Development of a method of applying nanostructured and wear-resistant coatings with high adhesion to the surface of the cutting tool

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Abstract. The article presents a method of obtaining a nanostructured wear-resistant high-hard coating with high physicomethical and strength characteristics resistance to shock and vibration loads. The result is an increase in adhesion between the substrate and the coating, as well as an increase in microhardness.

1. Introduction

One of the common methods of metal cutting are band sawing machines using closed band saws as a cutting tool. As in modern production, materials with high physicomethical characteristics (hardness, strength, etc.) are increasingly used, which significantly complicates the cutting process and places high demands on the cutting tool. To expand the range of materials to be processed, for which productive use of band-cutting machines is possible, it has become necessary to create a band saw with higher cutting characteristics. The specificity of the working conditions of the band saw shows that the blade must have such characteristics as increased vibration resistance, resistance to alternating and dynamic loads, and the cutting part of the saw must have increased resistance to impact, dynamic, alternating loads, have high hardness, and also increased wear resistance [1,2].

The idea of creating a laminated composite is one of the right directions to solve this problem. Thus, the layered composite material proved to be efficient under complex loading conditions on other engineering products. It firmly strengthened its position in production as well as with proper analysis of the working conditions of the product, be it a part or a cutting tool, in particular, a band saw. This or that zone or layer can work for a specific type of loading. Therefore, it can be made from a material with characteristics that satisfy these load 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. This is the right way to solve the arising problem, but the main drawback is the presence of a welded joint sensitive to vibration, dynamic and shock loads, as well as the difficulty of obtaining defect-free welded seam. An alternative may be surface plasma alloying of the teeth of the band saw blade, which allows a significant change in the physico-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 metallurgical, because the material of the band saw blade is alloyed, which is also the base material. And if the modes are correctly chosen, it is possible to reduce to zero the possible residual deformation due to
heat treatment [4]. A known method of applying antifriction wear-resistant coating on a titanium alloy product is known. It includes pre-cleaning and surface activation of a titanium alloy product by bombarding it with argon ions and ion-plasma deposition of a composite coating by magnetron sputtering of a cathode. It contains titanium carbide and molybdenum disulfide with a negative potential, applied on the product and the combination of the deposition process with the surface bombardment with argon ions. And the ion surface bombardment argon gas is carried out. Using a gas plasma generator and prior to coating deposition, a preliminary doping of the surface layer of a titanium alloy product is used by magnetron sputtering of a cathode containing titanium carbide and molybdenum disulfide. At the same time, argon ions are simultaneously bombarded with a gas plasma generator. A negative potential is applied to the product, and the initial ratio of the components of the sprayed cathode during the preliminary doping and deposition is: titanium carbide – 40-60 wt. % molybdenum disulfide - the rest. In this case, the pre-doping is performed at a negative potential application exceeding the capacity value during the deposition of the coating.

2. Materials and Equipment
The following equipment was used to carry out the research:
- JET band saw machine (testing of the received saws under conditions close to the factory ones);
- Falcon 500 microhardness meter (microhardness test for preliminary analysis of wear resistance);
- JEOL JSM7500F scanning electron microscope (microstructure of the coatings obtained);
- Instron 8801 (fatigue test);
- plasma doping unit (directly carrying out doping);
- HFC.

3. Analysis of Simulation Results and Experimental Data.
For deposition of nanostructured and wear-resistant high-hard coatings by magnetron sputtering on the surface of cutting tools, a sequential technological cycle is used. It includes:
1) Pre-etching the product surface with low-temperature argon plasma to improve adhesion of the applied protective coating.
2) Application by magnetron-plasma deposition of a nanostructured metal or alloy film on the surface of the product.
3) Thermal oxidative phase-forming annealing for the appearance of nanoparticles of highly solid cubic oxide oxides (oxides of aluminum, chromium, titanium, etc.), also leading to an increase in adhesion of the protective coating, an increase in hardness, wear resistance and fatigue strength due to the process of recrystallization of the applied coating.

Surface treatment 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, ion-plasma etching occurs (surface ablation of the material), which allows changing the structural and mechanical properties of the product, increasing 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 types of cutting tools of any composition and complex geometric shape.

Using magnetron-plasma sputtering, nanostructured metal thin-layer films of the desired chemical composition and thickness are applied. In the method of obtaining the coating there is no thermal heating of the cutting tool, so that there are no residual stresses on the tool surface and along the product-coating interfaces. In turn, the resistance of the coated cutting tool to fatigue cracking is increased. Also, ion-plasma sputtering occurring at room temperature provides a coating with a nanoscale structure in the size range of 5-15 nm. Thin nanostructured coatings with a certain shape (cubic and tetragonal syngonies) and nanoparticle size (belonging to the region of the maximum realization of the Hall-Petch effect) show ultrahigh hardness, high fatigue strength and increased wear resistance.
The composition of TiAlVW has high physicomechanical properties because the alternation of the \( \alpha_2 \)-phase lamella and the \( \gamma \)-phase of the intermetallic compound of titanium with aluminum is provided. At the same time, doping with vanadium and tungsten allows to increase the heat resistance of the material, hardness, with a decrease in the thickness of the lamellae of alternating \( \alpha_2 \)-phase and \( \gamma \)-phase, which additionally allows to improve the physical and mechanical properties of the coating of this composition and, as a consequence, the performance characteristics of the cutting tool.

Thermal oxidative phase-forming annealing allows you to create a surface layer of highly solid, highly heat-resistant nanoparticles of oxides of the cubic phase on the surface of a metal adhesive film, which results in 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 is pre-etching the surface of the product with low-temperature argon plasma to improve the adhesion of the applied protective coating in the vacuum chamber with accelerated ions at a pressure of 1-3 Pa. Then it is applied by magnetron-plasma spraying nanostructured film alloy TiAlVW in the following ratio, wt. %: Al 5.2-6.4; V 3.7-4.2; W 1.4-2; Ti – the rest. This happens by transferring from the target surface a similar composition applied to the coating on the surface of the cutting tool, after which thermal oxidative phase-forming annealing is performed at a temperature of 550-650 °C for 1-2 h. It is made to produce nanoparticles of highly solid oxides of the cubic system (oxides of aluminum, chromium, titanium, etc.), leading to an increase in adhesion of the protective coating, an increase in hardness, wear resistance and fatigue strength due to the process of recrystallization of the applied coating.

To test the concept of the proposed project, studies of the hardness of nanostructured metallic coatings with nanoparticles in situ of organized high strength cubic oxide phases on the surface of high-speed steel tools (metal-cutting saw and carbide cutters) were carried out.

For deposition of nanostructured coatings with a thickness of 100 nm on the surface of the cutting edge of high-speed steel tools, a Q150T ES magnetron-sputtering unit with corresponding metal targets was used. The following currents of magnetron sputtering were used: for the alloy Ti6Al4V – 120 mA, for nichrome X15H60 – 80 mA, for aluminum – 120 mA, for chromium – 50 mA. A nanoscale aluminum film to be converted into the cubic phase of the oxide was annealed at 6000 °C. The remaining alloys were not modified by annealing, but according to IR spectroscopy, they contained oxide phases due to magnetron sputtering under low pressure in an argon plasma with air oxygen impurities.

The microstructure of the obtained coatings (Figure 1) was studied on a JEOL JSM7500F scanning electron microscope. The microhardness of the obtained samples was measured on a Falkon 500 Microhardness tester. Vickers/Rockwell microhardness values were taken as the average of 10 measurements. The microstructure of the coatings on the saw teeth is shown in Figure 1.

![Figure 1](image1.png)

**Figure 1.** The microstructure of the obtained coatings: (a) nichrome X15H60; (b) alloy Ti6Al4V; (c) annealed aluminum (Al\(_2\)O\(_3\)).

One can see that clusters of nanoparticles 15–35 nm in size are present in the coatings. At the same time, the size of nanoparticle clusters is different in different coatings. It can be assumed that, in accordance with the Hall – Petch equation, the size of nanoparticles of deposited alloy films and the
resulting aluminum oxide is close to the transition boundary from the direct Hall – Petch law to the opposite. Thus, a high microhardness can be expected from the resulting coatings.

The experimentally determined microhardness of the films of obtained coatings on the teeth of the saw is presented in Table 1.

Table 1. Rockwell hardness of raw material samples of saw teeth and coated nanostructured coatings

| saw tooth material | chrome | aluminum | X15H60 | Ti6Al4V |
|--------------------|--------|----------|--------|---------|
| 54±2               | 55±6   | 70±1     | 62±2   | 73±2    |

From the data in Table 1 it follows that, with the exception of chromium, the coatings used significantly increase the hardness of the working surfaces of the teeth of HSS saws.

Table 2. Vickers hardness of samples of the starting material of the cutting edge of the incisors and coated with nanostructured coatings

| tool edge material | aluminum | X15H60 | Ti6Al4V |
|--------------------|----------|--------|---------|
| 1770±100           | 2030±140 | 1530±105 | 1950±110 |

From the data of Table 2 it follows that, with the exception of nichrome, the coatings used significantly increase the hardness of the working surfaces of the cutting edge of high-speed steel cutters.

Thus, preliminary results show the validity of the proposed approach in the grant, since the developed nanostructured coatings significantly increase the hardness of the working surfaces of high-speed steel tools.

4. Conclusion
As a result of the research, a method was developed for obtaining a nanostructured wear-resistant high-hard coating with high physicomechanical and strength characteristics, resistance to shock and vibration loads. The result is an increase in adhesion between the substrate and the coating, as well as an increase in microhardness.

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