ISSN 1063-4576, Journal of Superhard Materials, 2018, Vol. 40, No. 6, pp. 424–431. © Allerton Press, Inc., 2018.
Original Russian Text © A.S. Manokhin, S.A. Klimenko, S.An. Klimenko, V.M. Beresnev, 2018, published in Sverkhtverdye Materialy, 2018, Vol. 40, No. 6, pp. 78–88.

Promising Types of Coatings for PCBN Tools

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Received November 13, 2017
Revised December 26, 2017
Accepted December 26, 2017

Abstract—The paper reviews the present-day trends in the development of new types of wear-resistant coatings, including nanostructured ones, for PCBN tools. The main currently pursued approaches to creation of high-hardness nanostructured coatings are discussed. Based on the analysis of wear behavior of PCBN tools, some new approaches to the development of promising wear-resistant coating systems have been identified, namely: (i) selecting the structural components of a coating, which should act as a hard grease to effectively reduce the tool wear rate; (ii) adding the compounds that inhibit any chemical reactions in the cutting zone; (iii) reducing the friction coefficient and contact loads through the use of solid lubricants and running-in layers of a coating; (iv) providing a coating with the required structural state.

DOI: 10.3103/S1063457618060084

Keywords: wear-resistant coatings, PCBN, coating application, turning, tool wear.

1. INTRODUCTION

The world leading tool manufacturers (ISCAR, Sandvik Coromant, Sumitomo Electric, and others) offer commercial cutting tools made of polycrystalline cubic boron nitride (PCBN), either solid or brazed-on inserts, with TiN, Ti(C,N), TiAlN coatings deposited by the PVD (physical vapor deposition) method. The recommended applications include machining of hardened steels at high and medium cutting speeds, continuous or light-duty interrupted cutting. According to the manufacturers' statements, the coatings on commercial PCBN tools improve wear resistance, especially resistance to crater wear, protect tools against the action of high temperatures, and serve the information purpose by facilitating a more accurate determination of the extent of wear on the cutting tools [1–3]. It has been also noted that the coated PCBN tools produce a workpiece surface microprofile with a relatively stable height of microirregularities.

There have been publications, though not numerous, regarding wear behavior of PCBN tools with AlCrN, TiN, TiAlN, and TiSiN coatings [4–8]. Figure 1 summarizes the tool life data for coated PCBN tools versus non-coated ones. It is evident that the deposition of coatings provides an improvement of tool life by, on an average, 30 to 40%, and it is only the nanostructured materials which significantly raise this parameter.

When analyzing the tool life of coated PCBN inserts under various cutting conditions and their wear mechanisms, researchers usually note that the main factor that dictate the coating effectiveness is the capability of the coating to retain its mechanical properties under high temperatures. The diagram shows that an increase in the cutting speed, which causes the contact temperature to exceed 1000°C, makes almost pointless the use of even the most thermally stable coatings, such as TiAlN and TiSiN, on PCBN tools. Clearly, thermal stability is a necessary prerequisite, but the mechanical strength of a coating is equally important. As recent experience demonstrates, a distinctive feature of wear kinetics of coatings on PCBN tools is that they tend to break down rather than be gradually worn with the formation of a wear land as early as during the running-in period (within 0.5–1.5 minutes of cutting), which is due to high stresses in the contact zone in the case of machining of hard-to-cut materials.

In this context, to achieve a further improvement of PCBN tools, it is necessary to develop and apply coatings whose working principle should be based on a more complex combination of tribological and mechanochemical effects that impart a coating with a capability to retain its integrity and properties under the action of high temperatures and contact stresses; this is related primarily with the control of structuring of protective coatings.

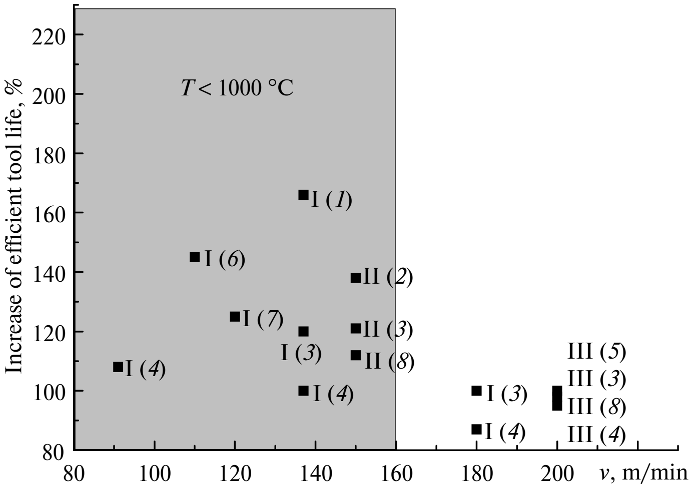


Fig. 1. The influence of coatings on the PCBN tool life in machining various workpiece materials: *I*—Din100Cr6 (HRC 62); *II*—AlSi330 (HRC 52); *III*—16MnCr5 (HRC 60); the tool coating composition: *1*—nACo(AlTiN-TiAlN/Si_3N_4); *2*—n-TiAlN; *3*—TiAlN; *4*—TiN; *5*—TiSiN; *6*—Al_2O_3-NbN; *7*—a-BN; *8*—AlCrN.

2. REVIEW AND DISCUSSION OF PROMISING TYPES OF COATINGS FOR PCBN TOOLS

The investigations addressing physical-mechanical properties of protective coatings and deposition methods as well as the coated tools application conditions have shown that nanostructured systems have higher values of hardness, fracture toughness, thermal stability, and offer better performance in comparison with the coatings whose structural elements are micron sized. With this background, one of the main tendencies in the development of coatings for cutting tools is to provide the nanoscale dimensionality both during the formation of structural elements of a coating and during the structuring of individual layers in multilayer composite coatings. The above-mentioned advantages of nanostructures has been theoretically substantiated by the fact of significantly changing physical-mechanical properties of a material with decreasing size of its structural components (grains, crystals) [9–12]. This effect is observed when the mean size of structural elements is within 40 nm. It is described by the Hall-Petch equation $\sigma_y = \sigma_0 + kd^{-0.5}$, which represents the dependence of the yield strength (hardness) of a polycrystalline material on its grain size. The strength of a composite should tend to theoretical ultimate shear strength. However, an increase of the volume fraction of grain boundaries and triple junctions with decreasing grain size leads to a changeover of the deformation mechanism, where the motion of dislocations that pass through the grains is replaced by the effects of slip at their boundaries. This results in deterioration of mechanical properties of the material when its grain size is below 10 nm [12].

Thus, the nanostructuring of a coating material is associated with choosing an optimal grain size from the strength standpoint, based on the balance between the Hall–Petch relation and the expression that describes the grain-boundary creep rate during any further decrease of the grain size.

A review of the currently available relevant publications enables us to identify the main lines of research on this range of problems:

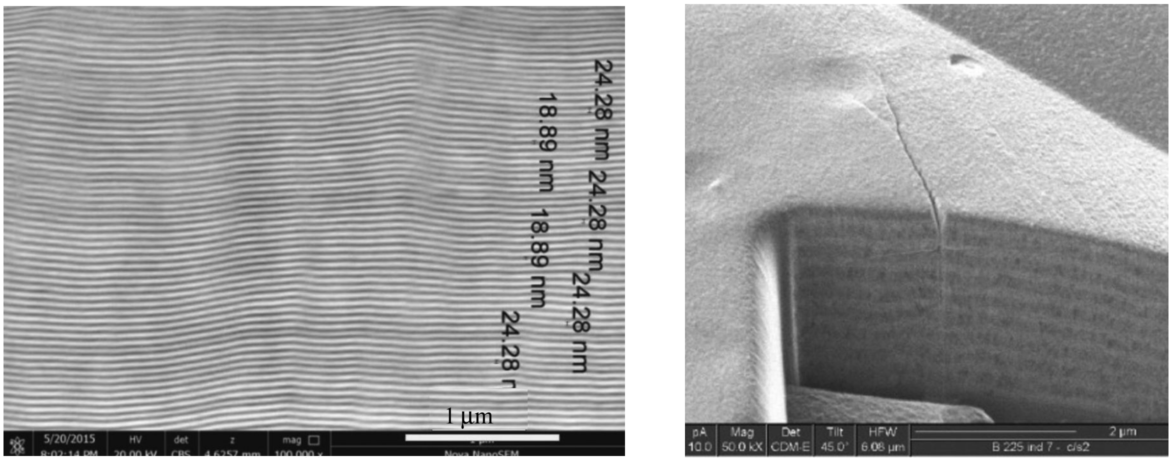
- a study of the process of ion bombardment during the coating deposition;
- creating a coating that would consist of hundreds of layers, each about 10 to 20 nm thick;
- formation of nanocomposite structures whose grain growth would be limited.

The ion bombardment during the coating deposition (ion beam assisted deposition (IBAD)) causes substantial changes in the structure and properties of the coatings. Specifically, the grain size is reduced, the grain boundaries become denser, some point defects arise inside the coating, and compressive stresses are formed. The investigations aimed at clarifying the pattern of influence of the substrate bias potential (that governs the energy of ions being deposited) on hardness, grain size, and residual stresses in coatings have demonstrated that with $U_b = 0-(-300)$ V the grains become smaller and the coating hardness grows, which is accompanied by an increase of residual stresses. Extremums of these relations are usually within the range $U_b = (-150)-(-300)$ V. Higher values of the bias potential (about −500 V) lead to degradation of mechanical properties of the coating due to depletion of light elements (Al, Si), reduction of nitrogen content, intensive formation of radiation-induced defects and buildup of an amorphous-like phase [11].

The drawbacks of the IBAD coatings include a low stability for their hardness decreases intensively with increasing annealing temperature up to 400–600°C [9], which is due to the relaxation of defects—the main source of strengthening and hardening. This fact outweighs the benefits of this approach to the development of coatings intended for improving performance of tools in cutting high-hardness materials.

In the case of producing multilayer nanothick coatings (Fig. 2a) [13], the fraction of interphases grows versus the total volume of interfaces. These interphases are obstacles for propagation of cracks and dislocations, thus providing an increase in hardness and strength of the material. One more factor that facilitates hardening is that the values of Young modulus of neighbor layers differ drastically. It has been also found out that in the case of friction testing of a coating with a nanolayered structure its wear was accompanied by the material damage to a depth of 1 or 2 layers of the film (6 to 8 nm). On the other hand, in a monolithic coating under the action of tangential contact stresses the plastic deformation of individual grains occurs in the layers at a depth down to 50–75 nm. Consequently, the wear rate of samples with nanolayered coatings during the tribological tests is much lower [14]. Alongside this, our experience suggests that in comparison with monolithic films the vacuum-arc-deposited nanolayered one on PCBN substrates offer a lower susceptibility to adhesive detachment, thus improving performance of cutting tools with this type of coating.

A clear experimental evidence of effectiveness of nanolayer-structured coatings is a micrograph of a surface area with a crack that runs into the coating in the vicinity of the indent. The coating cross-section was prepared by the focused ion beam (FIB) etching (see Fig. 2b) [16]. The crack growth into the coating is hindered due to the energy dissipation where the crack has to cross phase boundaries at layer interfaces.



(a) (b)

Fig. 2. The structure of a nanolayered coating (a) [15] and a crack in a multilayered coating (b) [16].

Much promise from the standpoint of application for PCBN cutting tools is shown by nanocomposite coatings. This is owing to the combination of high physical-mechanical properties, resistance to oxidation and dissociation of constituent chemical compounds, which is provided by a peculiar structure of nanocomposite films.

There are two types of nanocomposite structures [13]:

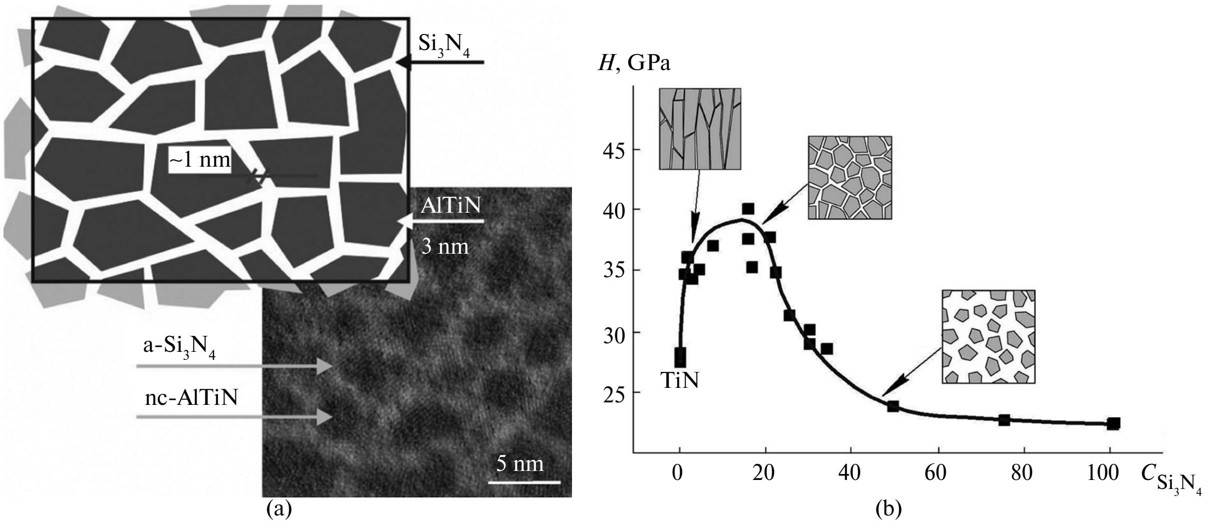
– a nitride nanosized phase embedded into an intercrystallite medium (nc-MeN/intercrystallite phase);

– grains of the same material make two phases with different crystallographic orientation, or a mixture of nanograins of different materials.

Wide acceptance has been gained by the first method of producing nanocomposite coatings of the type nc-MeN/α-phase, where the coatings are formed from nanograins of hard nitrides of transition metals with an amorphous intercrystallite phase matrix of TiB_2, Si_3N_4, BN, or other covalent-bond nonmetal nitrides. During the condensation of nitride-forming metals, with the introduction of silicon the grains growth of TiN, TiAlN, TiCr, etc., is suppressed due to the fact that these grains are embedded into the amorphous matrix whose thickness (based on the condition of providing the highest coating hardness) is as small as a few atomic layers (Fig. 3a) [17].

The resulting high hardness is qualitatively attributed to the finding that owing to small dimensions of nanograins the nucleation and glide of dislocations are hindered, while the high cohesive strength of the thin intergranular phase blocks the grain boundary sliding [10]. In this case, the amorphous component is capable to fit well with the surface of nanocrystals and provides a good adhesion, thus resulting in a higher strength [11]. The concept of producing such materials was first proposed by Veprek, and the last decade has seen intensive research efforts towards creating nanocomposite coatings. The authors of this concept state that such coatings, provide that a correct approach to their deposition is taken, can offer an unusual combination of mechanical properties, such as hardness of 40 to 100 GPa, elastic recovery of 80 to 94%, tensile strength close to theoretical strength for nonplastic materials (from 10 to more than 40 GPa). Furthermore, the nanostructure and the corresponding superhard state can remain stable at temperatures above 1100°C [12].

The best-studied systems that hold much promise for further progress of the nanocomposite coating concept are nc-TiN/α-Si_3N_4 and nc-TiAlN/α-Si_3N_4. It has been found out that the fundamental possibility of producing high-performance coatings based on these systems is subject to some critical prerequisites. Specifically, one of the main features of such systems is the presence of an optimal silicon concentration. The diagram in Fig. 3b) [18] schematically shows the mechanism of structuring of a nanocomposite coating.



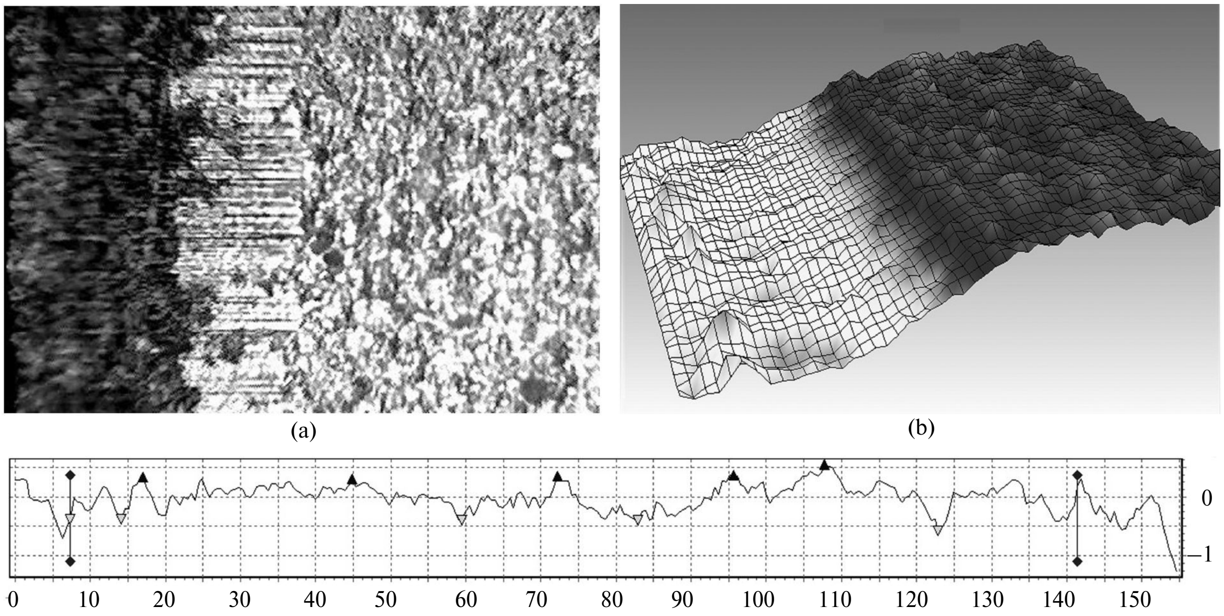
(a) (b)

Fig. 3. The structure of the coating nc-TiN/Si_3N_4 (a) and the influence of silicon content on the coating microhardness (b).

With an optimal concentration of the α-Si_3N_4 phase that builds the matrix, the growth of grains of the transition-metal nitride is suppressed, which provides an increase of the composite hardness in accordance with the Hall-Petch relation as mentioned above. As the silicon amount increases further on, the thickness of interlayers grows, cracks would start running through the matrix, and thus the mechanical properties of the coating deteriorate.

At present, the technology of producing nanostructured composite coatings has been commercialized by PLATIT (Switzerland). In particular, the coating *n*ACo^3® (nc-AlTiN/a-Si_3N_4) of hardness 41 GPA, with a special adhesive sublayer on a PCBN tool improves the tool life up to 1.6-fold in turning hardened steel 100Cr6 (*HRC* 61) (v = 140 m/min, s = 0.12 mm/rev, t = 0.25 mm). The materials of this type are nanocomposite coatings of the second generation. In addition to a significant hardness, they offer high thermal stability and low oxidizability and are recommended for the use in tools for machining high-hardness materials.

As mentioned above, brittle fracture of a coating during the tool running-in period is a typical case in turning of hardened steel workpieces. The assessment of contact loads shows that in machining high-hardness steel the normal and tangential stresses are as high as 2500 and 1100 MPa, respectively. The actual stresses are likely to be even higher because the real contact area of rough surfaces that participate in friction is much smaller than the nominal one, which is due to contacting on individual microirregularities. The magnitude of the loads can be reduced by making the coating design include a top layer serving the running-in purposes. The basic requirement to such a layer is that it should have a certain combination of plasticity and strength and its hardness may be essentially lower than that of the main working layer. Analysis of topography of the coating zones formed during the contact with the workpiece material in the process of cutting (Fig. 4) demonstrates that the height of microirregularities is represented by the values Rz = 0.8 μm (R_{max} = 1.6 μm). Thus, based on the condition that an equilibrium surface roughness should be generated within the running-in layer, the thickness of this layer should be at least 2 μm.



(a) (b)

(c)

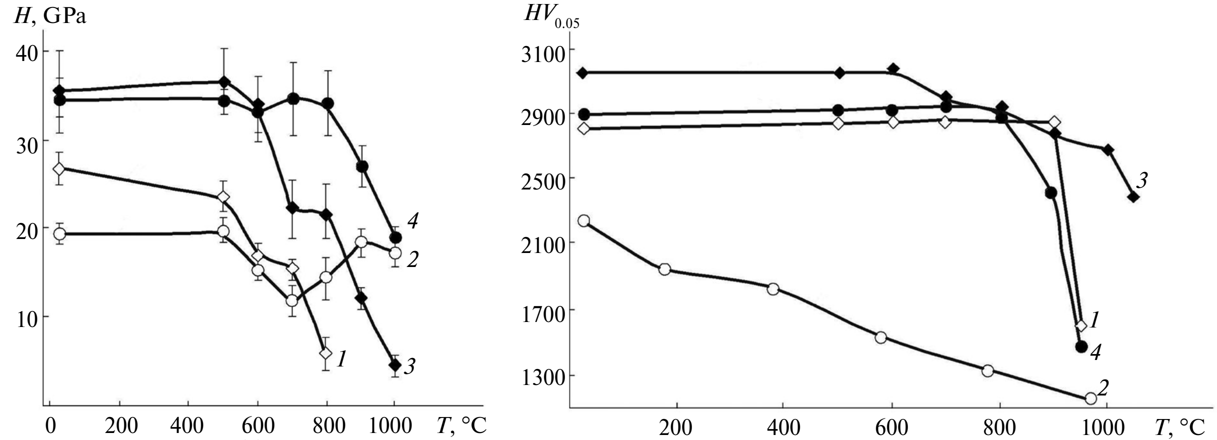
Fig. 4. A zone of the worn coated surface (a); topography of the contact surface (b); and a profile chart of the zone shown in a and b (c).

It can be assumed that the running-in layer material should have an amorphous-crystalline low-modulus structure (α-BN, α-Si_3N_4 or α-TiB_2), which would enable it to act as a solid lubricant. This coating design will reduce the likelihood of brittle spalling of the coating within a zone adjacent to the cutting edge, and thus will significantly improve the tool life.

Thermal stability is the second most important requirement imposed on coatings for PCBN tools. The experimental investigations on annealing of coatings and assessment of changes in their mass have demonstrated that thermal stability of conventional TiN, TiCN coatings is within 450 to 600°C. The most thermally stable coatings are those containing aluminum and chromium. The oxide (Ti, Al)N film that arises on the surface provides protection of the main coating material against oxidation at temperatures up to 850°C. If one considers only the chemical composition as a factors that governs thermal stability, the most effective coatings are those containing Cr for they are capable of resisting the action of high temperatures (1000 and 1100°C for CrN and AlCrN, respectively), while retaining their chemical stability, high hot hardness (Fig. 5) [19, 20] and hardness after annealing. This is attributed to an intensive diffusion of chromium towards the surface and the formation (at temperatures of 700 to 1000°C) of a dense structure of Cr_2O_3 that prevents destruction of AlCrN; therefore, this composition is very promising for further research. Another additive that effectively improves thermal stability of coatings is yttrium, which facilitates increasing oxidation resistance by forming the phase YO_x at grain boundaries. This additive leads to grain fragmentation and loss of columnarity of the condensate structure, which is important for ensuring wear resistance in friction [11].

Much like the mechanical properties, the thermal stability of coatings depends greatly not only on their chemical composition but also on their structure. In particular, the above-mentioned nanocomposite systems of type nc-MeN/α-phase (Fig. 6) feature an increased thermal stability [20]. The fine-grained polycrystalline materials undergo re-crystallization when subjected to annealing at $T \geq 0.4T_m$. The coating nc-TiN/a-Si_3N_4 on a silicon substrate has a thermal stability limit as high as 1100°C, which is 63% of the dissociation temperature of Si_3N_4. This increase of the temperature limit is due to the fact that no oxidation reaction occurs at the interface of the immiscible stoichiometric phases TiN and Si_3N_4, which is explained by the spinodal nature of phase segregation in this system [21].

The concept of structurally induced thermal stability has logically led to the approach as described below. It was assumed in [22] that grains, including nanosized ones, that make up a coating were in contact with the free surface and the grain boundaries served as conductors for oxygen, thus spreading oxidation processes throughout the coating. This is especially the case with columnar structures which are typical of the coatings such as TiN. Then, for the purpose of improving thermal stability of coatings it was proposed to use an intergranular vitreous phase which can be formed in nanocomposites by, for example, increasing the silicon content (> 40%) and thus the amount of the phase α-Si_3N_4. This concept is further supported by an experiment with annealing of the coating system TaSiN. With the silicon concentration above 50%, the coating structure is amorphous and at temperatures up to 1300°C it is only a thin top layer which undergoes oxidation, with no changes occurring inside the coating [23].



(a) (b)

Fig. 5. Hardness of coatings upon annealing (a), hot hardness of coatings and PCBN substrate (b): a—TiN (*1*), CrN (*2*), TiAlN (*3*), CrAlN (*4*); b—*n*-TiAlN (*1*), PCBN (*2*), AlCrN (*3*), TiAlN (*4*).

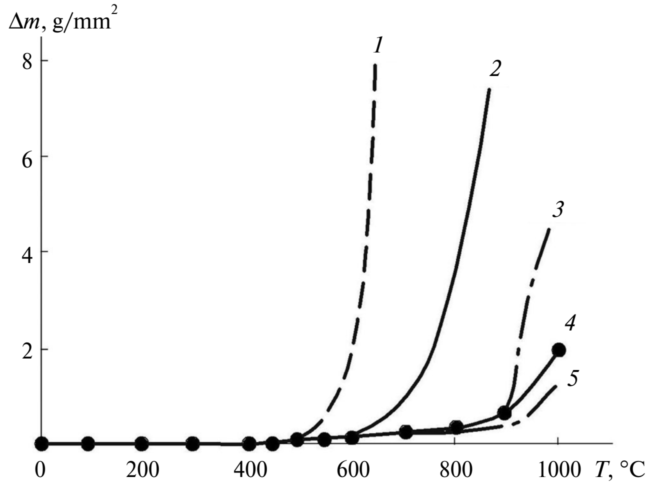


Fig. 6. Kinetics of oxidation of nanocomposite coatings in comparison with coatings of previous generations: cermet (*1*), TiN (*2*), TiAlN (*3*), nc-TiN/α-Si_3N_4 (*4*), TiAlCrYN (*5*).

A different mechanism of raising life of the tools designed for high-speed (and thus high-temperature) machining conditions takes place in the case of using self-adapting coatings. The main idea is not to prevent oxidation but to utilize this phenomenon in order to control the parameters of contact interaction in cutting and reduce the friction coefficient, thus lowering the pressure-and-temperature loads in the contact zone. In the process of cutting, such coatings are oxidized to form a polyoxide secondary structure (a tribofilm) that serves as a solid lubricant. It is known that the conventional solid lubricant materials are graphite, disulfates of molybdenum or tungsten, but they fail to provide the thermal stability required for the cutting-tool coatings. In view of this requirement and that a solid lubricant should have a low shear strength, it was proposed to use the coating AlN–Ti(Cr)B_2 [24]. In turning with a tool that has this coating, a polyoxide tribofilm comprising Al_2O_3, Fe_2O_3 and aluminum oxynitride $Al_xO_yN_z$ is formed on the tool surface. These compounds are thermally stable up to 1300°C and, furthermore, in these systems there arise homologous series of solid solutions of oxides, which have a good lubricating property. A study of the elemental composition of the coating upon the machining tests has revealed that at a depth of 70 nm there is an abruptly increased amount of oxygen, i.e., the top nanosized layer undergoes intensive oxidation, goes into wear debris, and is oxidized again. In this case, some limited solid solutions based on Al_2O_3 (systems Al_2O_3–Fe_2O_3, Al_2O_3–TiO_2, Al_2O_3–AlN) arise in the sublayer located at a depth of 30 to 70 nm. The performance testing of PCBN tools coated with AlN–

$Ti(Cr)B_2$ (the coating hardness $HV_{50} = 22.18$ GPa, which is lower than that of the substrate) has demonstrated a significant decrease of the tool wear resistance in turning hardened steel. This approach seems to hold much promise for finishing operations, while the main line of research would be to develop the coating systems containing SiC and AlN and remaining chemically stable at temperatures above 1300°C.

In [25] we put forward a concept of increasing PCBN tool life, which is based on lowering the contact temperature by coating the tool working surfaces with a material that reduces the friction coefficient. The main distinction of this coating is its amorphous-crystalline structural state and the similarity of its chemical composition to that of the substrate material. The effect is achieved through (i) a decrease of hardness in comparison with the tool base material (15 versus 38–40 GPa, respectively), which reduces residual internal stresses in the coating and brittleness of the coating material; (ii) a decrease of Young modulus, which improves elastic properties of the coating and its resistance to abrasion; and (iii) a lowering of the friction coefficient, which facilitates reducing of pressure and temperature loads on the tool working surfaces. The experimental investigations have demonstrated high performance characteristics of the cutting tool coatings. Specifically, the friction testing has revealed a decrease of the friction coefficient from 0.4 to 0.3 over the range of speed of relative movement 75–90 m/min. Also, it has been found out that the cutting temperature has been lowered by 15% and the tool life has been increased by 25%.

One more approach to improving tool life, which implements the idea of using a coating as an intermediate medium that would have a direct influence on the cutting process parameters, is to add coating components to inhibit chemical interaction between the tool composite and the workpiece material in the contact zone [26]. By suppressing the chemically induced wear mechanism of the cutting tool [27], such coatings increase the PCBN tool life in high-speed cutting or in machining of structural alloys whose constituents exhibit a high chemical activity in contact with PCBN.

3. CONCLUSIONS

Based on numerous investigations of the influence of various coatings on the PCBN tool wear mechanism, we recognize several interrelated approaches that provide a theoretical background for developing various promising coating systems:

– choose structural constituents for a coating, which would give rise, under the conditions of cutting in air, to some high-temperature polyoxide tribofilms acting as a solid lubricant on the tool working surfaces, thus effectively reducing the tool wear rate;

– add some compounds to serve as inhibitors of chemical interaction, which would shift the onset of active chemical interaction in the cutting zone toward higher cutting speeds;

– reduce the friction coefficient and contact loads through the use of solid lubricants and running-in layers in coatings;

– ensure a required structural state (amorphous-crystalline or nanostructured one) of coatings.

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Translated by Yu. Kravchenko