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IMPROVING THE INDUCTIVELY COUPLED PLASMA TECHNOLOGICAL PROCESS OF ALUMINUM POWDER SPHEROIDIZATION

Mykola Lyutyk*
ORCID: http://orcid.org/0009-0000-8229-7327
Mykola Skulskyi*
ORCID: http://orcid.org/0009-0001-4584-2194
Serhii Maikut
Doctor of Philosophy (PhD), Senior Lecturer
Department of General Physics and Modeling of Physical Processes***
ORCID: https://orcid.org/0000-0002-0913-4190
Anatoly Kuzmichev
Doctor of Technical Sciences, Professor
Department of Electron Devices and Systems***
ORCID: https://orcid.org/0000-0003-0087-275X
Valeriy Pashchenko
Doctor of Technical Sciences, Associate Professor**
ORCID: http://orcid.org/0000-0003-3742-6913
Volodymyr Lysak
Doctor of Philosophy (PhD)**
ORCID: https://orcid.org/0000-0002-6565-2793
Andrii Chornyi
PhD, Associate Professor**
ORCID: http://orcid.org/0000-0002-7424-0264
Ihor Sieliverstov
Corresponding author
PhD, Associate Professor
Department of Automation, Robotics and Mechatronics
Kherson National Technical University
Instytutska str., 11, Khmelnytskyi, Ukraine, 29016
E-mail: sia04041972@gmail.com
ORCID: http://orcid.org/0009-0009-6135-8165
Igor Smirnov
Doctor of Technical Sciences, Professor**
ORCID: http://orcid.org/0000-0002-1818-7403
*LLC KLAKONA SYSTEMS
Zhmerynska str., 1, Kyiv, Ukraine, 03148
Department of Welding Production*
***National Technical University of Ukraine
“Igor Sikorsky Kyiv Polytechnic Institute”
Beresteiskyi ave., 37, Kyiv, Ukraine, 03056

This study explores the process of the inductively coupled plasma spheroidization of aluminum powder. The task addressed relates to the complexity of spheroidization of low-melting materials, as well as to the growing need to use spheroidized powders from new materials in additive manufacturing, powder metallurgy, and gas-thermal coating.

To define the process of particle spheroidization, a comprehensive approach was used, including experimental studies, analytical description of thermal processes, and numerical modeling using the COMSOL Multiphysics software environment.

Based on the simulation results, parameters of the inductively coupled plasma, the regularities of heating, melting and crystallization of aluminum powder particles were determined. It was found that the full cycle of heating to the melting temperature and phase transition occurs over an extremely short time – on the order of 10-5 s to 10-4 s for a particle with a diameter of 50 μm. The temperature gradients inside the particles are insignificant, which contributes to their uniform melting and the formation of a spherical shape under the influence of surface tension forces. The key factors of the process are the plasma temperature and the time the particles spend in the high-temperature zone.

The simulation results made it possible to establish technological modes of spheroidization: inductor current 40–42 A, current frequency 1.76 MHz, gas flow rate 5 l/s, gas pressure at the plasmatron inlet 13×10^{-3} *MPa. The adequacy of the proposed modeling was confirmed by obtaining aluminum powder with a high degree of spheroidization (from 95% to 98%).*

The model built could be used to predict the process parameters and its further optimization in order to obtain spherical powders from other materials and fractions

Keywords: spheroidization, aluminum powder, additive manufacturing, simulation, inductively coupled plasma

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1. Introduction

Spheroidized powders are becoming increasingly popular in additive manufacturing due to their improved rheological and technological properties. Specifically, the high fluidity and homogeneity of such powders provide increased performance characteristics of manufactured products, in particular strength, hardness, and density. This determines their active use in various industries [1].

Powder materials used in additive technologies are subject to strict requirements regarding particle morphology, in particular minimal roughness and high surface sphericity. At the same time, conventional methods of obtaining powders do not always provide the required level of these characteristics, which necessitates the need for additional technological operations, in particular spheroidization.

One of the most effective spheroidization methods is the treatment of powders in a low-temperature plasma flow. Different types of electrical discharges are used to generate plasma: arc, high frequency (HF), radio frequency (RF), as well as their combinations.

Special attention is drawn to spheroidization technologies using RF and microwave plasmatrons, which have a number of advantages:

– the absence of electrodes and, accordingly, their erosion products;

– high purity of the working medium;

– a possibility of axial powder supply to the zone of maximum temperatures;

– long-time residence of particles in the plasma flow;

– the possibility of operation in various gas environments.

The process of high-frequency plasma spheroidization is characterized by many parameters: gas flow rate, power, powder feed rate, particle trajectory, temperature. The plasma temperature can reach 10,000°C, which allows any material to be quickly melted, but this can lead to excessive overheating of the powder and its partial evaporation.

An additional issue of the process is the change in the chemical composition of the material during processing, which is associated with oxidation or reduction processes and is determined by the thermal and dynamic parameters of the interaction of powder particles with the plasma flow. Considering the complexity of the powder spheroidization process, preliminary establishment of process modes is important, for which modern methods of mathematical modeling and computer simulation can be successfully used.

Given the rapid evolution of additive technologies, the design and improvement of powder material spheroidization processes is an urgent scientific and technical task.

2. Literature review and problem statement

Powder spheroidization is one of the successful applications and can play a key role in significantly improving the quality and flowability of the powder [2]. In [3], the possibilities of inductively coupled plasma (ICP) technology are highlighted, with the aim of obtaining high-quality powders for the additive manufacturing industry, but this direction is mainly used for the production of nanopowders or is in the stages of development and preparation for industrial application.

In [4], plasma spheroidization was applied to SS316L stainless steel powder, which is used in additive manufacturing. It is shown that during the plasma spheroidization process, the aspect ratio and sphericity of the processed powder slightly increase, and there is also a shift in the particle size distribution towards larger diameters compared to the original powder. Under the influence of plasma, the powders had a slight, undesirable austenitic-pearlite transformation at the level of 3.5% and the problem of preventing this phenomenon remained unresolved.

In work [5], AISI 304L stainless steel powder particles were also spheroidized using induction-plasma technology. After the induction-plasma spheroidization process, the particles changed their shape to spheres, while their size remained practically unchanged. It was shown that under the selected spheroidization process modes, significant changes were observed in the chemical composition and microstructure of the powder, which primarily depend on the parameters of the plasma flow. The issues of rational selection of technological modes remained unresolved, the choice of which is difficult due to the process itself.

In [6], only a technological scheme for the production of spherical titanium alloy powders for the aviation industry using a complex method of hydrogenation-dehydrogenation (HDH) and plasma spheroidization (PS) was proposed; the features of the technological modes were not considered.

In [7], a new technology for obtaining spherical metal powder using high-temperature remelting and spheroidization (HRS) technology was proposed. The effect of feed rate and temperature on the properties of spheroidized copper powder (particle morphology, particle size distribution, oxygen content, bulk density, fluidity) was investigated. HRS technology effectively avoids defects characteristic of other methods, but the work was carried out with copper powder, which, unlike active materials, has good spheroidization characteristics.

Current research on inductively coupled plasma (ICP) and the design of new plasmatron structures are also important, especially in the context of powder spheroidization. Thus, in [8], the results of a study using 2D modeling for a low-pressure induction plasmatron at a frequency of 2.45 GHz are reported. The spatial distributions of the discharge plasma parameters and the absorption of electromagnetic energy were calculated, and the proposed model can be used to design new plasma generators. In work [9], the characteristics of a pulsed high-current plasma source were investigated, which is the main technological tool for creating high-frequency induction plasma, the regulation of the characteristics is extremely necessary for the spheroidization process.

Of particular interest is paper [10], which presents a multiphysics model of the ICP spheroidization process of refractory tungsten powder, which takes into account the presence of an electromagnetic field, heat transfer processes, plasma flow dynamics, as well as particle motion. The multiscale multiphysics model that was used was built to optimize the spheroidization process of refractory materials only. When working with other materials, the modeling may not give reliable results.

Work [11] summarizes the information that the key factors for effective ICP spheroidization are plasma temperature, the time particles spend in the hot zone, and their trajectory. The authors of [12] found that optimizing these parameters makes it possible to obtain powders with a spherical shape, narrow particle size distribution, and minimal defects, which is critically important for selective laser melting and electron beam sintering technologies.

In addition, the results from [11] prove that the processes of melting and spheroidization of particles in ICP are determined by the balance between heat input from the plasma and heat loss, which directly affects the final structure of the powder.

Among the large number of studies aimed at obtaining spherical powders and the variety of materials used, there are no papers on spheroidization of technically pure aluminum, although there are known works on obtaining spheroidized powder from the AlSi11Mg alloy by spraying from a liquid alloy in a nitrogen environment [13].

A separate, little-studied issue is the process of melting and spheroidization using high-performance technology using ICP plasma. Given the complexity of the ICP spheroidization process for selecting optimal technological modes, the use of mathematical modeling could allow for a clearer understanding of the behavior of powder particles at all stages of transformation from the initial irregular shape to the final spherical one.

Thus, our review of the literature [4–7, 11, 13] showed that the technologies for obtaining spherical powder are aimed at a wide range of materials, in addition to active light metals, in particular aluminum, magnesium. The choice of technological modes of the process was determined only on the basis of experimental studies and therefore was not always rational. The issues of the influence of physical quantities: temperature, time, gas flow rate on the spheroidization process were not considered.

In this sense, work [10] is useful, which provided an understanding of the interaction of IC plasma on the process of formation of spherical particles. The proposed numerical modeling in the work has made it possible to determine rational technological modes at a plasmatron operating frequency of 3 MHz. The issues of the universality of the proposed model, the adequacy of work with other materials and technological equipment remained unresolved.

Thus, available studies demonstrate a successful spheroidization process for many materials but there are no papers on the spheroidization of aluminum. There are no studies on determining the spheroidization conditions specifically for aluminum. Effective study on the influence of induction plasma on powder particles and determination of technological modes is provided by the use of numerical modeling of processes [10]. However, simulation is focused on specific technological equipment, taking into account its technical characteristics and design features.

Therefore, when changing any design or technological parameter, it is necessary to construct a new model.

All the above conclusions indicate the feasibility of computer simulation to determine the temperature-time characteristics of aluminum powder particles in IC plasma, which is necessary for improving spheroidization technology and for establishing rational technological modes of the process.

3. The aim and objectives of the study

The aim of our research is to improve the technological process of spheroidization of aluminum powder by numerical modeling of inductively coupled plasma. This will enable the production of aluminum powder with a high degree of spheroidization for use in additive manufacturing.

To achieve the goal, the following tasks were set:

– to establish the thermal conditions of heating, melting, and cooling of aluminum powder particles depending on the time of spheroidization and the operating parameters of the inductively coupled plasma torch;

– to obtain spheroidized aluminum powder using justified technological modes of spheroidization.

4. The study materials and methods

The object of our study is the process of high-frequency induction plasma spheroidization of aluminum powder.

The principal hypothesis assumes that by modeling, the conditions in the IC plasma under which the spheroidization of aluminum powder particles occurs can be determined. According to the established conditions, the basic technological parameters of the process can be determined, which are subject to control and regulation.

The main task of modeling the process of spheroidization of powder particles by the plasma method is to determine the temperature regime of heating the particle in the plasma flow. During the flight, the particle must melt without reaching the evaporation temperature, then completely solidify, and reach the surface of the powder collector with a temperature that makes deformation impossible during impact.

When modeling the heating process of a particle in a plasma flow, the following assumptions were adopted:

– the particle has an ideal spherical shape;

– the particle is a homogeneous, isotropic body;

– there are no internal heat sources.

In the process of conducting the study, the following simplifications were accepted:

– the use of a simplified model of the plasmatron inductor in the form of a monolithic structure;

– the use of a coarse calculation grid to determine the initial results.

In the work, angular aluminum powder was used for spheroidization, some particles had a length to transverse dimension ratio of more than five. The morphology of the powder was studied on a Tescan Vega 3 LMU scanning electron microscope manufactured by the Czech company Tescan. This powder is obtained by spraying the liquid phase. The physicochemical characteristics and particle size distribution are given in Table 1.

Table 1

Physical-chemical characteristics of the powder

Aluminum, %, not less	Iron, %, not exceeding	Silicon, %, not exceeding	Copper, %, not exceeding	Moisture, %, not exceeding
98.0	0.35	0.4	0.02	0.2
Granulometric composition of the powder				
residue on sieve 0.16%, not more		passage through sieve 0.16%, not less	bulk density, g/cm^3, not less	
15.0		100.0	0.96	

The input powder was spheroidized using a standard induction plasma spheroidization system from the Ukrainian company Klakona Systems. The system consisted of an an inductive power supply with a inductively coupled plasma torch (ICP torch) , a powder feed system, a powder collector, a gas feed system, and a gas filtration system (including a cyclone and a filtration chamber). The general view of the powder spheroidization installation is shown in Fig. 1.

The main technological device in the induction plasma installation is a ICP torch (operating frequency 1.76 ± 0.044 MHz), designed to produce a high-temperature plasma jet.

The ICP torch has the ability to regulate the composition and gas-dynamic properties of the plasma jet within wide limits, as well as feed dispersed materials into the melting zone. Spheroidization of powder particles of materials occurs during their passage through the plasma jet generated by the ICP torch.

Fig. 1. Installation of inductively coupled plasma spheroidization of powders

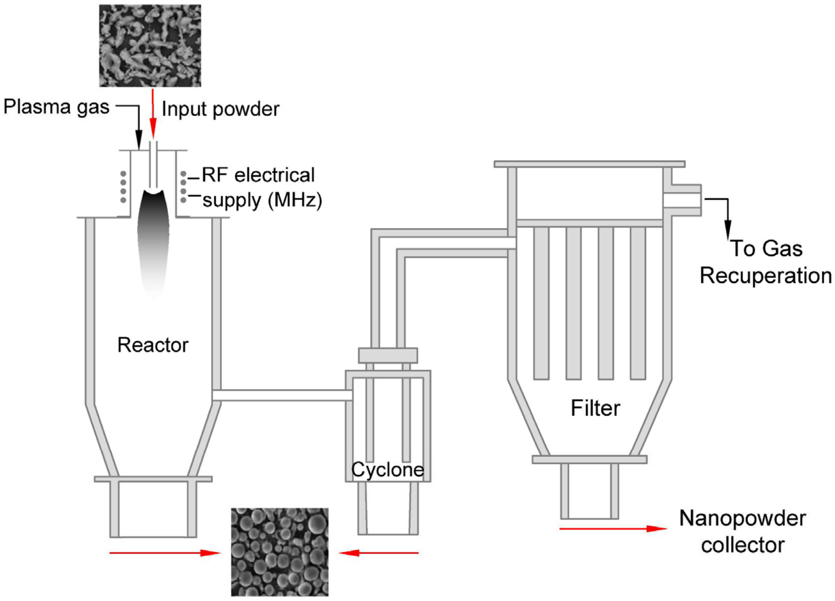


Fig. 2. Schematic of the IC plasma spheroidization process to obtain micro- and nanopowders

The ICP torch is made in the form of a copper water-cooled chamber placed in a quartz ceramic tube located in the inductor of the RF generator, which generates a powerful high-frequency electromagnetic field. During the passage of the plasma-forming gas through the ICP torch, its heating and ionization occur. The resulting plasma jet is a source of heating of dispersed materials, having a temperature from 7000 K to 10000 K.

The use of IC plasma is due to the possibility of changing the temperature and velocity of the plasma jet in a wide range, which makes it possible to process a wide range of materials. The second important advantage of this process is the absence of electrode erosion products in the plasma, which makes it possible to process materials of the highest purity.

The process includes the following basic stages:

1. Preparation of equipment and excitation of low-temperature plasma.
2. Vertical feeding of the starting powder through the probe into the plasma.
3. Unloading of spherical micropowder from the reactor chamber and cyclone.
4. Unloading of nanopowder from the filter collector.

The scheme of the process of spheroidization of powders in induction plasma is shown in Fig. 2.

The powder with structural defects is melted in the plasma flow (Fig. 3), as a result of which the particles acquire the correct spherical shape and are suitable for further use in additive technologies. The qualitative process of heating, melting, cooling, and spheroidization of powder particles in an ICP torch is shown in Fig. 3.

In the plasma flow, particles of irregular angular shape were heated to the melting temperature and during cooling in free fall due to surface tension forces were transformed into spherical granules.

To analyze the process of spheroidization in inductively coupled plasma, a mathematical model was used to determine the temperature regime, which was proposed in [14] and where the temperature state of a powder particle in the process of plasma-arc spheroidization was described.

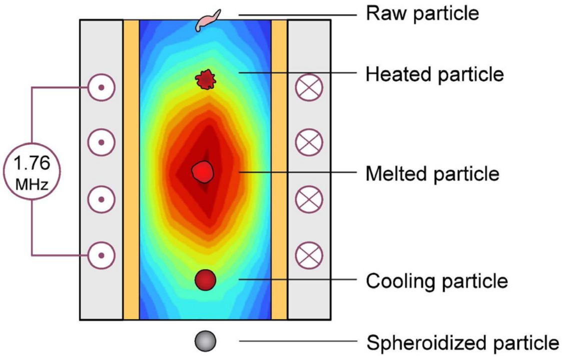


Fig. 3. Schematic showing the process of heating, melting, and spheroidization of powder particles in a ICP torch

Based on the assumptions, the heating of the particle is described by the well-known heat conduction equation

$$\frac{\partial T(r,t)}{\partial t}-a^{2}\left(\frac{\partial^{2}T(r,0)}{\partial r^{2}}-\frac{2}{r}\frac{\partial T(r,t)}{\partial t}\right)=0,\quad 0\le r\le R, \tag{1}$$

where $a^{2}=\dfrac{\lambda}{c\rho}$; λ is the thermal conductivity coefficient of the particle; c is the heat capacity of the particle; ρ is the density of the particle material; R is the radius of the particle.

On the surface of the particle, convective heat exchange with plasma occurs, the temperature of which $T_g(t)$ depends on the time the particle stays in the flow

$$\lambda\frac{\partial T(R,t)}{\partial r}=\alpha\left(T_{g}(t)-T(R,t)\right), \tag{2}$$

where α is the heat transfer coefficient between the powder particle and the gas.

To this boundary condition, the condition of temperature limitation in the center of the particle was added

$$T(0,t)<+\infty, \tag{3}$$

as well as the initial condition

$$T(r,0)=T_0=\text{const}. \qquad (4)$$

The boundary value problem (1) to (4) describes the process of heating a particle in a plasma flow.

Since the thermal conductivity of aluminum is quite high, 200–236 W/(m·K), and the diameter of the particles is small (approximately 50 μm), the temperature difference on the surface and in the center of the particle, as will be shown below, does not exceed 20°C, and it can be assumed that there is no heat flow through the boundary of the change of aggregate states. In this case, the melting time of the particle can be determined from the following formula

$$\tau_{melt}=\frac{R\rho\sigma}{3\alpha\left(T_g-T_{melt}\right)}, \qquad (5)$$

where σ is the heat of fusion; T_{melt} is the melting temperature of the particle; R is the particle radius. According to this formula, the melting time of an aluminum particle is $0.85\cdot10^{-4}$ s.

For the purpose of calculation, visualization, and analysis of the calculated data, the COMSOL Multiphysics software was used [15].

The simulation is divided into several stages:

1 – generation of IC plasma in an argon gas flow and determination of its spatial temperature;

2 – finding the heating and melting time of the powder particle.

5. Results of improving the technological process of spheroidization of aluminum powder; its simulation

5. 1. Temperature-time conditions of spheroidization and operating parameters of the induction plasmatron

Before modulation, the working space of the induction ICP torch model was built (Fig. 4).

The design of the model of the ICP torch consists of a 5-turn inductor, a working space with a height of 400 mm and a diameter of 200 mm, a quartz tube with a thickness of 3 mm, which is located between the working and external spaces. To simplify the model, an equivalent monolithic model was built, which is shown in Fig. 4, *a*, *b*.

The gas flow rate was set at 50 l/min, which gave the gas a maximum velocity in the center of the tube of ~3 m/s and a pressure of up to 13×10^{-3} MPa.

The results of calculating the gas velocity and pressure in the ICP torch are shown in Fig. 5, *a*, *b*.

The current for initial calculations was set at 40 A, which resulted in a normalized magnetic field at 50 μT – sufficient for ignition of induction-coupled plasma (Fig. 6, *a*, *b*). The data were obtained for a coarse grid, as the task was to obtain initial results for further development of the model with more precise settings.

Fig. 7 shows one-dimensional distributions of electron density (*a*), electron temperature (*b*), and electron potential (*c*) along the central axis. From the plots (Fig. 7, *a*–*c*) it is clear that the increase in the maximum values of the parameter coincides with the central location of the inductor. This fully corresponds to the physical essence of the process.

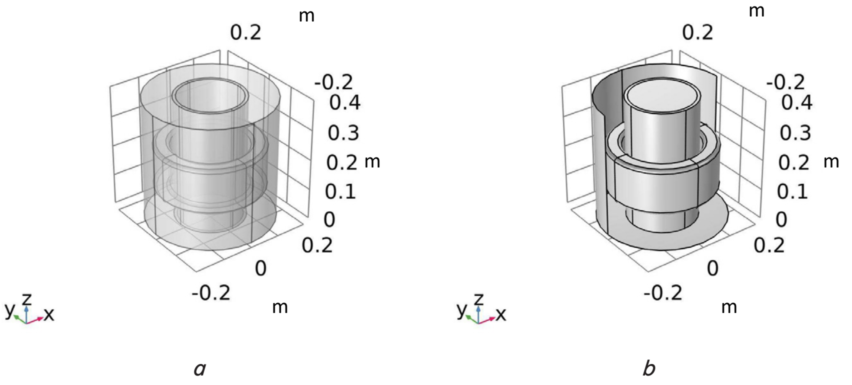
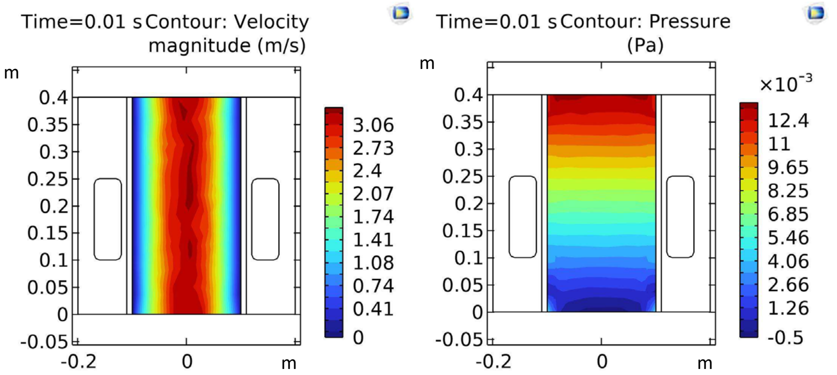
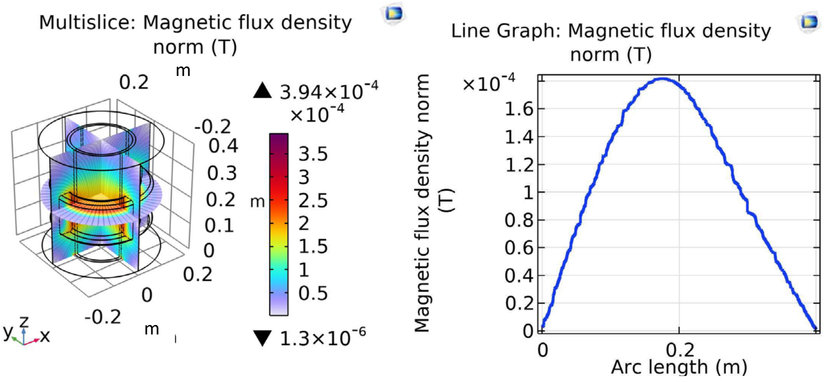


Fig. 4. General view of the geometry of the ICP torch model: *a* — with translucent positioning; *b* — with removed outer walls



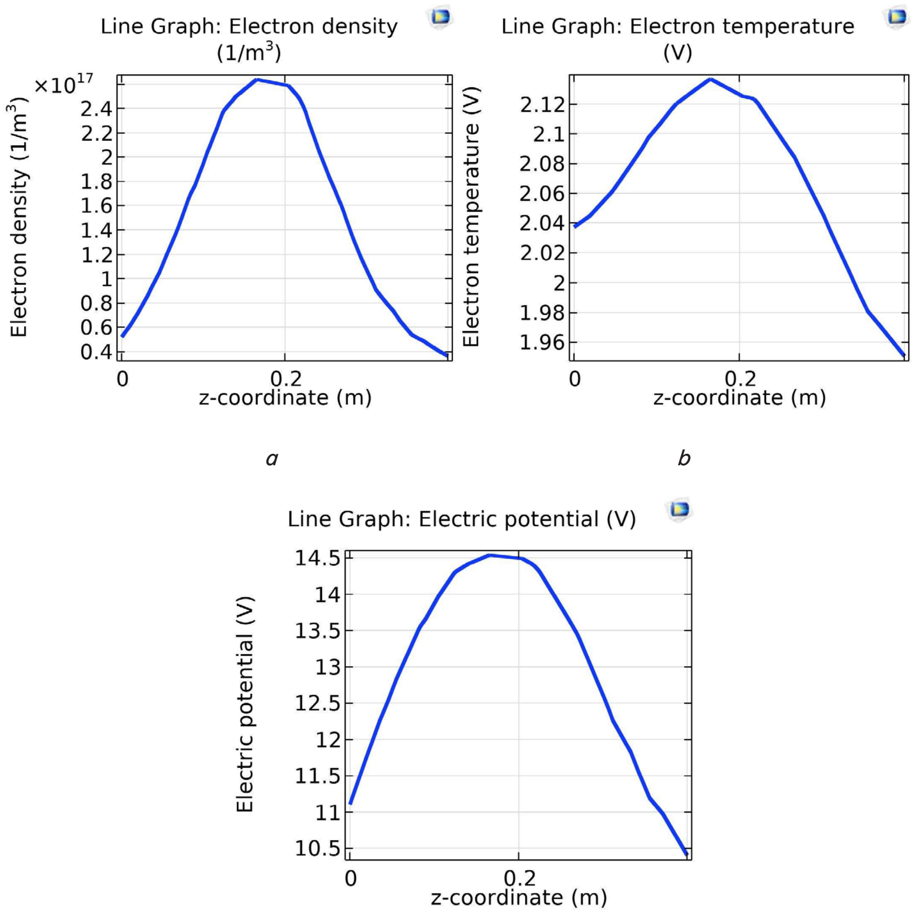
a *b*

Fig. 5. Distribution: a — gas flow velocity; *b* — pressure in the working space of the ICP torch



a *b*

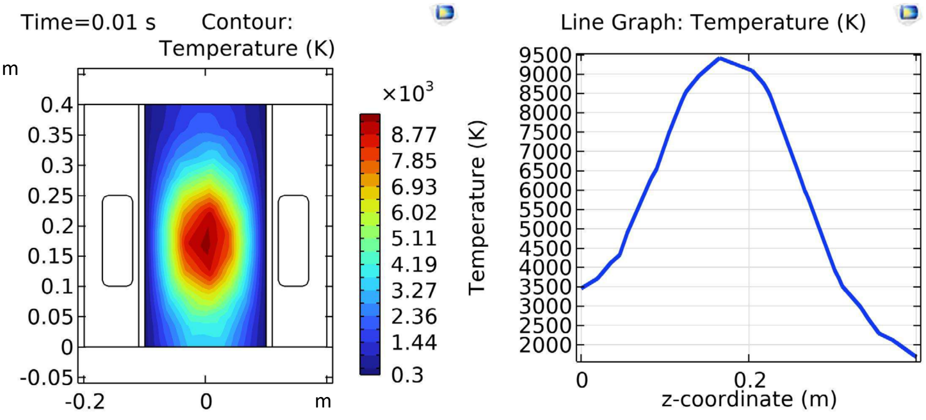
Fig. 6. Magnetic field distribution: *a* — three-dimensional statement, *b* — one-dimensional distribution of the normalized magnetic field along the axial symmetry from bottom to top



a *b*

c

Fig. 7. Distributions along the central axis: *a* – electron density; *b* – temperature; *c* – plasma potential



a *b*

Fig. 8. Temperature distribution of the ionized gas flow:
a – in the longitudinal section; *b* – in the section of the central axis

Subsequently, the spatial energy absorption data in the working space were used to calculate the steady-state thermal distribution (Fig. 8, *a*, *b*) and subsequently to be used as input boundary conditions for the problem of heating a single powder particle with a diameter of 50 μm. The modeling allowed us to establish that it took at least ~0.1 ms for the complete melting of one object, and the melting process itself lasted less than 10 μs (Fig. 9, *a*–*d*).

More illustrative in this case are the one-dimensional plots of temperature distribution (Fig. 10, *a*) and phase transition (Fig. 10, *b*) over time from $1.1 \cdot 10^{-4}$ s to $1.2 \cdot 10^{-4}$ s. The temperature difference from the center to the surface at the calculated intervals was no more than 20 K, with the main heating stage during the passage of the active plasma zone.

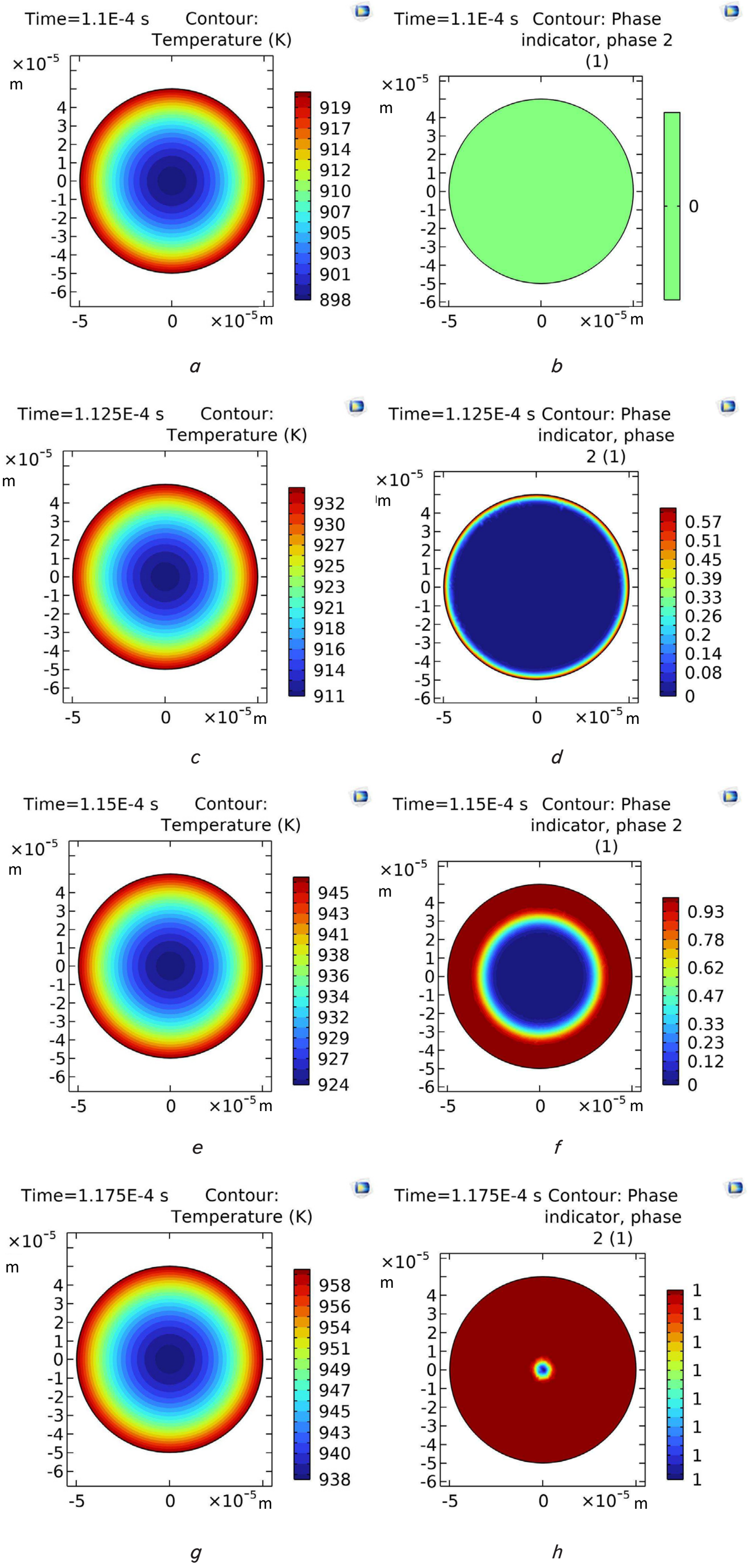
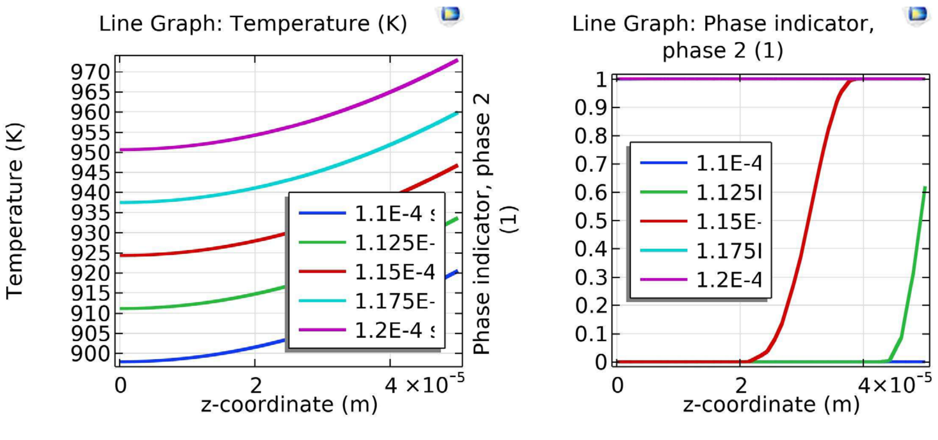


Fig. 9. Temperature distribution in the cross-section of the particle depending on time: *a* — $1.1 \cdot 10^{-4}$ s; *c* — $1.125 \cdot 10^{-4}$ s; *e* — $1.15 \cdot 10^{-4}$ s, *h* — $1.175 \cdot 10^{-4}$ s; phase transition boundaries depending on time *b* — $1.1 \cdot 10^{-4}$ s, *d* — $1.125 \cdot 10^{-4}$ s, *f* — $1.15 \cdot 10^{-4}$ s, *h* — $1.175 \cdot 10^{-4}$ s

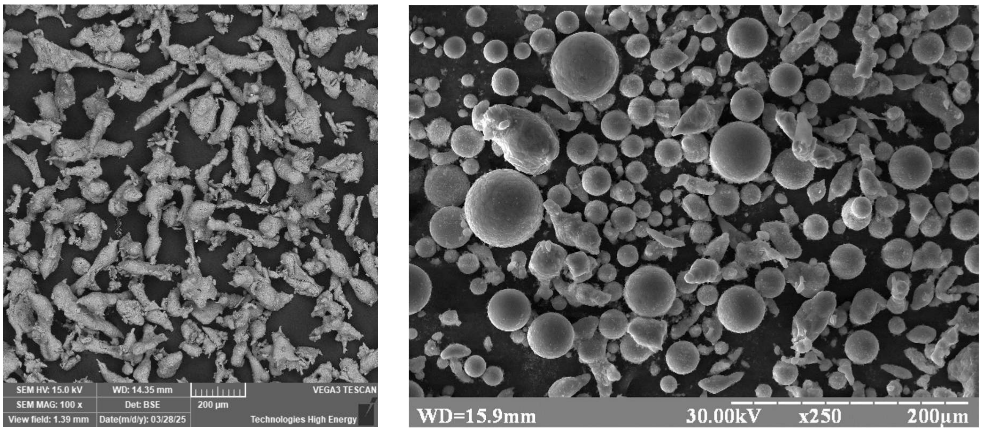


a *b*

Fig. 10. Temperature distribution from the center of the particle to its edge (averaged) over the time interval from $1.1\cdot10^{-4}$ s to $1.2\cdot10^{-4}$ s: *a* – temperature, *b* – phase transition boundary

5. 2. Determining the technological modes of the process and obtaining spheroidized aluminum powder

The results of modeling the process of IC plasma spheroidization determined the conditions of interaction of an aluminum particle with a diameter of 50 μm with an HF plasma flow, according to which the main controlled technological modes were obtained: inductor current 40–42 A, current frequency 1.76 MHz, gas flow rate 50 l/min, gas pressure at the plasmatron inlet 13×10^{-3} MPa. At a productivity of 1.5 to 3 kg/h, aluminum powder with a spherical particle shape was obtained (Fig. 11).



a *b*

Fig. 11. Morphology of aluminum powder:
a — before spheroidization; *b* — after spheroidization

As can be seen from Fig. 11, the powder particles after spheroidization underwent a significant transformation of shape from distorted (Fig. 11, *a*) to spherical (Fig. 11, *b*).

6. Discussion of results based on the study of IC plasma spheroidization of aluminum powder

Based on the results of modeling the IC plasma flow, new experimental and numerical results were obtained that describe the process of heating and melting of aluminum particles; the conditions under which the maximum degree of spheroidization is achieved were determined.

The simulation showed that to ensure stable plasma ignition, the required inductor current should be in the range from 40 A to 42 A (Fig. 6), under which a magnetic field of sufficient intensity is formed (~50 μT). Under these conditions, the plasma flow temperature reaches approximately 9000 K (Fig. 8), which is sufficient for effective heating and melting of aluminum powder particles.

Using the calculated plasma temperature field as a boundary condition has determined the kinetics of heating a particle with a diameter of 50 μm. The complete cycle of heating to the melting temperature and phase transition occurs over an extremely short time – on the order of 10^{-5} s to 10^{-4} s. Under these conditions, the direct melting process lasts less than 10 μs. This is consistent with theoretical estimates in [10] and literature data on processes occurring in plasma [11, 12]. The temperature distributions inside the particle showed a slight gradient between the center and the surface of no more than 25 K, which confirms the assumption about a quasi-isothermal state of small particles, and the width of the phase transition is from 5 μm to 7 μm (Fig. 9). This is an important factor in the formation of a spherical shape since uniform melting contributes to the effective influence of surface tension forces.

The distribution of plasma parameters along the axis of symmetry was close to normal, the electron density in the geometric center of the inductor was from $2\cdot10^{17}$ to $2.5\cdot10^{17}$ per cubic meter, the electron temperature was ~2.1 eV, the electron potential was 14.5 V (Fig. 7), which coincides with the temperature distribution along the axial symmetry starting from 1500 K to 9000 K within the geometric center of the inductor solenoid and dropping to 3500 K near the exit from the plasmatron.

Our results of the temperature distribution in the particle cross-section and the phase transition boundaries also indicate that the main heating of the particle occurs during the passage of the active plasma zone with the maximum temperature. The critical parameter of the process is the time the particle stays in the high-temperature region, according to the gas velocity distribution (Fig. 5*a*), the time the particle passes through the active plasma zone is 20 ms, which is quite sufficient for the processes of complete melting and phase transition.

The predicted parameters of the technological process, namely the inductor current of 40–42 A, the current frequency of 1.76 MHz, the gas flow rate of 5 l/s, the gas pressure at the plasmatron inlet of 13×10^{-3} MPa, allowed us to obtain spherical aluminum powder with a fraction of 40–63 μm, the degree of spheroidization of which reaches 95%, and the average particle roundness coefficient is 1.01 (Fig. 11, *b*). The result of a high degree of HF spheroidization coincides well with the authors of other studies [4–12] regardless of the technology and the powder materials used.

The obtained powder has significant advantages over non-spheroidized powder, in particular, excellent flowability, high bulk density, uniformity of the melting process; therefore, without any restrictions, it can be used in 3D printing, gas-thermal coating. and metallurgy.

Modeling the IC plasma flows and the temperature state of aluminum powder particles adds general theoretical ideas about the mechanisms of heating, melting, and spheroidization and makes it possible to establish dependences between process parameters and technological modes, which lays the basis for further development of models of IC plasma processing of powder materials.

The limitations of our study are that simulation was carried out in the working space, which was determined by the structural dimensions of the plasma torch, and when any structural size changes, the thermal conditions of spheroidization change significantly. In addition, the study was conducted only on powdered aluminum material. The use of other materials for spheroidization requires a new modeling process.

However, our simulation has shortcomings as it was performed using simplified geometric parameters and a coarse mesh, which necessitates further refinement of the model.

In further work, it is planned to use a more detailed model and take into account the real trajectories of particle motion, flow turbulence, and provide a developed, accurate description of heat transfer between plasma and particle.

7. Conclusions

1. The conditions for heating, melting, and cooling of aluminum powder particles in HF induction plasma have been established. The process of heating to the melting temperature and phase transition of particles with a diameter of 50 μm occurs in a time of 10^{-5}–10^{-4} s. The temperature gradients inside the particles do not exceed 20 K, which ensures uniform melting of the material and the formation of a spherical shape under the influence of surface tension forces.

2. We have experimentally confirmed the production of spherical aluminum particles with a degree of spheroidization from 95% to 98%, with a high average particle roundness coefficient of 1.01, according to the specified main technological modes: inductor current 40–42 A, current frequency 1.76 MHz, gas flow rate 50 l/min, gas pressure at the plasmatron inlet 13×10^{-3} MPa.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

Use of artificial intelligence

Artificial intelligence was used in accordance with the permitted norms.

Specifically: checking grammar, spelling, punctuation without changing the text, searching for sources for literature review; however, all articles have active, working links, the papers are in the public domain. All results in the manuscript are original; in no way did AI influence the conclusions of the study.

The free version of Chat GPT was used.

Authors' contributions

Mykola Lyutyk: Formal analysis, Resources; **Mykola Skulskyi**: Formal analysis, Resources; **Serhii Maikut**: Methodology, Formal analysis; **Anatoly Kuzmichev**: Writing – review & editing, Supervision; **Valeriy Pashchenko**: Writing – review & editing; **Volodymyr Lysak**: Validation, Data Curation; **Andrii Chornyi**: Visualization; **Ihor Sieliverstov**: Validation, Investigation; **Igor Smirnov**: Conceptualization, Supervision, Project administration.

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