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ORIGINAL ARTICLE

Comparative analysis of cutting properties and nature of wear of carbide cutting tools with multi-layered nano-structured and gradient coatings produced by using of various deposition methods

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Abstract The aim of this work was to investigate mechanical and cutting properties, as well as the nature of wear and failure of carbide cutting tools with modifying coatings of two types: nano-structured multi-layered coating Zr-ZrN-(ZrCrAl)N, applied through the use of the technology of filtered cathodic vacuum arc deposition, and multi-layered nano-structured and gradient coating Ti-(TiAl)N-(TiAl)N, applied through the use of the technology of LARC® (lateral rotating cathodes). It is found out that the both types of coatings under test significantly improve tool life of a carbide cutting tool. The studies of mechanisms of wear and failure of carbide tools with coatings under test, conducted at macro and micro levels, have identified their major differences and revealed their most preferable field of application. The carbide tools, equipped with cutting inserts with the nano-structured multi-layered coating under study, provided a significant increase in cutting properties (tool life) of the tool in comparison with the uncoated carbide tool and in comparison with the reference carbide tool with TiN coating. The tool with the coating Ti-(TiAl)N-(TiAl)N under study demonstrated the increased wear resistance during 30–35 min of cutting, and then, the process of coating failure and tool wear was sharply intensified. For the tool with coating Zr-ZrN-(ZrCrAl)N, the tests revealed more evenly balanced wear during the whole operating time between failures. It should be noted that NMCC Zr-ZrN-(ZrCrAl)N are substantially thinner, and that fact predetermines their better resistance to failure because of crack formation, and the technology of its generation is more cost-effective.

Keywords PVD coatings · Tool life · Wear resistance coating · Carbide cutting tool

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1 Introduction

The need for constant growth of productivity of technological cutting systems produces ever greater requirements for the cutting tool, which is the weakest link in those systems. The operational properties of the cutting tool that have the greatest impact on the efficiency of cutting is the tool life, determined by operating time to failure and reliability defined by variation spread of wear resistance. The improvement of those properties increases the efficiency of machine-tool-workpiece system (MTWS).

One of the most effective and widely used methods to increase the performance properties of the cutting tool is in the directed modification of the properties of its working surfaces by application of functional coatings. It should be noted that, despite significant achievements in improving the different indicators of cutting performance in application of a coated tool, the application of such tool does not satisfy the increasingly growing demands for further improvement of the efficiency of technological cutting processes. In this context, the further studies directed to development of new concepts, innovative processes, and advanced technologies of generation of coatings for cutting tools that can confidently predict the further significant increase of operational properties of the cutting tools that contribute to the solution of challenges to improve the general efficiency of MTWS.

Among the main directions of such development, it is possible to determine, in particular, the coatings with nanometric structure (nanometric grain sizes of crystal structure and thickness of sublayers), multi-layered composite, and gradient and multicomponent coatings. The studies in this direction are being actively carried out in recent years [1–31].

In particular, the studies, the results of which are presented by Luo et al. [1], are focused on low-friction and wear-resistant TiAlN/VN multi-layered coating with a thickness of nanolayers about 3 nm. Coating has been deposited by using the combined cathodic arc etching and unbalanced magnetron sputtering deposition on HSS tools for dry cutting of aluminum alloys. The results show that the TiAlN/VN coated HSS tools achieved lower cutting forces, lower metal surface roughness, and significantly longer tool lifetime by three times over the uncoated tools as a result of the low friction and eliminated tool-metal adhesion. Under the same conditions, a TiAlN based multicomponent coating TiAlCrYN [1] also increased the tool lifetime by up to 100% despite the high cutting forces measured. Hovsepian et al. [2] presents the results of the studies of nano-scale TiAlCrN/TiAlYN coating. The coatings have been deposited by the combined steered cathodic arc unbalanced magnetron sputtering method. It is found out that this coating not only improves the oxidation resistance but also effectively reduces the coefficient of friction of the coating from 0.9 to 0.65 at temperatures in the range of 850–950 °C. The analyzed paper [2] has also revealed that during friction the coatings adapt themselves to the combined thermal and mechanical wear by the formation of highly lubricious vanadium-oxides due to high flash temperatures at the asperity contacts on the surface. Kathrein et al. [3] presents the results of the tests of $Ti_{1-x}Al_xN$-based coatings, which compositions included such elements as V, Ta, and B. The tests were carried out to study the cutting properties of cemented carbide inserts with single-layer coatings (TiAlVN, TiAlTaN, TiAlBN) and multi-layer coatings (TiAlN/TiAlVN, TiAlN/TiAlTaN, TiAlN/TiAlBN) compared with the TiAlN reference by dry milling of 42CrMo4 steel and by drilling and turning of Ck60 steel. The presented results show that the developed coatings provide the tool life which is 1.5–2 times higher than in the use of TiAlN reference, and multi-layered coatings provide the tool life, which is in average 50% longer than the tool life of a tool with monolayer coatings.

Stueber et al. [4] is focused on self-lubricating wear-resistant coatings. Those coatings make use of lubricious phases such as graphite, amorphous carbon, or MoS_2 incorporated into coatings. A series of (Ti, Al)(N, C) coatings with different carbon contents (0–28 at %) have been deposited by reactive magnetron sputtering of TiAl in a mixture of Ar, N_2, and CH_4 gases. Starting from a pure TiAlN coating significant changes in the microstructure of the coatings were observed dependent on the carbon concentration. Under optimum conditions nanocomposite coatings with a structure of a coexisting metastable hard, nanocrystalline fcc TiAlNC phase, and an amorphous carbon phase (a-C) have been deposited. Stueber et al. [5] considers different aspects of the synthesis, deposition methods, growth, microstructural evolution and properties of multifunctional, wear resistant, and lubricious nanocomposite coatings. These coatings have a special nano-architecture and are composed of the different carbon-based nanocomposite layers. The same paper presents the results of the tests of nanolaminated composite coating with a stacking sequence of each 50 layers of TiC/a-C and (Ti, Al)(N, C)/a-C shows promising properties and performance in tribological testing and in tool testing as well. The thicknesses of layers of the developed coating were 100–150 nm, and it was applied through new deposition route for magnetron sputtering method using ceramic composite targets.

Neidhardt et al. [6] presents the results of the studies of nanocomposite Ti–B–N coatings, deposited by high-rate reactive arc evaporation. Microstructural characterization shows a highly stressed nanocrystalline TiBN solid solution formed at lower N_2 fractions and a stable TiN/(amorphous) BN dual-phase structure. Stueber et al. [7] considers the challenges of design of protective PVD coatings for wear and tribological applications. In particular, it is focused on low-friction carbon-based nanocomposites in advanced multi-layered structures or the stabilization of a specific coating in another structure in a nanolaminated multi-layered composite.

The studies presented in papers [2, 8–15] are focused on various properties of multi-layered composite and nano-structured coatings of different compositions and architectures. In particular, the coatings with superlattice structures like (TiAl)N-VN [2], (TiAl)N-ZrN [8], (TiAl)N-CrN [9], (TiAlY)N-VN [10], (TiAlCr)N-(TiAlY)N [11], (TiAl)N-(TiAlCr)N [12], (CrAlY)N-CrN [13], TiCN-ZrCN [14], and (TiHf)N-CrN [15] were studied.

A number of papers are devoted to various studies of multi-layered composite nano-structured coatings with three-layer architecture [16–19], as well as nano-structured coatings of different compositions [20–23]. In particular, the studies were focused on such systems as Ti-TiN-(TiCrAl)N [16, 17], Zr-(Zr,Cr)N-CrN, and Ti-TiN-(Ti,Cr,Al)N [18]; Ti-(AlCr)N-(TiAl)N, Ti-(AlCr)N-(TiCrAl)N, Zr-(AlCr)N-(ZrCrAl)N [19].

It should be noted that the analyzed papers contain no justification for the choice of a multi-layered architecture of coating and present mainly the results of the study of crystal-chemical and physic-mechanical properties of coatings, while their cutting properties and the nature of wear and failure of a tool with developed coatings are not sufficiently studied. Thus, the conducted analysis of the results of the above studies allowed determining the main purpose of this paper.

The aim of the paper is to develop innovative types of nano-structured multi-layered composite coatings with increased efficiency for deposition on carbide cutting tools, designed for stationary conditions of cutting of structural steels. The objectives of the paper included the comparative studies of the efficiency of nano-structured multi-layered composite coatings, deposited on carbide substrates by using innovative technologies for generation of coatings on the basis of arc processes of filtered cathodic vacuum arc deposition (FCVAD) and magnetron processes of LARC® (lateral rotating cathodes).

Comparative data on the efficiency of both technologies allow developing the basis for the creation of physical models of the process, equipment, and technologies, combining both processes in one process unit to form a new generation of high-performance coatings.

The objectives of the paper also included the studies of cutting properties and mechanisms of wear of carbide tools with nano-structured multi-layered composite coatings, formed through the use of the technologies of FCVAD and lateral rotating cathodes. The tested coatings had a three-layer architecture that included an internal adhesive underlayer, an intermediate layer with nano-structured architecture, and a wear-resistant outer layer with nano-structured or gradient architectures.

2 Theoretical prerequisites

The coatings for carbide cutting tools used for stationary cutting of steels were developed on the basis of the conceptual provision on coating as an intermediate process medium between the tool material (carbide substrate) and the material being machined (structural steel). The dual nature of intermediate process medium is in the modifying effect on the working surfaces of the tool in order to improve their properties and at the same time reduce the level of thermo mechanical effect on tool contact areas. This concept requires using multi-layered architecture of coating, each layer of which should strictly perform the specific functions. In this regard, the study used three-component architecture of coating, consisting of:

- outer (wear-resistant) layer interacting with the material being machined;
- inner (adhesive) layer, directly adjacent to the tool material (substrate); and
- an intermediate layer in contact with both the outer and inner layers of the coating.

To improve the performance properties of the coating and the balanced combination of such important features as its hardness and plasticity, a technology for deposition of the coating was developed to form the nanostructure of each of the coating layers with three-component architecture. Those coatings were named nano-scale multi-layered composite coatings (NMCC).

The choice of composition and properties of each layer of coatings for cutting tools depends on such factors as:

– thermal-physical and physico-mechanical properties of the material being machined and the tool material;
– features of technological operations of machining (continuous and interrupted cutting, free and non-free cutting, hole machining, threading, gear cutting, etc.); and
– technological parameters of process and technology to form a coating.

The most important challenge in the development of a tool with NMCC is a qualitative assessment of the composition and properties of each of its layers for specific machining conditions. For this purpose, the study adopted a model of adhesion-fatigue wear of carbide tools for stationary machining of workpieces of steel, most adequately reflecting the processes of wear of its contact areas for the general machining conditions [24]:

$$M_a = K_a \cdot \rho\left(I \cdot \sigma_a / \sigma_p\right) \cdot F_a \qquad (1)$$

where,

$$\mathrm{I} = (N_T + N_M) \cdot F_a; N_T = \omega \cdot T \cdot e^{Q_T} \Big/ _{K_{\mathrm{BQ}}}; N_M \cong \rho_1 \cdot S_b$$

Ma—weight of tool material lost in wear; *Ka*—adhesion coefficient (volume); ρ—density of tool material; *I*—intensity of adhesion; σ_a—bond strength in adhesion nodes; σ_p—resistance power of tool material; F_a—actual area of contact; N_T, N_M—number of active centers per unit of contact area in thermal and mechanical activation, respectively; ω—frequency of natural oscillation of atoms of valence; *T*—time; Q_T—thermal activation energy; k_B—Boltzmann constant; θ—absolute temperature; ρ_1—dislocation density; *S*—average length of dislocation path; *b*—burgers vector.

In accordance with the assumed model of wear of carbide tools in the machining of structural steel, the criterion for optimal composition of wear-resistant coating layer is the minimization of the value of weight lost by the tool material (tool wear rate) $M_a \to min$. Qualitative measure of reduction in value of M_a can be as follows: melting point, hardness, and thermal conductivity of the material being machined, while the value of M_a will tend towards its minimum with the growth of those properties of the material of wear-resistant layer.

The material of wear-resistant layer was selected on the basis of the condition of minimization of the friction coefficient with relation to the material being machined, which can be fulfilled at a positive value of the isobaric potential of reaction between the material of wear-resistant layer and the material being machined at cutting temperatures. In this case, the tendency of both materials to adhesive interaction minimizes, and the temperature threshold of the beginning of hardening increases, while the power of frictional heat sources decreases.

When selecting a compound to be used as the material of wear-resistant layer of *NMCC*, the preference was given to the most hard and refractory compounds, containing statistical weight of atoms of the most stable electron configurations *(SWASC)* of sp^3 type (materials with predominantly metal bonds) and s^2p^6 type (materials with mixed types of bonds). The compound, which was used as the material of wear-resistant layer, provided the highest possible positive value of isobaric potential with regard to the material being machined and thus minimized the probability of the formation of stable adhesion build-up edge, increased the temperature of the onset of adhesion between the tool material and the material being machined at cutting temperatures, thus reducing friction.

When selecting the material for adhesive sublayer of *NMCC*, the study gave preference to compounds with predominantly metal bonds. One of the main conditions for selection of composition of adhesive underlayer was to provide a negative value of isobaric potential of the reaction (at temperatures of tool operation) not only with regard to the tool material, but also with regard to the properties of the outer (wear-resistant) layer of *NMCC*. The above condition of negative values of isobaric potential of the reactions was also implemented during the formation of intermediate layer of *NMCC* based on composite compounds with heterogeneous structure, which crystal-chemical properties were complementary with relation to the corresponding properties of the outer and adhesive layers.

Based on previously carried out research [19, 24, 28, 29, 32] *NMCC* Zr-ZrN-(ZrCrAl)N was chosen, as it previously showed the best result in turning of steel C45 (HB 200). This optimum coating thickness was 3–4 μm. Coatings with gradient properties Ti-(TiAl)N-(TiAl)N as it previously also showed the best result in turning steel C45 (HB 200) [20–23]. In this case the best result demonstrated when turning steel "thick" coating thickness of 8 to 12 μm. The object of the study was to compare the properties of the two coatings deposited using different techniques. In a sense, the selected coatings are "opposed" in their properties.

Thinner (about 3 μm) coating *NMCC* Zr-ZrN-(ZrCrAl)N, characterized by very high hardness (up to 42 GPa) and nanostructure with sublayer thickness of about 40 nm, was opposed to coatings with gradient properties Ti-(TiAl)N-(TiAl)N, characterized by hardness of about 33 GPa and thickness (10–12 μm) very high for PVD coatings.

Sobol et al. [33] have shown that the use of nano-scale sublayers during deposition of coatings on the basis of systems (TiZr)N results in formation of solid solutions: in sublayers ZrN, it is (Zr, Cr)N with reduced lattice period (period of 0.44221 nm), and in sublayers CrN (period of 0.4162 nm), it is solid solution (Cr ,Zr)N (period of 0.42934 nm). Formation of such transition zones of solid solution results in decrease in hardness from 42 GPa under condition of mononitride sublayers without registered solid solution formations down to lower hardness 30 GPa in appearance of solid solution zones. In the range of sublayer thicknesses of 20–300 nm, the tests revealed the dependence of hardness from sublayer thickness. Meanwhile, sublayers with smallest thickness showed the maximal hardness. Consequently, for the formation of *NMCC* Zr-ZrN-(ZrCrAl)N, the sublayer thickness was assumed as minimal (about 40 nm).

The presence of Al in surface layers of both *NMCC* Zr-ZrN-(ZrCrAl)N and coatings with gradient properties Ti-(TiAl)N-(TiAl)N allows, on the one hand, to significantly increase the oxidation temperature due to formation at elevated temperatures of thin dense layer Al_2O_3 on coating surfaces, which acts as a diffusion barrier, preventing penetration of oxygen into the coating [34, 35].

On the other hand, the presence of Al in surface layer of coating results in formation of aluminum oxides with favorable influence on cutting process [27].

Thus, the object of this study was to compare the cutting properties and wear mechanisms for two coatings, very different in structure and in technology of deposition, which meanwhile showed the best values of tool life during the earlier studies.

3 Experimental details

3.1 Deposition method

For deposition of *NMCC* on the base of Zr-ZrN-(ZrCrAl)N, a vacuum arc VIT-2 unit was used, which was designed for the synthesis of coatings on substrates of various tool materials. The unit is equipped with an arc evaporator with filtration of vapor-ion flow, which in this study were named as filtered cathodic vacuum arc deposition (*FCVAD*) [16–19, 32], which were used for deposition of coatings on tool of significantly reduces the formation of droplet phase during the formation of coating. The use of *FCVAD* process does not cause structural changes in carbide and provides:

high adhesion strength of the coating in relation to the carbide substrate;
control of the level of the "healing" of energy impact on surface defects in carbide in the form of microcracks and micropores and formation of favorable residual

compressive stresses in the surface layers of the carbide material; and

formation of the nano-scale structure of the deposited coating layers (grain size, sublayer thickness) with high density due to the energy supplied to the deposited condensate and transformation of the kinetic energy of the bombarding ions into thermal energy in local surface volumes of carbide material at an extremely high rate of about 10^{14} K/s.

When choosing the composition of NMCC layers, forming the coating of three-layered architecture, the Hume-Rothery rule was used (difference in atomic dimensions in contacting compounds should not exceed 20%).

Coatings with gradient properties on the basis of the system Ti-(TiAl)N-(TiAl)N were formed through the use of technologies LARC® (lateral rotating cathodes) on a unit Platit Pi 80 [25].

During the deposition of the coating, the following parameters of the process were used:

substrate bias voltage (*V*): −60... – 150,
cathode arc current (*A*): 52–125 (Ti) 65–110 (Al),
vacuum $\times 10^{-3}$ mbar:1.3 × 10^{-2}–8 × 10^{-3}, and
gas flow Q (sccm) Ar, 6; N_2, 200

An uncoated carbide tool and a carbide tool with traditional coating TiN, deposited through the use of standard vacuum arc technology of arc-PVD, were used as an object for comparative studies of tool life. Prior to deposition of coating, all carbide samples, as well as a reference uncoated sample, were preliminary subjected to low-energy high-current electron beam and alloyed with the reaction of formation of hafnium carbide within a composite carbide on the surface [20].

3.2 Microstructural and mechanical properties studies

For microstructural studies of samples of carbide with coatings, a raster electron microscope FEI Quanta 600 FEG was used. The studies of chemical composition were conducted with the use of a same raster electron microscope. To perform X-ray microanalysis, the study used characteristic X-rays emission resulting from electron bombardment of a sample.

Hardness (HV) of coatings was determined by measuring the indentation at low loads, according to the method of Oliver and Pharr, which was carried out on mikroindentometre microhardness tester (CSM Instruments) at a fixed load of 300 mN. The penetration depth of the indenter was monitored so that it did not exceed 10–20% of the coating thickness to limit the influence of the substrate.

The adhesion characteristics were carried out on a Nanovea scratch-tester. Indenter represents a diamond cone with apex angle of 120° and radius of top curvature of 100 μm. The tests were carried out with a load linearly increasing from 0.05 N to final (60 N). Crack length was 5 mm. Each sample was subjected to 3 trials. The obtained curves were used to determine two parameters: the first critical load L_{C1}, at which first cracks appeared in coating, and the second critical load L_{C2}, which caused the total failure of coating.

3.3 Study of cutting properties

The studies of cutting properties of the tool made of different grades of carbide with developed NMCC was conducted on a lathe CU 500 MRD in longitudinal turning of steel C45 (HB 200).

The study used cutters with mechanical fastening of inserts made of carbide (WC + 15%TiC + 6%Co) with square shape (SNUN ISO 1832:2012) and with the following figures of the geometric parameters of the cutting part: $\gamma = -8°$; $\alpha = 6°$; $k = 45°$; $\lambda = 0$; $r = 0.8$ mm.

3.4 Experimental plan

The experiments were carried out in dry turning of steel C45 at a_p = 1.0 mm; f = 0.25 mm/rev; at two cutting speeds: v_c = 200 m/min and v_c = 250 m/min.

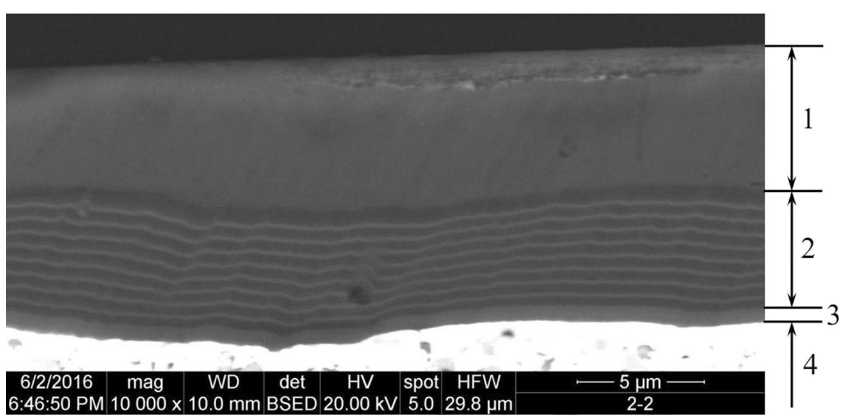

Fig. 1 Microstructure of transverse section of sample on the NMCC Ti-(TiAl)N-(TiAl)N. (LARC®): *1*—wear-resistant layer (thickness—6.0 μm, gradient structure); *2*—intermediate layer (thickness—4.8 μm, thickness of nanolayers 80–160 nm); *3*—adhesive layer (thickness—800 nm); *4*—carbide substrate.

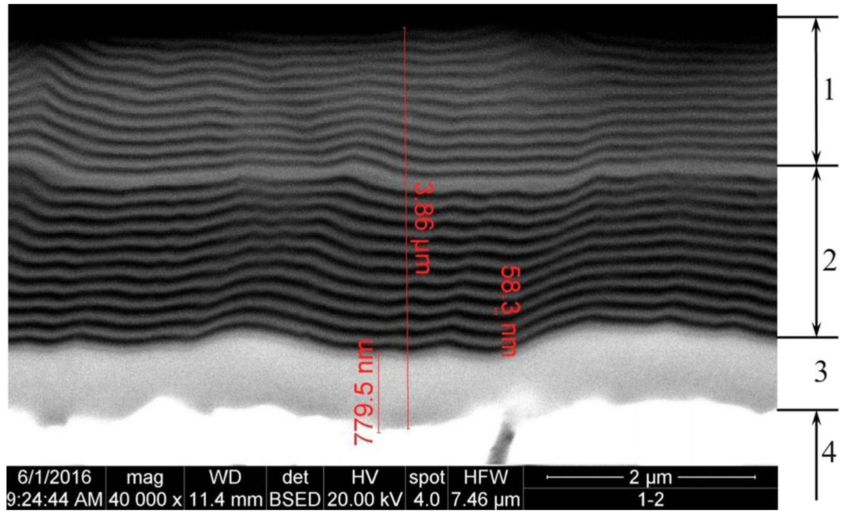

Fig. 2 Microstructure of transverse section of sample on the NMCC Zr-ZrN-(ZrCrAl)N. (FCVAD): *1*—wear-resistant layer (thickness—1.55 μm, thickness of nanolayers 40–100 nm); *2*—intermediate layer (thickness—1.53 μm, thickness of nanolayers 40–100 nm); *3*—adhesive layer (thickness—780 nm); *4*—carbide substrate.

To study the wear mechanism, the cutting process was interrupted after 1, 4, 7, 10, 13, 16, 19, 22, and 26 min and further after every 5 min of cutting. The cutting insert was installed on a toolmakers' microscope in order to measure rake and flank face wear rates, as well as to take images of wear. After that, the process of cutting was resumed.

Wear limit criterion was assumed at flank wear land VB_{max} = 0.4 mm.

4 Results and discussion

4.1 Study of microstructure and physical and mechanical properties of coatings

Examples of NMCC of three-layered architecture and nano-scale thicknesses of sublayers on transverse section are shown in Fig. 1 and Fig. 2. The results of the tests of the structure of NMCC Ti-(TiAl)N-(TiAl)N (technology LARC®) and Zr-ZrN-(ZrCrAl)N (technology FCVAD) reveal the following.

NMCC Ti-(TiAl)N-(TiAl)N consists of wear-resistant layer 1 with thickness 6.0 μm, with gradient structure, intermediate layer 2 with thickness 4.8 μm, with sublayer structure with thickness of sublayers of about 80–160 nm and adhesive layer 3 with thickness of 800 nm (see Fig. 1). NMCC Zr-ZrN-(ZrCrAl)N has a slightly different structure: outer layer 1 with thickness 1.55 μm, intermediate layer 2 with thickness 1.53 μm, with substructural composition with thickness of sublayers of about 40–100 nm, and adhesive layer 3 with thickness 780 nm (see Fig. 2). Microdroplets with diameter of 0.5–1 μm are detected in the structure of NMCC Ti-(TiAl)N-(TiAl)N. In the structure of NMCC Zr-ZrN-(ZrCrAl)N, small amounts of microdroplets of analogous dimensions were detected only on flank face of the tool.

The studies of strength of adhesive bond to substrate, carried out with the use of the method of scribing, showed sufficiently high strength of adhesive bond for the NMCC under study, while NMCC Ti-(TiAl)N-(TiAl)N demonstrated slightly higher strength of adhesion (56 N) in comparison with the analogous indicator for NMCC Zr-ZrN-(ZrCrAl)N (51 N). The measurement of microhardness of the NMCC under study, conducted with the use of microindentometer microhardness tester, demonstrated higher microhardness (38 GPa) of NMCC Ti-(TiAl)N-(TiAl)N in comparison with microhardness of NMCC Zr-ZrN-(ZrCrAl)N (34 GPa).

Table 1 presents the summarized results of the studies of microstructure and mechanical properties of the coatings under study, as well as the uncoated carbide insert and the carbide insert with the "reference" coating TiN.

The results of the tests of element composition of the NMCC under study are presented in Fig. 3a, b.

The results obtained find out the following. The processes LARC and FCVAD for the formation of NMCC Ti-(TiAl)N-(TiAl)N and Zr-ZrN-(ZrCrAl)N and the

Table 1 Microstructure and mechanical properties of NMCC under study.

No.	Structure of **NMCC**	The thickness of the sub layers (nm) and the total thickness (μm) of *NMCC*		Adhesion, N	Hardness, HV (GPa)
		nm	μm		
1	Ti-(TiAl)N-(TiAl)N	80–160	11.6	56	38
2	Zr-ZrN-(ZrCrAl)N	55–76	3.86	51	34
3	TiN	–	2.85	32	30

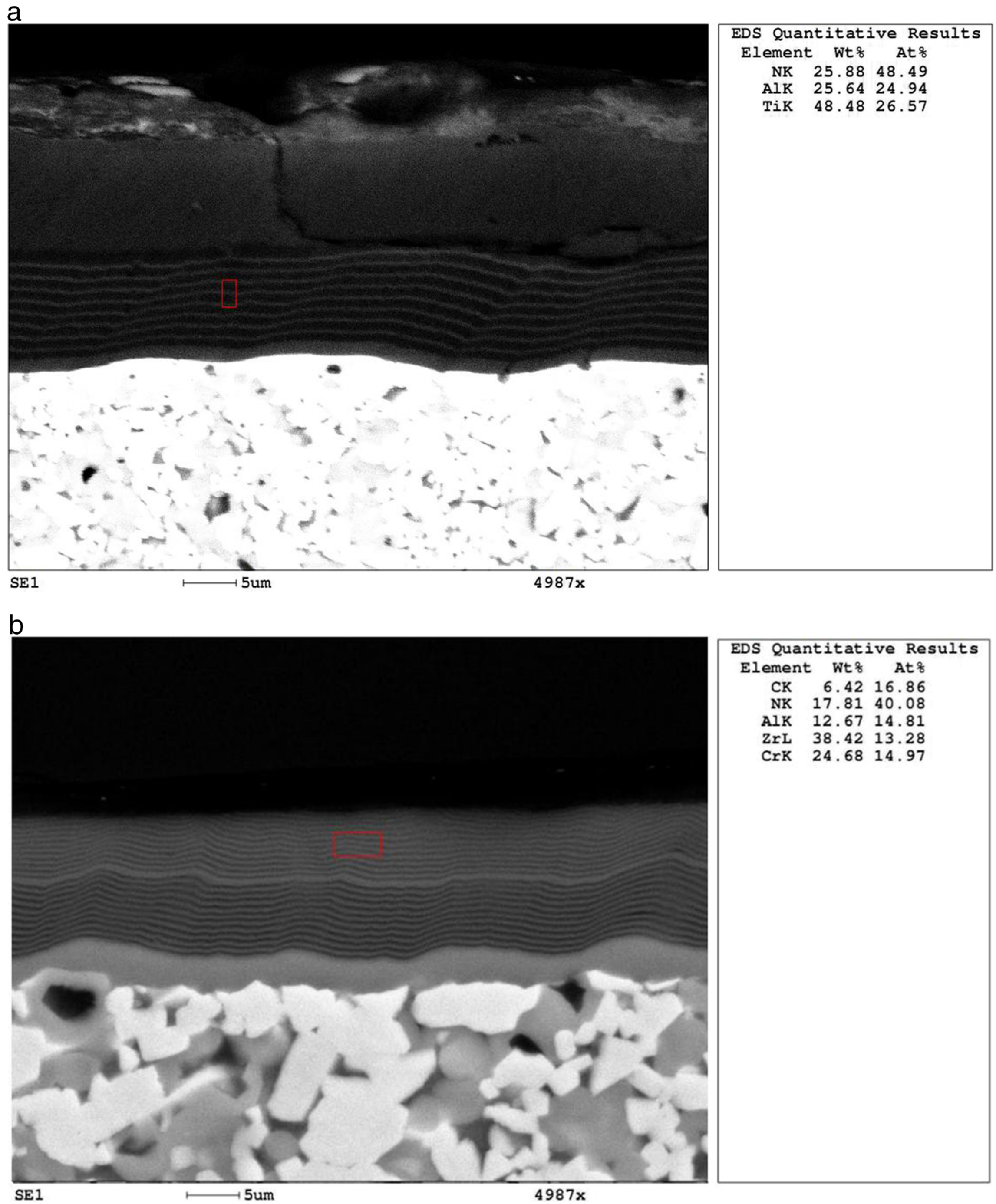

Fig. 3 Results of the tests of chemical composition of NMCC Ti-(TiAl)N-(TiAl)N (**a**) and Zr-ZrN-(ZrCrAl)N (**b**).

technologies based on them have significant differences; however, the NMCC under study are characterized by fairly similar properties, such as:

- low content or almost complete absence of microdroplets within NMCC volume or on its surface;
- high hardness and sufficiently high adhesion strength towards carbide substrate;
- nano-scale substructure of NMCC layers, providing maximum resistance of NMCC to cracking and brittle fracture; and
- three-layer architecture, consisting of outer, intermediate, and adhesive layers to provide complete compliance with the dual nature of the coating as the intermediate process medium between the tool material and the material being machined.

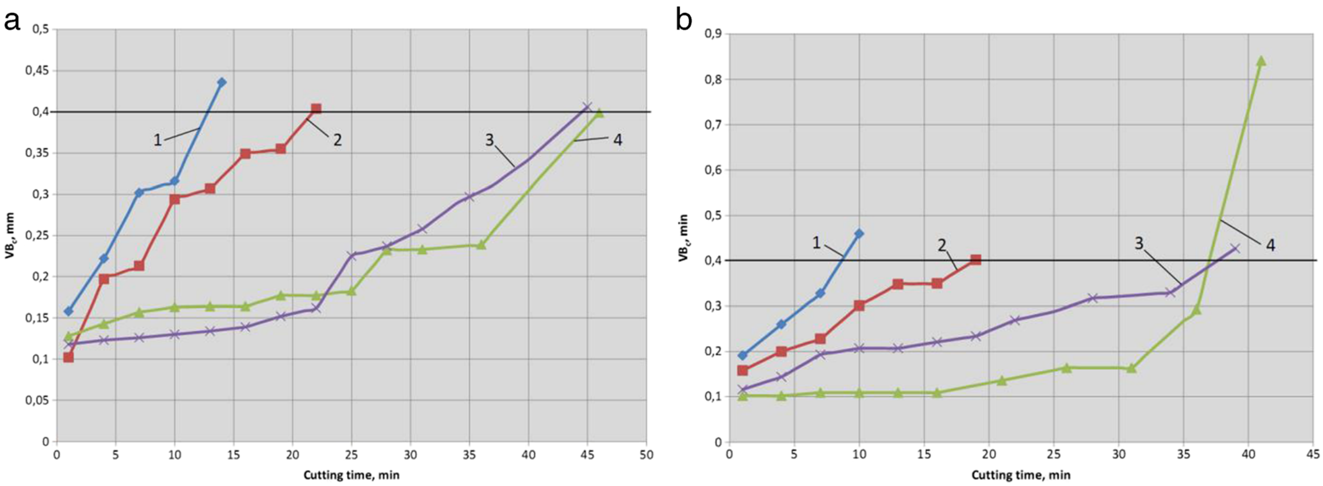

Fig. 4 Dependence of wear VB_{max} on cutting time at dry turning of steel C45 at a_p = 1.0 mm; f = 0.25 mm/rev; v_c = 200 m/min (**a**), and v_c = 250 m/min (**b**). *1* uncoated commercial carbide tool, *2* commercial carbide tool with TiN coating, *3* carbide tool with NMCC Zr-ZrN-(ZrCrAl)N, *4* carbide tool with NMCC Ti-(TiAl)N-(TiAl)N.

Meanwhile, NMCC Ti-(TsiAl)N-(TiAl)N is characterized by higher thickness and hardness and has slightly higher adhesive bond to the substrate.

4.2 Cutting properties of carbide tool with NMCC under study

The results of the study of cutting properties of carbide tools without coating, with standard reference coating TiN and with NMCC Zr-ZrN-(ZrCrAl)N and Ti-(TiAl)N-(TiAl)N under study are presented in Fig. 4.

When analyzing the results of the conducted studies of cutting properties of the tool, equipped with carbide inserts with the NMCC under study, the following can be noted:

– the carbide tools, equipped with cutting inserts with the NMCC under study, provided a significant increase in cutting properties (tool life) of the tool in comparison with the uncoated carbide tool and in comparison with the reference carbide tool with standard coating TiN;
– the carbide tools, equipped with cutting carbide inserts with the NMCC, deposited through the use of different techniques, had approximately the same cutting properties with different dynamics of their wear; and
– the difference in wear rates was particularly clear in machining at speed of v_c = 250 m/min; meanwhile, during about 30 min of cutting, the tool with NMCC Ti-(TiAl)N-(TiAl)N demonstrated significantly lower

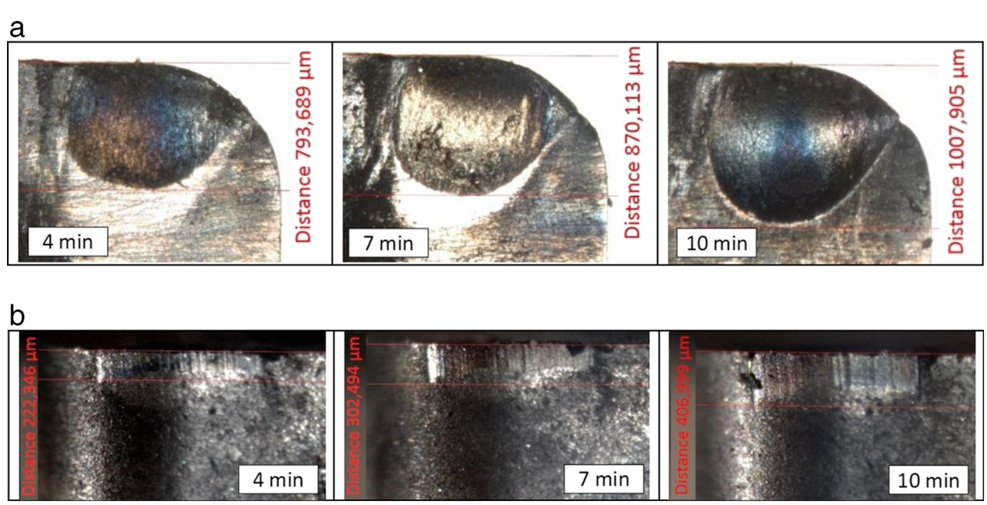

Fig. 5 Dynamics of wear of rake (**a**) and flank (**b**) faces of the uncoated carbide tool at dry turning of steel C45 at a_p = 1.0 mm; f = 0.25 mm/rev; v_c = 250 m/min.

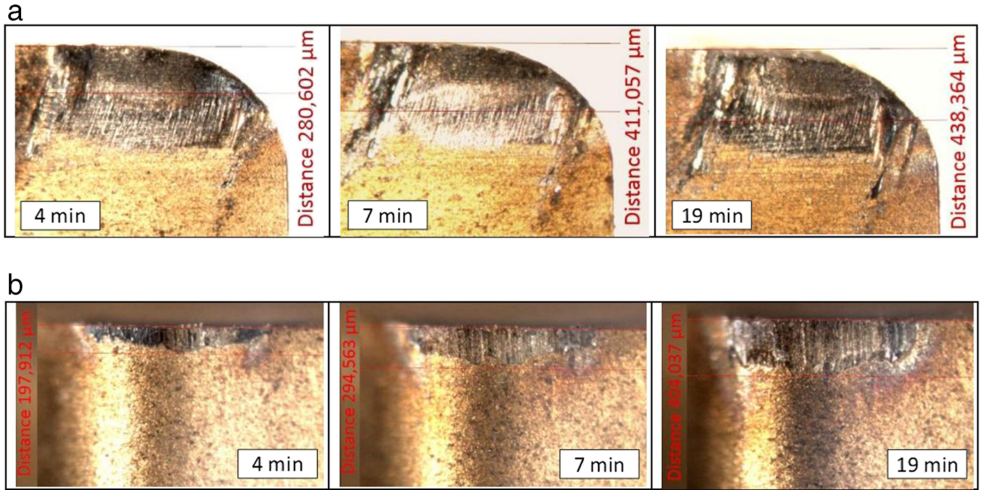

Fig. 6 Dynamics of wear of rake (**a**) and flank (**b**) faces of the carbide tool with coating TiN at dry turning of steel C45 at a_p = 1.0 mm; f = 0.25 mm/rev; v_c = 250 m/min.

wear in comparison with wear of the tool with NMCC Zr-ZrN-(ZrCrAl)N (see Fig. 4b). However, 30 min of cutting was followed by intensive (almost catastrophic) wear of carbide tool with NMCC Ti-(TiAl)N-(TiAl)N. It should be noted that the tool with coating Zr-ZrN-(ZrCrAl)N demonstrated more balanced wear (see Fig. 4b).

During machining at speed of v_c = 200 m/min, the kinetics of wear of the carbide tool with the NMCC under study was practically equal; however, at v_c = 200 m/min, 25 min of cutting were followed by significant increase in wear of the tool with NMCC Ti-(TiAl)N-(TiAl)N (see Fig. 4a), while at speed of v_c = 200 m/min, the tool with NMCC Zr-ZrN-(ZrCrAl)N demonstrates more balanced wear.

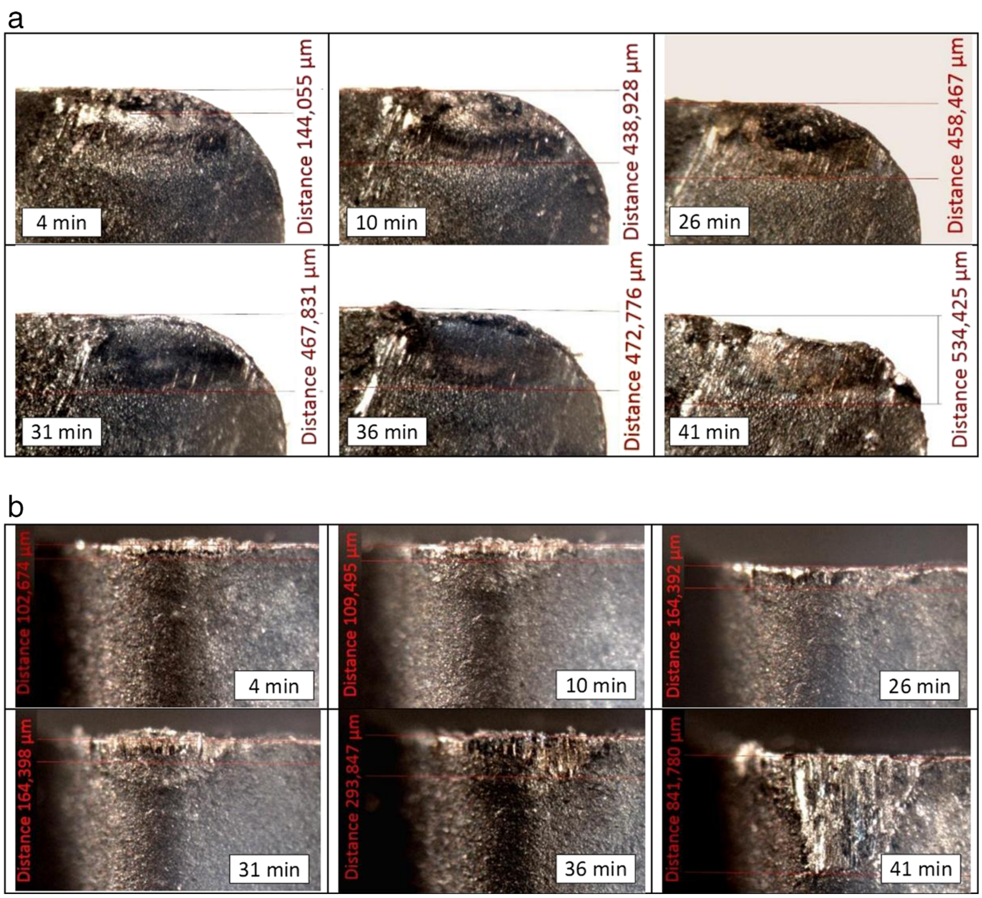

Fig. 7 Dynamics of wear of rake (**a**) and flank (**b**) faces of the carbide tool with NMCC Ti-(TiAl)N-(TiAl)N at dry turning of steel C45 at a_p = 1.0 mm; f = 0.25 mm/rev; v_c = 250 m/min.

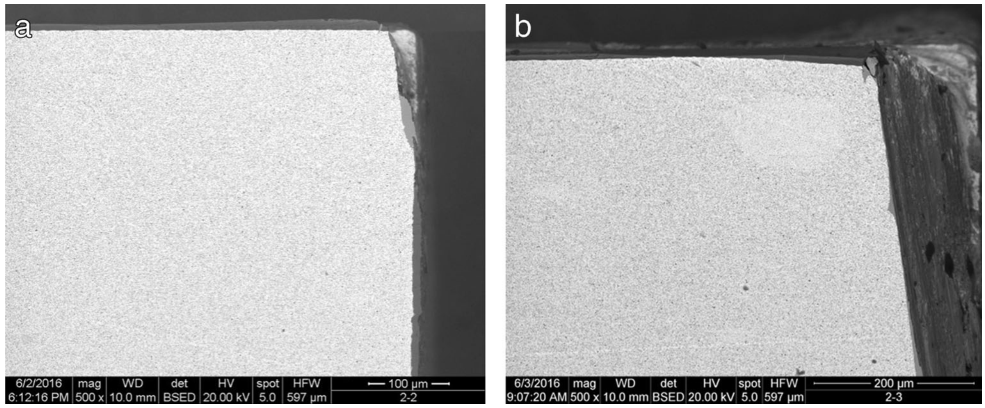

Fig. 8 General view of wear of the carbide tool with NMCC Ti-(TiAl)N-(TiAl)N after 41 min of cutting at dry turning of steel C45 at a_p = 1.0 mm; f = 0.25 mm/rev; v_c = 200 m/min (**a**) and v_c = 250 m/min (**b**).

4.3 Study of macromechanisms of wear and failure of carbide tools with developed NMCC

Macrostudies Mechanisms of wear and failure of carbide tools with developed *NMCC* were studied with the use of a standard toolmaker's microscope. Find below the data on the mechanism of wear of rake and flank faces of the tool, obtained at turning at cutting speed of v_c = 250 m/min; meanwhile, at turning at cutting speed of v_c = 200 m/min, the similar, but less clear dynamics of tool wear was observed.

The analysis of the pattern of wear of rake and flank faces of the tool shown in Fig. 5 allows noting the following. Wear of the uncoated carbide tool complies with the well-known assumptions: it occurs with formation of a clear wear crater on rake face and flank wear land (Fig. 5). In tool wear, the abrasive and adhesive-fatigue mechanisms of wear prevail.

The carbide tool with reference coating TIN showed a slightly different mechanism of wear. In particular, it demonstrated practically no wear craters on rake face and the most pronounced notch wear.

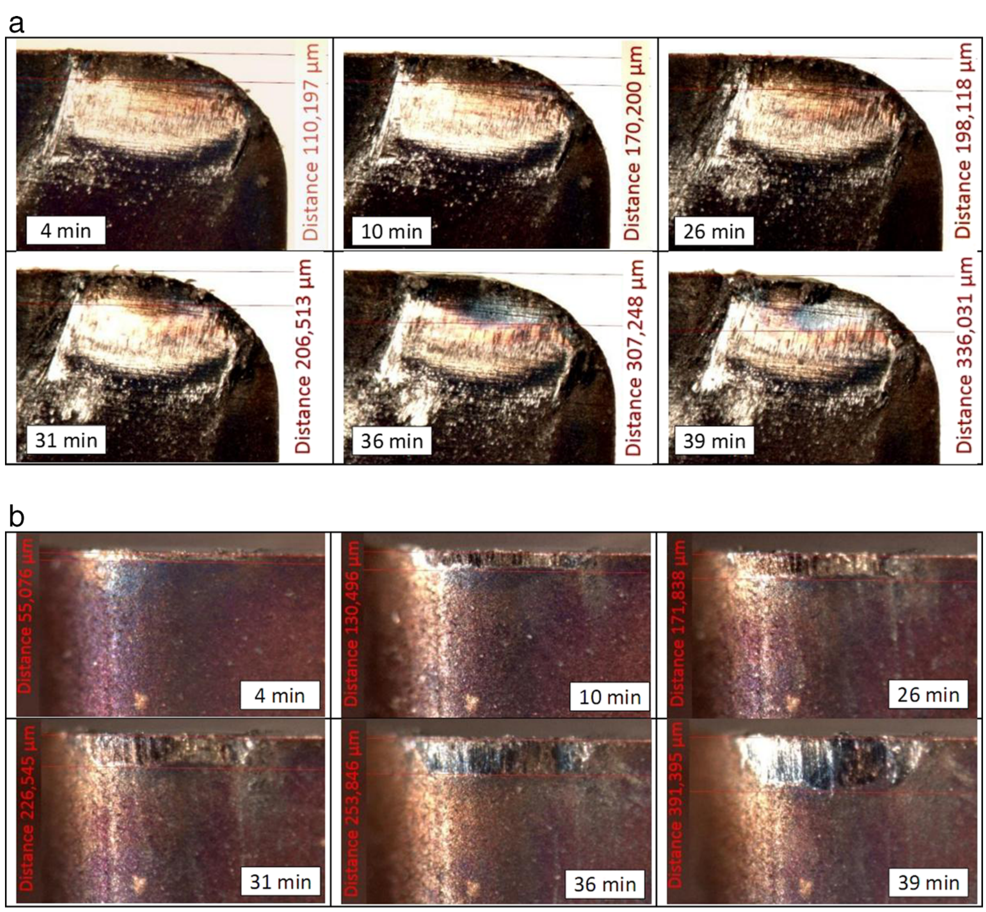

Fig. 9 Dynamics of wear of rake (**a**) and flank (**b**) faces of the carbide tool with NMCC Zr-ZrN-(ZrCrAl)N at dry turning of steel C45 at a_p = 1.0 mm; f = 0.25 mm/rev; v_c = 250 m/min.

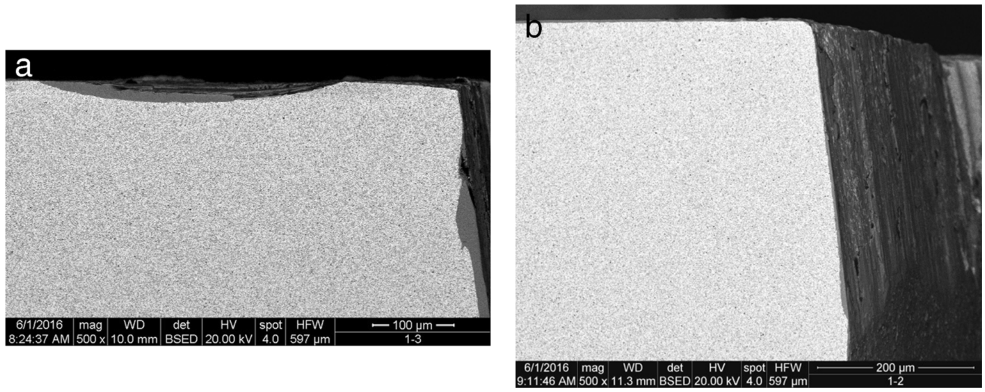

Fig. 10 General view of wear of the carbide tool with NMCC Zr-ZrN-(ZrCrAl)N on transverse section after 39 min of cutting at dry turning of steel C45 at a_p = 1.0 mm; f = 0.25 mm/rev; v_c = 250 m/min

The carbide tool with the NMCC Ti-(TiAl)N-(TiAl)N under study demonstrates significantly different pattern of wear. The tests showed practically complete absence of wear on rake face in a form of wear craters at longitudinal turning of steel both at v_c = 200 m/min and at v_c = 250 m/min (Figs. 6, 7 and 8). After 36 min of cutting at speed of v_c = 250 m/min, the tests showed sharp increase in the intensity of failure of NMCC on flank face, accompanied by a sharp increase in tool wear rate.

For carbide tool with NMCC Zr-ZrN-(ZrCrAl)N, it is typical when mechanism of wear takes an intermediate position between the pattern of wear of the uncoated tool and of the tool with NMCC Ti-(TiAl)N-(TiAl)N (Fig. 9). In particular, at turning at speed of v_c = 200 m/min, the tests demonstrated formation of a small wear crater on rake face (Fig. 10a); however, with the increase of cutting speed up to v_c = 250 m/min, the tests reveal practically complete absence of a wear crater on rake face (Fig. 10b).

4.4 Study of micromechanisms of wear and failure of coating

The analysis of the pattern of wear and failure of the NMCC under study on rake and flank faces of the tool, based on the studies of the cross-cut sections with the help of a scanning electron microscope (Figs. 11, 12), makes it possible to note the following:

- for the carbide tool with NMCC Zr-ZrN-(ZrCrAl)N, the tests revealed sufficient plastic deformation of carbide substrate, while the NMCC maintained strong adhesive bond to the substrate and was hardly affected by wear;
- the material adheres to flank face of the tool, and for the carbide substrate with NMCC Ti-(TiAl)N-(TiAl)N, the tests show "wedging" penetration of the material being machined between the substrate and the coating, especially at cutting speed of v_c = 200 m/min, while fairly extensive areas of carbide substrate still maintain the fragments associated with the adhesive layer of NMCC, while for NMCC Zr-ZrN-(ZrCrAl)N, no such a phenomenon is observed; and

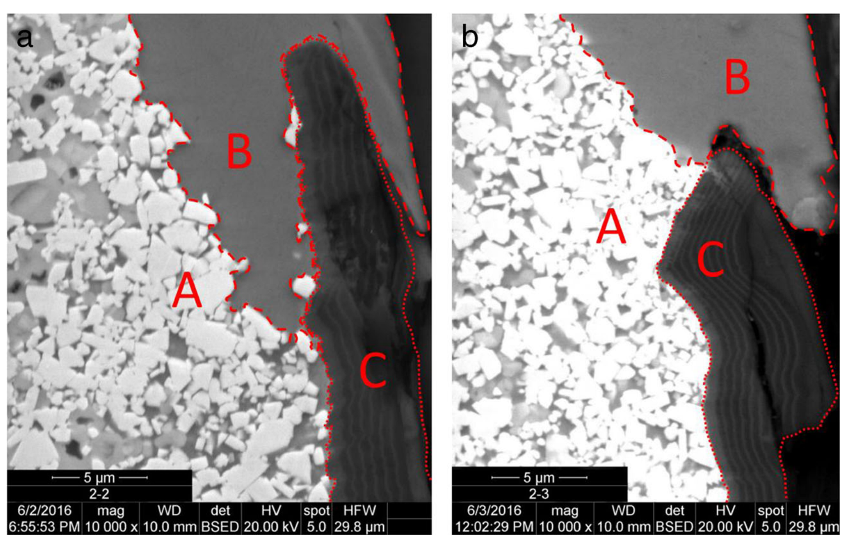

Fig. 11 Pattern of wear and failure of NMCC Ti-(TiAl)N-(TiAl)N on flank face of the tool at dry turning of steel C45 at a_p = 1.0 mm; f = 0.25 mm/rev; v_c = 200 m/min, (**a**) and v_c = 250 m/min, after 41 min of cutting (**b**). *A* carbide substrate, *B* machined material adherent, *C* coating.

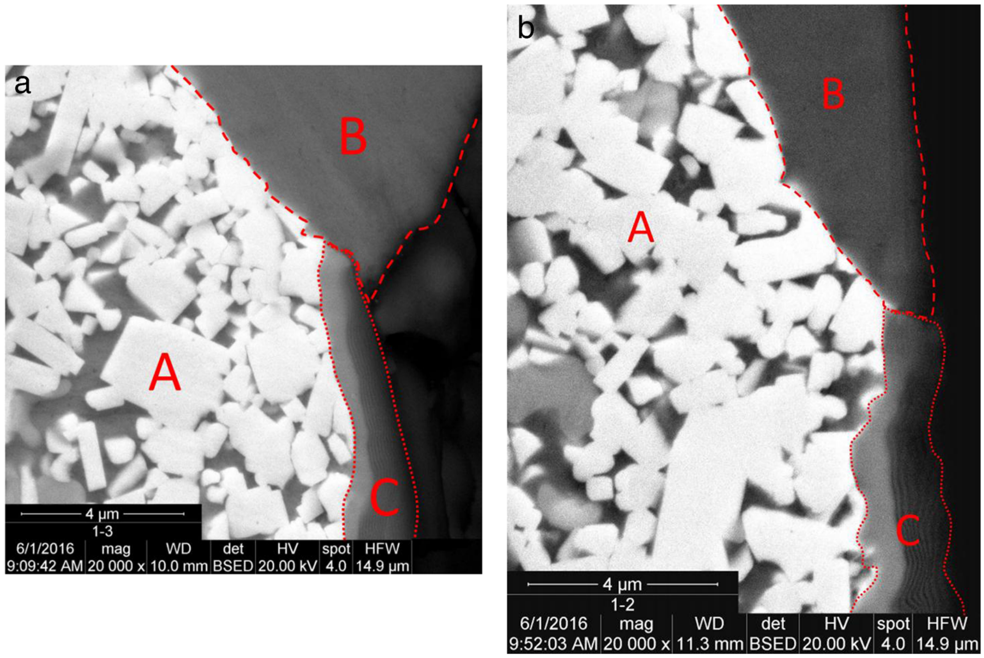

Fig. 12 Pattern of wear and failure of NMCC Zr-ZrN-(ZrCrAl)N on flank face of the tool at dry turning of steel C45 at a_p = 1.0 mm; f = 0.25 mm/rev; v_c = 200 m/min, (**a**) and v_c = 250 m/min, after 39 min of cutting (**b**). *A* carbide substrate, *B* machined material adherent, *C* coating.

for NMCC Ti-(TiAl)N-(TiAl)N, the tests showed intensive abrasive wear and brittle fracture of the surface layer, and that results in reduction of thickness of NMCC down to 5–6 μm. Thickness of NMCC Zr-ZrN-(ZrCrAl)N also reduces down to 1.7–2 μm, ~~but~~ mostly because of abrasive wear.

It is found out that the pattern of wear and failure of the NMCC under study on rake face is characterized by a number of essential features (see Figs. 13, 14, 15):

- NMCC on the basis of system Ti-(TiAl)N-(TiAl)N (see Fig. 13) is typically subjected to brittle fracture, accompanied by the formation of transverse cracks (see Fig. 14);
- the elements of the material being machined, which play a role of "wedge", simultaneously penetrate into some cross-cut sections of the coating, and that results in their "wedging" effect over the length of up to 1 μm (see Fig. 13b and Fig. 14a), with little changes in the total thickness of the coating, while no signs of abrasive wear are observed.

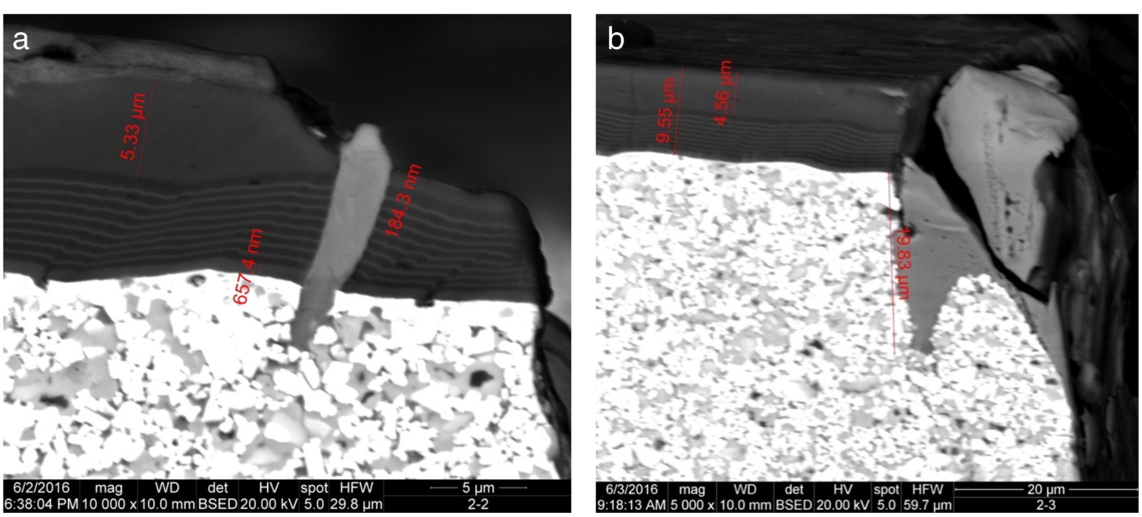

Fig. 13 Pattern of failure of NMCC Ti-(TiAl)N-(TiAl)N on the borders of cutting edge of carbide tool at dry turning of steel C45; v_c = 200 m/min, (**a**) and v_c = 250 m/min (**b**).

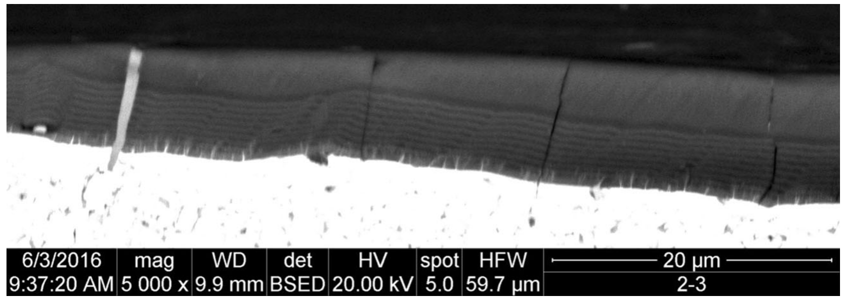

Fig. 14 Crack formation in NMCC Ti-(TiAl)N-(TiAl)N at dry turning of steel C45 v_c = 250 m/min.

– carbide tools with NMCC Zr-ZrN-(ZrCrAl)N are typically subjected to clear plastic deformation in the area immediately adjacent to the cutting edge, with the maintenance of a sufficiently strong adhesive bond between NMCC and carbide substrate, and the structure of NMCC is subjected to formation of longitudinal cracks resulting in its delamination (Fig. 15), especially at cutting at speed of v_c = 250 m/min.

5 Conclusion

As a result of the tests carried out, the study focused on mechanical properties, microstructure, cutting properties, as well as mechanisms of wear and failure of wear-resistant modifying NMCC, deposited on carbide cutting tools. As an object of the research, NMCC of two types were selected: NMCC Zr-ZrN-(ZrCrAl)N, deposited on carbide substrate with the use of the technology of filtered cathodic vacuum arc deposition, and multi-layered nano-structured gradient NMCC Ti-(TiAl)N-(TiAl)N, deposited with the use of the technology of LARC® (lateral rotating cathodes). The selection of NMCC with developed composition for the tests was justified by the designed theoretical concepts of NMCC and conditioned by high wear resistance of carbide tool with the coatings under study, found out by the results of the preliminary wear resistance tests. The tests of mechanical properties of NMCC revealed that the NMCC on the basis of system Ti-(TiAl)N-(TiAl)N is characterized by slightly higher

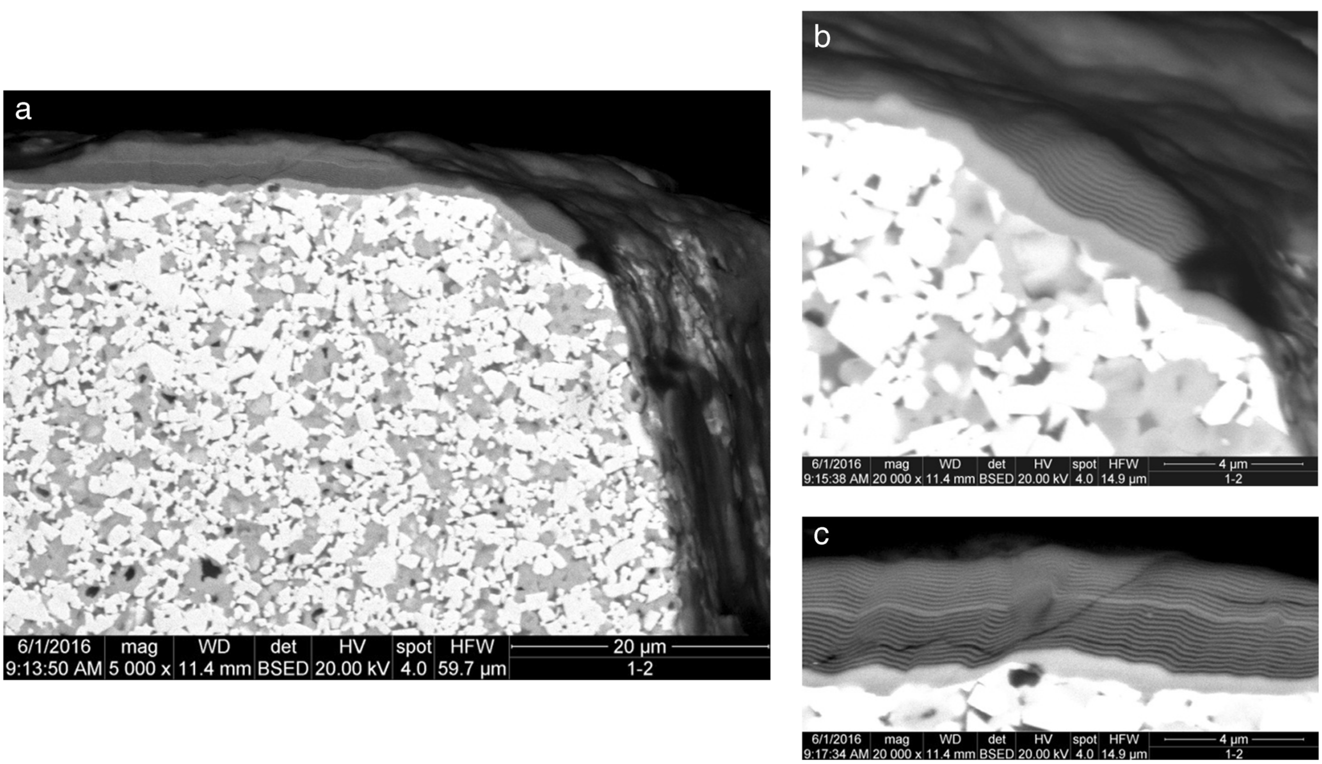

Fig. 15 Pattern of failure of NMCC Zr-ZrN-(ZrCrAl)N at dry turning of steel C45; v_c = 200 m/min.

microhardness and strength of adhesive bond to the substrate (56 N and 38 GPa, respectively), in comparison with coating Zr-ZrN-(ZrCrAl)N (51 N and 34 GPa), respectively. The thicknesses of the NMCC Ti-(TiAl)N-(TiAl)N and Zr-ZrN-(ZrCrAl)N under study reached 11.6 and 3.86 μm, respectively. Despite rather significant differences in their mechanical properties, the NMCC under study were characterized by approximately similar cutting properties at dry turning of steel C45 at $a_p = 1.0$ mm; $f = 0.25$ mm/rev; $v_c = 200$ m/min and $v_c = 250$ m/min. Meanwhile, the tool with the NMCC Ti-(TiAl)N-(TiAl)N under study demonstrated the increased wear resistance during 30–35 min of cutting, and then, the process of coating failure and tool wear was sharply intensified. For the tool with NMCC on the basis of system Zr-ZrN-(ZrCrAl)N, the tests revealed more evenly balanced wear during the whole operating time between failures. The studies of the mechanisms of wear and failure of the carbide tool with developed NMCC revealed their essential difference from the similar mechanisms of wear for the reference tool without coating and the tool with standard coating TiN. It is found out that at turning of steel, the uncoated carbide tool got a clear wear crater on rake face, and its combination with flank wear land resulted in the immediate complete failure of the tool. As far as a wear crater of rake face is concerned, then for the tool with the types of NMCC under study, it practically did not occur (for NMCC Ti-(TiAl)N-(TiAl)N), or it was unclear (for NMCC Zr-ZrN-(ZrCrAl)N). The mechanisms of wear and failure of NMCC Ti-(TiAl)N-(TiAl)N were accompanied by the active formation of through transverse cracks, with ill-defined abrasive wear and practically complete absence of thermoplastic deformation of carbide substrate. In that case, the main mechanism of wear was represented by brittle fracture of coating. For the tool with NMCC Zr-ZrN-(ZrCrAl)N, the studies revealed abrasive wear, accompanied by the formation of longitudinal (delaminating) cracks, with more sufficient plastic deformation of the surface layers of the substrate. Meanwhile, NMCC Zr-ZrN-(ZrCrAl)N was characterized by higher plasticity and sufficiently lower tendency to brittle fracture. The NMCC under study maintained strong adhesive bond to the substrate until the complete failure. The absence of significant plastic deformations in the surface layers of the carbide substrate with coating Ti-(TiAl)N-(TiAl)N can be explained by the fact that this thick and substantial coating plays a role of a kind of reinforced element, constraining the development of wear and plastic deformation of the carbide substrate. However, the relatively thick NMCC Ti-(TiAl)N-(TiAl)N are a subject to the formation of a crack network, which causes intensive failure of the coating and wear of the carbide substrate.

It should be noted that NMCC Zr-ZrN-(ZrCrAl)N are substantially thinner, and that fact predetermines their better resistance to failure because of crack formation, and the technology of its generation is more cost-effective.

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