On plasma thermal spraying by the torch with divergent output nozzle

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Abstract. The analysis of the current state of the technological process and equipment for plasma coating of various powder materials has been carried out. To increase the processing efficiency during the deposition of ceramic materials and refractory alloys a novel technological scheme of plasma spraying with a powder feed axially to the cathode was proposed and preliminarily tested. Basing the plasma torch with an expanding channel of the output electrode its plasma-spraying version has been developed in which the sprayed powder was supplied both to the cathode or anode arc striking zone and to the current-free plasma jet. The electrophysical parameters of the argon plasma torch and the speed, size and temperature of particles of sprayed powder were investigated. It was shown that the particle velocity of Al₂O₃ powder depending on the gas flow and arc current reaches up to 100 m/s. The temperature of the powder particles in the vicinity of substrate at a current of 300 A approximately equals to 2400–2500 K.

1. Introduction

Over the past forty years, the processes of heating particles in thermal plasma have proven their technological advantage in a wide range of applications [1–4]. The high energy (10⁶–10⁷ J/m³) and heat (10⁷–10⁹ W/m²) flux densities make it possible to use particles with various thermophysical properties as a sprayed material and to ensure high efficiency of the deposition process.

Among the various spraying technologies, the group of methods related to the methods of gas thermal spraying (GTS), such as electric arc metallization, gas-flame, detonation and plasma spraying, has unmatched advantages. They have been used for several decades for spraying widely known materials at various substrates. To obtain gas-thermal coatings (GTC) with desired properties, plasma torches with high stability of operating characteristics are required.

Among known GTS installations, heterogeneous plasma flows are created by introducing powdered materials at a section of the plasma torch anode. In this case plasma-sprayed particles, such as ceramic or refractory materials and alloys, do not have enough time to reach the melting temperature and high speed. Therefore, powder feeding system arranged axially to the cathode allows enhancing particle heating efficiency over the entire adjustment range of arc parameters. At the same time, a significant quality improvement of coatings is also expected due to an increase of powder residence time in the plasma jet. It is important to emphasize that increasing
the speed and temperature of particles is considered a common strategy in the development of new plasma spraying units.

Plasma spraying consists of several successive stages, including plasma stream generation, heat and momentum transfer between the jet and the dispersed phase, the heterogeneous flow stagnation at the substrate, liquid particles spreading, their cooling and solidification, diffusion of the particle material into the substrate.

Numerous papers have treated various aspects of the theory and mathematical modeling of plasma-sprayed coatings [1, 5–11], in which different approaches and models for calculating the thermal and gas-dynamic characteristics of plasma jets, the processes of their interaction with the sprayed material and the sample surface, as well as processes of coating formation were discussed.

The current-free basic plasma jet is generated using non-transferred arc plasma torches, in which the electric arc usually burns inside the forming channel blown by a turbulent gas stream. In this case the flow can be separated into different sections. In the first one, the plasma-forming gas is heated and accelerated by an electric arc (electric arc section), whereas in the second one the inertial plasma motion (inertial section) takes place. Thermal and gas-dynamic characteristics of the plasma jet generated by such plasma torches are largely determined by the processes occurring in the arc section of the flow, which, in turn, depend on the design and plasma generator operation mode (channel profile and size, arc current, composition and flow rate of the plasma-forming gas).

The aim of this work is an experimental study of the heating efficiency of dielectric and metal particles with characteristic sizes of 10–100 µm in high-speed plasma jets and its comparison with model calculations. A wide parameter range in plasma jets, the possibility of using various working gases allow to combine phase and chemical transformations in a single technological process to obtain the desired characteristics of sprayed powders and coatings. Using a plasma torch enables to get a wider range of temperatures and speeds than other methods of particle spraying, such as flame and detonation spraying.

2. Experimental setup

The study was conducted using arc plasma spraying facility, described in detail in the previous paper [12]. A vortex-stabilized arc with divergent anode was used. Such a plasma torch provides high flow characteristics, the heating efficiency of the working medium and the small heat losses to the water-cooled surface of the anode [13]. There are several ways to supply particles into the plasma torch through the holes at the first or at the second sections of the anode or at various locations in the cathode.

The main method for feeding particles of the sprayed material was their injection into the plasma jet through holes coaxially to the plasma torch near the cathode tip, which allows the use of the cathode region (with the maximum plasma temperature) for heating refractory particles. The image of the cathode used is shown in figure 1.

This design provides a more uniform field of velocities and temperatures of the sprayed particles compared to other feeding methods. To spray particles with a lower melting point and to prevent particles from sticking to the walls of the plasma torch channel, feeding holes are also provided in the anode zone.

As a diagnostic tool, this facility uses high-speed and high-sensitive charge-coupled device (CCD) cameras operating in the visible and infrared ranges, a pulsed-periodic laser for illuminating particles according to the laser knife scheme, and a spectrometer used to determine plasma parameters, both with and without particles.

The particle velocity and temperature were measured by 4 high-speed cameras in different zones of the plasma injector. A measuring system based on an infra-red matrix allows to determine simultaneously such particle parameters as speed, size, and temperature [14]. In the
Figure 1. Photo of the cathode with four off-axis holes (a), and the cathode during operation of the plasma torch (b), obtained using high-speed imaging. White circle on (b) marks the position of the off-axis hole. Exposure time is 10 µs.

Table 1. Experimental setup characteristics.

| Setup parameter                                      | Value                |
|------------------------------------------------------|----------------------|
| The pressure in the vacuum chamber, 10³ Pa           | 50–100               |
| Plasma gas mixture (with variable weight coefficient $\alpha$) | $\alpha$Ar + (1 − $\alpha$)N₂ |
| Mass flow rate of plasma-forming gas $G_g$, g/s      | 1.5–5                |
| Mass flow rate of the transporting gas $G_{tr}$, g/s  | 0.05–0.25            |
| Powder mass flow rate $G_p$, g/s                     | 0.05–0.20            |
| Arc current $I_d$, A                                 | 200–450              |
| Arc voltage $U_d$, V                                 | 30–120               |
| The diameter of the expanding anode channel, mm      | from 4 to 12          |
| Nozzle diameter, mm                                  | from 12 to 20         |

measurement scheme, the field of view is $35 \times 25 \text{ mm}^2$ in size (width $\times$ height), therefore, for the given exposure times of the camera, one can determine the maximum speed as $V_{\text{max}} = h/\tau$, where $h$ to be the height of the frame, $\tau$ to be the exposure time.

The minimum temperature that can be determined using an automated algorithm depends on the exposure time of the camera (the shorter the exposure time, the higher the temperature should be) and on the geometric parameters of a particular measurement circuit. To determine the temperature using this system, it was calibrated via reference black body in the temperature range from 800 to 3000 K.

Particles flying through the plasma form light tracks, the length of which is proportional to the exposure time. The particle size can vary over a wide range of 10–150 µm, so the transverse size of small particles is extremely critical for the analysis. The size of these particles must be recorded with an error of 2–5 µm. The used CCD camera has the resolution of 1400 × 1040 pixels. Thus, the physical resolution of the system is about 20–25 µm per pixel. To ensure a measurement error of 2–3 µm, it is necessary to have a resolution of about 0.1–0.2 pixels. Such a subpixel resolution can be obtained by using a special mathematical apparatus for processing the gray source image and a special procedure for calibrating geometric distortions introduced by the optical elements of the camera.
The ir camera uses a special CCD array, which provides higher sensitivity in the infrared spectral region than conventional matrices designed for the visible range. Such a matrix in the infrared region of the spectrum at 800–1000 nm has a sensitivity of 2–3 times higher.

To calculate the main parameters of flying particle (brightness temperature, diameter and speed), a special software package has been developed. It allows to recognize appropriate particles automatically in the real time and to determine their size with subpixel accuracy. Images of proper particles are to meet certain criteria, in particular:

- the particle is in the focal plane of the lens;
- the particle does not fall on the border of the image;
- particle image does not intersect with another image.

The processing includes three main stages: source image filtering, the isolation of particle traces, individual particles handling.

The frame sequence recorded at a frequency of up to 20 kHz and an exposure of up to 2 µs using high-speed cameras VS-Fast and Motion Pro allows to construct the fields of longitudinal and transverse velocities and particle accelerations as they move to the target. An algorithm has been developed for the automated processing of such series of images using a tray with several frames to determine particle trajectory, its coordinate and velocity change over time. This algorithm also allows determining the average luminous intensity of the track. Intensity calibration shows particles temperature variation in the domain under study. Automated processing of frame series displays the velocity and acceleration fields of particles experiencing drag as the plasma flow approaches an extended target.

3. Experimental results
A series of frames containing tracks of powder particles sprayed onto the sample were obtained using various systems for high-speed detection. Varying exposure time of images in the range of 10–100 µs one can study the particle velocity field attributing the length of the track to the exposure time. The main problem is the automated determination of the length of all tracks in the image for experimental series consisting of more than 1000 frames. To solve this problem, a program was developed in the MATLAB environment for recognizing tracks of flying particles on frames obtained.

The average temperature and particle velocity were measured together using a calibrated ir camera. Figure 2 shows a graph of the average temperature of the particles of aluminum oxide and molybdenum over time.

Figure 3 shows the dependencies of the temperature and velocity of alumina particles on the flow rate and arc current. Each point on the graph was obtained by averaging the speed or temperature over 300–500 frames.

Figure 4 shows the radial velocity distributions of the particles of titanium and molybdenum, obtained by dividing the observed region into vertical sections 2 and 4 mm wide, respectively.

Fractographic studies of Al₂O₃ powder were carried out using JEOL JSM-6610 LV scanning microscope with magnification up to 300 000 times equipped with the JNCA Energy Feature XT energy dispersive microanalysis system manufactured by Oxford Instruments. Studies were carried out at magnifications of 100–25 000 times. The results of the study found that the alumina powder consists of particles with irregular-shaped faces. The particle size is in the range of 33–110 µm with the average value of about 70 µm. No particles stick together (figure 5).
Figure 2. Time-varying surface temperature of molybdenum and alumina particles. Arc current 300 A, argon consumption 3 g/s. Error is within 10%.

Figure 3. Dependence of temperature (a) and particle velocity (b) of aluminum oxide $\text{Al}_2\text{O}_3$ on arc current and plasma-forming gas flow. Temperature error is within 10%; velocity error—within 5%.

4. Calculation of the movement and heating of particles, comparison with experiment

4.1. **Modeling the motion, heating and evaporation of spherical particles in a plasma jet**

Let us perform the calculation for particles moving in the axial region of the plasma jet using the results of [15]. The concentration of heterogeneous particles in a plasma jet is usually small, so the particles do not interact with each other, and their influence on the plasma parameters is not very significant. On the other hand, the optical thickness of the jet is small, and the thermal radiation can be estimated from the thermal balance of one particle. The equations for particles moving along the axis of the jet are as follows [15]:

$$\frac{du_p}{dt} = \frac{3C_d \rho_p}{8r_p \rho_p} \left( u_g - u_p \right) |u_g - u_p|,$$

(1)
Figure 4. An example of the radial velocity distribution near the target of 40 \( \mu \)m Ti particles (a) and 10 \( \mu \)m molybdenum particles (b).

Figure 5. Alumina powder at \( \times 100 \) (a) and \( \times 500 \) (b) magnification. The average particle size is about 70 \( \mu \)m.

where \( u_p \) to be particle speed, \( C_d \) to be drag coefficient, \( r_p \) to be radius, \( \rho_g \) to be plasma density, \( \rho_p \) to be particle material density, \( u_g \) to be plasma speed. The initial condition for this equation:

\[
u_p(0) = u_{p0}, \quad (2)
\]

where \( u_{p0} = 0.9u_g(0) = 60 \) m/s. The drag coefficient \( C_d \) and the Nusselt number are calculated using the following relationships [15]:

\[
C_d = \frac{24}{\text{Re}_p + 4.3 \varphi} + \frac{4.5 + 0.4 \psi}{1 + \psi} \exp \left( -\frac{M_p}{2 \sqrt{\text{Re}_p}} \right) + 0.6 \varphi \left[ 1 - \exp \left( \frac{M_p}{\text{Re}_p} \right) \right], \quad (3)
\]

\[
\text{Nu} = \frac{\zeta}{1 + 3.4 \zeta M_p \text{Re}_p \sqrt{Pr}} \quad \varphi = M_p \sqrt{0.5 \gamma}, \quad \psi = 0.03 \text{Re}_p + 0.5 \sqrt{\text{Re}_p}, \quad (4)
\]

\[
\zeta = 2 + 0.5 \text{Re}_p^{0.6} \sqrt{Pr}, \quad \text{Re}_p = \frac{2\rho_g |u_g - u_p| r_p}{\eta_g} \quad (5)
\]
Figure 6. Theoretical (solid lines) and experimental (dashed line) values of particle velocities. The experimental data were obtained at current 350 A, Ar flow rate 3 g/s, particles size 60 µm.

The equation of heat balance inside a particle:
\[ \rho_p c_p \frac{\partial T_p}{\partial t} = \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 k_p \frac{\partial T_p}{\partial r} \right). \]  (6)

with initial condition \( T_p(0, r) = T_{p0}(r) \) and boundary conditions:
\[ \frac{\partial T_p}{\partial r} \bigg|_{r=0} = 0, \quad k_p \frac{\partial T_p}{\partial r} \bigg|_{r=r_p} = k_g \frac{N_u}{2r_p} [T_g - T_g(y, r_0)] - U_{rad}. \]  (7)

The heat of fusion in the heat balance equation can be taken into account through an increase in specific heat in a narrow temperature range near the melting temperature. Upon reaching the boiling point, the reduction in particle radius during its evaporation is taken into account according to the formula:
\[ \frac{dr}{dt} = \frac{3q_s}{\Delta H_{vap}\rho}. \]  (8)

4.2. Plasma torch modeling

For an equilibrium plasma, the energy balance equation has the following form [16]:
\[ \text{div}(\rho v \nabla T) = \text{div}(\lambda_p^{-1} \nabla T) + c_p^{-1}(\sigma E^2 - U_{rad}). \]  (9)

The equations of motion of the plasma flow relative to the velocity components \( v_z \) and \( v_r \) in a cylindrical coordinate system can be written in a convenient form as
\[ \text{div}(\rho \mathbf{v} v_z) = \text{div}(2\mu \text{grad} v_z) - \frac{\partial P}{\partial z} + S_z, \]  (10)
\[ \text{div}(\rho \mathbf{v} v_r) = \text{div}(2\mu \text{grad} v_r) - \frac{\partial P}{\partial r} + S_r. \]  (11)

Figure 6 presents the results of calculating the axial velocities of particles of three diameters: 20, 40, and 60 µm, as well as the speed of particles with a diameter of 60 µm, determined experimentally.

Particle velocities were calculated regardless the influence of the target on the heterogeneous flow, which resulted in somewhat overestimated particle velocities near the sample. Also, the
experimental value of the velocity is underestimated by taking into account the tracks of particles located on the periphery of the plasma stream and having a lower velocity in comparison with particles located on the axis.

5. Conclusion
The average values of velocity and temperature, as well as changes in particle velocities along the axis of the jet were determined experimentally under various modes of operation of the plasma torch. These data provide the basis for choosing the optimal spraying mode in which particles collide with the surface of the substrate in the liquid phase, and the velocity and temperature fields of the particles are fairly uniform. The obtained experimental data on temperatures, velocities, and particle sizes are in good agreement with their calculated values derived from model description of motion, heating, and evaporation of particles in plasma torch channel for a given plasma temperature distribution along the jet.

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