Peculiarities of wear of nanostructured topocomposites on the hard-alloy basis

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Abstract. The article considers the wear resistance and wear peculiarities of nanostructured topocomposites with the clustered gradient architecture. The authors regard the specificity of the impact of the cluster morphology on the contact interaction under microcutting conditions. They study the causes of persistence of the high wear resistance for the given class of nanostructured topocomposites. The mechanisms of energy dissipation from the tribocontact zone due to their nanogeometry and the structural-phase structure are analyzed. The contribution of triboactivated diffusion and deformation processes to providing the increased wear resistance of topocomposites on the hard-alloy basis is differentiated. Their approbation in the conditions of edge cutting processing of heat-resistant titanium alloy is carried out.

1. Introduction

The development of tool production is currently associated with the application of ion-plasma coatings based on the transition metal compounds, as well as ceramics, with high hardness and wear resistance. On an industrial scale, the leading tool manufacturers (Sandvik Coromant, Balzers, Cemicon, Metaplas, Leybold, Platit, etc.) have mastered the production of multilayer composite coatings up to several micrometers thick. The method of physical deposition - PVD (Physical Vapor Deposition) of coatings in vacuum on the tool and cutting inserts is most widely used. The PVD method has wide possibilities of obtaining coatings with the required characteristics in thickness, structure and composition. In addition, the PVD method is quite technological. At the same time, the use of a cutting tool with PVD coating allows the processing of steels and alloys with virtually no lubrication-cutting fluids. The PVD method was implemented in the technology of the vacuum-arc synthesis MEVVA (Metal Vapor Vacuum Arc), which allows forming coatings for various applications, including composite coatings with alternating metastable and multicomponent layers.

Despite the creation of multilayer-composite coatings characterized by the presence of barrier layers, the problem of obtaining reliable interfaces in the area of the interface between the surface compositions remains unsolved. In particular, when cutting extra strong heat-resistant alloys under conditions of elemental chip formation, the effectiveness of coatings is reduced due to the low cyclic crack resistance of the latter ones [1 – 4]. The development of new versions of the architecture of single-, many-layer and multi-layer nanoscale coatings is a promising area of improvement of coatings [5 – 13]. Within this approach, there is a possibility of obtaining composite coatings comprising alternating and metastable multicomponent structures, combining various properties of individual layers within the coating. The relevance of the development of superhard and ultrahard coatings with the nanocomposite architecture, in which the level of hardness can reach 40-60 GPa and 100 GPa, respectively [4], should be noted. The structure of such coatings is usually a two-phase one. Crystalline grains of nitrides, carbides, borides and oxides of about 3-10 nm are surrounded by an amorphous matrix consisting, for example, of metals or diamond-like carbon. The size among the crystals is about 1-3 nm.

Recently, the authors are developing the concept of nanostructured topocomposite coatings and nanostructured topocomposites (NSTC) [14 - 18], which are structurally dependent on the geometry of the substrate, coating thickness and its morphology. The evaluation of the performance of products with such coatings is confirmed by the researches and production tests. However, the effectiveness of their application in the cutting technology of materials processing is at the stage of testing.

2. Problem statement

Despite the fact that within the framework of MEVVA technology it is possible to synthesize a wide range of many-component, multi-layer coatings for various functional purposes, the problem of obtaining coatings with high cyclic crack resistance remains unsolved. In principle, it is impossible to eliminate the negative role of the pronounced interface boundaries, which are extended zones of stress concentrators. Internal stresses at the boundaries of the "coating-substrate" in the conditions of cyclic triboloading initiate the formation and development of the cracks, which can lead to chipping and delamination of coatings on the contact surfaces of the cutting tool at the initial stage of its operation. The character of the development of the brittle fracture of two-layer coatings in term of the cyclic tribomechanical loading under normal and shear stresses can be represented in the form of two main stages, shown in Fig.1: cracking (Fig. 1a) and "opening" of the crack in the area of the inner boundary (Fig. 1, b).

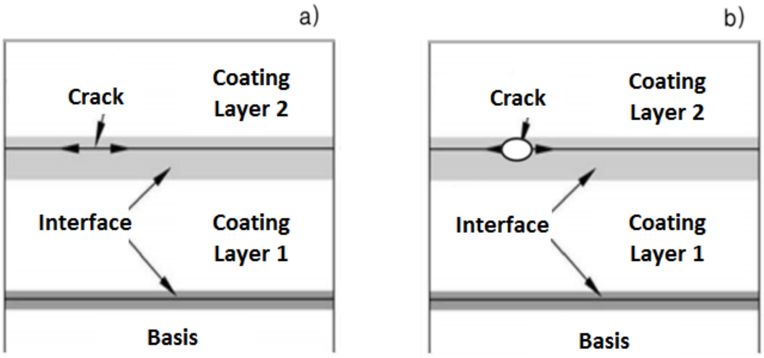

Figure 1. The scheme of the mechanism of the brittle fracture of the coatings with the two-layer architecture

Increasing the cyclic crack resistance of coatings can be achieved through the implementation of the authors' concept of the cluster and gradient architecture (CGA) of nanostructured topocomposites [14 - 18]. The concept is based on the joint implementation of the two ideas to ensure the increased cyclic crack resistance of coatings: the idea of limiting the formation of dislocations and their movements, which are the basis for the creation of super-hard and ultra-hard nanocomposite coatings, and the idea of creating locally dissipative structural elements. In particular, under the conditions of the NSTC tribocontact, the energy dissipation of the cracks is achieved by the energy dissipation directly on the clusters, "nanoplasticity" during their shift and rotation, as well as the braking of the cracks at the internal interface between the two layers by creating the barriers in the form of the "wave-like" transition layers (Fig. 2).

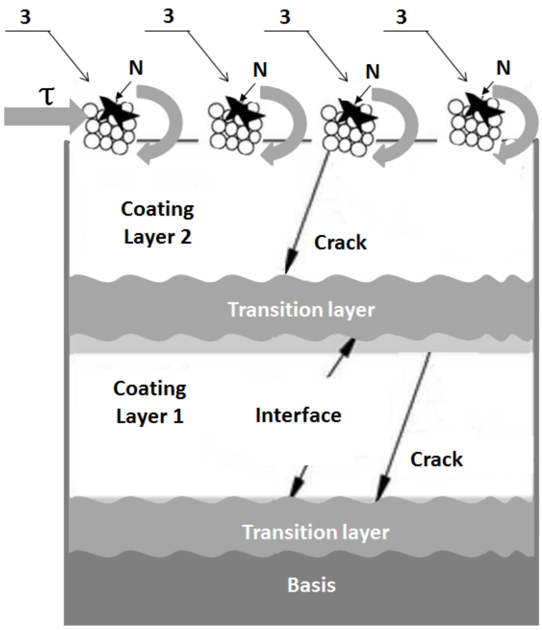

Figure 2. The scheme of the cluster-gradient architecture of nanostructured topocomposites. Designations: 3 – nanoclusters; N and τ – normal and tangential stresses respectively (The arrows indicate the directions of shift and rotation of nanoclusters)

In addition, under certain conditions of tribomechanical loading of NSTC, other mechanisms of manifestation of their structural and dissipative properties are possible.
The aim of the work is to study the wear resistance of nanostructured topocomposites with the clustered gradient architecture on the hard-alloy basis and peculiarities of their wear in terms of microcutting.

3. Materials and methods
The study of the wear resistance of NSTC with the cluster-gradient architecture (Table. 1) was carried out under microcutting conditions. For this purpose, the comparative assessment on values changes of friction coefficient and wear resistance of the samples was conducted. These samples were compared with the samples: BK8 with the coating TiN (h = 4 μm); 3 – BK8 with the coating, TiN/(Ti,Al)N (h = 60nm).

Table 1. Cluster-gradient architecture NSTC.

Mode number	Designations of the layer	Elements of the layer	Thickness of the layer
1	Basis	Hard alloy BK8	h = 5 μm
2	Transition layer 2	Ti, Co, W, C, N, O	h ≤10 mn
3	Coating layer 1	TiN	h = 30 ±1 nm
4	Transition layer 2	Ti, Al, C, N, O with nanocluster morphology	h ≤5 nm

The synthesis of nanostructured topocomposites of CGA was realized by the ion-plasma processing at the upgraded installation NNV-6.6 using the three cathode system in the presence of a reflector and a template in several stages [15, 16]. At the first stage, the samples were cleaned in the glow discharge. At the second stage, the surface was sprayed. The third stage consisted in the application of a TiN film with a thickness of about 30 nm and the formation of the transition layer at the boundary with the base material. At the fourth stage, the film of the same size with the composition (Ti,Al)N was applied. The third and fourth stages were carried out under the conditions of the cascade cross-effect [18]. For this purpose, high-voltage pulses of voltage with an amplitude of about 20 kV, a duration of 10...20 μs and a frequency of 10-15 kHz at a bias voltage of 1000 V were supplied to the substrate from the alloy BK8.

The process of microcutting was modeled on a special installation for testing thin modified layers, in which the test pattern was implemented: a fixed indenter - a rotating disk. For this purpose, a diamond indenter with a radius of R = 230 μm was used. The rotation speed of the samples was 200 rev/min. The load on the indenter was equal to N = 1 H.

The study of tribohardening effects was carried out by means of transmission electron microscopy and secondary ion mass spectrometry. The study of the structural state of the boundary layer after the wear was carried out on a microscope brand EMV-100L by transmission electron diffraction microscopy of thin foils. The production of foils was carried out from the plates of hard alloy cut parallel to the processed surface. Electrolytic processing then thinned them. To determine the chemical composition of the wear craters, the concentration dependences of the element distribution were obtained by secondary ion mass spectrometry on the SAJW-0.5 SIMS mass spectrometer.

4. Results and discussion

Fig. 3 and 4 show research results of wear resistance and, accordingly, changes in the friction coefficients of different variants of hard alloys with coatings. One can see that these relationships are correlated with each other. The site of the initial wear corresponds to a lower intensity and a lower coefficient of friction.

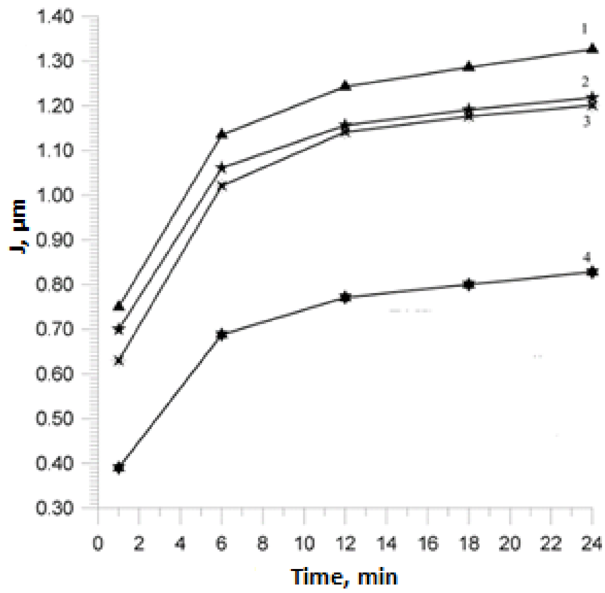

Figure 3. The dependence of the wear groove depth J of hard alloys on the test time t.
Designations: 1 – BK8; 2 – BK8 with the coating TiN (h = 4 μm); 3 – BK8 with the coating, TiN/(Ti,Al)N (h = 60 nm); 4 – BK8 with the coating, TiN/(Ti,Al)N (CGA)

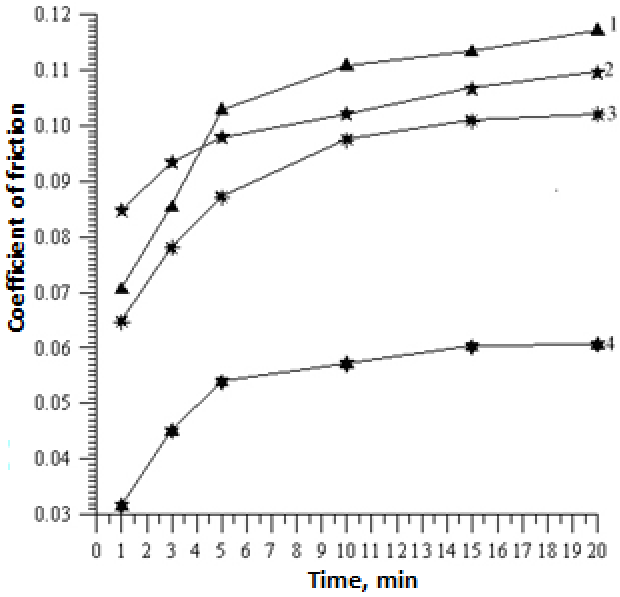

Figure 4. The dependence of the friction coefficient of hard alloys on the test time.
Designations: 1 – VK8; 2 – VK8-coated, TiN (h = 4 μm); 3 – VK8-coated, TiN/(Ti,Al)N (h = 60 nm); 4 – VK8-coated, TiN/(Ti,Al)N (KGA) (h = 60 nm)

The reason for the observed regularities can be interpreted from the perspective of the combined influence of two groups of factors. The first group of factors is associated with changes in the flow of physical and mechanical processes in the tribomechanical contact of the indenter with the surface of the NSTC. The second one – with the triboactive processes of structural-phase changes in the boundary layers of the topocomposite on the hard-alloy basis.
The first stage of the tribomechanical contact is the contact of the indenter with the clearly expressed structural inhomogeneous surface of the NSTC due to the presence of cluster formations, the length of which reaches a size of about 300 nm and a height of about 100 nm (Fig. 5). The second stage is the stage of interaction between the indenter and the nanocluster, because of which the elastic-plastic deformation of the modified layer and the dissipation of the tribocontact energy occur. It is due to both scattering directly on the clusters and implementing the deformation mechanism developing in accordance with the provisions of physical mesamechanics, according to the "shift + rotation" scheme [19].

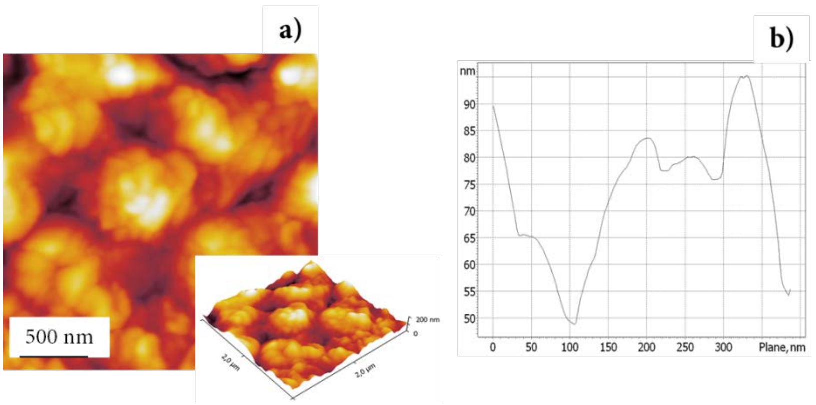

Figure 5. A typical image of the surface of nanostructured topocomposites with the nanocluster morphology. Designations: a – the circles show the areas of the nanoclusters; b – the sizes of the clusters

The third stage is the stage of the contact interaction, in which the friction goes into the process of microcutting (cutting) of the modified layers of the nanostructured topocomposites, accompanied by the cyclic character of the loading. The fourth stage is the stage of the tribointeraction of the diamond indenter directly with a hard-alloy basis, the dynamics of which is determined by the peculiarity of its heterogeneous structure. The specificity of this stage is that the microcutting process is also characterized by a cyclic character due to the periodic collisions of the indenter with the hard alloy carbides.

Despite the fact that the direct tribocontact of the indenter with the hard-alloy basis begins after about 5 minutes, there is a preservation of increased wear resistance of the hard-alloy material (see Fig. 3). The data obtained suggest that these effects are due to the formation of the secondary structures [20]. This is confirmed by the results shown in Fig. 6. It can be seen that even after 10 minutes of microcutting in the boundary layer of the hard alloy, signs of its strain hardening are observed. The formation of the block structure of the cobalt bond of strain microtwins in the carbide grains gives evidence to it.

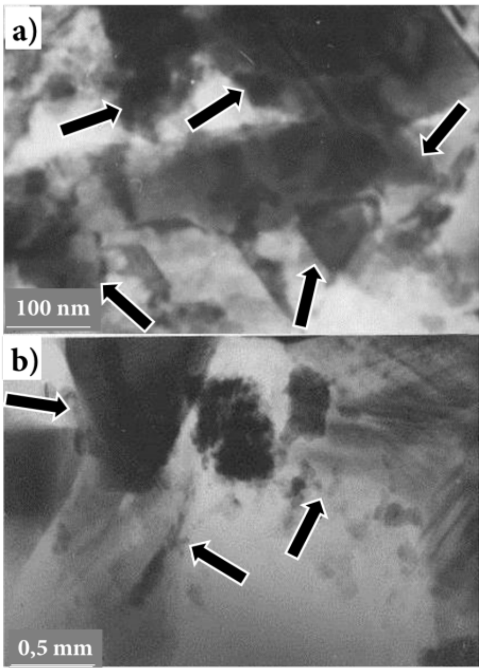

Figure 6. An electron microscopic image of the alloy structure in the contact zone. Microcutting time is 10 min. Designations: a) – microtwins in the tungsten carbide and a block dislocation substructure in the Co-phase in the area of the intrerphase; b) – deformation microtwins in the tungsten carbide (indicated by the arrows)

In addition, the formation of secondary structures at the initial stage of microcutting because of the triboactive processes according to the results of the chemical composition of the grooves as they wear (Fig. 7).

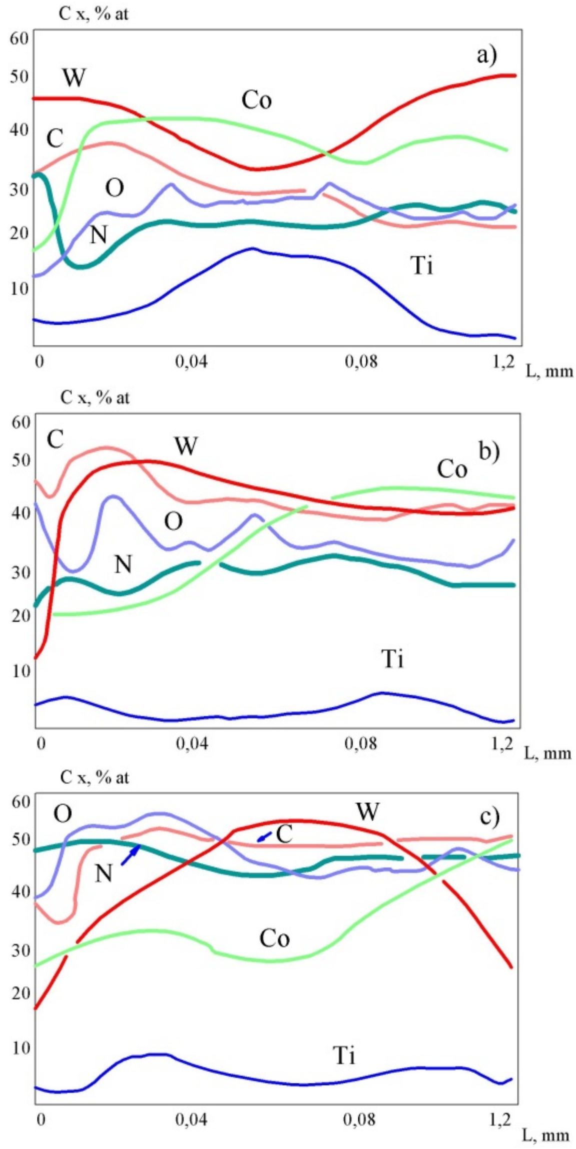

Figure 7. Concentration profiles of the distribution of the elements along the wear groove: a - after microcutting for 2 min; b – after microcutting for 4 min; c – after microcutting for 6 minutes

The analysis of the above dependencies shows that with the NSTC wear, the oxygen content in the contact surfaces increases, which indicates the formation of metastable oxygen-containing compounds. The obtained data are in good agreement with the results of the previous studies [21, 22], in which the positive role of the formation of energy-consuming oxide phases contributing to the effective dissipation of the frictional contact energy is justified. In addition, the formation of these compounds can help to protect the contact areas from adhesion hardening. It is confirmed by the results of the study of NSTC in the conditions of the edge cutting processing of the titanium alloy, characterized by the processes of the cyclic loads due to the elemental chip formation and the intensive course of the adhesion-fatigue effects (Fig. 8).

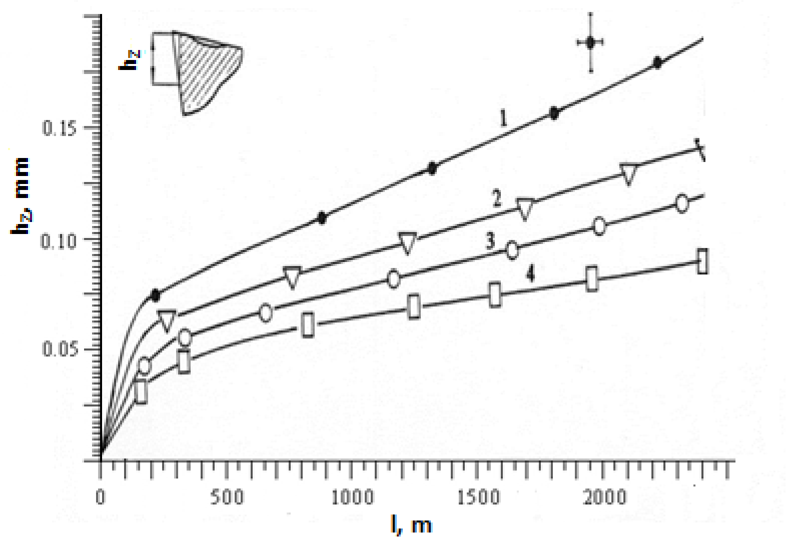

Figure 8. The kinetic dependence of the wear of the hard alloy ВК8 during cutting of the titanium alloy OT–4. Designations: 1 – ВК8; 2 – ВК8 with the coating TiN (h = 4μm); 3 – ВК8 with the coating, TiN/(Ti,Al)N (h = 60 nm); 4 – ВК8 with the coating TiN/(Ti,Al)N, (CGA); Cutting conditions: the speed V=80 m/min; the feeding S = 0.07 mm/rev; the cutting depth t = 1 mm

5. Conclusion

Studies have shown the feasibility of obtaining nanostructured topocomposites with the clustered gradient architecture for the technological purposes. The impact of their morphology on the specifics of tribointeraction in terms of microcutting. The specifics of cyclic loading were revealed. The analysis of the results showed that the high wear resistance of the NSTC is maintained after the wear of the modified layers, which is due to the formation of secondary structures. Moreover, the triboactive diffusion-oxidative processes contribute to providing wear resistance at the initial stage, and then maintaining high performance properties is due to the formation of the hardened sublayer at considerable depths.

Based on the conducted research, it is found that the creation of nanostructured topocomposites with cluster-gradient architecture allows us not only to increase the cyclic crack resistance of the surface layers of the material in the model conditions of microcutting, but also to increase the wear resistance of the carbide cutting tool in the edge cutting processing of the heat-resistant titanium alloy.

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