Diagnostic system «Yuna» for disperse phase properties control in plasma and laser powder deposition processes

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Abstract. The possibilities of using the optical diagnostic complex «Yuna» for studying the characteristics of a disperse phase gas-powder jets under conditions of thermal spraying, laser cladding, as well as modeling physical experiments with cold gas-powder jets are presented. The optical system allows measurements of particles larger than 10 μm, the measureable velocities range is 1-1000 m/s, measureable temperature range is 1500-5000 K, and the field of view size can vary from 1 to 20 cm. The particle velocity measurements are performed using the Particle Track Velocimetry (PTV) method, and temperature measurements - using the Spectral-Brightness Pyrometry (SBP) method. For diagnostics of gas-powder flows with cold particles, a pulsed LED illumination system is used. Various examples of the application of the diagnostic system for investigation of hot and cold gas-powder flows are presented.

1. Introduction

One of the most intensively developing fields of modern industry is additive manufacturing, in which products and details of complex shape are grown by layer-by-layer sintering (fusion) of powder materials. Traditionally, such methods include Direct Metal Deposition (DMD) [1], in which the coating is formed in the interaction of laser radiation and gas-powder flows with a substrate. Increasing the technological characteristics of laser installations (spatial resolution, the shape of the deposition roller, powder deposition efficiency) requires the formulation of both numerical simulation [2] and physical experiments [3] to study the geometric characteristics of flows, dynamic and temperature parameters of particles in the dispersed phase. In addition, modern automated plasma deposition plants [4] allow the concept of additive manufacturing of parts to be realized using the highest-temperature materials, for example oxide ceramics Al₂O₃, ZrO₂, etc.

The purpose of this work is to demonstrate the capabilities of the Yuna optical diagnostic system for investigating the characteristics of the dispersed phase of gas-powder plasma spraying, laser surfacing, and simple model experiments with cold jets.

2. Optical diagnostic system «Yuna»

The optical system for diagnostics of two-phase flows «Yuna» is a joint development of the Institute of Theoretical and Applied Mechanics SB RAS and Ugra State University [5, 6]. Initially, the system was oriented to measuring the velocity and temperature distributions of «hot particles» (from 1500 K and above) of two-phase high-velocity and high-temperature jets in thermal spraying (APS, HVOF,
TWAS, flame spray etc.) [7-10]. Recently, the diagnostic system has been adapted to work in laser cladding DMD field, as well as cold gas-powder jets, in which there is no intrinsic thermal radiation of the particles.

When diagnosing «hot» gas-powder flows, thermal radiation from the particles of the dispersed phase is registered. The hardware part of the complex combines brightness (digital video camera) and a spectral (photospectrometer) data recording channels (figure 1a). Particle Track Velocimetry (PTV) is used to measure particles velocity and coordinates using the results of image processing of a digital images array, and the particle temperature is based on a new Spectral-Brightness Pyrometry (SBP) method [11] using data from both measurement channels. The range of measureable values of the particle velocity is 1-1000 m/s, and that of particles temperature is 1500-5000 K. Usually the field of view of the video camera is 1-10 cm in size, to cover a full zone of interest the gas powder jet is scanned using an automated system for moving optical equipment.

![Figure 1](image.png)

**Figure 1.** Schematic drawing and appearance of diagnostic system operation in experiments with heated radiating particles (plasma spraying, laser deposition) (a) and cold particles illuminated with external flash (gas-powder jets interacting with obstacles) (b).

To adapt the diagnostic system to the conditions of «cold» flows, a channel of pulsed LED backlighting (figure 1b) was developed. The flash driver allows to generate a 10-1000 μs pulse of an LED array, synchronized with the exposure period of video camera, as well as changing the power supply voltage for adjusting the brightness of the flash.

After software processing of the recorded frames and spectra, a database of recognized particles is created, each of which contains the values of two-dimensional coordinates, the magnitude and direction of velocity, temperature, and image of the particle track. During the diagnostics process of 1-5 minutes, a database of 10-50 thousand particles is formed, on the basis of which the statistical characteristics of the particle parameters are restored.

3. **Experimental results and discussion**

Below are some examples of the application of the diagnostic system «Yuna» for the investigation of gas-powder flows in various conditions.
3.1. Plasma spraying flows diagnostics

The particles of depositing material in thermal spraying usually have a size of 20-100 μm, the average velocity, depending on the deposition method, is 100-800 m/s, and the average temperature is 1800-3500 K.

Figure 2a shows the operation of the diagnostic system in the plasma spraying facility equipped with an industrial spray chamber. The optical unit is placed on a portable tripod and installed at a distance of 30-120 cm from the spraying jet. Figure 2b shows a single registered video frame with images of the tracks of the sprayed particles (about 100 tracks), and figure 2c shows a visual reconstruction of a section of the spraying jet on which all tracks of particles detected in a series of frames (about 10 000 tracks) are placed.

![Figure 2. Optical system «Yuna» operation at industrial plasma spraying facility (a). Single frame captured by diagnostic system with images of particle tracks (b). Reconstructed image of spraying jet integrating all the tracks identified during diagnostics.](image)

![Figure 3. Statistical distribution of particles radial coordinate, velocity and temperature at spraying distance 200 mm (upper row). Dependence of spraying jet diameter, mean particles velocity and temperature along the spraying jet length for 4 different technological regimes: arc current 150 and 200 A; plasma gas flow 1.5 and 2.0 g/s.](image)
When developing technological processes for plasma spraying of coatings, the most important information provided by the diagnostic system is data on the average values and dispersion (or span) of the velocity and temperature of the particles at the spray distance, the size of the spray spot, and also the variation of these parameters along the length of the spraying jet.

Figure 3 shows examples of the results obtained in the study of plasma spraying flows. Spraying of a coarse (250-350 μm) metal powder at the distance 150-250 mm from a plasma torch was investigated. The upper row shows the statistical distribution of the radial coordinates of the identified particles, their velocities and temperature for an individual spraying regime. According to the data presented, it can be seen that the spray spot diameter (includes 90% of the particles) is 22.4 mm, the average particle velocity is 118 m/s (deviation 28 m/s), and the average particle temperature is 1953 K (deviation 93 K). The lower row of figure 3 shows the dependence of the particle parameters on the distance from the plasma torch for four different spraying regimes. The results of diagnostics make it possible to determine explicitly the influence of the spraying regime parameters on the characteristics of particles and to make an informed choice of the technological regime for obtaining coatings with specified properties.

3.2. DMD powder jet diagnostics

For gas-powder flows formed in laser cladding, typical values of the average particle velocity lie in the range 1-20 m/s. The ratio of the maximum and minimum values of the particle velocity can reach values of ~20÷50. For comparison, in plasma spraying this ratio rarely exceeds 2÷5. The same applies to the temperature of the material: the maximum temperatures of the particles heated by laser radiation reach 2500÷3500 K, but there always are cold particles in the flow that have escaped heating. For example, figure 4 clearly shows that the total particle flow from the coaxial nozzle (figure 4b, external illumination) differs significantly from the flow of «hot» particles heated by the laser (figure 4c).

Figure 4. Image of coaxial laser head during operation (a). Single frame of powder jet captured by diagnostic system: cold particles – without laser radiation and with external illumination (b); heated particles – with laser radiation.

Figure 5 shows the statistical distributions of the particle characteristics in the laser cladding two-phase flow at a distance of 30 mm from the nozzle. Attention is drawn to the wide distribution of
particles velocities (figure 5b): from 1 to 30 m/s. The distribution of the particles temperature (figure 5c) in this case does not refer to the total powder flow («cold» and «hot» having geometry of figure 4b), but only to the «hot» particles effectively heated by laser radiation (figure 4c).

Figure 6. Analysis of powder jets produced by a single 4mm ID tube: reconstructed image of the powder jet (a); mean particle velocity dependence on distance from tube exit for 6 different gas velocities 5-40 m/s (b); particles velocity distribution (c) at 15 mm from tube exit; dependence of particle velocity magnitude on velocity direction (d).

Figure 7. Analysis of powder jets interacting with other jet (a-c) and with flat obstacle surface (d-f): reconstructed image of powder jets (a, d); comparison of primary/secondary powder jets velocity direction distributions (b, e); comparison of primary/secondary powder jets velocity magnitude distributions (c, f).
3.3. Cold powder jet diagnostics

The diagnostics of cold gas-powder flows is a source of reliable experimental data for studying the fundamental processes of interaction of a dispersed phase with a gas stream and a barrier, and also for verification of various CFD models.

Figure 6 shows the results of a study of the velocity characteristics of gas-powder jets formed by a round tube with an internal diameter of 4 mm when the gas velocity varies from 5 to 40 m/s. The presented results make it possible to clearly define the particle acceleration zone 0-15 mm from the outlet of the tube (figure 6b), the particle velocity distribution (figure 6c) and the dependence of the (average) particle velocity on its direction (figure 6d).

A similar approach can be used to investigate the interaction of several gas-powder jets with each other (figures 7a-c) or with the surface of a solid barrier (figures 7d-f). Special processing algorithms allow to select in a general database the groups of particles related to different flows: different tubes, colliding and reflected from the surface of the stream, etc.

In figures 7 b-c it can be seen that for approximately the same particle velocity distributions, the angular distribution of one of the tubes is much wider. Figure 7f shows that the average velocity of the powder particles reflected from a plane copper barrier is about half the initial velocity of the particles.

4. Conclusion

The optical diagnostics used to study the characteristics of the dispersed phase of hot and cold gas-powder flows allows obtaining reliable experimental data necessary for the development of technological processes, the verification of numerical models, and the study of basic physical phenomena. The diagnostic complex «Yuna», based on the PTV and SBP methods, provides measurements of the velocity, temperature and coordinates of the particles of the disperse phase in technological and scientific investigations.

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