Influence of electrode arrangement method on specific energy consumption and productivity in electrosynthesis of fine graphite powder

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Abstract
In this work, the influence of the location of the electrodes on the productivity of electrochemical process and specific energy consumption during direct current electrosynthesis of finely dispersed graphite powder is considered. The authors consider the possibility of using finely dispersed graphite powder obtained by electrolysis as the main component of a multifunctional aerospace coating. For this purpose, two types of devices were constructed: with a coaxial and parallel arrangement of the electrodes. The main elements of the device are a stainless steel cathode and a graphite anode immersed in electrolyte (an aqueous solution of salts). The authors consider the influence of the arrangement of the electrodes in the installation for direct current electrosynthesis from the point of view of the energy efficiency and productivity of electrochemical process. As a result of anodic oxidation, a fine powder from graphite of the MPG-6 brand was obtained. The size of the resulting graphite particles is 1–50 µm. This finely dispersed graphite powder can be used as the main component of a multifunctional coating in aircraft, since it has an even homogeneous structure, as well as higher values of the main mechanical properties of a multifunctional coating, which will lead to a decrease in the number of layers and the thickness of the coating applied. The resulting graphite powder can also be used in the production of fire-retardant and heat-insulating materials for the chemical, nuclear industry, instrumentation, and heat power engineering.

Keywords Multifunctional coating · Fine graphite powder · Electrochemical action · Agglomeration · Sedimentation · Specific energy consumption

Nomenclature
C (C4+) Carbon (carbon ions)
Cl¯ Chloride ion
Cl2 Chlorine gas
CO2 Carbon dioxide (carbonic acid gas)
DC Direct current
e¯ Electron
H2 Dihydrogen
H2O Hydrogen oxide
K (K+) Potassium (potassium ion)
KCl Potassium chloride

MgCl2 Magnesium chloride
MPG-6 Brand of graphite (graphite has a fine-grained structure)
Na (Na+) Sodium (sodium ion)
NaCl Sodium chloride
O2 Molecular oxygen
OH¯ Hydroxide
SEM Scanning electron microscope

Abbreviations
A Cm2, area of the working surface of the anode
e KJ/g, specific energy consumption
E V/m, electric field strength
I A, electric current
j A/m2, current density
j̅ A/m2, average current density
m G, mass of the obtained fine graphite powder
r Mm, distance of a given point in the electrolyte
r1 Mm, distance from center of anode to extreme surface of cathode
r0 Mm, radius of the anode

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Introduction

A multifunctional coating is a multilayer structure applied on the surface of a product to protect it from external influence (pressure, temperature, corrosion, erosion, vibration) [1, 2].

During operation, aircraft, in addition to force influences, is continuously exposed to an extensive complex of external physical influences of a heterogeneous type: ionizing and radio emissions, large differences in thermal disturbances, harmful effects of electrodynamic and gravitational fields, and geomagnetic and ionospheric factors [3–6]. Therefore, the creation of an external multifunctional coating for the protection of rocket and space objects, which has a huge range of possibilities for reflection and absorption from external negative factors, is an urgent task in modern aerospace engineering.

In aerospace engineering, the main purpose of multifunctional coatings is thermal protection, protection against ionizing, electromagnetic and radio emission, and reflection of laser influence, aimed at influencing the control system, electrical equipment, and product devices. The secondary functions of multifunctional coating in rocket technology include increasing the strength and stiffness of individual external parts of the product, as well as protection against corrosion and erosion [7, 8].

Description of the problem

The raw materials for the production of graphite are igneous rocks, which are extracted from ores by flotation. Despite the emergence of more technologically advanced graphite production (pyrolysis of gaseous hydrocarbons, thermal decomposition of carbides), the main method of producing graphite in modern industry is pressing a mixture of petroleum or metallurgical coke and anthracite and pitches up to 250 MPa. Then, firing is performed at a temperature of 1200 °C in the Acheson furnace and graphitization is carried out when heated to 2600–3000 °C [9–13]. Individual particles of the initial carbon materials during firing as a result of carbonization are bound into a monolithic solid. To reduce porosity, the resulting graphite is impregnated with synthetic resin or liquid pitch, and then again subjected to firing and graphitization. In the production of high-density graphite, impregnation, firing, and graphitization are repeated up to five times [14–16]. Further, massive pieces of graphite are crushed in a special crusher, and then one of the types of mechanical grinding: vibration grinding, fine turning, vibration abrasion, and jet grinding. The result is a finely dispersed graphite powder.

In addition to the complex technological process, the disadvantage of graphite powder obtained by mechanical action is structural defects in the crystal lattice of the resulting particles—micropores, cracks, and increased interlayer distance [17–19]. Figure 1 shows a snapshot of the microstructure of a particle of finely dispersed graphite powder obtained by mechanical grinding. The image shows the defects obtained as a result of grinding—the inhomogeneous shape of the particle and microcracks on the surface.

Therefore, an important problem in the production of multifunctional coatings today is the heterogeneity of particles of the main component [20]. The role of the shape and size of fillers for distribution and sedimentation in the polymer composite is very important for obtaining coatings with specified quality and functional characteristics [21]. The uniform distribution of filler particles in the polymer composite is determined by their tendency to agglomeration and sedimentation.

The influence of density and surface area of the filler particles has a significant effect on dispersion within the composite coating matrix.

It is known that the degree of aggregation and sedimentation of the polymer coating is always determined by the relative magnitude of the attractive forces of the filler particles [22, 23].

Figure 2 shows SEM micrographs of the microstructure of the surface layer of the multifunctional coating of the structural element of rocket and space technology.
filler of the coating is a finely dispersed graphite powder obtained by mechanical grinding.

In Fig. 2, it can be seen that the filler particles have a heterogeneous shape and different sizes. The inhomogeneity of graphite powder particles obtained by mechanical grinding leads to a significant technological disadvantage—the production of coatings with a significantly increased density: instead of a given limit, the specific density value is significantly higher [24]. With a strictly specified coating thickness, this leads to a greater mass of sprayed coating layers, and, consequently, an excess mass of the manufactured product. There are several possible reasons for this problem: obtaining defects during production and disruption of the technological process during the manufacture of the filler [25], improper transportation conditions, and errors in mixing components, insufficient control during the formation of the polymer mixture of the composition.

Excess multifunctional coating is almost impossible to remove from the surface of the product without damage to the body [26]. Which leads to a number of problems: unnecessary costs for the removal of the aircraft, an increase in additional fuel volume, a decrease in the level of forecasting the behavior of the object in the atmosphere, a possible change in the trajectory of movement.

3 Electrochemical method for obtaining graphite powder

An interesting solution to the problem of obtaining particles of fine graphite powder of heterogeneous shape is the use of methods of electrochemical oxidation of graphite particles [27]. The paper [28] presents a technique for obtaining oxidized graphite powder by the method of electrochemical exfoliation of graphite foil at direct current (DC) in a two-electrode cell in a solution of sulfuric acid. Platinum is used as an anode, and graphite foil is used as a cathode. The current density passed through the electrodes is 0.25 A/cm². As a result of experiments performed according to this technique, we obtained graphite particles ranging in size from 17 to 100 mcm, the microstructure images of which are shown in Fig. 3.

In Fig. 3, it can be clearly seen that graphite particles have an irregular shape; micro-damages of the crystal lattice of the obtained particles were detected. This is due to the significant oxidation of graphite particles and structural degradation of the carbon crystal lattice [29].

This paper presents an alternative method for obtaining fine graphite powder using the anodic oxidation of high-strength finely dispersed dense graphite of the MPG-6 brand. Two main methods of producing graphite powder
using a device with parallel and coaxial arrangement of electrodes are considered. Let's define the main advantages and disadvantages of both methods.

The main objective of the study is to establish the most advantageous method in terms of specific energy consumption, mass, and size of the obtained particles.

The experiments were carried out under similar conditions: electrolytes of the same temperature range of 20–25 °C, concentration and nature, electrolyte volume \( V_e = 790 \text{ ml} \), equal value of DC voltage, and processing time of 35 min; a constant voltage is applied to the electrodes after a single-half-period rectification with a voltage range of 2–5 V.

3.1 Electrosynthesis of finely dispersed graphite powder by electrolysis with a coaxial arrangement of electrodes

For the graphite powder production an electrolyzer was created, Fig. 4 shows its schematic diagram. The unit consists of a cylindrical fluoroplastic body (1), inside which the electrodes: cylindrical stainless steel cathode (2), anode—a graphite electrode of the MPG-6 brand (3)—are placed. Between the electrodes, there is a cylindrical plastic perforated container (4), the outer surface of which is covered with a dacron (5), which acts as a diaphragm. Current leads (7) and the anode (3) are installed on the plastic cover (6).

The method of producing a finely dispersed powder from graphite is based on the property of oxidized graphite to be dispersed during electrochemical oxidation. Coaxially located electrodes: a stainless steel cathode on the periphery and an anode—a graphite electrode located in the center of the diaphragm electrolyzer. The electrolyte: a 15–25% aqueous solution of soluble salts—is poured into a diaphragm electrolyzer. Voltage is applied to the electrodes after a single-half-period rectification, at an electric field strength of 40–100 V/m and an electric current of 100–200 mA.

Figure 5 shows a snapshot of a specially prepared graphite anode.

A diode is connected to the circuit in front of the anode, and an ammeter is connected to the circuit with the cathode to monitor the current value. When the electrodes are immersed in water and sufficient voltage is supplied to them, the process of electric current transfer starts by ions moving...
to the electrodes in the electrolyte and electrons in the external circuit. Positively charged ions migrate to the cathode, and negatively charged ions migrate to the anode under the influence of the electric field strength. The electron transition takes place on the electrodes. The cathode releases electrons into the solution, and reduction processes occur in the near-electrode space. The processes of electron transfer from reacting particles to the electrode—oxidation takes place in the near-anode space.

The electric field strength of a system with coaxial arrangement of electrodes [30, 31] is determined by:

\[ E = \frac{V}{r \times \ln \left(\frac{r_1}{r_2}\right)} \]  

where \( r \) is the distance of a given point in the electrolyte, \( r_1 \)—distance from the center of the anode to the extreme surface of the cathode, and \( r_0 \) is the radius of the anode.

The electrochemical process on electrodes in an aqueous solution of potassium chloride (KCl) is considered.

Cathode reaction [32, 33]:

\[ \frac{1}{2}O_2 + H_2O + 2e^- \rightarrow 2(OH)^- \]  

Reaction at the anode [34, 35]:

\[ 2Cl^- \rightarrow 2Cl + 2e^- \]  

\[ Cl + Cl \rightarrow Cl_2 \uparrow \]  

The total reaction:

\[ 2KCl + \frac{1}{2}O_2 + H_2O \rightarrow H_2 \uparrow + Cl_2 \uparrow + 2K + 2(OH)^- \]  

When an electric current is passing through the anode, the \( C^{4+} \) ion is formed from carbon atoms:

\[ C \rightarrow C^{4+} + 4e^- \]
Further passage of an electric current through the system leads to the formation of molecular oxygen $O_2$ from hydroxide ions in the near-anode space [36, 37]:

$$4OH^- - 4e^- \rightarrow O_2 + 2H_2O$$ \hspace{1cm} (7)

Molecular oxygen reacts with carbon ions $C^{4+}$ to form carbon dioxide:

$$C^{4+} + 4e^- + O_2 + 2H_2O \rightarrow CO_2 + 2H_2O$$ \hspace{1cm} (8)

The electrolyte is heated, the current increases, which indicates the heating of the aqueous solution—the graphite electrode begins to interact with oxygen, and $CO_2$ is released. That is, electrochemical oxidation proceeds to the tetravalent state of $CO_2$, and a significant amount of oxygen is bound in an intermediate carbon compound in the general form [38]:

$$C_xK_y(H_2O)_n$$ \hspace{1cm} (9)

The values of $x$, $y$, $n$ depend on the oxidation state of carbon. $x$ for different compounds is 8, 24, 48, and 64. The value of $y$, $n$ depends on the nature of the anion [39].

A hydrate shell is formed around $C^{4+}$ ions. The hydrated ions formed stay in the water as a sediment [40, 41]:

$$C^{4+} + 2H_2O \rightarrow C(H_2O)_2$$ \hspace{1cm} (10)

After the end of the electrochemical process, solutions were obtained—anolyte and catholyte. Due to the presence of suspended graphite particles, the anolyte has a darker color (Fig. 6) than the catholyte.

Anolyte with graphite precipitate is passed through a special filtering device, the basis of which is a chemical conical funnel and several layers of filter paper; as a result, particles of fine graphite powder remain on the filter.

After washing with distilled water and drying, the finished product was obtained—fine graphite powder (Fig. 7).

### 3.2 Electrosynthesis of finely dispersed graphite powder by electrolysis with parallel arrangement of electrodes

An electrolyzer with a parallel arrangement of electrodes is an open structure in which there is no separation by the diaphragm, and, consequently, there is no catholyte.

![Fig. 7](image7.png) The obtained product is a finely dispersed graphite powder

![Fig. 8](image8.png) Schematic diagram of a device with a parallel arrangement of electrodes: 1—device body; 2—stainless steel cathode; 3—graphite anode; 4—current leads

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Fig. 6 Results of the electrochemical process—flask with anolyte

Fig. 7 The obtained product is a finely dispersed graphite powder

Fig. 8 Schematic diagram of a device with a parallel arrangement of electrodes: 1—device body; 2—stainless steel cathode; 3—graphite anode; 4—current leads
Figure 8 shows the design of a special electrochemical device consisting of an organic glass body (1), inside which the electrodes are placed: the cathode is a stainless steel plate (2); the anode is a graphite electrode of the MPG-6 brand, plate shape (3). Between the electrodes is a working medium—a strong electrolyte: aqueous solutions of soluble salts. On the upper part of the electrodes, there are current leads (4), which are connected to a direct current source through a diode.

Figure 9 shows a snapshot of a specially prepared graphite anode of a flat shape.

The electrolyte is a 15–25% aqueous solution of soluble salts. Voltage is applied to the electrodes after a single-half-period rectification, at an electric field strength $E$ of 20–60 V/m and an electric current $I$ of 200–900 mA.

The electrochemical process on electrodes in an aqueous solution of sodium chloride (NaCl) is considered.

Cathode reaction [42]:

$$2H_2O + 2e^- \rightarrow H_2 + 2(OH)^- \tag{11}$$

The reaction at the anode is similar to that for the coaxial arrangement of the electrode [43, 44].

The total reaction:

$$2NaCl + 2H_2O \rightarrow H_2 \uparrow + Cl_2 \uparrow + 2Na + 2(OH)^- \tag{12}$$

As with the coaxial arrangement of the electrodes when an electric current is passing through the anode, the $C^{4+}$ ion is formed from carbon atoms. Molecular oxygen reacts with carbon ions $C^{4+}$ to form carbon dioxide:

$$C^{4+} + 4e^- + O_2 + 2H_2O \rightarrow CO_2 + 2H_2O \tag{13}$$

During the electrolysis process, the aqueous solution is heated and $C^{4+}$ ions begin to interact with oxygen, and $CO_2$ is released. A significant amount of oxygen is bound in an intermediate carbon compound in the general form [45]:

$$C_xNa_y(H_2O)_n$$

$$C^{4+} + 4e^- + O_2 + 2H_2O \rightarrow CO_2 + 2H_2O \tag{14}$$

The values of $x$, $y$, $n$ depend on the oxidation state of carbon. $x$ for different compounds is 8, 24, 48, and 64. The value of $y$, $n$ depends on the nature of the anion. According to the results of the analysis, the largest number of detected compounds is $C_8Na_4\cdot(H_2O)_2$ and $C_{24}Na_{12}\cdot(H_2O)_6$ [46].

A hydrate shell is formed around $C^{4+}$ ions. The hydrated ions formed to stay in the water as a sediment.

After the end of the electrochemical process, an electrolyte with a sediment in the form of graphite powder was obtained. The further stages of obtaining graphite powder are similar to the methods of electrolysis with a coaxial electrodes arrangement.

4 Experimental results

The resulting graphite powder in two electrolyzers was used for analysis. Photos of graphite powder obtained using a digital microscope are shown in Fig. 10.

The analysis of graphite particles was carried out by laser diffraction and scanning electron microscopy (SEM). The results are shown in Fig. 11.

Based on the results of laser diffraction of graphite particles (Fig. 11), it can be concluded that the particles have sizes in the range from 0.001 to 0.05 mm for two methods of arrangement the electrodes. With the coaxial arrangement of the electrodes, the largest number of particles has a size range from 2.1 to 4.2 mcm. With the parallel arrangement of the electrodes (without separating the...
electrolyte into the anode and cathode spaces), the resulting particles have a size in the range from 7.9 to 11.9 mcm.

The result of the analysis of SEM images of the structure of the obtained particles in two devices with different arrangement of electrodes (Fig. 12) showed a similar microstructure and shape of graphite particles.

Analysis of the microstructure showed no damage (or minor damage) to the crystal lattice of the particles of the obtained fine graphite powder. Due to the same shape and size range of graphite powder particles, the multifunctional coating will have a smooth uniform structure without a difference in particle density and with a given degree of sedimentation, since the particles are tightly bound to each other.

The uniform homogeneous structure of the graphite powder particles contributes to the creation of an even surface of the applied layers of a multifunctional coating with a given density and thickness.

**Fig. 11** Results of analysis of graphite particle sizes: a for coaxial arrangement of electrodes; b for parallel arrangement of electrodes

**Fig. 12** SEM micrograph of the microstructure of a graphite powder particle
5 Data analysis

In order to obtain reliable results with different methods of arrangement of the electrodes, the anode process was carried out at different current densities $j$. This is possible when using anodes with different geometric dimensions, but the same cathode size. Consequently, the intensity of the electric field strength will be different.

The experimental results are summarized in Tables 1 and 2.

It can be noted that, with the coaxial arrangement of the electrodes, the current density $j$ is higher, with a lower value of the electric field strength $E$. Consequently, the electric current $I$ and the mass of the obtained powder $m$ are lower.

To determine the influence of the method of arrangement of the electrodes during electrosynthesis, it is necessary to estimate the Specific energy consumption $e$. This is the energy consumption per unit mass of the product obtained [47]:

$$
e = \frac{V \times I \times t}{m}$$

(15)

where $V$ is the voltage during electrosynthesis, $I$ is the electric current of electrosynthesis, $t$ is the time of electrosynthesis, and $m$ is the mass of the obtained fine graphite powder.

The productivity of electrosynthesis $u$ is determined [48]:

$$u = \frac{m}{t \times A}$$

(16)

where $A$ is the area of the working surface of the anode.

According to the results of the study in Fig. 13 shows the dependence of specific energy consumption $e$ on the volume concentration $\sigma_r$ and nature of the electrolyte for coaxial arrangement of electrodes. The current density $j$ ranges are 29–51 A/m² at an electric field strength $E=41.545$ V/m and 12–19 A/m² at an electric field strength $E=67.298$ V/m, depending on the volume concentration $\sigma_r$ and nature of the electrolyte.

### Table 1 Results of electrosynthesis experiments with a coaxial arrangement of electrodes

| Electrolyte | $\sigma_r$, % | $E=41.545$ V/m | $E=67.298$ V/m |
|-------------|--------------|----------------|----------------|
|             | Average $I$, mA | $m$, g | $j$, A/m² | Average $I$, mA | $m$, g | $j$, A/m² |
| NaCl        | 15 146 0.00945 42.8907 128 0.00827 14.3593 |
|            | 20 153 0.00992 44.9471 134 0.00868 15.0324 |
|            | 25 169 0.01098 49.6475 142 0.00921 15.9299 |
| KCl         | 15 151 0.00978 44.3596 133 0.0086 14.9202 |
|            | 20 161 0.01047 47.2973 149 0.00968 16.7152 |
|            | 25 174 0.01135 51.1163 166 0.01081 18.6223 |
| KNO₃        | 15 100 0.00633 29.3772 109 0.00689 12.2279 |
|            | 20 112 0.00712 32.9025 126 0.008 14.1350 |
|            | 25 128 0.00818 37.6028 137 0.00873 15.3690 |
| MgCl₂       | 15 131 0.00846 38.4841 119 0.008267 14.3593 |
|            | 20 145 0.00938 42.5969 128 0.008267 14.3593 |
|            | 25 159 0.01031 46.7098 139 0.00901 15.5933 |

### Table 2 Results of electrosynthesis experiments with a parallel arrangement of electrodes

| Electrolyte | $\sigma_r$, % | $E=47.67$ V/m | $E=51.25$ V/m |
|-------------|--------------|----------------|----------------|
|             | Average $I$, mA | $m$, g | $j$, A/m² | Average $I$, mA | $m$, g | $j$, A/m² |
| NaCl        | 15 518.91 0.02837 54.1882 437.92 0.02415 59.5813 |
|            | 20 613.99 0.03412 64.1178 538.34 0.03007 73.2433 |
|            | 25 716.99 0.04051 74.8734 591.37 0.03355 80.4579 |
| KCl         | 15 527.07 0.02934 55.0407 470.97 0.02658 64.0776 |
|            | 20 631.10 0.03571 65.9043 562.43 0.03209 76.5217 |
|            | 25 733.57 0.04199 76.6051 620.83 0.03591 84.4660 |
| KNO₃        | 15 344.01 0.01791 35.9239 322.61 0.01699 43.8928 |
|            | 20 406.25 0.02132 42.4238 378.17 0.02001 51.4510 |
|            | 25 503.57 0.02672 52.5862 456.27 0.02445 62.0776 |
electrolyte. Therefore, for graphical display, instead of the value ranges, we will use the average values \( j \) for each electrolyte.

Despite different values of current density \( j \), the specific energy consumption \( e \) at the same value of direct current voltage is practically the same and varies depending on the change in the volume concentration \( \sigma_i \) of the electrolyte. This is primarily due to the nature of the anion and cation. The lowest specific energy consumption \( e \) of the electrochemical process of 132 kJ/g was achieved at the highest current density of 51.12 A/m², using an aqueous solution of KCl with a volume concentration of 25% as an electrolyte. That is, higher values of the electrical conductivity \( \gamma \) of the electrolyte lead to lower specific energy consumption \( e \). This is due to the high absolute mobility ions of \( K^+ \) and \( Cl^- \).

Figure 14 shows the dependences of specific energy consumption \( e \) on the volume concentration \( \sigma_i \) and nature

**Fig. 13** Dependence of specific energy consumption \( e \) on the volume concentration and composition \( \sigma_i \) of the electrolyte for coaxial arrangement of electrodes

**Fig. 14** Dependence of specific energy consumption \( e \) on the volume concentration \( \sigma_i \) and composition of the electrolyte for parallel arrangement of electrodes
of the electrolyte for parallel arrangement of electrodes. The current density \( j \) ranges are 35–77 A/m\(^2\) at an electric field strength \( E = 47.67 \) V/m and 43–85 A/m\(^2\) at an electric field strength \( E = 51.25 \) V/m, depending on the volume concentration \( \sigma_i \) and nature of the electrolyte.

With a parallel arrangement of electrodes, the specific energy consumption \( e \) is higher. At the same time, the same pattern is visible with the dependence of specific energy consumption \( e \) on the volume concentration \( \sigma_i \) of the electrolyte and the nature of the anion and cation, with the same voltage value. The specific energy consumption \( e \) has the lowest value of 149 kJ/g when using a 25% aqueous solution of KCl as an electrolyte, with the highest current density \( j \) of 84.47 A/m\(^2\).

Figure 15 shows the dependence of the productivity of electrosynthesis \( u \) on the volume concentration \( \sigma_i \) and nature of the electrolyte for coaxial arrangement of electrodes.

Figure 15 shows that it can be concluded that a high current density \( j \) increases the productivity of electrosynthesis \( u \). At the same time, the dependence of productivity of electrosynthesis \( u \) on the volume concentration \( \sigma_i \) and nature of the electrolyte is also traced: with an increase in volume concentration, productivity of electrosynthesis increases. Electrolytes with higher values of the absolute mobility of ions have higher indicators of the productivity of electrosynthesis.

Figure 16 shows the dependence productivity of electrosynthesis on the electric field strength at the coaxial arrangement of electrodes.

From the data obtained, we can conclude that, with an increase in the electric field strength, the productivity of electrosynthesis increases. This is due to an increase in the value of ion velocity with an increase in the electric field strength.

6 Conclusion

In this paper, the authors present a new approach to solving the problem of obtaining a fine graphite powder with a homogeneous particle structure and without crystal lattice defects. As a result, a method of electrosynthesis of fine graphite powder on DC with a graphite anode was created.
The experiments were carried out on two setup devices: with coaxial and parallel arrangement of electrodes. As a result of the experiments, graphite powder with a particle size from 0.001 to 0.05 mm was obtained. The particles of graphite powder have a similar microstructure and shape. Analysis of the structure showed no damage (or minor damage) to the crystal lattice of the particles of the obtained finely dispersed graphite powder.

Thus, theoretically, when using as a filler a multifunctional coating of graphite powder obtained by electrosynthesis from MPG-6 brand graphite with a particle size range of 0.004–0.05 mm, in comparison with mechanically crushed graphite powder, provides the following advantages:

1. Higher values of the main multifunctional coating mechanical properties (strength, rigidity, and hardness) and the possibility of reducing the thickness and number of coating layers, due to the high particle density of the main component;
2. Obtaining coatings with a given density, due to a greater degree of aggregation and sedimentation of the obtained particles.

From the point of view of the influence of the method of arrangement of electrodes during electrosynthesis on specific energy consumption and productivity of electrosynthesis:

1. Under the same conditions, the specific energy consumption has higher values with a parallel arrangement of the electrodes of 149–165 kJ/g, that is, the method with a coaxial arrangement of the electrodes is more energy-efficient—specific energy consumption of 132–136 kJ/g;
2. The value of specific energy consumption directly depends on the current density—the higher the anode current density, the lower the values of specific energy consumption of the electrochemical process;
3. The particles of graphite are more actively separated from the anode at higher values of the current density, that is, with an increase in the anode current density, the number of microbubbles of the O2 gas increases, which contributes to the separation of the particles of graphite from the anode;
4. The productivity of electrosynthesis directly depends on the intensity of the electric field strength—with increasing intensity of the electric field strength, the productivity of electrosynthesis also increases;
5. The productivity of electrosynthesis is higher at a high anode current density; the highest value of 10.6 g/ min x cm² is achieved at a current density of 51.12 A/m².

In the studied range, the lowest specific energy consumption of 132 kJ/g was obtained by an electrochemical process on a device with a coaxial arrangement of electrodes, using a 25% aqueous solution of KCl at a current density of 51.12 A/m².

It is worth noting that the described technique relates to the technology of obtaining a fine powder based on graphite by electrosynthesis. The obtained fine graphite powder can be used as the main component of multifunctional coatings and materials for rocket and space, aviation, and transport equipment, in the production of fire-resistant and heat-insulating materials for the chemical, nuclear industry, instrumentation, and thermal power engineering. It can also have industrial applications in the production of electrical engineering, chemical equipment, electrical contacts, various rheostats, shut-off, and connecting valves.

**Author contribution** Andrei V. Kupriashov: conceptualization, methodology, experimental work, investigation, and writing the original draft. Ivan Y. Shестakov: resources, advisory, experimental work, review, editing, and supervision.

**Availability of data and material** Materials are commercially available at a reasonable cost, and the quality result was obtained.

**Code availability** Not applicable.

**Declarations**

**Ethical approval** All authors confirm that they follow all ethical guidelines.

**Consent to participate** The authors declare that they consent to participate in this paper.

**Consent for publication** The authors declare that they consent to publish this paper and agree with the publication.

**Conflict of interest** The authors declare no competing interests.

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