figure 3. The physical diagram of the optimized laser cladding coaxial powder feeding nozzle.
The laser cladding system used in this experiment consists of a KR 16-2 6-axis mechanical arm, a YLR SM series 500W single-mode continuous mirror-doped fiber laser, a cooler and a powder feeder. The manufactured nozzle is installed on the laser cladding system and the powder feeding experiment is compared with the original nozzle to verify the nozzle powder feeding performance. Experiments are designed to determine the powder converging distance, powder converging diameter, powder utilization rate and powder feeding stability to analyze whether the optimized nozzle has better powder feeding performance than the original nozzle.

4.1. Determination of the concentration focus of powder

According to the above analysis, the powder concentration should be the largest at the focal point of the powder pool, and the powder utilization rate should be the highest at the focal point. Therefore, the focal point of the powder pool is the highest point of powder utilization rate. According to the simulation analysis, the actual focal point of the powder pool should be about 10mm from the nozzle group outlet. Therefore, some experimental points are designed around 10mm to determine the focal position of powder convergence. According to the query equipment manual, the YLR SM500 single-mode continuous-mirror-doped fiber laser used in the experiment adopts the TEM00 laser mode. The diameter of the laser's influence area at the convergent focal point is 3mm, so a ring hole with a diameter of 3mm is selected to receive the powder. The powder falling in the powder collector can be considered to fall into the molten pool and melt during the laser cladding process. The ratio of powder falling into the powder collector \( m_1 \) and not falling into the powder collector \( m_2 \) within 1 min can be determined to determine the powder utilization rate \( \eta \). The powder feeding rate is 8r/min. According to the calculation, the powder feeding amount per revolution of the powder feeding tray is about 4.375g, and the powder feeding rate per minute is about 35g. Table 6 shows the optimized powder gathering position and recovery test table.

It can be seen from Table 6 that the powder recovery rate of the powder particles is the highest at 10mm from the nozzle outlet, that is, the focal distance of the nozzle powder feeding is about 10mm, and the powder recovery rate \( \eta \) is about 57.06%. In order to verify the effect of nozzle structure optimization, the convergence position and recovery rate of the original nozzle were measured. According to the equipment manual, the original nozzle focal position is 15mm.

### Table 6. Experimental table of optimized powder gathering position and recovery rate.

| Height of powder collecting plane \( h \) (mm) | 9.0  | 9.5  | 10.0 | 10.5 | 11.0 | 11.5 | 12.0 | 12.5 | 13.0 |
|--------------------------------------------|-----|------|------|------|------|------|------|------|------|
| \( m_1 \) (g)                              | 6.75| 10.07| 13.96| 17.37| 19.97| 18.91| 17.42| 14.47| 10.55|
| \( m_2 \) (g)                              | 28.23| 24.86| 21.02| 17.59| 14.92| 15.86| 17.55| 20.32| 24.41|
| Powder utilization rate \( \eta \) (%)     | 19.29| 28.77| 39.89| 49.63| 57.06| 54.03| 49.77| 41.34| 30.14|

As shown in Table 7, the original nozzle converging position is about 15mm, which is consistent with the equipment manual. This shows that the experiments to determine the focal distance and recovery rate of the powder are accurate. The powder utilization rate \( \eta \) of the original nozzle is 46.59%, which is quite different from the optimized nozzle and proves that the optimized nozzle has better powder feeding effect and higher powder utilization rate than the original powder nozzle. According to Table 6 and Table 7, the powder recovery rate of the original nozzle and the optimized nozzle near the focal position can be obtained. Through the comparison of the nozzle powder utilization rate before and after the optimization, it can be known that the optimized nozzle has a larger increase in the powder utilization rate compared with the original nozzle, and the powder utilization rate is also higher than the original nozzle at 2mm above and below the focal plane.

### Table 7. The original nozzle powder gathering position and recovery rate experiment table.

| Height of powder collecting plane \( h \) (mm) | 13.0  | 13.5  | 14.0  | 14.5  | 15.0  | 15.5  | 16.0  | 16.5  | 17.0  |
|--------------------------------------------|------|------|------|------|------|------|------|------|------|
| \( m_1 \) (g)                              | 5.49 | 7.55 | 12.16| 14.23| 16.31| 15.39| 13.19| 10.84| 6.68  |
| \( m_2 \) (g)                              | 28.51| 26.98| 21.97| 20.57| 18.01| 18.02| 21.34| 23.69| 27.97|
| Powder utilization rate \( \eta \) (%)     | 15.69| 21.56| 34.73| 40.65| 46.59| 43.97| 37.68| 30.96| 19.07|
4.2. Determination of powder aggregation diameter

In order to measure the powder aggregation diameter of the original nozzle and the optimized nozzle, the laser cladding powder feeding experiment is carried out under the condition that the carrying airflow velocity was 1.81 m/s, the internal shielding gas flow velocity is 6 m/s, the external shielding gas flow velocity is 1.5 m/s and the powder feeding amount is 8 r/min.

Figure 4 is the effect diagram of powder feeding by nozzle before and after optimization. In order to facilitate data processing, PS software is used to change the background colour to black and conduct grayscale processing to facilitate the measurement of powder aggregation diameter. Figure 4 (a) and (c) are the effect drawings of powder feeding between the optimized nozzle and the original nozzle. Figure 4 (b) and (d) are processed images. After measurement, the original nozzle powder aggregation diameter was 4.3 mm, and the optimized nozzle powder aggregation diameter was 2.9 mm. This indicates that the optimized nozzle can meet the powder feeding requirements of laser cladding and obtain better laser cladding quality.

![Figure 4. Effect diagram of powder feeding by nozzle before and after optimization.](image)

4.3. Determination of powder feeding stability of nozzle

In order to determine the powder feeding stability of the original nozzle and the optimized nozzle, the powder feeding stability experiment of the nozzle is designed. Seven groups of powder feeding experiments with the duration of 2 min are carried out on the original nozzle and the optimized nozzle respectively, and the stability of powder feeding is determined according to the powder utilization rate of each group of experiments.

| Group number | 1    | 2    | 3    | 4    | 5    | 6    | 7    |
|--------------|------|------|------|------|------|------|------|
| Original nozzle utilization rate (%) | 46.55 | 43.21 | 47.98 | 49.02 | 53.31 | 54.39 | 41.20 |
| Optimized utilization rate (%) | 57.92 | 55.45 | 54.23 | 59.35 | 54.24 | 56.96 | 56.08 |

It can be seen from Table 8 that, in the seven groups of experiments, the range of powder utilization ratio of the original nozzle is 13.19, while that of the optimized nozzle is 7.9. It can be seen that the powder feeding stability of the optimized nozzle is far better than that of the original nozzle, which achieves the purpose of optimization. Use the nozzle powder utilization rate measured in Table 6 and Table 7 to make the difference between the nozzle powder utilization rate obtained in each experiment in Table 8 and draw a comparison chart of nozzle powder supply stability.

Figure 5 shows that the powder feeding stability of the optimized nozzle is greatly improved compared with that of the original nozzle. This is because there is no area in the flow field inside the optimized nozzle that can cause powder accumulation. Turning the plane into a surface at the entrance of the annular powder guide channel helps the powder to fall into the annular powder guide channel better. The structure of the original nozzle has many areas which are easy to be blocked by powder.
accumulation, so the powder feeding stability is poor. Therefore, the optimized nozzle has better powder feeding stability than the original nozzle.

Figure 5. Comparison of powder feeding stability of nozzle.

5. Conclusion
The simulation software FLUENT and experiment are used to study the coaxial powder feeding nozzle of laser cladding. The influence law of structural parameters of laser cladding coaxial powder feeding nozzle on the powder feeding effect is obtained. A ring laser cladding coaxial powder feeding nozzle with excellent performance is optimized and designed by response surface method, orthogonal experimental method and BP neural network optimized by genetic algorithm. A laser cladding coaxial powder feeding nozzle with unsupported structure was printed with photosensitive resin material, and its powder feeding performance is verified.

The test data designed by response surface method is used to train the BP neural network and predict its effect. The results show that the BP neural network can accurately predict the powder feeding effect of the nozzle. The optimized structure parameter combination is: powder cavity inclination angle 19°, powder cavity radius 6.3mm and powder cavity gap 0.6mm. The predicted value corresponding to the combination of structural parameters is compared with the actual value obtained by the simulation experiment using the combination of structural parameters, and the results are found to be basically consistent. The powder convergence diameter was 2.89mm and the focal distance of the powder was 10.98mm.

The optimized nozzle is measured for the powder converging point, powder converging diameter and powder utilization rate, which verified the authenticity of the simulation results. It is proved that the powder feeding effect of the optimized nozzle is greatly improved compared with the original nozzle. After optimization, the powder convergence diameter is 2.71mm, the powder utilization rate is about 57%, and the powder convergence focal length is 10mm.

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