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EFFECTIVENESS OF THE PROCESS OF PLASMA-ARC SPHEROIDIZATION OF CURRENT-CONDUCTING TITANIUM WIRE

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ABSTRACT

The possibility of producing spherical titanium powders by application of the technology of plasma-arc atomization of compact current-conducting Ti wire of Grade 2 of 1.6 mm diameter was experimentally confirmed. Analysis of granulometric composition of the powder showed that the main fraction of the powder is 25–250 μm, making up 95 % of the total powder volume, quantity of particles of <25 μm and 250–315 μm fractions not exceeding 5 %. Parameters of the titanium powder shape were studied. It was shown that the majority of the particles are of a regular spherical shape with sphericity coefficient close to 0.8. The quantity of defective particles is not more than 3 % of the total weight of the powder. It was found that atomization by the wire-anode scheme leads to a considerable increase of wire heating efficiency (by approximately 4 times), compared to the scheme of atomization of neutral wire, which promotes an increase of process efficiency from 2–5 to 12 kg/h. It is shown that application of the technology of plasma-arc spheroidization of the titanium wire allows producing spherical powders for 3D printing of high-quality products for the aerospace industry by the technologies of selective and direct laser melting, electron beam melting and sintering and by the methods of powder (granulated) metallurgy (hot isostatic pressing with subsequent thermomechanical treatment).

KEYWORDS: plasma-arc atomization, current-conducting wire, spheroidization, titanium powder, granulometric composition<; sphericity

INTRODUCTION

In recent time due to intensive development of aerospace, shipbuilding, power, chemical and biomedical branches there is a need in repair and manufacture of volumetric parts of complex shape from titanium and its alloys using additive manufacturing technologies (3D printing) and granular metallurgy [1].

Selective and direct laser melting and sintering (SML — Selective Laser Melting, SLS — Selective Laser Sintering, DMLS — Direct Metal Laser Sintering), electron beam meting (EBM) should be referred to the main technologies of 3D printing of products from titanium and its alloys. Indicated methods are used for manufacture of such parts as components of jet and rocket engines — blades, disks of compressor and fan, fixture elements, support arms, protective shells, branch pipes; parts of airplane hulls — flaps, wing spars, frames, landing gear flaps; parts of ship power units — valves, heat-exchanger pipes, turbine components; parts of biomedical designation — surgery (dental) implants and endoprostheses etc. [2].

Hot Isostatic Pressing (HIP) [3] is the most perspective among the technologies of granular metallurgy which includes compacting of spherical particles (granules) with microcrystalline (nanocrystalline) structure, that was crystallized from a melt with high velocity, for manufacture of structural, including granular composites based on titanium alloys and titanium intermetallics with a complex of improved physical-chemical characteristics. HIP allows creating the materials with previously set properties due to formation of combinations of granules of different chemical, phase and fractional content in necessary proportions. Such granular composites are perspective for manufacture of parts of aeronautical and automotive engineering (compressor blades of gas-turbine engines, valves of gas distribution, parts of hydraulica, liners, pistons etc.).

Specialized spherical titanium powders with high requirements to their grain-size composition, shape, mechanical and technological properties are used in these methods as consumables for formation of additive layers and granular compositions. For example, powders of narrow fraction of 25–45 μm are used for SLM process, 45–106 μm for EBM, 45–150 μm for DMLS and 106–250 μm for HIP technology [4]. Besides, these powders should have low content of gas blends (oxygen — not more than 0.15 wt.%, hydrogen — not more than 0.01 wt.%) and high technological properties (flowability, yield, apparent density, sphericity coefficient et al.) The powders for HIP should have high apparent density and yield for provision of high density of packaging and further pressing, absence of inner defects (pores) as well as microcrystalline (in some cases nanocrystalline)

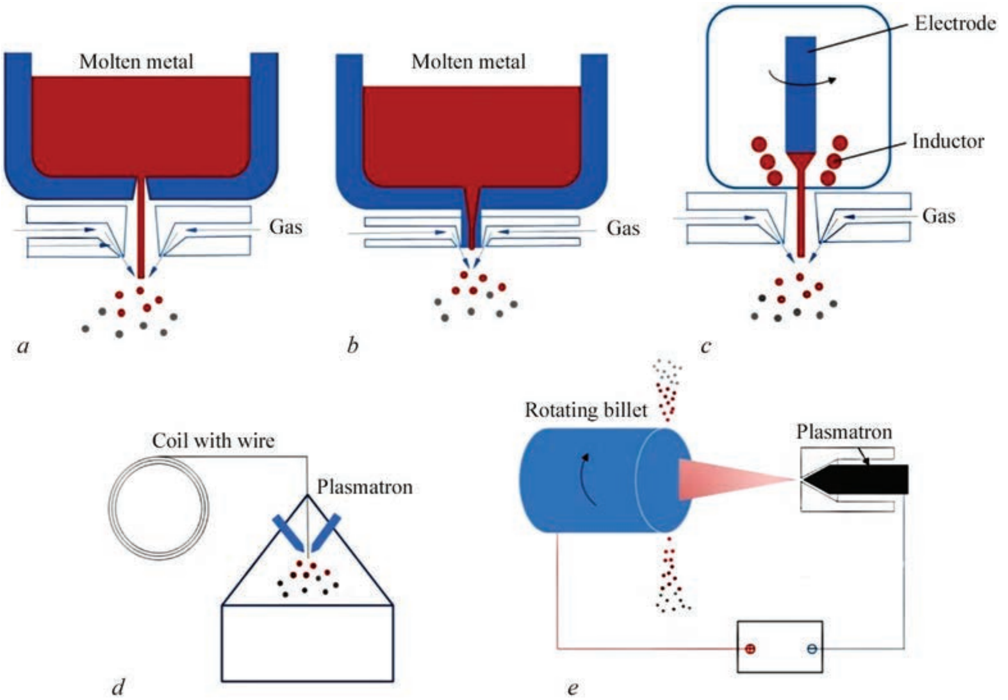

Figure 1. Schemes of atomization process: *a* — FFGA; *b* — CCGA; *c* — EIGA; *d* — PREP [1]

structure which is formed at ultra-high cooling velocities (10^4–10^6 °C/s) and provides increased mechanical properties of finished product [5].

ANALYSIS OF REFERENCE DATA AND PROBLEM STATEMENT

The general practice of production of such powders includes the following technologies (Figure 1): FFGA — Free Fall Gas Atomization, CCGA — Close Coupled Gas Atomization, EIGA — Electrode Induction Gas Atomization, PREP — Plasma Rotating Electrode Process, PA — Plasma Atomization [6].

Table 1 provides the key peculiarities of mentioned above methods of atomization and characteristics of produced powders [7].

The most widespread methods of production of spherical powders of titanium are GA and PREP technologies [8]. However, regardless the presence of large number of advantages they have a series of disadvantages, to which it is necessary to include: GA — relatively low coefficient of sphericity; presence of defective satellite particles and often non-spherical shape, closed argon pores et. al.; PREP — difficulty

Table 1. Peculiarities of different methods of production of spherical powders

Production method	Output material	Grain-size composition	Efficiency	Powder morphology	Powder characteristics
FFGA/CCGA	Preliminary prepared melt	Size of particles 25–500 μm, percent of fine fraction <100 μm up to 40 wt.%	Up to 100 kg/8 h	Shape is almost spherical, sphericity coefficient 0.6–0.7	Presence of satellites, non-spherical particles and particles with pores and inclusions <15 wt.%
EIGA	Precision-machined cylinder billets	–	–	Shape is almost spherical, sphericity coefficient <0.7	Presence of satellites, non-spherical particles and particles with pores <10 wt.%
PA	Wire materials, rods	Size of particles 25–300 μm, percent of fine fraction <100 μm up to 40–50 wt.%	–	Shape is spherical, sphericity coefficient <0.8	Presence of satellites, non-spherical particles and particles with argon pores <5 wt.%
PREP	Precision-machined cylinder billets	Size of particles 50–500 μm, percent of fine fraction <100 μm up to 20 wt.%	Up to 150 kg/ 8h	Shape is spherical, sphericity coefficient <0.9	Complexity of fraction production <50 μm, presence of particles with tungsten inclusions <1.5 wt.%

of production of powders <100 μm, problems related with production of cylindrical billet with accurate dimensions, complexity of kinematic scheme of this equipment, need of its operation at ultra-high velocities of billet rotation assemblies (20000–40000 rpm), difficulties appearing at that.

A significant potential to further development and practical application for production of spherical powders from titanium and highly-alloyed titanium alloys lies in a technology of plasma-arc spraying of wires or rods, one of the varieties of which is PA process mentioned above [9]. The advantage of this technology is the large number of technological parameters which allows regulation of grain-size composition of powder in wide limits as well as possibility of application of wide range of standard consumables from solid wires and rods [10].

It is known that there are two types of the process of plasma-arc spraying of wire (rod), namely the schemes using as a filler material neutral and current-conducting wires (wire-anode) [10]. Because the technology of plasma-arc spraying is only on the stage of industrial implementation the most widespread method is atomization of neutral wire. However, this method has a significant drawback — low efficiency. The researchers from work [11] used a complex of three plasma torches, for spraying of titanium wire Ti6Al4V, which provide total efficiency at 2–5 kg/h level. At that total electric power into wire makes from 20 to 90 kW, i.e. specific electric power for production of 1 kg of titanium wire makes not less than 10 kW·h. A variant of increase of technical-economic parameters of the process can be application of a technology of plasma-arc spraying of current-conducting wires that allows significantly rising efficiency of heating process and wire melting.

AIM AND TASKS OF INVESTIGATION

The aim of work is the analysis of possibility and evaluation of perspectives of application of the process of plasma-arc spraying of current-conducting wires for production of spherical titanium powders, including in comparison with a variant of neutral wire spraying. To reach the aim it is necessary to study a grain-size composition and parameters of sphericity of titanium powder, produced using a technology of plasma-arc spraying in water of current-conducting wire of Ti Grade 2; carry an analysis of efficiency of process of heating of current-conducting titanium wire; provide the recommendations as for practical application of spherical powders of titanium and titanium alloys produced in the process of plasma-arc spraying.

MATERIALS AND INVESTIGATION PROCEDURE

An essence of the process of plasma-arc spraying lies in melting of current-conducting wire-anode which is entered in a zone of high-velocity plasma jet and further breaking of a melt separating from a wire end [12]. An arc burns between nonconsumable tungsten cathode and current-conducting wire-anode being fed behind an edge of plasmatron nozzle. Working (plasma-forming) gas coming into operating chamber is heated using electric arc and comes out from a nozzle in form of plasma-forming jet. Open section of discharge behind the plasma-forming nozzle is blown by gas flow coming out of a circular gap between the plasmatron nozzles. The peculiarity of this method is the fact that melting and jet spraying of wire material is carried out by argon plasma and concurrent gas prevents expansion of open section of a plasma jet. This allows reducing an angle of its opening due to constriction of the plasma jet with concurrent gas flow that provides it acceleration and increase of gas-dynamic pressure on wire edge and promotes production of optimum fractional composition of dispersed phase.

Technological experiments were carried out in open atmosphere using plasma-arc spraying unit PLAZER-30 [13], in which current-conducting electrode wire was used as consumable anode (Figure 2). In order to capture sprayed titanium particles the wire was sprayed in a water-filled vessel from 500 mm distance.

Indicated technological equipment was used for investigation of grain-size composition of particles in spraying of wire-anode from commercial titanium corresponding to Ti Grade 2, USA (analog of VT1-0 grade GOST 19807–91) of 1.6 mm diameter.

Ti Grade 2 titanium wire of 1.6 mm diameter has the next composition, wt.%: Fe — <0.25; C — < 0.07; Si — 0.10; N — <0.04; O — 0.020; H — < 0.01; Ti —base and thermodynamic and thermophysical properties of commercial titanium (VT1-0 grade [15] are:

melting temperature (T_{ml}), K	1945
boiling temperature (T_{boi}), K	3560
melting heat (λ), J/kg	$3.58 \cdot 10^5$
evaporation heat (L_{eva}), J/kg	$8.97 \cdot 10^6$
heat capacity of titanium (C_p) at 1945 K, J/kg·K	989.2
enthalpy of titanium (H) at heating from 298 to 1945 K (liquid titanium), J/kg	$3.15 \cdot 10^5$

An optimum mode was selected according to earlier obtained practical data, by criterion of visual evaluation of shape of plasma jet, at reaching its minimum opening angle and stability of the process. Following it the changes of mode parameters were introduced for discovering the effect of each of them on change of particle fractional composition. Argon of high

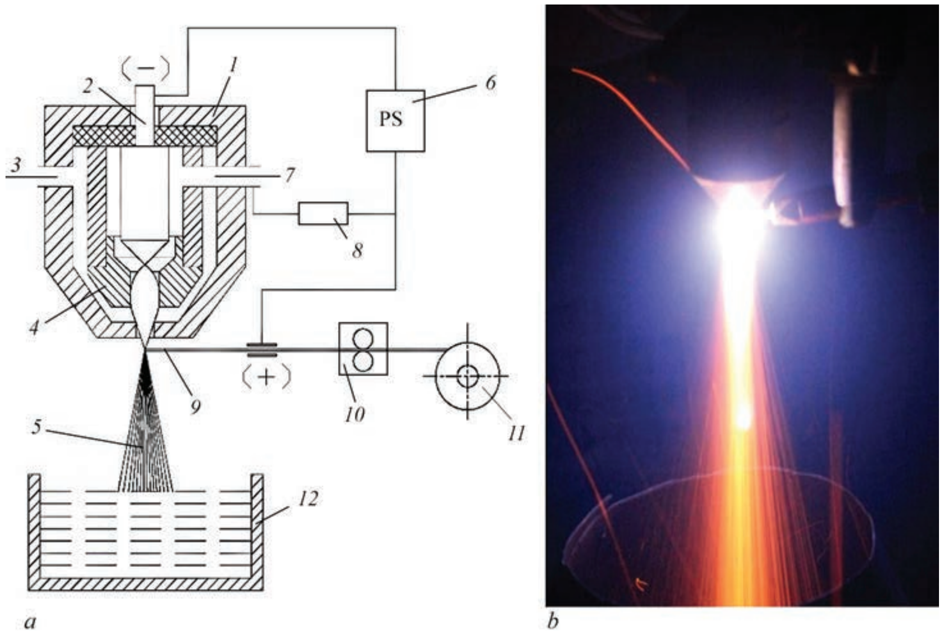

Figure 2. Scheme of the process of plasma-arc spraying and spheroidization of current-conducting wire (*a*) and appearance of spraying process (*b*): *1* — plasmatron operating chamber; *2* — tungsten electrode (cathode); *3* — channel for concurrent gas supply; *4* — plasma-forming nozzle; *5* — jet of particles being sprayed; *6* — power source; *7* — channel for supply of plasma-forming gas; *8* — current-limiting resistance; *9* — wire-anode; *10* — feeding mechanism; *11* — coil with wire; *12* — fridge with water [14]

grade 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, air was used as a concurrent gas.

Spraying was carried out at the following process parameters, namely current — 250 A, consumption of plasma-forming gas — 30 l/min, wire feed rate — 10.5 m/min, cathode-anode distance — 8 mm.

Selection of the samples for examination of grain-size composition of a powder, morphology of surface et al. was carried out using laboratory vibroshaker Analyzzette 3 Spartan (Germany) with a set of sieves 25–500 μm, weight of sample made less than 100 g of powder. Grain-size composition of laboratory batches of powder was determined using the method of sieve analysis according to procedure ISO 25911:1988 "Test sieving. Pt 1: Methods using test sieves of woven wire cloth and perforated metal plate" with the help of vibroshaker Analyzzette 3 Spartan with a set of sieves 25–40, 40–63, 63-80, 80–100, 106–125, 125–160, 160–200, 200–250, 250–315, 315–400, 400–450, 450–500 μm. Shape of particles, their microstructure were investigated using the methods of light (microscope Neophot-32 (Germany) and analytical scanning electron (microscope PHILIPS SEM-515, Netherlands) microscopy. Description of shape of particles was carried out by a procedure from standard ISO 9276-6:2008 "Representation of results of particle size analysis — Pt 6: Descriptive and quantitative representation of particle shape and morphology".

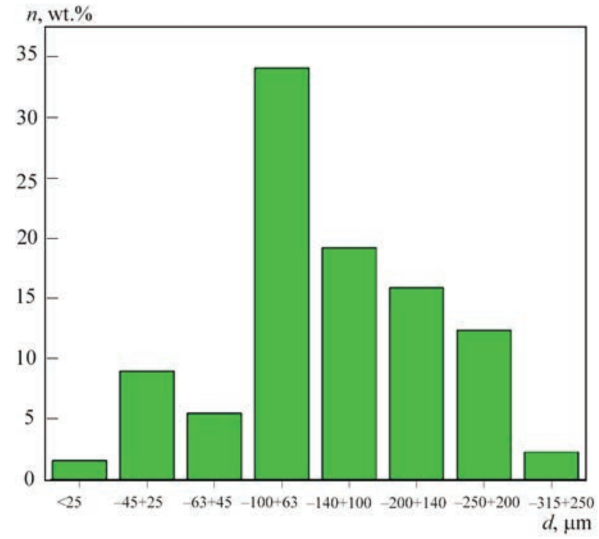

Figure 3. Grain-size composition of titanium powder produced in process of plasma-arc spraying of current-conducting wire of Ti Grade 2

INVESTIGATION RESULTS

INVESTIGATION OF GRAIN-SIZE COMPOSITION AND PARAMETERS OF SPHERICITY OF TITANIUM POWDER

Examination of grain-size composition of particles (Figure 3) showed that in spraying of current-conducting compact wire Ti Grade 2 in water the main fraction is 25–250 μm fraction which makes 95 % of total powder weight. At that amount of particles of fraction <25 μm and 250–315 μm at this mode of spraying does not exceed 5 %.

Portion of 25–45 μm fraction from total weight of powder makes 9.2 wt.%, 45–100 — 39.6; 45–140 — 58.6; 100–250 — 47.5.

Investigation of powder shape showed that powder in general has regular spherical shape (Figure 4) at that a sphericity coefficient makes 0.76.

Typical defects in produced powder are satellites, oxidized particles and particles of irregular shape, portion of which approximately makes not more than 3 wt.%.

It is necessary to note that wire spraying and formation of jet from overheated particles and their further solidification was carried out on air and in water, where processes of intensive chemical interaction of titanium with oxygen, nitrogen and hydrogen take place. The latter can provoke deterioration of parameters of powder sphericity. Similar effect appears in spraying of another chemically active metal–aluminium. The authors of work [16] explain this by formation of a dense oxide layer on the surface of particles in process of their spheroidization and solidification that results in decrease of surface tension force of molten metal and promotes formation of irregular shape particles. In work [17] it is noted that plasma-arc spraying of wire in chambers with inert atmosphere allows producing powder a coefficient of sphericity of which can reach approximately 0.90. Therefore, increase of parameters of sphericity of particles can be reached due to creation of inert atmosphere in a medium where processes of spraying, dispersion and solidification of powders take place.

EVALUATION OF PERFORMANCE FACTOR AND EFFICIENCY OF PROCESSES OF HEATING OF CURRENT-CONDUCTING AND NEUTRAL WIRE WITH PLASMA ARC IN TITANIUM WIRE SPRAYING

Calculation of the processes of heating and melting of wire was carried out using approximated method of V.V. Kudinov [10]. At that the following assumptions were made: anode spot, located on wire, promotes evaporation of 2 wt.% from weight of used wire (based on experimental investigations it was discovered that in spraying of neutral wire in water weight of gathered powder by 4 wt.% less the weight of sprayed wire and in spraying of current-conducting wire this value makes almost 6 wt.%; temperature of liquid drops in a place of melt formation at wire edge equals a metal melting temperature (temperature of particles in a zone of melt formation was measured using optical pyrometer and it was discovered that their temperature exceeds metal melting temperature by 200–300 °C, therefore this overheating was neglected and it was assumed that wire in a zone of spraying is heated to melting temperature); a coefficient of total heat emission from gas to wire was determined based on a heating mode and rate of neutral wire melting (at that a mode of wire heating was determined in such a way that weight-average temperature of plasma in spraying of neutral wire equaled weight-average temperature of plasma in current-conducting wire spraying).

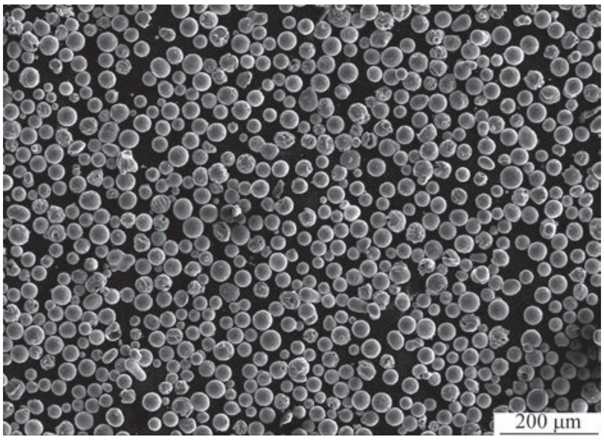

Figure 4. Morphology of powder of 25–45 μm fraction produced by technology of plasma-arc spraying of compact current-conducting wire of Ti 2 Grade into water

There was calculated a total balance of power on wire-anode being heated with plasma arc:

$$q_{\mathrm{h}} + q_{\mathrm{e}} + q_{\mathrm{J}} = q_{\mathrm{ml}} + q_{\mathrm{eva}}, \qquad (1)$$

where q_{h} is the power being transferred to wire due to radiant and convective heat exchange with gas jet; q_{e} is the power being transferred to wire from electrons; q_{J} — power being emitted in wire stick-out at current passing; $q_{\mathrm{ml}} + q_{\mathrm{eva}}$ — power used for heating, melting and evaporation of wire.

Weight-average temperature of gas in a nozzle channel of plasmatron was calculated by the following formula [10]:

$$T_{\mathrm{Ar}} = \frac{I[U - (U_{\mathrm{c}} + U_{\mathrm{a}})]}{\pi d_{\mathrm{n}} \alpha_{\mathrm{n}} l_{\mathrm{a}}} \left(1 - e^{-\frac{\pi d_{\mathrm{n}} \alpha_{\mathrm{n}} l_{\mathrm{a}}}{c_{\rho} \vartheta}} \right), \qquad (2)$$

where I is the current, A; U is the arc voltage, V; d_{n} is the nozzle diameter, m; ϑ is the argon consumption (mass velocity), kg/s; l_{a} is the arc length, m; $U_{\mathrm{c}} + U_{\mathrm{a}}$ is the sum of cathode and anode voltage drop that equals 7 V; α_{n} is the coefficient of heat exchange between gas and nozzle channel, $\alpha_{\mathrm{n}} = 8.38 \cdot 10^{2}$ W/m^{2}·K; c_{ρ} is the specific heat of argon which can be considered constant and equal $11.3 \cdot 10^{2}$ J/kg·K in temperature interval 8000–12000.

In case of spraying of current-conducting wire the arc current made 250 A, arc voltage — 65 V, argon consumption (mass velocity) — $1.49 \cdot 10^{-3}$ kg/s, nozzle diameter — $3 \cdot 10^{-3}$ m, nozzle length — $2 \cdot 10^{-3}$m,

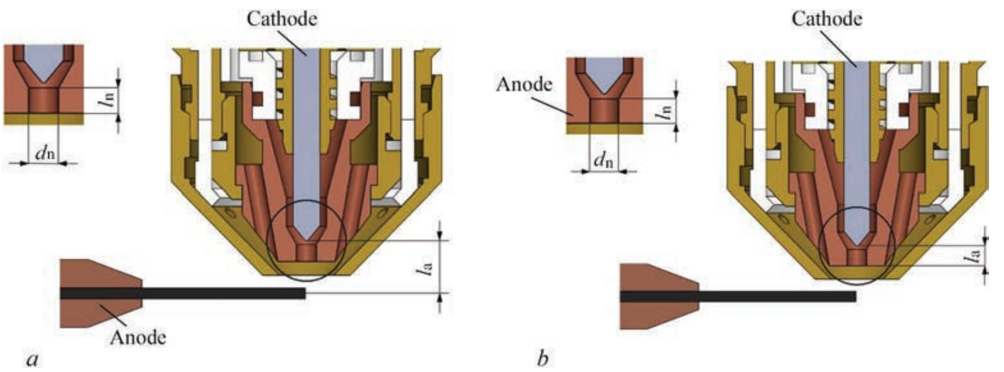

Figure 5. Structural parameters of plasmatron, mm: *a* — in spraying of current-conducting wire ($l_a = 7$; $d_n = 3$; $l_n = 2$); *b* — in spraying of neutral wire ($l_a = 3$; $d_n = 3$; $l_n = 2$

arc length — $7\cdot10^{-3}$ m (Figure 5), plasma jet melted $3.3\cdot10^{-3}$ kg/s of titanium wire of Ti Grade 2 of 1.6 mm diameter.

In case of spraying of neutral wire the different parameters were: arc current — 380 A, arc voltage — 45 V and its length — $3\cdot10^{-3}$ m (Figure 5). This provided the same weight-average temperature of argon plasma for both cases and respectively similar power being transferred from plasma to wire. Based on experimental data it was taken that in such mode of operation the plasma jet melts 4 kg/h ($1.1\cdot10^{-3}$ kg/s) of neutral titanium wire of Ti Grade 2 of 1.6 mm diameter.

The next empirical formula was proposed by the authors to determine power being transferred due to heat exchange with gas jet in melting of neutral wire:

$$q_h = V_{ml}(\lambda + H) = 1.1\cdot10^{-3}\cdot(3.58\cdot10^5 + 3.15\cdot10^5) = 741 \text{ W},$$

where V_{ml} is the rate of melting of neutral titanium wire ($1.1\cdot10^{-3}$ kg/s); λ is the heat of titanium melting ($3.58\cdot10^5$ J/kg); *H* is the enthalpy of titanium in heating from 298 to 1945 K ($3.15\cdot10^5$ J/kg) (see thermodynamic and thermophysical properties of titanium).

The results obtained by the authors based on experimental investigations [10] showed that heat exchange between gas and wire appears in a section $d_n/2$ (Figure 6), where wire is heated from room temperature to temperature of metal melting (T_{ml}). At that the authors made an assumption that wire in the section $d_n/2$ has average temperature $T_{wr} = T_{ml}/2$.

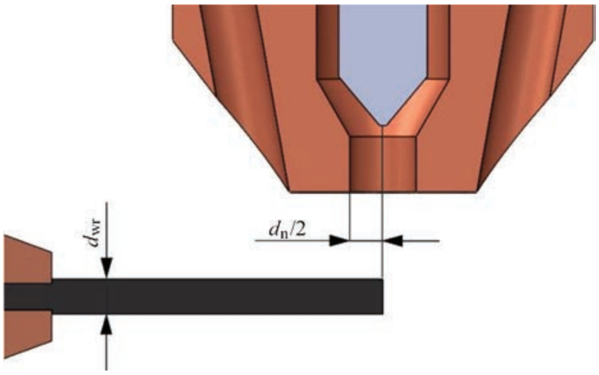

Figure 6. Structural parameters of plasmatron (mm) in determination of surface of heat exchange with gas jet: $d_n = 3$; $d_{wr} = 1.6$

Then power being transferred to wire due to heat exchange with gas jet is determined by formula:

$$q_h = F\alpha_h\left(T_{Ar} - T_{wr}\right), \tag{3}$$

where *F* is the area of surface heat exchange, m^2; α_h is the coefficient of complete heat emission from gas to wire, W/m^2; T_{Ar} is the weight-average temperature of argon plasma, K; T_{wr} is the wire temperature, K.

Area of surface heat exchange is determined:

$$F = \frac{\pi d_{wr}^2}{4} + \pi d_{wr}\frac{d_n}{2}, \tag{4}$$

where d_{wr} is the wire diameter which equals $1.6\cdot10^{-3}$ m; d_n is the nozzle diameter which equals $3\cdot10^{-3}$ m.

Power being transferred to wire from electrons is determined:

$$q_e = I\left(U_{a(Ar)} + \varphi\right), \tag{5}$$

where *I* is the current passing through wire, A; $U_{a(Ar)}$ is the value of anode voltage fall for wire metal in argon (2.5 V); φ is the work of electrons output for anode metal (3.9 V).

Power being emitted in wire stick-out at current passing is described by formula:

$$q_J = I^2\frac{\rho l}{S}, \tag{6}$$

where *I* is the current passing through wire, A; ρ is the electric resistance of conductor with current for titanium equals $1.68\cdot10^{-6}$ Ohm·m; *l* is the length of conductor (distance from current contact jaw place); $l = 0.01$ m; *S* is the area of wire cross section of 1.6 mm diameter which equals $2.6\cdot10^{-6}$ m^2.

Since spraying of current-conducting wire promotes evaporation of 2 % from total powder weight, the velocity of titanium evaporation is determined by equation: $V_{eva} = V_{ml}\cdot\%_{eva} = 6.6\cdot10^{-5}$ kg/s.

The authors proposed the next empirical formula for determination of power being used for wire material evaporation:

$$q_{eva} = V_{eva}L_{eva} = 6.6\cdot10^{-5}\ 8.97\cdot10^{6} = 592\ \text{J},$$

where V_{eva} is the velocity of titanium evaporation in spraying of current-conducting wire ($6.6\cdot10^{-5}$ kg/s); L_{eva} is the heat of evaporation ($8.97\cdot10^{6}$ J/kg).

Total amount of heat embedded in wire in process of plasma-arc spraying is determined by the next formula:

$$q_{\text{tot}} = \eta IU. \qquad (7)$$

There was calculated a contribution of each constituent in a total balance of power on titanium wire-anode at arc power 16 kW. The results of calculation are given in Table 2.

In case of heating with plasma arc of neutral titanium wire the efficiency equals:

$$\eta = \frac{741}{380\cdot45} \approx 4\ \%,$$

and in spraying of current-conducting titanium wire:

$$\eta = \frac{2744}{250\cdot65} \approx 17\ \%.$$

Carried experimental investigations showed that efficiency of the method of plasma-arc spraying of current-conducting titanium wire of 1.6 mm diameter of Ti Grade 2 in a range of utilized power of plasmatron 15–20 kW is at a level of 10–12 kg/h. Efficiency of the method of plasma-arc spraying of neutral wire of 3.2 mm of Ti6A14V grade according to reference data can make approximately 2.5 kg/h at plasmatron power about 28 kW [18] and up to 5 kg/h at power up to 90 kW [19]. Also it is necessary to note that for PREP technology of plasma spheroidization of rods of Ti6A14V grade alloy of 75 mm diameter the process efficiency makes approximately 12.5 kg/h at utilized power 38 kW [20].

Thus, the process of plasma-arc spraying of current-conducting wire-anode is characterized by 4.25 times higher values of efficiency in comparison with plasma-arc spraying of neutral filler wire that significantly effects the process efficiency, the maximum values of which can reach 12 kg/h for utilized power 20 kW. Further increase of efficiency of this process is achieved by means of increase of electric power of sources, plasmatron and equipment for plasma-arc spraying of current-conducting wires.

The calculations show that increase of power of this equipment from 15–20 kW could provoke increase of efficiency index of the process up to 18–20 kg/h. In general, capabilities of plasma equipment allow rising power to 100–120 kW that provides the possibility to use for spraying wires as well as rods of 3–6 mm diameter and larger and to greater extent increase the efficiency indices of the process of production of spherical titanium powders.

Table 2. Total balance of power on wire-anode

Balance item	Power, W	Relative balance value, %
Obtained wire power:	1600	~58
from electrons		
at heat exchange with plasma jet	741	~27
in current passing	403	~15
Total	2744	100
Power spent for:		
heating and melting of wire	2172	~79
wire evaporation	572	~21
Total	2744	100

ANALYSIS OF INVESTIGATION RESULTS

Analysis of the results of investigations of grain-size composition of the products of plasma-arc spraying of current-conducting Ti Grade 2 wire showed that they mainly present themselves spherical powders with particles of 25–250 μm size. Portion of main fractions from total weight of produced powder, which correspond to the requirements of different methods of 3D printing makes: 45–106 μm — 39.6 % (EBM); 45–140 μm — 58.6 % (DMLS); 106–250 μm — 47.5 (HIP).

Investigation of a shape of titanium powder particles showed that in general the particles have regular spherical shape with coefficient of sphericity (S_{sph}) 0.76 at small quantity of defective particles (<3 wt.%). However, in this aspect it is necessary to note that plasma-arc spraying of titanium wire was carried out in air atmosphere with further crystallization into water. During this process a wire end melting and dispersion of a melt take place in argon plasma, hardening and shaping of particles of powders occur in air atmosphere and in water that can be a factor effecting formation of indicated portion of particles of imperfect spherical shape.

Investigation of the processes of heating of current-conducting wire showed that the main source of wire heating is current that makes approximately 58 % of total power embedded into wire. At this efficiency of heating of current-conducting wire is almost 4 times greater in comparison with heating of neutral wire that is revealed in increase of process efficiency from 2–5 to 12 kg/h. Rapid rise of efficiency of wire heating with plasma arc in comparison with plasma jet can be explained by partial change of heating process from heat exchange to mechanism of electron bombardment, when electrons passed an arc column are slowed down in anode area forming excessive negative charge and deposit on anode giving their energy to it [21].

Also it is necessary to note that the index of specific energy consumption for production of 1 kg of titanium powder using the technology of plasma-arc spraying of current-conducting wire makes 1.5–1.7 kW·h/kg. It is considerably lower index in comparison with other commercial technologies of plasma spraying — spraying of neutral wire, where the values of index of specific power consumption can vary in wide limits depending on characteristics of equipment and make 11 kW·h/kg at plasmatron power 28 kW or 18 kW·h/kg at total power of three plasmatrons 90 kW. For PREP technology a specific utilized power for production of 1 kg of titanium powder makes around 3 kW·h/kg. At that it is necessary to consider that investigations in this work were carried out by the example of titanium wire of 1.6 mm diameter. Using of the larger diameter wires in this process has a potential of further decrease of specific energy efficiency.

Obtained results of grain-size composition and sphericity parameters of powder allow recommending the technology of plasma-arc spheroidization of current-conducting wire for production of spherical powders (granules) of titanium and titanium alloys for 3D printing using the methods of direct laser and electron-beam melting as well as with the help of the methods of powder metallurgy. Analysis of grain-size composition of content of particles showed that for application of titanium powders in selective laser melting and sintering it is necessary to carry out further investigations on optimization of the modes of plasma-laser spraying of wire for the purpose of increase of portion of 25–45 μm fraction in the total powder volume. Also it is necessary to note that the significant portion of fraction of produced powder on size and coefficient of sphericity correspond to the requirements to materials for technology of compacting in granular metallurgy, particularly, for HIP process (106–250 μm). Especially, indicated powders, produced at ultra-high cooling velocities, create the conditions for formation of microcrystalline (and in some cases nanocrystalline) structure that has positive effect on mechanical properties of products made of them.

CONCLUSIONS

1. By the example of titanium wire Ti Grade 2 of 1.6 mm diameter there were proved the perspectives of application of technology of plasma-arc spraying of current-conducting wire for production of spherical powders from titanium and titanium alloys. It was determined that in plasma-arc spheroidization of current-conducting titanium wire the main fraction is 25–250 μm fraction which makes 95 % of total weight of powder, number of particles of fraction <25 and 250–315 μm under optimum modes of spraying is at sufficiently low level and does not exceed 5 %. In total, the particles have regular spherical shape with index of sphericity coefficient close to 0.8 at small number of defective particles (< 3 wt.%).

2. It was grounded an increase power efficiency of the process of plasma-arc spraying of current-conducting wire-anode, which in comparison with plasma-arc spraying of neutral filler wire is characterized with 4.25 times greater values of efficiency and 1.5–6.0 times index of maximum process productivity 12 kg/h at 20 kW and 2–5 kg/h, respectively, in case of index of utilized electric power 20–90 kw) and smaller specific energy consumption (1.6 kW·h/kg for plasma-arc spraying of current-conducting wire and 11–18 kW·h/kg for neutral one). Also this technology has the advantages on indices of efficiency and specific energy consumption over the PREP process (3 kW·h/kg), which is used in industry for production of titanium powders of spherical shape.

3. Obtained results allow considering plasma-arc spheroidization of current-conducting wire as an effective technology for production of powders (granules) of spherical shape from titanium and titanium alloys that correspond to the requirements to materials for 3D printing of high-quality products using the methods of selective and direct laser melting and sintering, electron-beam melting as well as requirements to materials for granular metallurgy (production of high-quality structural materials by means of compacting of particles (granules) with microcrystalline structure that was crystallized from melt with high velocity).

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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