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DEVELOPMENT OF HYBRID TECHNOLOGY OF PRODUCING SPHERICAL POWDERS FROM WIRE MATERIALS USING HIGH-SPEED PLASMA JETS AND ELECTRIC ARC

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ABSTRACT

A technological scheme and equipment for hybrid process were developed, which is based on application of the energy of supersonic plasma jet and electric arc to produce high-quality spherical powders at wire material atomization. Performed experimental studies of the particle size distribution, morphology and technological properties of the produced powder showed that the above-mentioned process allows producing spherical powders in the range of 25–160 μm, where the share of finely dispersed fraction of 25–63 μm can be up to 70 wt.% with the coefficient of sphericity higher than 0.8, which results in high technological properties (bulk density, flowability, etc.) of the produced powders, and is extremely necessary for their application in additive technology. It is shown that the hybrid process is characterized by 2.5–6.0 times smaller specific flow rates of gas for producing 1 kg of powder and 1.25–6.0 times higher productivity, compared to other industrial technologies of plasma and electric arc atomization.

KEYWORDS: hybrid atomization, plasma jet, electric arc, productivity, spherical powders, additive manufacturing

INTRODUCTION

Over the recent years, the world has seen significant development of additive manufacturing (AM) technologies of metal product synthesis, which is due to a number of their essential advantages, compared to the traditional (subtractive) technologies of casting, metal treatment, etc. [16]: complete automation of the process and flexibility of the product manufacturing process is achieved; production cycle of component parts from their design stage to manufacturing the final products is significantly shortened; product manufacturing cost is lowered due to a more rational use of materials and production resources; there is a possibility of designing products with a functionally-gradient structure and properties with optimized geometrical, strength and weight characteristics.

It is anticipated that the world market of additive technologies will increase more than 6 times by 2032, from 15 to 95.6 bln USD (Figure 1) [7], where the groups of methods of direct energy deposition (DED) (up to 5 % of the total volume) and powder bed fusion (PBF) (up to 35 % of the total volume) with take up a considerable share of this market [8].

In our time the above-mentioned groups of metal product synthesis methods are used predominantly in high-tech industry segments at manufacture of complex metal components of aviation and aerospace engineering and locally in power industry and medicine. The main factors, limiting the application of additive technologies of metal product synthesis, also in other industry sectors, in addition to complex expensive equipment, is the need to use high-quality spherical powders of a certain particle size distribution as consumable material to form additive layers and granular compositions [9].

So, the above-mentioned group of DED methods includes the processes of direct metal deposition (DMD) and Laser Engineering Net Shaping (LENS), cold atomization (CA) and plasma powder transferred arc atomization (PPTAA), which use powders predominantly in the fraction range of 45–160 μm (15–45 μm for CS process), and the group of PBF methods consists of the processes of selective and direct laser melting and sintering (Selective Laser Melting (SLM), Selective Laser Sintering (SLS), Direct Metal Laser Sintering (DMLS)) and Electron Beam Melting (EBM)), where powders predominantly in the fraction range of 15–45 μm (45–160 μm for EBM process) are used for layer-by-layer synthesis [10]. These powders should also have minimal porosity, high degree of sphericity, stable chemical and phase composition, so that the most promising group of methods, satisfying all the above-listed requirements, and well as allowing adjustment of the particle size distribution of the powders in a broad range of 15–160 μm, are the technologies using the energy of plasma and electric arc.

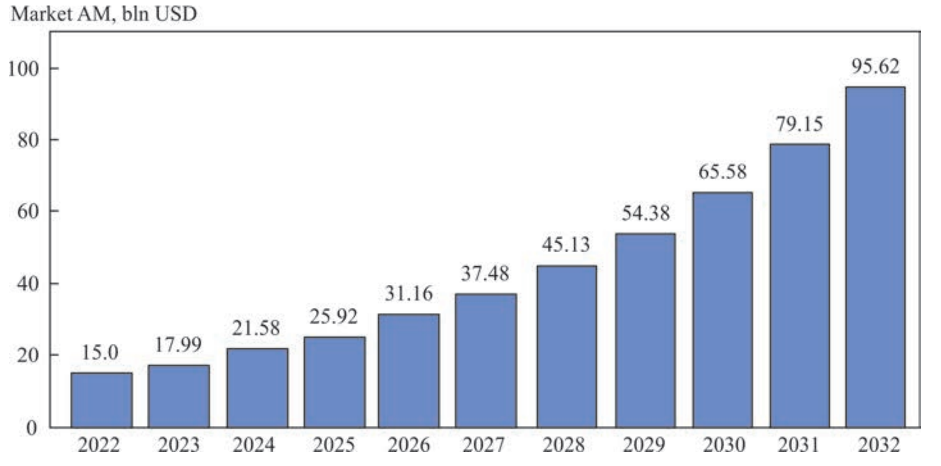

Figure 1. Trends in development of the world market of additive technologies for 2022–2033

ANALYSIS OF PUBLISHED DATA AND PROBLEM DEFINITION

It is known that such promising spheroidization technologies include the processes of plasma and electric arc atomization of the melt, namely plasma rotating electrode process (PREP), electric arc atomization (AA), plasma-arc atomization (PA) of neutral and current-carrying wires [11–13].

At present the PREP technology (Figure 2, *a*) is one of the most wide-spread processes of manufacturing high-quality spherical powders, as it allows producing powders from various materials with the coefficient of sphericity of 0.93 and higher. Here, the powder morphology is characterized by a practical absence of defects in the form of satellites and particles of an irregular shape, internal porosity, etc. [14]. However, operation of the above-mentioned equipment is characterized by considerable difficulties, associated with producing a finely-dispersed fraction of <100 μm, complex process of manufacturing a precision sputtered blank, insufficiently efficient use of this blank material, low process productivity, etc.

Arc atomization (Figure 2, *b*) is a widely applied technology, which is now used predominantly for coating deposition and features simplicity and affordability of the equipment, high productivity, which in some cases can be equal up to 40 kg/h, yield of a large quantity of fine fraction (<63 μm), etc. However, despite the large number of advantages, a significant drawback of arc atomization is use of cold gas for dispersion of the melt, forming at the end face of atomized wires, which leads to formation of powders with a high percentage of irregularly-shaped particles, satellites and with considerable internal porosity, making their application in the field of additive technologies impossible.

Another known technology of wire material spheroidization is the plasma atomization process (Figure 2, *c*), having two variants — atomization of neutral (Plasma non-transferred arc (PNTA)) and current-conducting (Plasma transferred wire arc (PTWA)) wires. A feature of the above technology is application of plasmatrons, generating high-velocity, and in some cases supersonic plasma jets, the velocity of which is in the range of $(2.5–18.5)\cdot10^2$ m/s that greatly intensifies the dispersion processes and increases the quantity of the produced fine fraction of the powder [15]. Known is the equipment of Pyrogen-

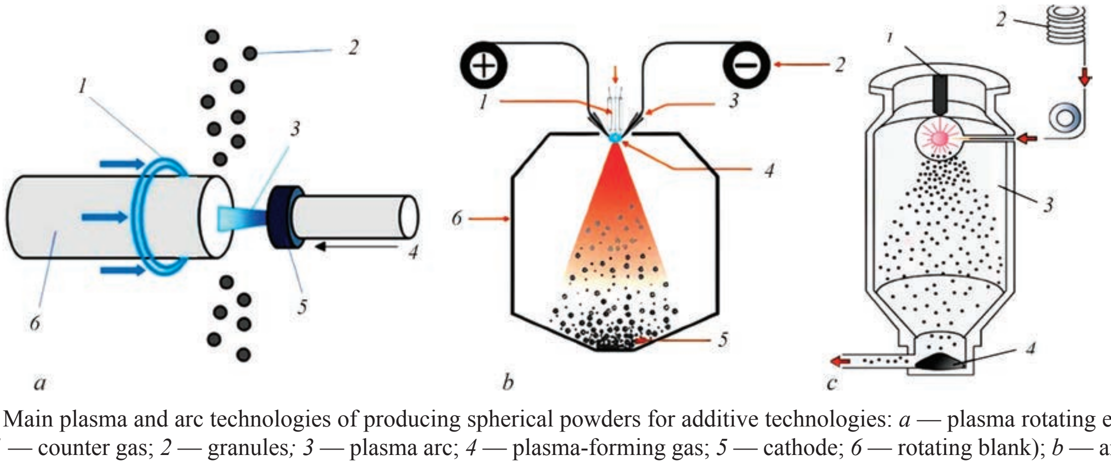

Figure 2. Main plasma and arc technologies of producing spherical powders for additive technologies: *a* — plasma rotating electrode process (*1* — counter gas; *2* — granules; *3* — plasma arc; *4* — plasma-forming gas; *5* — cathode; *6* — rotating blank); *b* — arc atomization of wire (*1* — arc soldering iron; *2* — wire; *3* — wire feeder; *4* — arc; *5* — powder; *6* — atomization chamber); *c* — plasma atomization of wire materials (*1* — plasmatron; *2* — wire; *3* — work chamber; *4* — container for powder collection)

esis Company (Canada), operating by plasma atomization scheme, where the neutral wire is atomized by three plasmatrons, that allows producing high-quality spherical powders from titanium and titanium alloys (Grade 1, Ti6A14V) and other materials, which by their morphology and technological properties correspond to powders, produced by the technology of plasma atomization [16]. The productivity of the process of plasma atomization of neutral wire, however, does not exceed 3 kg/h (up to 5 kg/h in the case of additional heating of atomized wire by an inductor before its feeding into the plasma jet) at 143 kW total power of the plasmatrons. Another approach to solving the above problem of increasing the productivity of plasma atomization process is application of a scheme with current-conducting wire. Corresponding equipment of PLAZER PL-30W [17] and PLAZER PL-50-W brands was developed at PWI, together with "Scientific and Production center "PLAZER"" LLC (Ukraine) [18], and theoretical and experimental investigations of the efficiency of the process of the efficiency of atomized wire heating were conducted [19], which showed that in the case of plasma atomization of current-conducting wire an increase of the quantity of heat applied to the wire by more than 4 times occurs, and this, in its turn leads to increase of the process productivity to 10–12 kg/h.

Thus, the most promising version of further evolution of the above processes is development of a hybrid plasma-arc technology (hybrid plasma-arc atomization (HPPA)), which is based on simultaneous application of the processes of arc plasma atomization for spheroidization of wire materials, as it allows combining the advantages of both the processes and reaching a productivity layer higher than that at application of arc atomization process, with the powder morphology and particle size distribution, inherent to the plasma atomization process. A variant of such a device was proposed in patent [20]. It is noted that this device allows reaching a productivity of up to 28 kg/h for 3.2 mm titanium wire of Ti6A14V grade diameter at atomization at the total power of 113 kW, where the share of the fine fraction of 20–63 μm is equal to 32 wt.%. However, in addition to the need for further increase of the yield of fine powder fraction, the above-mentioned process is characterized by super high flow rates of inert gas (higher than 90 m^3/h) that is much higher than in the known devices for ultra-high speed plasma atomization, where the plasma-forming gas losses are usually not higher than 30 m^3/h.

As there are no open-access data on the design and technological parameters of the process, equipment characteristics, and other technological aspects of hybrid atomization technology, except for the above-mentioned patent, it necessitates performance of investigations for development and evaluation of the suitability of the process of hybrid plasma-arc atomization for spherical powder manufacturing. For this purpose, PWI, in cooperation with "Scientific and Production center "PLAZER"" (Ukraine) where the specialists have extensive experience of operation of equipment for arc atomization, equipment for high-velocity (PLAZER-30, PLAZERT-50) and supersonic plasma atomization (PLAZER-80) [21]) was developed.

RESEARCH OBJECTIVE AND TASKS

The objective of this study is development of the technology and equipment for hybrid plasma-arc atomization and checking the effectiveness of their application to produce spherical powders, where the following tasks should be performed to achieve the defined objective: select the optimal design parameters of the hybrid device, study the particle size distribution, morphology and technological properties of the produced powders, determine the technical-economic characteristics of the above-mentioned method, compare them with other plasma and arc processes.

MATERIALS AND INVESTIGATION PROCEDURE

Solid wire from low-carbon steel of ER70S-6 brand of 1.6 mm diameter was used as model material for investigation of the powder particle size distribution, produced by different atomization technologies and 1.6 mm molybdenum wire of MCh brand was used to investigate the powder morphology and technological properties. Chemical composition of the above-mentioned wires is given in Table 1.

Atomization experiments were performed in air using equipment of PLAZER-50, PLAZERT-80 brand ("Scientific and Production center "PLAZER" LLC, Ukraine), for plasma atomization of current-conducting and neutral wire, respectively (Figure 3), which allows using the subsonic and supersonic modes of

Table 1. Chemical composition of the studied wire materials, wt.%

Wire brand	C	Mn	Si	P	S	Ni	Cr
ER70S-6	<0.07	0.9–1.4	0.4–0.7	<0.025	<0.035	<0.15	<0.15
	Mo	V	Al	Zr	Ti	Cu	–
	<0.15	<0.03	0.05–0.15	0.02–0.12	0.05–0.15	<0.5	–
MCh	Mo		Si			Other	
	>99.92		0.02–0.04			<0.04	

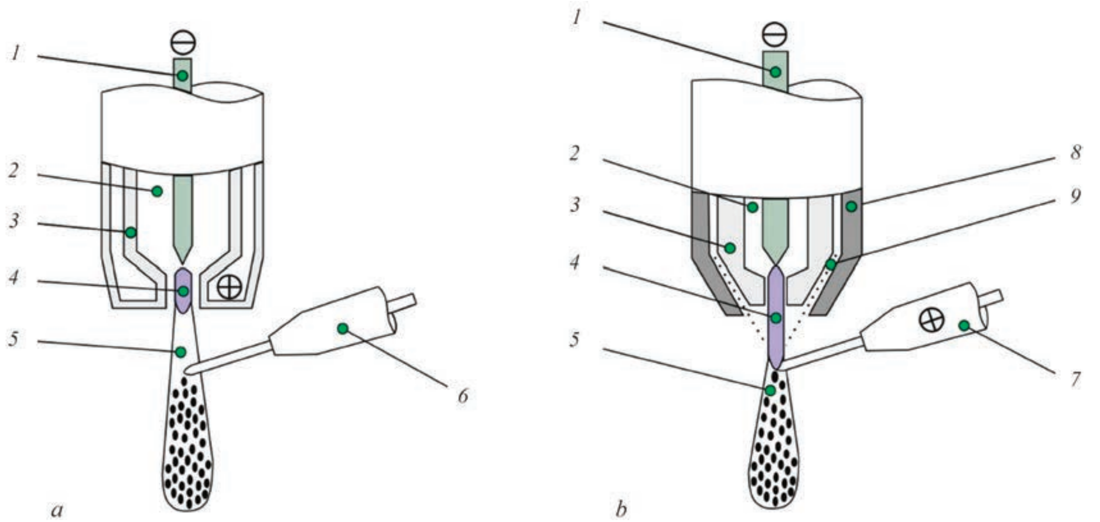

Figure 3. Scheme of the process of plasma atomization of neutral (*a*) and current-carrying wires (*b*): *1* — nonconsumable tungsten electrode (cathode); *2* — plasma-forming gas supply; *3* — plasma-forming nozzle; *4* — plasma arc; *5* — two-phase plasma jet; *6* — neutral atomized wire; *7* — current-conducting wire (anode); *8* — compression nozzle for accompanying gas supply; *9* — accompanying gas supply

plasmatron operation. PLAZER-15AS unit (“Scientific and Production center “PLAZER””, Ukraine) was used for arc atomization.

Technological parameters of the processes of plasma, arc and hybrid atomisation of wires are as follows:

PA (PNTA) — plasma atomization of neutral wire (PLAZER-80 unit):
- plasmatron power, kW 68
- plasma-forming gas flow rate, l/min. 500

PA (PTWA) plasma atomization of current-conducting wire (PLAZER-50 unit):
- plasmatron power, kW 27
- plasma-forming gas flow rate, l/min. 50
- accompanying gas flow rate, l/min 800

AA — arc atomization (PLAZER 15AS unit):
- electric arc device power, kW. 14
- plasma-forming gas flow rate, l/min. 1000

HPAA — hybrid plasma-arc atomization (PLAZER 15AS + PLAZER 80):
- total power, kW. 82
- plasma-forming gas flow rate, l/min. 500

Note: Atomization of the studied wire materials was conducted in open atmosphere.

Hybrid plasma-arc atomization was performed by the following scheme (Figure 5): plasmatron switching on and supersonic plasma jet formation were performed (Figure 5, *c*) at gas flowing through plasma-forming nozzle *1*, which was followed by switching on feed mechanism *2* of the wires which were under the potential from the arc power source, their feeding and convergence *3* in the axial zone of the plasma jet at 10–15 mm distance from the plasma-forming nozzle edge, where their melting, melt formation and its further fragmentation occurred as a result of aerodynamic influence of the plasma jet (Figure 5, *d*).

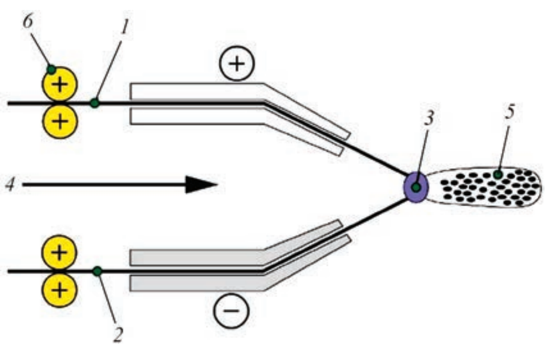

Figure 4. Scheme of the process of arc atomization of wire materials: *1* — anode wire; *2* — cathode wire; 3 — arc; *4* — atomizing gas; *5* — plume with atomized particles; *6* — wire feed mechanism

Produced particles were collected in a container with water, in keeping with a procedure, given in [22], followed by selection of samples to study the particle size distribution and morphology of powder surface (sample weight was not less than 200 g). Particle size distribution of laboratory powder batches was determined by the method of sieve analysis, in keeping with the procedure of ISO 25911:1988 “Test sieving, Part 1: Methods using test sieves of woven wire cloth and perforated metal plate”, using vibro screen RLU-3 (Ukraine) with the following set of sieves: 2545, 4563, 6375, 75100, 100125, 125160, 160200, 200250, 250315, 315400. Investigation of particle shape and coating porosity was performed by the methods of analytical scanning electron microscopy in scanning electron microscope MIRA3 LMU (Ltd TESCAN, Czech Republic) with further analysis of the obtained images in MIPAR program package. Chemical composition of the powder was determined by microprobe analysis using scanning electron microscope MIRA-3 LMU fitted with microanalysis system INCA Energy 450 XMax-80 (Ltd Oxford Instruments, Great Britain). Investigation of the powder technological properties (flowability, bulk and appar-

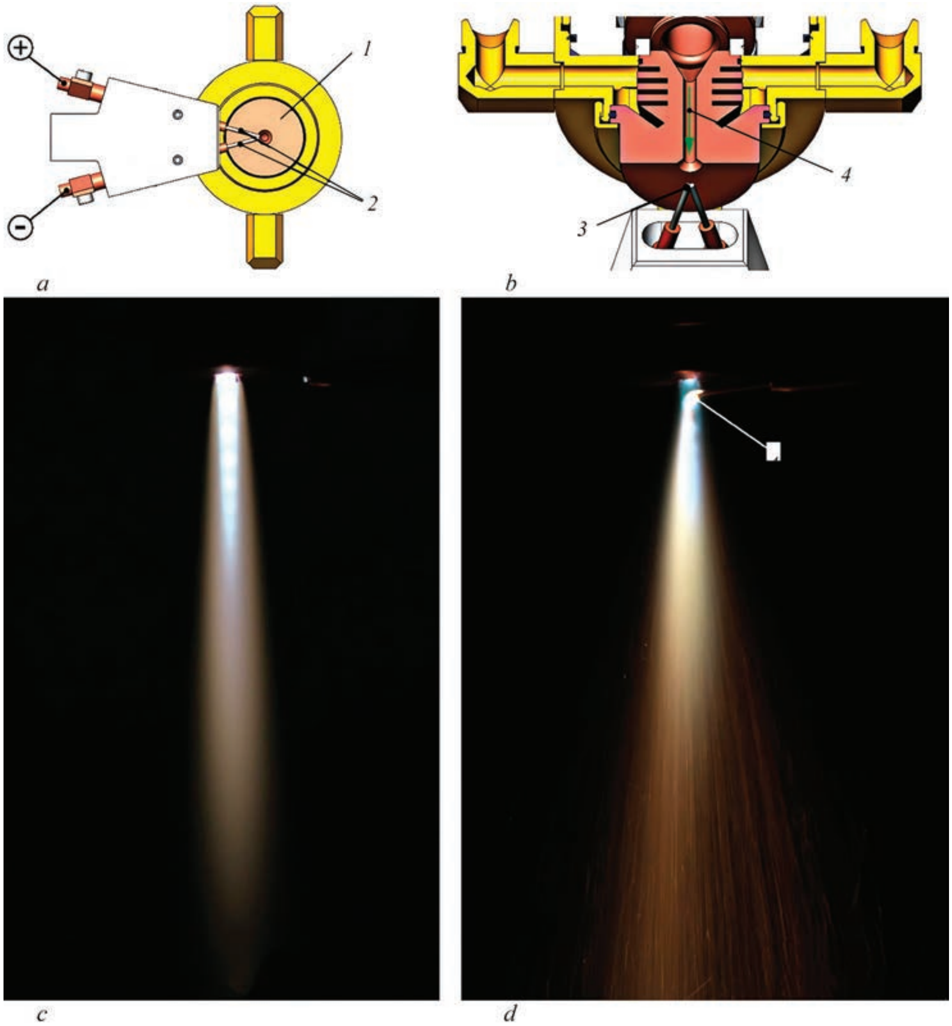

Figure 5. Schemes of plasmatron and arc device arrangement in the process of hybrid plasma-arc atomization (*a*, *b*), appearance of supersonic plasma jet of 1.5 Mach without (*c*) and with wire feed (*d*) into the plasma jet zone: *1* — plasma-forming nozzle of the plasmatron; *2* — atomized wires; *3* — wire convergence in the zone of plasma jet axial outflowing; *4* — direction of plasma-forming gas outflowing; *5* — fragmentation of the melt forming at atomized wire tips

ent density) was performed using Hall instrument, by the procedures of ISO 4490:2018 "Metallic powders — Determination of flow rate by means of a calibrated funnel (Hall flowmeter)" and ISO 39231:2018 "Metallic powders — Determination of apparent density, Part 1: Funnel method". Process productivity, G, and material utilization rate (MUR) were determined by weighing of powder obtained at wire atomization for 5 min, and initial wire weight before atomization in laboratory scales TBE-12-0.5-(250×300)-13P (Ukraine) with up to ±0.5 g accuracy.

INVESTIGATION RESULTS AND THEIR DISCUSSION

INVESTIGATIONS OF THE PARTICLE SIZE DISTRIBUTION, MORPHOLOGY AND TECHNOLOGICAL PROPERTIES OF THE PRODUCED POWDERS

Figure 6 gives the results of studying the particle size distribution of powder, produced at plasma, arc and hybrid plasma-arc atomization of 1.6 mm steel compact wire of ER70S-6 brand.

Investigations of the particle size distribution of the produced powders showed that the hybrid plasma-arc and plasma atomization of the neutral wire provide the largest quantity of the fine powder fraction. Here, much smaller particles are formed than in the processes of plasma atomization of current-conducting wire and arc atomization, with average diameter of 67 and 54 μm, respectively, and the quantity of fine fraction of 25–63 μm may reach 70 wt.% that is attributable to increased gas-dynamic pressure on the melt, formed during melting of the atomized wire tips in supersonic mode of plasma jet outflowing that, in its turn, promotes size reduction of the forming fragments [15].

Figure 7 shows a SEM image, obtained at hybrid plasma-arc atomization of molybdenum wire of MCh brand and the results of its processing in MIPAR program. Application of exactly the refractory metals in the hybrid plasma-arc atomization was due to the

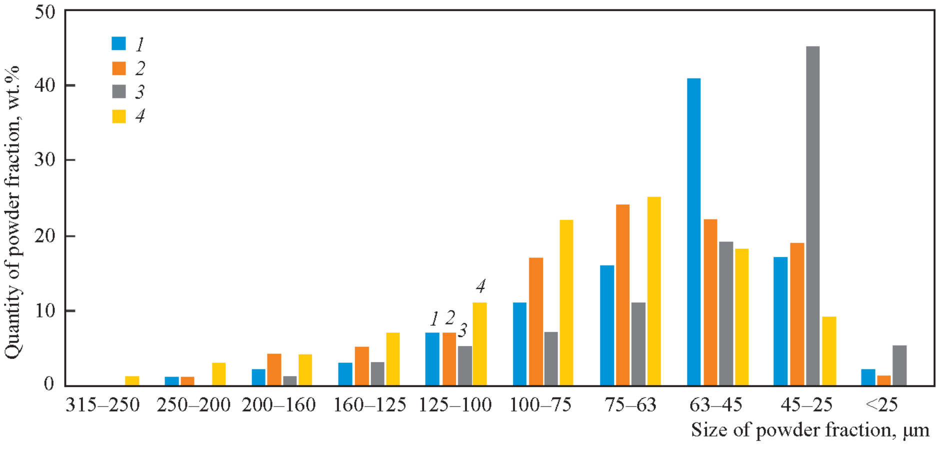

Figure 6. Particle size distribution of powder produced by different technologies of plasma atomization and arc atomization of 1.6 mm steel wire of ER70S-6 brand: *1* — PA (PNTA), *G* = 4 kg/h; *2* — PA (PTWA), *G* = 11 kg/h; *3* — HPAA, *G* = 24 kg/h; *4* — AA, *G* = 19 kg/h

problems of spheroidization of these materials, because of their physical and thermophysical properties, such as high melting temperature (2620 °C for MO and 3420 °C for W), heat conductivity, etc.

Analysis of powder morphology in MIPAR program showed that the powder is of a spherical shape with average coefficient of sphericity (*S* = 0.84), defects in the form of satellites and irregularly-shaped particles being practically absent. A more detailed consideration of powder morphology showed the presence of oxide film in some local zones of its surface, which may form during movement of molten particles as a result of their intensive interaction with oxygen, present in the air and may lead to deterioration of the coefficient of sphericity. To study this phenomenon energy-dispersive X-ray spectroscopy (EDX) of the mentioned local zones of powder surface was performed (Figure 8, Table 2).

Oxygen content on the studied powder surface is explained by the fact that the process of molybdenum

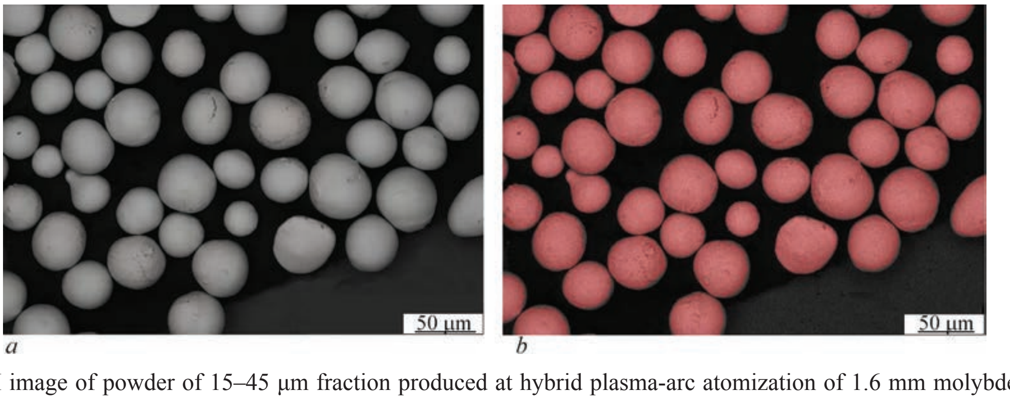

Figure 7. SEM image of powder of 15–45 μm fraction produced at hybrid plasma-arc atomization of 1.6 mm molybdenum wire of MCh brand before (*a*) and after (*b*) processing in MIPAR program

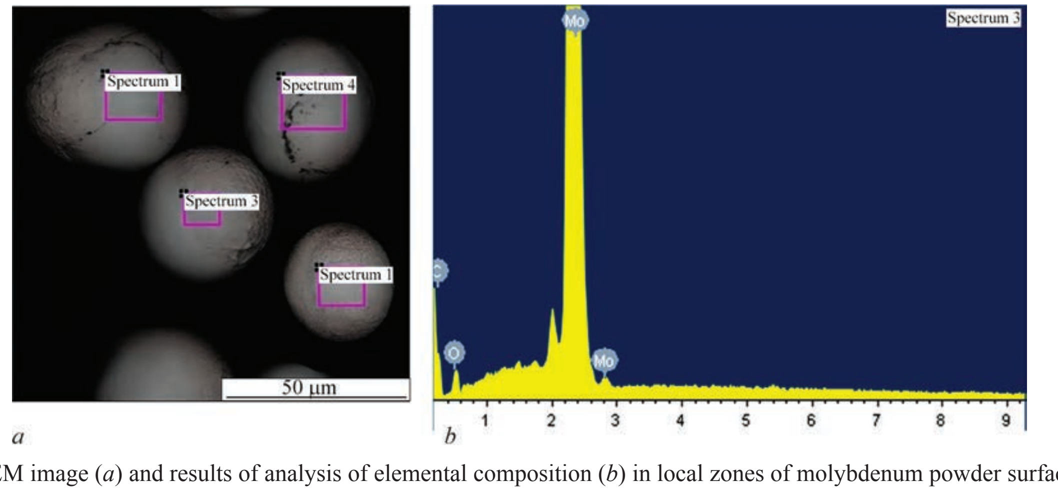

Figure 8. SEM image (*a*) and results of analysis of elemental composition (*b*) in local zones of molybdenum powder surface by EDX method

Table 2. Results of EDX of local zones on the surface of powder produced in the hybrid process of plasma-arc atomization of 1.6 mm molybdenum wire of MCh grade

Local zone	Chemical composition of local zones, at.%	
	Mo	O
Spectrum 1	97.32	2.68
Spectrum 2	98.73	1.27
Spectrum 3	98.29	1.71
Spectrum 4	97.04	2.96

Table 3. Technological properties of molybdenum powder produced by the technology of spheroidization of irregularly-shaped particles in induction plasma (ICPS) and hybrid plasma-arc atomization (HPAA)

Production method	Fraction size, μm	Bulk density, g/cm^3	Tap density, g/cm^3	Flowability, s/50 g
ICPS	2553	6.25	6.80	11
HPAA	2545	6.05	6.45	14

wire atomization was conducted in an open atmosphere with cooling in water, leading to interaction of the surface layers of molten particles with oxygen with oxide formation on their surface.

Investigations of technological properties (bulk density, tap density and flowability) of molybdenum powder produced by the technology of hybrid plasma-arc atomization, showed that the above powders do not essentially differ by these characteristics (Table 3) from commercial powders made by the technology of spheroidization of irregularly-shaped powders in induction plasma (Induction Coupled Plasma Spheroidization (ICPS), Tekna Company, Canada). Lower technological characteristics of the powder can be due to presence of oxide film on the particle surface and narrower range of the particle size distribution, shifted towards the finely-dispersed fraction, which impairs the sphericity characteristics, and furtheron can be eliminated when performing atomization in chambers with a shielding atmosphere.

DETERMINATION OF THE TECHNICAL-ECONOMIC CHARACTERISTICS OF THE HYBRID PROCESS OF PLASMA-ARC ATOMISATION AND ITS COMPARISON WITH OTHER COMMERCIAL PROCESSES

Studying the productivity (Figure 6) of the above-mentioned processes showed that its highest values are achieved at application of the processes of hybrid plasma-arc atomization and arc atomization, and they are equal to 24 and 19 kg, respectively. Improvement of productivity of the hybrid plasma-arc process relative to arc atomization by 25 % can be due to additional heating of the atomized wires as a result of their con-

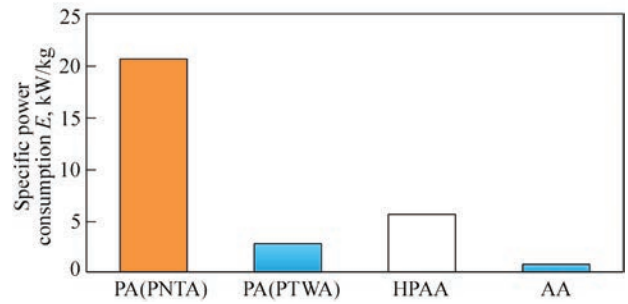

Figure 9. Specific power consumption E to produce 1 kg of steel powder at atomization 1.6 mm wire of ER70S-6 brand produced by different atomization technologies

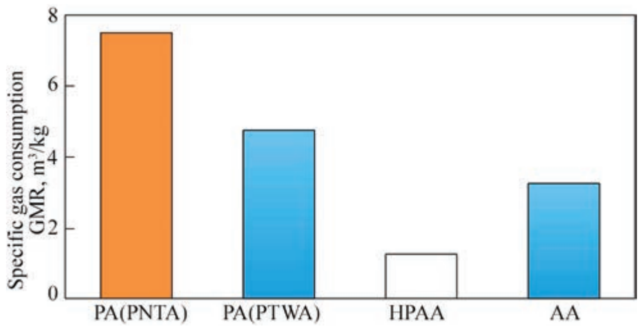

Figure 10. Specific gas consumption (GMR) to produce 1 kg of steel powder at atomization 1.6 mm wire of ER70S-6 brand produced by different atomization technology

vective heat exchange with the plasma jet [17]. Calculations of the material utilization rate for the hybrid plasma-arc process showed that the above coefficient is equal to 0.97, i.e. up to 3 % of the total weight of the wire evaporates during atomization.

Determination of specific power consumption (Figure 9) showed that in terms of its economy the most rational is application of the processes of arc and plasma atomization of the current-conducting wire, where power consumption is equal to 0.75 and 2.75 kW/kg, respectively, while the process of hybrid plasma-arc atomization is characterized by higher values of power consumption equal to 5.5 kW/kg.

Determination of specific gas consumption (gas to metal ratio (GMR)) to produce 1 kg of steel powder of ER70S-6 grade at HPAA atomization (Figure 10) showed that gas flow rate is the lowest in the processes of hybrid plasma-arc atomization and arc atomization, where the value of specific gas consumption is equal to 1.25 and 3.25 m^3/kg, respectively.

CONCLUSIONS

1. A scheme and equipment for hybrid plasma-arc atomization process was developed, which uses the arc for heating and melting of the atomized material, and the supersonic plasma jet is applied predominantly for melt fragmentation at the atomized wire tip at radial feeding of the wires into it.

2. The effectiveness of application of the hybrid process of plasma-arc atomization to produce high quality spherical powders, meeting the requirements by their particle size distribution and technological properties, to powders used in additive technologies (SLM/SLS, CS, EBM, PPTAA and LENS) was confirmed in the case of a compact steel and molybdenum wires of ER70S-6 and MCh brands of 1.6 mm diameter. It is shown that the above process allows producing powders with average diameter (less than 70 μm), where the share of the fine fraction of 25–63 μm can reach 70 wt.%. Studies of powder morphology showed that the above process allows producing powders with the coefficient of sphericity of 0.8. This, in its turn, ensures the high technological properties of the powder (bulk density, tap density and flowability), compared to the technological properties of powders produced by the method of spheroidization of irregularly-shaped particles in induction plasma.

3. Studies of technical-economic characteristics of the hybrid process of plasma-arc atomization showed that the above process has a number of advantages relative to other plasma atomization and arc atomization processes, namely: increase of productivity by 25 %, compared to the process of arc atomization, which may reach 24 kg/h for steel and reduction of specific gas consumption to produce 1 kg of powder by 2.5 times: from 3.25 up to 1.25 m^3/kg are achieved.

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CONFLICT OF INTEREST
The Authors declare no conflict of interest

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