Numerical and experimental investigation of two phase flow for direct metal deposition

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Abstract. In this work, one of the main scientific and technological problem of laser cladding technology, increasing the powder usage coefficient are studied. Two-phase gas-powder flow are investigated. Physical and mathematical models of powder transportation process are discussed. The structure of gas-powder flows formed by the laser-cladding nozzle and the accuracy of focusing the jet of powder being researched. The main attention is focused on interaction between powder particles and nozzle wall. Presented data collected by gas-powder jet optic diagnostic, results of numerical simulation and their comparison.

1. Introduction
Laser cladding is an effective method of production of various coatings including functional-gradient, multi-layer ones, plus it is a flexible way to produce the machine elements with complex 3D geometry.

At the same time there are several unsolved problems in laser cladding technology such as difficulty to achieve high powder catchment efficiency, which negatively affects the cost of application because powder for direct metal deposition is not a cheap material. Other important problems are increasing spatial resolution of material deposition and reducing the roughness of the cladded bead, protecting the optical elements of the laser nozzle head from the damage of hot powder particles.

The structure of gas-powder flows formed by the laser-cladding nozzle and the accuracy of focusing the jet of powder into the region of the melt created by the laser beam is of decisive importance of the tasks mentioned above.

Despite the greater number of works on laser cladding, the problem of forming a jet of powder has been poorly understood. Most of the work about laser cladding is devoted to processes of object forming or to studying the structure and properties of the deposited layer.

The classical works in which the particle flux is considered, for example [1, 2], the law of interaction of particles with the nozzle walls is not given any attention. Although, as was shown in the work [3], this law fundamentally determines the shape of the powder jet.

Pan H. et al proposed the model for collision of highly non-spherical powder particles with the nozzle walls [4] in the laser aided deposition process. Unfortunately, the model is quite complex. Its application is very resource intensive for engineering calculations and requires values of the rotation
speed of particles, which is almost impossible to measure for particles with good sphericity. At the same time, the characteristics of the surface of the nozzle walls are not included in the model.

There is a huge group of papers that is not directly related to laser additive technologies, but concerns the general models for interaction two-phase flows and walls, for example [5]. Usually, these works consider the particle velocities much higher than for laser cladding. The problem of applying these models is the same – you need to know the angular velocity, and the surface parameters are not included in the model.

Some works used the visualization of the particle flow for model revision [3, 6], but usually it is only qualitative analyze, for example, it is comparison photo of the jet and computational visualization of powder tracks.

In this work, we have tried to build a relatively simple model to simulate the powder flow, with a focus on the building of particle–wall collision model. To fit the coefficients and checkup the model, we used a large amount of experimental data such as statistical distributions of particles in space and their velocities.

2. Task models

Despite the fact that gas flows containing microparticles have been studied for a long time, the area of object application area is so wide that there are different physical models for each specific field.

For laser cladding, usually velocities of particles and gas do not exceed 30 m/s. The dimensions of the channels are about several millimeters. Therefore, in the nozzle the particles experience multiple collisions with the walls.

So far, shape of the powder jet depends on the powder material density, size distribution and sphericity. However, the most important factors is the material of the nozzle wall and the quality of its processing. It determines the law of interaction of particles and a nozzle.

The size of the particles is usually used for laser cladding in the range of 30 to 100 μm. The finer powder disperses along with the gas flow, and the larger powder makes noticeable oscillations in the cladding process. It is more convenient to use particles with high sphericity. They have behavior that is more predictable in flow and during heating.

Therefore, powder we used in our work is a nickel-chromium alloy with good sphericity and 20-60 μm particle size and copper and steel tubes with 3-8 mm diameter for powder supply. Range of gas velocity was 5-40 m/s.

For industry, the most important characteristic of powder jet is the size of the spot on the substrate. So it will be the main object we observe that directly affects the utilization rate of powder. Moreover, change in the angle of scattering of particles, even by a couple of degrees, can lead to a change in the area of the powder spot several times.

The force acting on the particle in the gas stream can be divided into the following terms: the drag force, the Magnus force, the Saffman force, the effect of the attached mass. As our investigations have shown, for the conditions of laser cladding the last three terms have a small effect and can be neglected.

Thus, we can neglect the phenomena the rotation of particles in a gas. This is convenient, because it is very difficult to determine the characteristics of spherical microparticle rotation experimentally. However, the rotation of particles is an important during particle-nozzle interaction, for example, in the works of Sommerfeld and Tsirkunov.

In our work, we tried to avoid the need to monitor the angular velocity of particles by introducing simpler models for the interaction of particles and nozzle walls. Here we used the model with restitution coefficients of the tangent and normal velocity.
Figure 1 illustrated mechanism of the model. The components of the particle velocity after collision with the wall obtained from the original by multiplying on some coefficients. These coefficients are strongly empirical ones based on statistical experimental data. Always they strongly connected to definite nozzle material and powder. However, looking ahead, sometime this model may not represent a real situation of a single collision.

At first glance, we cannot neglect the force exerted by the particles on the gas. In our work, we came to an interesting observation. In spite of that the gas transmits a significant momentum to the particles of the powder, in the process of laser cladding the gas rate is kept constant, not its pressure. So adding particles to the gas stream, we change the distribution of the gas pressure inside the nozzle, but not its velocity. The pressure distribution has very little effect on the particle compared to the drag force. Thus, in most cases, the effect of particles on the gas force can be neglected.

It is generally accepted that the interaction of particles with each other should be considered at a volume fraction of more than 0.01. In most cases, this concentration of particles was not achieved in our work. But it is very important to take into account the collision in the area of focusing the powder with a coaxial nozzle.

Software development for numerical modeling was performed on the basis of the OpenFOAM open source software package. The built-in functions of the interaction of particles with the walls and with each other (which were very resource intensive, and most importantly gave a result that did not coincide with the experiments) were replaced by our own. At a preliminary stage it was shown that the influence of particles on gas flows in most problems can be neglected. Therefore, in the beginning, the gas flow pattern was calculated by solving the Navier-Stokes equations with the SST-model of turbulence. On the obtained distribution of gas velocities, the particle trajectories were calculated in the Lagrangian approach.

3. Experimental setup
An experimental study of the characteristics of powder jet was carried out using an original optical system based on a digital camera and a positioning system. The diagnostic system was equipped with a pulse LED illumination module, which synchronized with the exposure period of the camera (pulse duration 10-500 μs). The use of illumination made it possible to increase the resolution to 15 μm / pixel. About 3000 frames with tracks of moving particles were recorded in each experiment. Software image processing allows identifying individual particle tracks (up to 50 tracks per separate frame) on each frame, their coordinates and speed.
The powder PR-HX16CP3 with particle size 20-63 μm of the system (Ni (base) -16Cr-3.2Si-2.7B) was used in all experiments. Particle size distribution additionally investigated. Volume fraction distribution of the powder particles diameter obtained using a Particle Sizing Analizer LS-13-320 (Beckman Coulter). Results presented in Figure 2.

Most of experiments was carried out to the study of the behavior of gas-powder jets that flow from single tubes. The tubes were made of copper (inner diameter 3–8 mm) and steel (inner diameter 2–8 mm). All the tubes had a length of 100 mm. For each diameter, a series of experiments was performed with different values of the average mass velocity of the gas: 5–40 m/s. Roughness of the inner surface of the tubes was different. Roughness parameters Ra were 0.38 - 0.83 μm and Rz were 2.5 - 4.1 μm for copper tubes. For steel pipes Ra range was 0.79 - 2.7 μm, and Rz range 6.6 - 12.8 μm.

In total, more than 100 separate experiments were conducted. A huge amount of accumulated statistical data makes it possible to obtain many characteristics of a powder jet. There is only small part of them were presented in this work. Figure 3 shows how the jet width (a) and velocity of particles (b) depend on the distance from the nozzle exit for 6mm steel tube (a) and 4 mm copper tube (b, c). It can be seen that the jet has almost conical shape and nearly does 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.

**Figure 2.** The powder particle size distribution obtained by the LS-13-320 Particle Sizing Analyzer (Beckman Coulter).
Therefore, the average angle of inclination of the particle velocities after the nozzle mainly determines the shape of the powder jet.

According to experimental data full angle of scatter for copper tube lay in range of 10-11 degrees. At the same time for steel tubes it reaches values of 30-35 degrees.

4. Numerical investigation
Numerical simulation was carried out for gas flow 10 m / s and tubes 4, 6 and 8 mm in diameter. Particle sizes in the numerical calculation based on the previously obtained distribution. Similarly to the experiment in numerical simulation traced particles coordinates and velocity components. Additionally, average particle volume density calculated. In the process, the coefficients of restitutions for the particle velocity after interaction with nozzle changed.

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%.

Figure 3. Jet width vs distance from nozzle exit for 6x100 mm steel tube,. Gas speed varies from-5 to 40 m/s.
Table 1 presents the simulation results for various restitution coefficients and their comparison with the diameter of the powder jet at a distance of 20 mm from the nozzle exit. It can be seen that tangential velocity recover almost do not influence on angle of jet divergence. The most suitable coefficients for steel tubes lie in the range from 0.95 to 1.

Figure 4. Calculated average volume fraction field. (a) Coefficients range 0.9-0.95 and jet scatter angle for copper tube. (b) Coefficients range 0.95-1 and experimental jet scatter compare to steel tube.

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**Table 1.** Computational jet parameters and their comparison with experimental for steel tubes

| d (mm) | Kn,% | Kt,% | Jet angle (deg) | Comp. Diam. Z=20 (mm) | Exper. Diam. Z=20 (mm) |
|--------|------|------|----------------|-----------------------|------------------------|
| 100    | 100  |      | 35,16          | 15,94                 |                        |
| 4      | 100  | 95   | 35,16          | 15,84                 | ~14                    |
| 95     | 100  |      | 22,79          | 10,42                 |                        |
| 95     | 95   |      | 22,79          | 10,42                 |                        |
| 100    | 100  |      | 35,92          | 16,84                 |                        |
| 6      | 100  | 95   | 35,92          | 16,84                 | ~16                    |
| 95     | 100  |      | 26,58          | 13,02                 |                        |
| 95     | 95   |      | 26,58          | 13,02                 |                        |
| 100    | 100  |      | 55,32          | 21,54                 | ~17                    |
| 8      | 100  | 95   | 55,32          | 21,54                 |                        |
| 95     | 100  |      | 25,65          | 14,82                 |                        |
| 95     | 95   |      | 25,65          | 14,82                 |                        |

Additionally, the interaction of two gas-powder jets investigated. The jets formed by two tubes and the angle between them was 40-45 degrees.

Figure 5 shows that movement of the powder particles after leaving the tubes are not attracted to streamlines. This confirms the assumption that the shape of the powder jet under conditions typical for laser cladding, is primarily determined by the velocity and angle of inclination of the particle at the outlet to the free space.

![Figure 5](image-url)
5. Conclusions

Optical diagnostics of gas-powder flows from copper and steel tubes with diameters from 4 to 8 mm was carried out with gas velocities of 5-40 m/s in typical laser-cladding conditions.

It is shown experimentally that after the leaving the tube, the particle velocity change insignificantly. Hence, the size of the powder spot on the substrate mainly depends on the processes inside the tube (or nozzle) and, accordingly, the law of particle–wall interaction.

Model with coefficients of velocity restitution was used for numerical simulation. Coefficient 0.9 for copper tubes and between 0.95 and 1 for steel tubes gave a good agreement with experimental data.

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