Приборы и методы измерений
2021. – Т. 12, № 1. – С. 38–45
M.A. Kuznetsov et al.

Devices and Methods of Measurements
2021, vol. 12, no. 1, pp. 38–45
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Development of Executive Equipment Design for Implementing the Process of Generating of Drops of Micro- and Nanoscale Range

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Received 30.11.2020
Accepted for publication 15.02.2021

Abstract

Modeling of velocities and temperatures processes distribution in the plasma-forming channel determining the design features and optimal parameters of the plasma torch nozzle is one of promising directions in development of plasma technologies. The aim of this work was to simulate the processes of velocities and temperature distribution in the plasma-forming channel and to determine the design features and optimal geometric parameters of the plasmatron nozzle which ensures the formation of necessary direction of plasma flows for generation of surface waves on the surface of a liquid metal droplet under the influence of the investigated instabilities.

One of the main tasks is to consider the process of plasma jet formation and the flow of electric arc plasma. For obtaining small-sized particles one of the main parameters is the plasma flow velocity. It is necessary that the plasma outflow velocity be close to supersonic. An increase of the supersonic speed is possible due to design of the plasmatron nozzle especially the design feature and dimensions of the gas channel in which the plasma is formed. Also the modeling took into account dimensions of the plasma torch nozzle, i. e. the device should provide a supersonic plasma flow with the smallest possible geometric dimensions.

As a result models of velocities and temperatures distribution in the plasma-forming channel at the minimum and maximum diameters of the channel were obtained. The design features and optimal geometric parameters of the plasmatron have been determined: the inlet diameter is 3 mm, the outlet diameter is 2 mm.

The design of the executive equipment has been developed and designed which implements the investigated process of generating droplets of the micro- and nanoscale range. A plasmatron nozzle was manufactured which forms the necessary directions of plasma flows for the formation of surface waves on the metal droplet surface under the influence of instabilities. An algorithm has been developed for controlling of executive equipment that implements the process of generating drops of micro- and nanoscale range.

Keywords: modeling, arc plasma, plasma torch nozzle, geometric parameters, control algorithm.

DOI: 10.21122/2220-9506-2021-12-1-38-45

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Разработка конструкции исполнительного оборудования, реализующего процесс генерации капель микро- и нанодиапазона

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Поступила 30.11.2020
Принята к печати 15.02.2021

Моделирование процессов распределения скоростей и температур в плазмообразующем канале, определение конструктивных особенностей и оптимальных параметров сопла плазмотрона является одним из перспективных направлений в развитии плазменных технологий. Целью данной работы являлось моделирование процессов распределения скоростей и температур в плазмообразующем канале и определение конструктивных особенностей и оптимальных геометрических параметров сопла плазмотрона, которое должно обеспечивать формирование необходимых направлений плазменных потоков для образования на поверхности капли жидкого металла поверхностных волн под действием исследуемых неустойчивостей.

Одной из главных задач является рассмотрение процесса формирования плазменной струи и течения электродуговой плазмы. Для получения мелкоразмерных частиц одним из главных параметров является скорость течения плазмы. Необходимо, чтобы скорость истечения плазмы была близка к сверхзвуковой. Увеличение скорости до сверхзвуковой возможно добиться за счёт конструкции сопла плазмотрона, а именно конструктивной особенностью и размерами газового канала, в котором образуется плазма. Также при моделировании учитывались размеры сопла плазмотрона, т. е. устройство должно обеспечивать сверхзвуковое течение плазмы при возможно меньших геометрических размерах.

В результате исследований получены модели процессов распределения скоростей и температур в плазмообразующем канале при минимальных и максимальных диаметрах канала. Определены конструктивные особенности и оптимальные геометрические параметры сопла плазмотрона: диаметр на входе 3 мм, диаметр выходной 2 мм.

Разработана и спроектирована конструкция исполнительного оборудования, реализующая исследуемый процесс генерации капель микро- и наноразмерного диапазона. Изготовлено сопло плазмотрона, формирующее необходимые направления плазменных потоков для образования на поверхности капли жидкого металла поверхностных волн под действием исследуемых неустойчивостей. Разработан алгоритм управления исполнительным оборудованием, реализующем процесс генерации капель микро- и наноразмерного диапазона.

Ключевые слова: моделирование, плазма дуги, сопло плазмотрона, геометрические параметры, алгоритм управления.

DOI: 10.21122/2220-9506-2021-12-1-38-45

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Introduction

Currently, one of the most promising areas for the implementation of various technological processes is mathematical modeling. It is based on the construction of a model created by means of computer simulation of various physical and technological processes [1–7]. Development of various models that are as similar as possible to natural processes is very important in the case when setting up a natural experiment is impossible, very difficult or very expensive. Development of computer technology creates good prospects for application of rather complex models reflecting the multifactor nature and interconnection of various physical processes and phenomena. One of the most powerful modeling tools is the *COMSOL Multiphysics* software package which is designed to simulate various physical processes, systems and their interconnection [8, 9].

In literary sources [1–7], the authors provide data on modeling of various technological processes: the model of the effect of a shielding gas on heat distribution in the welding zone [1, 2], the model of temperature fields and resistance to deformation in cylindrical billets during heating [3], the model of optimization of remelting mode parameters of tungsten-inert gas with nanomodification of the surface layer [4], the model of the molten pool, when welding with a consumable electrode in shielding gas [5], the model of the influence of the input parameters of the laser welding mode on the quality of the weld [6], the model of welding technology for high-strength steel sheets [7]. The disintegration of a liquid jet into droplets is a common phenomenon both in industrial processes and in natural phenomena. Droplets are formed due to disturbances and a certain type of instability on the surface of the liquid jet. The resulting surface waves with different amplitudes are a prerequisite for the formation of drops [10–12].

The work is aimed at the experimental determination of technological conditions for creating a technology for the formation of micro- and nanodroplets under conditions of exposure to the transfer of the electrode metal by concentrated plasma energy flows. The paper proposes a mechanism for the formation of droplets of nano- and micrometer sizes, based on the appearance and development of a thin liquid interlayer of the micro- and nanometer range on the surface of a liquid metal under the action of heterogeneous plasma flows. This phenomenon occurs when a metal wire is fed into the heterogeneous plasma zone of an electric arc.

The aim of the work was to simulate the processes of distribution of velocities and temperatures in the plasma-forming channel and to determine the design features and optimal geometric parameters of the plasmatron nozzle which should provide the formation of the necessary directions of plasma flows for the formation of surface waves on the surface of a liquid metal droplet under the influence of the instabilities under study.

Mathematical problem statement

To develop the design of the executive equipment that implements the process of droplets′ generating of the micro- and nanoscale range we simulated the process of obtaining small-sized particles using plasma spraying.

One of the main tasks is to consider the process of a plasma jet formation and the flow of electric arc plasma. For obtaining of small-sized particles one of the main parameters is the plasma flow velocity. It is necessary for plasma outflow velocity to be close to supersonic. An increase in speed to supersonic can be achieved due to the design of the plasma torch nozzle, namely, the design feature and dimensions of the gas channel in which the plasma is formed. Also, the modeling took into account dimensions of the plasma torch nozzle, i. e. the device should provide a supersonic plasma flow with the smallest possible geometric dimensions.

When formulating the problem the following boundary conditions were established in the *COMSOL Multiphysics* software package:

– the gas flow is laminar;
– the effect of gravity is not taken into account;
– an axisymmetric problem is considered;
– thermodynamic and transport properties of gas depend on temperature.

The developed model is described by the following basic equations:

1. Maxwell's equations:

$$\begin{cases} \boldsymbol{J} = \left(\sigma + \varepsilon\varepsilon_0 \dfrac{\partial}{\partial \boldsymbol{t}} \right) \boldsymbol{E}; \\ \quad \boldsymbol{E} = -\nabla V; \\ \sigma \dfrac{\partial \boldsymbol{A}}{\partial t} + \nabla \times \boldsymbol{H} = \boldsymbol{J}; \\ \quad \boldsymbol{B} = \nabla \times \boldsymbol{A}, \end{cases}$$

where $\boldsymbol{J}$ – current density; $\boldsymbol{E}$ – electric field strength; $\boldsymbol{A}$ – magnetic vector potential; $\boldsymbol{B}$ – magnetic induction vector; $\boldsymbol{H}$ – vector of magnetic intensity; V – electric potential; σ – electrical conductivity; ε – relative permittivity.

2. Energy balance equation:

$$\rho Cp\frac{\partial T}{\partial t}+\rho Cp\boldsymbol{u}\cdot\nabla T=\nabla\cdot\left(k\nabla T\right)+Q;$$

$$Q=E\cdot J+Q_{rad},$$

where ρ – density; Cp – heat capacity; k – thermal conductivity; EJ – Joule heating; Q_{rad} – radiation losses; $\boldsymbol{u}$ – velocities field.

3. Equation of motion:

$$\rho\frac{\partial u}{\partial t}+\rho\left(u\cdot\nabla\right)\cdot u=\nabla\cdot\left[-pI+\mu\cdot\left(\nabla u+\left(\nabla u\right)^{T}\right)\right]+F;$$

$$F=\frac{1}{2}\mathrm{Re}\left(J\times B\right),$$

where F – Lorentz force; p – pressure; T – temperature; μ – dynamic viscosity; ρ – the density; the relative magnetic permeability; Re – Reynolds number.

4. The continuity equation:

$$\rho\frac{\partial\boldsymbol{u}}{\partial t}+\nabla\left(\rho\boldsymbol{u}\right)=0,$$

where $\boldsymbol{u}$ – instantaneous velocities field at time t.

Modeling of the process of obtaining small-sized particles was carried out using plasma spraying in the *COMSOL Multiphysics* software package. For the operation of the plasmatron, the geometric dimensions of the gas channel in which the plasma is formed are important. An image of the structural elements of the plasmatron gas channel is shown in Figure 1.

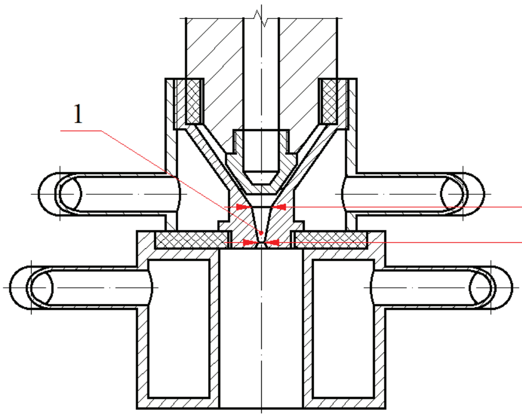


Figure 1 – The main structural elements of the plasmatron: 1 – gas channel; 2 – inlet diameter; 3 – outlet diameter

In order to optimize the geometry of the nozzle and the parameters of the plasmatron mode, the process of the plasmatron operation was simulated. The computational domain of the problem is the gas channel of the designed plasmatron and is shown in Figure 2. Various values of the inlet and outlet diameters of the supersonic nozzle and its length were considered. The hydrodynamic flow of the arc plasma jet depends on the geometric parameters (diameter and shape) of the gas channel of the plasmatron.

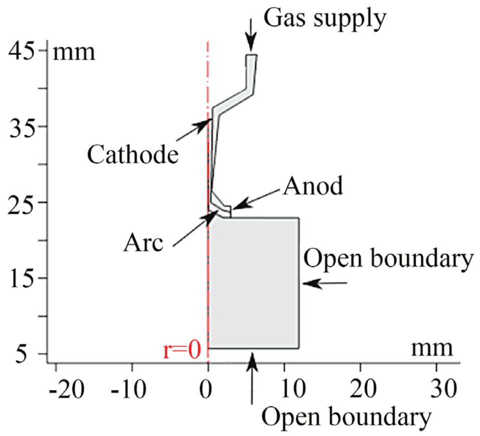


Figure 2 – Calculation area

Varying the input parameters when modeling the nozzle of the plasmatron was carried out in the ranges shown in Table.

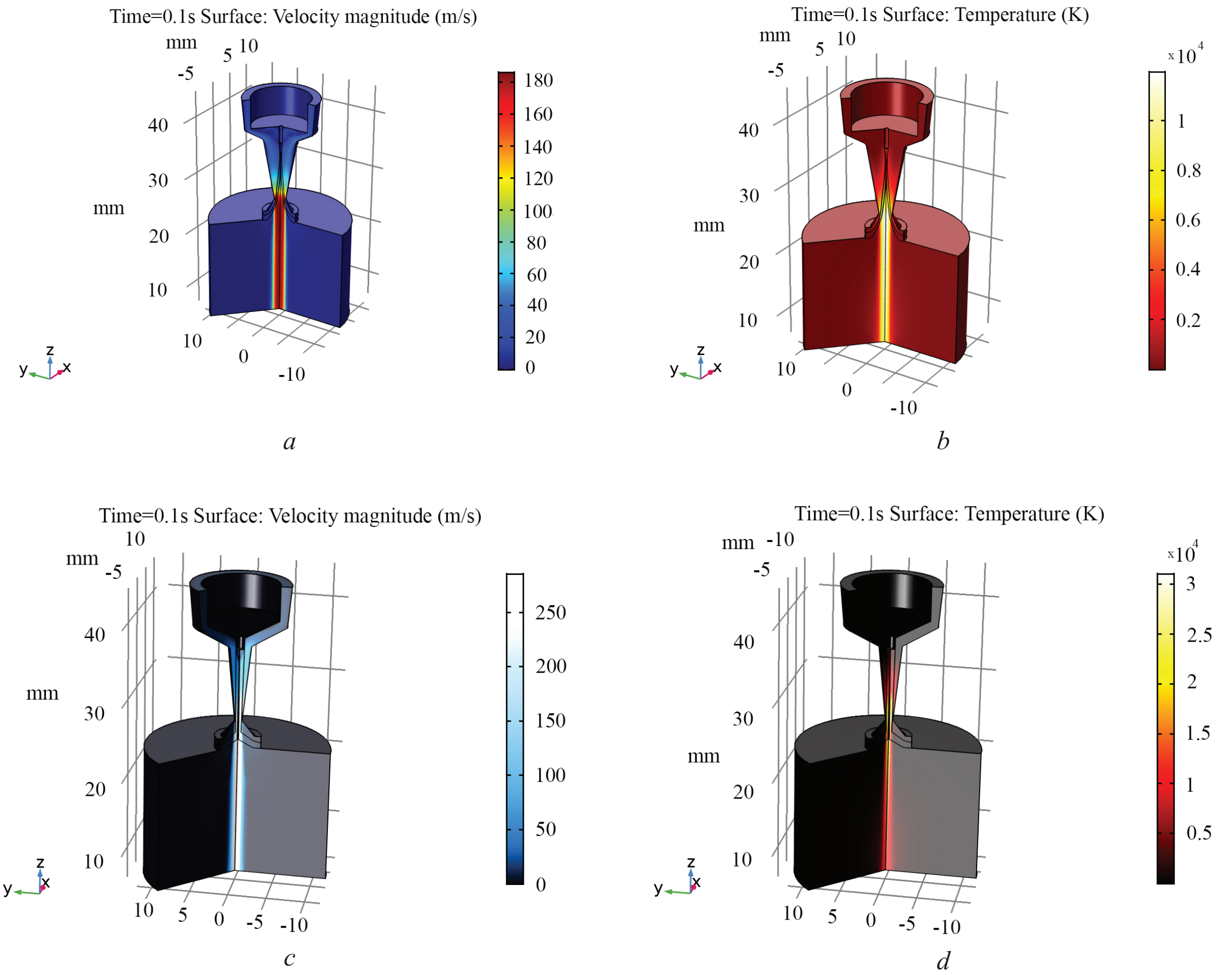
Table

Parameters for the production of micro- and nanoscale range powders

Gas consumption, *l*/min	10...40
Current, A	100...200
Outlet diameter, mm	2…4
Nozzle length, mm	10...30
Inlet diameter, mm	3...10

Results and discussion

Figure 3 shows the results of modeling of the plasmatron nozzle with the following input parameters: gas flow rate 20 *l*/min, current 150 A, nozzle length 20 mm. The values of the gas velocity in the throat of the jet nozzle and the temperature distribution in the flow were considered (Figure 3*a*, *b* at maximum channel diameters: outlet diameter 4 mm, inlet diameter 10 mm; Figure 3*c*, *d* at minimum channel diameters: outlet diameter 2 mm, diameter at the inlet 3 mm). In this case, the design



a *b* *c* *d*

Figure 3 – Distribution of velocities and temperatures in the plasma-forming channel: *a* – velocity distribution at the maximum channel diameter; *b* – temperature distribution at the maximum channel diameter; *c* – velocity distribution at the minimum channel diameter; *d* – temperature distribution at the minimum channel diameter

features and optimal dimensions of the gas channel should ensure effective melting of the filler material and it's crushing into particles.

Based on the simulation results a plasmatron nozzle was developed (Figure 4) with design features and optimal geometric parameters: inlet diameter – 3 mm, outlet diameter – 2 mm, which provide a plasma flow rate close to supersonic, and the formation of the necessary direction of plasma flows for the formation on the liquid metal drop surface waves under the influence of the investigated instabilities.

The size and chemical composition of the obtained micro- and nanoscale range powders depends on the plasmatron operating mode: amperage, gas consumption, wire: diameter (from 0.8 to 1.2 mm) and chemical composition.

The developed nozzle (Figure 4) will be one of the main details of the laboratory equipment being created for the production of micro- and nanosized powders, the block diagram of which is shown in Figure 5.

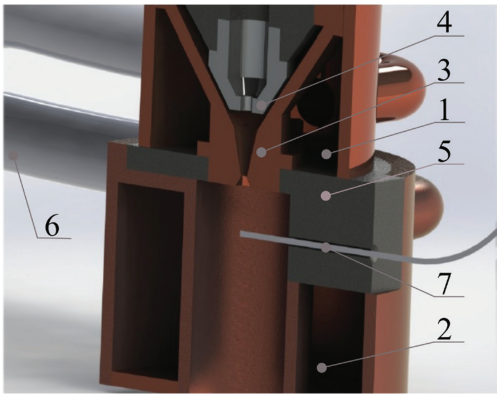


Figure 4 – Plasmatron nozzle model: 1 – upper body; 2 – lower body; 3 – nozzle; 4 – tip; 5 – insulator; 6 – water supply pipes; 7 – wire

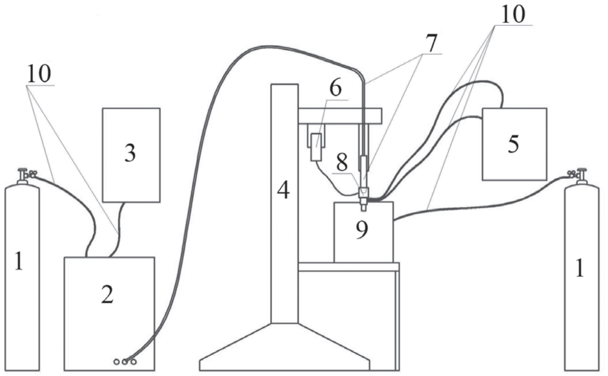


Figure 5 – Equipment block diagram: 1 – inert gas cylinder; 2 – plasma power supply; 3 – compressor; 4 – rack; 5 – chiller (industrial cooler); 6 – wire spool; 7 – plasmatron; 8 – nozzle; 9 – particle catcher; 10 – hose

The work of the equipment for the production of micro- and nanoscale range powders is as follows: the plasma power supply 2 and the compressor 3 are turned on; a cylinder with inert gas 1 is opened. The inert gas (argon, helium) is selected depending on the chemical composition of the wire from which the powders are obtained. Then we turn on the chiller 5 and open the cylinder with inert gas 1. We start the wire feeder, which feeds the wire from the spool 6 to the nozzle 8, located on the stationary stand 4. The diameter and chemical composition of the wire is selected depending on the size and chemical composition of the powders obtained. The wire, entering the nozzle 6, passes through a high-temperature section; a drop of molten metal is formed at the end of the wire. In nozzle 6, plasma flows move at a high speed, the directions of which contribute to the formation of surface waves on the surface of a liquid metal droplet under the influence of the instabilities under study. Under the action of high-frequency ultrasonic action on the wire and, accordingly, on a drop of molten metal from its surface, the plasma flow tears off liquid objects several microns in size or less. Liquid objects torn off from the surface are accelerated to high speeds in a nozzle, additionally crushed, take a spherical shape under the influence of surface forces, condense in a particle catcher in an inert gas atmosphere and form micro- and nanoscale range powders. The dispersion of the resulting powder granules was determined by the method of simulation and visualization [13].

The equipment control algorithm (Figure 5) is shown in Figure 6.

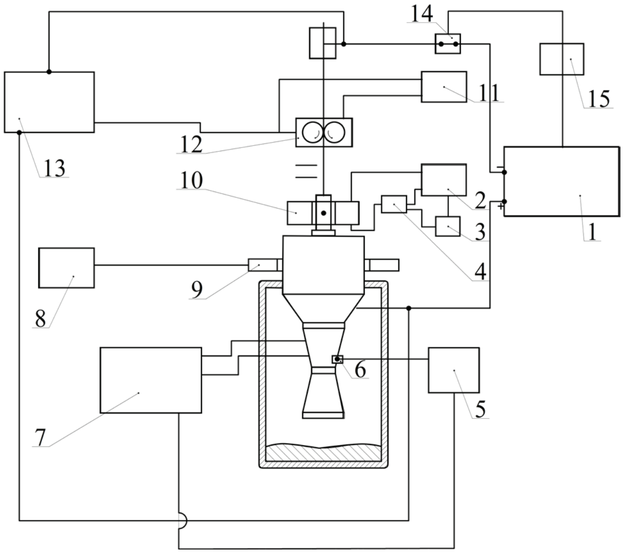


Figure 6 – The scheme of the equipment control algorithm: 1 – plasma power source; 2 – ultrasonic generator; 3 – frequency matching and correction unit; 4 – resonance sensor; 5 – temperature control unit; 6 – thermal sensor; 7 – chiller; 8 – arc stabilizer control unit; 9 – arc stabilizer; 10 – magnetostrictive inertialess solenoid; 11 – wire feed control unit; 12 – wire feeder; 13 – arc gap length control unit; 14 – current sensor; 15 – block of comparison and correction of current; 16 – arc plasmatron; 17 – particle catcher; 18 – gas cylinder

The control algorithm of the installation shown in Figure 6 is as follows:

– the feed mechanism (12), controlled by the wire feed control unit (11), feeds the wire into the arc plasmatron (16), where it melts. The formation of the Kelvin–Helmholtz [14, 15] and Marangoni instabilities on a drop of molten metal is carried out due to the special design of the plasmatron, which transfers the rotation of plasma streams formed from the plasma-forming gas (18). High-frequency oscillations are used to detach the formed instabilities from the droplet surface. To generate high-frequency vibrations, the wire pass through a magnetostrictive inertialess solenoid (10) controlled by an ultrasonic generator (2), while an ultrasonic wave is formed in the wire due to the effect of magnetostriction. An ultrasonic wave forms Rayleigh waves on a drop of molten metal, causing particles to detach. The resulting particles enter the particle catcher (17). The resonant frequency of oscillations is set via the feedback channel through the frequency matching and correction unit (3) and the resonance sensor (4);

– additional rotation of the arc and stabilization of plasma flows occurs due to the arc stabilizer (9), controlled by the arc stabilization control unit (8);

– to ensure the stabilization of the preset operating temperature in the laboratory setup, a thermal sensor (6) is installed on the nozzle. Temperature control and regulation is carried out by the chiller (7) through feedback channels through the temperature control unit (5);

– to control the size of the received particles in the installation there is an automatic regulation of the arc length. The arc length is controlled by the voltage of the arc gap and is controlled by feedback channels through the arc gap length control unit (13);

– automatic maintenance of the current of the specified parameters, carried out by the plasma power supply (1) through the feedback channels, including through the current sensor (14) and the unit for comparison and current correction (15).

Thus, the control system of the installation automatically regulates four main parameters: the frequency of ultrasonic vibrations, the current in the plasmatron, the length of the arc gap, and the operating temperature in the nozzle, the change of which makes it possible to control the size of the particles obtained.

Conclusion

Models of the processes of distribution of velocities and temperatures in the plasma-forming channel at the minimum and maximum diameters of the channel are obtained.

The design features and optimal geometric parameters of the plasmatron nozzle have been determined: the inlet diameter is 3 mm; the outlet diameter is 2 mm. The design of the executive equipment has been developed and designed, which implements the investigated process of generating droplets of the micro- and nanoscale range. A plasmatron nozzle was manufactured, which forms the necessary directions of plasma flows for the formation of surface waves on the surface of a liquid metal droplet under the influence of the investigated instabilities.

An algorithm has been developed for controlling the executive equipment that implements the process of generating drops of micro- and nanoscale range. Thus, the control system of the laboratory facility automatically regulates four main parameters: the frequency of ultrasonic vibrations, the current in the plasma torch, the length of the arc gap and the operating temperature in the nozzle change of which allows you to control the size of the particles obtained.

In contrast to the existing electric arc plasmatrons, which are designed for metal processing, this development has a different purpose and is designed to produce powders of the micro- and nanoscale range.

Acknowledgments

The study was performed by a grant from the Russian Science Foundation (Project № 18-79-10035).

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