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NUMERICAL SIMULATION OF COOLING OF FINE METAL POWDER IN VARIOUS GASEOUS ENVIRONMENT

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ABSTRACT

The article discusses the dispersion of metal powders in a plasma installation, and the cooling of metal particles in various gaseous environment such as argon, helium and their mixtures. The main interest in this study is the trajectory, flight range, the rate of crystallization and cooling of the obtained particles. The data obtained during this investigation are necessary for the development and creation of full-fledged plasma equipment. In order to calculate the distribution of the flow velocity and temperature when modeling the process, it is necessary to carry out an analysis of the conditions for the formation of spherical metal powders under the action of plasma jets on the basis of the accepted concept of the physical and thermal model of the arc. To obtain the non-stationary mathematical models correctly, it is also necessary to know the geometric characteristics of the plasma installation, the flow rate of the plasma-forming gas, the electromagnetic parameters of the arc, the composition and the properties of the molten metal, and a number of other factors. Initially, the problem of choosing of a plasma-forming and technical gas to fill the working chamber of a plasma installation was solved. The properties of gases were calculated, which are necessary for further mathematical modeling of the physical processes of interaction of metal particles with the gaseous environment of the working chamber. On the basis of the results of mathematical modeling of particle cooling, it can be unambiguously concluded that a gas environment with a predominance of helium is the most effective option for filling the process chamber, which serves to cool and collect the resulting metal powder, because cooling occurs 4 times faster than in argon.

KEYWORDS

PREP method; fine metal powder; additive technologies; plasma properties; mathematical modeling.

ЧИСЛЕННОЕ МОДЕЛИРОВАНИЕ ОХЛАЖДЕНИЯ МЕЛКОДИСПЕРСНОГО МЕТАЛЛИЧЕСКОГО ПОРОШКА В РАЗЛИЧНЫХ ГАЗОВЫХ СРЕДАХ

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АННОТАЦИЯ

В данной статье рассматривается охлаждение металлических частиц, полученных методом PREP, в различных газообразных средах, таких как аргон, гелий и их смеси. Основной интерес в данном исследовании представляют траектория, дальность полета, скорость кристаллизации и охлаждения полученных частиц. Данные, полученные в ходе данного исследования, необходимы для разработки и создания полноценного плазменного оборудования. Анализ условий формирования сферических металлических порошков при воздействии плазменных струй на основе принятой концепции физической и тепловой модели дуги необходим для расчета распределения векторов скорости потока и температуры при моделировании процесса. Для корректного получения установленных нестационарных математических моделей необходимо также знать геометрические характеристики плазменной установки, расход плазмообразующего газа, электромагнитные параметры дуги, свойства и состав расплавленного металла и ряд других факторов. В первую очередь решалась задача по выбору плазмообразующего и технического газа для заполнения рабочей камеры плазменной установки. Рассчитаны свойства газов, которые будут необходимы для дальнейшего математического моделирования физических процессов взаимодействия металлических частицам с газовой средой рабочей камеры. По результатам математического моделирования охлаждения частиц можно сделать однозначный вывод, что газовая среда с преобладанием гелия является оптимальным вариантом заполнения технологической камеры, служащей для охлаждения и сбора получаемого металлического порошка, т.к. охлаждение происходит в 4 раза быстрее, чем в чистом аргоне.

КЛЮЧЕВЫЕ СЛОВА

Процесс вращающегося электрода в плазме; мелкодисперсный порошок; аддитивные технологии; свойства плазмы; математическое моделирование.

Introduction

The use of additive technologies is currently one of the most relevant trends in the global engineering industry. With the help of innovative technology, developing industrial companies have the opportunity to apply new methods to the design and manufacture of parts. They significantly reduce the time spent on subsequent processing and improve product quality by producing parts whose shape is closest to the data of a computer model [1].

An important section of the additive manufacturing of metal parts is the starting material. There are different additive manufacturing approaches that use different kinds of raw materials, and the most popular technologies, such as selective laser sintering or electron beam melting and deposition, use the raw material in powder form [2–4].

Despite the fact that this direction is extremely promising, at the moment in Russia it is still in its initial stage [5–7].

Sputtering by a rotating electrode under the action of centrifugal force is a commercial process for dispersing powdered material. This process, called REP (Rotating Electrode Process) or PREP (Plasma Rotating Electrode Process), was invented by Nuclear Metals, Inc. in 1963 [8–10]. Since its invention, REP has been widely used to produce pure mild steel spherical powders as a carrier for carbon black in office copiers. For the past ten years, this method has been applied to the production of cobalt-chromium and titanium alloy powders for prosthetic devices. It has also been adapted to produce ultrapure titanium alloy powders for potential aerospace applications [11, 12].

1. Methods of experimental and theoretical investigations

A technique for producing metal powder by rotating billet AC plasma arc spraying (PREP) is shown in Fig. 1. Preliminary investigations of this technology were reported at the conference [13]. In this technology, the production of metal particles occurs due to the effect of a plasma arc on a melted part rotating around its axis at a speed of 10.000 rpm (in the study the part has a diameter of 5 cm).

Compared with atomization methods such as gas atomization and water atomization, the energy used in REP is small and the atomization occurs due to centrifugal forces. In addition, REP does not require retention of liquid metals, which eliminates refractory oxide contamination. Consequently, particles sputtered by a rotating electrode are usually very smooth, spherical, of high purity, and almost devoid of satellites. This is a distinguishing feature of REP and other centrifugal atomization methods operating in inert gas or vacuum at low speeds.

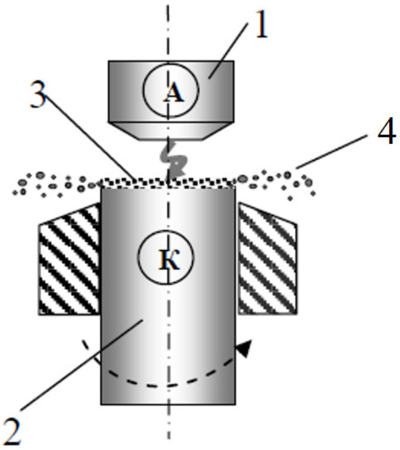


Fig. 1. Melt sputtering technology by rotating electrode process:
1 – cathode; 2 – rotating electrode; 3 – liquid metal; 4 – droplets-particles

Рис. 1. Технология распыления расплавов способом вращающегося электрода:
1 – катод; 2 – вращающийся электрод; 3 – жидкий металл; 4 – капли-частицы

Rotating electrode process can be applied to almost all metals and alloys because it does not require a crucible for melting and/or pouring. High melting point metals and alloys such as titanium and zirconium are well suited for this process.

For the theoretical analysis of the technological process, it is necessary to calculate the properties of the gas environment of the working chamber. The calculation method was substantiated and tested for various gases in [14–19].

1.1. Calculation of the properties of the gas environment of the working chamber

An important factor for obtaining a quality product is the environment in which the metal powder crystallizes. The main peculiarity of the plasma-forming gas for use in the technology under study is its neutral relationship to metals (inert gases). The noble gases include helium (He), neon (Ne), argon (Ar), krypton (Kr), xenon (Xe), and radioactive radon (Rn). However, most of these gases are difficult to obtain and become uneconomical to use. The most common and easiest to obtain are argon (Ar) and helium (He). In addition, argon, due to its large atomic mass of 39.948 a.m.u. and high density, effectively pushes the melt out of the anode spot because a large kinetic energy of the plasma jet is achieved. Due to the fact that argon has a relatively low ionization potential, it is excellent for ignition of a plasma arc. However, in addition to melting the metal workpiece in the process of obtaining metal powders, it is necessary to accelerate the crystallization process of the sputtered metal drops as much as possible; for this purpose, the chamber volume is filled with a gas mixture consisting of argon and helium that are neutral gases with respect to metals. Helium is added to the mixture because it is characterized by an extremely high thermal conductivity which accelerates the solidification of liquid metal droplets. It follows from this that the composition of the plasma jet will mostly consist of argon with a small addition of helium.

The composition, thermodynamic and transport properties of the plasma of argon, helium, and a mixture of 90% Ar + 10% He were calculated by the method described in [15–17]. The necessary data for calculations were taken from [20–23].

Some results of calculation, namely the temperature distributions of specific heat, density and thermal conductivity are shown in Figs. 2–4.

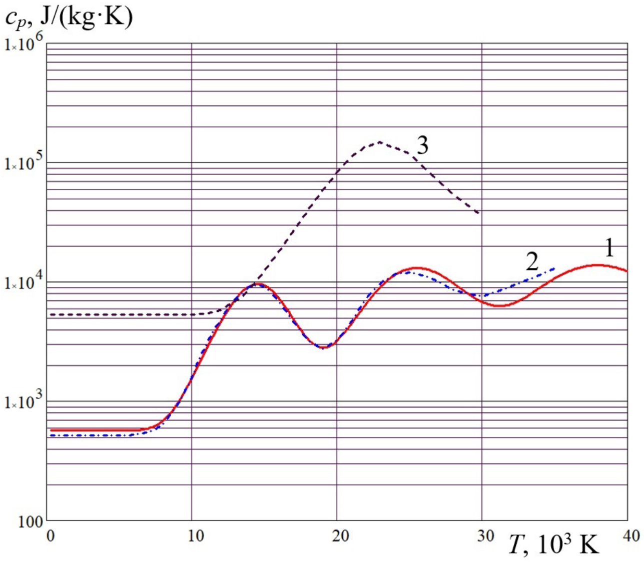


Fig. 2. Temperature dependences of the specific heat of various gaseous environment:
1 – 90% Ar + 10% He; 2 – Ar; 3 – He

Рис. 2. Температурные зависимости теплоемкости различных газовых сред:
1 – 90% Ar + 10% He; 2 – Ar; 3 – He

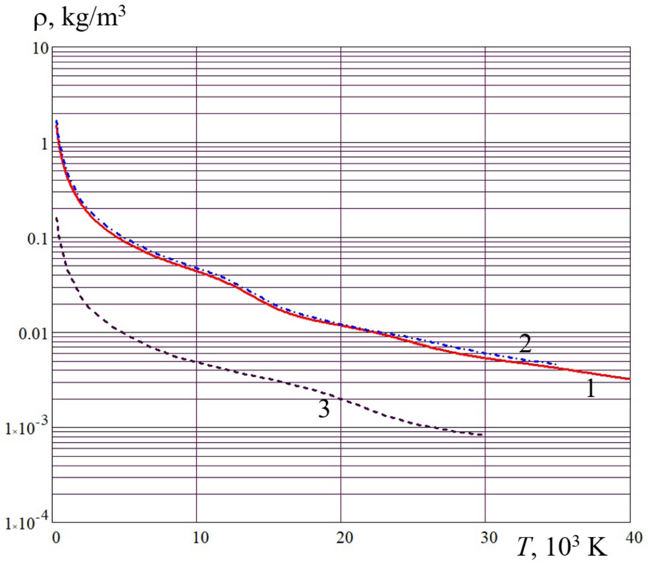


Fig. 3. Temperature dependences of the density of various gaseous environment:
1 – 90% Ar + 10% He; 2 – Ar; 3 – He

Рис. 3. Температурные зависимости плотности различных газовых сред:
1 – 90% Ar + 10% He; 2 – Ar; 3 – He

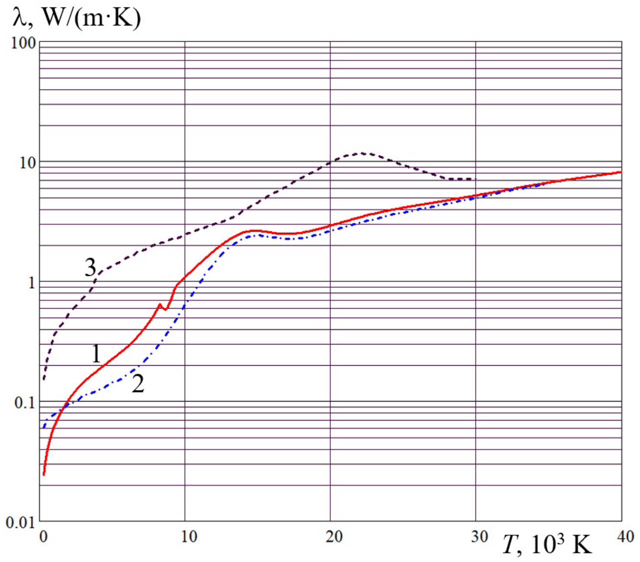


Fig. 4. Temperature dependences of the thermal conductivity of various gaseous environment:
1 – 90% Ar + 10% He; 2 – Ar; 3 – He

Рис. 4. Температурные зависимости теплопроводности различных газовых сред:
1 – 90% Ar + 10% He; 2 – Ar; 3 – He

1.2. Calculation of the formation of metal particles during their detachment from the melted rotating workpiece and their crystallization in the technological chamber

The formation of metal particles during their detachment from the melted billet under the action of centrifugal forces during its rotation as well as their cooling and crystallization take place in the technological chamber in an inert gaseous environment to avoid oxidation of the particle material.

When modeling the processes in plasma arc and the process of metal billet melting, it can be seen that a particle does not interact with the gaseous environment in the technological chamber at the stage of its detachment from a rotating workpiece. This fact eliminates the gas components in the composition of the resulting liquid droplet. However, the stage of cooling and crystallization takes place in the technological chamber in an environment of inert gases of argon and helium. This composition of the gas mixture makes it possible to accelerate the solidification of the metal droplet and exclude the oxidation of its surface.

For the calculation, it is necessary to establish the holding tension force F_t in the zone of particle detachment and the detaching centrifugal force F_c [13].

To determine the mass of a particle formed during plasma sputtering, we use the formula:

$$m_p = \pi \rho_p d_p^{\,3}/6, \tag{1}$$

where m_p is the particle mass, ρ_p is the particle density, d_p is the particle diameter.

The particle diameter in the first approximation can be determined on the basis of experimental studies according to the formula given in [24]:

$$d_p = \frac{W_{\exp}\sigma_m}{\rho_g v_g}, \tag{2}$$

where W_{exp} is the critical number corresponding to the crushing of the droplet (it is in the range of 22–24), σ_m is the surface tension at the melting temperature, v_g is the gas velocity in the melting zone, ρ_g is the gas density.

The thermophysical properties of the considered granules of various metals are shown in Table 1.

Table 1. Thermophysical properties of the considered granules for different types of metals

Таблица 1. Теплофизические свойства рассматриваемых гранул для разных видов металлов

Parameter / Параметр	Symbol / Символ	Value / Значение			Unit / Ед. изм.
		Titanium / Титан	Copper / Медь	Steel / Сталь	
Particle diameter / Диаметр частицы	d_p	$(20 \div 60) * 10^{-6}$			m
Melting temperature / Температура плавления	T_m	1941.15	1356	1450	K
Boiling temperature / Температура кипения	T_b	3533.15	2840	2861	K
Particle specific heat / Теплоемкость частицы	c_p	540	381.8	460	J/(kg·K)
Particle density / Плотность частицы	ρ_p	4500	8940	7850	kg/m^3
Specific heat of melting / Удельная теплота плавления	ΔH_m	315	214	205	J/kg
Particle thermal conductivity / Теплопроводность частицы	λ_p	18.85	401	45.4	W/(m·K)

To detach a particle, it is necessary to fulfil the condition $F_c > F_t$, where the force of centrifugal acceleration is equal to:

$$F_c = m_c \cdot a_c. \tag{3}$$

The centrifugal acceleration a_c is equal to:

$$a_c = \frac{V_w^2}{R_w}, \tag{4}$$

where R_w is the workpiece radius, V_w is the linear velocity of the rotating workpiece. The linear velocity of rotation of the workpiece relates to the angular ones ω by the following dependence [25]:

$$V_w = R_w \cdot \omega. \tag{5}$$

To find the tension force F_t, the following formula is used:

$$F_t = \sigma \cdot \pi \cdot \eta \cdot d_p, \tag{6}$$

where σ is the surface tension:

$$\sigma = K_\sigma \cdot \left(\frac{\rho_m}{\rho}\right)^{\frac{2}{3}} \cdot \exp\left(-0.0594 \cdot \frac{S}{R}\right), \tag{7}$$

The surface tension of melts refers to 1 m^2 of surface. When the temperature changes, the number of metal particles involved in the formation of surface tension forces changes. If the surface tension coefficient σ (J/m^2) is multiplied by the ratio $(\rho_m/\rho)^{2/3}$, then the complex $\sigma^* = \sigma(\rho_m/\rho)^{2/3}$ will be related to a constant number of particles (ρ_m and ρ are the melt density at melting temperature and current temperature, respectively). Also, the thermodynamic probability and the entropy of matter are related by the Boltzmann formula: $S = k \cdot \ln W$, where k is the Boltzmann constant, W is the thermodynamic probability. The coefficient K_σ is taken depending on the metal from [26].

Thus, the required angular velocity for particle detachment must be greater:

$$\omega > \frac{\left(\frac{6\sigma\eta}{\rho R_w}\right)^{0.5}}{d_c}. \tag{8}$$

In order to obtain a particle of the required fraction of 20–60 μm, the angular frequency must correspond to the following formula:

$$n > \frac{23.39 \cdot \left(\frac{6\sigma\eta}{\rho R_w}\right)^{0.5}}{d_c}. \tag{9}$$

After the liquid metal droplet is detached from the base of the workpiece, the process of cooling and formation of a metal particle is initiated. The most important parameters influencing the rate of granule solidification are the thermal conductivity of the gas mixture in the chamber, the particle diameter, and the temperature difference between the metal droplet and the gaseous environment [25].

To find for the heat transfer coefficient from a metal particle in a gas flow, one can use the formula [27]:

$$\alpha = \frac{\mathrm{Nu} \cdot \lambda_g}{d_p}, \qquad (10)$$

where λ_g is the thermal conductivity of the gaseous environment.

The Nusselt number Nu, which determines the intensity of convective heat transfer between the particle surface and the gas mixture flow, can be found as follows [27]:

$$\mathrm{Nu} = 2 + 0.03 \cdot \mathrm{Re}^{0.54} \cdot \mathrm{Pr}^{0.33} + \\ + 0.035 \cdot \mathrm{Re}^{0.58} \cdot \mathrm{Pr}^{0.36}, \qquad (11)$$

where Re is the Reynolds number, Pr is the Prandtl number.

2. Results and discussion

Based on the presented experimental and theoretical research methods, the results were obtained that allow analyzing the developed technology for obtaining fine powders of various fractions of 20–60 μm used in additive technologies.

Thus, for the obtained initial particle detachment velocity and the properties of the working environment of the gas mixture, we can create a model that describes peculiarities of the cooling of the metal granule.

The velocity field for a titanium particle moving in a helium environment with a detachment velocity of 5 m/s is presented in Fig. 5.

Knowing the particle velocity and the working environment, the cooling time of the particle was calculated (Figs. 6, 7).

To compare the cooling rate of a particle in different gaseous environment, results of calculations with argon medium are shown in Figs. 8–10.

Based on the results of mathematical modeling of particle cooling, it can be concluded that a gas environment with a predominance of helium, which has a high energy content, is a more efficient case for filling the technological chamber, which serves to cool and collect the resulting metal powder, because cooling takes place 4 times faster than in pure argon.

Knowing the values of the particle velocity and the time of its cooling, it is possible to calculate the diameter of the technological chamber. If we take a cooling time of 0.3 s and a particle velocity of 5 m/s, then the chamber diameter will be approximately 1.5 m.

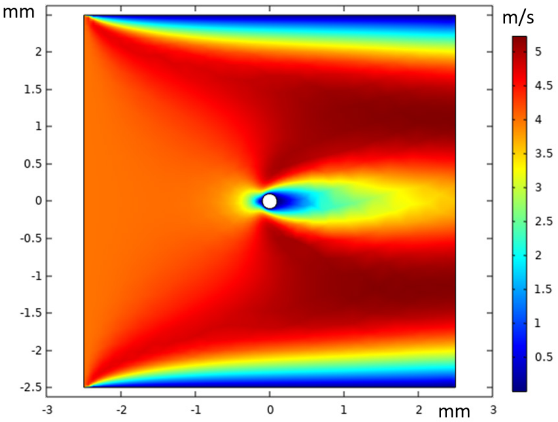


Fig. 5. Velocity field for a titanium particle in a helium environment

Рис. 5. Поле скоростей для титановой частицы в гелиевой среде

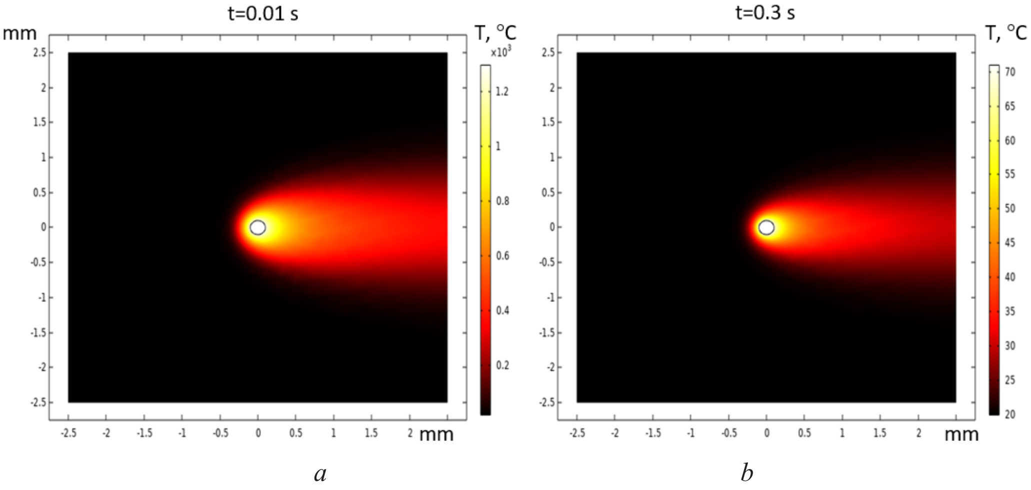


Fig. 6. Particle cooling pattern depending on time in helium:
a – t = 0.01 s; b – t = 0.5 s

Рис. 6. Картина охлаждения частицы в зависимости от времени в гелии:
a – t = 0,01 с; b – t = 0,5 с

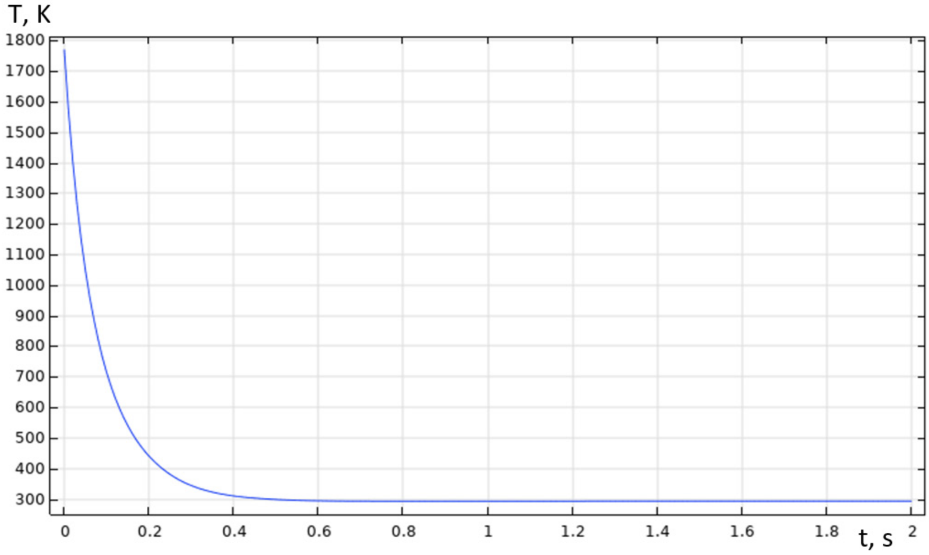


Fig. 7. Time dependence of particle temperature in helium

Рис. 7. Зависимость температуры частицы от времени в гелии

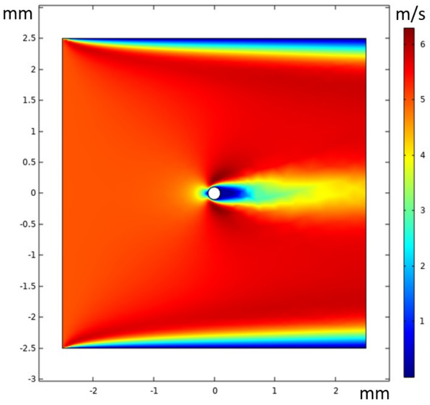
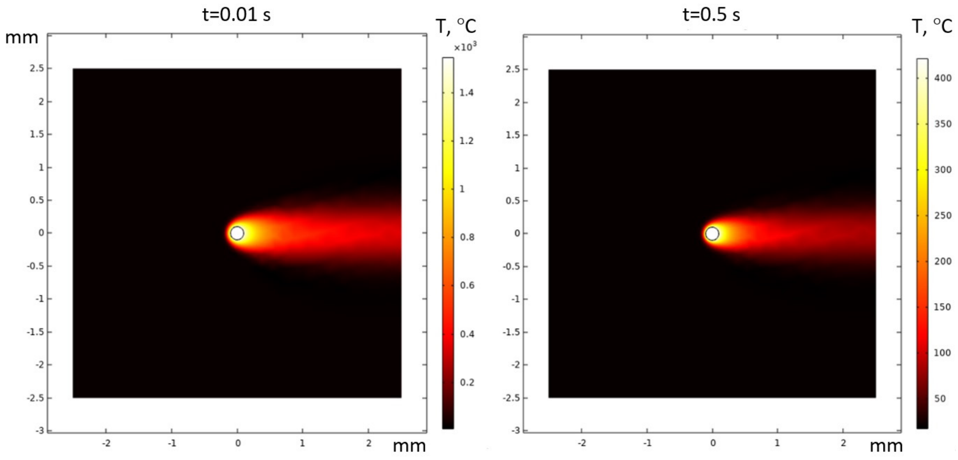


Fig. 8. Velocity field for a titanium particle in an argon environment

Рис. 8. Поле скоростей титановой частицы в аргоновой среде



a *b*

Fig. 9. Particle cooling pattern depending on time in argon:
a – t = 0.01 s; b – t = 0.5 s

Рис. 9. Картина охлаждения частицы в зависимости от времени в аргоне:
a – t = 0,01 c; b – t = 0,5 c

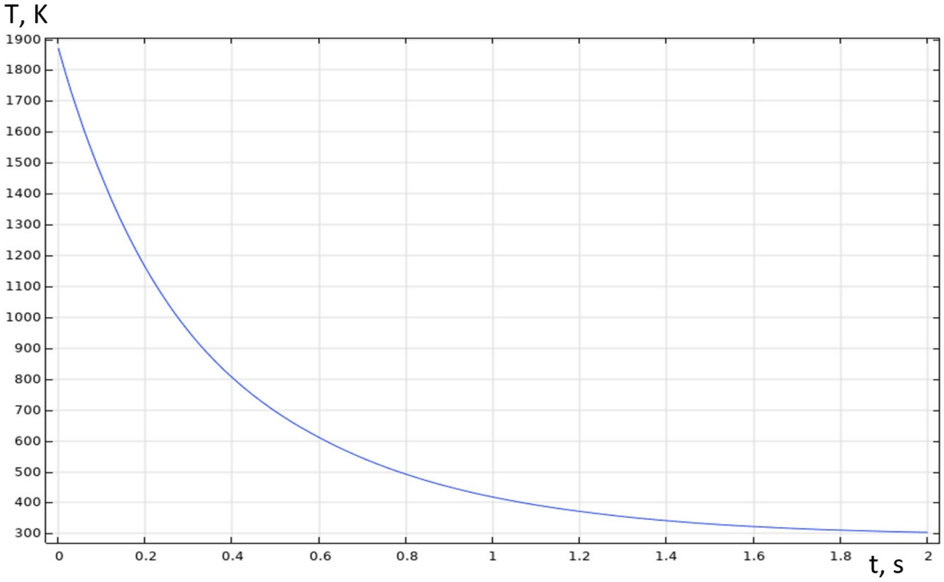


Fig. 10. Time dependence of particle temperature in argon

Рис. 10. График зависимости температуры частицы от времени в аргоне

Conclusions

1. The paper substantiates the possibility of using the method of arc spraying by a single- and multi-jet plasma torch to obtain fine metal particles, on the basis of which the patent [28] was obtained.

2. Based on the results of the developed calculation methodology taking into account the properties of the plasma-forming gas, an analysis of the operability and stability of this technology was made at gas flow rates G = 0.3–0.5 g/s.

3. A comparison was made of plasma technology at different operating frequencies, and it was found that at an increased frequency in the range of 1–10 kHz, the operating characteristic of arc plasma torches PN-PA1 is more efficient than at a frequency of f = 50 Hz.

4. Based on the mathematical calculation describing the effect of the plasma flow on the metal workpiece including the rate of melting

and movement of the metal during cooling, the parameters of the technological chamber and the operating modes of the technological equipment were found.

5. An analysis of the cooling of titanium particles was made in two different gaseous environments: argon and helium. The conclusion is drawn on the choice of the best technical gas both for ignition of the plasma arc and for filling the technological chamber.

6. A new design of the high-speed plasma torch PN-PA1 with a shortened arc channel for metal products sputtering has been developed and tested.

7. A titanium powder with high sphericity and fraction of 20–60 μm was obtained, which is suitable for use in additive technologies.

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