Technological aspects of wear-resistant coating treatment on the surface of a cutting tool

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The article presents a method for producing a nanostructured wear-resistant high-hardness coating with high physical, mechanical and strength characteristics, resistance to shock and vibration loads on the surface of spring-spring and tool steels used in the manufacture of cutting tools, including band saws. Technological modes were selected for the entire cycle of coating deposition of the developed compositions that have high adhesion to substrates made of steels of various grades, as well as provide high microhardness due to the nanostructure of the protective coating obtained on the surface. Studies are shown on the example of one of the most common methods of metal cutting — cutting on band-cutting machines, using closed band saws as cutting tools made of spring-spring steels with obtained carbide cutting edges. Since in modern production, structural steels are replacing materials with high physical and mechanical characteristics (hardness, strength, etc.), the cutting process becomes much more complicated and imposes increased requirements on the cutting tool itself. To expand the range of materials to be processed, for which production use of band-cutting machines is possible, it became necessary to create a band saw with higher cutting characteristics. At the same time, the specificity of the operating conditions of the band saw shows that the blade should have such characteristics as increased vibration resistance, resistance to alternating and dynamic loads, and the cutting part of the saw should have increased resistance to shock, dynamic, alternating loads, have high hardness, as well as increased wear resistance. Therefore, one of the ways to solve this problem proposed in the article is to avoid the manufacture of band saws using the “bimetal” technology and use the same material as a tooth and a blade when applying a wear-resistant hard-alloy nanostructured coating on the surface of the cutting edge of the tooth. The practical usefulness of the developed protective nanostructured coatings for increasing the service life of carbide turning inserts is also shown.
Key words: high-temperature protection coating, wear resistance, heat resistance, high-speed tool steel, magnetron sputtering.
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Introduction

It is known that the idea of creating a layered nanocomposite from the highly hard phases Al_2O_3, ZrN, TiC, Zr (C, N), Ti-Zr-C, TiB_2 is one of the recognized directions for solving the problem of thermomechanical wear of metalworking tools [1–4]. Thus, laminated composite materials have shown themselves to be efficient under complex loading conditions on other mechanical engineering products [3–7] and have firmly strengthened their positions in production. With a correct analysis of the operating conditions of the product, whether it is a part or a cutting tool, in particular a band saw blade, it can be found that this or that zone or layer can work for a specific type of loading. Consequently, it can be made from a material with characteristics that meet the given loading conditions. Thus, based on the analysis of the loading conditions during the operation of the band saw blade, the idea of a bimetallic saw was proposed, which is the correct way to solve the arising problem, but the main disadvantage is the presence of a welded joint sensitive to vibration, dynamic and shock loads, as well as the difficulty of obtaining a defect-free welded seam, which is also complicated by the criterion of weldability of many materials with each other and in general. An alternative can be the application of a coating on their surface of saw tooth by the method of ion-magnetron sputtering, which allows to significantly change the physical and mechanical characteristics of the material of the cutting edge of the teeth (which will be the material of the entire band saw blade - spring steel). At the same time, the output is a layered composite with high adhesion, comparable in value to the metallurgical one. Obtaining a coating by ion-magnetron sputtering, which allows spraying thin films and is currently the most optimal technology for obtaining coatings on cutting tools, both in terms of adhesion and the resulting structure of the sprayed nanostructured coating [4].

Materials and Equipment

For the research, the following equipment was used: a JET band saw (testing the obtained saws under conditions close to factory conditions), a Falcon 500 micro hardness meter (micro hardness tests for preliminary analysis of wear resistance), an Instron 8801 testing machine (fatigue test), installation of a magnetron radio frequency spraying Q150T ES (coating process), scanning electron microscope "JEOL JSM-7500F" (studying the microstructure of coatings), Bruker Vertex 70 FTIR IR spectrometer (for analyzing the composition of coatings), TR100 Surface Roughness Tester (for roughness measurements).

Analysis of Simulation Results and Experimental Data

To apply nanostructured and wear-resistant high-hard coatings by magnetron sputtering on the surface of cutting tools, a sequential technological cycle is used in the work, which includes:

1) Preliminary etching of the product surface with low-temperature argon plasma to improve the adhesion of the applied protective coating;

2) Application by the method of magnetron-plasma spraying of a nanostructured film of metal or alloy on the surface of the product;

3) Thermal oxidative phase-forming annealing for the appearance of nanoparticles of high-hard oxides of a cubic system (aluminum or chromium oxides) and nanoparticles of medium-hard oxides (oxides of titanium, niobium, vanadium), which also leads to an increase in the adhesion of the protective coating, an increase in hardness, wear resistance and fatigue strength due to the recrystallization process applied coating.

Processing the surface of the cutting tool with low-temperature argon plasma makes it easy to clean the surface of the product from dirt and grease residues. At the same time, argon ion-plasma etching (surface ablation of the substrate material) occurs, which makes it possible to change the structural and mechanical properties of the product, increase the roughness, which will improve the adhesion between the metal surface of the cutting tool and the applied material. Plasma treatment can be applied to a wide range of cutting tools of any composition and complex geometries.

With the help of magnetron-plasma spraying, nanostructured metal thin-layer films of the desired chemical composition and thickness are deposited. With the method of obtaining the coating, no thermal heating of the cutting tool occurs, due to which there is no occurrence of residual stresses on the surface of the tool and along the product-coating interface. In turn, the resistance of the coated cutting tool to fatigue cracking is improved. Also, ion-plasma spraying occurring at room temperature provides a coating having a nanoscale structure in the size range of 5–15 nm. Thin nanostructured coatings, with a certain crystal structure (cubic and tetragonal syngonies) and size of nanoparticles (belonging to the region of maximum realization of the Hall-Petch effect), show ultra-high hardness, high fatigue strength, and increased wear resistance.

The TiAlVW composition used in our study has high physical and mechanical properties due to the fact that the alternation of lamellae of the α2-phase and γ-phase of the titanium-aluminum intermetallic compound is provided. At the same time, alloying with vanadium and tungsten makes it possible to increase the heat resistance of the material, hardness, with a decrease in the thickness of the lamellas of alternating α2-phase and γ-phase, which additionally makes it possible to increase the physical and mechanical properties of the coating of this composition and, as a consequence, the operational characteristics of the cutting tool.

Thermal oxidative phase-forming annealing makes it possible to create a surface layer of highly hard, highly thermally stable cubic or tetragonal phase oxide nanoparticles on the surface of a metal adhesive film, which leads to the production of highly hard coatings with high wear resistance and significant fatigue strength.

The method of applying nanostructured and wear-resistant coatings with high adhesion to the surface of the cutting tool at the first stage, the surface of the product is preliminarily etched with low-temperature argon plasma to improve the adhesion of the applied protective coating in a vacuum chamber with accelerated ions at a pressure of 1–3 Pa, after which it is applied by magnetron-plasma spraying nanostructured film of TiAlVW alloy with the following weight % ratio: Al 5.2–6.4; V 3.7–4.2; W 1.4–2; Ti — the rest, by transferring from the target surface a composition similar to the coating applied to the surface of the cutting tool, after which thermal oxidative phase-forming annealing is carried out at a temperature of 550–650 °C for 1–2 hours for the appearance of nanoparticles of high-hard oxides of a cubic system (oxides of aluminum, chromium, titanium, etc.), which also leads to an increase in the adhesion of the protective coating, an increase in hardness, wear resistance and fatigue strength due to the process of recrystallization of the applied coating.

As a proof of concept of the proposed project, studies of the hardness of nanostructured metal coatings with nanoparticles of organized high-strength oxide films of cubic or tetragonal phases on the surface of high-speed steel tools (metal cutting saw and metal-ceramic carbide cutters) were carried out.

For the deposition of nanostructured coatings 100 nm thick on the surface of the cutting edge of HSS band saw or VNMG160404-PM type diamond carbide turning inserts (Zhuzhou Jintai Cemented Carbide Co., Ltd., WC-8% Co) without protective coatings a Q150T ES RF magnetron sputtering unit with appropriate metal targets was used. The following values of magnetron sputtering currents were used: 120 mA for Ti6Al4VW alloy, 80 mA for Kh15N60 nichrome, 120 mA for aluminum, and 50 mA for chromium. A produced nanosized aluminum film was annealed at a temperature of 600 °C to convert it to the cubic oxide phase. The rest of the alloys were not modified by annealing, but according to IR spectroscopy data, oxide phases were present in them in a small amount due to the used method of magnetron sputtering at weak discharge (10^{-4} Pa) in argon plasma with air oxygen impurities.

The microstructure of the obtained coatings on the saw teeth was studied using a JEOL JSM7500F scanning electron microscope and shown in **Fig. 1**.

According to electron microscopy data, the nanostructured coating of thermally oxidized aluminum (Al_2O_3)

exhibits the highest microroughness. It can be seen that the fabricated coatings contain clusters of nanoparticles 10–45 nm in size. In this case, the size of clusters of nanoparticles in different coatings is different. The size distribution of nanoparticles in derived coatings is shown in **Fig. 2**.

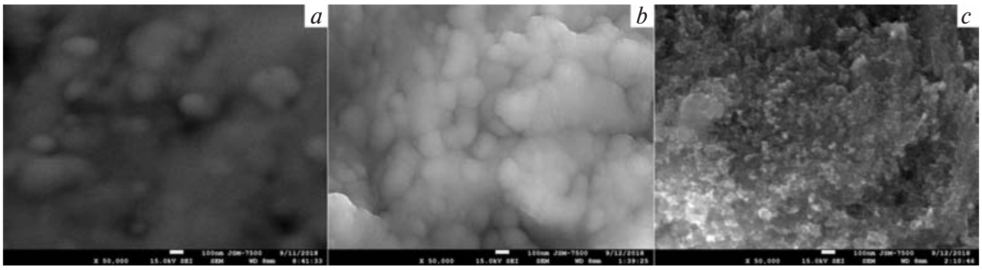


Fig. 1. Microstructure of the obtained coatings: *a* — nichrome Kh15N60; *b* — Ti6Al4VW alloy; *c* — thermally oxidized aluminum (Al_2O_3)

The size distribution of nanoparticles in the coating based on the Ti6Al4VW alloy is close to unimodal, and for the coating based on nichrome Kh15N60 and chromium it is bimodal. The bimodal distribution of nanoparticles in a coating deposited by magnetron sputtering is associated with the processes of recrystallization of nanoparticles. The nanostructured Al_2O_3 coating shows a wide-range distribution of nanoparticles in size, which is characteristic of secondary crystallization processes due to the oxidation of metal nanoparticles with remelting and coalescence [8, 9] due to the low values of the enthalpy of fusion characteristic of small aluminum nanoparticles.

The weighted average calculated size of nanoparticles in the applied nanostructured coatings is presented in **Table 1**.

It can be assumed that, in accordance with the well-known Hall-Petch equation [10], the size of the nanoparticles of the deposited alloy films and the resulting aluminum oxide is close to the transition boundary from the forward Hall-Petch law to the reverse one [11–13]. Thus, a high microhardness can be expected from the obtained nanostructured coatings. For chromium coating it can be expected, that size of produced nanoparticles is smaller than transition from Hall-Petch region to inverse Hall-Petch range.

The Rockwell microhardness of the obtained coating samples on the band sew teeth was measured on a Falkon 500 microhardness tester and microhardness values were taken as averages over the results of 10 measurements (**Table 2**).

From the data in Table 2, it follows that, with the exception of the chromium film, the nanostructured coatings used noticeably increase the hardness of the working surfaces of the HSS saw teeth. In the case of a chromium film, it can be assumed that the small size of chromium nanoparticles, characteristic of the region with the manifestation of the inverse Hall-Petch effect, leads to the formation of an amorphous film coating with low microhardness.

The Vickers microhardness for the cutting inserts studied by us on the cutting edge line was determined in a standard way using a Falcon 500 microhardness tester and the corresponding software according to the results of 5 independent measurements (**Table 3**) for two investigated samples of cutting inserts with and without coatings (a total of 10 measurements of microhardness values for each modifying sample coverage).

From the data in Table 3 it follows that, with the exception of nichrome film, the coatings used noticeably increase the hardness of the working surfaces of the cutting edge of carbide cutting inserts. For the case of a nanostructured film coating of Al_2O_3 obtained by thermal oxidation of aluminum, high hardness is quite expected, since according to the data of [14], oxidation of metallic aluminum in air above 5000 °C produces a film of the cubic spinel phase γ-Al_2O_3 with a high microhardness up to ~ 19 GPa [15]. In the case of the formation of the hexagonal α-phase of Al_2O_3 in the film, the it microhardness will also be significant and can be up to 23.5 GPa [16]. In the case of the prepared coating of the Ti6Al4VW alloy, the obtained considerable microhardness result is rather unexpected. Nevertheless,

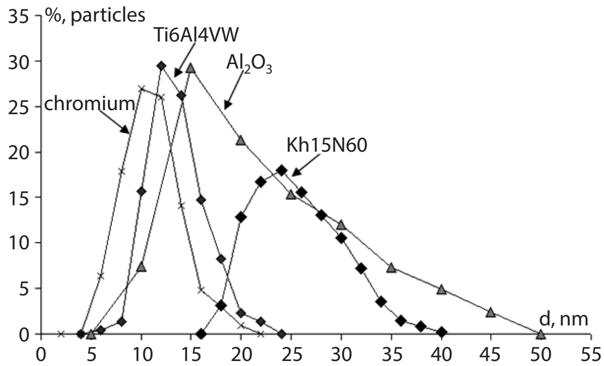


Fig. 2. Size distribution of nanoparticles in derived coatings

Table 1. **Average size of nanoparticles (nm) in applied nanostructured coatings**

Chromium	Al_2O_3	Kh15N60	Ti6Al4VW
11 ± 3	23 ± 9	26 ± 6	14 ± 4

Table 2. **Rockwell microhardness (GPa) of samples of the initial material of saw teeth and with applied nanostructured coatings**

Saw tooth material	Chromium	Al_2O_3	Kh15N60	Ti6Al4VW
54 ± 2	55 ± 6	70 ± 1	62 ± 2	73 ± 2

Table 3. **Vickers microhardness (GPa) of samples of the initial material of the cutting edge of carbide inserts and with applied nanostructured coatings**

Cutter edge material	Al_2O_3	Kh15N60	Ti6Al4VW
1770 ± 100	2030 ± 140	1530 ± 105	1954 ± 108

according to the data of studies, a decrease in the grain size in the Ti6Al4V alloy [17, 18] leads to a strong increase in its strength and plasticity, and it was recently shown in [19] that the Ti6Al4V alloy nanostructured by laser sintering has a nanohardness of 7.43 GPa. Also, one should take into account the possibility of the formation of a certain fraction of the high-hard TiN phase when using the magnetron sputtering method at a weak discharge ($2 \cdot 10^{-3}$ mbar) in an argon plasma with air nitrogen impurities. As shown in [20], the formation of a cubic high-hardness TiN phase on the surface of the Ti6Al4V alloy leads to a significant increase in its microhardness.

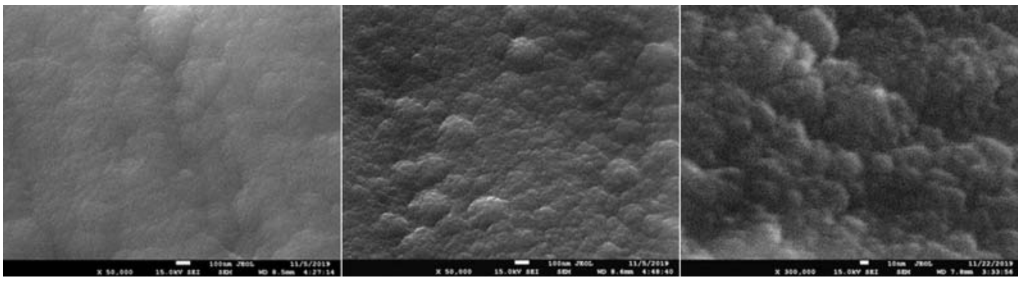
Thus, the preliminary results show the validity of the proposed approach, since the developed single-layer nanostructured coatings noticeably increase the hardness of the working surfaces of tools made of high speed steel and carbide composition WC-8% Co.

Next, the preparation of a combined wear-resistant coating for a cutting tool in the form of HSS band saws and carbide cutting inserts was considered. The wear-resistant protective coating was applied as follows. At the first stage, the surface of the protected item was pre-etched with a low-temperature argon plasma to improve the adhesion of the applied protective coating in a vacuum chamber with accelerated ions at a pressure of 1–3 Pa. Next, a nanostructured film of the composition TiAlVNbB was deposited by the method of radio-frequency magnetron-plasma spraying by spraying a combined target made of TiAlVNb alloy with a small proportion of pressed TiB2 micropowder at the following weight % ratio: Al 5.5–6.5; V 7–8; Nb 2–4; TiB_2 1–2; Ti — rest (compositions are indicated in Table 3), by transferring from the target surface a composition similar to the coating applied to the surface of the cutting tool. After deposition of the protective film, thermal oxidative phase-forming annealing was carried out in air at temperatures from 550 to 650 °C for 1 hour for the appearance of highly hard γ-Al_2O_3 nanoparticles of cubic syngony with admixtures of the phases of oxide nanoparticles TiO_2, VO_2 and Nb_2O_5, which also leads to an increase in the adhesion of the protective coating , an increase in hardness [21], wear resistance, corrosion resistance [22] and fatigue strength due to the process of recrystallization of the applied coating.

The microstructure of samples of the obtained protective coatings before and after thermal phase-forming annealing is shown in **Fig. 3 and 4**. According to these figures, in the course of thermal annealing, a pronounced change in the microstructure of magnetron-sputtered protective cermet coatings occurs both from the oxidation of metal nanoparticles according to IR spectroscopy data and due to recrystallization of the formed oxide phases. In all cases studied

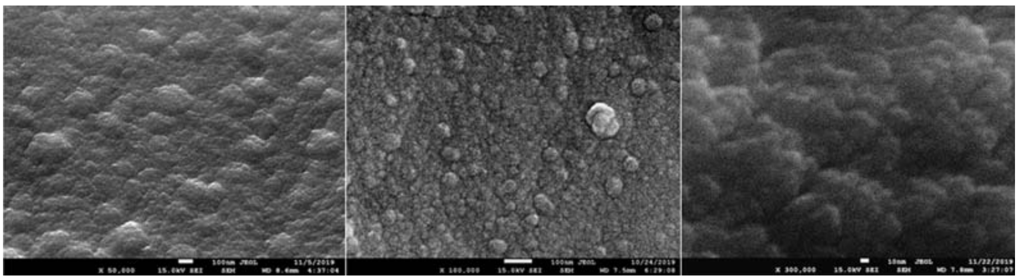
Table 4. **Results of testing the service life of carbide cutter inserts with manufactured protective coatings**

Sample	Composition, %	Plasma etching pressure, Pa	Annealing temperature / time, °C/hour	Treatment resistance for 30KhGSA, min.	Microhardness, GPa
Example 1	Al 5.5; V 7.0; Nb 2.0; TiB_2 1.0; Ti — rest	3	550/1	83 ± 1	47.3
Example 2	Al 6.0; V 7.5; Nb 3.0; TiB_2 1.5; Ti — rest	2	600/1,5	86 ± 2	47.9
Example 3	Al 6.5; V 8.0; Nb 4.0; TiB_2 2.0; Ti — rest	1	650/2	89 ± 1	49.2
Prototype	–	–	–	81 ± 1	46.7



a *b* *c*

Fig. 3. Microstructure of the obtained protective coating of composition $(Ti_{76.10}Al_{8.89}V_{5.99}Nb_{0.94}B_{8.07})_xO_y$ (example 1): *a* — before thermal annealing; *b* — after thermal annealing; *c* — after thermal annealing at high magnification



a *b* *c*

Fig. 4. The microstructure of the obtained protective coating of composition $(Ti_{70.63}Al_{10.51}V_{6.85}Nb_{1.88}B_{16.14})_xO_y$ (example 3): *a* — before thermal annealing; *b* — after thermal annealing; *c* — after thermal annealing at high magnification

by us, the obtained samples of oxide protective coatings are nanostructured with a nanoparticle size from 15 to 30 nm.

It is known that during thermal oxidation of titanium alloys, according to X-ray photoelectron spectroscopy data [23], amorphous oxide films of three types of titanium oxide phases TiO, Ti_2O_3, and TiO_2 are formed on the surface. Under our conditions of prolonged thermal oxidative annealing, the expected main phase in the obtained coatings is TiO_2. It is known that the main crystalline phases of TiO_2 are tetragonal anatase and rutile phases. At low-temperature oxidation up to 400 °C, the anatase phase predominates, and at temperatures above 600 °C anatase is almost completely transformed into a thermodynamically more stable and harder [24] rutile phase. Based on the thermal annealing conditions we used, it can be assumed that the basis of the created nanostructured wear-resistant high-hard protective coatings is a film of medium-hard rutile nanoparticles interspersed with high-hard nanoparticles of the cubic phase γ-Al_2O_3, TiB_2, the pseudohexagonal phase of the tetrahedral phase of the Nb_2O_5 medium-hard phase [25].

Tests of the manufactured protective coatings on commercial carbide cutting inserts of the VNMG160404-PM type were carried out by orthogonal turning of cylindrical parts with a diameter of 20 mm and a length of 200 mm from structural alloy steel 30KhGSA in the form of a bar with an initial diameter of 22 mm with the following parameters of turning 30HGSA steel: V (cutting speed) = 80 m/min, s (feed) = from 0.2 (initial stage of turning) to 0.1 (final treatment) mm/rev; t (depth of cut) = 0.5 mm. We determined the wear criterion of the cutting inserts by the quality of the processed surface, namely, the required level of roughness of the processed cylindrical surface of steel 30HGSA at the level of Ra ≤ 2.5 μm in accordance with measurements with a digital profilometer TR100. The service life of carbide cutters with developed protective nanostructured coating when turning a cylindrical part made of steel 30HGSA was estimated by averaging over five time measurements and. the test results are shown in **Table 4**. Thus, the wear of cutting inserts that did not provide the required roughness were considered outside the service life for a particular production with the required turning parameters.

Analysis of the data presented in the Table 3 allows us to conclude that cutting carbide inserts with prepared wear-resistant nanostructured coatings obtained by the above method are characterized by higher physical and mechanical characteristics and a longer service life (up to 10 % of the time when turning steel 30HGSA), compared with cutting plates of metal-ceramic cutters made according to previously known methods.

The reasons for this may be the complex cooperative nature of interparticle and interphase interactions in the created protective film coatings. Thus, for example, upon oxidative phase-forming annealing in air in nanostructured TiAlVNbB films, in addition to nanoparticles of various Al_2O_3 phases, nanoparticles of titanium, vanadium, and niobium oxides with various combinations of microhardness and plasticity can be formed.

Conclusion

As a result of the research, a method was developed for obtaining a wear-resistant coating for a cutting tool, including the application of a magnetron sputter coating on the surface of a cutting tool based on an alloy of titanium, aluminum and niobium with small additions of titanium diboride. Obtaining a coating on the surface of the cutting tool (HHS band saws and carbide cutting inserts) is carried out by the method of magnetron-plasma sputtering, including preliminary plasma etching of the surface of the cutting tool in a vacuum chamber with accelerated argon ions, followed phase-forming thermal oxidative annealing to derived films of high-hard nanoparticles of Al_2O_3, titanium/vanadium/niobium oxides and borides.

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