Studying the process of powder transportation during laser cladding with a coaxial nozzle

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Abstract. Results of experiments and numerical modeling of gas-powder flow for laser cladding are presented. Numerical simulation is based on solving Navier-Stokes equations with Lagrange approach for particle. The main attention is paid to the process of interaction between powder particles and nozzle walls. Simple particle-wall interaction model was suggested and verified with experiments for gas-powder jet formed in the long tubes with different diameters. The model was used for simulation of powder transport in the coaxial nozzle for laser cladding.

1. Introduction
Laser cladding is additive technology that uses laser radiation for a local heating of base material and powder of metal, ceramics and metal mixture for building new details with complex 3D geometry. The technology has become widespread in industry, but several unresolved problems remain. One of the main problems is difficulty to achieve high powder usage coefficient, which directly influences the cost of the process. Other problems are associated with roughness of the cladded bead and measures to protect optical elements of the laser nozzle head from the damage of hot powder particles. Main goal of the research is construction of new cladding nozzles with high powder usage coefficient. Despite a large number of works on the modeling of a gas-powder mixture for laser cladding technology, including recently published \cite{1,4}, we found that one of the main reasons determining the shape of a powder jet is not considered qualitatively. In our previous works, it was shown \cite{2-3} that the law of particle reflection from the nozzle walls is one of the most important. In this paper, we continued our study, specifying the laws and coefficients that describe the interaction between particles and walls and applied the model to research processes in the coaxial nozzle for laser cladding.

2. Models
Despite the fact that gas flows containing microparticles have been studied for a long time, the area of object application is so wide that there are different physical models for each specific field. Laser cladding characterized by gas and particle velocities not exceed 30 m/s. Usually particle size of powder is in range of 30 to 100 μm and dimensions of the channel are several millimeters. Therefore, particles experience multiple collisions with the walls in nozzle. The main parameter for practical application is size of powder jet spot on the substrate, it determined directly the utilization rate of powder.

The main phenomena usually considered for moving particles in the gas are the drag force, the Magnus force, the Saffman force, the effect of the attached mass. According to our research \cite{2-3}
under conditions specific to laser cladding the last three terms have a small effect and can be neglected. It means we could neglect influence particles rotation on their trajectories between collisions with walls and other particles.

But works of Sommerfeld [5] and Tsirkunov [6] showed that particle rotation may be important in the process particle-wall interaction. In our model, we tried to avoid using angular velocity with introducing simpler laws for particle-wall interaction. The model based on two restitution coefficients of the tangent and normal velocity. These coefficients are strongly empirical. They were calculated from statistical experimental data and heavily depend on nozzle and powder material. In most cases particle-particle interactions also can be neglect because of volume fraction does not exceed $10^{-4}$ that less then generally accepted value 0.01 [6].

In [2-3] we showed that particle backward influence on the gas could be neglected and task could be solved in two stages: 1) the gas flow pattern is calculated by solving the Navier-Stokes equations with the SST-model of turbulence, 2) the particle trajectories are calculated in the Lagrangian approach on the obtained distribution of gas velocities. We neglect direct influence of turbulence pulsation on particle motion and use averaged gas flow field because turbulent oscillations weakly affect the particle motion inside the channel ($Re < 500$), and the gas motion outside the nozzle is not so decisive for the spot size of the powder jet on the substrate.

The particle size distribution in simulation was consistent with experimental one (Fig. 2). Volume distribution were converted to number distribution and every time particle started motion with size chosen randomly with built function.

Simulation software developed on base of open source package OpenFOAM. Additional user library with new particle interaction and injection models in order to expand functionality and replace computationally time-consuming built-in procedures was written.

3. Experimental setup and results
Experimental investigation of powder jet characteristics performed using original optical diagnostic system based on digital camera and positioning system, additionally equipped with pulse LED illumination module. Module synchronized with the camera exposition time (pulse duration 10-500 μm). That made possible to increase the resolution to 15 μm/pixel and allow to register particles with a diameter of ~20 μm or more. Frames with tracks of moving particles (about 3000 for each experiment) were recorded and processed to identify individual particle tracks on each frame, their position and velocity vector components.

**Figure 1.** Powder PR-HX16CP3 particle shape.

**Figure 2.** Powder PR-HX16CP3 particle size distribution.
All experiments were carried out with powder PR-HX16CP3 of the system (Ni (base) -16Cr-3.2Si-2.7B) characterized by particle size mostly in range 20 – 63 μm with high sphericity (figures 1 and 2).

The experiments studied the structure of gas-powder jet forming by single 100 mm long tubes of various diameters and material. The copper tubes with diameters 3, 4, 6, 8 mm and the steel tubes with diameters 2, 4, 6, 8 mm were used.

Additionally, roughness of tubes inner surface is investigated. Roughness parameters Ra and Rz were measured for all tubes on optical profiler NewView 7300. The results are presented in Table 1.

| Inner diameter | Copper tubes | Steel tubes |
|----------------|--------------|-------------|
|                | Ra           | Rz          |
| 3              | 0.83         | 4.1         |
| 4              | 0.72         | 3.5         |
| 6              | 0.45         | 3.1         |
| 8              | 0.39         | 2.5         |
| 2              | 0.79         | 6.6         |
| 4              | 2.14         | 12          |
| 6              | 1.48         | 8.8         |
| 8              | 2.7          | 12.8        |

Figure 3 shows how the experimental particle jet width (a) depends on the distance from the nozzle exit for 6 mm steel tube and average particle velocity changes (b) after leaving 4 mm copper tube. The jets had almost conical shape and nearly do not depend on speed of carrying gas. The velocity of the particles remains almost the same after leaving the nozzle for the gas speed less than 20 m/s. Similar results are obtained for other tubes. Therefore, the average angle of inclination of the particle velocities after the nozzle mainly determines the shape of the powder jet.

4. Numerical simulation

4.1. Long tubes experiments comparison

Numerical simulation was carried out for gas flow 10 m/s and tubes 4, 6 and 8 mm in diameter. Similarly to the experiment, in the numerical simulation, the coordinates and components of the particle velocity were tracked. Additionally, average particle concentration calculated. Model coefficients varied for to achieve better comparison with experimental results.

For copper tubes, a good agreement with the experimental data on the scattering angle of the particles was obtained with coefficients of velocity restitution about 90%. Coefficients for steel tubes lie in the range from 95% to 99%.
4.2. Coaxial nozzle simulation

At this stage, triple coaxial nozzle is investigated. Velocity field was calculated with the following flow rates for each gas type: shielding and transport – 10 l/min, shaping - 30 l/min. With such parameters strong gas flow from outer ring to center is forming (figure 4).

![Figure 4. Gas velocity field.](image)

Using this flow field, particle movement calculation was made with different particle-wall interaction laws.

For first case mirror reflection model was used. A large dispersion of particles in space was observed despite the presence of a gas flow directed toward the center (figure 5).

![Figure 5. Average particle concentration for mirror reflection (Kn = 1, Kt = 1) in logarithmic scale.](image)

Case with experimentally obtained coefficients gives better jet focusing (figure 6). This confirms the assumption that the shape of the powder jet under conditions typical for laser cladding, is primarily determined by process inside nozzle than gas influence on particles in free space.
5. Conclusion

Optical diagnostics of gas-powder flows forming by long steel and copper tubes with diameters 2-8 mm was carried out with gas velocities of 5-40 m/s in typical laser-cladding conditions. According to results, particle velocity changes insignificantly after leaving tube. It means powder spot size depends on processes inside tube or nozzle due to particle-wall interaction. A model of particles collision with a wall, based on restitution coefficients of the tangent and normal velocity, is proposed and coefficients are selected by comparing numerical simulations with experimental results. Using the model and coefficients, the spatial distribution of the powder in coaxial nozzle jet is studied numerically. Simulation showed that, as in the case of tubes, the influence of the gas flow on the particle trajectory after leaving the nozzle is negligible. The use of steel nozzle walls as material with coefficients close to 100% leads to a significant expansion of the jet. Copper wall provides better focusing.

Acknowledgments

This work was partially supported by Russian Foundation for Basic Research (Project No. 18-08-00449)

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