

UDC 669-1(66-965);544.556.1(544.558);537-523.5

<https://doi.org/10.32362/2410-6593-2026-21-1-120-135>

EDN QYQWPB



RESEARCH ARTICLE

## Technologies for production and treatment of powder materials in thermal plasma of electric arc discharge

Andrey V. Samokhin, Nikolay V. Alekseev, Mikhail A. Sinayskiy✉, Andrey A. Fadeev,  
Alexey G. Astashov, Dmitry E. Kirpichev, Alexey A. Dorofeev

*A.A. Baikov Institute of Metallurgy and Material Science (IMET RAS), Moscow, 119334 Russia*

✉ *Corresponding author, e-mail: ms18@mail.ru*

### Abstract

**Objectives.** To summarize the results from studies of plasma processes for the production of specified composition powder materials; to implement plasma processes: plasma-chemical synthesis of nanopowders, granulation of nanopowders, plasma spheroidization of microgranules and micropowders in order to perform nanotechnologies and additive technologies tasks.

**Methods.** Thermal plasma generation was used at the A.A. Baikov IMET RAS by means of direct-current electric arc plasmotrons with a rated power up to 45 kW with self-adjusting arc length and gas stabilization of discharge, as well as plasmotrons with an interelectrode insert. In order to carry out the processes of nanopowders synthesis and metal powders spheroidization, the plasma reactor design with confined jet flow using thermal plasma of reducing, oxidizing, and inert media was used.

**Results.** The use of electric arc plasmatron in the processes of plasma chemical synthesis of nanopowders and plasma spheroidization of powders enabled productivity of 0.5 and 10 kg/h, respectively, to be achieved for various metals, alloys, compounds, and their compositions. In the case of the implemented processes of producing nanopowders, where the formation of particles depends on various macro-mechanisms, it was established that the average size of the particles obtained is controlled. This also depends on the synthesis parameters—the initial concentration of the precursor, enthalpy, and flow rate of the plasma jet, cooling rate and vapor condensation. The study shows the results of examining the processes of producing spheroidized powders in thermal plasma flows. These include (Ti, Ta, Fe, Ni, Mo, W), alloys (based on Fe, Ti, Ni, Co, Nb, W, Mg, including stainless, heat-resistant, refractory, hard), compounds (borides, oxides) and compositions (W–Ni–Fe, ZrB<sub>2</sub>–SiC, Ni–TiCN, etc.). The possibility of obtaining nonporous spherical powders of various dispersity was also shown: for particles of about 10–100 μm and for granules having a particle size of less than 1 μm. The study described the main process parameters determining the quality of spheroidization, including dispersity of precursor, plasma enthalpy, gas composition, characteristics of plasma flow, and their mixing with initial powders.

**Conclusions.** The research and development results presented here show the possibilities of plasma processes and apparatuses for producing nanopowders of various metal, inorganic compounds and compositions with given properties. The study also confirmed that powders of metals and alloys, compounds and compositions obtained by a variety of methods can be spheroidized in a plasma reactor with confined jet flow in a wide range of melting points, particle sizes, and morphology. The demonstrated approach using successive stages of plasma-chemical synthesis of nanopowders, their granulation and subsequent plasma spheroidization of microgranules enables tungsten-based composite micropowders with dense spherical particles and submicron structure to be obtained.

### Keywords

thermal plasma, plasma-chemical synthesis, granulation, plasma spheroidization, spherical micropowders, nanopowders

**Submitted:** 11.07.2025

**Revised:** 21.11.2025

**Accepted:** 16.01.2026

### For citation

Samokhin A.V., Alekseev N.V., Sinayskiy M.A., Fadeev A.A., Astashov A.G., Kirpichev D.E., Dorofeev A.A. Technologies for production and treatment of powder materials in thermal plasma of electric arc discharge. *Tonk. Khim. Tekhnol. = Fine Chem. Technol.* 2026;21(1): 120–135. <https://doi.org/10.32362/2410-6593-2026-21-1-120-135>

### НАУЧНАЯ СТАТЬЯ

# Технологии получения и обработки порошковых материалов в термической плазме электродугового разряда

А.В. Самохин, Н.В. Алексеев, М.А. Синайский✉, А.А. Фадеев, А.Г. Асташов,  
Д.Е. Кирпичев, А.А. Дорофеев

*Институт металлургии и материаловедения им. А.А. Байкова (ИМЕТ РАН), Москва, 119334 Россия*

✉ Автор для переписки, e-mail: [ms18@mail.ru](mailto:ms18@mail.ru)

### Аннотация

**Цели.** Обобщить результаты исследований плазменных процессов, обеспечивающих получение порошковых материалов заданного состава; осуществить плазменные процессы: плазмохимический синтез нанопорошков, грануляцию нанопорошков, плазменную сфероидизацию микрогранул и микропорошков для выполнения задач в области нанотехнологий и аддитивных технологий.

**Методы.** Генерация термической плазмы осуществлялась разработанными в ИМЕТ РАН электродуговыми плазмотронами постоянного тока мощностью до 45 кВт с самоустанавливающейся длиной дуги и плазмотронами с межэлектродной вставкой. В процессах плазмохимического синтеза нанопорошков и плазменной сфероидизации металлических порошков была использована конструкция плазменного реактора с ограниченным струйным течением с использованием термической плазмы восстановительных, окислительных и инертных сред.

**Результаты.** Использование электродугового плазмотрона позволило в процессах плазмохимического синтеза нанопорошков и плазменной сфероидизации порошков достигнуть производительности 0.5 и 10 кг/ч соответственно для различных металлов, сплавов, соединений и их композиций. Для реализованных процессов получения нанопорошков, формирование частиц в которых происходит по различным макромеханизмам, установлено, что средний размер получаемых частиц управляется и зависит от параметров синтеза — начальной концентрации прекурсора, энтальпии и скорости истечения струи плазмы, скорости охлаждения и конденсации паров. Показаны результаты исследования процессов получения сфероидизированных порошков в потоках термической плазмы, включая металлы (Ti, Ta, Fe, Ni, Mo, W), сплавы (на основе Fe, Ti, Ni, Co, Nb, W, Mg, в том числе нержавеющие, жаропрочные, тугоплавкие, твердые), соединения (бориды, оксиды) и композиции (W–Ni–Fe, ZrB<sub>2</sub>–SiC, Ni–TiCN и др.). Показана возможность получения беспористых сферических порошков различной дисперсности: для частиц с размерами 10–100 мкм и для микрогранул, состоящих из частиц с размерами менее 1 мкм. Описаны основные параметры процесса, влияющие на качество сфероидизации, среди которых дисперсность прекурсоров, энтальпия плазменной струи, состав используемых газов, характеристики плазменного потока и его смешения с исходным сырьем.

**Выводы.** Продемонстрированные результаты исследований показывают диапазон возможностей плазменных процессов и аппаратов для получения нанопорошков различных металлов, неорганических соединений и композиций с необходимыми характеристиками. Подтверждено обеспечение возможности сфероидизации порошков металлов и сплавов, соединений и композиций, полученных различными методами, в плазменном реакторе с ограниченным струйным течением в широком диапазоне температур плавления, размеров и морфологии частиц. Представленный подход с использованием последовательных стадий плазмохимического синтеза нанопорошков, гранулирования полученных нанопорошков и последующей плазменной сфероидизации микрогранул позволяет получать композитные микропорошки на основе вольфрама с плотными сферическими частицами и субмикронной структурой.

### Ключевые слова

термическая плазма, плазмохимический синтез, грануляция, плазменная сфероидизация, сферические микропорошки, нанопорошки

**Поступила:** 11.07.2025

**Доработана:** 21.11.2025

**Принята в печать:** 16.01.2026

### Для цитирования

Самохин А.В., Алексеев Н.В., Синайский М.А., Фадеев А.А., Асташов А.Г., Кирпичев Д.Е., Дорофеев А.А. Технологии получения и обработки порошковых материалов в термической плазме электродугового разряда. *Тонкие химические технологии.* 2026;21(1):120–135. <https://doi.org/10.32362/2410-6593-2026-21-1-120-135>

## INTRODUCTION

This work presents the results of applying thermal plasma generated by electrical discharges to the processes of producing and processing various powder materials. These results were obtained on the basis of research and developments carried out at the A.A. Baikov Institute of Metallurgy and Materials Science of the Russian Academy of Sciences (IMET RAS), in the aims of creating technologies and equipment for the nano- and additive technologies (ATs) fields.

Nanopowders serve as the basis for creating nanostructured materials for a variety of applications, including ceramic materials and hard alloys with enhanced mechanical properties, dispersion-strengthened and modified structural alloys, nanostructured coatings with improved thermal, corrosion, and wear resistance, as well as composites containing fillers and modifiers based on inorganic nanoparticles, among others [1–4].

Nanopowders can be synthesized by a variety of methods, including gas-phase, liquid-phase, solid-phase, and combined processes, such as mechanical milling, gas-phase deposition, precipitation from solutions, and others. Plasma-chemical synthesis is a gas-phase process and can serve as a universal method for producing nanopowders of elements, compounds, and composites when carried out in different gaseous environments— inert, reducing, or oxidizing [5, 6].

Numerous studies on the plasma-chemical synthesis of nanopowders in thermal-plasma flows generated by plasma torches of various types have confirmed the efficiency of producing nanopowders of various metals, oxides, carbides, nitrides, borides, and diverse compositions [7–12].

Various types of electrical discharges can be used to generate thermal plasma, including direct current (DC) arc, radio frequency (RF), microwave (MW), as well as combined discharges [13]. The leading company in the field of nanopowder production is *Tekna* (Canada) which employs plasma reactors based on RF plasma torches.<sup>1</sup> Modern high-power plasma torches with capacities of up to 2400 kW have a thermal efficiency of 70–85%, enabling highly energy-efficient operation. They can be used for the implementation of high-temperature processes on an industrial scale.<sup>2</sup>

At the present time, IMET RAS is actively conducting research into the production of nanopowders in thermal-plasma flows generated by DC arc plasma torches. The main focus of these studies is the implementation

of plasma-chemical synthesis of nanopowders with predetermined physicochemical properties, defined according to their specific applications in the creation of corresponding materials. This can be achieved by controlling the dispersity, phase and chemical compositions of the nanopowders during their synthesis, as well as through subsequent additional thermochemical and/or thermo-vacuum treatment.

Over the past decades, ATs have been rapidly developing worldwide. This is due to their ability to encompass all stages of the production cycle—from design to final product manufacturing [14–18]. ATs significantly reduce production time, quickly introduce design modifications, manufacture complex-shaped components, and substantially reduce the amount of industrial waste.

The most versatile and widely used variant of ATs for manufacturing metal and alloy components is implemented by the sequential layering of the part according to a specified geometry. A laser or electron beam acting on a powder layer 20–60 μm thick is used, ensuring local melting of the powder particles due to intense energy exposure. The properties of the metallic powders largely determine the efficiency of the processes, as well as the quality of the produced components. Consequently, one of the key challenges in the development of AT is the creation of efficient methods for producing metal and alloy powders with the required properties and their subsequent successful application [19–21].

Technologies have already been implemented on an industrial scale to produce spherical powders of various metals and alloys (based on iron, aluminum, titanium, chromium, copper) with the ability to achieve the desired particle size distribution. These include processes such as inert gas atomization of molten metal and melt film atomization using centrifugal forces. However, these processes have several significant limitations (for example, low yield of product with the required particle size) which substantially increases the cost of the resulting powders. In addition, the molten metal atomization method does not allow for the production of powders of refractory metals and alloys.

An alternative to the atomization method for producing spherical powders is the spheroidization of irregularly shaped metal particles by melting them in a high-temperature gas flow generated by electric-discharge thermal plasma generators. The leading technology is the spheroidization processes carried

<sup>1</sup> TEKNANO Nanopowder synthesis systems. 2016. <http://www.tekna.com/nanopowder-synthesis-systems>. Accessed November 21, 2025.

<sup>2</sup> Nyun A. Plasma Torches by Westinghouse Plasma Corporation. 2005. [https://www.academia.edu/24044626/Plasma\\_Torches\\_by\\_Westinghouse\\_Plasma\\_Corporation](https://www.academia.edu/24044626/Plasma_Torches_by_Westinghouse_Plasma_Corporation). Accessed November 21, 2025.

out in thermal plasma flows generated by RF and MW discharges, using equipment from *Tekna*<sup>3</sup> and *6K Inc.*<sup>4</sup> (USA).

At present, IMET RAS is conducting research into the field of plasma spheroidization of powder materials using DC arc plasma torches, including the following directions:

- investigation and development of technologies for spheroidizing metallic powders in thermal plasma flows generated by arc discharges;
- creation of foundational technologies for the recycling of spent metallic powders used in ATs;
- development and production of efficient powder spheroidization systems based on arc plasma torches.

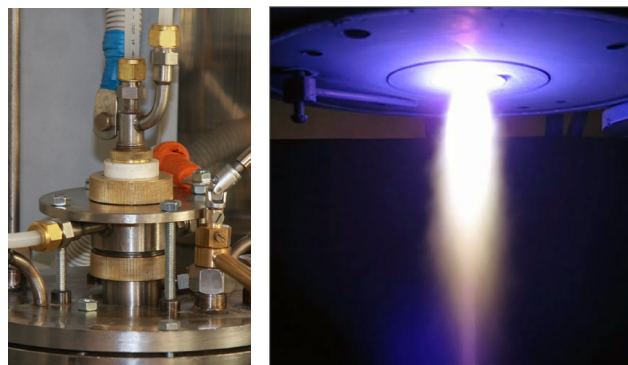
This article presents a review of the results of experimental studies conducted at IMET RAS on plasma-chemical synthesis of nanopowders and spheroidization of powder materials, with particle sizes ranging from 10 to 100  $\mu\text{m}$ , in thermal DC arc plasma jet flows.

## METHODS AND EQUIPMENT

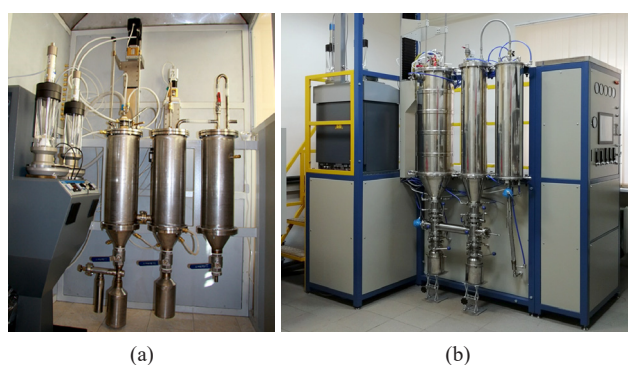
DC arc plasma torches with a nominal power of up to 45 kW, featuring a self-adjusting arc length, as well as plasma torches with an interelectrode insert, were used (Fig. 1) for the generation of thermal plasma in laboratory and pilot-scale setups at IMET RAS. These plasma torches enabled the stable generation of thermal plasma flows in reducing, oxidizing, and inert atmospheres, with equilibrium mean mass temperatures of  $2\text{--}10 \cdot 10^3$  K. They also enabled plasma-chemical synthesis of nanopowders and plasma spheroidization processes.

The design of a plasma reactor with a confined jet flow for plasma-chemical synthesis of nanopowders [22] and plasma spheroidization of powder materials [23], developed at IMET RAS, is protected by patents of the Russian Federation. Figure 2 shows general views of a plasma system based on a 35 kW DC arc plasma torch for nanopowder synthesis and plasma spheroidization of powder materials.

The following methods were used for characterization and study of the main properties of the powders produced. The specific surface area  $S_{\text{sp}}$  ( $\text{m}^2/\text{g}$ ) of nanopowders was measured by means of the Brunauer–Emmett–Teller method using a TriStar 3000 surface area analyzer (*Micromeritics*, USA). Particle size distribution and related parameters were determined by laser diffraction using a Mastersizer 2000M particle size analyzer with an automatic Hydro 2000S dispersion and sample delivery module (*Malvern*, United Kingdom). The total contents



**Fig. 1.** Electric arc plasma torches of A.A. Baikov Institute of Metallurgy and Material Science at the Russian Academy of Sciences (IMET RAS) with rated power up to 45 kW



**Fig. 2.** General view of a plasma setup with restricted jet flow reactor based on 35-kW DC arc plasma torch for plasma chemical synthesis of nanopowders (a) and for plasma spheroidization of powders materials (b)

of oxygen, nitrogen, and hydrogen were measured on an RNH-836 analyzer (*Leco*, USA). This was achieved by heating samples in a graphite crucible under a helium flow and detecting the evolved gases using infrared (IR) and thermal conductivity sensors. The total carbon content was measured using a CS-600 analyzer (*Leco*, USA) by combusting the sample in an oxygen flow and detecting the evolved gases with an IR sensor. The morphology and characteristic particle size were studied by scanning electron microscopy using a Scios instrument (*FEI*, USA) and by transmission electron microscopy using an Osiris instrument (*FEI*, USA) with elemental energy-dispersive microanalysis performed on an EDAX Elite attachment (*EDAX*, USA). Phase composition analysis was carried out using Ultima-4 (*Rigaku*, Japan) and XRD-6000 (*SHIMADZU*, Japan) X-ray diffractometers with monochromatized copper radiation at room temperature (20°C).

<sup>3</sup> TEKSPHERO. Spheroidization Systems. 2023. <http://www.tekna.com/spheroidization-systems>. Accessed November 21, 2025.

<sup>4</sup> 6K Production of Breakthrough Materials. 2023. <https://www.6kinc.com>. Accessed November 21, 2025.

## RESULTS AND DISCUSSION

### Plasma-chemical synthesis of nanopowders

The plasma-chemical synthesis of nanopowders is governed by a complex of physicochemical processes in turbulent gas-disperse non-isothermal flows. Reactors with confined jet flow are widely used to implement plasma processes for nanopowder production. Here the plasma jet is discharged into a reactor volume bounded by reactor walls with the ratio of the reactor diameter to the plasma torch nozzle diameter significantly exceeding 10. The formation of nanoparticles in the plasma reactor takes place through condensation of components from the gas phase followed by their deposition onto the water-cooled reactor walls.

The evolution of nanoparticles within the reactor volume leads to changes in their particle-size distribution as a result of condensational and coagulation growth. Changes in their chemical and phase composition may also occur. Parameters can vary in the plasma-chemical process of nanopowder production: composition, enthalpy, and velocity of the plasma jet; reagent concentrations and their delivery characteristics; as well as the size of the initial particles of the dispersed precursor. In this context, not only the technological implementation of the plasma-chemical synthesis process is important, but also the method of collecting and storing the nanopowders. This is essential to prevent physicochemical transformations in the layer of deposited particles, including sintering and possible phase transformations. In order to achieve this, the thickness of the nanoparticle layer must not exceed a specified limit. This requires periodic removal of deposited particles from the reactor walls and their collection in hermetically sealed containers.

In order to carry out the plasma-chemical synthesis of nanopowders, a reactor with confined jet flow was used. Some syntheses were performed in a combined reactor equipped with a unit for preliminary evaporation of the dispersed raw materials in a thermally insulated channel and the subsequent use of gas chemical quenching.

Table 1 presents nanopowders of metals and their inorganic compounds produced at IMET RAS in a confined-jet-flow plasma reactor using a 25 kW DC arc plasma torch [22, 24]. Various individual gases and their mixtures (with a purity of at least 99.98%) were used as plasma-forming gases. The initial raw material consisted of powders of elements and their compounds with particle sizes not exceeding 25–40  $\mu\text{m}$ ; liquid reagents were pre-evaporated before being fed into the reactor. Commercial chemical reagents (manufactured in Russia) with a purity of no less than 99.9% were used as starting materials.

### Particle-size distribution of the obtained nanopowders and particle morphology

One of the most important characteristics of nanopowders, which determines the feasibility of their use in scientific tasks and practical applications, is their particle-size distribution. In the process of plasma-chemical synthesis, the formation of nanoparticles occurs via three macromechanisms:

- vapor–liquid–crystal (VLC);
- vapor–crystal (VC);
- a mixed mechanism which combines the above processes (VLC and VC).

The formation of nanoparticles and the corresponding mechanism in the plasma-chemical process can be assessed using thermodynamic calculations of nanopowder yield as a function of temperature. If the material exists in both liquid and solid states, its yield will depend on temperature. In this case,  $T^*$  is the minimum temperature corresponding to the maximum yield of the nanoparticle material.  $T_{\text{cond}}$  is the maximum temperature at which the nanoparticles remain in the condensed state, while  $T$  is the temperature at which melting of the nanoparticle material occurs.

The plasma process occurs at a temperature initially exceeding  $T_{\text{cond}}$ , which gradually decreases. Accordingly, the temperature conditions for nanoparticle formation via the specified macromechanisms can be described as follows:

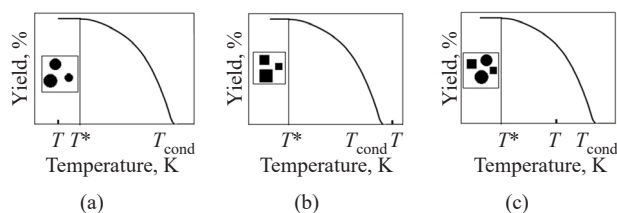
- VLC mechanism:  $T < T^* < T_{\text{cond}}$ , all nanoparticles have a spherical shape;
- VC mechanism:  $T^* < T_{\text{cond}} < T$ , all nanoparticles have a faceted shape;
- VLC–VC mixed mechanism:  $T^* < T < T_{\text{cond}}$  nanoparticles exhibit both spherical and faceted shapes.

Under conditions of decreasing process temperature, the formation of predominantly spherical nanoparticles via the VLC mechanism occurs when the maximum particle yield is achieved at temperatures above the melting point of the substance (Fig. 3a). If nanoparticle formation occurs at temperatures below the melting point, or if the substance does not exist in a liquid state, the process follows the VC mechanism which primarily leads to the formation of faceted particles (Fig. 3b). When the substance crystallizes before reaching the maximum yield, a transition from the VLC to the VC mechanism occurs, resulting in a product containing both spherical and faceted particles (Fig. 3c).

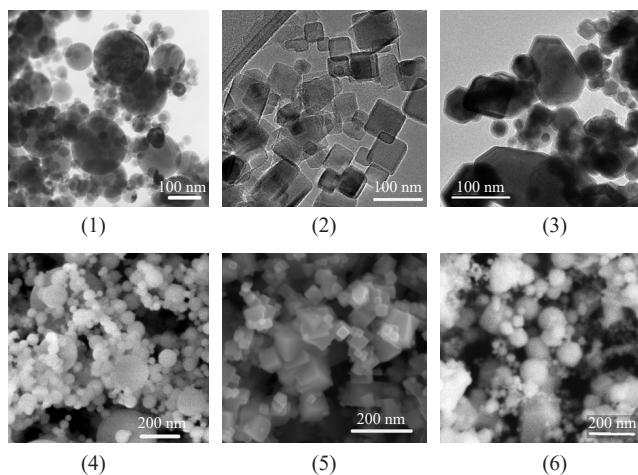
Figure 4 shows the results of electron microscopy studies of nanopowders obtained by plasma-chemical synthesis. All powders are polydisperse and consist of particles with equiaxed rounded or faceted shapes. It is demonstrated that nanoparticle formation can occur via all three mechanisms—VLC, VC, and VLC–VC (corresponding to  $\text{Al}_2\text{O}_3$ , TiCN, and W nanopowders, respectively).

**Table 1.** Nanopowders produced in plasmochemical synthesis at IMET RAS

No.	Produced nanopowder	Reagents	Plasma-forming gas	Specific surface area, m <sup>2</sup> /g
Individual metals				
1	W, Mo, Ni, Co, Re	Me <sub>x</sub> O <sub>y</sub> , H <sub>2</sub> , C <sub>3</sub> H <sub>8</sub> +air	H <sub>2</sub> +N <sub>2</sub> , C <sub>3</sub> H <sub>8</sub> +air	2–30
2	Cu	CuCl, H <sub>2</sub>	H <sub>2</sub> +N <sub>2</sub>	2–5
		Cu(CH <sub>3</sub> COO) <sub>2</sub> ·H <sub>2</sub> O	N <sub>2</sub>	5–35
		Cu	N <sub>2</sub>	20–36
Composite materials				
3	W–Ni–Fe (W = 95%)	WO <sub>3</sub> , NiO, Fe <sub>2</sub> O <sub>3</sub> , H <sub>2</sub>	H <sub>2</sub> +N <sub>2</sub>	4–10
4	W–Cu (W = 80%)	WO <sub>3</sub> , CuO, H <sub>2</sub>	H <sub>2</sub> +N <sub>2</sub>	4–10
5	W–Y <sub>2</sub> O <sub>3</sub> (W = 95–99.7%)	WO <sub>3</sub> , Y(CH <sub>3</sub> COO) <sub>3</sub> , H <sub>2</sub>	H <sub>2</sub> +N <sub>2</sub>	4–10
6	W–B (W = 88–97%)	WCl <sub>6</sub> , BCl <sub>3</sub> , H <sub>2</sub>	H <sub>2</sub> , Ar+H <sub>2</sub>	13–20
7	Ag–SnO <sub>2</sub>	Ag, SnO <sub>2</sub>	Air	5–12
Anoxic compounds				
8	TiN	Ti, TiH <sub>2</sub> , N <sub>2</sub>	N <sub>2</sub>	12–18
		TiCl <sub>4</sub> , H <sub>2</sub> , N <sub>2</sub>	H <sub>2</sub> +N <sub>2</sub>	11–39
9	AlN	Al, NH <sub>3</sub> , N <sub>2</sub>	N <sub>2</sub>	30–70
10	TiC	TiCl <sub>4</sub> , H <sub>2</sub> , CH <sub>4</sub>	H <sub>2</sub> +Ar	15–30
11	TiCN	TiCl <sub>4</sub> , H <sub>2</sub> , N <sub>2</sub> , CH <sub>4</sub>	H <sub>2</sub> +N <sub>2</sub>	13–23
12	SiC	SiCl <sub>4</sub> , H <sub>2</sub> , CH <sub>4</sub>	H <sub>2</sub> +Ar	15–30
13	WC	WO <sub>3</sub> , CH <sub>4</sub> , H <sub>2</sub>	H <sub>2</sub> +N <sub>2</sub>	20–40
14	ZrB <sub>2</sub>	ZrCl <sub>4</sub> , BCl <sub>3</sub> , H <sub>2</sub>	H <sub>2</sub> +Ar	10–50
15	HfB <sub>2</sub>	HfCl <sub>4</sub> , BCl <sub>3</sub> , H <sub>2</sub>	H <sub>2</sub> +Ar	5–30
Oxides				
16	Al <sub>2</sub> O <sub>3</sub>	Al, O <sub>2</sub>	Air	15–35
17	Al <sub>2</sub> O <sub>3</sub> –MeO (Me: Mg, Co)	Al, Me, O <sub>2</sub>	Air	15–25
18	AlON	Al, NH <sub>3</sub> , N <sub>2</sub> , O <sub>2</sub>	N <sub>2</sub>	30–50
19	TiO <sub>2</sub>	TiCl <sub>4</sub> , O <sub>2</sub>	O <sub>2</sub> +Ar	30–120
20	SiO <sub>2</sub>	SiCl <sub>4</sub> , O <sub>2</sub>	O <sub>2</sub> +Ar	120–250
21	ZrO <sub>2</sub>	ZrCl <sub>4</sub> , O <sub>2</sub>	O <sub>2</sub> +Ar	18–32
22	ZrO <sub>2</sub> –Al <sub>2</sub> O <sub>3</sub>	ZrCl <sub>4</sub> , Al, O <sub>2</sub>	O <sub>2</sub> +Ar	17
23	Y <sub>2</sub> O <sub>3</sub>	Y(CH <sub>3</sub> COO) <sub>3</sub> , O <sub>2</sub>	O <sub>2</sub> +Ar	12–25



**Fig. 3.** Conditions for the formation of nanoparticles morphology at characteristic temperatures in various macromechanisms: (a) VLC, (b) VC, (c) VLC-VC



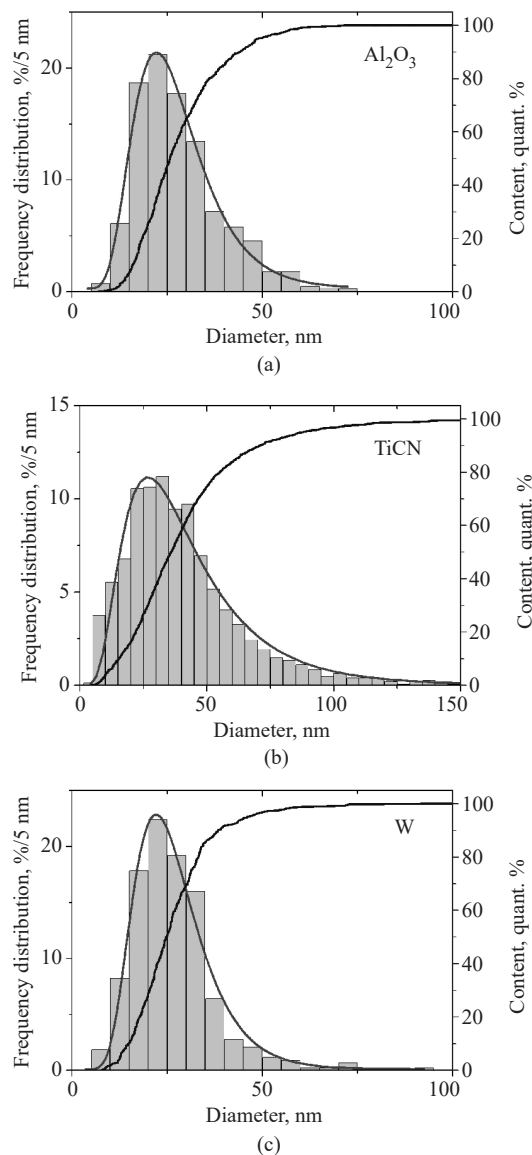
**Fig. 4.** Transmission electron microscopy (1–3) and scanning electron microscopy (4–6) micrographs of nanopowders formed in a plasma reactor by various macromechanisms: (1), (4)  $\text{Al}_2\text{O}_3$  (VLC); (2), (5) TiCN (VC); and (3), (6) W (VLC-VC)

Figure 5 presents the results of particle size distribution analysis for  $\text{Al}_2\text{O}_3$ , TiCN, and W nanopowders [25]. It was noted that all nanopowders are reliably described (with a correlation coefficient greater than 0.95) by a log-normal particle size distribution function:

$$p(d) = \frac{1}{d\sigma\sqrt{2\pi}} \exp\left(-\frac{1}{2}\left(\frac{\ln d - m}{\sigma}\right)^2\right),$$

where  $d$  is the particle diameter,  $\sigma$  is the standard deviation, and  $m$  is the median of the distribution. The conformity to a log-normal particle size distribution has been confirmed for nanopowders produced via the coagulation-driven VLC mechanism [26]. In the absence of coagulation growth [4], a log-normal distribution of particle residence times in the growth zone can also result in a log-normal distribution of particle sizes, as observed in experimental studies of plasma-chemical synthesis of nanopowders.

In the case of nanopowder production processes, in which particle formation occurs via different macromechanisms, it was established experimentally



**Fig. 5.** Histograms of particle size distributions for nanopowders formed by various macromechanisms: (a)  $\text{Al}_2\text{O}_3$  (VLC), (b) TiCN (VC), and (c) W (VLC-VC) [25]

that the average size of the resulting nanoparticles increases with an increase of the precursor concentration in the gas components. The results also showed that the average particle size depends on synthesis parameters: initial precursor concentration, plasma jet enthalpy, and the jet velocity in the reactor volume. The nanoparticle size decreases with a reduction in the concentration of the condensing component in the gas or with an increase in the plasma jet velocity. However, lowering the concentration reduces productivity, while increasing the jet velocity is subject to technical and physical limitations. The use of gas quenching allows for forced suppression of coagulation growth of particles, thereby controlling the particle size formed via the VLC

mechanism. The results demonstrate the feasibility of producing a variety of nanopowders and controlling their particle-size distribution using plasma-chemical synthesis in a confined-jet-flow reactor.

### Plasma spheroidization of metal powders

Spherical powders with particle sizes on the order of tens microns are used for the production of metal and alloy components using modern additive manufacturing methods. The formation of spherical micropowders is achieved by treating irregularly shaped particles in thermal plasma. Their morphology changes as the particles are heated and melted. They form liquid droplets with a rounded shape due to surface tension forces. Upon subsequent cooling within the reactor volume with water-cooled walls, the droplets solidify and crystallize into metallic microspheres.

Experiments conducted on plasma spheroidization of powder materials established that micropowders of various metals and alloys with particle sizes ranging from 10 to 100  $\mu\text{m}$ , predominantly with a spherical shape, can be produced. The degree of spheroidization of plasma-treated particles can reach up to 99 vol %.

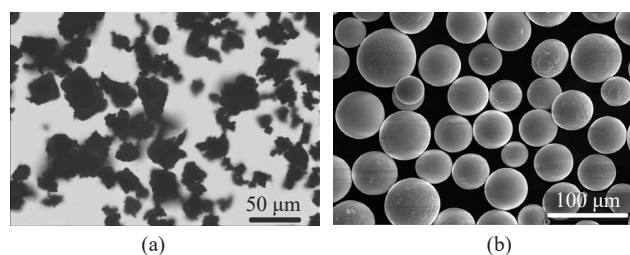
The particle roundness coefficient ranges from 1 to 1.4, with an average value of 1.01. The spherical shape of the powder particles ensures high bulk density and good flowability, which are essential for their further use in ATs.

For the production of spheroidized powders of various metals (Ti, Ta, Fe, Ni, Mo, and W), alloys (stainless, heat-resistant, and refractory), compounds, and composites (Table 2), their treatment in a thermal plasma jet at IMET RAS is currently accompanied not only by intensive research on the processes but also by the development of technologies and the necessary equipment.

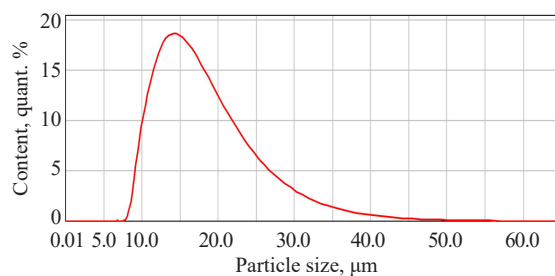
The results of plasma treatment and the characteristics of certain spheroidized powders are presented in Figs. 6–12: spheroidization of titanium powders [27] (Figs. 6 and 7); spheroidization of iron powders [28] (Figs. 8 and 9); spheroidization of Ti–Al–V alloy VT6 powders (Fig. 10); and spheroidization of Ni–Al–Cr–Co alloy CompoNiAl-M5-3 powders [29] (Fig. 11). Experimental studies demonstrated the feasibility of producing pore-free spherical powders of multicomponent metal alloys with particle sizes

**Table 2.** Powders produced by spheroidization in thermal plasma at IMET RAS

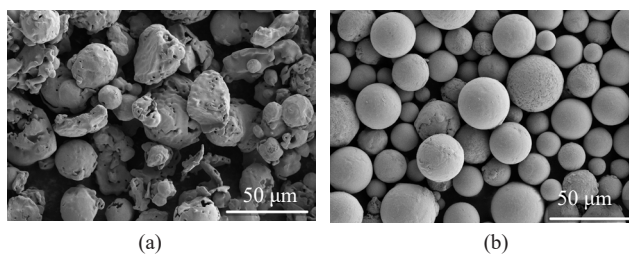
Metals	W, Mo, Ta, Fe, Ti
Alloys	316L, 12Kh18N10T, Kh15N5D4B, AISI321 (stainless steel) Inconel (718, 625), VKM, VZh159, VNL14 (Ni alloys) VPr27-50 (Ni solder) VT6, VT14 (Ti–Al–V alloys) CCM (Co–Cr–Mo alloys) CuCrZr (bronze) Nb–Si, Nb–C, Nb–Al, Nb–Mo (Nb alloys) Ni–Al, Ti–Al, Nb–Al, Ni–Al–Co–Cr, Ti–Ni, CompoNiAl-M5-3 (intermetallic compounds) WC–Co (hard alloy) 27KKh (Mg alloy)
Composites	W–Ni–Fe, W–Cu, W–Y <sub>2</sub> O <sub>3</sub> , W–B, W–C–Co, ZrB <sub>2</sub> –SiC, Ni–TiCN
Oxides	Ta <sub>2</sub> O <sub>5</sub> , Al <sub>2</sub> O <sub>3</sub> , SiO <sub>2</sub>
Compounds	ZrB <sub>2</sub> , HfB <sub>2</sub> Ca <sub>3</sub> (PO <sub>4</sub> ) <sub>2</sub> , Ca <sub>10</sub> (PO <sub>4</sub> ) <sub>6</sub> (OH) <sub>2</sub>



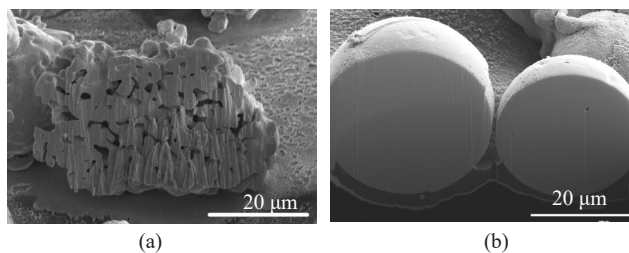
**Fig. 6.** Micrographs of particles for 20–50- $\mu\text{m}$  fraction of titanium powder (a) before and (b) after plasma spheroidization



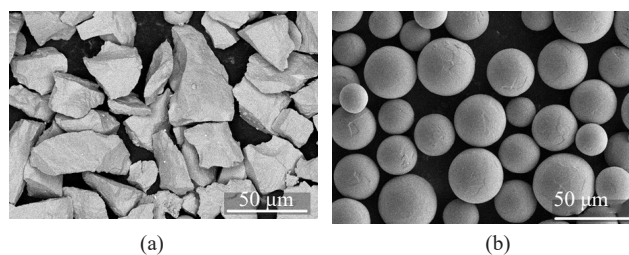
**Fig. 7.** Particle size distribution of spheroidized titanium powder



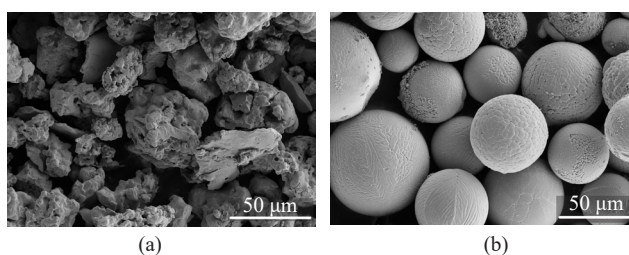
**Fig. 8.** Micrographs of 25–50- $\mu\text{m}$  iron powder (a) before and (b) after plasma spheroidization



**Fig. 9.** Micrographs of iron powder particles in focused ion beam cross section (a) before and (b) after plasma spheroidization



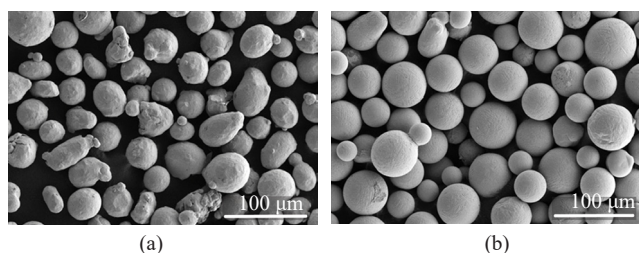
**Fig. 10.** Micrographs of particles for powder of Ti–Al–V alloy (VT6 grade) (a) before and (b) after plasma spheroidization



**Fig. 11.** Morphology of 20–50  $\mu\text{m}$  powder particles of CompoNiAl-M5-3 alloy (a) before and (b) after plasma spheroidization

ranging from 10 to 100  $\mu\text{m}$  from initial powders of various dispersities composed of irregularly shaped particles. The experimental results indicate the possibility of producing spherical powders of metals and alloys from various initial powder materials in a confined-jet-flow plasma apparatus based on a DC arc plasma torch.

IMET RAS is also carrying out research on the use of plasma-based regeneration for the spheroidization of previously used powders and the reduction of gas impurities [30]. An example of spheroidization and regeneration of X-IN718 stainless steel powders is shown in Fig. 12.



**Fig. 12.** Micrographs of particles for powder of Fe–Ni–Cr alloy (IN718 grade) (a) before and (b) after plasma regeneration

The use of a hydrogenous plasma jet during the regeneration of powders of Fe-, Ni-, Co-, W-, and Mo-based alloys allows gas impurities to be significantly reduced: oxygen by 1.5–6 times and nitrogen by 1.5–10 times (depending on the plasma enthalpy and hydrogen content). They also allowed for an improvement in particle morphology and a decrease in oxygen and nitrogen content (Table 3). Gas impurities (oxygen) are present in the surface layer of the particles in the form of metal oxides, which allows these oxides to be reduced to metals via reactions with hydrogen during the residence time of the particles in the high-temperature zone.

Factors which determine the quality of powders obtained in plasma spheroidization processes include: the thermophysical properties of the treated material and its particle size distribution; the characteristics of the thermal plasma flow; the arrangement of powder mixing with the plasma flow; as well as the organization of the high-temperature gas–disperse flow within the processing chamber. For each powder material, the

combination of process parameters which ensures optimal performance—high particle spheroidization, the desired particle size distribution, and maximum productivity—is determined experimentally.

The spheroidization process of particles by melting in a thermal plasma flow, where the gas temperature exceeds the boiling point of the treated material, is accompanied by its evaporation. Upon cooling of the gas-disperse flow, the vapor condenses, resulting in the formation of nanoparticles.

The presence of nanoparticles in plasma-spheroidized powders is highly undesirable, since it reduces powder flowability. Also due to the high chemical reactivity of metallic nanoparticles, it can lead to their oxidation upon exposure to air. A special classification method in a liquid medium is used, in order to remove nanoparticles from powders treated in a thermal plasma flow. This involves preliminary ultrasonic treatment to break up nanoparticle aggregates and remove them from the surfaces of the spheroidized microparticles.

In order to reduce the nanoparticle content in spheroidized metal and alloy powders, it has been proposed to separate the treated powder into narrower particle size fractions and then process each fraction under the corresponding optimal spheroidization parameters. After processing, the powder fractions are blended. This approach allows for a reduction in the nanoparticle content in the final product.

### Plasma spheroidization of composite powders

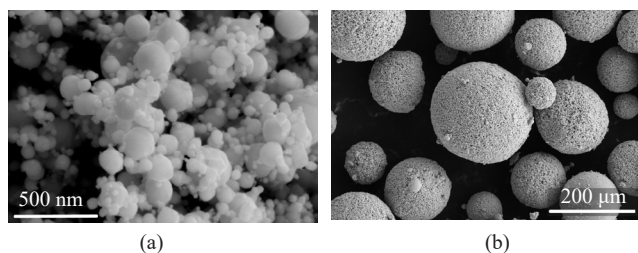
The study of obtaining spherical micropowders of W–C–Co, W–Ni–Fe, W–Cu, W–Y<sub>2</sub>O<sub>3</sub>, and W–B composites from nanopowders of the corresponding systems, produced by plasma-chemical synthesis is new direction in the production of powders with spherical particle shapes.

The main stages of such processes are:

1. Production of nanopowders of the W–Ni–Fe and W–Cu systems by reduction of mixtures of metal oxide powders of the corresponding systems in a hydrogenous plasma flow generated by a DC arc plasma torch. For the W–C–Co system, the reaction is carried out in the presence of methane, while for

**Table 3.** Properties of IN718 powder alloy before and after plasma regeneration

Sample	[O], wt %	[N], wt %	Flowability, s/50 g	Bulk weight, g/cm <sup>3</sup>
Initial powder	0.031	0.14	19	4.6
After plasma regeneration	0.019	0.071	18	4.6



**Fig. 13.** Micrographs of nanopowder (a) and resulting nanopowder granules (b) for W–Ni–Fe composition

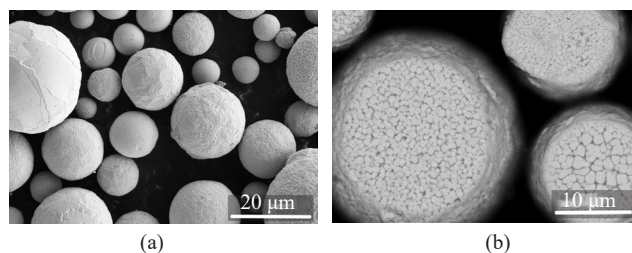
the W–Y<sub>2</sub>O<sub>3</sub> system, the raw materials consists of tungsten trioxide and yttrium acetate. Nanopowders of the W–B composition are produced by hydrogen reduction of a mixture of chlorides, or the W–B and other compositions can be obtained by mixing individual nanopowders produced via plasma-chemical synthesis.

2. Preparation of the corresponding liquid suspensions with an additionally introduced binder (e.g., sucrose).
3. Spray drying of the suspensions to obtain nanopowder porous microgranules.
4. Classification of the microgranules to isolate the required particle size fraction.
5. Densification and spheroidization of the microgranules by sintering and/or melting in a thermal DC plasma flow.

The synthesis of nanopowders in the considered systems in a plasma jet flow is achieved through reduction reactions in the gas phase, resulting in the formation of target metals as nanosized particles. One example of such composites is the W–Ni–Fe system nanopowder. As shown in Fig. 13a, these nanopowders predominantly consist of spherical nanosized particles with a “core–shell” structure, in which nickel and iron form an alloy in the near-surface layers of the nanoparticles, while the core consists of tungsten. The specific surface area of the nanopowders ranges from 4 to 10 m<sup>2</sup>/g.

The aqueous suspension prepared from the nanopowder, containing 2 wt % organic binder (sucrose), was granulated by spray drying using a laboratory Mini Spray Dryer B-290 (*Buchi*, Switzerland). The resulting microgranules were sieved on an AS 200 sieve machine (*Retsch*, Germany) to isolate particles smaller than 50 μm (Fig. 13b). The yield of microgranules within this size range was approximately 60%. The obtained nanopowder microgranules have a uniform structure, free of internal voids, with a homogeneous distribution of metals [31].

Spherical microparticles of the W–Ni–Fe system were obtained (Fig. 14a) as a result of processing the microgranules in an argon–hydrogen (up to 20 vol % H<sub>2</sub>) DC plasma flow, exhibiting a predominantly dense



**Fig. 14.** Micrograph of particles (a) and grinding thin sections (b) for powder of W–Ni–Fe composition after plasma treatment of nanopowder granules

structure without internal voids (Fig. 14b). Analysis of the microstructure of the plasma-treated powder particles revealed that the tungsten grain size falls within the micron and submicron range (Fig. 14b).

The micropowders obtained exhibited a low content of oxygen (up to 0.2 wt %) and carbon (up to 0.01 wt %). The bulk density of the powder was 10 g/cm<sup>3</sup>, and the flowability was 9 s/50 g.

The conducted studies demonstrated the feasibility of spheroidizing metal and alloy powders, produced by various methods, across a wide range of melting temperatures, particle sizes, and morphologies.

Particular attention is paid to the development and creation of plasma equipment and technologies. Plasma technologies for producing nanopowders with a productivity of up to 0.5 kg/h and spherical micron-sized powders with a productivity of up to 10 kg/h are implemented on IMET RAS installations with power ratings up to 45 kW. These installations enable powder production and can be used both for research purposes and for the fabrication of experimental batches of spherical micropowders and nanopowders.

Based on many years of accumulated experience in the research of powder spheroidization in thermal plasma flows, IMET RAS has developed a plasma installation based on a DC plasma torch with a nominal power of 30 kW for spheroidizing powders of metals, alloys, and metal-matrix composites, which it supplies to customers. The installation is included by the Ministry of Industry and Trade of the Russian Federation in the “Catalog of Additive Equipment Produced in the Russian Federation.” Since early 2024, this installation has been in operation directly at IMET RAS, as well as at *GIREDMET* (Russia), the Institute of Advanced Technology (Harbin, China), and the All-Russian Scientific Research Institute of Aviation Materials of the National Research Center “Kurchatov Institute” (Russia). At IMET RAS, the plasma spheroidization installation is used for processing batches of powders of various alloys in quantities up to 1000 kg under orders from Russian companies operating in the ATs field.

## CONCLUSIONS

The results of developments and experimental studies confirm the wide potential of plasma processes and equipment for producing metal nanopowders, their inorganic compounds, and composites. Powders obtained at plasma-chemical synthesis installations have been used in a large number of research studies in the aim of creating new materials with enhanced properties for specialized applications.

In addition to the production of various nanopowder materials, the confined-jet-flow reactor developed at IMET RAS enables plasma spheroidization of metal and alloy powders for their subsequent use in ATs. The study also demonstrated the feasibility of spheroidizing metal and alloy powders produced by different methods across a wide range of melting temperatures, particle sizes, and morphologies.

A new approach involving sequential stages of plasma-chemical synthesis of nanopowders, granulation of the obtained nanopowders, and subsequent plasma spheroidization of the microgranules enables the production of composite micropowders with dense spherical particles and a submicron structure.

The accumulated experience in the development and use of plasma apparatuses based on DC plasma torches serves as a foundation for establishing highly efficient industrial-scale production of powder materials.

## Acknowledgments

The research was funded by the Russian Science Foundation (grant No. 22-19-00112-P, <https://rscf.ru/en/project/22-19-00112/>).

## Authors' contributions

**A.V. Samokhin**—conceptualization, supervision, funding acquisition, manuscript writing, data analysis and results.

**N.V. Alekseev**—manuscript writing, methodology, data analysis and results, references.

**M.A. Sinayskiy**—experimental studies and analyses, references, manuscript writing and editing, data analysis and results.

**A.A. Fadeev, A.G. Astashov, D.E. Kirpichev**—engineering and preparation of equipment for experiments, experimental research.

**A.A. Dorofeev**—experimental research and analysis.

*The authors declare no conflicts of interest.*

## REFERENCES

1. Koch C.C. *Nanostructured Materials: Processing, Properties and Applications*. William Andrew; 2006, 784 p.
2. Wang Z.L., Liu Y., Zhang Z. *Handbook of Nanophase and Nanostructured materials*. Springer; 2002, 406 p.
3. Shaw D., Liu B. *Handbook of Micro and Nanoparticle Science and Technology*. Springer; 2012, 2400 p.
4. Hosokawa M., Nogi K., Naito M., Yokoyama T. *Nanoparticle Technology Handbook*. Elsevier; 2007, 644 p.
5. Tsvetkov Yu.V., Panfilov S.A. *Nizkotemperaturnaya plazma v protsessakh vosstanovleniya (Low-Temperature Plasma in Reduction Processes)*. Moscow: Nauka; 1980, 360 p. (In Russ.).
6. Tumanov Yu.N. *Plazmennye, vysokochastotnye, mikrovolnovyye i lazernyye tekhnologii v khimiko-metallurgicheskikh protsessakh (Plasma, High-Frequency, Microwave, and Laser Technologies in the Chemical and Metallurgical processes)*. Moscow: Fizmatlit; 2010, 968 p. (In Russ.).
7. Seo J.-H., Hong B.-G. Thermal plasma synthesis of nano-sized powders. *Nuclear Eng. Technol.* 2012;44(1):9–20. <https://doi.org/10.5516/NET.77.2012.002>
8. Tanaka Y. Synthesis of nanosize particles in thermal plasmas. In: *Handbook of Thermal Science and Engineering*. Springer; 2018. P. 2791–2828. [https://doi.org/10.1007/978-3-319-26695-4\\_31](https://doi.org/10.1007/978-3-319-26695-4_31)

## СПИСОК ЛИТЕРАТУРЫ

1. Koch C.C. *Nanostructured Materials: Processing, Properties and Applications*. William Andrew; 2006, 784 p.
2. Wang Z.L., Liu Y., Zhang Z. *Handbook of Nanophase and Nanostructured materials*. Springer; 2002, 406 p.
3. Shaw D., Liu B. *Handbook of Micro and Nanoparticle Science and Technology*. Springer; 2012, 2400 p.
4. Hosokawa M., Nogi K., Naito M., Yokoyama T. *Nanoparticle Technology Handbook*. Elsevier; 2007, 644 p.
5. Цветков Ю.В., Панфилов С.А. *Низкотемпературная плазма в процессах восстановления*. М.: Наука; 1980, 360 с.
6. Туманов Ю.Н. *Плазменные, высокочастотные, микроволновые и лазерные технологии в химико-металлургических процессах*. М.: Физматлит; 2010, 968 с.
7. Seo J.-H., Hong B.-G. Thermal plasma synthesis of nano-sized powders. *Nuclear Eng. Technol.* 2012;44(1):9–20. <https://doi.org/10.5516/NET.77.2012.002>
8. Tanaka Y. Synthesis of nanosize particles in thermal plasmas. In: *Handbook of Thermal Science and Engineering*. Springer; 2018. P. 2791–2828. [https://doi.org/10.1007/978-3-319-26695-4\\_31](https://doi.org/10.1007/978-3-319-26695-4_31)
9. Kim K.S., Kim T.H. Nanofabrication by thermal plasma jets: From nanoparticles to low-dimensional nanomaterials. *J. Appl. Phys.* 2019;125(7):070901. <https://doi.org/10.1063/1.5060977>

9. Kim K.S., Kim T.H. Nanofabrication by thermal plasma jets: From nanoparticles to low-dimensional nanomaterials. *J. Appl. Phys.* 2019;125(7):070901. <https://doi.org/10.1063/1.5060977>
10. Phillips J., Luhrs C.C., Richard M. Review: Engineering particles using the aerosol-through-plasma method, *IEEE Trans. Plasma Sci.* 2009;37(6):726–739. <https://doi.org/10.1109/TPS.2009.2016969>
11. Shigeta M., Murphy A.B. Thermal plasmas for nanofabrication. *J. Phys. D: Appl. Phys.* 2011;44(17):174025. <https://doi.org/10.1088/0022-3727/44/17/174025>
12. Szabó D.V., Schlabach S. Microwave Plasma Synthesis of Materials—From physics and chemistry to nanoparticles: a materials scientist’s viewpoint. *Inorganics.* 2014;2(3):468–507. <https://doi.org/10.3390/inorganics2030468>
13. Vollath D. Plasma Synthesis of Nanoparticles. *KONA Powder and Particle J.* 2007;25:39–55. <https://doi.org/10.14356/kona.2007007>
14. Dongdong Gu. *Laser Additive Manufacturing of High-Performance Materials.* Springer; 2015, 311 p. <https://doi.org/10.1007/978-3-662-46089-4>
15. Shishkovsky I.V. (Ed.). *New Trends in 3D Printing.* InTechOpen; 2016, 268 p. <https://doi.org/10.5772/61398>
16. Lewis G. Aspects of the powder in metal additive manufacturing: A review. *World J. Eng. Technol.* 2022;10(02):363–409. <https://doi.org/10.4236/wjet.2022.102022>
17. Wohlers T.T., Campbell R.I., Diegel O., Kowen J., Mostow N. *Wohlers Report 2021: 3D Printing and Additive Manufacturing Global State of the Industry.* Wohlers Associates Inc.; 2021, 374 p.
18. Kendrick A. *3D Printing: The Next Industrial Revolution? A Look into the Impacts on the Aerospace Industry.* Nerac Inc.; 2013, 276 p. Available: <https://www.nerac.com/wp-content/uploads/2014/07/3D-Printing-Dec.pdf>. Accessed July 15, 2024.
19. Vock S., Klöden B., Kirchner A., *et al.* Powders for powder bed fusion: a review. *Prog. Addit. Manuf.* 2019;4(4):383–397. <https://doi.org/10.1007/s40964-019-00078-6>
20. Dejene N.D., Lemu H.G. Current status and challenges of powder bed fusion-based metal additive manufacturing: literature review. *Metals.* 2023;13(2):424. <https://doi.org/10.3390/met13020424>
21. Ladani L., Sadeghilaridjani M. Review of powder bed fusion additive manufacturing for metals. *Metals.* 2021;11(9):1391. <https://doi.org/10.3390/met11091391>
22. Alekseev N.V., Samokhin A.V., Tsvetkov Yu.V. *Plasma Device for Producing Nano-Powders:* RF Pat. 2311225. Publ. 27.11.2007 (in Russ.).
23. Samokhin A.V., Fadeev A.A., Kirpichev D.E., Alekseev N.V., Berestenko V.I., Astashov A.G., Zavertyaev I.D. *Plasma Unit for Spheroidising Metal Powders in a Thermal Plasma Flow:* RF Pat. 2756327. Publ. 29.09.2021 (in Russ.).
24. Samokhin A., Alekseev N., Sinayskiy M., Astashov A., Kirpichev D., Fadeev A., Tsvetkov Y., Kolesnikov A. Nanopowders Production and Micron-Sized Powders Spheroidization in DC Plasma Reactors. In: Cavalheiro A.A. (Ed.). *Powder Technology.* London: IntechOpen; 2018. Ch. 1. <https://doi.org/10.5772/intechopen.76262>
10. Phillips J., Luhrs C.C., Richard M. Review: Engineering particles using the aerosol-through-plasma method, *IEEE Trans. Plasma Sci.* 2009;37(6):726–739. <https://doi.org/10.1109/TPS.2009.2016969>
11. Shigeta M., Murphy A.B. Thermal plasmas for nanofabrication. *J. Phys. D: Appl. Phys.* 2011;44(17):174025. <https://doi.org/10.1088/0022-3727/44/17/174025>
12. Szabó D.V., Schlabach S. Microwave Plasma Synthesis of Materials—From physics and chemistry to nanoparticles: a materials scientist’s viewpoint. *Inorganics.* 2014;2(3):468–507. <https://doi.org/10.3390/inorganics2030468>
13. Vollath D. Plasma Synthesis of Nanoparticles. *KONA Powder and Particle J.* 2007;25:39–55. <https://doi.org/10.14356/kona.2007007>
14. Dongdong Gu. *Laser Additive Manufacturing of High-Performance Materials.* Springer; 2015, 311 p. <https://doi.org/10.1007/978-3-662-46089-4>
15. Shishkovsky I.V. (Ed.). *New Trends in 3D Printing.* InTechOpen; 2016, 268 p. <https://doi.org/10.5772/61398>
16. Lewis G. Aspects of the powder in metal additive manufacturing: A review. *World J. Eng. Technol.* 2022;10(02):363–409. <https://doi.org/10.4236/wjet.2022.102022>
17. Wohlers T.T., Campbell R.I., Diegel O., Kowen J., Mostow N. *Wohlers Report 2021: 3D Printing and Additive Manufacturing Global State of the Industry.* Wohlers Associates Inc.; 2021, 374 p.
18. Kendrick A. *3D Printing: The Next Industrial Revolution? A Look into the Impacts on the Aerospace Industry.* Nerac Inc.; 2013, 276 p. Available: <https://www.nerac.com/wp-content/uploads/2014/07/3D-Printing-Dec.pdf>. Accessed July 15, 2024.
19. Vock S., Klöden B., Kirchner A., *et al.* Powders for powder bed fusion: a review. *Prog. Addit. Manuf.* 2019;4(4):383–397. <https://doi.org/10.1007/s40964-019-00078-6>
20. Dejene N.D., Lemu H.G. Current status and challenges of powder bed fusion-based metal additive manufacturing: literature review. *Metals.* 2023;13(2):424. <https://doi.org/10.3390/met13020424>
21. Ladani L., Sadeghilaridjani M. Review of powder bed fusion additive manufacturing for metals. *Metals.* 2021;11(9):1391. <https://doi.org/10.3390/met11091391>
22. Алексеев Н.В., Самохин А.В., Цветков Ю.В. *Плазменная установка для получения нанодисперсных порошков:* пат. 2311225 РФ. Заявка № 2006110838/15; заявл. 05.04.2006; опубл. 27.11.2007.
23. Самохин А.В., Фадеев А.А., Кирпичев Д.Е., Алексеев Н.В., Берестенко В.И., Асташов А.Г., Завертяев И.Д. *Плазменная установка для сфероидизации металлических порошков в потоке термической плазмы:* пат. 2756327 РФ. Заявка № 2020134059; заявл. 16.10.2020; опубл. 29.09.2021.
24. Samokhin A., Alekseev N., Sinayskiy M., Astashov A., Kirpichev D., Fadeev A., Tsvetkov Y., Kolesnikov A. Nanopowders Production and Micron-Sized Powders Spheroidization in DC Plasma Reactors. In: Cavalheiro A.A. (Ed.). *Powder Technology.* London: IntechOpen; 2018. Ch. 1. <https://doi.org/10.5772/intechopen.76262>

25. Sinayskii M.A., Samokhin A.V., Alexeev N.V., *et al.* Extended characteristics of dispersed composition for nanopowders of plasmachemical synthesis. *Nanotechnol. Russia*. 2016;11(11-12):805–814. <https://doi.org/10.1134/S1995078016060185>  
[Original Russian Text: Sinayskiy M.A., Samokhin A.V., Alekseev N.V., Tsvetkov Yu.V. Extended characteristics of dispersed composition for nanopowders of plasmachemical synthesis. *Rossiiskie Nanotekhnologii*. 2016;11(11-12): 110–115 (in Russ.).]
26. Granqvist C.G., Buhman R.A. Ultrafine metal particles. *J. Appl. Phys.* 1976;47(5):2200–2219. <https://doi.org/10.1063/1.322870>
27. Kotlyarov V.I., Beshkarev V.T., Kartsev V.E., *et al.* Production of spherical powders on the basis of group IV metals for additive manufacturing. *Inorg. Mater. Appl. Res.* 2017;8(3):452–458. <https://doi.org/10.1134/S2075113317030157>  
[Original Russian Text: Kotlyarov V.I., Beshkarev V.T., Kartsev V.E., Ivanov V.V., Gasanov A.A., Yuzhakova E.A., Samokhin A.V., Fadeev A.A., Alekseev N.V., Sinayskiy M.A., Tret'yakov E.V. Production of spherical powders on the basis of group IV metals for additive manufacturing. *Fizika i khimiya obrabotki materialov = Physics and Chemistry of Materials Treatment*. 2016;2:63–70 (in Russ.).]
28. Samokhin A.V., Fadeev A.A., Alekseev N.V., *et al.* Spheroidization of Fe-based powders in plasma jet of DC arc plasma torch and application of these powders in selective laser melting. *Inorg. Mater. Appl. Res.* 2020;11(3):579–585. <https://doi.org/10.1134/S2075113320030417>  
[Original Russian Text: Samokhin A.V., Fadeev A.A., Alekseev N.V., Sinayskiy M.A., Sufiyarov V.Sh., Borisov E.V., Korznikov O.V., Fedina T.V., Vodovozova G.S., Baryshkov S.V. Spheroidization of Fe-based powders in plasma jet of DC arc plasma torch and application of these powders in selective laser melting. *Fizika i khimiya obrabotki materialov = Physics and Chemistry of Materials Treatment*. 2019;4:12–20 (in Russ.).]
29. Tsvetkov Y.V., Samokhin A.V., Alekseev N.V., *et al.* Plasma spheroidization of micropowders of a heat-resistant alloy based on nickel monoaluminide. *Dokl. Chem.* 2018;483(2):312–317. <https://doi.org/10.1134/S0012500818120030>  
[Original Russian Text: Samokhin A., Tsvetkov Yu., Alekseev N., Fadeev A., Sinayskiy M., Levashov E., Kaplanskii Yu. Plasma spheroidization of micropowders of a heat-resistant alloy based on nickel monoaluminide. *Doklady Akademii nauk*. 2018;483(4):403–408 (in Russ.). <https://doi.org/10.31857/S086956520003276-6> ]
30. Samokhin A.V., Alekseev N.V., Fadeev A.A., Zavertyaev I.D., Kirpichev D.E., Sinayskiy M.A. *Method for Regeneration in Thermal Plasma of Waste Metal Powders of Additive Technologies*: RF Pat. 2779558. Publ. 09.09.2022 (in Russ.).
31. Dorofeev A.A., Samokhin A.V., Fadeev A.A., *et al.* Investigation of nanopowder granulation in W–Ni–Fe systems using spray-drying approach. *Inorg. Mater. Appl. Res.* 2023;14(3): 884–895. <https://doi.org/10.1134/s2075113323030115>
25. Синайский М.А., Самохин А.В., Алексеев Н.В., Цветков Ю.В. Расширенные характеристики дисперсного состава для нанопорошков плазмохимического синтеза. *Российские нанотехнологии*. 2016;11(11-12):110–115.
26. Granqvist C.G., Buhman R.A. Ultrafine metal particles. *J. Appl. Phys.* 1976;47(5):2200–2219. <https://doi.org/10.1063/1.322870>
27. Котляров В.И., Бешкарев В.Т., Карцев В.Е., Иванов В.В., Гасанов А.А., Южакова Е.А., Самохин А.В., Фадеев А.А., Алексеев Н.В., Синайский М.А., Третьяков Е.В. Получение сферических порошков для аддитивных технологий на основе металлов IV группы. *Физика и химия обработки материалов*. 2016;2:63–70.
28. Самохин А.В., Фадеев А.А., Алексеев Н.В., Синайский М.А., Суфияров В.Ш., Борисов Е.В., Корзников О.В., Федина Т.В., Водовозова Г.С., Барышков С.В. Сфероидизация порошков на основе железа в потоке плазмы электродугового плазмотрона и их применение в селективном лазерном наплавлении. *Физика и химия обработки материалов*. 2019;4:12–20.
29. Самохин А., Цветков Ю., Алексеев Н., Фадеев А., Синайский М., Левашов Е., Капланский Ю. Плазменная сфероидизация микропорошков жаропрочного сплава на основе моноалюминиды никеля. *Доклады Академии наук*. 2018;483(4):403–408. <https://doi.org/10.31857/S086956520003276-6>
30. Самохин А.В., Алексеев Н.В., Фадеев А.А., Завертяев И.Д., Кирпичев Д.Е., Синайский М.А. *Способ регенерации в термической плазме отработанных металлических порошков аддитивных технологий*: пат. 2779558 РФ. Заявка № 2021135511; заявл. 03.12.2021; опубл. 09.09.2022. Бюл. № 25.
31. Дорощев А.А., Самохин А.В., Фадеев А.А., Алексеев Н.В., Синайский М.А., Литвинова И.С., Завертяев И.Д. Исследование процесса гранулирования нанопорошка системы W–Ni–Fe методом распылительной сушки. *Физика и химия обработки материалов*. 2022;6:54–69. <https://doi.org/10.30791/0015-3214-2022-6-54-69>

[Original Russian Text: Dorofeev A.A., Samokhin A.V., Fadeev A.A., Alekseev N.V., Sinayskiy M.A., Litvinova I.S., Zaverlyaev I.D. Investigation of nanopowder granulation in W–Ni–Fe systems using spray-drying approach. *Fizika i khimiya obrabotki materialov = Physics and Chemistry of Materials Treatment*. 2022;6:54–69 (in Russ.). <https://doi.org/10.30791/0015-3214-2022-6-54-69> ]

### About the Authors

**Andrey V. Samokhin**, Cand. Sci. (Eng.), Head of the Laboratory of Plasma Processes in Metallurgy and Metal Processing, A.A. Baikov Institute of Metallurgy and Material Science, Russian Academy of Sciences (49, Leninskii pr., Moscow, 119334, Russia). E-mail: samokhin@imet.ac.ru. Scopus Author ID 7005200081, ResearcherID L-8328-2013, RSCI SPIN-code 4448-7132, <https://orcid.org/0000-0002-1708-5501>

**Nikolay V. Alekseev**, Cand. Sci. (Eng.), Leading Researcher, Laboratory of Plasma Processes in Metallurgy and Metal Processing, A.A. Baikov Institute of Metallurgy and Material Science, Russian Academy of Sciences (49, Leninskii pr., Moscow, 119334, Russia). E-mail: nvalexeev@yandex.ru. Scopus Author ID 57197595257, ResearcherID M-1438-2013, RSCI SPIN-code 8351-1958, <https://orcid.org/0000-0003-2499-9229>

**Mikhail A. Sinayskiy**, Researcher, Laboratory of Plasma Processes in Metallurgy and Metal Processing, A.A. Baikov Institute of Metallurgy and Material Science, Russian Academy of Sciences (49, Leninskii pr., Moscow, 119334, Russia). E-mail: ms18@mail.ru. Scopus Author ID 56901263200, ResearcherID W-2469-2019, RSCI SPIN-code 9915-7447, <https://orcid.org/0000-0001-7515-4248>

**Andrey A. Fadeev**, Cand. Sci. (Eng.), Researcher, Laboratory of Plasma Processes in Metallurgy and Metal Processing, A.A. Baikov Institute of Metallurgy and Material Science, Russian Academy of Sciences (49, Leninskii pr., Moscow, 119334, Russia). E-mail: afadeev@imet.ac.ru. Scopus Author ID 57191970491, ResearcherID A-6273-2014, RSCI SPIN-code 9309-5732, <https://orcid.org/0000-0003-2147-1787>

**Alexey G. Astashov**, Cand. Sci. (Eng.), Senior Researcher, Laboratory of Plasma Processes in Metallurgy and Metal Processing, A.A. Baikov Institute of Metallurgy and Material Science, Russian Academy of Sciences (49, Leninskii pr., Moscow, 119334, Russia). E-mail: alexey.astashov@gmail.com. Scopus Author ID 55353606400, ResearcherID A-5601-2014, RSCI SPIN-code 8533-7836, <https://orcid.org/0000-0002-5647-2109>

**Dmitry E. Kirpichev**, Cand. Sci. (Eng.), Senior Researcher, Laboratory of Plasma Processes in Metallurgy and Metal Processing, A.A. Baikov Institute of Metallurgy and Material Science, Russian Academy of Sciences (49, Leninskii pr., Moscow, 119334, Russia). E-mail: dkirpichev@imet.ac.ru. Scopus Author ID 23397493800, ResearcherID A-5603-2014, RSCI SPIN-code 1101-5370, <https://orcid.org/0009-0000-9122-5448>

**Alexey A. Dorofeev**, Junior Researcher, Laboratory of Plasma Processes in Metallurgy and Metal Processing, A.A. Baikov Institute of Metallurgy and Material Science, Russian Academy of Sciences (49, Leninskii pr., Moscow, 119334, Russia). E-mail: adorofeev@imet.ac.ru. Scopus Author ID 57222373498, ResearcherID KOC-6589-2024, RSCI SPIN-code 4987-3835, <https://orcid.org/0000-0003-0624-6944>

## Об авторах

**Самохин Андрей Владимирович**, к.т.н., заведующий лабораторией № 16 (Лаборатория плазменных процессов в металлургии и обработке металлов), ФГБУН «Институт металлургии и материаловедения им. А.А. Байкова Российской академии наук» (119334, Россия, Москва, Ленинский пр-т, д. 49). E-mail: samokhin@imet.ac.ru. Scopus Author ID 7005200081, ResearcherID L-8328-2013, SPIN-код РИНЦ 4448-7132, <https://orcid.org/0000-0002-1708-5501>

**Алексеев Николай Васильевич**, к.т.н., ведущий научный сотрудник, лаборатория № 16 (Лаборатория плазменных процессов в металлургии и обработке металлов), ФГБУН «Институт металлургии и материаловедения им. А.А. Байкова Российской академии наук» (119334, Россия, Москва, Ленинский пр-т, д. 49). E-mail: nvalexeev@yandex.ru. Scopus Author ID 57197595257, ResearcherID M-1438-2013, SPIN-код РИНЦ 8351-1958, <https://orcid.org/0000-0003-2499-9229>

**Синайский Михаил Александрович**, научный сотрудник, лаборатория № 16 (Лаборатория плазменных процессов в металлургии и обработке металлов), ФГБУН «Институт металлургии и материаловедения им. А.А. Байкова Российской академии наук» (119334, Россия, Москва, Ленинский пр-т, д. 49). E-mail: ms18@mail.ru. Scopus Author ID 56901263200, ResearcherID W-2469-2019, SPIN-код РИНЦ 9915-7447, <https://orcid.org/0000-0001-7515-4248>

**Фадеев Андрей Андреевич**, к.т.н., научный сотрудник, лаборатория № 16 (Лаборатория плазменных процессов в металлургии и обработке металлов), ФГБУН «Институт металлургии и материаловедения им. А.А. Байкова Российской академии наук» (119334, Россия, Москва, Ленинский пр-т, д. 49). E-mail: afadeev@imet.ac.ru. Scopus Author ID 57191970491, ResearcherID A-6273-2014, SPIN-код РИНЦ 9309-5732, <https://orcid.org/0000-0003-2147-1787>

**Асташов Алексей Григорьевич**, к.т.н., старший научный сотрудник, лаборатория № 16 (Лаборатория плазменных процессов в металлургии и обработке металлов), ФГБУН «Институт металлургии и материаловедения им. А.А. Байкова Российской академии наук» (119334, Россия, Москва, Ленинский пр-т, д. 49). E-mail: alexey.astashov@gmail.com. Scopus Author ID 55353606400, ResearcherID A-5601-2014, SPIN-код РИНЦ 8533-7836, <https://orcid.org/0000-0002-5647-2109>

**Кирпичев Дмитрий Евгеньевич**, к.т.н., старший научный сотрудник, лаборатория № 16 (Лаборатория плазменных процессов в металлургии и обработке металлов), ФГБУН «Институт металлургии и материаловедения им. А.А. Байкова Российской академии наук» (119334, Россия, Москва, Ленинский пр-т, д. 49). E-mail: dkirpichev@imet.ac.ru. Scopus Author ID 23397493800, ResearcherID A-5603-2014, SPIN-код РИНЦ 1101-5370, <https://orcid.org/0009-0000-9122-5448>

**Дорофеев Алексей Андреевич**, младший научный сотрудник, лаборатория № 16 (Лаборатория плазменных процессов в металлургии и обработке металлов), ФГБУН «Институт металлургии и материаловедения им. А.А. Байкова Российской академии наук» (119334, Россия, Москва, Ленинский пр-т, д. 49). E-mail: adorofoev@imet.ac.ru. Scopus Author ID 57222373498, ResearcherID KOC-6589-2024, SPIN-код РИНЦ 4987-3835, <https://orcid.org/0000-0003-0624-6944>

*Translated from Russian into English by N. Isaeva*

*Edited for English language and spelling by Dr. David Mossop*