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# Investigation of self-propagating high-temperature synthesis based on TiB+Ti composite powders

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**Abstract.** This article considers modern methods of increasing wear resistance and reliability of machine parts using composite materials, especially in the field of powder surfacing and synthesis of metal-matric composites. One of the effective methods is self-propagating high-temperature synthesis (SHS), which allows obtaining composite coatings with improved mechanical and thermal properties. Powder surfacing methods, such as electron beam surfacing (EBF), provide wear-resistant, heat-resistant and hardening coatings on a titanium base. Powders of titanium and its alloys are obtained by reduction of oxides with calcium hydride, which contributes to the formation of materials with high strength and good flowability. Special attention is paid to titanium boride as a strengthening phase for composites. The use of these technologies contributes to a significant increase in the durability and reliability of machines and mechanisms, which leads to resource saving and reduction of operating costs. The studies include the analysis of structural characteristics of the obtained powders and coatings, as well as the determination of their physical and mechanical properties. The variations in these properties as a function of the titanium binder content in the composite powder are analyzed. The description of the microstructure of powders and coatings, as well as the influence of composition on their characteristics, allows us to draw conclusions about the possibility of using these materials to create functional coatings with improved performance characteristics, such as increased wear resistance and heat resistance. The results of the study can be useful for the development of new materials with improved operational properties for use in various industries.

***Keywords:*** *composite powder, titanium boride, titanium, electron-beam coatings, powder surfacing, self-propagating high-temperature synthesis.*

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## 1. Introduction

In modern manufacturing, the introduction of highly efficient technological processes is a key factor in advancing the engineering industry. The primary objective of the mechanical engineering sector today is to ensure high product quality at minimal cost and within tight deadlines. At the same time, the requirements for finished products remain stringent: materials must combine reliability, precision in manufacturing, and an optimal balance between low specific weight and high strength while providing sufficient hardness, wear resistance, and (or) chemical resistance of the surface layer of parts. Enhancing the operational efficiency of dynamic structures (aerospace, energy, construction, and others) is possible through the use of materials with specialized properties. One such group of materials is composite materials (CMs), which consist of a combination of two or more chemically and structurally different components distributed throughout the volume of the part. This allows the development of materials with tailored properties. Composite materials outperform individual components in strength, thermal resistance, and especially reliability. They exhibit unique properties not found in their individual constituents and demonstrate 50-100% greater resistance to transient loads and fatigue limits compared to conventional alloys. They also have a higher modulus of elasticity and specific strength and are less prone to crack formation.

Powder metallurgy is one of the most promising areas of modern manufacturing. This approach enables the production of high-volume structural elements for general applications as well as specialized materials such as antifriction, friction, electrical contact, highly porous, hard, and refractory materials. The use of powder technology allows for the enhancement of useful properties in existing materials, for example, increasing material utilization efficiency up to 80-96% by influencing their structural characteristics. Powders differ in chemical properties (content of base metal, impurities, contaminants, and toxicity), physical properties (shape, size, specific surface area, true density, particle microhardness), and technological properties (bulk density, flowability, compactability, formability, and pressability). The main advantage of powder metallurgy lies in the ability to produce components with diverse compositions. This method allows easy fabrication of products from refractory materials (e.g.,

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ceramics) and from mixtures of metallic powders and refractory compounds, such as metal-ceramic composites. Additionally, powder metallurgy enables the production of components from metals that cannot form alloys in the molten state due to significant differences in melting temperatures (e.g., tungsten and copper). This method is also effective for producing metal-nonmetal composites, such as copper-graphite or aluminum-aluminum oxide.

Another advantage of powder material is their structural homogeneity. During the manufacturing of products using powder metallurgy, powders are thoroughly mixed in advance to achieve uniform particle distribution in the charge. As a result, products made from such powders exhibit a consistent distribution of components throughout their entire volume. Practice has shown that using pure powders allows for the production of materials with lower impurity content compared to cast materials. This is because sintering occurs in an inert environment or vacuum, preventing the formation of oxides, nitrides, and other undesirable chemical compounds. Thus, it is crucial that the composition and distribution of elements in the final product, obtained through powder metallurgy, remain the same as during the initial powder mixing and charge preparation stages. Powder metallurgy technology enables the production of precision components and is also used to create materials with special properties or specified characteristics that cannot be achieved by any other method.

The process of obtaining metallic powder is the first and one of the key operations in powder metallurgy. The chemical composition, structure, and other characteristics of powders depend both on the production method and the properties of the metal used.

Powder production methods vary depending on the required dispersion and volume and include the following main techniques:

1. Mechanical grinding;
2. Atomization of melts with compressed air;
3. Reduction of ore or scale;
4. Electrolytic depositionl
5. Explosion of a conductor with an electric current

From an economic standpoint, the most efficient methods are ore or scale reduction and atomization of melts with compressed air. Conductor explosion is used to obtain powders from electrically conductive materials, while mechanical grinding of certain powders requires consideration of their separation tendencies. In industry, other specialized methods are also employed, such as thermal decomposition of volatile compounds, precipitation, carburization, and other advanced techniques.

## 2. Materials and methods

The technological process of obtaining a product begins with the preparation of a powder mixture that includes several different powder components. First, the powders are weighed and then thoroughly mixed in rotating drums, mills, mixers, or other mechanical devices. This results in a homogeneous powder mixture with uniformly distributed particles of various types. The prepared charge is then shaped into a powder blank with specified form, dimensions, and density. During this stage, the initial powder volume decreases as consolidation occurs. Powder compaction is achieved by pressing it in a metal die under pressure, resulting in a solid pressed part that closely resembles the final product in shape and size.

However, since the process of powder compaction is quite complex, predicting the exact outcome of pressing is difficult, as different powders behave differently, and even slight changes in composition or substitution of powder grades can alter the result. Therefore, the pressing load must be selected individually for each mixture. Some powder mixtures do not compact properly, even under high loads, leading to crumbling or cracking of the products. In most cases, cold pressing is used, but it does not always provide the necessary mechanical strength for the blanks, and under low loads, such blanks may break apart. To prevent this, plasticizers or other additives are introduced into the powder mixture before pressing to improve particle adhesion without taking up much volume or affecting the final properties of the products. After pressing, the powder blanks undergo sintering to achieve the required mechanical properties and impart the necessary physical and chemical characteristics. Sintering is one of the key processes in powder metallurgy, largely determining the final properties of materials and products. This process involves a complex combination of various physicochemical phenomena occurring simultaneously or sequentially during the heating of the compact or free powder.

Some of these phenomena are associated with the typical effects of high temperature on polycrystalline materials, while others are specific to porous powder bodies. The primary goal of sintering is to achieve the desired material properties that develop during the heating of the initial powder body. In the process of heating to high temperatures, two main types of sintering can occur: solid-phase sintering, in which no liquid phase is formed, and liquid-phase sintering, in which low-melting components of the powder mixture partially melt. When examining the sintering processes of multicomponent powder systems, it is necessary to consider several characteristics unique to this process. First, the reduction of free energy depends not only on factors typical of single-component powders and heterodiffusion, which facilitates concentration equalization in the system, but also on the formation of interphase surfaces, whose energy is usually lower than the surface energy at the boundary between a substance and a void. The progress of the sintering process is largely determined by the phase diagrams of the components in the multicomponent system. The kinetics of densification and changes in the physical and mechanical properties of the material depend on the extent of alloy formation during the process. Unlike single-component systems, where diffusion processes typically promote densification, in multicomponent systems, heterodiffusion can slow down shrinkage. After sintering is completed, the product undergoes additional processing, such as finishing, calibration, and heat treatment.

Among the various physicochemical and physico-mechanical processes occurring in the powder medium during processing, one of the key factors is interparticle contact interaction. Depending on the type of impact (electron-beam surfacing, selective laser melting, plasma sintering, vacuum sintering, self-propagating high-temperature synthesis (SHS), etc.), this interaction may be solid-phase or occur in the presence of a liquid phase. As a result, even when using the same initial components, different processes may take place, such as shrinkage or volumetric growth with the formation of a large number of pores.

Each powder system has its own specific features, which are determined by equilibrium phase diagrams for the selected elements. Although powder technological processes are inherently non-equilibrium, primary parameters (concentrations, temperature regimes) are typically determined based on equilibrium diagrams while considering possible chemical reactions [1].

In this study, the main focus is on self-propagating high-temperature synthesis (SHS) of metal-matrix composite materials [2,3]. SHS is one of the promising methods for obtaining composite materials, based on the interaction of two or more elements in an exothermic reaction, which occurs in the form of layer-by-layer combustion or a thermal explosion. This synthesis method relies on localized exothermic reactions that release heat, allowing the exothermic reaction wave to propagate throughout the entire volume of the material [4]. This method has several advantages, such as reduced energy consumption, increased process efficiency, and improved product purity. The primary method of initiating an SHS reaction involves the local application of a thermal impulse to the surface of the system (e.g., using an electric coil, spark discharge, laser beam, etc.), which leads to the formation of a combustion wave that then propagates through the unheated starting material [5].

The SHS process can be carried out in three ways: gasless combustion, filtration combustion, and hybrid combustion. Gasless combustion is used in «solid-solid» systems, filtration combustion in «metal-gas» systems, while hybrid combustion combines both previous methods. In filtration combustion, gas filtration can be either spontaneous or forced, depending on the gas supply, and is classified based on the direction of the combustion front relative to the filtering gas flow as either co-current or counter-current. For weakly exothermic reactions or mixtures with a high content of inert fillers, preheating of the charge in a furnace is required to initiate the synthesis reaction. In SHS processes, the charge can be located in a vacuum, in open air, or in an inert or reactive gas under pressure. Figure 1 presents a schematic representation of the SHS technology for powder production.

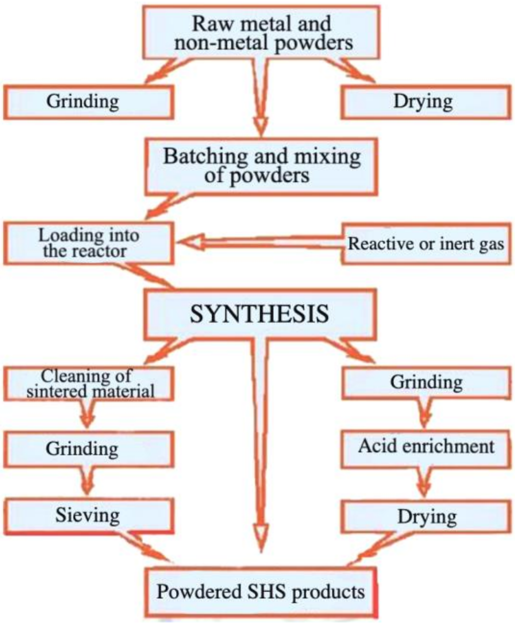


***Figure 1. Schematic representation of the SHS technology for powder production***

The SHS method enables an increase in productivity at significantly lower costs compared to vacuum sintering of powder mixtures, offering significant advantages in the following aspects:

– product output per unit time;
– energy consumption for batch production;
– equipment and maintenance costs.

When using the SHS method, certain challenges arise related to production characteristics such as controlling the composite structure and matrix properties. In the process of vacuum sintering of powder mixtures, it is possible to flexibly regulate the heating rate and isothermal holding temperature, allowing for adjustments in phase composition, structural dispersion, and sintered material strength. In SHS technology, parameters that influence the phase composition and properties of the final product include the composition, degree of compaction, and volume of the reaction mixture, the dispersion of powder reactants, and the initial temperature at which the synthesis reaction begins [6-10]. Thus, the process proceeds based on predefined parameters that determine the course of the reaction.

The task of improving the reliability and durability of machine and mechanism components is often directly related to the wear resistance of their friction surfaces. Enhancing the wear resistance of parts extends the service life of machines, leading to significant savings in financial resources, labor, and materials.

One of the most effective ways to improve the reliability of machine components and mechanisms in mechanical engineering is the application of various coatings to the working surfaces of parts. Wear-resistant coatings for titanium alloys provide high wear resistance due to their bonding with metallic materials. Powder surfacing is widely used as a method for obtaining wear-resistant coatings for titanium and its alloys. To significantly enhance wear resistance and restore the dimensions of worn-out parts, surfacing is performed on the surfaces that experience continuous wear. Pre-prepared surfacing alloys in the form of rods or tubes are applied. Surfacing is the process of depositing a layer of metal onto a part’s surface to modify its dimensions or impart specific properties such as hardness, corrosion resistance, and wear resistance. The composition of the powder filler material is selected to create composite coatings with a matrix structure containing dispersed particles of refractory compounds, such as carbides, borides, and nitrides. Reinforcing phases may include TiC, TiB, TiN, and $TiB_2$.

Special attention is given to titanium boride as a hard and refractory strengthening phase in titanium-based metal-matrix composites. The formation of «titanium boride + titanium» composites can be achieved through the «titanium + $B_4C$» reaction [11-12], as well as by synthesizing pure powders [13-14]. The study of composite powders and coatings derived from them has significant practical importance. To produce titanium boride coatings, electron beam surfacing is used, in which an electron beam is employed to create coatings with specified shapes and properties on the surface of a part. This technology enables the creation of both single-layer and multilayer coatings for various applications, including wear-resistant, heat-resistant, and strengthening coatings. Electron beam surfacing is performed using powders with a particle size range of 50 to 350 μm. Depending on the shape of the part and coating requirements, different application schemes may be used. For example, an electron beam with a power of several kilowatts can be focused into a spot less than a millimeter in diameter. When directed at the surface of a part, the metal in the beam's impact area instantly melts while the rest of the part remains cool. Once the beam is removed, the molten metal immediately solidifies. The principle of electron beam surfacing is illustrated in Figure 2. The electron beam creates a molten metal pool on the surface of the part. Powder is fed into this molten pool via a dosing system, and the particles form a coating with the required properties on the surface. The workpiece being surfaced moves within a vacuum chamber relative to a stationary electron gun and powder feeder, or the electron gun and feeder move relative to a stationary workpiece.

The technology of multi-pass electron beam surfacing is based on the phenomenon of «freezing» the powder into the liquid-metal melt pool. With each successive pass, a new portion of powder is incorporated into the melt while the previously deposited layer is remelted. The powder fed into the molten metal pool accelerates the crystallization process, promoting the formation of a fine-grained structure and reducing residual stresses in the deposited coating. The required thickness of the deposited layer is achieved by adjusting the powder feed rate or increasing the number of passes. A higher crystallization rate contributes to the formation of a uniform, fine-dispersed structure in the deposited layer [6-7].

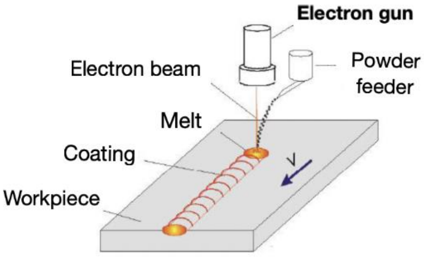


***Figure 2. Principle of electron beam surfacing***

Powders with particle sizes smaller than 50 μm have insufficient flowability in a vacuum, making it difficult to feed them into the molten pool. Powders larger than 350 μm require higher energy input for melting, which can lead to excessive penetration of the base material and increased residual stresses. The key parameters characterizing the surfacing process include the energy and current of the electron beam, its diameter, the size and shape of the beam scan on the surface of the part, the movement speed of the workpiece, and the powder feed rate. A distinctive feature of electron beam surfacing is the presence of a prolonged transition zone between the base material and the coating. Since the powder melts directly on the surface of the part, the material properties gradually change from the base to the coating.

Titanium and titanium alloy powders are obtained by reducing metal oxides with calcium hydride, a method developed in the 1950s. The choice of calcium hydride as a reducing agent is due to its high reactivity, which allows it to reduce almost all metal and non-metal oxides regardless of their thermodynamic activity. At the same time, no solid solutions or chemical compounds of calcium with the «reduced» metals are formed. The reduced titanium and alloy powders have an irregular shape and a highly developed particle surface, which allows them to be easily compacted at relatively low pressing pressures in rigid molds, as well as by hydrostatic pressing in flexible casings. These powders can be easily rolled into strips and sintered in a vacuum or a neutral atmosphere. Titanium and titanium-based alloy powders are used in the production of corrosion-resistant filters for fine purification of technical liquids in the form of porous rolled sheets. Titanium powders have also found applications in medicine for the manufacture of implants, in the food industry for producing regenerative filters in purification systems for drinking and mineral water, juices, and beverages, in the production of highly reliable pyrotechnic devices, and in non-dispersible porous getters (gas absorbers) with high sorption capacity and absorption rate. Additionally, these powders are used for manufacturing aluminum and other metal composites, watch mechanism components, and acid-resistant equipment. They are also employed for plasma and microplasma coating applications [7].

The first attempts to obtain titanium boride through surfacing or sintering of compressed powder compacts were made by Moissan [15-16] and Wedekind [17]. Titanium boride has gained widespread use in many modern industries due to its numerous technical advantages relevant to different fields. Figure 3 presents the phase diagram of B–Ti composites.

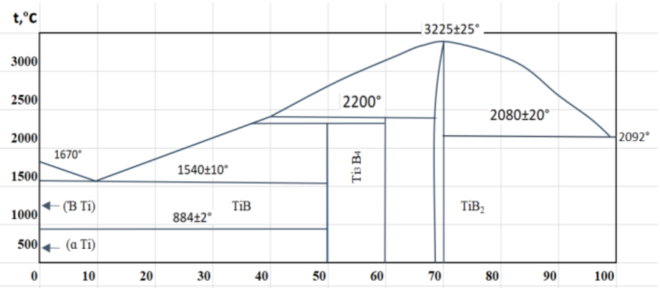


***Figure 3. Phase diagram of B–Ti composites***

In metallurgy and mechanical engineering, titanium diboride is primarily used as a component of powder mixtures for coating and surfacing applications. Additionally, titanium boride powder is utilized in the production of heat-resistant, refractory, and wear-resistant alloys, as well as a base material for high-temperature cutting tools, in cermets for nuclear technology, for manufacturing thermocouple sheathings, and in the tool industry as an abrasive material and a filler in diamond wheels and pastes for processing various materials.

Matrix and reinforcing materials are typically selected based on the following criteria [18]:

– b oth materials should have low density.

– the modulus of elasticity of the reinforcing material should be significantly higher than that of the matrix material (considering the relatively low modulus of elasticity of Ti alloys);

– the matrix and reinforcing materials should have similar coefficients of thermal expansion;

– the materials must be chemically stable relative to each other to prevent the formation of unfavorable regions along the boundaries between the matrix and the reinforcing material.

In our research, the TiB + Ti metal-matrix composite was synthesized using the SHS method.

## 3. Results and discussion

In this study, composite powders were obtained using the self-propagating high-temperature synthesis (SHS) method from powder mixtures of titanium grade TPP-8 with a particle size of 50-100 μm and amorphous technical boron grade «A» with varying titanium binder content (20 vol.%, 30 vol.%, 40 vol.%, 50 vol.%, 60 vol.%). To prepare the powder mixtures, the powders were blended, and their chemical composition, along with the volumetric percentage of each component, is presented in Table 1. Composite powders with 50 vol.% and 60 vol.% metallic matrixes were prepared by mixing in a gravity mixer of the «drunken barrel» type with steel balls for 3-4 hours to achieve a homogeneous structure.

***Table 1. Batching for SHS composites TiB+%Ti (20 vol.% – 60 vol.%)***

| Vol. % Ti | Batching, wt. % | | Theoretical density, g/cm³ |
|---|---|---|---|
| | Ti | B | |
| TiB + 20 vol.% Ti | 84.86 | 15.14 | 3.9675 |
| TiB + 30 vol.% Ti | 86.57 | 13.43 | 4.022 |
| TiB + 40 vol.% Ti | 88.33 | 11.67 | 4.079 |
| TiB + 50 vol.% Ti | 90.14 | 9.86 | 4.141 |
| TiB + 60 vol.% Ti | 91.99 | 8.01 | 4206 |

Samples for synthesis were obtained using the cold double-sided pressing method in a cylindrical mold MS-500 (Figure 4). The pressure was selected to achieve an initial porosity of 40-45%. As a result, the samples had a cylindrical shape with a diameter of 25 mm and a height of up to 10 mm.

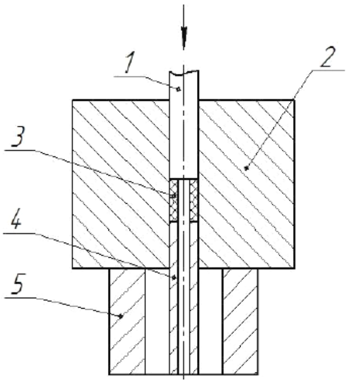


***Figure 4. Diagram of double-sided pressing: 1 - upper punch; 2 - die; 3 - pressed charge; 4 - lower punch; 5 - backing plate***

SHS composite powders were synthesized from pre-pressed tablets without preliminary heating, in an argon atmosphere with an excess pressure of about 0.5 atm, followed by slow cooling in the reactor (Figure 5). To ignite the powder and initiate the combustion wave, a small layer of Ti+Si powder mixture was sprinkled onto the Ti+B tablets.

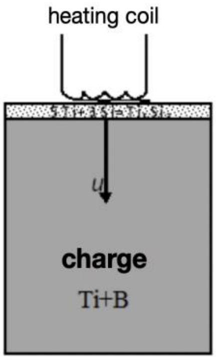
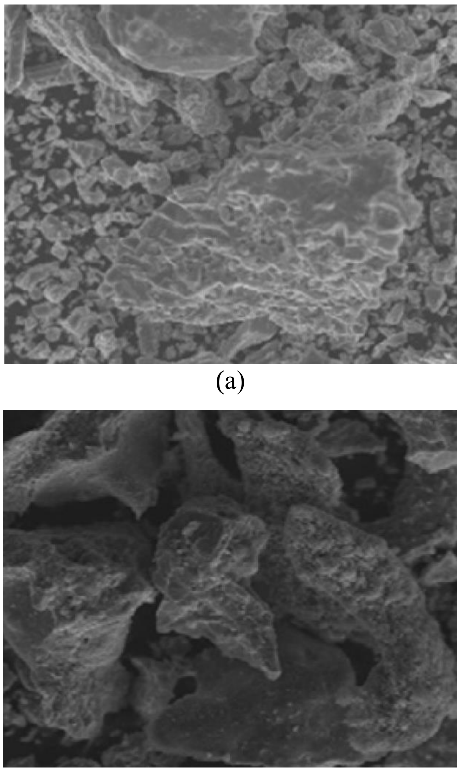


***Figure 5. Implementation of SHS composite powders without preliminary charge preheating***

The obtained porous SHS compacts were crushed, and a sieving process was used to isolate the fraction suitable for surfacing, ranging from 56 to 200 μm. The synthesized powders initially had different metallic binder contents (20 vol.%, 30 vol.%, 40 vol.%, 50 vol.%, 60 vol.%). To achieve high-quality coatings and improve the weldability of the powders during electron beam surfacing (EBS), the SHS powders were diluted with titanium powder up to 80 vol.% Ti. Electron beam coatings made from composite powders of «titanium boride + 20% and 50% titanium» were applied in a vacuum using an EBS setup at the Institute of Solid-State Chemistry and Mechanochemistry of the Siberian Branch of the Russian Academy of Sciences (ISSCM SB RAS). This setup consisted of an electron source, a scanning electron beam control system, a powder feeder, and a manipulator for moving the substrate relative to the scanning electron beam. Composite powders were obtained through layer-by-layer combustion of cylindrical compacts made from powder mixtures of titanium grade TPP-8 and amorphous technical boron grade «A» in an argon atmosphere.

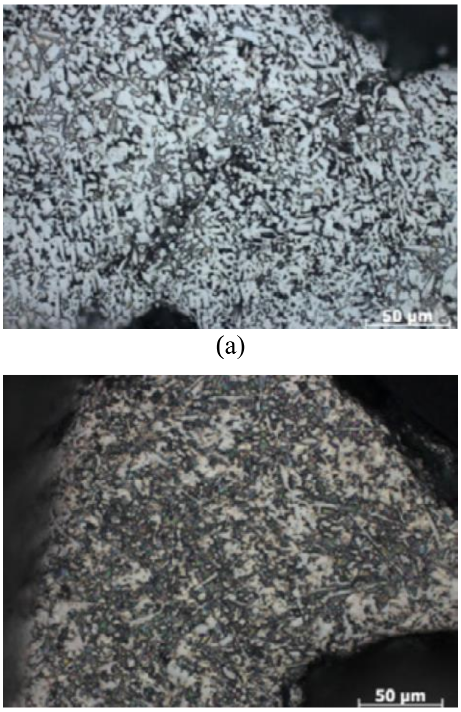
The combustion was initiated by heating an ignition tablet using a molybdenum coil. The synthesis was carried out in a sealed reactor under an argon atmosphere with an excess pressure of approximately 0.5 atm, followed by slow cooling in the reactor. The porous SHS compacts were crushed, and a sieving process was used to isolate the fraction suitable for surfacing, ranging from 56 to 200 μm. The structure and phase composition of the SHS powders and coatings were analyzed using equipment from the «Nanotech» Shared Research Facility at ISSCM SB RAS. The methods included X-ray phase analysis (DRON-7 diffractometer, Burevestnik, Russia, CuKα radiation) and optical metallography (AXIOVERT-200MAT, Zeiss, Germany). After crushing, the SHS composite powder predominantly had a fragmented shape (Figure 6).


(a)

(b)

***Figure 6. Morphology of SHS powder: (a) – TiB + 20% Ti; (b) – TiB + 50% Ti***

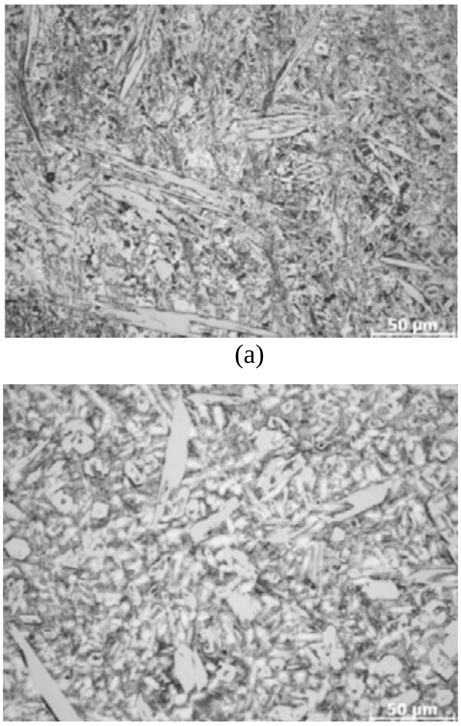
The typical microstructure of the composite powder is shown in Figure 7a. The powder product synthesized with a low titanium binder content (20-40%) consists of titanium boride agglomerates or individual large needle-like structures. The structure of SHS products with a higher titanium content (50-60%) and prior mechanical activation is more dispersed (Figure 7b).



(a)

(b)

***Figure 7. Microstructure of SHS powder: (a) – TiB + 20% Ti; (b) – TiB + 50% Ti***



(a)

(b)

***Figure 8. Microstructure of the surfacing: (a) – TiB + 20 → 80% Ti; (b) – TiB + 50 → 80% Ti***

X-ray phase analysis of SHS powders revealed that in all cases of «titanium-boron» synthesis, a multiphase material was obtained, with titanium monoboride as the primary phase. To improve the weldability, titanium powder was added to the composite powders with different titanium binder contents (20% and 50%) in amounts sufficient to achieve powder mixtures with an integral binder content of 80%. The microstructure of the coatings deposited using powder mixtures containing composite powders of the two studied compositions is shown in Figure 8.

## 4. Conclusions

Composite powders of «titanium monoboride + titanium» were obtained and studied using the self-propagating high-temperature synthesis (SHS) method.

Electron beam coatings deposited using composite powders exhibited hardness and abrasive wear resistance that were 2.2 and 3.7 times higher, respectively, than those of the titanium alloy VT-1-0.

## Author contributions

Conceptualization: A.M., A.U.; Data curation: E.K, G.S., A.U.; Formal analysis: A.M., E.K., G.S.; Funding acquisition: E.K.; Investigation: A.M., E.K.; Methodology: A.M., E.K., A.U.; Project administration: A.M., A.U.; Resources: E.K, G.S.; Software: E.K., A.U.; Supervision: E.K, G.S., A.U.; Validation: G.S., A.U.; Visualization: E.K, G.S., A.U.; Writing – original draft: A.M.; Writing – review & editing: A.M., G.S., A.U. All authors have read and agreed to the published version of the manuscript.

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## Conflicts of interests

The authors declare no conflict of interest.

## Data availability statement

The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

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# Tib+Ti композициялық ұнтақтарына негізделген өздігінен таралатын жоғары температуралы синтезді зерттеу

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**Аңдатпа.** Бұл мақалада Композициялық материалдарды қолдана отырып, машина бөлшектерінің тозуға төзімділігі мен сенімділігін арттырудың заманауи әдістері, әсіресе ұнтақты балқыту және металломатиялық композиттерді синтездеу саласында қарастырылады. Тиімді әдістердің бірі-механикалық және термиялық қасиеттері жақсартылған композициялық жабындарды алуға мүмкіндік беретін өздігінен таралатын жоғары температуралы синтез (ӨТЖТС). Электронды сәулелік қаптау (ЭСҚ) сияқты ұнтақты қаптау әдістері титан негізіндегі тозуға төзімді, ыстыққа төзімді және қатайтатын жабындарды қамтамасыз етеді. Титан және оның қорытпаларының ұнтақтары кальций гидридімен оксидтерді тотықсыздандыру әдісімен алынады, бұл жоғары беріктігі мен жақсы ағындылығы бар аналардың пайда болуына ықпал етеді. Титан боридіне композиттер үшін қатайтатын фаза ретінде ерекше назар аударылады. Бұл технологияларды пайдалану машиналар мен механизмдердің беріктігі мен сенімділігінің едәуір артуына ықпал етеді, бұл ресурстарды үнемдеуге және пайдалану шығындарының төмендеуіне әкеледі. Жүргізілген зерттеулерге алынған ұнтақтар мен жабындардың құрылымдық сипаттамаларын талдау және олардың физикалық және механикалық қасиеттерін анықтау кіреді. Бұл қасиеттердің өзгеруі композициялық ұнтақтағы титан байламының көлемдік құрамына байланысты қарастырылады. Ұнтақтар мен жабындардың микроқұрылымының сипаттамасы, сондай-ақ композицияның олардың сипаттамаларына әсері тозуға төзімділік пен ыстыққа төзімділіктің жоғарылауы сияқты жақсартылған пайдалану сипаттамалары бар функционалды жабындарды жасау үшін осы материалдарды қолдану мүмкіндігі туралы қорытынды жасауға мүмкіндік береді. Зерттеу нәтижелері әртүрлі салаларда пайдалану үшін жақсартылған өнімділігі бар жаңа материалдарды әзірлеу үшін пайдалы болуы мүмкін.

***Негізгі сөздер:*** *композициялық ұнтақ, титан бориді, титан, катодты сәулелік жабындар, ұнтақты қаптау, өздігінен таралатын жоғары температуралы синтез.*

# Исследование самораспространяющегося высокотемпературного синтеза на основе композиционных порошков TiB+Ti

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**Аннотация.** В данной статье рассматриваются современные методы повышения износостойкости и надежности деталей машин с использованием композиционных материалов, особенно в области порошковой наплавки и синтеза металломатричных композитов. Одним из эффективных способов является самораспространяющийся высокотемпературный синтез (СВС), который позволяет получать композиционные покрытия с улучшенными механическими и термическими свойствами. Методы порошковой наплавки, такие как электронно-лучевая наплавка (ЭЛН), обеспечивают создание износостойких, жаропрочных и упрочняющих покрытий на титановом основании. Порошки титана и его сплавов получают методом восстановления оксидов гидридом кальция, что способствует формированию материалов с высокой прочностью и хорошей сыпучестью. Особое внимание уделяется бориду титана как упрочняющей фазе для композитов. Использование данных технологий способствует значительному увеличению долговечности и надежности машин и механизмов, что приводит к экономии ресурсов и снижению эксплуатационных затрат. Проведенные исследования включают анализ структурных характеристик полученных порошков и покрытий, а также определение их физических и механических свойств. Рассматриваются изменения этих свойств в зависимости от объемного содержания титановой связки в композиционном порошке. Описание микроструктуры порошков и покрытия, а также влияние состава на их характеристики, позволяет сделать выводы о возможности применения данных материалов для создания функциональных покрытий с улучшенными эксплуатационными характеристиками, таких как повышенная износостойкость и термостойкость. Результаты исследования могут быть полезны для разработки новых материалов с улучшенными эксплуатационными свойствами для использования в различных отраслях промышленности.

***Ключевые слова:*** *композиционный порошок, борид титана, титан, электронно-лучевые покрытия, порошковая наплавка, самораспространяющийся высокотемпературный синтез.*

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