

PROSPECTS OF ULTRASOUND APPLICATION IN THE PRODUCTION OF DISPERSED GRANULES BY GAS AND PLASMA-ARC ATOMIZATION OF METAL MELTS AND COMPACT MATERIALS (REVIEW)

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ABSTRACT

The technological features of ultrasonic vibrations utilizing for the atomization of microvolumes of metal melts in production technologies of dispersed spherical powders are considered, such as: gas atomization, ultrasonic atomization on sonotrode, plasma arc atomization by means of ultrasonic standing wave, electric arc atomization with the application of ultrasound to the wire, and plasma arc atomization with the application of ultrasonic vibrations to the atomized material. The influence of ultrasonic vibrations on the process of melt droplet formation and detachment for the aforementioned methods is analyzed. It is established that the superposition of ultrasound promotes a refinement of the initial melt droplets, intensifies dispersion due to putting additional pressure on the melt droplets, and, as a result, contributes to the narrowing of the particle size distribution. It has been found that among the analyzed approaches for obtaining spherical powders using high-frequency acoustic vibrations, the most promising is the technology of plasma arc atomization of wires and rods under the condition of applying ultrasound directly to the billets. An analysis of the efficiency and prospects of using plasma-arc atomization technologies with the introduction of ultrasonic vibrations into the atomized billets has been conducted, and it is hypothesized that this approach will allow increasing the yield of $-63\ \mu\text{m}$ fraction powders up to 80–90 %, which is promising for application in the production of powders for additive manufacturing technologies.

KEYWORDS: ultrasonic atomization, dispersion, plasma arc atomization, gas atomization, spherical powders, particle size distribution

INTRODUCTION

Influence of acoustic vibrations in the ultrasonic range is widely applied in engineering and industry to solve the tasks on non-destructive testing (flaw detection, determination of coating thickness, medical research), for ecological cleaning of materials in special baths for degreasing or deburring for the surface activation prior to coating deposition, for soldering and welding of metals and alloys, for dispersion of liquids in analytical equipment and of metal melts in powder production, in metal treatment for reducing the friction coefficient and in finish treatment of holes after drilling and milling [1]. In addition, ultrasound application in industrial technologies includes impact treatment of welds for relaxation of internal stresses and surface hardening, ultrasonic wire drawing with reciprocating oscillatory motion of the wire die, solution homogenizing and formation of suspensions and emulsions [2]. A separate important feature of ultrasonic vibrations is intensification of motion of the environment through which they propagate, which can be applied to improve the efficiency of currently available technologies, which is especially true for welding and related processes [3].

It is known that in the electric arc welding technologies application of ultrasonic vibrations to the parts proper, to the molten metal or to the consumable electrode leads to active stirring of the weld pool due to mechanical vibrations, improvement of heat conductivity of the particles in the arc at increase of thermal diffusion coefficient and increase of pressure generated by the electric arc [4–6]. The arc proper under the influence of vibrations is constricted with increase in its energy density, which enhances the heat input into the metal particles [7]. More over, due to high-frequency vibrations the ionized particles stay in the arc longer after passing the resonant frequency [8]. Use of ultrasound in the technology of semi-automatic consumable electrode welding demonstrates a more active transfer of the melt particles from the wire tip: drop flight velocity rises by 10–20 % in case of 3 times increase of the frequency of drop detachment due to the melt film resonating at the wire tip, and to its surface fluctuations, and further imparting additional acceleration to the drops forming on the melt surface, which leads to reduction of the force required for drop detachment and to intensification of the processes of mass transfer in the electric arc, respectively [7–14].

Considering the above-mentioned influence of ultrasonic vibrations, use of these effects can be prom-

ising in such an application, as powder atomization in additive manufacturing (AM) technologies, which require spherical particles of narrow classes. At present the problem of producing powders of $-63\ \mu\text{m}$ class with a high sphericity coefficient has not been solved completely by technological implementation. The most promising technologies for producing fine spherical particles with a high sphericity coefficient and purity and chemical composition reproducibility are the plasma atomization (PA) processes [15, 16]. Proceeding from the fact that PA technologies traditionally use wires as feedstock materials for atomization, superposition of ultrasonic vibrations on them, owing to the influence on the electric arc and the melt, can be potentially applied to increase the yield of finely dispersed fraction of $-100\ \mu\text{m}$ class, improve the atomization process efficiency and increase the sphericity coefficient of the produced powders.

Accordingly, the objective of this work is establishing the influence of ultrasonic vibrations when producing the powders by gas and plasma-arc atomization of metal melts and compact materials on the dispersity and particle size distribution of the produced powders.

In connection with the fact that this aspect of application of high-frequency acoustic vibrations in melt atomization technologies requires further detailed investigation, this study addresses the following tasks: conducting a critical review of the currently available technologies of dispersion of metal melt microvolumes using ultrasound; assessment of the prospects for and conducting analysis of the effectiveness of ultrasound application in plasma-arc atomization of wire and rod materials and prospects for application of such an approach.

APPLICATION OF ULTRASONIC VIBRATIONS IN THE PROCESSES OF DISPERSION OF METAL MELT MICROVOLUMES

Ultrasonic generators are widely used for dispersion (atomization) of liquids and producing aerosols for medical applications and in analytical equipment to conduct investigations of chemical composition of liquids or dissolved solids by the method of emission spectroscopy. Unlike other dispersion methods, ultrasonic atomization is not related to formation of high-speed flows due to drop breakup by gas jets, and it requires more than 100 times lower power to produce drops of the required diameter. The main atomization mechanisms here are cavitation and resonance. The main variable, which determines the produced drop size, is the frequency of vibrations, which, in its turn determines the vibration amplitude [17–20].

The authors of work [21], which studied the influence of the oscillatory circuit elements on the average size of atomized particles, confirmed this hypothesis in practice and derived an empirical formula (1), from which it follows that the parameters, influencing the mean size of atomized particles are the liquid surface tension σ , density ρ and vibration frequency f , which is the main variable of the process:

$$D_{av} = 0.73 \left(\frac{\sigma}{\rho f^2} \right)^{1/3}. \quad (1)$$

The authors of [19] established that in order to initiate the process of melt dispersion due to excitation of standing waves at the resonant frequency, it is necessary to reach a certain value of vibration amplitude. It follows from the proposed model that the minimal vibration amplitude depends on dynamic viscosity μ , density ρ , liquid surface tension σ and vibration frequency f :

$$A_m = \frac{2\mu}{\rho} \sqrt[3]{\frac{\rho}{\pi \sigma f}}. \quad (2)$$

A separate application of ultrasound spraying of liquids is spray drying. The method consists of spray drying, during which a liquid flow is injected into a reactor blown by hot air or heated gas, through an injector to which high-frequency vibrations are applied. This flow is a suspension or liquid dissolved using the respective solvent. When passing through the injector nozzle, the flow is broken up into small particles due to cavitation, their size being determined by the vibration frequency and liquid characteristics. After that, the solvent evaporates due to convection. The result of this is superfine particles with a narrow particle size distribution, which is an impossible task for conventional spray drying. However, the main applications of this method are food industry, pharmaceutical production and producing powder granulate for powder metallurgy. The latter allows solving the problem of producing composite nanopowders and significantly increasing the adaptability to fabrication of submicron powders, while also reducing the transportation losses through entrainment [20–25].

The above-mentioned regularities lead to the conclusion that atomization with application of ultrasonic vibrations, can be used not only for liquids, but also for metal melts. Accordingly, ultrasonic vibrations can be regarded as the method of improving the quality, and dispersity and increasing the yield of the most needed product in the technologies of producing dispersed powders by atomization.

GAS ATOMIZATION OF METAL MELTS WITH ULTRASOUND APPLICATION

Melt atomization by cold gas jets is a long-known and very common technology of producing metal powders. The atomization system consists of the crucible heating system, into which the feedstock material is charged, intermediate ladle with a special nozzle for pouring, gas supply system and process chamber. The first stage of gas atomization process is pouring the molten metal from an intermediate ladle through a special nozzle. Then, the liquid metal is broken up by inert gas jets, which promote melt separation into fine drops and their cooling, which occurs during drop falling into the hopper-collector [26].

The traditional gas atomization technology has significant imperfections: wide range of powder particle size distribution from 25 to 500 μm , low sphericity coefficient of up to 0.7, satellite formation on the surface of large particles and closed porosity [27]. In order to solve these problems, work was performed to optimize the gas atomization process, using ultrasonic vibrations, applied to the melt pouring tube, which is inserted into the nozzle, and which is the sonotrode for ultrasonic vibration transmission [28–30]. Figure 1 gives the schematic of such a process.

Local researchers [31] used the approach with ultrasonic vibration transmission to the melt through atomization gas with application of an intermediate nozzle, operating on the principle of an acoustic radiator. Vibrations in the intermediate nozzle arise due to gas flow cutting by the upper edge, which promotes vibration excitation in the gas before collision with the melt flow. Using a standard injection assembly for gas atomization with an ultrasonic intermediate nozzle and without it the authors determined that at atomization of NM79 alloy the yield of $<80 \mu\text{m}$ fraction was not less than 75 % against 58 % without ultrasound application.

However, the technology of gas atomization with ultrasonic vibrations has not been implemented in industry, due to impossibility to eliminate the main drawbacks of the process, such as formation of close gas porosity and developed surface of the particles.

ULTRASONIC ATOMIZATION OF THE METAL MELT ON THE SONOTRODE

One of the newest methods for production of high-quality metal powders is melt atomization in a crucible, which is part of an ultrasonic oscillatory circuit.

So, the authors of work [32] developed a technological approach, which allows producing spherical powders of metals and alloys, using the feedstock in the form of a lumpy material, placed into the crucible of the induction furnace, from which the melt drops,

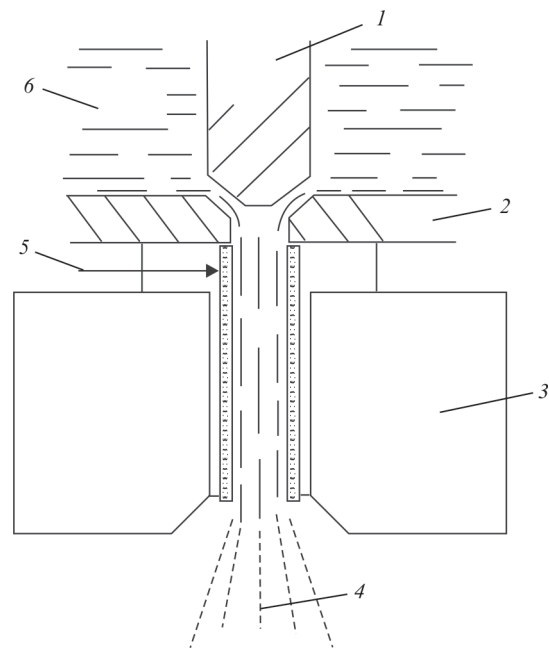


Figure 1. Ultrasonic gas atomization [28]: 1 — locking rod; 2–3 — ultrasonic injector; 4 — atomization cone; 5 — ceramic pouring tube; 6 — melt

flowing out through the nozzle, freely fall onto the sonotrode, to which vibrations of 20 kHz frequency are applied, and the electric arc is used to maintain the liquid state of the material (Figure 2). The atomization process chamber proper is filled with argon, and the drops, broken up by the capillary waves, which separate from the melt, are blown off by the argon flow and solidify. Removal of atmospheric gases before chamber filling with argon is performed using the vacuum pumps.

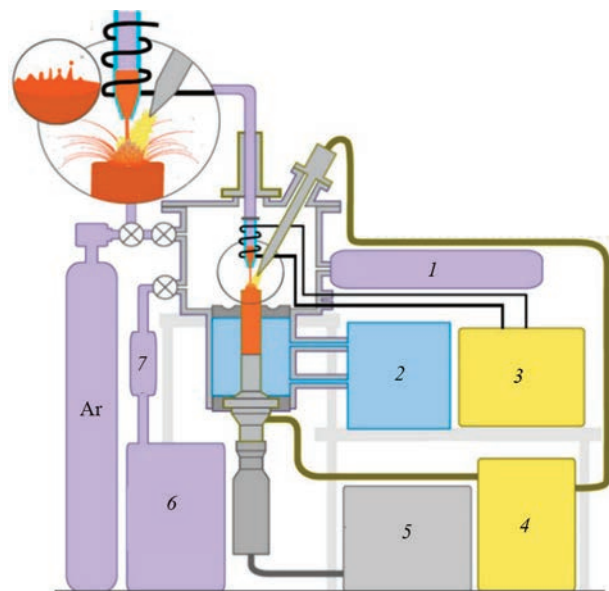


Figure 2. Schematic of ultrasonic atomization of the melt on the sonotrode with additional heating by an electric arc [32]: 1 — pressure sensor; 2 — water cooling; 3 — high-frequency generator; 4 — arc remelting system; 5 — ultrasonic generator; 6 — vacuum pump; 7 — filter

In work [33] researchers showed that atomization of metal melt of iron alloys on the sonotrode allows producing particles of less than 100 μm size, the yield of 32–45 and 45–63 μm fractions being not less than 60 % of the total powder yield. In work [34] it is shown that for titanium alloys Ti–6Al–4V and Ti25Al12Nb this technology allows ensuring particle sphericity coefficient of 0.9 and increasing the yield of the composition of –63 + 20 μm class, compared to gas atomization: gas atomization provides the yield of –63 μm fraction at the level of 30 % of the total volume, while ultrasonic atomization on the sonotrode has the yield of the order of 80–90 %, depending on vibration frequency.

During the experiments, researchers [24] found that for metal melt atomization on a surface vibrating at a high frequency, equation (3) is valid, which establishes the dependence of particle mean size on capillary wave length λ and empirical function f , which depends on the values of Weber (We), Onezorge (Oh) and intensity (In) criteria. In the majority of melt atomization processes the value of the function is taken equal to a unity ($f(\text{We}, \text{Oh}, \text{In}) = 1.0$):

$$D_{\text{av}} = 0.34\lambda f(\text{We}, \text{Oh}, \text{In}). \quad (3)$$

For calculation of the capillary wave length the authors of [34] propose applying empirical dependence (4), which includes surface tension σ and density ρ of the melt at a given temperature, vibration frequency f , as well as melt film thickness h :

$$\lambda = \sqrt[3]{\frac{8\pi\sigma \tan h\left(\frac{2\pi h}{\lambda}\right)}{\rho f^2}}. \quad (4)$$

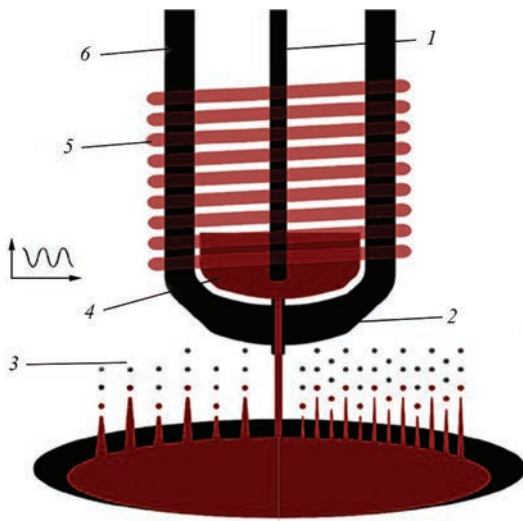


Figure 3. Schematic of ultrasonic atomization of the melt on the sonotrode [35]: 1 — locking graphite rod; 2 — graphite nozzle; 3 — aluminium powder; 4 — aluminium melt; 5 — inductor; 6 — graphite crucible

After substitution of the capillary wave length into formula (3) and assuming the value $f(\text{We}, \text{Oh}, \text{In}) = 1$, we obtain formula (5), which can be used to determine the mean value of the particle size using the value of density and surface tension of the melt at known temperature T .

$$D_{\text{m}} = 0.34\sqrt[3]{\frac{8\pi\sigma_T}{\rho_T f^2}}. \quad (5)$$

Conducting studies of the process of atomization of commercial aluminium powders in work [35] the researchers used simplified equipment without application of additional heating of the melt being poured. The process schematic is given in Figure 3, and the atomization technique is as follows: graphite crucible was filled with granulated aluminium powder and placed into the electromagnetic field of the inductor, the crucible was fitted with a graphite nozzle for pouring, the aluminium melt was poured onto the sonotrode from a copper alloy, vibrating at the frequency of 60 Hz. The process chamber was pumped down by a vacuum pump and was filled with argon to the pressure of 100 mbar, while the furnace was pumped down and filled with argon to the pressure of 200 mbar, i.e. pouring occurred at a certain differential pressure in addition to the gravity component. In this study the influence of vibration amplitude on the material particle size distribution was established, and it was shown that lowering of vibration amplitude narrows the particle size distribution and reduces the particle mean size. At 9.9 μm amplitude the mean size of aluminium particles was equal to 41.7 μm , and at 8.55 μm amplitude it was 31.8 μm , respectively.

PLASMA ARC ATOMIZATION DUE TO THE STANDING WAVE

Investigations of the possibility of metal melt atomization using the energy of high-frequency acoustic vibrations, began in the middle of the previous century. However, in 1987 researchers K. Bauckhage, P. Schockenberg and H. Vettters in their Patent 39 178A made an assumption as to the possibility of process intensification through application of two oscillatory circuits, where the sonotrodes are located opposite to each other, and to which ultrasonic vibrations are applied with a slight difference in the frequency. Under such a condition, a standing acoustic wave, close to a spherical shape, is generated between the sonotrodes, and the molten metal is fed from the crucible into the gap between the sonotrodes through the nozzle, its drops being torn apart from within due to cavitation, and the fragmented droplets flying out radially with subsequent cooling.

In further papers the researchers from [36] and [37] demonstrated the potential of the possible technology of atomization due to a standing wave (Ultrasonic Standing Wave Atomization) and defined the theoretical concepts of the processes of acoustic vibration transmission through the gas medium, heat transfer and the assumptions on particle formation from metal melts, giving the conclusion about the possibility of producing powders with mean size less than $15\text{ }\mu\text{m}$.

However, there is no real data as to implementation of this approach in metal melt atomization, just a tentative schematic of closed-cycle process equipment is available, which is shown in Figure 4.

Despite the lack of technology implementation, potential application of a standing ultrasonic wave in plasma atomization of rod and wire materials is of interest. We assume that acoustic vibrations will propagate through the gas medium to the plasma, and from it — to the feedstock being atomized, which will generate additional pressure of melt drop detachment.

On the other hand we assume that according to investigations of [38], use of sonotrodes directed towards each other, will influence the plasma arc profile, constricting it, and increasing the energy density and heat transfer, optimizing, or intensifying the billet surface melting mode, respectively. This will potentially allow producing finer powders of a narrower fraction with higher productivity.

ELECTRIC ARC ATOMIZATION WITH APPLICATION OF VIBRATIONS TO THE ATOMIZED MATERIAL

Electric arc atomization is a long-known approach, traditionally used for spraying functional coatings by electric arc metallization technology. It is characterized by relative simplicity and affordability of the equipment, which consists of a block of electrode wire feed, atomization gas supply system, electric arc power system and atomization chamber. This technology also features high productivity, which can reach 40 kg/h in some cases. This technology provides a significant yield of the fine fraction ($<63\text{ }\mu\text{m}$) and other advantages. However, despite the numerous advantages, a significant disadvantage of electric arc spraying is the use of cold gas for melt atomization, which forms at the tip of atomized wires. This leads to production of powders with a high content of particles of an irregular shape, satellites and considerable internal porosity because of atomization gas entrapment by the melt, making their application in additive technologies more complicated [39, 40]. The process schematic is given in Figure 5.

Researchers of the work [40] during atomization of wires from stainless steel AISI 630 and melt drop dis-

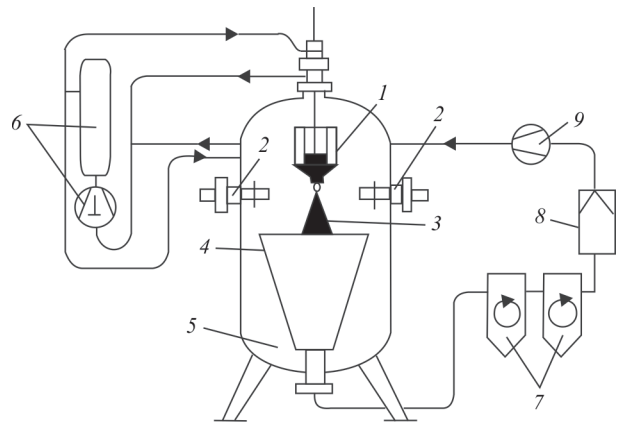


Figure 4. Schematic of the unit of ultrasonic atomization by a standing wave [36]: 1 — crucible with the melt; 2 — sonotrodes; 3 — atomization cone; 4 — device for waste gas removal; 5 — hopper-collector; 6 — tank with working gas; 7 — cyclones and sieves; 8 — filter; 9 — compressor

persion by argon in the reactor in an argon atmosphere produced powders with particle size distribution from 10 to $160\text{ }\mu\text{m}$ at mean particle size of about $70\text{ }\mu\text{m}$.

In work [41] the authors conducted experiments on aluminium wire atomization by an electric arc during melt dispersion by argon in an air atmosphere and obtained particles with sphericity coefficient in the range of 0.71 to 0.81 at mean particle size of $50\text{--}80\text{ }\mu\text{m}$.

Coming back to the possibility of introducing high-frequency vibrations into the wires fed during electric arc atomization, at present there is no data on implementation of this approach. There are, however, several studies of heat- and mass transfer in electric arc MIG/MAG processes with simultaneous supply of ultrasonic vibrations to the welding wire. These investigations showed an active influence of ultrasound, applied to the wire-cathode, on surface tension and acceleration, which is additional to free fall acceleration due to gravity. The established regularities in semi-automatic MIG welding demonstrate that ultrasonic vibrations promote formation of elongated drop-shaped particles as opposed to spherical ones,

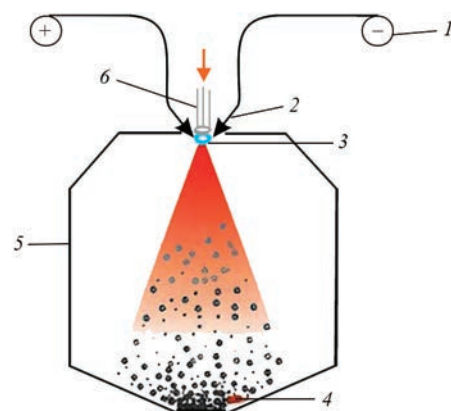


Figure 5. Block-diagram of electric arc atomization of the wire [40]: 1 — wire; 2 — wire feeder; 3 — electric arc; 4 — powder; 5 — atomization chamber; 6 — electric arc torch

forming during wire tip melting without vibrations. This, in its turn, allows narrowing the detachment zone, reducing the required detachment force, and accelerating the detachment proper by 20 %, which was established and modelled in works [11, 12].

On the other hand, ultrasonic vibrations have an essential influence on the electric arc proper: the electric arc becomes narrower, and its energy density increases, respectively. At the same time, heat input into the smallest constituent particles of the metal flow at melting by the arc is much higher, as the ionized particles stay in the arc longer after passing the resonance frequency due to the high-frequency vibrations [7, 8]. The authors of works [9, 10] determined that ultrasound application in the technology of semi-automatic welding by a consumable electrode in the form of wire demonstrates a more active transfer of the melt particles from the wire tip: drop flight velocity rises by 10–20 % with three times increase of the drop detachment. This effect is reached by melt film resonance at the wire tip and its surface fluctuations, leading to intensification of the processes of mass transfer into the weld pool [10].

Accordingly, we can make an assumption about the possible activation of the process of electric arc atomization and reduction of power consumption for it due to narrowing of the arc with increase of its specific energy. On the other hand, such a process will require use of two individual oscillatory circuits to transmit the ultrasound to the wire-anode and wire-cathode. The influence on the atomization process can be also inter-

esting, namely — on formation of the melt drop and its disintegration, cavitation and, possibly, of the standing wave, which will form between the wire tips and will propagate through the gas medium, intensifying the atomization and narrowing the particle size range.

PLASMA ARC ATOMIZATION WITH ULTRASONIC VIBRATIONS, APPLIED TO THE ATOMIZED MATERIAL

One of the most promising technologies for production of high-quality spherical powders is plasma spraying, which is not without its difficulties: a large number of variable working parameters complicate achieving a repeatable result and productivity. In work [42], investigations were performed and it was established that at least eight working parameters have their influence on the final size of the powder particles during atomization of the current-conducting wire, the influence of arc current, wire feed rate, arc length, accompanying gas flow rate and gap between the plasmaforming and compression nozzles being the strongest.

One of the commercially implemented approaches to plasma atomization was carried out by “PyroGenesis” Company. Three plasmatrons are used during atomization, between which the wire is fed without supplying the electric potential, i.e. material melting occurs due to the plasma arc heat, and atomization — owing to plasma pressure [43]. The schematic of such a process is shown in Figure 6.

Notwithstanding the adaptability-to-fabrication, the productivity of the process of plasma atomization of powders is equal to 2–3 kg/h for titanium alloy powders, and it can be increased to 5 kg/h, when using additional induction heating of the wire material before feeding it into the plasmatron working zone [43].

There exist different approaches to increasing the productivity of plasma atomization process, such as material atomization by a transferred plasma arc, use of accompanying gas jets with supersonic plasma, as well as hybrid technologies [45]. Development and investigation of these technologies are performed by researcher teams all over the world. However, one of the hypothetically feasible, but not realized and not implemented ways of optimization and intensification of plasma arc spraying is application of ultrasonic vibrations to wires or rods fed into the process.

ANALYSIS OF THE EFFECTIVENESS AND PROSPECTS FOR ULTRASOUND APPLICATION IN PLASMA-ARC ATOMIZATION OF WIRE AND ROD MATERIALS

Plasma-arc atomization is one of the effective methods of producing spherical metal powders,

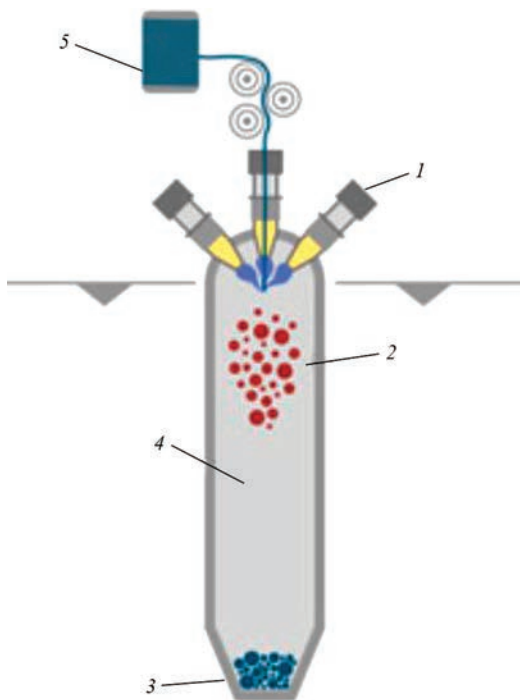


Figure 6. Plasma atomization of wire by PyroGeness technology [44]: 1 — plasmatron; 2 — melt drops; 3 — wire; 4 — argon; 5 — wire spool

which are widely used in aviation, rocket and additive manufacturing industries. Improvement of this process by introducing ultrasonic vibrations can considerably improve the powder characteristics, in particular, their particle size distribution and sphericity. Plasma-arc atomization is based on the use of high-temperature plasma heat for surface melting of the tip of metal wires or rods, melt drop detachment and their dispersion by the plasma jet. The main parameters of the process are plasma temperature, flow velocity, electric parameters of the arc and atomized material properties. The influence of all these parameters determines the final characteristics of the produced powder.

Moreover, promising is introduction of another kind of influence, namely ultrasonic vibrations, which during propagation through the atomized material lower the surface tension of the melt film, cause intensification of the heat- and mass transfer, generate additional pressure on the melt drop accelerating its detachment, promote refinement of the initial drop and improvement of atomization homogeneity. According to investigations, conducted in work [34], where comparison of ultrasonic atomization on the sonotrode is compared to the traditional gas atomization, addition of high-frequency vibrations into the metal melt promotes an increase of the yield of fine particles with a narrow particle size distribution of $-63 + 20 \mu\text{m}$ to 80–90% due to reduction of the initial size of the melt drop. Here, according to equations (1) and (5), the frequency of vibrations applied to the melt, has a considerable influence on the critical (initial) size of the drop. The particle size becomes smaller with frequency increase.

During investigations the authors of [4] determined that the use of ultrasonic vibrations superposed onto the welding wire, promotes an increase of particle heat conductivity in the plasma arc with increase of the thermal diffusion coefficient and increase of pressure generated by the arc. The latter was mathematically modelled and experimentally confirmed by the authors of works [5, 6]. The proposed mathematical model (6) allows for the influence of the following variables on the arc pressure: arc parameters, nozzle geometrical parameters, process gas density and plasma flow velocity, as well as the sound pressure magnitude. Proceeding from the established regularities, the amplitude of wire tip vibration makes a significant contribution to arc pressure, increasing it by 15–31 %:

$$P(x, y, z) = \frac{\eta_i 3r_n^2 \rho_{\text{Ar}} Q_{\text{pl}}}{A_1 S_n} \times \sqrt{\frac{P_{\text{osc}}^2}{\rho_{\text{Ar}}^2 c^2} + \frac{2\eta_v IU}{\rho_{\text{Ar}} Q_{\text{pl}}} + \frac{Q_{\text{pl}}^2}{S_n^2} \frac{\mu_0 I^2}{4\pi^2 r_p^2}} \times \exp\left(-3 \frac{x^2 + y^2}{r_p^2}\right). \quad (6)$$

Author teams in works [13, 14] conducted investigations, which agree with theory and are confirmed by high-speed filming. It was established that wire vibrations with the frequency from 1 kHz and higher promote an earlier drop detachment, and the most efficient mode of new drop detachment at each vibration is achieved at the frequency of 20 kHz.

Mathematical modelling which was conducted in work [10], proposes a description of the magnitude of ultrasound force F_U , acting on the melt drop (7), as such which depends on the gas medium density ρ , in which the vibrations propagate, vibration amplitude A , wave number k , particle radius R and coefficient λ , allowing for the relationship between the medium density and melt drop:

$$F_U = \frac{1}{3} \pi \rho A^2 (kR)^3 \sin(2k) \frac{5 - 2\lambda}{2 + \lambda}. \quad (7)$$

According to our assumptions and the above investigation results, the experience of introducing ultrasonic vibrations into the melt can be transferred to the process of plasma atomization of compact materials. Superposition of ultrasonic vibrations in plasma-arc atomization offers the prospect of intensification of the dispersion process and increasing the yield of $-63 \mu\text{m}$ fraction to 80–90 %. The most promising appears to be the process of plasma arc atomization of rods and wires with application of ultrasonic vibrations to them, which propagate through the material of the wires and rods as if along a sonotrode, up to the tip with the velocity greatly exceeding that of propagation in the gas medium.

CONCLUSIONS

1. An approach has been substantiated to improvement of melt atomization process by introducing ultrasonic vibrations, which during propagation through the atomized material or gas medium, allows lowering the surface tension of the melt film, intensifying mass transfer, achieving drop refinement and improving the atomization uniformity. The main mechanism of such an influence is generation of capillary forces and cavitation in the melt drops during propagation of

high-frequency vibrations in them, which, in its turn, will put additional pressure on the melt drop and will reduce the force required for the drop detachment. All this significantly improves the technological characteristics of the produced powders, in particular, promotes reduction of particle sizes and increase of the sphericity parameter.

2. Conducted analysis of the effectiveness of ultrasound application in plasma-arc atomization of the wire and rod materials confirmed the good prospects of introducing ultrasonic vibrations not into the gas medium or plasma arc, which is inefficient because of the low velocity of acoustic vibration propagation in gases, but exactly into the atomized feedstock in the form of wires or rods, which promotes more frequent detachment of the melt drops from the atomized tip, with reduced size of the initial drops. In keeping with our assumptions, superposition of ultrasonic vibrations on the wires and rods during plasma arc atomization will increase the yield of fine-dispersed spherical particles of –63 µm class from 40–50 to 80–90 %.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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