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# NEW ELECTRODE MATERIALS FOR ALUMINUM PRODUCTION

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The successful development and implementation of inert anodes in the aluminum industry could significantly reduce or even completely eliminate greenhouse gas emissions. The search for suitable inert anode materials with the necessary combination of properties remains an active area of research. Currently, three main classes of materials are being considered: ceramics, metal-ceramics, and metals. This study aims to develop a new type of composite ceramic material for use as inert anodes in the electrolytic reduction of alumina. Based on an analysis of the requirements for inert anodes in aluminum electrolysis, the oxidation-resistant and conductive $ZrB_2$–$MoSi_2$ composite ceramic is proposed for operation within the required temperature range. It has been demonstrated that these anodes exhibit inert behavior toward atomic oxygen and can operate stably in atomic oxygen atmospheres at temperatures up to 2000°C. Furthermore, the feasibility of applying a protective $ZrB_2$–$MoSi_2$ coating to conventional carbon anodes via vacuum arc deposition has been experimentally confirmed. The use of non-consumable anodes with $ZrB_2$–$MoSi_2$ protective coatings is also proposed for the direct electrolysis of lunar regolith at 1600°C, enabling oxygen and metal extraction on the Moon.

**Keywords:** inert anodes, aluminum, production, ultra-high-temperature ceramics, zirconium diboride.

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## *Introduction*

The production of aluminum through the electrochemical reduction of alumina is a highly energy-intensive process (about 13–16 kWh per kg of aluminum) and causes significant environmental damage: emissions of greenhouse gases (direct emissions of $CO_2$ and perfluorocarbon compounds (PFCs), and indirect emissions from electricity production). More than 400 kg of carbon is consumed for the production of one ton of aluminum due to the oxidation of anodes by electrolysis products. The oxidation of anodes by electrolysis products leads to the formation of 1220 kg of carbon dioxide.

The successful development and application of inert anodes can bring significant environmental benefits to the aluminum industry worldwide – greenhouse gas emissions can be significantly reduced or completely eliminated. $CO_2$ and PFC emissions can be almost fully eliminated since the inert anode will not contain carbon.

According to experts' estimates, from a thermodynamic point of view, carbon should contribute to the reduction of alumina and, to some extent, reduce specific energy consumption (by almost 30%) (Table 1). However, this approach overlooks the costs of the specific material consumption of the process as

a whole.

The use of non-consumable inert anodes is more economically feasible, as it eliminates the need for their constant renewal. Therefore, the development of inert anodes for aluminum production is being pursued by specialists in many countries.

An inert anode for aluminum production by the Hall-Heroult process must have a set of properties that ensure its functionality. Namely, an inert anode should be:

– physically stable at operating temperatures;
– resistant to molten fluoride electrolyte;
– resistant to pure oxygen;
– electrochemically stable;
– electrically conductive;
– resistant to thermal shock;
– mechanically strong,
– easy to install and operate (for example, electrical connection to the bus, start-up, power outages).

Materials of three classes are considered for inert anodes: ceramics, metal-ceramics, and metals [1].

*Ceramics*

The temperature for the electrolytic reduction of aluminum by the Hall-Heroult process is 960$^0$C, and the choice of fully oxidized material, oxide ceramics, with a high melting point and a wide range of electrochemical stability is attractive. However, most oxides have unacceptably low electronic conductivity and quite high solubility in the electrolyte. Besides, ceramics have poor resistance to thermal shock and insufficient mechanical strength.

Tin oxide was considered a potential inert anode material due to its high electronic conductivity. However, tin oxide is highly soluble in the Hall bath. Other ceramics tested include semiconducting oxides such as ferrites, spinels, and some perovskites. Despite efforts to improve their electrical conductivity through doping, their conductivity remains insufficient. Moreover, they dissolve in the electrolyte, resulting in aluminum metal products containing unacceptably high levels of other metals.

Monolithic ceramic ICS was considered promising, but it was not possible to make pilot industrial anodes from it due to its low thermomechanical properties [1].

*Cermets*

Cermets are composite materials consisting of a ceramic matrix and dispersed metallic filler. The ceramic matrix provides chemical stability, while the metal offers conductivity and strength. However, the drawbacks of monolithic ceramics, such as solubility in the electrolyte and unsatisfactory thermomechanical properties, remain. A promising cermet material consisting of a ceramic matrix of nickel ferrite and dispersed copper filler was developed by Alcoa. The company reported the successful operation of laboratory cells with a cermet anode. However, the industrial implementation of cermet anodes was unsuccessful due to the inability to produce metal of the required purity and the catastrophic failure of the anodes due to thermal shock [1].

*Metals*

Metals surpass the parameters of carbon anodes in properties such as high electronic conductivity combined with excellent thermal shock resistance and mechanical strength. Additionally, metals are easier to manufacture and maintain.

The chemical and electrochemical stability of metals is ensured by a surface film containing aluminum oxide, which is thick enough to prevent the destruction of the base metal and thin enough to provide minimal resistance to electronic current.

The main problem is the stability of the surface film thickness. An example of an anode material of this type is aluminum bronze: copper containing 7–15% aluminum by weight. The surface film self-renews during operation. At the Massachusetts Institute of Technology, a laboratory cell equipped with anodes made from various copper-aluminum alloys operated for hours, producing aluminum and oxygen. However, in other cases, the anode failed catastrophically, and the aluminum was heavily contaminated with copper. It should be noted that in these experiments, the electrolyte was not saturated with alumina, and the metal anode was able to operate over a wide range of current densities (from 0.25 to 2.4 A/cm$^2$) [1].

*Coatings*

Coatings are also being developed as a means of protecting anodes. The most promising are the oxyfluorides produced by DeNora, Eltech, and Moltech. However, the mismatch between the thermal

Table 1

**The alumina decomposition voltage**

| Type of anode | Electrochemical reaction | $\Delta G^0_{1300}$, kJ/mol | $E^0_{desin}$, V | U, V |
|---|---|---|---|---|
| inert | $Al_2O_3$=2Al+1.5$O_2$ | 1262.0 | 2.18 | 2.18 |
| coal | $2Al_2O_3$+3C=4Al+3$CO_2$ | 667.6 | 1.15 | 1.5–1.6 |
| coal | $Al_2O_3$+3C=2Al+3CO | 583.0 | 1.01 | 1.5–1.6 |

expansion of the substrate and the coating leads to the formation of cracks through which the electrolyte can penetrate. Various barrier layers have been proposed to prevent such phenomena, but the problem remains unsolved.

Currently, metals are considered the most suitable materials for inert anodes.

An analytical review of the problem of inert anodes for the electrolysis of oxide melts shows that they have been developed for many years, but an energy-efficient technology for aluminum extraction using them has not yet been created. The search for materials for inert anodes with the necessary set of properties continues [1].

The goal of this work is to develop a new type of composite ceramic material for inert anodes for the electrolytic reduction of alumina.

***Results and discussion***

*Selection of prospective ceramic materials for non-consumable inert anodes*

For applications requiring thermal stability in an oxidizing environment at extremely high temperatures, a new class of composite materials with a ceramic matrix of borides, reinforced with continuous or discrete fibers, whiskers, platelets, or isometric particles of refractory compounds (carbides, silicides, borides, and nitrides) has been developed. Due to their high thermal stability, they are called ultra-high-temperature ceramics (UHTC). UHTC has surface structures that protect against oxidation [2].

The best performance parameters for operation in oxidizing environments are exhibited by ultra-high-temperature ceramics based on zirconium diboride ($ZrB_2$), which has a sufficient level of conductivity, making it a suitable material for inert anodes for aluminum extraction by the electrolytic reduction of alumina. Additionally, zirconium diboride-based ceramics have a high thermal conductivity of nearly 100 W/m·K [3], which enables reducing the temperature gradient across the material section and internal thermal stresses.

Monolithic $ZrB_2$ ceramics oxidize to form porous $ZrO_2$ crystals and glassy $B_2O_3$. The latter is liquid and partially protective at temperatures up to 1000$^0$C, but above this temperature, it evaporates, leaving a porous zirconium oxide layer that leads to further oxygen penetration. Resistance to high-temperature oxidation and mechanical properties can be improved by "binding" boron and forming borosilicate glass, which is stable at temperatures up to 1600$^0$C, and by introducing silicon carbide into the ceramic composition in a wide range of its content [4].

Ceramics based on the $ZrB_2$–SiC composite have significantly higher resistance in high-temperature oxidizing environments than their components. The oxidation process occurs in two stages: at a temperature of 1200$^0$C with the formation of $ZrO_2$ and liquid boron oxide, and at higher temperatures up to 1600$^0$C, when active oxidation of silicon carbide begins with the formation of $SiO_2$, which prevents the evaporation of $B_2O_3$ by binding it into borosilicate glass [5].

However, at higher temperatures, intensive interaction develops according to the following reaction:

$$SiC+SiO_2 \rightarrow 2SiO(g)+CO(g).$$

The formation of gaseous silicon oxide leads to a decrease in oxidation resistance. Therefore, other components such as carbides, silicides, and borides of transition metals are introduced into the ceramic composition in addition to silicon carbide.

When zirconium disilicide is introduced into the composite, the main oxidation products are monoclinic $ZrO_2$ and amorphous $SiO_2$ and $ZrSiO_4$ (zircon). The latter can provide protection for the base material at temperatures up to 1600$^0$C, so $ZrSi_2$ is used to enhance oxidation resistance [6].

An analysis of the properties of existing heat-resistant materials showed that the weight loss of the ternary ceramic $ZrB_2$–SiC–$ZrSi_2$ is 0.017 mm over 50 hours and 2.92 mm over a year, which is 2.6 times less than the consumption of iridium anode materials (~7.7 mm/year), which are considered among the most promising.

The main parameters of the $ZrB_2$–SiC–$ZrSi_2$ ceramic system, determined experimentally, are presented in Table 2.

The oxidation resistance of $ZrB_2$-based ceramics further increases with the addition of $MoSi_2$. This system has the highest resistance to high-temperature oxidation among materials of this type [7]. The optimal content of $MoSi_2$ should be 14–20%. The formation of protective structures in the oxygen environment begins at a temperature of 470$^0$C:

$$2ZrB_2+5O_2=2ZrO_2 \text{ (monoclinic)}+2B_2O_3\uparrow.$$

This process continues until T=745$^0$C. The oxidation of $MoSi_2$ begins at 740$^0$C according to the reaction:

$$2MoSi_2+7O_2=2MoO_3\uparrow+4SiO_2,$$

and at 1150$^0$C according to the reaction:

$$5MoSi_2+7O_2=Mo_5Si_3+7SiO_2.$$

In the temperature range of 1155–1530$^0$C, a

fairly stable amorphous $SiO_2$ film with inclusions of $ZrO_2$ and $Mo_5Si_3$ crystallites forms on the surface of the sample. During the final stage of the oxidation of the sample at T=1540–1600$^0$C, an oxidized layer forms on the surface, consisting of two sublayers:

– the upper amorphous layer consists of $SiO_2$ (with inclusions of $ZrO_2$) and may lose continuity at higher temperatures,

– the lower layer has a needle-like lamellar structure of $ZrO_2$ crystallites.

In the $ZrB_2$–$MoSi_2$ material, small $ZrO_2$ grains are formed during oxidation, and the molar volume of the oxidation products does not exceed 200%. This allows the formation of a dense scale and increases the strength of the ceramic.

The mass loss with the temperature increase and the curves of oxidation with time have standard parabolic dependencies, indicating the formation of a stable protective film on the material's surface due to the diffusion laws that govern the oxidation process.

Thus, at temperatures up to 2000$^0$C in an oxidizing environment, a protective layer forms on the surface of the $ZrB_2$–$MoSi_2$ material, the composition of which changes depending on the temperature. It can ensure the operability of the anode during aluminum extraction by the reduction of molten alumina at temperatures of 960$^0$C for an extended period.

Such anodes can be used at melt temperatures of up to 1800–2000$^0$C, but their lifespan will be significantly shorter: the higher the operating temperature in the oxidizing environment, the shorter the anode's service life.

Composite ceramic materials based on zirconium diboride have sufficient conductivity and heat resistance at extremely high temperatures, making them promising for use as inert anode materials for the direct electrolysis of lunar regolith melt. This will enable the extraction of oxygen and certain metals on the Moon and could accelerate the establishment of a lunar base.

*Experimental study*

*Experimental determination of the electrical conductivity of zirconium diboride-based ceramics*

To determine the electrical conductivity, the zirconium diboride-based ceramics were densified by hot pressing at a temperature of 1900–2100$^0$C under a pressure of 32 MPa for 15 minutes. According to the results of electron microscopy, the microstructure of the ceramics is heterophase and non-porous, as shown in Fig. 1. The matrix phase for the two composites is zirconium diboride of a gray color with inclusions of other phases (SiC – dark color and $MoSi_2$ – light gray color).

According to ceramic analysis, the grain size of zirconium diboride in ceramics varies. The microstructure of $ZrB_2$–$MoSi_2$ is finer-grained with inclusion sizes up to 1 μm. Meanwhile, the grain size of the main phase in $ZrB_2$–SiC ceramics ranges from 4 to 20 μm. Different grain sizes and chemical compositions, consequently, affect the overall electrical conductivity of the ceramics. The results of measuring the electrical conductivity of composite ceramics are presented in Table 3.

Analysis of the results of the experimental study of the electrical conductivity of ceramics showed that the measured values are close to some metallic materials (titanium) and are within the range of values for most metals and alloys commonly used for electrolysis. Ceramics of the SiC–$ZrB_2$ and $ZrB_2$–$MoSi_2$ systems belong to n-type semiconductors, where the main charge carriers are conduction electrons.

Inert anodes made of $ZrB_2$–$MoSi_2$ ceramics surpass the inert anode materials developed by other specialists in terms of their properties. The higher the operating temperatures, the greater the oxidation resistance of the ceramics. Therefore, $ZrB_2$–$MoSi_2$ ceramics, with their higher heat resistance and electrical conductivity, will have the longest service life among

Table 2

**Parameters of $ZrB_2$–SiC–$ZrSi_2$**

| Parameter | Value |
|---|---|
| density (kg/m$^3$) | 4000–6200, depending on the composition |
| electrical resistance at 0–800$^0$C (mΩ·cm) | 0.02–0.08 |
| heat capacity at 0–2000$^0$C (J/g·K) | 0.5–0.8 |
| thermal conductivity at 0–2000$^0$C (W/m·K) | 60–100 |
| elastic modulus (GPa) | 490–515 |
| oxidation in oxygen (mass gain at 1500$^0$C for 50 hours) (mg/cm$^2$) | 6–7 |
| flexural strength at room temperature (MPa) | 400–800, depending on the composition |
| flexural strength at 1800$^0$C (MPa) | 300–800 or more, depending on the composition |
| maximum working temperature ($^0$C) | 1700–1800, depending on the composition |

all known ceramic materials and are promising for use in anodes for aluminum extraction by the electrolytic reduction of alumina.

*Development of coatings from $ZrB_2$–$MoSi_2$ ultra-high-temperature ceramics for the protection of carbon anodes*

The technology for manufacturing products (plates, rings) from $ZrB_2$–$MoSi_2$ UHTC by hot pressing has been developed in Ukraine on a pilot-industrial scale. However, such composite ceramics, although possessing better properties than conventional ceramics, are brittle materials, which can lead to the destruction of large-sized products. Moreover, replacing carbon anodes will require re-equipping production, which is economically inefficient. It is more attractive to use existing carbon anodes protected with heat-resistant electrically conductive coatings. An undeniable advantage of choosing ultra-high-temperature ceramics based on zirconium diboride for application to graphite anodes, along with a sufficient level of electrical conductivity and resistance in the flow of atomic oxygen at high temperatures, is the similarity of the coefficients of thermal expansion of the substrate and the coating (Table 4).

Reactive magnetron sputtering and vacuum-arc deposition methods are most often used to obtain oxide-free ceramic coatings. Magnetron sputtering is a low-energy method that cannot provide sufficient adhesion and coating thickness.

These disadvantages are overcome by the vacuum-arc deposition method. The fundamental difference of this method is the deposition of cathode material onto the surfaces of products from a high-energy plasma flow generated by a vacuum arc on the cathode surface. Compared to other vacuum coating methods, this method has significant advantages, namely: simplicity and high efficiency of the process, low energy consumption, and the ability to adjust the main process parameters, which allows the easy control of the structure and properties of the obtained coatings [8].

Yuzhnoye State Design Office has equipment for vacuum-arc deposition of UHTC-based coatings ($ZrB_2$). Coatings are applied to the surfaces of samples in a special vacuum installation based on the vacuum chamber (Fig. 2).

$ZrB_2$–$MoSi_2$ coatings were deposited by vacuum-arc method on the UVN-75 (Yuzhnoye) installation on substrates of steel 40X, steel 12X18H10T, and carbon.

*$ZrB_2$–$MoSi_2$ coating on 40X steel substrate*

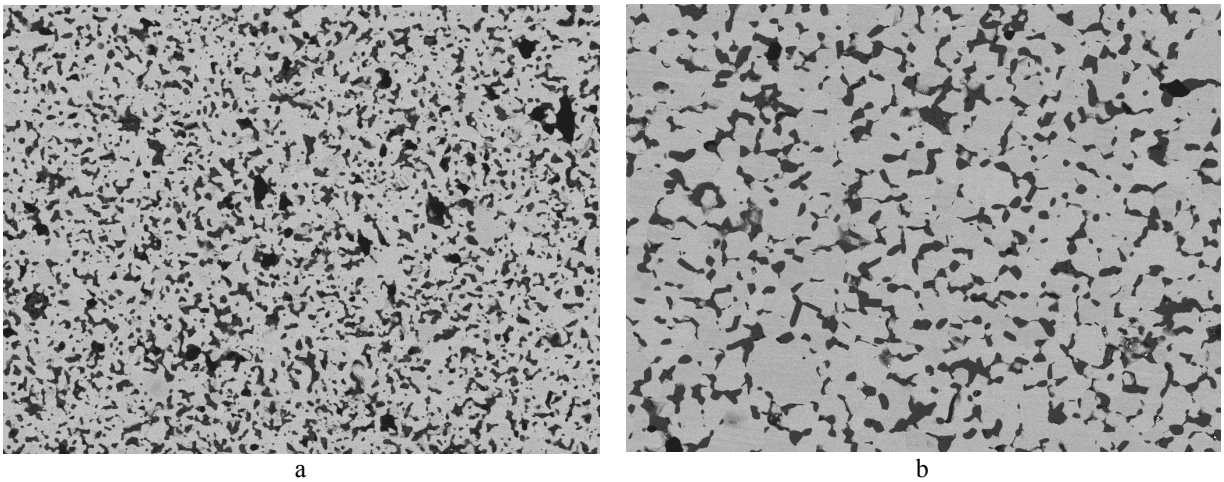
According to electron microscope studies, the $ZrB_2$–$MoSi_2$ coating deposited on 40X steel substrates showed weak adhesion between the coating material and the substrate (Fig. 3a). The coating thickness did not exceed 15 μm (Fig. 3).

The microstructure of steel 40X is characterized by pearlitic (lamellar) and ferritic matrix phases. The coating was not uniformly distributed on the substrate surface. The distribution pattern of the coating was island-like, with widths ranging from 200 to 500 μm and lengths up to 1 mm. The microstructure of the coatings is homogeneous and globular in shape. The

Table 3

**Electrical conductivity of zirconium diboride-based ceramics**

| Material | Electrical conductivity ($10^6$ S/m) |
|---|---|
| $ZrB_2$–$MoSi_2$ | 5.6 |
| $ZrB_2$–SiC | 4.4 |
| $ZrB_2$–SiC–WC | 3.5 |
| titanium | 2.5 |
| iridium | 21.0 |



a b

Fig. 1. The microstructure of ceramics $ZrB_2$–$MoSi_2$ (a) and $ZrB_2$–SiC (b) produced by hot pressing (×1500)

size of the globules ranges from 1 μm to 20 μm. The number of globules sized 20 μm did not exceed 20 vol.%, indicating the formation of a homogeneous coating on the material surface.

The chemical composition of the coating after deposition corresponds to the cathode material. This indicates that during deposition, the main elements evaporate and deposit on the substrate. The amount of residual oxygen in the coating was 5 wt.%, which is a standard oxygen content value for $ZrB_2$–$MoSi_2$ coatings obtained by plasma spraying.

Therefore, the $ZrB_2$–$MoSi_2$ coating on the 40X substrate has a homogeneous structure but weak adhesion, which may be related to the significant difference in thermal expansion coefficients between the coating and the substrate.

*$ZrB_2$–$MoSi_2$ coating on 12X18H10T substrate*

The coating thickness did not exceed 15 μm. The structure and the chemical composition of the coating are identical to that applied to steel 40X. The adhesion between the coating and the substrate is significantly higher than on 40X steel.

*$ZrB_2$–$MoSi_2$ coating on a graphite substrate*

A general view of the $ZrB_2$–$MoSi_2$ coating

Table 4

**Coefficients of thermal linear expansion of ceramics, carbon, and graphite**

| Material | Application temperatures | $10^{-5}/\,^0$C max | $10^{-5}/\,^0$C min |
|---|---|---|---|
| zirconium and silicate ceramics | room temperature to 100–390$^0$C | 1.3 | 0.2 |
| carbon and graphite | room temperature to 100–390$^0$C | 1.3 | 0.2 |

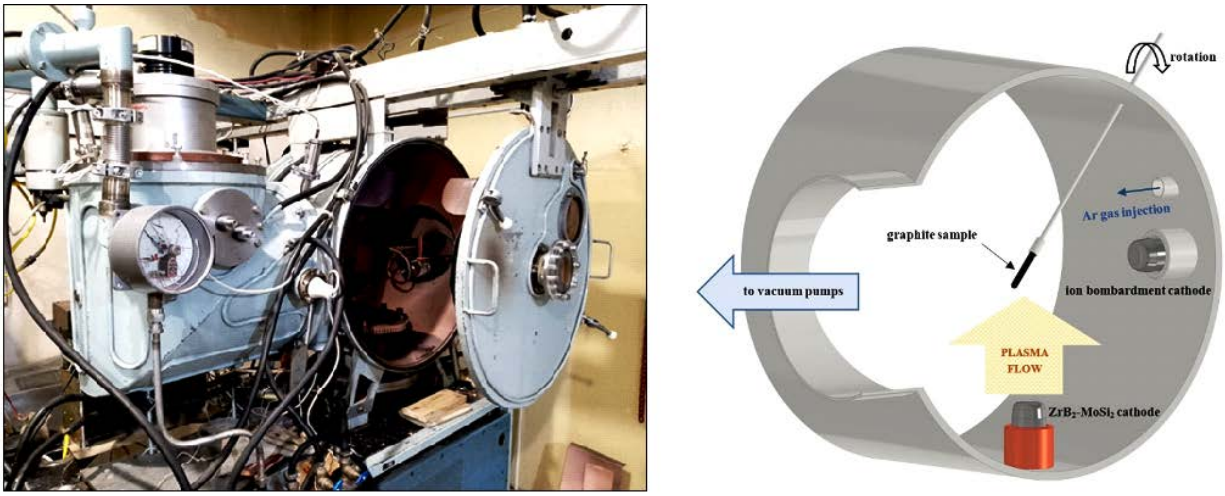



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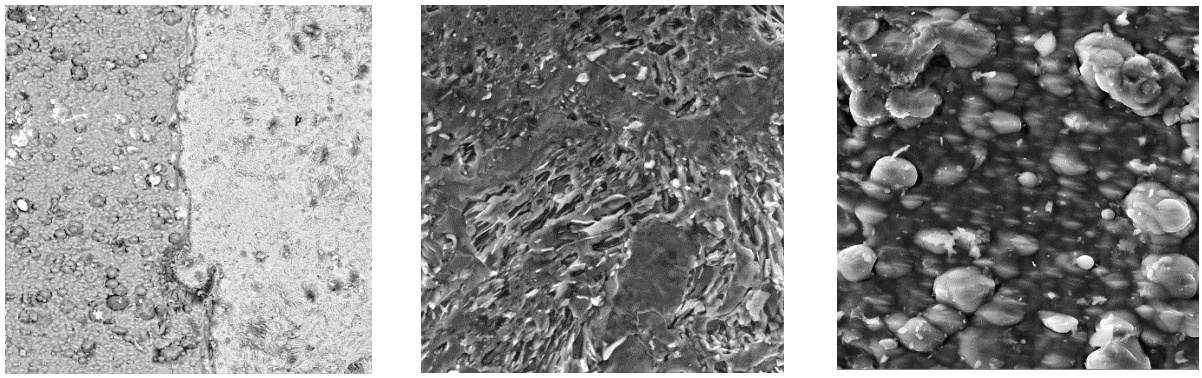
Fig. 2. The vacuum-arc deposition installation (a) and its schematic (b)



a b c

Fig. 3. The interface between the $ZrB_2$–$MoSi_2$ coating and the 40X substrate (at magnification ×948) (a); the microstructure of steel 40X (b); and the $ZrB_2$–$MoSi_2$ coating (c) after coating application (at magnification ×4700)

deposited on a graphite substrate is shown in Fig. 4.

The $ZrB_2$–$MoSi_2$ coating deposited on a graphite substrate has a different microstructure compared to the steel substrates. It is characterized by the formation of a two-layer coating (Fig. 5). The first layer, which is closer to the substrate, has a structure consisting of well-defined crystals up to 1 μm in size (Fig. 5a). Closer to the surface, the coating structure differs significantly and has a globular form (Fig. 5b).

This difference is most likely related to the cooling rate and heat removal from the surface during deposition. At the beginning of the process, the rate of heat removal into the substrate is higher, resulting in the formation of rectangular parallelepiped-shaped crystals, whereas, during the deposition of subsequent layers, the heat removal is lower, leading to the formation of spherical crystals.

The chemical composition of the coating is homogeneous and fully corresponds to the chemical composition of the cathode used during spraying. The oxygen content in the first and second layers did not exceed 2 wt.%, which should positively influence the physical and mechanical properties of the coating.

Therefore, the adhesion between the $ZrB_2$–$MoSi_2$ coating and the carbon substrate is the highest among all the studied materials, which can be explained by the similarity in thermal expansion coefficients (Table 4). Using a carbon substrate is the most promising among the studied materials.

***Conclusions***

For the first time, based on the analysis of the requirements for inert anodes for aluminum extraction

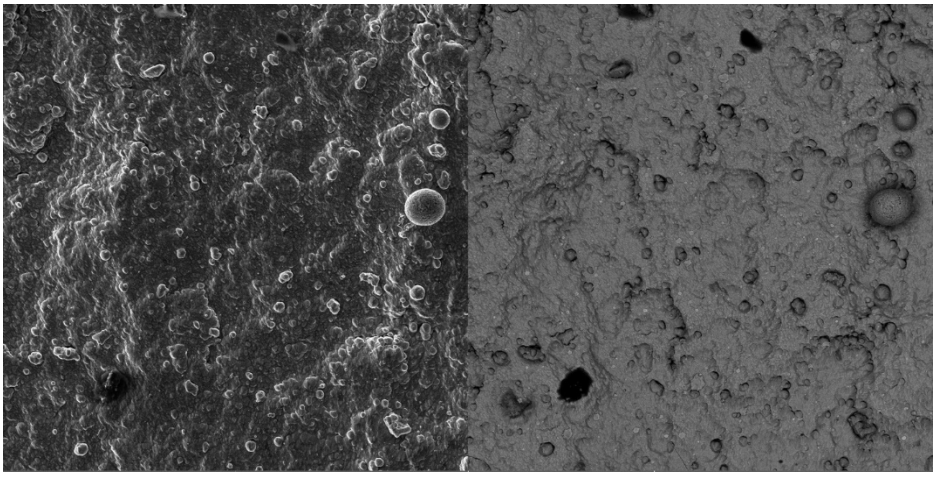
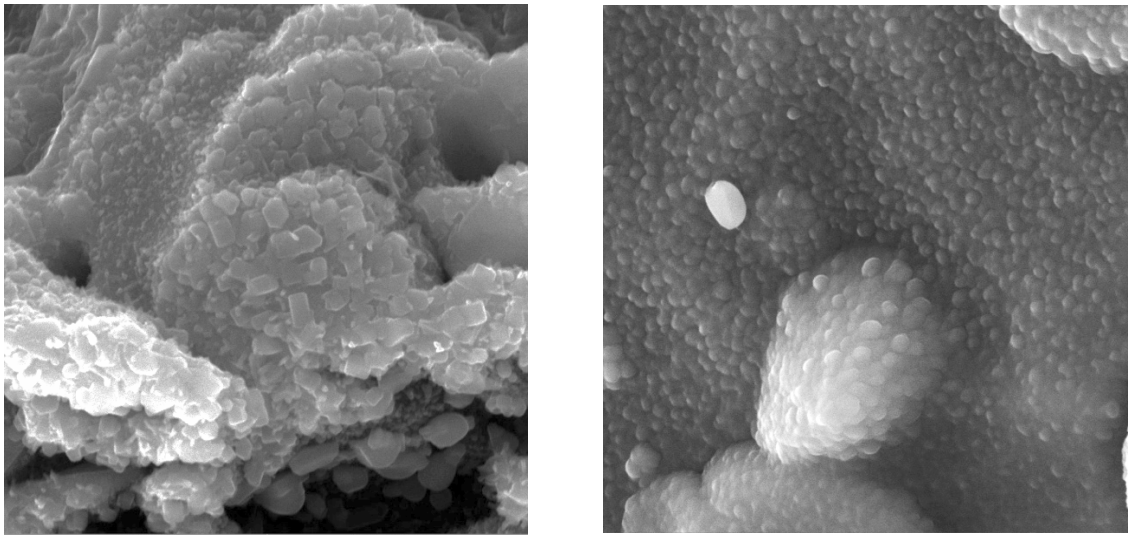


Fig. 4. A general view of the $ZrB_2$–$MoSi_2$ coating at a ×400 magnification in a SE detector (left) and a BSE detector (right)



a b

Fig. 5. The microstructure of the $ZrB_2$–$MoSi_2$ coating closer to the graphite substrate (a) and closer to the surface (b), (at magnification ×47000)

by the electrochemical reduction of molten alumina, the use of oxidation-resistant electrically conductive composite ceramics $ZrB_2$–$MoSi_2$ for inert anodes is proposed. It has been shown that such anodes are inert to the effects of atomic oxygen and can operate for a long time in an atomic oxygen atmosphere at temperatures up to 2000$^0$C.

The possibility of applying a protective $ZrB_2$–$MoSi_2$ coating to existing carbon anodes by vacuum-arc deposition has been experimentally proven.

The use of a non-consumable anode with a $ZrB_2$–$MoSi_2$ protective coating for the direct electrolysis of lunar regolith at a temperature of 1600$^0$C is proposed, which can enable the extraction of oxygen and certain metals on the Moon.

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**НОВІ ЕЛЕКТРОДНІ МАТЕРІАЛИ ДЛЯ ВИРОБНИЦТВА АЛЮМІНІЮ**

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Успішна розробка і застосування інертних анодів в алюмінієвій промисловості дозволить значно скоротити або повністю виключити викиди парникових газів. На даний час проводиться пошук матеріалів для інертних анодів з необхідним набором властивостей. Для інертних анодів розглядаються три класи матеріалів: кераміка, металокераміка і метали. Метою даної роботи є розробка нового типу композитного керамічного матеріалу для інертних анодів для електролітичного відновлення оксиду алюмінію. На основі аналізу вимог до інертних анодів для видобутку алюмінію методом електрохімічного відновлення розплавленого глинозему запропоновано використання стійкої до окислення провідної композитної кераміки $ZrB_2$–$MoSi_2$ в певному діапазоні робочих температур. Показано, що такі аноди інертні до дії атомарного кисню і можуть працювати тривалий час в атмосфері атомарного кисню при температурі до 2000$^0$C. Експериментально продемонстровано можливість нанесення захисного покриття $ZrB_2$–$MoSi_2$ на існуючі вугільні аноди методом вакуумно-дугового осадження. Запропоновано використання неруйнівного анода із захисним покриттям $ZrB_2$–$MoSi_2$ для прямого електролізу місячного реголіту при температурі 1600$^0$C, що дозволить видобувати кисень і деякі метали на Місяці.

**Ключові слова**: інертні аноди, алюміній, виробництво, наджароміцна кераміка, цирконієвий борид.

**NEW ELECTRODE MATERIALS FOR ALUMINUM PRODUCTION**

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The successful development and implementation of inert anodes in the aluminum industry could significantly reduce or even completely eliminate greenhouse gas emissions. The search for suitable inert anode materials with the necessary combination of properties remains an active area of research. Currently, three main classes of materials are being considered: ceramics, metal-ceramics, and metals. This study aims to develop a new type of composite ceramic material for use as inert anodes in the electrolytic reduction of alumina. Based on an analysis of the requirements for inert anodes in aluminum electrolysis, the oxidation-resistant and conductive $ZrB_2$–$MoSi_2$ composite ceramic is proposed for operation within the required temperature range. It has been demonstrated that these anodes exhibit inert behavior toward atomic oxygen and can operate stably in atomic oxygen atmospheres at temperatures up to 2000$^0$C. Furthermore, the feasibility of applying a protective $ZrB_2$–$MoSi_2$ coating to conventional carbon anodes via vacuum arc deposition has been experimentally confirmed. The use of non-consumable anodes with $ZrB_2$–$MoSi_2$ protective coatings is also proposed for the direct electrolysis of lunar regolith at 1600$^0$C, enabling oxygen and metal extraction on the Moon.

**Keywords:** inert anodes; aluminum; production; ultra-high-temperature ceramics; zirconium diboride.

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