Development of the arc plasma torch operation mathematical model for spheroidization of fine-dispersed powders

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Abstract. Brief review of the fine-dispersed powders production technologies for additive laser technologies is presented in the paper. Non-stationary mathematical model of DC plasma torch operation and stationary model of the reactor operation for powder spheroidization have been developed. Air is used as the plasma-forming gas. The influence of the transporting flow and compressing gases on the characteristics of the plasma flow is analyzed. Verification of the non-stationary mathematical model of DC plasma torch operation is based on experimental studies. Radial temperature distributions obtained from the results of numerical simulation and spectral diagnostics of the plasma torch PN-V1 are presented. The results of the experimental study describing plasma flow behavior for given parameters of the fine-dispersed powders spheroidization process are presented in the paper.

1. Introduction
There is a rapid development of additive laser technologies at the present time. The use of additive technologies has received wide application in the aerospace industry, engineering, medicine and other industries. One of the main problems in the development of this technology is the lack of quality powder materials. The methods of spherical shape powder production can be conditionally divided into two main groups:
- mechanical method;
- chemical and electrochemical method.

A block diagram of the methods classification for the powder production for additive laser technologies is shown in Fig. 1.

The most common methods of atomization are [1]:
- gas atomization;
- vacuum atomization;
- centrifugal atomization.

The resulted methods of atomization have a number of essential lacks [1]. An alternative way of obtaining powder is spheroidization in a plasma flow. Two main methods of generating a plasma flow are used in industry [2]:
- application of DC plasma torches;
- application of induction plasma torches.

The most adapted method for the powder spheroidization is the application of inductively coupled plasma, described in more detail in [3]. Despite the advantages of this spheroidization technology, there are significant drawbacks associated with the cost of manufacturing process equipment (power...
source and induction plasma torch). An alternative method of powder spheroidization for additive laser technologies is the application of DC plasma torches (see Fig. 2). The main technological task in developing the design of the "plasma torch-reactor" system and identifying the parameters of operating conditions is obtaining optimal parameters of the plasma flow. The creation of mathematical models makes it possible to significantly accelerate the process of developing structural elements of equipment and determine the parameters of the technological process, ensuring a reduction in the costs of conducting additional experimental studies.

Fig. 1. Classification of methods for obtaining metallic powders

Fig. 2. Scheme of powder spheroidization technological process in the plasma torch jet

2. Mathematical model

Non-stationary mathematical model of DC plasma torch operation is multiphysical task [4], including the equations of electromagnetism, gas dynamics and heat transfer. These equations are interrelated in explicit (the source function of Joule heating) and implicit (thermodynamic and transport properties) form [5].

The mathematical model of DC plasma torch operation contains the following main assumptions:

- plasma is in a local thermodynamic equilibrium (LTE);
- plasma is optically thin;
- two-dimensional axisymmetric;
- thermodynamic and transport properties depend on temperature;
- near-electrode processes are not taken into account.

Basic equations of mathematical model describing nonstationary processes in DC plasma torch:

- Maxwell’s system of equations:
\[
\begin{align*}
J &= \left( \sigma + \varepsilon_0 \frac{\partial}{\partial t} \right) \vec{E} \\
\vec{E} &= -\nabla V \\
\sigma \frac{\partial \vec{A}}{\partial t} + \nabla \times \vec{H} &= \vec{J} \\
\vec{B} &= \nabla \times \vec{A}
\end{align*}
\]  

(1)

- momentum equation (Navier-Stokes equation):
  \[
  \rho \frac{\partial \vec{v}}{\partial t} + \rho (\vec{v} \cdot \nabla) \vec{v} = \vec{F} + \nabla \cdot \left[ -p I + \mu \left( \nabla \vec{v} + (\nabla \vec{v})^T \right) \right]
  \]  
  \[
  \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0
  \]  
  \[
  \rho C_p \frac{\partial T}{\partial t} + \rho C_p \vec{v} \cdot \nabla T - \lambda \nabla T = Q_s - Q_{rad}
  \]  
  \[
  \frac{\partial \rho}{\partial t} = \frac{\partial \rho}{\partial t}
  \]  

(2)

(3)

(4)

Detailed description of the mathematical model and the calculation technique is presented in [5]. The existing design of the plasma torch PN-V1 was used as the geometry of the computational domain. The time dependences of the radial temperature distributions (see Fig. 3), the axial and radial velocities at the plasma torch outlet (used as boundary conditions for simulation of the plasma reactor) at plasma gas consumption of 0.5 g/s were obtained from the calculation results, which corresponds to the laminar plasma flow (according to the results of the experimental study) (see Fig. 4a).

Verification of the mathematical model is based on experimental studies (see Fig. 4). Techniques for conducting experimental studies on the plasma flow behavior and calculation of the radial temperature distribution on the basis of the results of spectral diagnostics are presented in [5]. Stationary mathematical model describing the reactor operation is developed on the basis of equations (2), (3) and (4) with allowance for \( \frac{\partial \rho}{\partial t} = 0 \).

Fig. 3. Dependences of the radial temperature distribution on time and time-averaged radial temperature distribution
Fig. 4. The results of experimental studies: a - experimental determination of the plasma flow behavior; b - radial temperature distribution based on the results of spectral analysis and numerical simulation

The results of the calculation for different values of the compressing "cold" gas consumption are shown in Fig. 5.

Fig. 5. The temperature distribution in the reactor for the transport gas consumption $G = 0.1$ g/s and "cold" gas consumption: a - $G=0.2$ g/s; b - $G=0.4$ g/s

Conclusions
Non-stationary mathematical model of DC plasma torch operation and stationary reactor operation model are developed. The results of the simulation are consistent with the results of experimental studies. The parameters ($I = 190$ A, $G_{\text{pl}} = 0.5$ g/s, $G_{\text{tr}} = 0.1$ g/s, $G_{\text{com}} = 0.2 - 0.3$ g/s) of powder spheroidization technological process are obtained based on the results of the simulation, which allows to obtain plasma flow (DC plasma torch) like plasma flow of induction plasma torch. Design elements of technological equipment are developed taking into account the results of simulation.

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