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FEATURES OF OBTAINING POWDERS FOR ADDITIVE MACHINES BY PLASMA SPRAYING

Ermakov Sergey✉**, Shvecov Oleg**

Peter the Great St. Petersburg Polytechnic University, 29 Politechnicheskaya st., St. Petersburg, 195251, Russia

✉ ermakov_sb@spbstu.ru

Abstract. The authors of this work have developed a model range of plasma atomizers, allowing to realize rapid production of metal powders of various chemical compositions. Up to date, powders of ferrous – low-alloy and carbon steels, stainless chromium-nickel and chromium-nickel-manganese steels, titanium, copper, niobium alloys, and heat-resistant alloys have been manufactured and have passed industrial testing, proving the possibility of their use in additive machines. The paper presents data confirming the possibility of using the method of plasma spraying of solid feedstock to obtain high-quality powders for additive machines and the results of studies of the influence of plasma spraying energy-power parameters on the geometric dimensions of the resulting powders, their crystal structure, and main characteristics. Data on the mechanical properties of samples made from sprayed powders are also provided.
Keywords: additive technologies, plasma spraying, powders, plasma atomizers

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1. Introduction

Additive technologies are increasingly used in various branches of science and technology, an increasing number of details, points, and finished products are obtained by printing on various types of 3D printers. One of the problems that must be solved when developing technology for receiving products by 3D printing is the initial metal powders, which are subject to fairly strict requirements for chemical purity and the absence of oxide films on their surface, sphericity, compliance of their sizes with the requirements for the granulometric composition of raw materials required by the operating instructions of 3D printers, various manufacturers. The product range development requires an expansion of the number of brands of materials used for printing.

The main methods of obtaining powders for additive machines are the dusting of solid metals or their melts by a high-pressure gas jet. It is on the use of the effect of crushing metal melts by a gas jet that is the most widely used method of obtaining powders for additive machines is based – gas atomization. However, modern gas atomizers are very large and expensive devices designed primarily for the production of large batches of powders of the

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same or similar chemical compositions. Obtaining small industrial batches of several tens of kilograms in size on such machines is not cost-effective enough, while for experimental production enterprises, where it is required to produce several test details, batches of one to ten to twenty kilograms of powders of various chemical compositions are required. Considering that powders have an increased oxidation rate, their long-term storage is a sufficiently complex technological process, and the purchase of the necessary powder formulations requires a very long time, large companies have mastered the process of producing small commercial batches of powders at their enterprises. According to a number of studies, the most cost-effective method for the production of small batches of powders is plasma spraying, based on spraying solid blanks (feedstock) of the material of the required chemical composition in a high-temperature gas-plasma flow. The reason for the plasma atomization method spread was that a number of studies have established that the maximum chemical uniformity of the resulting powder and the stability of its granulometric composition is achieved when solid feedstock wires of the sprayed substance are sprayed with gas streams, and this flow should have temperature significantly higher than the feedstock melting point.

The simplest and most technologically accessible method of such spraying is the method of spraying with a gas-plasma torch created by an arc plasma torch. The use of arc plasma torches makes it possible to regulate the energy-power parameters of the plasma within a wide range, therefore, plasma atomization is the most promising method for obtaining small commercial batches of powders for additive machines [10,11].

The method of plasma atomization allows to adjust the main characteristics of the obtained powders, for example, an increase or decrease in the feed rate of the plasma-forming gas changes the kinetic energy of the gas-plasma torch, and leads to a greater or lesser crushing of the melt droplets – that means, it is possible to regulate the granulometric composition of the resulting powder; by changing the strength of the current supplied to the plasma torch, it is possible to regulate the feedstock melting rate and the instantly sprayed liquid volume, by regulating the protective gas supply volume and, due to this, the gas atmosphere temperature in the atomizer spray chamber volume, it is possible to influence the processes of particle crystallization, liquation and segregation of the main alloying and impurity elements in the volume of the powder particles obtained.

Special attention should be paid to the feedstock sprayed diameter during the plasma spraying process. When choosing the feedstock diameter of the sprayed substance, it is necessary to take into account the main thermophysical sprayed metal properties, including the melting point, heat capacity, and thermal conductivity.

From an economic point of view, an increase in the feedstock diameter makes it possible to increase the spraying process productivity, on the other hand, an increase in its diameter leads to a decrease in the number of small particles in the powder since when using wires of large diameters, the moment mass of the melt entering the dusting zone increases and the percentage of explosive spraying of large primary droplets decreases [12]. This leads to certain contradictions, since on the one hand, an increase in the diameter of the wire is an increase in the productivity of the process, on the other hand, an increase in the diameter is an increase in the average particle's diameter of the resulting powder, a decrease in the yield of marketable products (usually powders with diameters from 100-140 to 10-20 microns). Determining the optimal ratio between the granulometric composition of the obtained powder and the diameter of the feedstock used is one of the most important tasks in the development of plasma treatment technology and modes [13,14].

Plasma spraying units for solid feedstock - plasma atomizers are easy to operate, do not require significant initial investments, and are easily converted to the production of powders from a variety of materials – from easily fusible solders and aluminum to refractory niobium, molybdenum, and tungsten. The plasma atomizers productivity is small and usually does not exceed 5-10 kilograms of product per hour, however, this allows to provide the experimental production of the enterprise with the necessary amount of the required powder for one or two working days. The advantages of plasma atomizers should also include the high quality of the powders obtained, their sphericity, the possibility of regulating their granulometric composition.

The fact is that the method of plasma atomization of metallic materials ensures maximum productivity in the medium-sized powders production – that is, powders with diameters from 40 to 140 microns. In the production of this group of powders, the yield of commodity fractions of powders sprayed on a plasma atomizer in this work was in the range of 60-65%, while providing an average particle size of 20-40 microns, the yield of commodity fractions averaged 30-32%. The process of a metal particle formation during spraying in a low-temperature plasma can be conditionally divided into several stages - the formation of a large drop of irregular shape, it's explosive spraying into small spherical droplets, their crystallization, cooling of the particle during movement in the gas volume of the spray chamber, the temperature of which is tightly controlled, and, finally, the collection of particles of dusty powder without access to them by an external aggressive environment.

The droplet lifetime at the wire end is significantly less than the lifetime of the droplet occurring at the end of the welding electrode or welding wire in protective gases, which is due to the gas plasma torch high speed and its instantaneous separation from the feedstock surface. Separation is carried out by various forces: arc pressure, reactive forces during metal evaporation and gas release, gravitational forces, surface tension forces, electrodynamics forces, etc. [15-17]. At the separation moment, the drop is characterized by certain dimensions, temperature, and initial velocity. The drop average diameter (d_k) can be estimated by the formula [9]:

$$d_k = \frac{\pi \sigma d_1 d_2}{\mathrm{M}_1 V_1 + M_2 V_2}, \qquad (1)$$

where σ – the surface tension coefficient of the feedstock material in the contact zone of metal and plasma arc; d_1 – feedstock diameter; d_2 – diameter of the plasma torch nozzle; M_1 and M_2 – plasma-forming and stabilizing gas mass; V_1 and V_2 – the rate of plasma-forming and stabilizing gas.

After separation droplet moves in an environment of almost cold protective gas, the temperature of which does not exceed several tens of degrees, gradually crystallizing and cooling. Depending on the spraying conditions, the melting temperature of the sprayed material, the free path of the particle inside the spray chamber (before impact with the chamber bottom), the protective medium may have a reduced, normal or increased pressure, be either stationary (in the absence of additional gas volumes through the nozzles of the "fluidized bed" belt located in the middle part of the cylindrical surface of the spray chamber), or mobile. In this case, the speed and direction of gas movement will be determined by the parameters of the blowing "fluidized bed system".

2. Methodology

A plasma atomization unit for metal feedstock was developed in this paper. Based on this development, plasma atomizers of various types have been manufactured, have been commercially tested, and are being successfully operated.

Figure 1 shows a schematic diagram of the most universal plasma atomizer, allowing regulating the performance of the device within a wide range by using one or three independently operating plasma generators – arc plasma torches in it at the same time. This device uses three plasma torches with inter-electrode inserts located on the spray column top cover and separated from each other by 1200. Each of the plasma torches can be given its own energy-power parameters of spraying – it means, it is possible to spray wires or one chemical composition, or several different materials, which can be used in the manufacture of raw materials for mechanic-alloying. It is possible to conduct the spraying process with a single plasma source in this device. To do this, an additional hatch is provided in the center of the upper cover for installing a plasma torch. Feedstock – wires of sprayed materials with diameters from 21 to 3.5 mm are supplied horizontally. Wires of the following materials were used for the research: steel 20G (0,18%C, 0,78%Mn); steel 07KH16N6 (0,07%C, 0,71%Mn, 16,2%Cr, 5,8%Ni), steel 37KH12N8G8MFB (0,36%C, 11,7%Cr, 8,1%Ni, 8,4%Mn, 1,2%Mo, 1,3%V, 0,4%Nb), heat-resistant alloy KhN60VT (0,07%C, 26,1%Cr, 64,1%Ni, 0,4%Mn, 15,0%W, 0,6%Ti, 0,4%Al), nickel alloy Inconel 718 (0,07%C, 56,2%Ni, 21,7%Cr, 9,1%Mo, 3,8%Nb, 0,8%Co, 0/4%Mn, 0,3%Ti), titanium alloy VT6 (89,0%Ti, 4,7%V, 0,2%Zr) and copper alloy BrAZH9-4 (85,8%Cu, 9,2%Al, 3,7%Fe). The all-wires diameters were chosen equal to 1.2 and 2.0 mm.

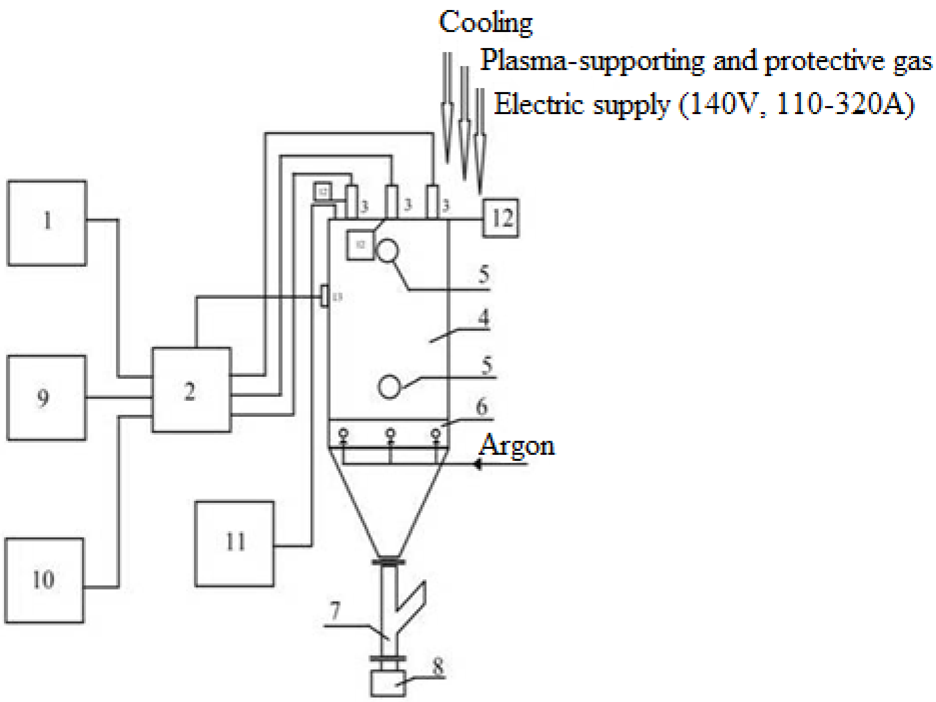

Fig. 1. Schematic diagram of the plasma atomizer: 1. Power supply, 2. Control and safety unit, 3. Plasma torches (three-plasmatron arrangement), 4. Spray column, 5. Peeping windows for visualizing the spraying process, 6. "Fluidized bed" belt - a system of multidirectional injectors through which protective gas is supplied, 7. Plasma-forming gas removal system during spraying, 8. Powder collection system, 9. Gas system, 10. Plasma torches cooling system, 11. Spray column cooling system, 12. Solid feedstock, 13. Measuring equipment (control and safety device)

The wire feed rate during the experiments varied from 1 to 5 m/min. High purity argon was used as the plasma-forming and protective gases, the plasma arc power was regulated by the current torches supplied to the plasma and ranged from 110 to 320 A for different alloys, and the voltage was 140 V. The plasma-forming gas velocity was estimated in liters of gas per minute and ranged from 35 to 55 l/min. The protective gas pressure in the spray chamber volume was equal to 1 at, the gas flow rate introduced through the "fluidized bed" system was regulated from 0 to 20 l/min.

3. Research results

At the first stage of the experiments, the optimal energy-power parameters of spraying for each of the alloys and the effect of feedstock diameters on the granulometric composition of the powders obtained were determined. By the example of two alloys – steel 37KH12N8G8MFB and Inconel 718 high-nickel alloy the data on the effect of the current strength (I) and the velocity of the plasma-forming gas (VPG) supplied to the plasma torch, as well as the feedstock diameter (D) on the granulometric composition and the percentage of yield of commercial fractions of sprayed powders are presented (Table 1).

Table 1 shows data on the average particle diameter of sprayed powders – d_{50} in the volume of commodity fractions of 40-140 microns, the percentage of yield of commodity fractions (T1 and T2 – the yield of commodity fractions when collecting powders of 20-40 and 40-140 microns, relatively) and the mass of the resulting powder per plasma torch at a spraying time of 60 minutes. The wire feed rate and the volume of protective gas supply in these experiments remained constant and equal to 2.5 m/min and 10 l/min, relatively.

According to the above data, the best results in terms of commodity fractions yield percentage are obtained when using feedstock with a diameter of 1.2 mm, increasing the diameter to 2 mm slightly reduces commodity fractions yield percentage, however, when converting the results into absolute values, the result is the opposite – the maximum mass of powder sprayed from feedstock with a diameter of 1.2 mm when calculated for one active plasma torch was 918 g – Inconel alloy 718 and 858 of 37KH12N8G8MFB steel, when using feedstock with a diameter of 2 mm, these values increased to 2.435 and 2.387 g, relatively, or 7-7.5 kilograms of commercial powder per hour.

Table 1. The current strength (I) effect and the velocity of the plasma-forming gas supplied to the plasma torch and the feedstock diameter on the granulometric composition and the yield of commercial fractions percentage of sprayed powders

Aloy	D, mm	I, A	V_{gs}, l/min	d_{50}, µm	Commercial fractions yield (%)		The resulting commercial powder fractions mass (g)	
					T_1	T_2	20-40 µm	40-140 µm
37KH12N8G8MFB	1.2	200	30	96	18	41	238	531
			60	71	24	52	318	690
		300	30	82	24	59	319	782
			60	66	30	65	398	858
	2.0	200	30	114	9	37	330	1354
			60	81	16	46	588	1693
		300	30	86	21	54	772	1984
			60	67	29	65	1070	2387
Inconel 718	1.2	200	30	86	17	39	238	541
			60	70	23	57	321	852
		250	30	68	21	52	293	734
			60	60	34	66	476	1238
	2.0	200	30	91	14	47	544	1812
			60	86	22	51	795	1968
		250	30	70	19	47	725	1812
			60	60	32	63	918	2435

During the research, the optimal technological parameters of the atomizer operation were determined to obtain the maximum amount of powders of commodity fractions of each of the alloys under study – Table 2. All the results in the table are averages obtained after five spraying cycles according to the optimal mode of operation of the atomizer determined at the preliminary stage of work.

The obtained particles of alloy powders were investigated for the possibility of their application in additive machines of direct and selective fusion. It was found that the powder particles of all alloys meet the necessary requirements and can be described as spherical particles of regular shape with a degree of disequilibrium from 1.0 to 1.1 (GOST 58418) – Fig. 2 and the level of sphericity is in the range of about 95% (alloy VT6) to 98% (steel 20G 07KH16N6, BrAZH9-4) – Fig. 2(a), oxides and other non-metallic compounds were not detected on the particle's surfaces. The maximum number of satellites was detected in the powder of the Inconel 718 alloy and did not exceed 0.5% – Fig. 2(b), the maximum number of particles with external and internal pores of the VT6 alloy – Fig. 2(c,d) – less than 0.25% of the powder particles total number.

Table 2. The average particle size of the sprayed powder and the percentage of yield of commodity fractions, the speed of the protective gas supply is V_{pg}, the wire feed rate is V_{wr}

Alloy	Parameters of the atomizer operation				$d_{50,}$ μm	T_1	T_2
	I, A	V_{gs}, l/min	V_{pg}, l/min	V_{wr}, m/min		%	
20G	250	50	10	2.5	70	34	64
07KH16N6	250	45	15	2.5	53	31	63
37KH12N8G8MFB	290	50	15	2.0	68	29	64
Inconel 718	230	50	12	3.0	61	32	62
KHN60VT	310	55	15	2.0	60	32	61
VT6	340	50	20	1.75	68	29	59
BrAZH9-4	115	35	10	3.0	65	32	64

One of the most important indicators of powder quality is the stability of the crystallization structure of the resulting particles. Metallographic studies of particles crystallized under various sputtering conditions allowed us to assert that the crystallization of powder particles obeys the laws of the so-called constitutional super cooling associated with the morphological instability of the crystallization front, in which there is a violation of the stability of the flat crystallization front. As it was mentioned by B. Chalmers [13] in the case of constitutional super cooling, due to the non-uniformity of the longitudinal temperature gradient from the solid crystal front, bulges increase in certain sections of the front takes place in the melting.

The formed "bumps" lead to the impurities runoff and the formation of a transverse concentration gradient of impurities from the axis of the "bump" to its borders (walls). In this case, a cellular crystallization substructure arises (Fig. 3(a)). Cell growth according to [3] occurs until the combined action of the super cooling gradient with the latent heat of melting released leads to the fact that such a bulge does not fall into the zone where super cooling is sufficient only to create the necessary kinetic driving force of growth. In this case, the cell dimensions in the transverse direction are stabilized, and the cell growth is carried out only in the longitudinal axis direction.

The curved shape of the cell front surface leads to the fact that it acquires a temperature of stable growth exceeding the temperature of the initial flat interface. This can lead to a decrease in the impurity elements concentration, primarily phosphorus, and sulfur, in the solid phase – pushing them towards the cell walls, which form low spots on the particle surface.

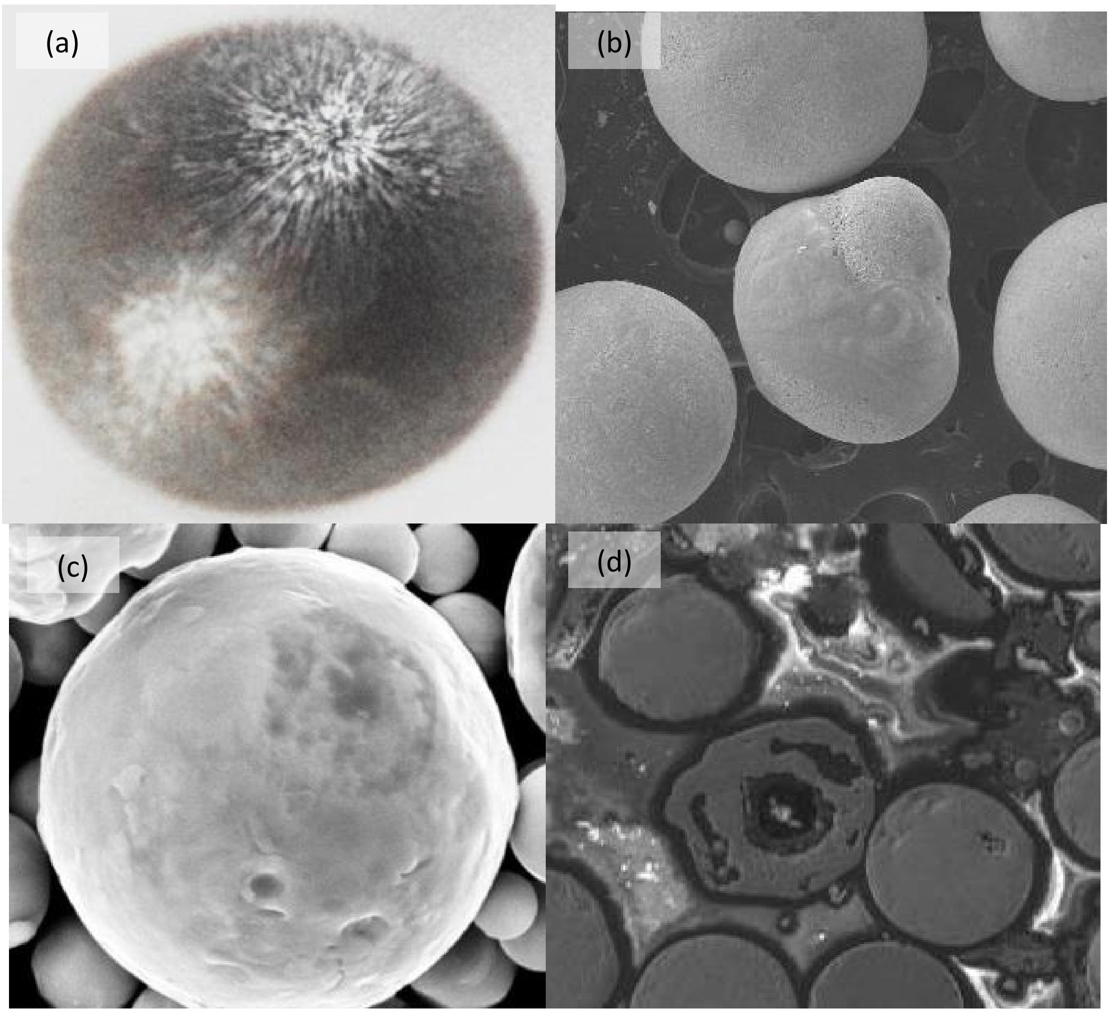

Fig. 2. Particles and microslips of sprayed powders: (a) – is the typical form of dispersed powder particle (steel 20G), (b) – satellites in the sprayed powder Inconel 718, craters (c) and pores (d) in the powder VT6 particles [x1000]

The resulting low spots on the crystallization front in the places where the cell walls are formed lead to the appearance of new bulges of the front and provoke the appearance of neighboring cells around the initial protrusion. New cells are arranged in the form of a densely packed structure, according to theoretical calculations – mainly in the form of a hexagonal structure – that is, each of the cells has basically six neighbors [3-6].

According to the data [6-8], it was possible to formulate a number of predictions for the crystallization of a powder particle, which required experimental verification:

1. It should be expected that impurities concentration in the volume of cells is uneven – minimal along the longitudinal axis of crystallization, increases as it approaches the cell walls and maximum in its corners.
2. There is a possibility that the cells formation increases with an increase in the rate of crystallization growth, and with its decrease, the probability of crystallization appears according to the classical – dendritic mechanism.

Thus, it can be assumed that the cell will size directly depends on the rate of its growth along the axis of the temperature gradient – the lower the temperature gradient and, consequently, the rate of cell growth, the more distance the impurity atoms will be able to overcome during diffusion in the transverse direction before they form an interface.

Analysis of the metal microstructure of alloy powders showed that when the temperature gradient decreases, the correct cellular shape of the crystallized particle

(Fig. 3(b)) gradually shifts towards cellular-dendritic (Fig. 3(c)) or dendritic, and cellular structures can form around free dendrites. That is when the temperature gradient decreases – a dendrite appears at the first stage and cellular crystallization structure forms around it.

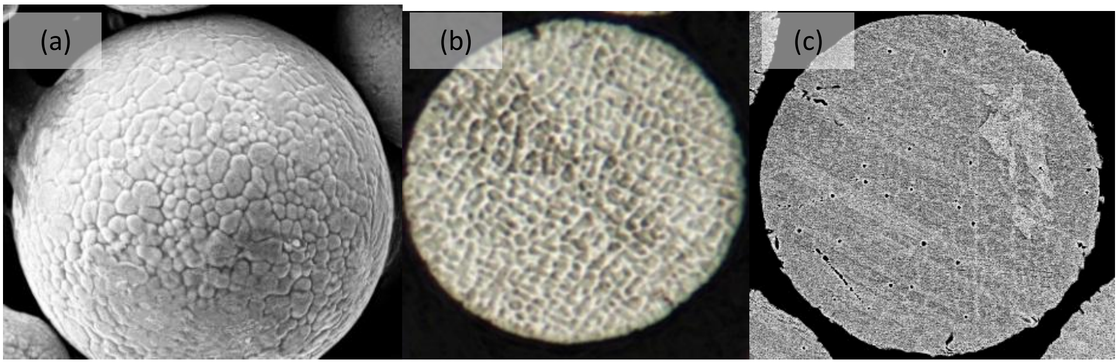

Fig. 3. Inconel 718 alloy. The appearance of a particle, crystallized by the mechanism of cellular crystallization (a) and micro slips of powder particles: (b) – cellular crystal structure, (c) – mixed structure – cellular matrix with structurally free dendrite [x500]

Cellular-dendritic growth of the crystallization front in a powder particle is a transitional form between cellular growth, which is a stable variant of a thin zone of constitutional supercooling, and free dendritic growth, which occurs as a result of the removal of latent melting heat outward from the crystal growing in the super cooled melt, due to the liquid high thermal conductivity.

Thus, the studying of the obtained metallographic analysis data and literature sources allowed us to make the following assumption about the process of crystallization of the micro-volume of molten metal in the volume of a powder microparticle.

Mathematical modeling of the crystallization process and a powdered particle cooling in the atomizer spray chamber, using a supercomputer, allows us to estimate the time of a powder particle spheroidization, which for the studied alloys is from 1.5 to 2.0×10^{-7} seconds, the time of separation of latent heat of crystallization from the particle volume is on average 5×10^{-3} seconds, and to estimate the total time of spheroidization, crystallization and the time spent by the powder particle to overcome the separation from the feedstock to the collection system powder – about 10^{-2}-10^{-3} seconds. During the simulation, the following assumption was made. Considering that the melting temperatures of all alloys, with the exception of BrAZH9-4, are in the range of 1800-1500°C, the primary drop temperature at the initial stage of crystallization was conditionally assumed to be equal to the average melting temperature of alloys – 1700°C. The temperature of the particle at the moment it touches the cone wall of the powder collection system is equal to the average temperature of the protective gas in the lower third of the spray chamber – 180-230°C. Then the difference between the initial and final temperatures is (approximately) 1500°C, and the maximum time spent on cooling is 10^{-2}-10^{-3} seconds, relatively, the particle cooling rate is in the range from 1×10^{5} to 2×10^{6} degrees per second.

During mathematical modeling of spraying processes, it was established that the time from a metal drop formation at the end of the feedstock, to the solidification of the particle and its cooling to temperatures that stop diffusion processes, is significantly less than one second and a significant diffusion redistribution of elements should not be expected. The absence of liquation and segregation processes in the powder particles metal is fully consistent with the cellular crystallization theory described by Chalmers and is confirmed by the microemission spectral analysis results conducted using attachments to scanning electron microscopes TESCAN-VEGA and SUPRA 55VP WDS.

Obviously, such conclusions cannot be considered strictly accurate, for each powder particle of each alloy, the crystallization rate of each liquid metal microdrops is different and depends on the presence or absence of a longitudinal temperature gradient, however, according to the analysis results of the particles crystal structure, it can be argued that the presence of a longitudinal temperature gradient necessary for the cellular mechanism of crystallization of the powder particles absolute majority is ensured by optimal conditions for cooling and crystallization of metal droplets in the spray chamber – that is, the optimal temperature ratio, velocity and direction of gas flows in the chamber, and the dendritic components structure appearance indicates the occurrence of delayed cooling local zones – deposits on the chamber walls, leading to local overheating of the walls, the formation of closed gas flows in the volume of the chamber, etc.

The overheated areas appearance, associated with the deposits of fine powder particles appearance (less than 20 microns) on the spray chamber walls is usually caused by the formation of gas flows closed in the volume of the chamber, directed along the walls of the spray chamber and pressing the particles of small fractions to the inner chamber surface.

Figure 4 demonstrates the results of mathematical modeling allowing us to estimate the distribution of gas flows and temperatures of the spray chamber wall in the conditions of the optimally selected mode and the spray mode carried out with deviations from the optimized parameters. The figure shows the calculation of the temperature of the chamber wall and the directions and velocity of the gas flows with a deviation from the only optimized parameter – the protective gas flow rate.

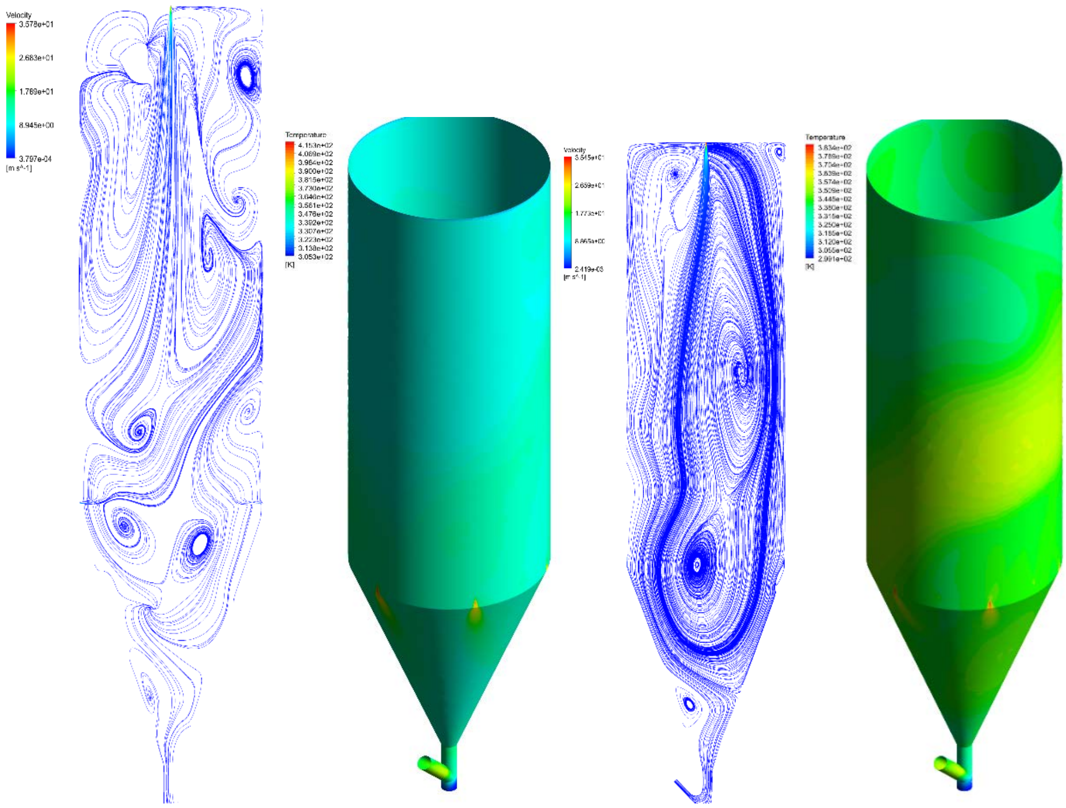

Fig. 4. Mathematical model of gas flows and temperatures distribution of the spray chamber wall at optimal (see Table 2) the spraying steel feedstock mode of 06H16N7 and with a decrease in the rate of the protective gas supply V_{gs} from 15 to 5 l/ min

It was found that exceeding the chamber wall temperature by 20% of the optimal one leads to the formation of 10 (VT6) to 18% (BrAZH9-4) powder particles crystallized by mixed or dendritic mechanisms; and at 50% excess, this amount increases from 25 (37KH12N8G8MFB) to 50% (BrAZH9-4). The proportion of satellite particles and particles with a crystal structure of a mixed type is also growing – with a 20% excess of the chamber wall temperature, the proportion of satellites in the Inconel 718 alloy powder increased from 0.5 to 3-4%, and the number of particles with cellular matrix and structurally free dendrites increased to 15-25%.

Analysis of the chemical element's distribution in the volume of particles, which we crystallized by the mechanisms of mixed and dendritic crystallization, showed that in this case, micro-volumes differing in the content of alloying and impurity elements arise in the metal – cleaner (in terms of the content of impurities) and more doped dendrites and more contaminated with impurities - inter-dendritic areas.

The microliquations and segregation occurrence in the particles volume can adversely affect the quality of the products obtained and should be minimized by strict control of temperature and protective gas flows in the spray chamber. Since it is quite difficult to ensure constant control of the gas temperature during the spraying process, a scheme, allowing to control this temperature by an indirect method - by measuring the temperature of the atomizer spray chamber wall, was proposed.

Based on the experimental results, it was found that the main technological spraying parameters, ensuring the quality of the powder being produced, should include: the current strength supplied to the plasma generator; the speed of the plasma-forming gas; the gas temperature in the volume of the spraying chamber and the gas supply rate directly connected with it to the counter-flow system and the creation of a so-called "fluidized bed" in the path of moving particles, in which braking and additional cooling of the powder occurs; the chemical composition of the sprayed material is its melting point and other their thermophysical properties. By optimizing these parameters, it is possible to obtain spherical powders of various steels and alloys by spraying solid feedstock in a gas-plasma torch. In case the technological mode of spraying the material is selected correctly – taking into account the thermophysical characteristics of the sprayed material, it is possible to obtain powders of the correct spherical shape with a minimum number of satellites, surface and volume defects, the absence of segregation and liquation of both alloying and impurity elements by particle volume. To confirm the possibility of using these powders in additive machines, samples for mechanical tests were made. They confirmed the compliance of the mechanical properties obtained by direct and selective laser fusion of samples made on additive machines and samples made from blanks of these steels and alloys obtained by traditional methods. According to the modes given in Table 2, sprayed blanks with dimensions of 250×100×5 mm were made from the obtained powders for this. In order to test the effect of chemical inhomogeneity of particles associated with a change in the cellular crystallization mechanism to a mixed or dendritic one on the mechanical properties of samples obtained by additive methods, samples for mechanical tests were also made from 07KH16N6 steel powder with a 20% content of particles with a mixed crystallization mechanism.

All samples before the tests were thermally treated according to the modes recommended for the studied alloys and tested for uniaxial static tension at 200°C. The results of mechanical tests are given in Table 3.

As mentioned in Table 3, the mechanical properties of the samples obtained by additive fusion practically correspond to the properties of steels and alloys made by traditional methods. This allows us to assert that powders sprayed in a plasma atomizer can be successfully used for production by direct or selective laser fusion of parts and assemblies of machines and mechanisms for various purposes, and the spraying technology itself and the equipment developed for this purpose can be widely used both in experimental production and research complexes of large companies and enterprises specializing in additive manufacturing.

Table 3. Mechanical properties of samples obtained by additive and traditional methods

Alloy	Additive methods			Traditional methods		
	σ_B	$\sigma_{0,2}$	δ_5	σ_B	$\sigma_{0,2}$	δ_5
	MPa		%	MPa		%
20G	450	275	24	462	280	22
07KH16N6[1)]	1000	890	14	995	890	15
07KH16N6[2)]	945	900	9	-	-	-
37KH12N8G8MFB	990	610	22	975	605	21
KHN60VT	750	320	46	700	325	41
Inconel 718	1075	950	22	1050	930	19
VT6	1100	-	16	1100	-	15
BrAZH9-4	480	-	42	455	-	39

Note: σ_B – tensile strength; $\sigma_{0,2}$ – yield strength; δ_5 – elongation

4. Discussion of results

The intensive development of additive manufacturing, the creation of new technologies and enterprises for the production of metal powders provoked the need to organize information about the impact of the initial powder's quality on the final product properties - printed on 3D printers – machine details and mechanisms for various purposes. The insufficient variety of chemical compositions of steels and alloys offered on the market limits the possibilities of using additive technologies narrows the possible range of manufactured products. One of the ways for further development of additive technologies is the creation of specialized production of metal powders within large companies. Since additive machines are primarily used in the conditions of experimental and research units, such productions should have increased flexibility – quickly and without significant investments to be rebuilt to produce powders of various chemical compositions.

In this case, it is most promising to equip such productions with atomizers using plasma powder spraying systems. Such atomizers are compact enough, easy to operate, do not require highly qualified service personnel, and allow for the transition from one type of powder product to another in the shortest possible time. So, in the case of using atomizers, the production transition time from one powder composition to another does not exceed 30-40 minutes. Powders obtained by plasma atomization have a high level of sphericity and a minimum number of particles with external and internal defects, which fully meet the requirements for powders for additive machines.

The only disadvantages of plasma atomization are the necessity of using sufficiently thin feedstocks – usually, the optimal thicknesses of wires are in the range from 1 to 3 mm, and the relatively low process productivity, that, however, is quite sufficient for the needs of experienced and research units. One of the most important factors ensuring the operability of parts manufactured on 3D printers is the quality of the powders used in the fusion process. In addition to the traditional geometric requirements for particles, their fluidity and bulk density, interparticle and intraparticle stability of chemical composition should also be attributed to the concept of quality. If the issue of interparticle stability under plasma sputtering conditions has been successfully solved for a long time, then the issues of intraparticle stability are still very relevant and require further research.

An attempt to link the problem of the intraparticle stability of the material's chemical composition and its crystallization structure was made in this paper. In the course of the research, it was found that the type of crystallization structure of powder particles and the associated stability of its intraparticle chemical composition depends on the correctly selected spraying mode, crystallization conditions, and cooling of powder particles in the atomizer chamber.

It is demonstrated, that from the point of view of stability within the partial chemical composition of the sprayed powder, the cellular crystallization structure is optimal, forming columnar crystals in the particles, the axis of which is directed along the super cooling gradient. The extremely short crystallization time of a metal drop moving in a gas stream does not allow stable liquation's and segregation of alloying and impurity elements to form within the boundaries of cells, as a result of which it is possible to achieve satisfactory uniformity of the chemical composition of the metal both in the volume of a single cell and in the volume of the particle as a whole. Violations of the thermal regime in the spray chamber, slowing down the rate of cooling and crystallization of particles lead to a gradual change of the cellular structure of crystallization to a mixed cellular-dendritic and even dendritic crystallization structure.

The appearance of even structurally free dendrites in the volume of the cellular crystallization powder particle structure leads to a decrease in the mechanical properties, first of all, the plasticity of samples obtained by direct and selective laser fusion methods, which is associated with the occurrence of segregation and liquation of elements between the dendritic formation and the inter-dendritic region in the particles crystalline structure.

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THE AUTHORS

Ermakov Sergey Borisovich
e-mail: ermakov_sb@spbstu.ru
ORCID: 0000-0003-4243-0984

Shvetsov Oleg Viktorovich
e-mail: shvec_off@mail.ru
ORCID: 0000-0001-9368-4074