Materials and coatings fabricated using the additive manufacturing technologies
Материалы и покрытия, получаемые методами аддитивных технологий

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Trajectories of titanium powder particles of diffferent size in a plasma flow

R. A. Okulov[1, 2], **S. M. Akhmetshin**[1], **B. R. Gelchinsky**[1], **A. A. Rempel**[1]

[1] **Institute of Metallurgy of the Ural Branch of the Russian Academy of Sciences**
101 Amundsena Str., Yekaterinburg 620016, Russia
[2] **Ural Federal University named after the First President of Russia B.N. Yeltsin**
19 Mira Str., Yekaterinburg 620002, Russia

okulov.roman@gmail.com

Abstract. The study focused on analyzing the trajectories of powder particles within a plasma flow, a process utilized for applying functional coatings and producing powders. An overview of contemporary scientific research dedicated to modeling these processes is presented. The primary objective of this study was to ascertain how the particle size of the powder, used as a raw material, influences the path of particles within a vertically directed plasma flow. We examined three sizes of titanium powder: 1 μm, 50 μm and 100 μm. These sizes were chosen based on production practices for the considered processes and the particle size distribution of the powder material used in full-scale experiments, employing specialized CAMSIZER-XT equipment. Our study reveals the significant impact of powder particle size on various parameters, including the opening angle, length, and width of the illuminated section of the plasma torch, as well as the distance traveled by particles entrained by the plasma flow from the plasma head. To investigate these effects, we conducted computer simulations, followed by validation through full-scale experiments for each case. Specifically, we employed the MAK-10 laboratory plasma facility at the Institute of Metallurgy, Ural Branch, Russian Academy of Sciences, which is designed for powder production and functional coatings. In order to ensure the reliability of our measurements, we performed statistical data processing of the full-scale experiment results using scatter plots and determination of their average values. The comparative analysis of results from both natural and computer experiments demonstrated a satisfactory level of convergence. This comparative analysis of three particle sizes of powder enabled us to formulate practical recommendations for enhancing equipment and process technology in the context of the considered procedures. Furthermore, our article introduces a computer model capable of predicting the dimensions of the reactor (the chamber for receiving powder materials), the optimal shape of components within the plasma facility, and the positioning of the substrate on which functional coatings are applied. This model can be applied to address similar problems within the scope of this study, facilitating the control of coating application processes and powder production.

Keywords: gravity force, particle trajectory, plasma method, powder production, coating application

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Траектория движения частиц титанового порошка различной фракции в плазменном потоке

Р. А. Окулов[1, 2], **С. М. Ахметшин**[1], **Б. Р. Гельчинский**[1], **А. А. Ремпель**[1]

[1] **Институт металлургии Уральского отделения РАН**
Россия, 620016, г. Екатеринбург, ул. Амундсена, 101
[2] **Уральский федеральный университет имени первого Президента России Б.Н. Ельцина**
Россия, 620002, г. Екатеринбург, ул. Мира, 19

okulov.roman@gmail.com

Аннотация. Исследованы траектории движения частиц порошка в плазменном потоке, который используется для процессов нанесения функциональных покрытий и получения порошков. Выполнен обзор современных научных исследований, посвященных моделированию рассматриваемых процессов. Цель работы заключалась в определении влияния размера частиц порошка, используемого в качестве сырья, на траекторию движения частиц в плазменном потоке, направленном вертикально вверх. Исследовали три фракции титанового порошка: 1, 50 и 100 мкм, выбранные исходя из производственной практики ведения рассмотренных процессов и результатов гранулометрического состава порошкового материала, использованного в натурном эксперименте, при помощи специализированного оборудования CAMSIZER-XT. В работе продемонстрированно, каким образом размер частиц порошка влияет на угол раскрытия, длину и ширину светящейся фракции плазменного факела, а также удаленность увлеченных плазменным потоком частиц от плазменной головки. Исследование выполнено с помощью компьютерного эксперимента с последующей верификацией путем проведения натурного эксперимента для каждого из рассматриваемых случаев. При этом использовалась лабораторная плазменная установка МАК-10 (ИМЕТ УрО РАН), применяемая для получения порошков и нанесения функциональных покрытий. С целью надежного получения итогов измерений была проведена статистическая обработка результатов натурного эксперимента методом точечных диаграмм размахов и определения их средних значений. Результаты сравнительного анализа итогов натурного и компьютерного экспериментов показали удовлетворительную сходимость. Сравнительный анализ применения трех фракций порошка позволил разработать практические рекомендации по совершенствованию оборудования и технологии ведения рассматриваемых процессов. В статье описана компьютерная модель, позволяющая прогнозировать размеры реактора (камеры приема порошкового материала), рациональную форму составных частей плазменной установки и положение подложки, на которую наносится функциональное покрытие. Представленную модель можно использовать для решения задач, подобных поставленной в рамках данного исследования, с целью управления процессами нанесения покрытий и получения порошка.

Ключевые слова: сила тяжести, траектория движения частиц, плазменный метод, получение порошков, нанесение покрытий

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Introduction

Plasma sputtering presents an efficient method for acquiring functional coatings [1; 2]. By precisely managing plasma parameters and deposition conditions, it becomes feasible to achieve top-quality coatings [3]. Extensive research exists concerning the examination of how deposition process parameters impact the characteristics of the resultant functional coatings [4–6]. Additionally, plasma spraying serves as a technique for generating powders that find application in additive technologies [7–10].

The finite element method serves as a convenient and precise tool for predicting and elucidating the influence of various factors on both powder production and coating application processes. Computer simulations are in high demand, especially for the investigation of functional coatings composed of high-entropy alloys like GdTbDyHoSc and GdTbDyHoY [11]. studies related to coating deposition [12–14], software packages such as ANSYS, SolidWorks, and JmarPro were employed. For simulating the powder production processes using the plasma method, researchers utilized ANSYS [15], FLOW-3D [16] and COMSOL [17].

The trajectories of particles within a plasma flow significantly affects the characteristics of coatings and the properties of the resulting powders. Conversely, it is also influenced by the particle size of the raw powder material. Additionally, among the contributing factors, the shape of the internal channel, which is defined by the components of the plasma head and the operational features of the facility, plays a pivotal role. While there are publications that discuss the impact of factors like nozzle shape [18], operating modes [19], powder material introduction methods [20], interelectrode inserts [21] and gas swirler shapes [22], insufficient attention has been given to exploring the effect of powder particle size on particle motion trajectories within the plasma flow.

The primary objective of this study was to investigate how three particle sizes (1, 50 and 100 μm) of titanium powder, used as raw material, influence the trajectories of particles within a vertically directed plasma flow.

Experimental

A computer model of the plasma facility was developed to predict plasma flow parameters, employing the finite element method. The SolidWorks Flow Simulation software package (version 2016) served as a valuable tool for computational fluid dynamics (CFD). Subsequently, the results of the computer experiment underwent verification. In the numerical solution process, the Euler and Navier-Stokes equations were employed. In order to accurately represent surface, subsurface, and intermediate processes occurring within the flow, a finite element grid size of 0.24 mm was chosen. This grid size ensured that a minimum of 8 elements were positioned within the narrowest section of the three-dimensional computer model of the plasmatron, specifically, the plasma-forming gas inlet channel of the swirler with a diameter of 2 mm [23].

In order to carry out a computer experiment, a three-dimensional model was created based on the MAK-10 laboratory facility, which is located at the premises of IMET, Ural Branch, Russian Academy of Sciences. The design and parameters of this facility are depicted in Figure 1.

The initial data for the computer experiment are as follows:

• plasma forming gas flow rate: 20 l/min;
• gas type: argon;
• gas pressure in the supplying system: 2 atm;
• diameter of the central hole of swirlers: 24 mm;
• plasma-forming gas is supplied in a tangential pattern through 6 channels, each with a diameter of 2 mm;
• the chosen raw material is titanium powder VT1-0, selected from the library of standard materials within the software package (State Standard GOST 19807-91) with the following composition (wt. %, not exceeding): N – 0.04, C – 0.07, H – 0.01, Fe – 0.25, Ni – 0.04, Si – 0.1, O – 0.2).

The environmental conditions are set as follows:

• gas type: air;
• absolute gas pressure at the outlet of the anode unit is 98,100 Pa, equivalent to the altitude of Yekaterinburg;
• temperature corresponds to room temperature, at 293 K.

The study focused on particle motion trajectories within the plasma flow for particle sizes of 1, 50 and 100 µm. The mass flow rate for each fraction was set at 1 g/s.

An indirect-acting plasmatron was employed with the following specifications:

• voltage: 26 V;
• current: 250 A;
• spraying direction: vertically, directed upwards;
• reactor length: 2.8 m;
• diameters of respective segments: 250 and 500 mm.

Results and discussion

In Figure 2 the trajectories of 100 particles for each of the three fractions are depicted. It's important to note that the particle sizes in the figure do not correspond to scale and have been chosen arbitrarily for illustration purposes. We assumed that the temperature at which titanium powder begins to glow and produce bright sparks is above 1573 K. This determination was based on reference data regarding the colors of heated titanium (bright red – 900 °C, yellow – 1200 °C, white – 1300 °C) [24]. Through computer simulation, several key findings were obtained, including the dimensions of the torch containing the luminous powder fraction with temperatures exceeding 1573 K, as well as the maximum distance covered by powder particles within the flow.

The obtained data is presented below:

Powder particle size, µm	1	50	100
Length of luminous fraction, mm	570	500	320
Width of luminous fraction, mm	45	55	60
Distance of particles to plasmatron edge, m	2.8	1.8	1.6

As observed, there is a negative correlation between particle size and the length of the luminous fraction, as well as the distance particles are carried by the flow away from the plasma torch's end. Conversely, the width and opening angle of the plasma flow torch increase with larger particle sizes. This phenomenon can be attributed to the influence of gravity acting upon powder particles entrained by the plasma flow. Notably, smaller powder

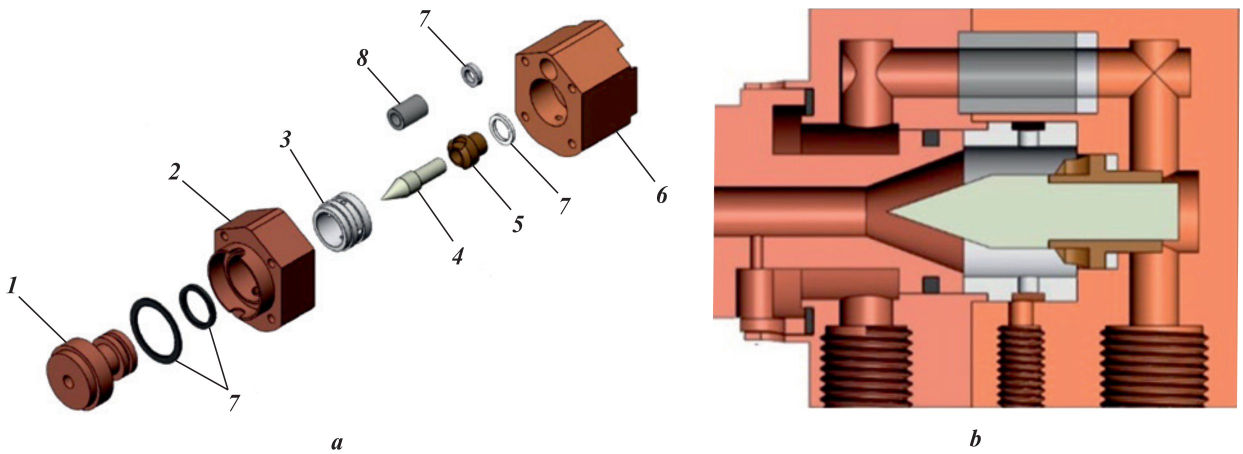

Fig. 1. The design of the plasma head of the installation in a disassembled state (*a*) and in cross section along the axis (*b*)
1 – anode, *2* – anode case, *3* – swirler, *4* – cathode, *5* – cathode sleeve, *6* – cathode case, *7* – sealing rings, *8* – sleeve

Рис. 1. Конструкция плазменной головки установки в разобранном состоянии (*а*) и в поперечном сечении вдоль оси (*b*)
1 – анод, *2* – корпус анода, *3* – завихритель, *4* – катод, *5* – втулка катода, *6* – корпус катода, *7* – уплотнительные кольца, *8* – втулка

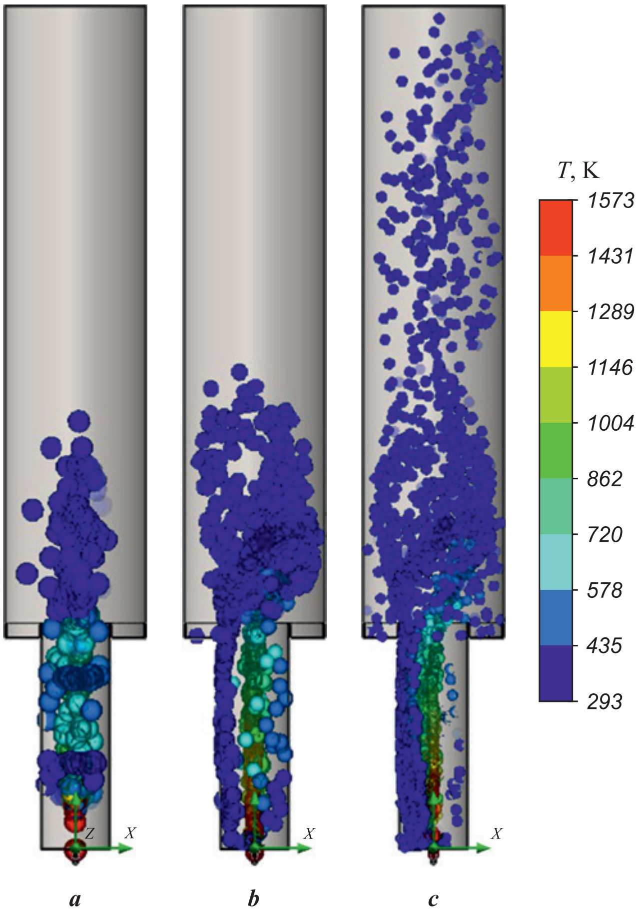

Fig. 2. Trajectories of particles with sizes of 100 (***a***), 50 (***b***), and 1 (***c***) μm

Рис. 2. Картины траекторий частиц размерами 100 (***a***), 50 (***b***) и 1 (***c***) мкм

particles tend to follow longer flight paths within the flow, resulting in greater distances from the plasma head.

In order to validate the outcomes of the computer experiment, two full-scale experiments were conducted. The first experiment aimed to compare the width and length of the torch containing luminous particles of PTM-1 titanium powder, which was sprayed using a laboratory facility (TU 14-22-57-92). In terms of chemical composition, PTM-1 corresponds closely to the titanium powder VT1-0 employed in the computer experiment (wt. %, not exceeding: N – 0.08, C – 0.05, H – 0.35, Fe + Ni – 0.4, Si – 0.1, Ca – 0.05, Cl – 0.004). The second full-scale experiment was designed to determine the temperature of the plasma flow during the plasma torch's idle mode (without powder particle spraying). This measurement aimed to assess the correspondence of this value to the one determined through the computer experiment.

Each of the full-scale experiments was conducted in five separate runs to ensure robust and reliable measurement results. In order to enhance the accuracy and credibility of the measurements, we applied statistical processing using scatter plots and the calculation of their average values [25–27].

In the first full-scale experiment, a granulometric analysis of PTM-1 titanium powder was conducted using CAMSIZER-XT (Germany). The data obtained revealed that 90 % of the powder had a size of less than 91 μm, while 50 % had a size of less than 50 μm. Furthermore, 98.1 % of the powder material exhibited a sphericity coefficient exceeding 0.9 (the ratio of the smallest particle size or diameter to the largest), and 90.9 % of the studied powder displayed sphericity coefficients exceeding 0.9. The particle size range of PTM-1 titanium powder fell within the range of 1–97 μm. Figure 3 presents a visual representation of the data from both full-scale and computer experiments.

In the first full-scale experiment, the initial conditions were as follows:

• plasma-forming gas flow rate: 20 l/min;

• gas type: argon; purity 99.993 % (complying with State Standard 10157-2016);

• gas pressure in the supplying system: 2 atm;

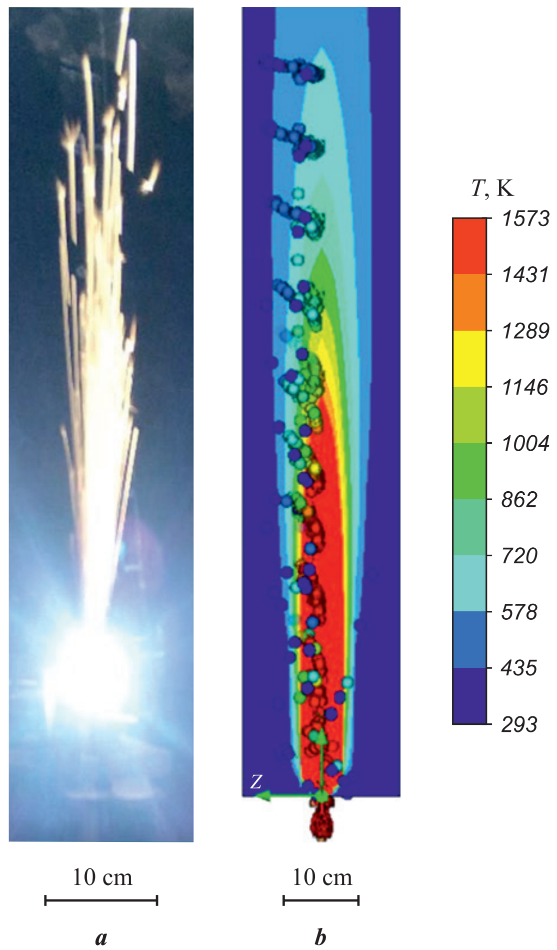

Fig. 3. Data from full-scale (***a***) and computer (***b***) experiments on the length and width of the luminous fraction

Рис. 3. Данные натурного (***a***) и компьютерного (***b***) экспериментов длины и ширины светящейся фракции

Comparison of the results of full-scale and computer experiments

Результаты сравнения натурного и компьютерного экспериментов

Material	Computer experiment, mm	Field experiment, mm	Deviation, %
Copper M1	141	135	4.4
Steel 10	82	85	3.5
Lanthanized tungsten	19	20	5.0

• diameter of the central hole of the swirlers: 24 mm;

• plasma-forming gas was introduced in a tangential pattern through 6 channels, each with a 2 mm diameter.

The environmental conditions were set as follows:

• gas type: air;

• absolute gas pressure at the outlet of the anode unit: 98,100 Pa, equivalent to the altitude of Yekaterinburg;

• temperature was maintained at room temperature – 293 K.

The study focused on analyzing the motion trajectories of particles within the plasma flow, encompassing particle sizes ranging from 1 to 97 μm. The mass flow rate for each fraction was set at 1 g/s. An indirect-acting plasmatron was employed, with the following specifications:

• voltage: 26 V;

• current: 250 A;

• spraying direction: vertical, directed upwards;

• reactor length: 2.8 m;

• diameters of respective segments: 250 and 500 mm.

During the experiment, measurements were taken for the length and width of the luminous fraction of titanium powder, which amounted to 600 mm and 65 mm, respectively. As a result, the deviation from the results of the computer experiment did not exceed 7.7 %.

In the second full-scale experiment, conducted during the idle mode of the plasmatron (without the use of powder), the temperature of the plasma flow on its axis was studied. To achieve this, a method involving the placement of rods with known melting temperatures within the plasma flow was employed. Specifically, 3 rods with a 3 mm diameter, composed of copper M1 (compliant with State Standard GOST 859-2014), steel 10 (in accordance with State Standard GOST 1050-2013) and lanthanized tungsten (as per Specifications TU 48-19-27-88) were selected. These materials were chosen for their varying melting points. The rods were fixed in a manner where one end was securely clamped, and the other end was left free to be exposed to the plasma flow. The head of the plasmatron was mounted on a manipulator, which enabled its uniform movement along the axis toward the rod at a speed of 10 mm per minute. The distance between the free end of the rod and the end plane of the anode of the plasmatron's head unit was meticulously recorded throughout the experiment. The initial distance between the free end of the rod and the plasma torch's head was assumed to be 0.5 m. When the melting process commenced on the rod's surface, the distance from the rod to the plasma torch was recorded.

In order to determine the temperature of the rod's surface at the point of melting onset, an optical pyrometer (EOP-66, Type No. 240, compliant with GOST 5.278) was employed. This pyrometer is specifically designed for accurately estimating the brightness temperatures of heated objects through their thermal radiation, covering a range from 900 to 10,000 °C. The measurement error does not exceed 5 °C.

In the second full-scale experiment, the initial conditions were as follows:

• plasma-forming gas flow rate: 20 l/min;

• gas type: argon; purity 99.993 % (complying with State Standard 10157-2016);

• gas pressure in the supplying system: 2 atm;

• diameter of the central hole of the swirlers: 24 mm;

• plasma-forming gas was introduced in a tangential pattern through 6 channels, each with a 2 mm diameter.

The environmental conditions for this experiment were as follows:

• gas type: air;

• absolute gas pressure at the outlet of the anode unit: 98,100 Pa, equivalent to the altitude of Yekaterinburg;

• temperature was maintained at room temperature – 293 K.

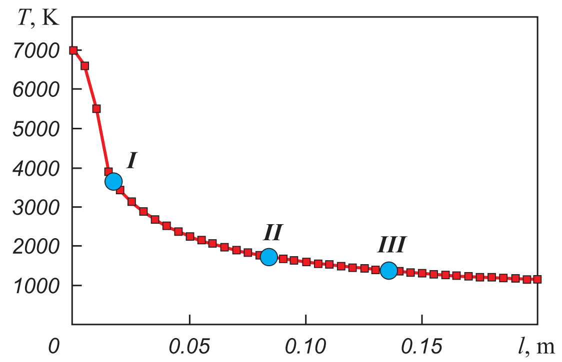

Fig. 4. Temperature distribution along the plasma flow axis (l) according to full-scale experiment
I – lanthanated tungsten, ***II*** – steel 10, ***III*** – copper M1

Рис. 4. Распределение температуры вдоль оси плазменного потока (l), по данным натурного эксперимента
I – лантанированный вольфрам, ***II*** – сталь 10, ***III*** – медь М1

For this experiment, an indirect-acting plasmatron with the following specifications: was utilized:

• voltage: 26 V;
• current: 250 A;
• spraying direction: vertical, directed upwards;
• reactor length: 2.8 m;
• diameters of respective segments: 250 and 500 mm.

The data derived from the second full-scale experiment indicated that the onset of melting for each of the rods occurred at temperatures closely aligned with the reference data for each rod material, with a slight deviation of no more than 22 K. A comprehensive account of this experiment can be found in [28] and the results are visually presented in Figure 4 and detailed in the accompanying Table.

Thus, the comparative analysis of the computer and field experiments demonstrated a satisfactory level of agreement, with the discrepancy not exceeding 5 %.

Conclusions

A comparative analysis of the motion trajectories of titanium powder particles of varying sizes in a vertically directed plasma flow has been successfully conducted. The study revealed that the size of powder particles significantly influences various parameters, including the dimensions of the luminous fraction, the opening angle of the plasma torch, and the distance of particles carried by the plasma flow from the plasma head. These findings are of great significance for processes involving coating and powder production.

Furthermore, the development of a computer model describing a laboratory plasma facility for applying functional coatings and producing powder materials represents a valuable contribution. This model can be employed to predict outcomes in powder production processes. Additionally, it enables the determination of optimal reactor (powder receiving chamber) dimensions and shapes, with the dual goal of reducing internal volume and mitigating issues such as molten particles adhering to chamber surfaces. This optimization is essential for minimizing the material consumption of process equipment, reducing facility dimensions, and cutting operational costs, especially when inert gases are used to fill the receiving chamber. A well-designed chamber shape not only lowers the unit cost of produced powder but also prevents contamination of internal reactor surfaces.

In the context of vertically upward plasma flow, the influence of gravity leads to a natural separation of sprayed powder into different fractions. Finer particles exhibit a larger scatter radius, while coarser ones are concentrated closer to the plasma jet's axis. This phenomenon can be harnessed for the selective collection of powdered material. As part of the chamber's design improvement, the proposal to introduce additional internal walls for particle deposition based on size is an innovative approach.

Overall, the use of gravity's effect in vertically directed spray patterns serves as an additional tool for segregating the produced powder material.

These study results hold particular utility in the application of functional coatings, aiding in the optimal positioning of the substrate on which they are applied. The computer model offers the capability to predict plasma flow torch characteristics, such as the opening angle and width, in relation to the distance from the plasmatron. This information is invaluable for estimating the coating area, determining the number of required passes of the plasma torch for surface coverage and considering particle temperatures. Moreover, it assists in defining the optimal substrate-to-plasma head distance and inclination.

The choice of directing the atomization process vertically upwards, taking advantage of the natural tendency of heat to rise due to the pressure difference in heated gases, offers several advantages over directing the plasma flow vertically downwards. In this configuration, the heat flow from the plasma is directed toward the substrate positioned above the plasma source. This setup minimizes the risk of overheating and potential damage to the plasma equipment's components, reducing the likelihood of plasma source failure. Additionally, when the plasma flow is directed upwards, the substrate receives more effective heating.

These recommendations have practical significance for both consumers and developers of technological equipment used in coating processes and powder production. By employing a computer model, it becomes feasible to anticipate process outcomes and make adjustments by manipulating influencing factors.

Furthermore, the results of the computer experiment were validated through a full-scale experiment and the comparative analysis of their findings demonstrated a satisfactory level of agreement.

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Information about the Authors

Roman A. Okulov – Cand. Sci. (Eng.), Assistant Professor of the Department "Engineering graphics", Ural Federal University named after the first President of Russia B.N. Yeltsin (UrFU); Senior Researcher of Laboratory of Powder and Composite Materials, Institute of Metallurgy of the Ural Branch of the Russian Academy of Sciences (IMET UB RAS).
ORCID: 0000-0003-4488-9190
E-mail: okulov.roman@gmail.com

Suleiman M. Akhmetshin – Engineer of Scientific-research, Laboratory of Powder and Composite Materials, IMET UB RAS.
ORCID: 0009-0000-0814-6790
E-mail: k009893@yandex.ru

Boris R. Gelchinsky – Dr. Sci. (Phys.-Math.), Head of the Department of Materials Science, IMET UB RAS.
ORCID: 0000-0001-5964-5477
E-mail: brg47@list.ru

Andrey A. Rempel – Dr. Sci. (Phys.-Math.), Academician of the Russian Academy of Sciences, Director of IMET UB RAS.
ORCID: 0000-0002-0543-9982
E-mail: rempel.imet@mail.ru

Сведения об авторах

Роман Александрович Окулов – к.т.н., доцент кафедры «Инженерная графика», Уральский федеральный университет имени первого Президента России Б.Н. Ельцина (УрФУ); ст. науч. сотрудник лаборатории порошковых и композиционных материалов, Институт металлургии Уральского отделения РАН (ИМЕТ УрО РАН).
ORCID: 0000-0003-4488-9190
E-mail: okulov.roman@gmail.com

Сулейман Муллаянович Ахметшин – инженер лаборатории порошковых и композиционных материалов, ИМЕТ УрО РАН.
ORCID: 0009-0000-0814-6790
E-mail: k009893@yandex.ru

Борис Рафаилович Гельчинский – д.ф.-м.н., руководитель отдела материаловедения, ИМЕТ УрО РАН.
ORCID: 0000-0001-5964-5477
E-mail: brg47@list.ru

Андрей Андреевич Ремпель – д.ф.-м.н., академик РАН, директор ИМЕТ УрО РАН.
ORCID: 0000-0002-0543-9982
E-mail: rempel.imet@mail.ru

Contribution of the Authors

R. A. Okulov – Conceptualization, goal and objective definition, manuscript writing, calculations, formulation of conclusions.

S. M. Akhmetshin – Experimental preparation, full-scale experiment conduct, manuscript writing.
B. R. Gelchinsky – Resource provision, manuscript writing, experimental results analysis.
A. A. Pempel – Academic supervision, experimental results analysis, manuscript revision, conclusions revision.

Вклад авторов

Р. А. Окулов – формирование основной концепции, постановка цели и задачи исследования, подготовка текста, осуществление расчетов, формулировка выводов.
С. М. Ахметшин – подготовка эксперимента, проведение натурного эксперимента, подготовка текста статьи.
Б. Р. Гельчинский – обеспечение ресурсами, подготовка текста, анализ результатов исследований.
А. А. Ремпель – научное руководство, анализ результатов исследований, корректировка текста, корректировка выводов.

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