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INFLUENCE OF THE PARAMETERS OF THE PROCESS OF PLASMA-ARC SPHEROIDIZATION OF CURRENT-CONDUCTING WIRE FROM LOW-CARBON STEEL ON THE GRANULOMETRIC COMPOSITION OF THE PRODUCED POWDERS

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ABSTRACT

The possibility of producing spherical powders by application of the technology of plasma-arc spraying of current-conducting wire of 1.6 mm dia. from low-carbon steel was experimentally confirmed. It was found that at different parameters of plasma arc spraying in the general case the main fraction of the powder is 25–250 μm fraction, which amounts to 95 % of the powder overall volume, quantity of particles of < 25 and 250–315 μm fractions in optimum spraying modes is at a rather low level and is not more than 5 %. The plasma-arc spraying mode was selected, which will ensure a change of the granulometric composition towards increase of the content of fine fractions (< 80 μm), which are in great demand in the field of additive 3D printing technologies: current — 280 A; wire feed rate — 12.0 m/min; arc gap length — 8 mm; plasma gas flow rate — 50 l/min; concurrent gas flow rate — 60 m^3/h; gap between plasma-forming and compression nozzle — 1 mm; cathode immersion depth — 1 mm. The shape and structure of the atomized particles was studied, most of which generally have a regular spherical shape. Here, the sphericity coefficient depends on process parameters and is equal to 0.7–0.9 on average at optimal spraying modes. In the total mass of the obtained spherical powders the share of satellites and isolated particles of an irregular shape is close to 1–3 %.

KEYWORDS: current-conducting wire, plasma-arc spraying; melt dispersion, powder spheroidization, solidification, spherical powder, mode parameters, granulometric composition

INTRODUCTION

Intensive development of powder metallurgy, additive technologies of 3D printing of metallic products (selective and direct laser melting and sintering (SLM, SLS, DMLS, granular metallurgy etc.)) requires creation of new materials in form of spherical granules and powders of complexly-doped alloys, refractory metals and intermetallics with set granulometric composition and rigid requirements to shape of particles (sphericity coefficient) and presence of minimum amount of defective particles [1].

The most widespread methods of production of such granules and powders are the technologies of gas atomization (GA) and plasma rotating electrode process (PREP) [2, 3]. However, regardless the large number of advantages these technologies have a series of disadvantages, including complexity of manufacture of < 100 μm powders; problems related to manufacture of rod stock for PREP; closed argon pores and relatively low sphericity coefficient for GA etc. [4, 5].

Today a technology of plasma-arc spraying being of a wide practical interest [6–9] is a perspective method for production of spherical powders with set granulometric composition. Among the advantages of this method are simplicity of the equipment that significantly simplifies the process of powder production and presence of large number of the parameters due to which it is possible to regulate the granulometric composition in a wide range as well as possibility of production of spherical powders of refractory materials [10–12].

Currently, there are not enough investigations on effect of the parameters of plasma-arc spraying mode on nature of distribution of sprayed particles on fractions, the results of the investigations are scattered, no information available on effect of some structural parameters of plasmatrons on change of granulometric composition of the particles being sprayed. Therefore, the aim of this work is investigation of effect of the mode parameters of plasma-arc spraying on a process of melt dispersion and change of granulometric composition of powder.

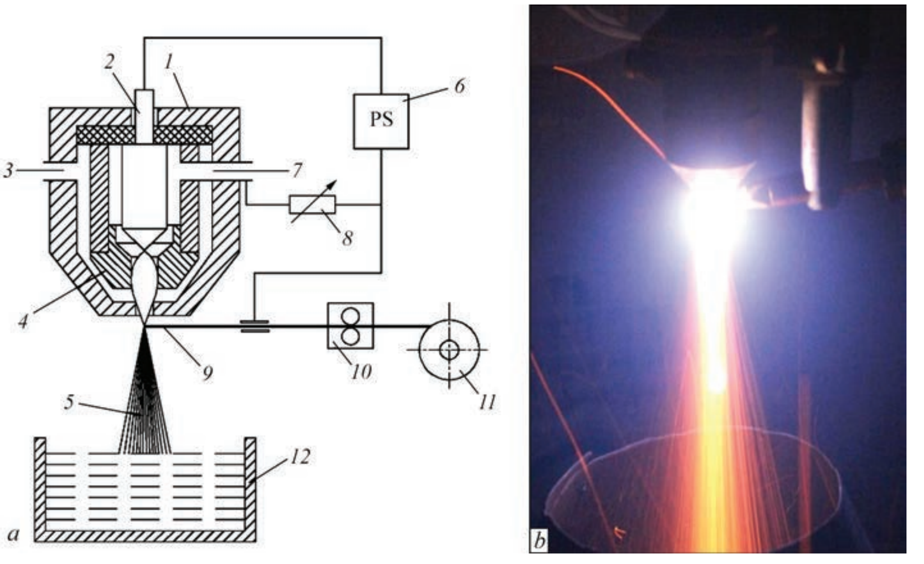

Figure 1. Scheme of the process of plasma-arc spraying and spheroidization of current-conducting wire (*a*) and appearance of spraying process (*b*): *1* — plasmatron operating chamber; *2* — rod electrode (cathode); *3* — channel for concurrent gas feed; *4* — plasma-forming nozzle; *5* — jet of particles being sprayed; *6* — power supply; *7* — channel for supply of plasma-forming gas; *8* — current-limiting resistor; *9* — wire (anode); *10* — feeding mechanism; *11* — wire coil; *12* — fridge with water

EXPERIMENT PROCEDURE AND EQUIPMENT

An essence of the process of plasma-arc spraying lies in melting of a current-conducting wire (anode) which is entered in a zone of high-speed plasma jet and further fragmentation of the melt stripping from a wire end [13]. An arc burns between a nonconsumable tungsten cathode and a current-conducting wire (anode) being fed through a plasmatron nozzle. Working (plasma-forming) gas entering an operating chamber is heated with an electric arc and comes out from the nozzle in form of a plasma jet. Open section of a discharge out of the plasma-forming nozzle is blown round by a gas flow coming out of a circular gap between the plasmatron nozzles [14]. Among the peculiarities of this method is the fact that melting and jet spraying of the wire material is carried out by argon plasma, meanwhile melt fragmentation and acceleration of disperse particles is performed by a jet of cold concurrent gas. This provides minimum losses on evaporation of wire material (up to 2 %), obtaining the optimum fraction composition of disperse phase, reaching a near-sonic velocity by the particles of sprayed material etc. [15]. The technological experiments were carried out using a plasma-arc spraying unit PLAZER-30 [16], which was modified for realization of the process of spraying and spheroidization of steel wire and powder production (Figure 1).

Indicated equipment was used for examination of the granulometric composition of particles in spraying of low-carbon steel wire (anode) of ER70S-6 grade (Sv-08G2S) of 1.6 mm diameter (Table 1).

According to earlier obtained practical data, an optimum mode was selected using a criterion of visual assessment of shape of the plasma jet at its reaching a minimum opening angle and process stability. It was used for corresponding change of the parameters of mode in order to determine the effect of each of them on change of the particle granulometric composition. High grade argon I1 according to ISO 14175–2008 “Welding consumables — Gases and gas mixtures for fusion welding and allied processes” was used as a plasma-forming gas and air was used as a concurrent gas, nozzle diameter made 3 mm.

Effect of the variable parameters of spraying was investigated is the next ranges, namely current — 220–265 A, plasma-forming gas consumption — 30–70 l/min, concurrent gas consumption — 30–60 m^3/h, wire feed rate — 9.5–12.5 m/min, cathode-anode distance — 8–12 mm, gap between the nozzle and ring electrode — 1–3 mm, cathode immersion depth — 0–1 mm (Table 2).

Besides, there were considered such structural parameters of the plasmatron as a gap between inner and outer nozzle 1–3 mm, through which concurrent gas is passed constricting the plasma jet, and cathode immersion depth 0–1 mm (Figure 2).

Table 1. Composition of wire of 1.6 mm diameter of ER70S-6 (Sv-08G2S) grade, wt.%

Steel	C	Si	Mn	P	S	Cr	Ni	Fe
Sv-08G2S DSTU 2246–70	0.05–0.11	0.70–0.95	1.80…–.10	0.03	0.025	< 0.20	< 0.25	Base

Table 2. Experimental modes of plasma-arc spraying of wire from Sv-08G2S steel of 1.6 mm diameter

Number of mode	Current, A	Arc voltage, V	Consumption		Cathode–anode distance, mm	Length of cathode immersion, mm	Distance between the nozzles, mm	Wire feed rate, m/min
			argon l/min	air m^3/h				
1	220	75	40	48	8	0.5	2	10.5
2	235	76	–»–	–»–	–»–	–»–	–»–	–»–
3	250	80	–»–	–»–	–»–	–»–	–»–	–»–
4	235	72	30	–»–	–»–	–»–	–»–	–»–
5	–»–	76	40	–»–	–»–	–»–	–»–	–»–
6	–»–	78	50	–»–	–»–	–»–	–»–	–»–
7	–»–	69	40	36	–»–	–»–	–»–	–»–
8	–»–	76	–»–	48	–»–	–»–	–»–	–»–
9	–»–	79	–»–	60	–»–	–»–	–»–	–»–
10	–»–	76	–»–	48	8	–»–	–»–	–»–
11	–»–	82	–»–	–»–	10	–»–	–»–	–»–
12	–»–	93	–»–	–»–	12	–»–	–»–	–»–
13	–»–	72	–»–	–»–	8	0	–»–	–»–
14	–»–	76	–»–	–»–	–»–	0.5	–»–	–»–
15	–»–	77	–»–	–»–	–»–	1.0	–»–	–»–
16	–»–	84	–»–	–»–	–»–	0.5	–»–	–»–
17	–»–	76	–»–	–»–	–»–	–»–	–»–	–»–
18	–»–	69	–»–	–»–	–»–	–»–	3	–»–
19	–»–	76	–»–	–»–	–»–	–»–	2	9.5
20	–»–	76	–»–	–»–	–»–	–»–	–»–	10.5
21	–»–	76	–»–	–»–	–»–	–»–	–»–	11.5

The wire was sprayed in a vessel filled with water from distance 500 mm, time of spraying made 200 s. Selection of samples for examination of the granulometric composition of powder, morphology of surface etc. was carried out using a laboratory vibro shaker Analissettte 3 Spartan (Germany) with a set of sieves 25–500 μm, weight of the sample made not less than 100 g of powder. Examination of the grain- size composition of laboratory batches of the powder was carried out using the method of sieve analysis according to the procedure ISO 2591-1:1998 "Test sieving — Part 1: Methods using test sieves of woven wire cloth and perforated metal plate" with the help of vibro shaker Analissettte 3 Spartan with a set of sieves: 25–40, 40–63, 63-80, 80–100, 100–125, 125–160, 160–200, 200–250, 250–315, 315–400, 400–450, 450–500 μm [17]. Value of pressure of the plasma jet was measured from the nozzle section to substrate at distance of 100 mm using electron scales of RADWAG PS grade 1000/R2 using procedure [18]. Examination of shape of the particles, their microstructure was carried out using the methods of optical (microscopes UNITRON Versamet -2 and Neophot-21) and analytical scanning electron microscopy (PHILIPS SEM 515 microscope). Description of shape of the particles was performed using the procedure of ISO 9276-6:2008 standard "Representation of results of particle size analysis — Part 6: Descriptive and quantitative representation of particle shape and morphology" [19].

RESULTS OF EXPERIMENTS AND THEIR ANALYSIS

Experimental check of the size of dispersed particles showed that in spraying of current-conducting com-

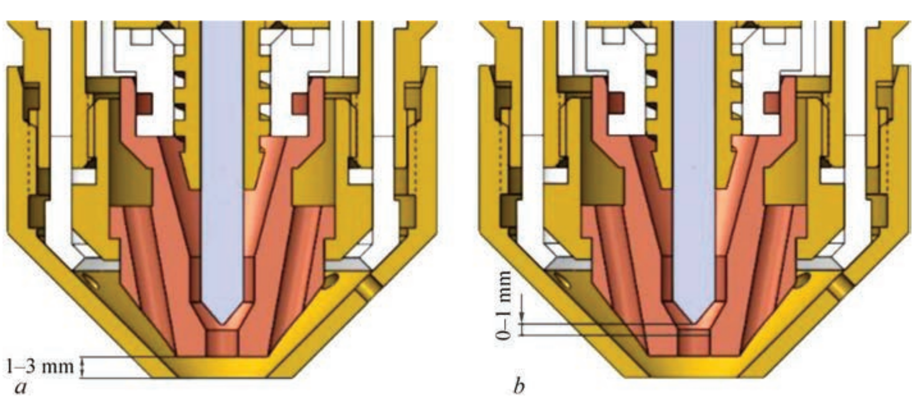

Figure 2. Investigated structural parameters of the plasmatron: *a* — gap between plasma-forming and constriction nozzles; *b* — distance at cathode immersion in relation to the nozzle

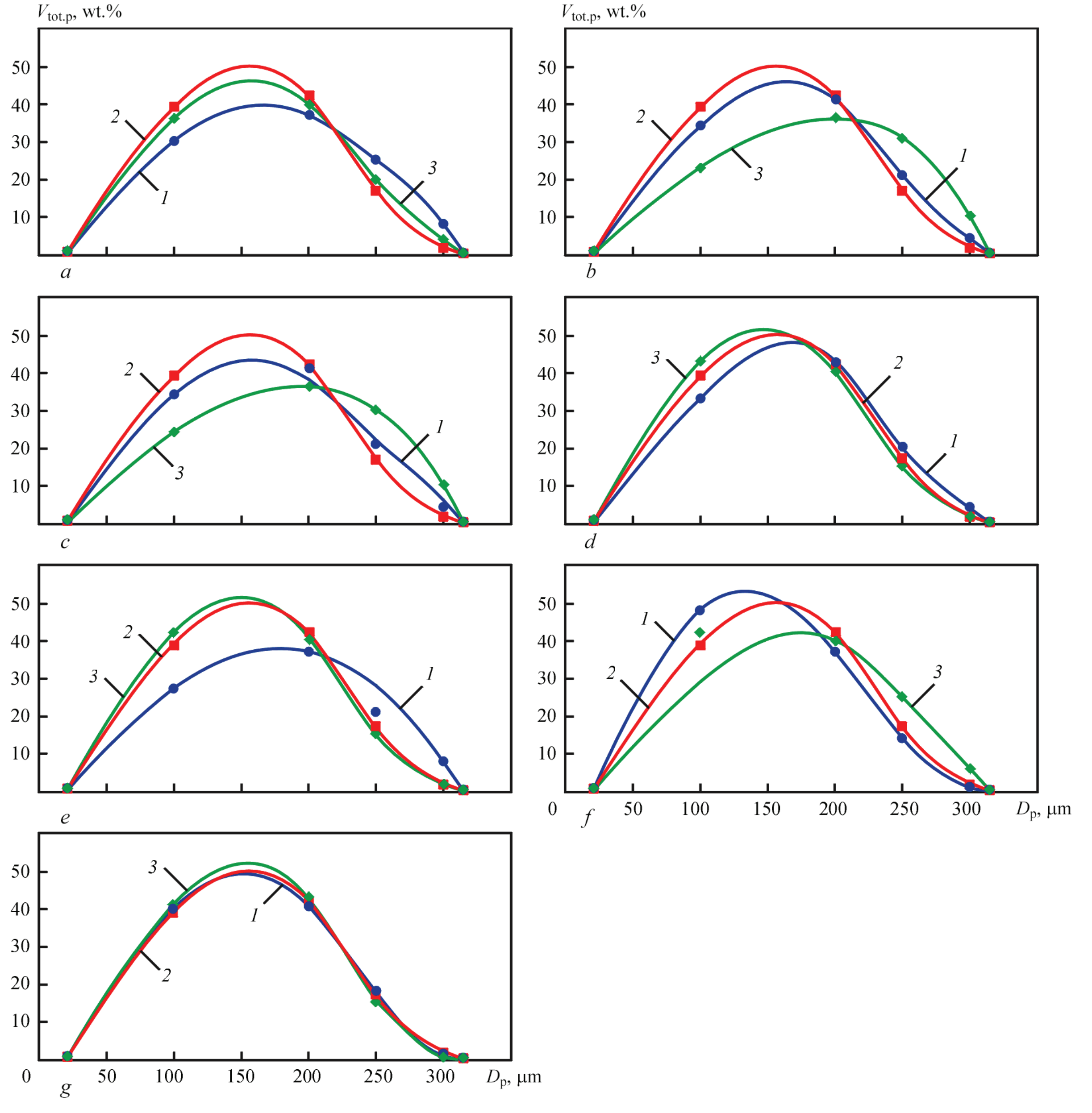

Figure 3. Dependence of granulometric composition of powder on current indices (*a*), A: *1* — 220; *2* — 235; *3* — 250; wire feed rate (*b*), m/min: *1* — 9.5; *2* — 10.5; *3* — 11.5; length of arc gap (*c*), mm: *1* — 8; *2* — 10; *3* — 12; consumption of plasma gas (*d*), l/min: *1* — 30; *2* — 40; *3* — 50; consumption of concurrent gas (*e*), m^3/h: *1* — 36; *2* — 48; *3* — 60; lengths of gap between plasma-forming and constriction nozzles (*f*), mm: *1* — 1; *2* — 2; *3* — 3; depth of cathode immersion (g), mm: *1* — 0; *2* — 0.5; *3* — 1.0

pact wire ER70S-6 the main fraction is 25–250 μm which makes 95 % of total weight of powder, amount of fraction particles < 25 μm and 250–315 μm at optimum modes of spraying is at sufficiently low level and do not exceed 5 %.

The curves of distribution of the granulometric composition of particles depending on spraying mode (Figure 3) were plotted. For convenience of description of these indices there was calculated an average diameter of the particles (D_p).

The analysis of obtained data revealed that increase of current from 235 to 250 A results in increase of the average size of particles by 7 % from 138 to 147 μm, respectively, and at 220 A current by 24 % from 138 to 171 μm (Figure 3, *a*). At that in both cases portion of the particles with size less than 80 μm decreases in the interval of values from 39 to 30 % of total powder weight ($V_{tot.p}$).

At visual evaluation of the spraying process it was observed that melting of the wire takes place mainly in a periphery part of the plasma jet.

The same effect reveals at increase of rate of wire feed from 10.5 to 11.5 m/min that results in rise of the average size of the particles by 33 % from 138 to 184 μm, respectively, and at wire feed rate from 9.5 m/min by 9 % from 138 to 151 μm (Figure 3, *b*). At that in both cases the portion of particles with size less than 80 μm decreases in the interval range from 39 to 23 % from powder total weight.

Authors of works [20, 21] explain the change of granulometric powder composition to the side of coarser fraction by the fact that due to change of the indices of current from some optimum value the wire melting takes place, mainly, in the periphery zone of the jet where its gas-dynamic pressure and level of concentration of energy significantly lower than along the axis. This creates the prerequisites for drop transfer of metal.

In order to investigate the phenomenon there was carried out spraying at current rise to 265 A and wire feed rate to 12.5 m/min. This mode provides location of an end of wire being sprayed along the axis of plasma jet due to what there is a change of granulometric composition of the particles to the side of smaller fraction, the average size of the powder decreases by 13 % to 120 μm. At that portion of the particles with size less than 80 μm rises from 39 to 44 % of total powder weight.

It is explained by the fact that increase of effective heat power of the plasma jet promotes a change of nature of transfer of electrode material from drop to spray one (due to decrease of surface tension forces at increase of overheating of liquid metal) that significantly rises outcome of small fraction of the powder [22, 23].

Increase of cathode–anode distance from 8 to 10 mm results to the fact that the average size of the particles rises by 11 % to 153 μm despite voltage growth from 76 to 82 V (Figure 3, *b*). Increase of distance to 12 mm promotes further rise of voltage from 82 to 100 V that leads to increase of power coming into the wire from 19 to 24 kW i.e. by 22 %. However, fractional composition of the particles shifts in a direction of coarser fractions, at that the average size of the particles increases by 34 % from 138 to 185 μm. Rise of length of the arc gap from 8 to 12 mm provokes decrease of portion of particles with sizes less than 80 μm in the interval of values from 39 to 24 % of total powder weight.

It is caused by decrease of a coefficient of anode heating due to rising loss of heat energy of the plasma jet on radiation and convection in a section of arc gap and drop of jet speed and, as a result, decrease of its dynamic effect on material being sprayed at increase of the distance from plasmatron nozzle [24, 25].

Consumption of the plasma-forming gas has more complex effect on the processes of dispersion of wire material melt than other parameters mentioned above (Figure 3, *d*). Thus, for example, increase of consumption from 30 to 40 l/min results in rise of dispersion of the sprayed particles. At that the average size of the granules decreases per 8 % from 150 to 138 μm, further shift of the fraction composition of particles takes place at rise of consumption from 50 l/min, the average size of particles drops by 4 % from 138 to 133 μm. However, further rise of consumption to 70 l/min leads to coarser fraction, the average size of the particles at that increases from 133 to 142 μm. Rise of the plasma gas consumption from 30 to 50 l/min provokes increase of portion of particles with size less than 80 μm from 39 to 43 % of the total powder weight.

Increase of gas consumption from 30 to 40 l/min and then to 50 l/min promotes rise of arc voltage from 72 to 76 and 80 V, respectively, due to its extension by gas flow, at that value of the arc gap is stable. This leads to growth of heat power and efficiency of wire heating, gives the possibility of rise of dynamic effect of the jet on the wire end (Table 2) and, thus, intensifies process of drops detachment from the wire end.

Nevertheless, further rise of gas consumption to 70 l/min results in a shift of fraction composition of the particles to the side of coarser fraction, at that the average size of the particles rises by 12 % from 138 to 154 μm. Further increase of consumption from 50 to 70 l/min provokes decrease of portion of the particles with size less than 80 μm from 43 to 36 % of the total powder weight.

This can be caused by cooling of the jet due to large heat expenses for heating of increased amount of the plasma-forming gas. Thus, it is necessary to note that at consumption of the plasma-forming gas less than 30 l/min there is an increase of wear of tungsten cathode.

Increase of consumption of a concurrent flow (air) from 36 to 48 m^3/h promotes rise of dispersion of the particles being sprayed, at that the average diameter of powder decreases by 21 % from 167 to 138 μm (Figure 3, *e*). Further increase of consumption of the concurrent flow from 48 to 60 m^3/ h does not provoke significant change of the granulometric composition, the average diameter of the particles decreases by 6 % from 138 to 129 μm. Increase of consumption of the concurrent flow from 36 to 60 m^3/h provides increase of the portion of the particles of size less than 80 μm from 32 to 41 % of the total powder weight.

Visual evaluation of the spraying process allows observing that in general case increase of consump-

Table 3. Calculation of forward pressure of plasma jet at 100 mm spraying distance

Number	Gas consumption, l/min	Area of spot being sprayed, mm^2	Pressure load, g	Forward pressure (σ), MPa
1	30	176	312	0.0177
2	40	181	356	0.0196
3	50	190	409	0.0215
4	70	212	514	0.0242

tion of the concurrent gas promotes more intensive constriction of the plasma jet that freely expends at the nozzle exit. This causes rise of a temperature gradient on the plasma axis jet, length and rate of its outcome [26]. Nevertheless, rise of consumption of the concurrent gas is possible to some conditions that are stipulated by plasmatron structure, namely inner intersection of a system of holes, through which concurrent gas passes. Also, it is necessary to note that at its consumption less than 36 m^3/h there is a decrease on average by 30–40 % of operation life of the inner plasmatron parts such as plasma-forming and protective nozzles.

Rise of the nozzle gap from 3 to 2 mm leads to decrease of fractional composition of the particles of finer fraction, the average diameter of the particles drops by 18 % from 163 to 138 μm and at 1 mm gap by 15 % from 138 to 117 μm (Figure 3, *f*). At that decrease of the gap between nozzles from 3 to 1 mm allows significantly rising portion of the particles with size less than 80 μm from 29 to 48 % of the total weight powder.

Change of the gap from 3 to 2 mm and then to 1 mm promotes increase of arc voltage from 69 to 76 and 84 V, respectively. It takes place due to change of an angle of interaction of concurrent flow and argon plasma that leads to more intensive local constriction of the plasma jet in the place of melting and detachment of drops of wire melt. This allows significantly rising rate of the jet and intensity of dispersion of the

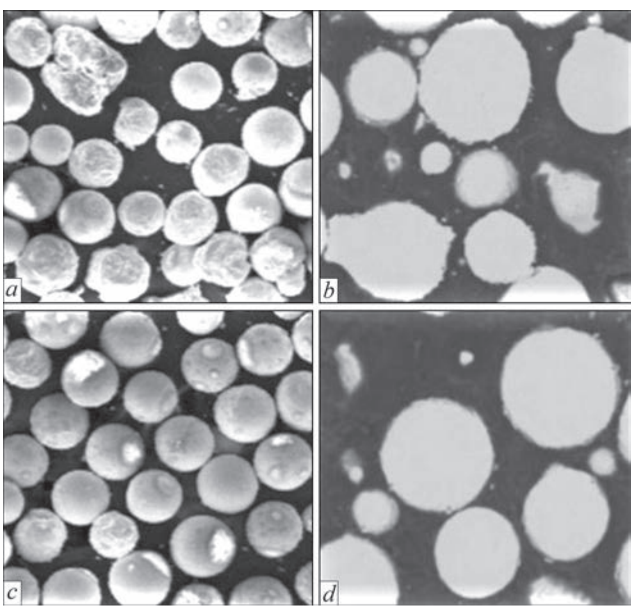

Figure 4. Morphology (*a*, *c*) and microstructure (*b*, *d*) of powders of 40–80 μm fraction obtained using the technology of plasma-arc spraying of compact wire ER70S-6 at inappropriate (*a*, *b*) and optimum (*c*, *d*) modes: I = 235 A; ω_{fw} = 9.5 m/min; l = 10 mm; G_1 (argon) = 30 l/min; G_2 (air) = 36 m^3/h (*a*, *b*); I = 235 A; V_{fp} = = 10.5 m/min; l = 8 mm; G_1 (argon) = 40 l/min; G_2 (air) = 48 m^3/min (*c*, *d*)

particles being sprayed. However, analysis of the appearance of the particles being sprayed shows that decrease of the gap from 3 to 1 mm leads to increase of a level of turbulence of the plasma jet that is observed in intensification of a process of drops coagulation at their collision between each other.

Increase of the immersion depth from 0 to 0.5 mm somewhat rises dispersion of particles being sprayed, their average size at that reduces by 5 % from 145 to 138 μm (Figure 3, *g*). Further increase of this value to 1.0 mm results in insignificant decrease of particles size to the side of finer fraction, change of the average size makes 2 %, i.e. a decrease from 138 to 134 μm. But we consider a change of fractional composition of the particles less than 80 μm then increase of depth of cathode immersion in the value interval from 0 to 1.0 mm allows insignificant rise of the portion of this fraction from 39 to 41 % of the total powder weight.

Change of the immersion depth from 0 to 0.5 mm and then to 1.0 mm promotes increase of arc voltage from 72 to 76 and 77 V, respectively, due to its extension and this results in small rise of heat power. Also, it is necessary to note that here the position of wire relatively to plasma-forming nozzle is stable, that gives the possibility to preserve initial dynamic effect of the jet on the wire end. However, further rise of cathode immersion depth deteriorates the conditions of arc stabilizing in the middle of a plasmatron operating chamber and creates the conditions for twin arc forming.

Thus, it is shown the possibility of regulation of the size of particles of obtained powder in a specific range of values of the granulometric composition by means of variation of the main technological parameters of the plasma-arc spraying of current-conducting wire. By the example of spraying of current-conducting wire of low-carbon steel ER70S-6 (Sv-08G2S) of 1.6 mm diameter it was determined an optimum mode, which will provide the maximum portion (60–75 %) of fine fractions (< 80 μm), which are of high demand in the field of additive technologies of 3D printing. They are current — 280 A; wire feed rate — 12.0 m/min; length of arc gap — 8 mm, consumption of plasma-forming gas — 50 l/min; consumption of concurrent gas 48 m^3/h; gap between plasma-forming and constriction nozzles — 1 mm; depth of cathode immersion — 1 mm.

The results of examination of morphology and microstructure of the particles of obtained powder show that in all examined powder samples the particles in general have regular spherical shape, at that the coefficient of sphericity depends on the parameters of the process and makes 0.7–0.9 at optimum spraying modes. The typical defects in the obtained powder are the satellites, portion of which for the optimum modes of spraying on average not more than 1–3 %. Also, there are separate particles of irregular shape and particles with closed porosity.

Figure 4 demonstrates a comparative analysis of appearance of the particles, obtained at optimum and nonoptimum modes of the process of plasma-arc spheroidization. It can be seen that at inappropriate modes there is a larger amount of defective particles, the level of their sphericity is somewhat smaller (0.65–0.75). This is explained by the fact that melting and dispersion of the melt from wire end at optimum modes take place mainly on the plasma jet axis, where it is significantly larger gas-dynamic pressure and level of energy concentration than on the periphery. This creates the prerequisites for change of type of transfer of electrode metal from drop to spray one, rise of amount of fine disperse fraction, increase of heat of its overheating and, as a result, more effective spherical shape of the particles [27].

In this aspect it is necessary to note that plasma-arc spraying of steel wire was carried out in air atmosphere. This process of the wire end melting and melt dispersion is performed in argon plasma, however, solidification and formation of particles of the powders takes place in air atmosphere and in water that can be a factor effecting formation of indicated portion of the particles with closed porosity and of imperfect spherical shape.

CONCLUSIONS

1. It is shown the possibility of production of spherical powders by means of application of the technology of plasma-arc spraying of current-conducting wire of 1.6 mm diameter low-carbon steel. Heating and melting of electrode material (anode) was performed in argon shielding atmosphere and constriction and acceleration of the argon plasma jet, its protection from jet mixing with air atmosphere was carried out using concurrent high-velocity air flow being fed through circular gas between the plasma-forming and shielding plasmatron nozzles. Further movement of the sprayed particles and their solidification take place in air atmosphere and in water.

2. It is discovered that in general case the main fraction in plasma-arc spheroidization of low-carbon steel current-conducting wire is fraction of 25–250 μm, which makes 95 % of the total powder weight, amount of the particles of < 25 μm fraction and 250–315 μm under optimum spraying modes lies at sufficiently low level and does not exceed 5 %.

3. It is determined that among the examined technological parameters current, wire feed rate, arc gap length, consumption of concurrent gas and gap between plasma-forming and constriction nozzles have the highest impact on the granulometric composition of the obtained powders. Variation of indicated parameters can regulate the granulometric composition of the obtained powders in a wide range of values, namely obtaining powder fraction not less than 80 μm up to 48 % from their total volume, at that the average diameter of the particles can vary in 117–184 μm interval.

4. It was selected a mode of plasma-arc spraying, which would provide change of the granulometric composition to the side of content of fine fractions (< 80 μm), which are of high demand in the field of additive technologies of 3D printing, namely current — 280 A; wire feed rate — 12.0 m/min; length of arc gap — 8 mm; consumption of concurrent gas — 48 m^3/h; gap between plasma-forming and constriction nozzles — 1 mm; depth of cathode immersion — 1 mm.

5. It is shown that most of the particles in general have regular spherical shape, coefficient of powder sphericity makes on average 0.7–0.9. Portion of the satellites and separate particles of irregular shape makes around 1–3 % in the total weight of the obtained spherical powders.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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