PROPERTIES OF COMPOSITE VACUUM-ARC COATINGS OF THE TiN-Ti/TiON STRUCTURE

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Complex investigation of composite coatings with the structure TiN-Ti/TiON is performed in work. It was identified that morphology of the surface of the multilayer coating TiN-Ti provides high adhesion between it and next layer of titanium nitride oxide; three phases in the samples covered with TiN-Ti/TiON and TiON is revealed TiN with the cubic grating of NaCl type, α-Ti and amorphous titanium oxide TiO_2; at titanium layer thickness in multilayer system TiN/Ti less than 100 nm sufficiently high mechanical properties are obtained (hardness more than 25 GPa at a plasticity index $H/E^* = 0.11…0.12$) that at known increase of crack resistance of such coatings make them promising for conditions of high alternating loads; after application of titanium oxynitride of ~ 1 μm thickness on the multilayer coating TiN/Ti of 6 μm (titanium layers – 30 nm, layers TiN – 300 nm) the hardness of the composite coating increases and reachs 27…28 GPa; the first cracks in scrubbing in the coating appear at the load 3.86 N the coefficient of friction does not exceed 0.1; the TiN-Ti/TiON coating has a significantly higher wear resistance than the TiN-Ti coating and in an order greater than the 12X18H9T steel; TiN-Ti/TiON coated samples have high corrosion resistance in a 2% NaCl solution, due to the very low rate of their corrosion, that is a consequence of the structure of the TiN-Ti multilayer coating that has no columnar structure.

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INTRODUCTION

In many cases increasing of various purposes products functional characteristics is achieved by coating of their surfaces. One of the most promising methods of coating is vacuum arc welding, that provides the formation of a wide range of coatings (pure metals, oxides, nitrides, carbonitrides, etc.) with high adhesion, anticorrosion, wear-resistant and other properties.

The titanium nitride (TiN) coating was one of the first that was widely used in engineering to increase the cutting tool lifetime and in medicine for protective and decorative coatings (gold color) on dental implants. Coatings applied for medical parts that are in contact with the human body tissues (various implants), in addition to high mechanical characteristics, should have special properties – biological indifference, low destruction *in vivo*, good ”implantability” with body, and in case of contact with blood (stents, heart valve, etc.) – have antithrombogenic properties. A complex of such properties is typical for titanium oxynitride TiON coatings [1, 2]. However, TiON coatings are more fragile than titanium nitrides and therefore they are not applied independently to increase products wear resistance. For the same reason, they can be applied in the form of layers with a thickness of not more than one micron.

In medical products (implants) it seems promising to apply composite coatings, the upper thin layer is made of biologically indifferent titanium oxynitride and the lower layers provide it with high elasticity. The development and investigation of such coatings properties is timely and relevant.

1. LITERATURE OVERWIEV AND TASK STATEMENT

Basically, only polycrystalline coatings of stoichiometric and non-stoichiometric compositions that can be applied as wear-resistant, anticorrosive, biologically indifferent and others as protective coatings based on titanium.

Applied for this monolayer TiN coatings usually have hardness of 24...28 GPa and internal compressive stresses about 2...4 GPa [3]. These stresses create tensile stresses in the substrate that reduces its fatigue strength.

The coatings resistance increase occurs during the transition from single-layer coatings to multilayer coatings. So, to reduce the coating softening effect on substrate (i. e., to reduce the compressive stresses in the coating) and to increase the coated products fatigue strength, multilayer structures of TiN-Ti are used [4]. In particular, the deposition of TiN-Ti coatings on the piston rings of an internal combustion engine three times increased their lifetime comparing to the uncoated rings and 1.7 times comparing to the rings covered with galvanic chromium. At the same time, wear of cylinders was decreased by 30% [5]. Such multilayer structures also increase the coating corrosion resistance, as it hinders the growth of end-to-end columnar grains that facilitate the generation of through pores.

In [6], TiN-Ti structure formation was provided by varying the nitrogen pressure in the vacuum chamber. Deposition of titanium layers is performed at a residual gas pressure $p = 2 \cdot 10^{-5}$ mm of mercury and TiN layers at a nitrogen pressure $p = 5 \cdot 10^{-3}$ mm of mercury at a deposition rate of ~ 1 nm/s. The obtained multilayer coatings with a thickness of the titanium layer in the TiN/Ti system less than 125 nm retain rather high mechanical properties (hardness 34...36 GPa under the modulus of elasticity 413...434 GPa), that at known growth of the crack resistance makes such coatings promising for application at high alternating load.

Formation of the layered structure of the TiN coating in [7] was provided by varying the density of titanium plasma flow during the deposition process due to variation of arc current. In this case, change in the titanium plasma density flow during the deposition process makes it possible to vary the coatings microstructure in depth, that has a significant effect on the titanium nitride resulting layers hardness. Unfortunately in [7] coatings elastic properties have not been studied but it can be assumed that they are lower than for the TiN/Ti system.

The titanium oxynitride coating is performed by different methods. Most often these coatings are obtained by the magnetron method [2, 8, 9]. Mechanical properties of titanium oxynitride coatings produced by the method of reactive magnetron sputtering (microhardness, modulus of elasticity, friction coefficient, elastic reduction coefficient) were investigated in [8]. It is also shown here that by varying the deposition regimes during the titanium oxynitride coatings deposition their mechanical properties can be changed. The oxynitride films [8] have ability to restore their shape after removing the mechanical load due to the combination of high hardness and elastic recovery in them, which makes it possible to judge the uniqueness of these coatings as a hard and at the same time resilient material that is an important factor for medical materials, operating under load. Unfortunately, the oxynitride coatings corrosion resistance in [8] has not been investigated.

The elasticity modulus obtained for the oxynitride films produced by the magnetron sputtering method in [9] are close to the data of [8]. The results of the investigations carried out by the authors [9] allowed them to predict the possibility of oxynitride films application as coatings for stents.

The tests carried out in [10] showed that nitrooxidized parts have the less number of corrosion foci in comparison with other processing methods. Anod current density of nitrooxidized samples obtained after nitriding with preliminary oxidation and subsequent steam oxidation in water vapor, depending on the regimes of treatment, is 1.5…5 orders lower in comparison with samples without such a film.

A investigation of the zirconium oxynitride coatings mechanical characteristics precipitated by magnetron sputtering was performed in [11]. Obtained results demonstrate that the mechanical parameters increase in the case of oxynitride coatings in comparison with nitrides and oxides.

The establishment of structure formation patterns and the investigation of nanostructured coatings morphological features obtained by the vacuum-arc method was performed in [12]. Ti-Zr-ON, Ti-Al-ON, and other coatings based on complex titanium nitrides have been investigated. As a result, coating with stable properties technology have been developed and tested, that provides the increasing of tool lifetime by 2...10 times and reducing the corrosion rate up to 10 times.

The analysis showed that multilayer film systems of the TiN-Ti type are characterized by high hardness along with the ability to work under dynamic loads. Such an important feature allows their application in transplantology. On the other hand, titanium oxynitride based coatings has no less mechanical characteristics are more indifferent to the tissues of the human body. Search for special materials with increased physical and mechanical properties and simultaneously with high biological compatibility requires the development of new technologies and methods of production with simultaneous investigation of the obtained coatings properties.

It seems to be promising to combine the properties under alternating loads with high biocompatibility in one composite TiN-Ti/TiON structure coating. Formation of the proposed structure is possible with the vacuum arc technology, as it provide one of the highest adhesion coatings to the substrate (the first requirements for coatings on transplants). In this case, the production of composite coating is one cycle and by varying the deposition process technological parameters it is possible to vary in a wide range the obtained coatings properties (their microhardness, modulus of elasticity, etc.). The purpose of this work is to investigate the surface morphology, structure, hardness, adhesion and other properties of the TiN-Ti/TiON structure composite coating.

2. METHODOLOGY AND EQUIPMENT FOR TiN-Ti/TiON COMPOSITE COATINGS PRODUCTION AND PROPERTIES INVESTIGATION

Coatings were deposited on the facility “Bulat-6” with titanium as evaporating material. The substrates were located 250 mm away from the evaporator. The polished substrates made of stainless steel with dimensions 20x20x3 mm and copper foil of 0.2 mm thickness. They were previously washed in the alkaline solution in ultrasonic bath and then with C2-80/120 solvent. Deposition of titanium layers was performed at residual gas pressure $p = 2{\cdot}10^{-5}$ mm of mercury and TiN layers at a nitrogen pressure of $5{\cdot}10^{-3}$ mm of mercury. The coating deposition rate was ~ 1 nm/s. The number of layers at different thicknesses was chosen so that the total thickness of the coating was about 6 µm. During coating the value of the negative potential U_F on the substrate was varied: from the “floating” potential (-3...-15 V) to a constant value of U_F = -40, -70, 200 V with an arc current 85…90 A.

Theoretical analysis and experimental data obtained earlier in [13] were used for the production of multilayer Ti-TiN coatings. Thickness of the Ti layer in the resulting coatings was within 30...50 nm and the TiN layer was -300 nm.

Without interrupting the process TiON layer was deposited after the formation of a multilayer TiN-Ti system with a total thickness of 6 µm. For this purpose gas mixture of nitrogen and oxygen with a component ratio 1:1 was supplied to the vacuum chamber. The mixture was preliminarily prepared with the help of gas mixture generator operating on a cyclic method for feeding gases portions into the mixing chamber [14]. The finishing layer thickness of was ~ 1 µm.

Surface morphology as well as coatings microfractography subjected to bending failure were examined with a JEOL JSM-840 scanning electron microscope.

Phase composition and structural state was investigated by X-ray diffraction method on a DRON-3M diffractometer in Cu-Kα radiation using a graphite monochromator in a secondary beam. For phase analysis the diffraction spectrum was registered according to scheme θ-2θ due to Bragu-Brentano over a range of angles from 25 to 90 deg in point-by-point mode with scanning step

$\Delta (2\theta) = 0.05...0.2$ deg and the accumulation duration of pulses at each point of 20...40 s (depending on the width and diffraction maximum intensity). To decode the diffractograms the JCPDS diffraction data base was used.

Investigation of adhesive strength, scratch resistance and determination of the coating destruction mechanism was performed with REVETEST scratch-tester (CSM Instruments). Surface scratches were performed by diamond spherical indenter "Rockwell S" type with a curvature radius of 200 μm at continuously increasing load, during this next physical parameters were recorded: acoustic emission, friction coefficient and indenter penetration depth.

TiN-Ti and TiN-Ti/TiON coatings wear resistance tests were performed according to the plane-cylinear scheme on a friction machine at a slip speed of 1.3 m/s, dry, without lubrication at 0.1 N load for 1 hour, after which the volume of lost material and the specific wear were calculated.

Nanoindentation was performed with the "MICRON-GAMMA" indenter with a Berkovich pyramid at 50 N load with automatic loading and unloading for 30 s, as well as recording of loading and unloading diagrams in the coordinates $F(h)$ (F – load value, h – indenter displacement). Characteristics F, h_{max}, h_p, h_c, and others were determined and calculated automatically according to ISO 14577-1:2002.

The obtained coatings electrochemical corrosion kinetics was investigated by the potentiodynamic method. Tests of the samples were performed in 2% aqueous NaCl solution at $T = 18$ °C. Corrosion rate, corrosion potentials, currents and Taffel coefficients of experimental samples and coatings were determined during corrosion investigation. All potentials are presented relative to the saturated calomel reference electrode. During investigations samples surface scanning was performed that allows predicting the material overall corrosion properties and its resistance to external influences in an aggressive environment.

3. RESULTS OF THE TiN-Ti/TiON COMPOSITE COATINGS PROPERTIES INVESTIGATION AND DISCUSSION

3.1. SURFACE MORPHOLOGY

First of all the morphology of the TiN-Ti multilayer coating surface was investigated. Knowledge of its characteristics is necessary, since the upper layer of titanium oxanitride is deposited to it. The TiN-Ti coating surface morphology, deposited at a constant substrate potential of -200 V and nitrogen pressure of 0.54 Pa (for the production of TiN) is shown in Fig. 1. The surface of the coating is cellular with a cell size of 0.2...4 μm, there are macroparticles (droplets) with dimensions of about 0.1...3 μm.

A possible reason of cells is the nonuniform surface sputtering of a growing coating by ions from a gas-metal plasma accelerated by the negative potential of the substrate during the coating deposition [15]. Such a developed surface of the TiN-Ti layer promotes its well adhesion with the subsequent TiON layer.

The study of the morphology of the TiON coating surface that contacts the human body tissues is important, since it determines the adhesion of biological cells to the surface. A micrograph of the surface of the TiON coating deposited on the TiN-Ti layer is shown in Fig. 2. Apparently, the cells on the coating surface, unlike the TiN-Ti coating, are absent (only weak traces from the cellular structure of TiN-Ti are observed, which may indicate a lower spray ratio of TiON coatings). A study of the break in the TiON coating confirms the absence of cells on its surface and shows that the coating itself has a columnar structure. During titanium oxynitride formation at supplying of O_2 and N_2 component ratio 1:1 film of the stoichiometric composition $TiO_{1.6}N_{0.4}$, has been formed. Film has the best hemocompatibility [17]. Such a composition of titanium oxynitride is due to a higher chemical activity of oxygen than nitrogen when coating is formed by the ion-plasma method.

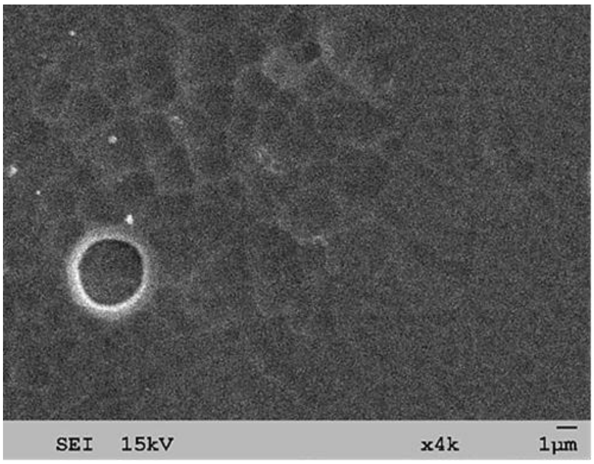

Fig. 1. Morphology of surface coating TiN-Ti (outer layer TiN)

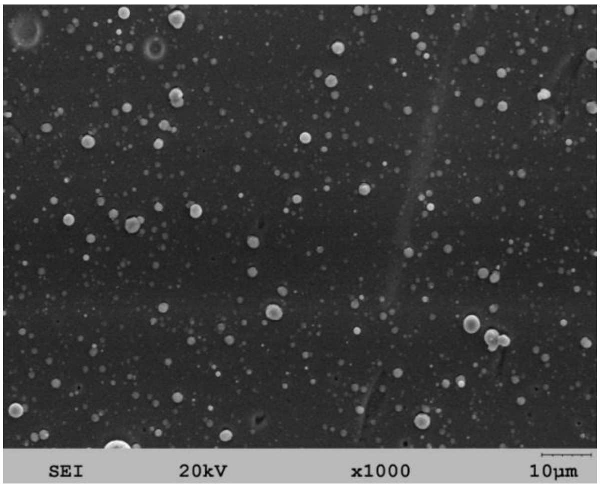

Fig. 2. Microphotography of TiON coating surface

3.2. TiN-Ti/TiON FILMS STRUCTURE

We investigated TiN-Ti films structure earlier in [13]. In the investigated samples have three phases: TiN with a cubic lattice of NaCl type, α-Ti and amorphous-like (ordering size by broadening is about 3 nm) titanium oxide TiO_2. In the titanium nitride layers strong preferential orientation of the crystallites with a plane (220) parallel to the growth surface is revealed.

Such a preferential orientation is usually associated with a large radiation factor contribution to texture formation and the initial layers of growth are the most sensitive to such a factor when the bias potential is applied.

The effect of the radiation factor in the case of the TiN-Ti/TiON film is much weaker as it is evidenced by the relative decrease in the intensity of the diffraction reflection from the (220) plane. It should be noted that the table intensities ratio (powder test, JCPDS 38-1420) is for the planes (111), (200), and (220) ratio 72/100/45.

The results obtained coincide with the data of known works. Thus, in [17], where titanium oxynitride films were obtained by method of plasma-immersion ion implantation and metal deposition wide diffraction peaks are observed at equal partial pressures of N_2 and O_2, that can be considered as a mixture of FCC (face centered cubic)-TiN and FCC-TiO phases. Obtained by a similar method in [18] oxynitride films had crystalline phases of FCC-TiN and FCC-TiO type the average atomic composition of $TiN_{0.4}O_{1.6}$ and the structure of $TiN+TiO+TiO_2$ (amorphous).

3.3. COATING HARDNESS

The relationship between multilayer coating of TiN-Ti and thickness of titanium layers is shown on Fig. 3.

When the titanium layer thickness in multilayer TiN/Ti system is less 100 nm, sufficiently high mechanical properties are achieved (hardness more than 25 GPa with the plasticity index of $H/E^* = 0.11…0.12$). So, these coatings with the known crack resistance [16] are perspective while operation at high alternating loading conditions.

The change in the potential of the U substrate while obtaining of multilayer TiN/Ti coating had shown the increasing of hardness and decreasing of U up to the zero that is non-typical for the single-layer coating.

In the case of multilayer coating this increasing of mechanical properties can be explained by increasing of the planarity of the interlayer boundaries (less mixing) with the decreasing of UF and, respectively, increasing of the mixed layer thickness on the boundary with increasing UF, due to the increasing of the average energy of the particles that bombard the growing particle coating.

After the depositing of titanium oxynitride with thickness of ~ 1 nm on a TiN/Ti multilayer coating with thickness of 6 nm (titanium layer – 30 nm, TiN layer – 300 nm), the hardness of composite coating increases up to 27…28 GPa.

3.4. ADHESIVE STRENGTH OF TiN-Ti/TiON COATINGS

Analysis of adhesion strength, scratch resistance and determination of the fracture mechanism was carried out using a REVETEST scratch tester.

The results of adhesive tests of TiN-Ti/TiON coating are shown at Fig. 4.

An analysis of scratching at the coating indicates that it was no cracks and chips under the load up to 3.86 N, which is confirmed by the absence of acoustic emission signals. Under the load of 13.2 N, the coating is covered with cracks, but the delamination occurs on a relatively small area, which indicates the high adhesion of the coating to the substrate.

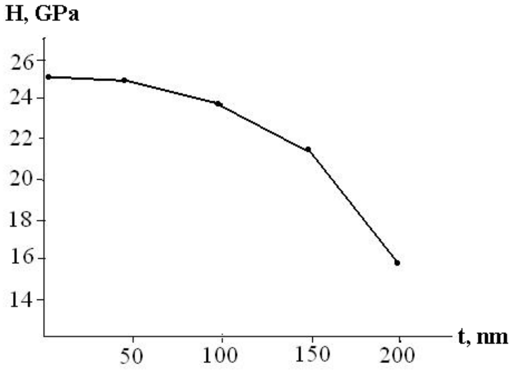

Fig. 3. Areas of diffraction spectra from the coating TiN-Ti/TiON: 1 – areas TiON; 2 – areas TiN-Ti/TiON; 3 – substrate x-ray

The process of coating destruction while scratching with a diamond indentor can be divided into several stages. At the beginning of the process, the indenter penetrates into the coating monotonically (0…140 µm while tests). Further, as the load increases, cracks and chips appear in the coating but delamination is relatively small, which confirms its high adhesion to the substrate.

As can be seen from Fig. 4, the acoustic emission signal, which indicates the appearance of cracks in the coating, appears only after increasing of load up to 3.86 N, and while this friction coefficient does not exceed 0.1.

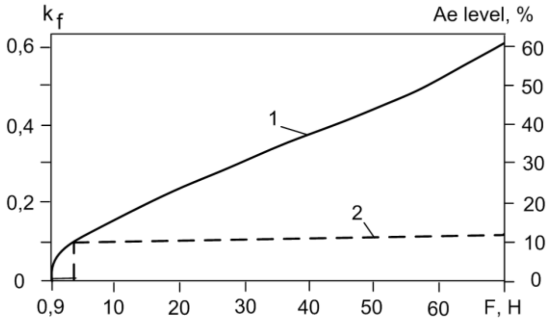

Fig. 4. Results of adhesion tests of TiN-Ti/TiON tests: relationship of friction coefficient (curve 1) and acoustic emission level (curve 2) from the applied load

Despite the significant deformation of the substrate, the coating does not delaminate. As the load increases and, consequently, the penetration depth of the indenter increases, the friction coefficient increases monotonically, which may be due to the increasing of the area of delaminated coating.

3.5. WEAR RESISTANCE OF TiN-Ti AND TiN-Ti/TiON COATINGS

Tests on the wear resistance of TiN-Ti and TiN-Ti/TiON coatings were carried out according to the plane-cylinder scheme on a SMC-2 friction machine at a slip speed of 1.3 m/s, by dry method, without lubrication at a load of 0.1 N for 1 hour. After this the volume of removed material and the specific wear were calculated – that is the volume of material that is removed per 1 length unit length of friction path. For comparison, the wear resistance of uncoated samples from 12X18H9T steel was investigated under the same conditions.

Tests results are show at Table.

Specific volumetric wear of samples made from stainless steel, TiN-Ti and TiN-Ti/TiON coatings

Sample	Specific volumetric wear, mm^3/m
Steel 12X18H9T	$1\cdot10^{-5}$
TiN-Ti coating	$3\cdot10^{-6}$
TiN-Ti/TiON coating	$1\cdot10^{-6}$

As can be seen from Table, the TiN-Ti/TiON coating has a significantly higher wear resistance than the TiN-Ti coating, and much greater than the 12X18H9T steel.

The intensity of wear depends strongly on the coating hardness and the adhesion value between the layers and the substrate. It should be noted that in the case of multilayer nanostructured coatings, intergranular and interlayer boundaries are a zone of intense energy dissipation and deflection of cracks from directed motion, partial or complete deceleration, which leads to the hardening of materials. Therefore, coatings with a nanoscale structure and multilayer architecture have a significantly longer life to failure.

We can note that the low friction coefficient of the upper layer of titanium oxynitride in the composite coating of TiN-Ti/TiON (according to the data of current analysis, $K_f \sim 0.1$ before the appearance of the acoustic emission signal, according to the data of [8] $K_f = 0.14...0.3$) provides significantly greater wear resistance of this coating in comparison with the coating of titanium nitride ($K_f = 0.6$) and specimens made from 12X18H9T steel ($K_f = 0.7…0.8$).

3.6. CORROSION RESISTANCE OF TiN-Ti/TiON COATING

The kinetics of electrochemical corrosion of coatings was studied by the potentiodynamic method.

Knowing the corrosion resistance of a metal which is coated with a composite coating is especially important when using a metal-coating system as an implant in the human body, where the implant is per se constantly in the contact with the electrolyte solutions.

While carrying out the corrosion analyses, the corrosion rate, corrosion potentials, currents and Tuffel coefficients of experimental samples and their coatings are determined.

All potentials are presented relative to the saturated calomel reference electrode. While analysis, surface scanning was performed on the samples, which allows predicting the overall corrosion properties of the material and its resistance to external influences in an aggressive environment.

The results of corrosion tests of TiN-Ti/TiON-coated stainless steel samples have shown that their corrosion rate is 6.883 mg/year.

Such a low corrosion rate is a consequence of the structure. First of all – of a multilayer TiN-Ti coating, which does not have a columnar structure like a conventional TiN film and therefore is a more effective barrier compared to this film, and this barrier prevents the penetration of the electrolyte solution to the surface of metal.

SUMMARY

1. The surface morphology of the multilayer TiN-Ti coating promotes good adhesion between this coating and the substrate layer of titanium oxynitride.

2. In the current samples coated with the TiN-Ti/TiON and TiON, the following phases can be seen: TiN with a cubic lattice of NaCl-type, α-Ti and amorphous-like (ordering size of broadening is about 3 nm) titanium oxide TiO_2, which agrees with known data.

3. At a thickness of the titanium layer in multilayer TiN/Ti system less than 100 nm, rather high mechanical properties are achieved (yardness more than 25 GPa with the plasticity index H/E^* of 0.11…0.12). So, these coatings with the known crack resistance [16] are perspective while operate at high alternating loading conditions. After the depositing of titanium oxynitride on a TiN/Ti multilayer coating, the hardness of composite coating increases up to 27…28 GPa.

4. The first cracks in the coating appear at a load of 3.86 N, while the coefficient of friction does not exceed 0.1. Despite significant deformation of the substrate, the coating does not delaminate.

As the load increases and, consequently, the penetration depth of the indenter increases, the friction coefficient increases monotonically, which may be due to the increasing of the area of delaminated coating.

5. It has been found that TiN-Ti/TiON coating has a significantly higher wear resistance than the TiN-Ti coating, and much greater than the 12X18H9T steel.

6. TiN-Ti/TiON coated samples have a high corrosion resistance in a 2% NaCl solution due to very low corrosion rates.

Such a low corrosion rate is a consequence of the structure. First of all – of a multilayer TiN-Ti coating, which does not have a columnar structure such as conventional TiN film.

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СВОЙСТВА КОМПОЗИЦИОННЫХ ВАКУУМНО-ДУГОВЫХ ПОКРЫТИЙ СТРУКТУРЫ TiN-Ti/TiON

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Выполнено комплексное исследование свойств композиционных покрытий структуры TiN-Ti/TiON. Установлено: морфология поверхности многослойного покрытия TiN-Ti способствует обеспечению высокой адгезии между ним и последующим слоем оксинитрида титана; в образцах, покрытых TiN-Ti/TiON и TiON, выявляется присутствие трех фаз: TiN с кубической решеткой типа NaCl, α-Ti и аморфноподобный окисел титана TiO_2; при толщине слоя титана в многослойной системе TiN/Ti менее 100 нм достигаются достаточно высокие механические свойства (твердость более 25 ГПа при индексе пластичности $H/E^* = 0,11…0,12$), что при известном росте трещиностойкости таких покрытий делает их перспективными для использования в условиях действия высокой знакопеременной нагрузки; после нанесения оксинитрида титана толщиной ~ 1 мкм на многослойное покрытие TiN/Ti толщиной 6 мкм (слои титана – 30 нм, слои TiN – 300 нм) твердость композиционного покрытия возрастает и составляет 27…28 ГПа; первые трещины при скрайбировании в покрытии появляются при нагрузке 3,86 Н, при этом коэффициент трения не превышает 0,1; покрытие TiN-Ti/TiON обладает значительно более высокой износостойкостью, чем покрытие TiN-Ti, и на порядок большей, чем сталь 12Х18Н9Т; образцы с покрытием TiN-Ti/TiON обладают высокой коррозионной стойкостью в растворе 2% NaCl, обусловленной очень низкой скоростью их коррозии, что представляется следствием структуры многослойного покрытия TiN-Ti, которая не имеет столбчатого строения.

ВЛАСТИВОСТІ КОМПОЗИЦІЙНИХ ВАКУУМНО-ДУГОВИХ ПОКРИТТІВ СТРУКТУРИ TiN-Ti/TiON

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Виконано комплексне дослідження властивостей композиційних покриттів структури TiN-Ti/TiON. Встановлено: морфологія поверхні багатошарового покриття TiN-Ti сприяє забезпеченню високої адгезії між ним та подальшим шаром оксинітриду титану; у зразках, вкритих TiN-Ti/TiON і TiON, виявляється присутність трех фаз: TiN з кубічною решіткою типу NaCl, α-Ti та аморфноподібний окисел титану TiO_2; при товщині шару титану в багатошаровій системі TiN-Ti менше 100 нм досягаються досить високі механічні властивості (твердість більше 25 ГПа при індексі пластичності H/E^* = 0,11...0,12); після нанесення оксинитрида титану товщиною ~ 1 мкм на багатошарове покриття TiN-Ti товщиною 6 мкм (шари титану – 30 нм, шари TiN – 300 нм) твердість композиційного покриття зростає і становить 27...28 ГПа; перші тріщини при скрайбуванні в покритті з'являються при навантаженні 3,86 Н, при цьому коефіцієнт тертя не перевищує 0,1; покриття TiN-Ti/TiON має значно більш високу зносостійкість, ніж покриття TiN-Ti, і на порядок більшу, ніж сталь 12Х18Н9Т; зразки з покриттям TiN-Ti/TiON мають високу корозійну стійкість в розчині 2% NaCl, яка спричинена дуже низькою швидкістю їх корозії, що представляється наслідком структури багатошарового покриття TiN-Ti, яка не має стовбчастої будови.