APPLICATION

Powder flow simulation of a ring-type coaxial nozzle and cladding experiment in laser metal deposition

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Abstract
A 3D full size numerical model of a ring-type coaxial nozzle was established to obtain particle space trajectory and convergence character. The realizable k-ε model was applied in the gas flow phase. The powder flow was coupled with the gas flow by using Euler–Lagrange approach as a discrete phase model. Different powder material and particle sizes were selected to calculate the powder concentration distribution. The simulated powder stream morphology matched well with the experimental results of high-speed camera observations. Simulation results showed that using mean diameter $d$ to replace Rosin–Rammler distribution of particle size could get accurate flowing characteristic results. Simulation results also showed that this substitution could save computational resources and reduce the computing time significantly. The presence of the coaxial shielding gas has direct impact on the powder mass concentration spatial distribution, maximum value convergence height, and spot size of the powder flow. For 316L with small particle size and Ni60A with large particle size, we found different change regularities and no linear relationship was found. Therefore, it is recommended not to change the input volume of coaxial shielding gas without special needs. Simulation results, combining with the laser cladding experiments of Ni60A, have demonstrated that the developed ring-type coaxial nozzle could transport powder efficiently and form excellent deposited layers. The conditional powder utilization ratio can be as good as 75.9%.

Keywords Laser metal deposition · Coaxial nozzle · Gas-powder flow · Numerical simulation · Cladding experiment

1 Introduction
The laser metal deposition (LMD) technology features low heat input, high solidification rate, excellent metallurgical bonding, and deposition of functionally graded materials. LMD has been used in various material processing industries for coating, repairing, rapid prototyping, and making complex-shaped parts. This process uses a focused high-power laser beam to interact with the feeding metal material and substrate to form a molten pool which solidifies rapidly. The quality of the metal material feeding system can affect the performance of deposited layers directly. With many years of development, the coaxial powder system has proven to be more robust than preplaced powder system, off axis powder system, and wire feeding system because it offers precise feeding rate in any direction [1].

The powder flow of the spot is important in order to obtain the maximum efficiency of the LMD process. Some research has been done in this field. Li et al. [2] used a 3D model to accurately simulate the internal and external powder stream characteristics of the coaxial discrete three-beam nozzle for laser metal deposition. Their simulated powder stream morphology was matched well with the experimental results of CCD and high-speed camera imaging. Li et al. [3] created a continuous-discrete phase coupling model to simulate the workflow of a three-beam coaxial powder feeder. Their work examined the influence of working distance, carrier gas flow rate, and shielding gas flow rate on the state of powder aggregation and the external flow field of the powder nozzle during the cladding process. Zhu et al. [4] used a 2D model to investigate the impact of deposited layer’s shape on coaxial powder feeding flow field in the metal forming process. In their research, different height and width parameters of deposited layers were used to calculate the powder concentration distribution. They also
performed experiments to investigate the effect of deposited layer height and width on additive height of single-trace cladding layer. Arrizubieta et al. [5] presented a new methodology for continuous coaxial nozzle design for the LMD process based on CFD results. The numerical model could be used to predict particle flow, speed, powder concentration, etc., and the nozzle design could be optimized based on the CFD predicted results. Tabernero et al. [6] carried out simulations and experiments on a coaxial continuous nozzle with complex cavity. The powder stream concentration distribution at different heights downstream the nozzle was analyzed. Liu et al. [7] studied the characteristics of the powder stream from a coaxial continuous nozzle under inclined state and investigated its influence on the manufacturing process. Zhang et al. [8] developed a double-ring coaxial nozzle. They also created a 3D numerical model to simulate particle space trajectory and powder jet structure. In their research, Ni60A reinforced coating and 3D sample constructed on the surface of the high-speed shaft sleeve of a coal miner after the optimization of process parameters, with the powder utilization ratio up to 54.2% and the microstructure being uniform and dense. According to the studies above, 2D or 3D model was created to study the powder flow and convergence characteristics. The simulation can get good results. However, the models were overly simplified, which may reduce the calculation accuracy and/or increase computing source. The convergence characteristics of different material and particle size with the same nozzle structure were not system studied.

In this study, a simplified full size computational fluid dynamics (CFD) model of a ring-type coaxial nozzle was created to research the powder transport, diffusing and convergence regularity with two different material and particle size ranges. The gas-powder convergence results were verified by the high-speed camera images. Furthermore, cladding experiment based on the designed nozzle was performed to verify its working ability. Since the gas-powder convergence results of simulation matched well with the experiment and the designed nozzle has demonstrated excellent performance in cladding process, the numerical model can be used to predict the powder transportation during the LMD process and optimize key dimensions of future nozzle design. It can also be used to optimize the LMD process powder feeding parameters.

2 Numerical analysis of designed coaxial nozzle

2.1 Coaxial nozzle description

Currently, the coaxial nozzles are categorized as ring type and pass type (tubulose) based on their structures [9, 10]. The coaxial nozzle studied in this work is one of the ring-type nozzles and consists of five components: metallic joint, inner cone, locking ring, cone base, and outer cone. The cone base is a core part joint with other parts through threading. The cone base was manufactured by hybrid process of selective laser melting (SLM) and machining. It includes powder route and conformal water cooling route. This design enables the nozzle to be more compact and to have high cooling ability. The metallic joint can be divided into two types by function: one for gas-powder flow and another for water flow. The inner cone and the outer cone were manufactured using Copper C14500 to take advantages of its high thermal conductivity and low absorptive to Infrared (IR) lasers [11, 12]. The middle section of the inner cone includes many raised features, which will collide with the powder particles during operation. The inner taper feature of the inner cone treated as passing route for the laser and the coaxial shielding gas. The locking ring can be used to adjust the gap formed between the inner cone and outer cone and lock the inner cone assembly in position. A cross-sectional view and a structure explosive view of the coaxial nozzle are shown in Fig. 1.

To feed the powder, specific amount of protective gas was mixed with the powder coming from the powder feeder. The mixture was then feed to the splitter. The gas-powder mixture was divided into three equal portions by the splitter.
before entering the coaxial nozzle. As shown in Fig. 2, the divided gas-powder mixture then enters the diffusing zone. The collision with the wall of the diffusing zone altered the mixture’s momentum, moving direction, and spatial distribution. The mixture then entered the sliding zone. The sliding zone has a reversed cone-shaped route which forced the mixture to increase momentum. The accelerated mixture then exited the sliding zone in a form of jet. Finally, the mixture jet converged to a small volume before diffusing again at the focusing zone.

2.2 Model mesh generation

ICEM CFD of ANSYS Workbench was used to mesh the designed nozzle model. As shown in Fig. 2, the nozzle was divided into three zones according to its structure and functional characteristics: diffusing zone, sliding zone, and focusing zone. The divergence zone consists of complex geometries. However, the requirements for the flow direction and calculation accuracy were low for this zone. Therefore, the sliding zone and the focusing zone directly affect the gas-powder flow convergence characteristics. Therefore, high flow direction and calculation accuracy were required for these two zones. Based on this, the multi-zone meshing method was adopted in this model. The diffusing zone uses a hybrid unstructured grid. The solid parts use tetrahedral elements, which represent complex geometries; the boundary layer uses a prismatic grid, which can well meet the fluid flow requirements in the boundary layer and improve the calculation accuracy. Both the sliding zone and the focusing zone adopt a hexahedral structure grid to ensure a higher grid quality and improve the calculation accuracy while reducing the amount of calculation.

2.3 Engineering assumptions used in our model

The following assumptions were taken by FLUENT 19.0 software during the gas-powder flow simulation in the computational model:

- The particle size distribution regularity conforms to the Rosin–Rammler expression [13].
- The particle inlet from the powder route with the same mass, direction, and velocity.
- Since the powder particle volume percentage in the gas-powder mixed stream is less than 10%, it is treated as a discrete phase and the collision between particles is ignored. This assumption allows the application of one-way coupled discrete phase modeling.
- Only drag, inertia, and gravity were considered in this study; other forces were neglected.
- The wall roughness effects were ignored since it cannot be used together with the realizable k-ε model.
- The discrete phase reflection coefficients of normal and tangential directions were set as a constant value of 0.9.
- Gas compressibility and density variation with pressure effects were ignored.
- The thermal effect caused by laser radiation on powder particles was neglected.

3 Numerical simulation methods

In this study, FLUENT 19.0 was used to compute the gas and gas-powder mixed stream behavior. FLUENT solves the conservation equations of mass and momentum by using finite-volume method [14]. The gas was treated as a continuous phase computed by the realizable k-ε model, and the
powder particle was treated as a discrete phase calculated by building trajectory model and solving particle kinematics equations.

### 3.1 Gas turbulent flow modeling

The k-ε turbulent model is the most popular turbulence model. It has been used in many applications. In this model, the turbulence field is characterized in terms of two variables, the turbulent kinetic energy $k$ and the viscous dissipation rate of turbulent kinetic energy $\varepsilon$. Transport equations for $k$ and $\varepsilon$ can be obtained from the Navier–Stokes equations by a sequence of algebraic manipulations.

In FLUENT, the realizable k-ε model has been extensively validated for a wide range of flows \[15, 16\], including rotating homogeneous shear flows, free flows including jets and mixing layers, channel and boundary layer flows, and separated flows. For all these cases, the performance of the model has been found to be substantially better than that of the standard k-ε model. Especially noteworthy is the fact that the realizable k-ε model resolves the round-jet anomaly; it predicts the spreading rate for axis symmetric jets that the realizable k-ε model. Especially noteworthy is the fact that the realizable k-ε model resolves the round-jet anomaly; it predicts the spreading rate for axis symmetric jets as well as that for planar jets. Based on this, the realizable k-ε model was used in this study to simulate the gas flow characteristics.

The modeled transport equations for $k$ and $\varepsilon$ in the realizable k-ε model are

\[
\frac{\partial}{\partial t} (\rho k) + \nabla \cdot (\rho u_i k) = \frac{\partial}{\partial x_j} \left[ \mu + \frac{\mu_t}{\sigma_k} \right] \frac{\partial k}{\partial x_j} + G_k + G_b - \rho \varepsilon - Y_M + S_k
\]

and

\[
\frac{\partial}{\partial t} (\rho \varepsilon) + \nabla \cdot (\rho u_i \varepsilon) = \frac{\partial}{\partial x_j} \left[ \mu + \frac{\mu_t}{\sigma_\varepsilon} \right] \frac{\partial \varepsilon}{\partial x_j} + \rho C_1 \varepsilon \frac{\varepsilon}{k} - \rho C_2 \frac{\varepsilon^2}{k + \sqrt{\varepsilon}} + C_{1r} \frac{\varepsilon}{k} G_b + S_\varepsilon
\]

where

\[
C_1 = \max \left[ 0.43, \frac{\eta}{\eta + 5} \right], \eta = \frac{k}{\varepsilon}, S = \sqrt{2S_i S_j}
\]

In these equations, $G_k$ represents the generation of turbulence kinetic energy due to the mean velocity gradients. $G_b$ is the generation of turbulence kinetic energy due to buoyancy, and $Y_M$ represents the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate.

The model constants $C_{1r}, C_2, \sigma_k$, and $\sigma_\varepsilon$ can be tuned to ensure that the model performs well for certain canonical flows. These model constants are

\[
C_{1r} = 1.44, C_2 = 1.9, \sigma_k = 1.0, \sigma_\varepsilon = 1.2
\]

### 3.2 Dispersed phase modeling

ANSYS FLUENT predicts the trajectory of a discrete phase particle by integrating the force balance on the particle, which is written in a Lagrangian reference frame. This force balance equates the particle inertia with the forces acting on the particle, and can be written as

\[
\frac{d\vec{u}_p}{dt} = \frac{\vec{u} - \vec{u}_p}{\tau_r} + \frac{\vec{g}(\rho_p - \rho)}{\rho_p} + \vec{F}
\]

where $\vec{F}$ is an additional acceleration (force/unit particle mass) term, $\tau_r$ is the drag force per unit particle mass and

\[
\tau_r = \frac{\rho_p d_p^2}{18 \mu} C_d R_e
\]

Here, $\tau_r$ is the droplet or particle relaxation time \[17\], $\vec{u}$ is the fluid phase velocity, $\vec{u}_p$ is the particle velocity, $\mu$ is the molecular viscosity of the fluid, $\rho$ is the fluid density, $\rho_p$ is the density of the particle, and $d_p$ is the particle diameter. $Re$ is the relative Reynolds number, which is defined as

\[
R_e = \frac{pd_p |\vec{u} - \vec{u}_p|}{\mu}
\]

### 4 Laser cladding experiments

Laser cladding is a technique to produce dense and metallurgically bonded protective layers on metallic substrates to improve surface properties like corrosion, wear, and thermal fatigue resistance \[18, 19\]. In comparison to competitive technologies such as thermal spray or conventional weld overlay, laser cladding has many advantages including, for example, lower heat input and workpiece distortion, limited dilution, smaller heat-affected zone (HAZ), and greater precision \[20, 24, 25\].

In order to verify the conditional working ability of the designed nozzle, laser cladding experiment was implemented based on it. In the experiment, the 27SiMn carbon steel rods with a diameter of 49 mm were used as substrates. Ni60A powders were used as coating material. The heat source was supplied by an EB-DDLG 4000A semiconductor laser system with a laser beam spot diameter around
2.8 mm. The schematic of the laser cladding process is shown in Fig. 3.

Table 1 lists the coaxial system powder feeding parameter. The coatings were prepared at cladding speeds of 2 m/min and 8 m/min, with the same laser power of 2300 W. Both coatings were prepared by one layer cladding. After the cladding process, the specimens were cut to a size of 10 mm × 5 mm × 5 mm. The specimens were firstly ground to 3000 grit size by silicon carbide papers. Then, the specimens were polished with diamond paste to a mirror finish.

5 Results and Discussion

5.1 Transport characteristics with different powder and particle size distribution

In industrial applications, different powder material and particle size distributions were needed because of different function or process requirements. However, it is usually unpractical to change the nozzle. Therefore, this will require the coaxial nozzle to have excellent performance with different powder material and particle size distributions. In this study, we used 316L and Ni60A as the power material with different powder particle sizes as researching objects. The powder particle size range and distribution contents are listed in Table 2.

In the gas-powder flow convergence simulation and experiments, we used the same parameters. The carrier gas flowing rate was 6 L/min. The powder feeding rate was 9 g/min. The effect of coaxial shielding gas and laser was ignored. For the particle size distribution, we set the distribute regularity to conform to the Rosin–Rammler expression, which has proven to be an effective method in previous similar studies [1, 4, 21]. One feature of the powder flow convergence was that the powder flowed out of the coaxial nozzle with a low particle mass concentration around the nozzle axis. It then converged to a small spot below the nozzle exit where the particle mass concentration became much higher. Finally, the particles continued moving in their respective motion directions and diverged from the convergence spot mentioned above. In our CFD simulation, we created a vertical plane and a vertical line (we called it Z line) to capture the Z location with the highest mass concentration along the nozzle axis. We also created a horizontal plane and a horizontal line (we called it X line) to capture the particle mass concentration distribution at the convergence spot. An example of the particle mass concentration distribution can be seen in Fig. 4. This figure also shows the afore-mentioned Z-line and X-line.

The diameter of the convergence spot was calculated using the contour with 3% of the peak particle mass concentration of the convergence spot. The powder stream convergence characteristics under the end face of the coaxial nozzle were monitored by a high-speed camera. Figure 5 shows the comparison of the simulation and experimental results. As one can see, the simulation results showed that the material of 316L has the highest particle mass concentration value of 102.0 kg/m³ at the location of 14.8 mm below the nozzle end face. This matched well with the experimental results, which showed the location of convergence is around 15 mm downstream the nozzle end face. The convergence spot diameter was 1.55 mm in simulation. This, again matched well with the experimental results, which showed the convergence spot diameter was around 1.7 mm.

For Ni60A, the highest particle mass concentration value is 82.1 kg/m³, and it is located at 13.6 mm below the nozzle end face. This matched well with the experiment results, which showed the location of convergence spot is around 14.0 mm downstream the nozzle end face. The convergence spot diameter was 2.4 mm in simulation. This matched well

Table 1 Powder feeding parameter of the coaxial system

| Powder | Particle size | Powder feeding rates | Carrier gas | Coaxial shielding gas |
|---------|---------------|----------------------|-------------|----------------------|
| Ni60A   | 53–150 μm     | 9 g/min              | 6 L/min     | 8 L/min              |

Table 2 Powder particle size range and distribution of 316L and Ni60A

| Powder | Size range | Particle size distribution X¹₀ | X₅₀ | X₉₀ |
|--------|------------|--------------------------------|-----|-----|
| 316L   | 15–53 μm   | 21.9 μm                        | 33.4 μm | 50.9 μm |
| Ni60A  | 53–150 μm  | 56.5 μm                        | 93.8 μm | 147.7 μm |

Fig. 3 Schematic of the laser cladding process
with the experimental results, which showed that the convergence spot diameter was around 2.6 mm.

As one can see, the simulation successfully predicted the location of the convergence spot as well as the diameter of the spot.

Figure 6 shows the simulated particle mass concentration distributions at multiple locations along the nozzle axis. From Fig. 6, it can be seen that the particle mass concentration distribution for 316L/Ni60A was not symmetric along the nozzle axis. Additionally, the powder particle convergence spot shape at the horizontal plane was not a perfect circle. This is especially true for the particle material of 316L with small powder particle sizes. To find the reason, multiple sections were created along the nozzle axis to further examine the particle mass spatial concentration distributions. As shown in Fig. 6, the particle mass spatial concentration distribution around the nozzle axis was determined by the diffusing zone in which the powder particles bounce off the wall and re-establish their flow speed and directions. The zones near the inlets have lower particle mass concentration, and the zones between every two inlets have higher particle mass concentration. This characteristic is maintained and extended all the way down to the convergence spot. Based on this, it can be said the particle spatial distribution in the diffusing zone determines the shape of the convergence spot.

5.2 Simulation of the particle distribution using mean particle diameter

In our simulation, we first used the Rosin–Rammler expression to simulate a realistic particle size distribution. In this approach, the full range of particle sizes is
divided into several groups with each group represented by a single stream. When using surface injection type, the location of the particle source is distributed on each grid of the emission plane by default. If the number of surface grids is large, it will have more particle sources, which will consume a large amount of computational resources and time. The Rosin–Rammler distribution function is based on the assumption that an exponential relationship exists between the particle diameter $d$, and the mass fraction of particles with diameter greater than $d$ is $Y_d$. The Rosin–Rammler expression is given by:

$$Y_d = e^{-\left(\frac{d}{\bar{d}}\right)^n} \quad (8)$$

where $\bar{d}$ is the mean diameter and $n$ is the spread parameter.

In order to reduce computational resources and time, we also tried using the mean particle diameter $\bar{d}$ to replace the particle size distribution calculated from the Rosin–Rammler expression. With this replacement, the particle tracked numbers decreased from 49,600 to 6200. We did the same simulation for both 316L and Ni60A powder and compared the results with those obtained from using the Rosin–Rammler expression. It can be seen from the results in Fig. 7, the particle mass concentration results of mean diameter $\bar{d}$ along the Z line and X line is similar to Rosin–Rammler distribution, the convergence spot size and shape is almost the same. Therefore, when there are no high requirements about the flowing simulating results, using of mean diameter $\bar{d}$ to replace Rosin–Rammler distribution of particle size can give us accurate flowing characteristic results while significantly reducing the computational resources and time.

### 5.3 Coaxial shielding gas

The coaxial shielding gas plays an important role in the LMD process. The presence of the coaxial shielding gas can not only blow away the smoke created during the processing along the laser passage, but also form an external gaseous protective layer of the melting pool. To save computational resources and time, we used the mean particle diameter $\bar{d}$ of 316L and Ni60A in our simulation, along with different input volume of coaxial shielding gas to study the convergence characteristics.

Figures 8 and 9 show the impact of coaxial shielding gas on particle mass concentrations. The presence of coaxial shielding gas would affect the spatial distribution of particle mass concentration and maximum value height location along the Z line directly. For 316L with small powder particle size, the maximum particle mass concentration height increased with increased inlet volume of the coaxial shielding gas. On the other hand, the maximum particle mass concentration value decreased with increased inlet volume of coaxial shielding gas. As to the convergence spot size, it would become larger and get an obvious increase at the beginning, and then get stable with increased inlet volume of coaxial shielding gas. The change regularity of simulation was similar with experiments. For Ni60A with large powder particle
size, the maximum particle mass concentration height increased with increased inlet volume of coaxial shielding gas. Unlike 316L, the concentration maximum value increased first before starting decreasing. The convergence spot size did not have obvious change with increased inlet volume of coaxial shielding gas; the change regularity of simulation was similar with experiments. There was no linear regularity found between different input volumes of coaxial shielding gas and maximum particle mass concentration height/value and convergence spot size. So it is recommended not to change the input volume of coaxial shielding gas without special needs.

5.4 Laser cladding experiments

Figure 10 shows the Ni60A reinforced coating processes and results on the surface of the rod. The surface of the coatings was bright and smooth. Figure 11 shows the micrographs of the coatings. As one can see from Fig. 11, the single track at 2.0 m/min was a bowl-shaped curve, while at 8.0 m/min, the single track was fairly flat. Due to the increase of cladding speed and lapped ratio, the low heat input leads to a wide and thin molten pool. The coating thickness at 2.0 m/min cladding speed is about 540 μm, and it is about 360 μm at 8.0 m/min.
After weighing the rod before and after coating \([4, 22, 23]\), the powder using ratio at cladding speed of 2.0 m/min is around 75.9%. At cladding speed of 8.0 m/min, it is around 66.7%. It could be found that the sizes of heat-affected zone (HAZ) decreases as the cladding speed increases.

Figure 12 shows the surface quality of the coatings with speed of 2.0 m/min and 8.0 m/min. Compared with the coating at 2.0 m/min, there are many more semi-melted powder particles on the coating surface at 8.0 m/min, which lowers the surface quality. The overlapping trace becomes indistinct at 8.0 m/min coating due to the high lapped ratio. As to the overlapping trace area, the surface at speed of 2.0 m/min coating is smoother as the powder melts better. Based on previous research, the rapid heating and cooling cycle during laser cladding process will induce rigorous metallurgical reaction and result in less-favorable microstructures. The Ni supersaturated solid solution can be easily formed and precipitated during multipass laser cladding process. The crystal lattice distortion can induce high level of internal stress in the coating and lead to cracking or pre-matured failure during service \([26]\). There are noticeable cracks existing on both coating surfaces. At a speed of 2.0 m/min, the cracks go across the rotating direction and emerge in similar distance; at a speed of 8.0 m/min, the cracks become much smaller and no regularity compared with speed of 2.0 m/min.
**Fig. 9** Impact of coaxial shielding gas on particle mass concentrations for Ni60A. **a** Particle mass concentration distribution along the Z line. **b** Maximum concentration value position along the Z line. **c** Particle mass concentration distribution along the X line. **d** Particle mass concentration spot size comparison between simulation and experiments.

**Fig. 10** Experiment of reinforced coating process for Ni60A. **a** Experiment setup and reinforced coating results. **b**
Conclusions

In this study, a full size 3D discrete phase model of the gas-powder flow in the LMD process was developed using Ansys Fluent. The powder convergence and concentration distribution were studied for the ring-type coaxial nozzle. The pictures captured by high-speed imaging were used to verify the simulation results. Furthermore, laser cladding experiments were performed to verify the conditional working ability of the coaxial nozzle.

The main conclusions derived from this study are summarized below:

1. The computational results of the ring-type coaxial nozzle gas-powder flow matched well with the experiment results. This proves that the simulation model and gas-solid flow theory can be used to predict the powder flow characteristic and optimize the nozzle structure design. To save the computational resource and reduce the computing time, the mean value of the powder particle size was used to replace the size distribution of Rosin-Rammler distribution in the simulation.

2. Both the computational and experimental results showed that this ring-type coaxial nozzle using powder particles with smaller diameter and distribution range can get much better convergence results in terms of the particle focusing spot and mass concentration. The presence of coaxial shielding gas can affect the powder mass distribution and convergence spot significantly. Increasing the shielding gas volume will cause the focusing spot to become larger and its location farther downstream from the nozzle exit, which in turn will affect the interactive between powder and laser.

3. This ring-type coaxial nozzle demonstrated to have excellent performance during the laser cladding process. It could create high-quality coatings above the substrate with the powder utilization ratio up to 75.9%, meeting the requirement of industrial applications. With increased cladding speed, the size of both coating thickness and heat-affected zone (HAZ) decreased.
The datasets used or analyzed during the current study are available from the corresponding author on reasonable request.

**Declarations**

**Ethics approval** Not applicable.

**Consent to participate** Not applicable.

**Consent for publication** Not applicable.

**Conflicts of interest** The authors declare there no competing interests.

**References**

1. Tamanna N, Crouch R, Naher S (2019) Progress in numerical simulation of the laser cladding process. Opt Lasers Eng 122:151–163. https://doi.org/10.1016/j.optlaseng.2019.05.026

2. Li L, Huang Y, Zou C, Tao W (2021) Numerical study on powder stream characteristics of coaxial laser metal deposition nozzle. Curr Comput-Aided Drug Des 2021(11):282. https://doi.org/10.3390/cryst11030282

3. Li C, Zhang D, Yang Y, Gao H, Han X (2021) Research on sputtering behavior of three beams coaxial laser cladding powder based on the interaction of lasers and powder. J Laser Appl 33(4):042020. https://doi.org/10.23517/00000449

4. Zhu G, Li D, Zhang A, Tang Y (2011) Numerical simulation of metallic powder flow in a coaxial nozzle in laser direct metal deposition. Opt Laser Technol 43(1):106–113. https://doi.org/10.1016/j.optlastec.2010.05.012

5. Arrizubieta JJ, Tabernero I, Ruiz JE, Lamikiz A, Martinez S, Ukar E (2014) Continuous coaxial nozzle design for fmd based on numerical simulation. Phys Procedia 56(56):429–438. https://doi.org/10.1016/j.phpro.2014.08.146

6. Tabernero I, Lamikiz A, Ukar E, De Lacalle LL, Angulo C, Urbiain G (2010) Numerical simulation and experimental validation of powder flow distribution in coaxial laser cladding. J Mater Process Technol 2010(210):2125–2134. https://doi.org/10.1016/j.jmatprot.2010.07.036

7. Liu Z, Qi H, Jiang L (2016) Control of crystal orientation and continuous growth through inclination of coaxial nozzle in laser powder deposition of single-crystal superalloy. J Mater Process Technol 2016(230):177–186. https://doi.org/10.1016/j.jmatprot.2015.11.017

8. Zhang J, Yang L, Li Z, Zhang Q, Yu M, Fang C, Xiao H (2021) Transport phenomenon, flow field, and deposition formation of metal powder in the laser direct deposition with designed nozzle. Int J Adv Manuf Technol 114(1). https://doi.org/10.1007/s00170-021-0913-x

9. Kovaliev OB, Zaitsev AV, Novichenko D, Smurov I (2011) Theoretical and experimental investigation of gas flows, powder transport and heating in coaxial laser direct metal deposition (DMD) process. J Therm Spray Technol 20:465–478. https://doi.org/10.1007/s11666-010-9539-3

10. Hua T, Fengying Z, Xin Fu, Jian M, Guang Hu, Wei F, Huang W (2016) Development of powder flow model of laser solid forming by analysis method. The International Journal of Advanced Manufacturing Technology. https://doi.org/10.1007/s00170-015-7481-8

11. Popovich A, Sufiliarov V, Polozov I, Borisov E, Masaylo D, Orlov A (2016) Microstructure and mechanical properties of additive manufactured copper alloy. Mater Lett 179:38–41. https://doi.org/10.1016/j.matlet.2016.05.064

12. Higashino R, Sato Y, Masuno S, Shobu T, Funada Y, Abe N, Tsukamoto M (2020) Development of blue diode laser for additive manufacturing. Laser 3D Manufacturing VII. https://doi.org/10.1117/12.2543119

13. Fan J, Zhao H, Cen K (1992) An experimental study of two-phase turbulent coaxial jets. Exp Fluids 1992(13):279–287. https://doi.org/10.1007/BF00189021

14. Fluent Inc. (2018) FLUENT 19.0 User Guide

15. Kim SE, Choudhury D, Patel B (1999) Computations of complex turbulent flows using the commercial code fluent. In: Salas M.D., Hefner J.N., Sakell L. (eds) Modeling Complex Turbulent Flows. ICASE/LaRC Interdiscip Ser Sci Eng 7. Springer, Dordrecht. https://doi.org/10.1007/978-94-011-4724-8_15

16. Shih TH, Liou WW, Shabhir A, Yang Z, Zhu H (1994) A New k-\(\varepsilon\) viscosity model for high reynolds number turbulent flows - model development and validation. Comput Fluids 24

17. Gosman AD, Ioannides E (2022) Aspects of computer simulation of liquid-fuelled combustors

18. Thomy C, Seefeld T, Vollertsen F (2008) Humping effect in welding of steel with single-mode fibre laser. Welding in the World 52.5–6(2008):9–18. https://doi.org/10.1007/BF03266636

19. Tong X, Li F, Liu M, Dai M, Zhou H (2010) Opt Laser Technol 42:1154

20. Steen WM (1998) Laser Materials Processing, second edition. Springer

21. Zekovic S, Dwivedi R, Kovacevic R (2007) Numerical simulation and experimental investigation of gas–powder flow from radially symmetrical nozzles in laser-based direct metal deposition. Int J Mach Tools Manuf 47(1):112–123. https://doi.org/10.1016/j.ijmachtools.2006.02.004

22. Yang N (2009) Concentration model based on movement model of powder flow in coaxial laser cladding. Opt Laser Technol 41:94–98. https://doi.org/10.1016/j.optlastec.2008.03.008

23. Zhang J, Yang L, Zhang W, Qu JB, Xiao HB, Yang L (2020) Numerical simulation and experimental study for aerodynamic characteristics and powder transport behavior of novel nozzle. Opt Lasers Eng 126:105873. https://doi.org/10.1016/j.optlaseng.2019.105873

24. Hemmati I, Ocelik V, De Hosson JTM (2011) The effect of cladding speed on phase constitution and properties of AISI 431 stainless steel laser deposited coatings. Surf Coat Technol 205.21(2011):5235–5239. https://doi.org/10.1016/j.surfcoat.2011.05.035

25. F S, Wang TA, Li A, Yz A, Wei WB, Sw B (2020) Effect of microstructure on the corrosion resistance of coatings by extreme high speed laser cladding. Appl Surf Sci. https://doi.org/10.1016/j.apsusc.2020.146085

26. Chen Z, Li R, Gu J, Zhang Z, Tao Y, Tian Y (2019) Laser cladding of ni60 + 17 4ph composite for a cracking-free and corrosion resistant coating. Int J Mod Phys B 34(1105):2040042. https://doi.org/10.1142/S0217979220400421