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Physical Alloying of Plasma Metallization Carbide Nanocomposite Coating by Allotropic Carbon Nanostructures

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Abstract

The fundamental scientific problem for micro- and nano-electronics has been solved—methods for creating and investigating properties of physically doped materials with spatially inhomogeneous structure at the micro- and nano-meter scale have been developed. For the application of functional nanocomposite film coatings based on carbides of various transition metals structured by nanocarbon, for the first time in the world, we developed a new technique for their plasma deposition on a substrate without the use of reaction gases (hydrocarbons such as propane, acetylene, etc.). We have created nanostructured film materials, including those with increased strength and wear resistance, heterogeneous at the nanoscale, physically doped with nanostructures—quantum traps for free electrons. We learned how to simultaneously spray (in a plasma of a stationary magnetron discharge) carbides and graphite from a special mosaic target (carbide + carbon) made mechanically. As a result of such stationary sputtering of carbides and carbon, plasma nanostructured coatings were obtained from nanocarbides, metal nanocrystals and nanocarbon. Our design of such a target made it possible to intensively cool it in the magnetron body and spray its parts (carbide + carbon) simultaneously with a high power density of a constant plasma discharge—in the range of values from 40 W/cm^2 to 125 W/cm^2. Such sputtering with a change in the power or the initial relative surface areas of various parts of the mosaic target (carbon and carbide) made it possible to change the average density of carbide, metal and carbon in a nanostructured (nanocarbon and metal nanostructures) coating. The changed relative density of various components of the nanocomposite (nanostructures of carbide, metal, and carbon in the form of graphite) significantly affected the physical properties of the nanocomposite coating. The creating method of multiphase nanostructured composite coatings (based on carbides of transition metals) with high hardness of 30

GPa, a low coefficient of friction to dry 0.13 - 0.16, with high heat resistance up to 3000˚C and thermal stability in the nanocrystalline state over 1200˚C is developed. It is established that the presence of nanographite in the composite significantly improves the impact strength and extends the range of possible applications, compared with pure carbides. The solution to this problem will allow creating new nanostructured materials, investigating their various physical parameters with high accuracy, designing, manufacturing and operating devices with new technical and functional capabilities, including for the nuclear industry and rocket science.

Keywords

Physical Alloying, Plasma Metal Coating, Coefficient of Dry Friction, Charged Layer

1. Introduction

Nanostructured carbon materials raise interest due to their unique properties. They are tens of times more durable and ductile and have improved luminescent characteristics, etc. [1] [2] [3] [4] [5]. To create modern devices, it is highly important to make use of high-temperature materials based on compounds of transition metals of IV - VI periodic system group with nitrogen, boron, silicon and carbon. There is a special place for carbides with a high melting temperature from 2580˚C for molybdenum semicarbide to 3880˚C for tantalum carbide, up to 31 GPa hardness, wear resistance, corrosion resistance, resistance to molten metals, low vapor pressure and low evaporation rate. In addition, they also possess some specific electrical and thermal properties and can be used as materials in the heating elements of high-temperature furnaces, thermocouples and thermionic device cathodes, etc. Among the new materials, special attention is paid to film materials, which have recently been widely used to modify the working surfaces of machines and mechanisms, significantly increasing the service characteristics of most parts and metalworking tools [1] [5] [6] [7]. Enhanced properties of the surface layers of the parts' material and improved contact conditions of their functioning result in an increase in terms of the machine operation and, accordingly, in huge savings in materials and energy [1]-[7].

At present, in the scientific literature, clear ideas about the mechanisms leading to the appearance of unique properties of such nanostructured physical alloying composites are found only in works [2] [3]. In works [1] [2] [3] [4] [5], the unique properties of nanocomposites based on copper and aluminum, physically doped with carbon nanostructures, are studied in detail. In this work, we experimentally investigate in detail the properties of physically doped materials based on transition metal carbides. We believe that the theory of physical doping of carbides with carbon nanostructures does not differ significantly from the theory of physical alloying of copper nanocomposites, built in [2] [3]. In the study of composites on the basis of transition metal carbides, we confine ourselves to the experimental results and when discussing them we will rely on the theory [2] [3]. Our design of such a target made it possible to intensively cool it in the magnetron body and spray its parts (carbide + carbon) simultaneously with a high power density of a ***constant*** plasma discharge—in the range of values from 40 W/cm^2 to 125 W/cm^2. Such sputtering with a change in the power or relative surface areas of various parts of the target (***carbon and carbide***) made it possible to change the average density of carbide, metal, and carbon in a nanostructured (nanocarbon and metal nanostructures) coating. The changed relative density of various components of the nanocomposite (nanostructures of carbide, metal, and carbon in the form of graphite) significantly affected the physical properties of the nanocomposite coating. We have proposed the new method for creating multiphase nanostructured composite plasma film coatings (based on transition metal carbides) with high hardness of 30 GPa, a low friction coefficient to dry of 0.13 - 0.16, with high heat resistance up to 3000˚C and thermal stability in the nanocrystalline state for more than 1200˚C designed. For the first time we will consider the experimental results study of the physical alloying of transition metal carbides as a result of joint magnetron sputtering of transition metal carbides and graphite. On the basis work [1] [2], we will reveal the synergetic effect essence of negatively charged traps for electrons on the modification of the physically alloying crystals properties as a function of the dopant concentration.

2. Theoretical Substantiation of the Carbide Physical Alloying by Allotropic Carbon Nanostructures

In [2] [3], we have analytically investigated a possibility of hardening and modifying properties of plasma metallization composite coating (nanocomposite materials) by creating spatial nanolayers of space charge on the nanocrystals surface by using nanostructures made of carbon allotropic forms with a high electron affinity (**Figure 1**). The carbon structures have a great electron affinity. Fullerenes, nanotubes, and other nano-structures of the allotropic carbon forms with a high electron affinity can be used as free electrons traps that generate a negative charged nanolayer on the surface of the hardened material. These nanostructures (modifiers) attach or capture free electrons and thus charge the crystals of the modifiable material with positive charge (**Figure 1**). This results in a Coulomb levitation of the positively charged nanocrystals with respect to each other and prevents recrystallization of the physically doped positively charged nanocrystals in the composite [1] [2] [3]. The Coulomb forces are determined at the level of nanoscale, they are long-range. Therefore, the formation of nanoclusters or nanostructures capable of capturing electrons with resonant energy (traps for free electrons) can substantially modify the macro properties of nanocomposites. These phenomena are associated with the quantum-size effects of polarization capture of electrons by carbon nanostructures [2] [3] (**Figure 1**).

With such alloying, the properties of the surface of spatially charged nanocrystals also change. This effect (physical alloying of nanostructured materials [2] [3]) may result in the development and production of new materials for various industries.

In [1] [2], we found that the nanoscale core-shell type coating consisting of copper and carbon phases is formed on the substrate surface. The coating crystallinity varies depending on the C concentration. Depending on the percentage of Cu and C on the substrate, different nanophases are formed, and the composite significantly changes its physical properties [1] [2]. Such alloying without chemical reactions between the components can be called as physical alloying (doping) [3]. The nanostructures of the C-allotropic forms have a great electron affinity and act as traps for free electrons (**Figure 1**). In this paper, the MeC_{1+x} composite coatings (based on transition metal carbides) have been experimentally and theoretically studied, according to the method [1] [2].

The environment of nanocrystals of the main material by nanostructures from allotropic forms of carbon is applied for drawing free electrons of physically doped material into traps for electrons. Positively charged crystallites of the base material are not recrystallized and this ensures the continued functioning of nanostructured by physical alloying of materials. This is applied not only to materials obtained as a result of magnetron sputtering, but also as a result of the compacting of mixtures and other methods of creating nanocomposites with physically doping impurities playing the role of traps for electrons previously located in nanocrystals of the main material.

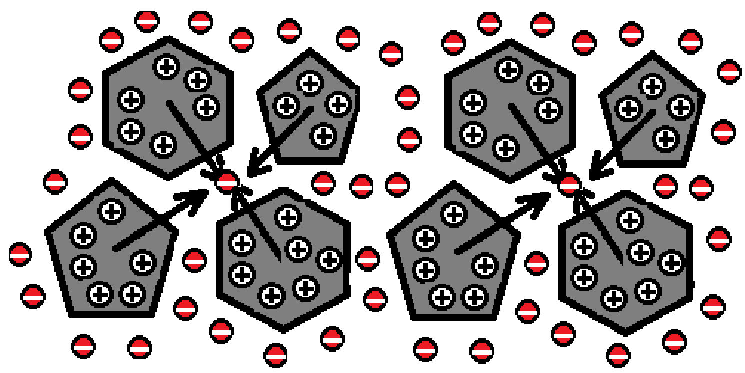

Figure 1. The scheme of physical doping of nanocomposites (gray nanocrystals with "+") by carbon nanostructures (circles with "−"). Carbon nanostructures have an affinity for free electrons and are charged with a negative charge. The arrows indicate the direction of the Coulomb forces that compress the nanostructured polarized composite. Circles with the minus sign inside are the nanostructures with the captured electron. Circles with the positive sign inside correspond to a positive ion in the positive nanocrystal. Hexagons—MeC (nanostructures of carbide metal—Me). Pentagons—Me (nanostructures of metal). All positively charged nanostructures upon deposition on the surface lie on negatively charged nanostructures with a high affinity for electrons. This leads to a necessarily directed effect—Coulomb hardening (compression) of the entire nanocomposite.

3. Experimental Technique

The coatings were produced by the method of high-speed ion-plasma magnetron sputtering (HIPMS) using composite mosaic targets (MT) [1]. It has been shown that the HIPMS method allows efficiently spraying such diverse materials as copper, other metals, carbides and carbon in a predetermined proportion at the same steady speed. To deposit the carbide coatings, a vacuum industrial unit VU-VSM 600/4 (MES60) was used, including: an ion source for surface activation of the sputtered samples, heater to a temperature of 450˚C - 500˚C; magnetrons for HIPMS with ***mosaic*** targets, a planetary carousel with sample substrates. The coating process scheme consisted of the following main operations: the sample surface activation by Ar ion bombardment, heating the sample surface to a temperature of 450˚C - 500˚C, coating deposition with a given thickness on a specific HIPMS mode, cooling, and testing the thickness of the coating layer by a "ball-crater" method using a BC-2 device by Teer Coating Ltd. (TCL). The mechanical properties of the obtained coatings were studied with the methods and devices listed below.

- The coating adhesion to the substrate (qualitative assessment) was carried out by the deep indentation technique (a diamond pyramid indenter) on a Vickers hardness tester of HVS-50 type at a 5 - 8 kg (50 - 80 N) load on the indenter, and by a sclerometry method (scribing or scratching) with a Scratch Testing ST-300 tool by Teer Co Ltd, UK, at loads in the range of 0.1 - 20 kg (1 - 200 N). The sample type for this technique was a plain washer of 15 - 20 mm in diameter, up to 5 mm thick, and the 15 × 20 × 1.5 mm stainless steel plates with a polished surface (like a metallographic specimen).
- The coating microhardness was studied by metallography. For measurements, a HVS-1000 microhardness tester was used. The samples for microhardness measurements were similar to the samples for adhesion measurements.
- The wear resistance and tribological characteristics of composite coating were determined using a specialized device—a PIN ON DISC TESTER type tribo-tester of TEER-POD-2 brand, by Teer Co Ltd., England.
- To study the Raman scattering (RS) spectra, we used a unit with a microscope device on the basis of a TRIAX 552 (Jobin Yvon) microscopic spectrometer and a detector CCD Spec-10, 2KBUV (2048 × 512) (as in [1]). The exciting laser Raman power did not exceed 1 mW.
- The coating ultimate (elemental) composition, its surface and fracture structure were studied by the field emission scanning electron microscope (SEM) LEO 1430 with a SAPHIRE add-on device for energy-dispersive spectroscopy by Sambridge Instruments Ltd., England.
- The phase composition of coatings was analyzed by a Rigaku D/max-RC and DRON-ZM X-ray diffractometer (as in [1]).

4. Experimental Results and Their Discussion

We created physically doped nanocrystalline carbide films by simultaneously sputtering ***graphite*** and ***carbide*** from a ***mosaic*** target in a ***stationary*** discharge (by the method of HIPMS). Physical doping of nanocomposites consists in the application of nanostructures with a high affinity for free electrons. All carbon nanostructures have such properties to capture and hold electrons for a long time [1] [8] [9]. All positively charged nanostructures upon deposition on the surface lie on negatively charged nanostructures with a high affinity for electrons. This leads to a necessarily directed effect—Coulomb hardening (compression) of the entire nanocomposite (**Figure 1**).

Nanocomposites of transition metal carbide nanocrystals were created by physical alloying with carbon nanostructures and their properties were investigated. These high-temperature nanostructured materials based on chemical compounds of transition metals of groups IV - VI of the Periodic Table of Elements with carbon are of interest both from the point of view of basic science and for the creation of modern 4+ and 5th generation technology. Among these compounds, as studies have shown, a special place is occupied by carbides having a high melting point from 2580˚C—molybdenum hemocarbide and up to 3880˚C—tantalum carbide, hardness up to 30 GPa, wear resistance, corrosion resistance, resistance to molten metals, low vapor pressure and low evaporation rate. Nanostructured composites have a set of properties important for many micro and nanoelectronics tasks: high melting point, high hardness, wear resistance, corrosion resistance, resistance to molten metals, low vapor pressure and low evaporation rate, weak recrystallization of nanostructures. These properties determine the high efficiency of application of nanostructured structures from allotropic forms of carbon composites, and therefore, determine the scientific and applied significance of our proposed method of physical doping of nanocomposites. We have developed a method for obtaining and controlling the properties of nanostructured composite multiphase coatings (based on transition metal carbides) with high microhardness up to 30 GPa, low dry friction coefficient up to 0.13 - 0.16, with high heat resistance up to 3000˚C and thermal stability in nanocrystalline condition more than 1200˚C. The nanocrystalline structure and the properties of carbide composite multiphase coatings were controlled by varying the concentration of free carbon in them with the formation of the amorphous nanographite phase in the material. It is established that the presence of nanographite in the composite significantly increases the impact strength and expands the range of possible applications compared to pure carbides.

We combined the experimental results in **Table 1**.

Management nanocrystalline structure and properties of carbide composite multiphase coatings is performed by varying the concentration of free carbon—C(fr.) in them to form in the material of the amorphous phase nanographite.

For monocrystalline graphite, a line in the 1580 cm^{-1} is characteristic, associated with vibrations of carbon atoms (E2g) in the six-membered cycles in the graphite plane—the G-line. When there are some structural defects in the crystal lattice of graphite, a line starts to appear (A1g) in 1355 cm^{-1}—a D-line [10], forbidden for a defect-free graphite crystal by the selection rules. The presence of the D-line is characteristic of polycrystalline graphite, all forms of amorphous graphite, and nanocrystalline graphite films [10].

With increasing graphite content in the nanocomposite, the intensity of the lines 1350 and 1580 cm^{-1} grows, indicating an increase in the proportion of amorphous carbon in them (**Figure 2**). The X-ray diffraction analysis confirms this as well. Details on the results of experiments can be found in [11].

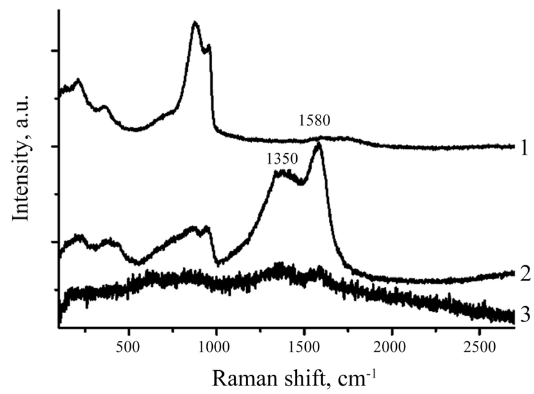

Figure 2. Raman spectrum of samples of deposited composite coatings excited by a laser with a wavelength of 514 nm: 1—Mo-C (70:30) Substrate material - stainless steel; 2—Mo-C (30:70). The substrate material is copper. 3—Cr-Mo-C (80%:10%:10%). The substrate material is copper.

Table 1. Composition and properties of nanocomposite coatings of metal carbides physically doped by carbon nanostructures.

№	Cathode composition, Me: C, ratio % per area	Coating phase composition, (X-ray)-wt%	Lattice type, parameters, nm	Crystal block size, nm	Microhar-Dness, GPa
1	70Mo ÷ 30C	Mo_2C-67; Mo-33; closer to the high temperature phase $-\beta Mo_2C$	Hexagonal $a = 0.301$ $c = 0.474$	Texture, 2.2 - 5.0	13.00 - 30.00
2	50Mo ÷ 50C	MoC – 95 ÷ 100; C(free) – 5 ÷ 0	FCC α-MoC $a = 0.427$	6.0 - 8.0	18.00 - 31.00
3	70Nb ÷ 30C	Nb_2C	Hexagonal $a = 0.3115$, $c = 0.4948$	Texture, 1.0 - 3.0	23.00 - 29.00
4	50Nb ÷ 50C	$NbC_{0.95-1.0}$	FCK A = 0.443	Texture, 2.2 - 5.0	18.90 - 23.00
5	50V ÷ 50C	$VC_{0.85-0.88}$	FCC $a = 0.4188$	1.5 - 5.0	13.00 - 26.00
6	50Zr ÷ 50C	$ZrC_{0.5-0.6}$ – 76.5 ± 0.4	Cubic B1-type 0.4683	5.0 - 6.0	18.50 - 30.00
7	80Zr ÷ 20C	$ZrC_{0.9-0.95}$ – 96.5 ± 0.4; Zr – 23.5 ± 0.4	Cubic B1-type 0.4683	Texture, 0 - 18	10.00 - 21.00
8	50Ta ÷ 50C	$TaC_{0.97-1.0}$ – 97.6 ± 0.4; C – 3.4 ± 0.4	FCC $a = 0.444$	6.0 - 8.0	15.30 - 27.00

Figures 3-6 show the structures of carbides, Scanning Electron Microscopy-SEM.

Due to the lack of carbon (Mo-70; C-30) and the presence of free metallic molybdenum (unreacted with carbon) in the coating, a two-phase nanocomposite is formed. It consists of a mesh-frame of brittle molybdenum carbide and a plastic metallic phase of molybdenum, enclosed in the form of nanograins in this frame. Also see Figure 4, the same as Figure 3 only at higher magnification.

A material with this structure has high strength and elasticity. The elastic properties of such a coating can significantly increase the wear resistance of the rubbing surface of the part under loads, including mechanical shock and sudden temperature changes. Stoichiometric carbides do not have these properties. They are hard and brittle and sensitive to alternating loads. The structure of such a carbide coating is shown in Figure 5.

The coverage in Figure 5 is brittle and has a fracture close to glassy, which allows us to make an assumption about the amorphous structure of this coating. A more brittle carbide coating with an excess of free carbon is shown in Figure 6. In a fracture, this coating is practically structureless and can be attributed to a material with an amorphous structure.

As seen from Figures 3-6, the nanocomposite coating material is uniform at the nanoscale. This leads to the separation of charges when used for physical alloying of nanostructures with a high affinity for electrons at the nanoscale and to the necessarily directional effect—Coulomb hardening (compression) of the entire nanocomposite (Figure 1). In such a nanocomposite coating, quantum-size effects of various nature are observed, associated with the formation of space charges and the generation of high-intensity internal electric fields (up to 10^{11} V/m) [1] [2] [3] [8] [11].

The technological process used in this work is a breakthrough. *First*, in it, using the VIPMR technique, it is possible to spray any materials from one target, setting their concentration by a simple ratio of the areas in the zone of maximum target erosion. *Secondly*, any physical alloying carbides (Figure 1) can be obtained by a simple joint sputtering of metal and graphite without feeding explosive gases into the working volume of the chamber. They are simply not needed in this process. *Third*, by controlling the sputtering mode (plasma discharge power density), it is possible to change the structure and phase composition (free amorphized graphite content) in a wide range and thereby control the properties of the most important performance characteristics of composite coatings based on carbides (hardness, wear resistance, friction coefficient, etc.).

In this work, the fundamentals of a strong bond formation mechanism between physically doped crystals of transition metal carbides and carbon nanostructures are investigated (Figure 1). The choice of optimal compositions and coating composition for elements of nanoelectronics and optoelectronics are made. The method of physical doping, developed by the authors, has no world analogues and can be used to solve problems of nanoelectronics and optoelectronics.

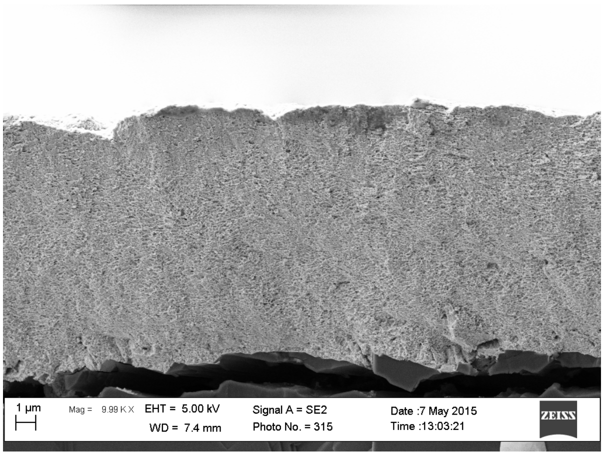

Figure 3. A typical microstructure of a 10 - 12 μm thick coating made of molybdenum and molybdenum carbide (Mo 70% at.: C 30% at.) is presented. A substrate—alumina ceramic, fracture, SEM.

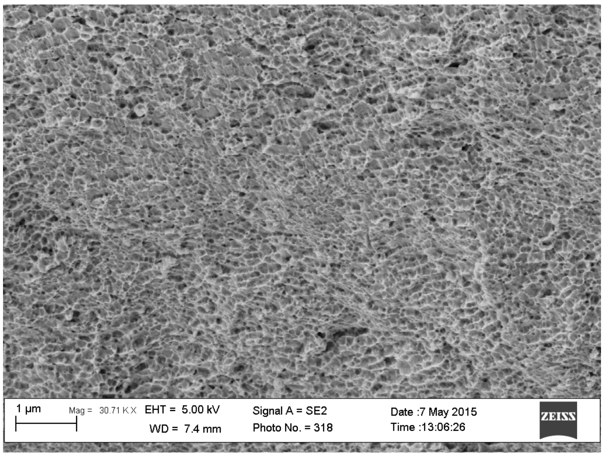

Figure 4. A typical microstructure of a molybdenum carbide coating with an excess of metallic molybdenum at an increase in ×3 compared to **Figure 1** is presented.

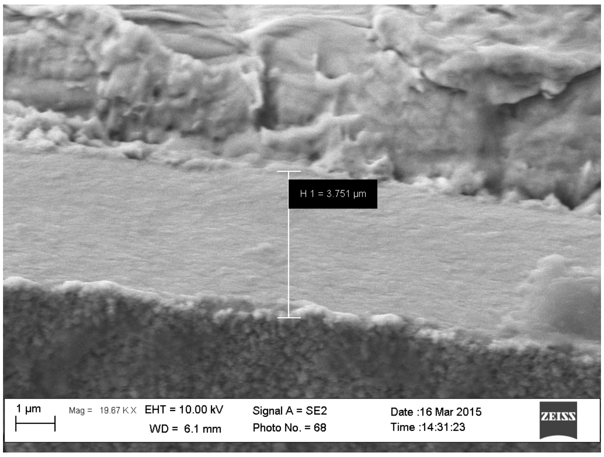

Figure 5. The microstructure of a coating layer with a thickness of 3.7 μm made of tantalum carbide of stoichiometric composition (Ta 50 at%: C 50 at%), a copper substrate, fracture, SEM is presented.

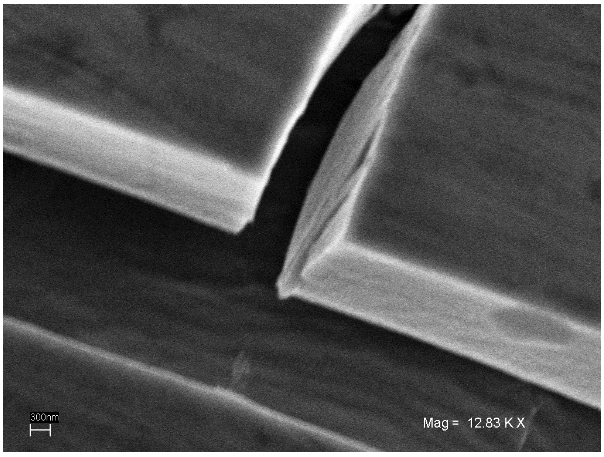

Figure 6. The microstructure of the iron carbide coating layer is presented. Fe 15% at: C 85% at with an excess of free carbon.

In its pure form, carbides have an increased brittleness. To increase their plastic properties, the metal phase is introduced into the composition of carbides and the grain is ground, then they are sintered. In this process, the formation of charged layers does not occur.

In order to preserve fine-grained carbides, we used an original method of physical doping of carbide nanocrystals with carbon nanostructures, which are traps for free electrons, for long-term operation of devices based on them. Structures made of carbon, polarized, pull over a portion of the free electrons of the composite. They themselves are charged negatively, and the nano-crystals of carbides that donated free electrons are charged with a positive charge (**Figure 1**). For this reason, positively charged carbide nanocrystals do not recrystallize with time. It is proposed to create physically alloyed materials using a high-speed ion-plasma magnetron sputtering (VIPMR) technology [1]. This method has a wide range of technological capabilities, both in terms of applying different materials on one equipment, as well as the complex use of various methods for activating substrates. The method allows, under certain conditions (changing the power density of a plasma discharge in the range of values from 40 to 125 W/cm^2), the joint spraying of ***mosaic*** targets with different compositions of materials, for example, metal-graphite; graphite-metal-carbide; carbide metal; carbide metal-graphite and in a wide range to vary equally the composition (the ratio of the areas occupied by the metal, carbide and graphite) and the dispersion of the crystal structure, the change in the discharge power. The carbide coating rates using this ***stationary discharge*** method at such sputtering power densities of materials (metal and graphite) are 0.1 to 0.7 μm/min, which is almost an order of magnitude more than with conventional magnetron sputtering (MRSPVD) and vacuum arc spraying (ARC-PVD). If using gases, the formation of carbides occurs directly on the target and then the molecular transfer of carbides takes place via sputtering onto the substrate. In HIPMS case, we can get not only carbides, but also other phases, including nanocarbon and metal nanostructures

(**Figure 1**). This idea is confirmed by the properties and features of the processes of applying a composite coating of metal-carbon, where the metal does not interact metallurgically with carbon. In this case, the coating has a two-phase composition consisting of metal nanostructures and a nanographite phase [1].

The theory of quantum-size effects, developed by us in [3] and tested in [1] [2] [5] [6], including these experiments, successfully works for physically doped carbides (**Figure 1**). Thus, in [1], during physical doping of copper and in [8] [9] aluminum, hardening of materials in 10 times, to 10 GPa was obtained, and in the case of carbides in this work, we obtained up to 31 GPa. According to the theory [3], hardening of nanocomposites is possible during physical doping with fullerene layers up to 100 GPa. Our research is of interest to the nuclear industry and rocket production, where high-temperature composites are needed [12].

We have created nanostructured materials, including materials with increased strength and wear resistance, heterogeneous at the nanoscale, physically doped with nanostructures—quantum traps for free electrons. The solution to this problem will create new nanostructured materials, investigate their various physical parameters with high accuracy, design, manufacture and operate devices with new technical and functional capabilities, including for the nuclear industry and rocket science. It has been established that the presence of nanographite in the composite significantly improves the toughness and expands the range of possible applications compared to pure carbides.

5. Major Technological Achievements

The comprehensive study results analysis of the phase composition, structure, mechanical and electrical properties of multiphase nanostructured composites based on metal carbides, obtained by magnetron sputtering from a composite (mosaic) target in a high-speed mode and a ***stationary discharge*** power density level > 40 W/cm^2, shows the following.

1) Composite coatings based on transition metal carbides with nanostructures (physically doped with carbon nanostructures) can be obtained by the joint sputtering of metal and graphite from a mosaic target.

2) A high-speed sputtering mode in the discharge power density range from 37 W/cm^2 to 125 W/cm^2 allows to vary the phase composition, nanostructure of the composite and its properties, including the mechanical ones: hardness, wear resistance and dry friction coefficient.

3) A high-speed sputtering mode significantly influences the steam dynamic generation and the condensate formation, generating several nanoscale phases: a carbide-based nanophase, a metal-based nanophase and a graphite nanophase. The latter is present in all compositions.

4) Free carbon in the form of nanographite has a significant impact on the composite properties: reduces friction, increases wear resistance, improves thermal stability, raises strength at high temperatures, facilitates production of a material with an ultrafine nanocrystalline carbide and metal structure.

5) The process of metal and graphite co-sputtering is a much simpler, more technological and environmentally friendly process compared to the metal sputtering in the reaction gas atmosphere: acetylene, methane, propane, etc.

6. Conclusions

The fundamental scientific problem for micro- and nano-electronics has been solved—methods for creating and investigating properties of physically doped materials with spatially inhomogeneous structure at the micro- and nano-meter scale have been developed. For the application of functional nanocomposite film coatings based on carbides of various transition metals structured by nanocarbon, for the first time in the world we developed a new technique for their plasma deposition on a substrate without the use of reaction gases (hydrocarbons such as propane, acetylene, etc.). We have created nanostructured film materials, including those with increased strength and wear resistance, heterogeneous at the nanoscale, physically doped with nanostructures—quantum traps for free electrons. We learned how to simultaneously spray (in a plasma of a stationary magnetron discharge) carbides and graphite from a special mosaic target (carbide + carbon) made mechanically.

We have developed a new technological process for the physical doping of nanostructured composite materials, which is a breakthrough and “green” (eco-friendly). First, in it, using the technique of HIPMS, you can spray any materials from one target, setting their concentration by a simple ratio of areas in the zone of maximum target erosion. Secondly, any carbides can be obtained by a simple joint sputtering of metal and graphite without feeding explosive gases into the working volume of the chamber. They are simply not needed in this process. Thirdly, by controlling the spraying mode, we can change the structure and phase composition in a wide range and control the properties, such as hardness, wear resistance and friction coefficient, the most important performance characteristics of composite coatings based on carbides. When using the HIPMS technology, explosive gases and their mixtures with hydrogen will not be used to apply carbide and other carbon-containing composites, unlike other technologies used in the research and production of coatings.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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