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Wear Mechanism and Failure of Carbide Cutting Tools with Nanostructured Multilayered Composite Coatings

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Additional information is available at the end of the chapter

Abstract

The aim of this work is to study physical and chemical properties of nanostructured multi-layered composite coating based on three-layered architecture, deposited to a carbide substrate, as well as to study the mechanism of wear and failure of coated carbide tools under the conditions of stationary cutting. The coating were obtained by the method of filtered cathodic vacuum arc deposition (FCVAD). Here, the microstructure of coating as well as its hardness, strength of the adhesive bond to the substrate, chemical composition and phase composition were investigated on a transverse cross-section of experimental samples. The studies of cutting properties of the carbide inserts with developed coatings was conducted on a lathe in longitudinal turning of steel C45 (HB 200). The analysis of mechanisms of wear and failure of coated tool was carried out, including the processes of diffusion and oxidation in the surface layers of the coated substrate. Tools with harder and less ductile coatings showed less steady kinetics of wear, characterized by sharp intensification of wear and failure in transition from "steady" to drastic wear, i.e., at the end of the tool life. The X-ray microanalysis showed a considerable increase in oxygen content in the transverse cracks in the coating.

Keywords: nanostructured multilayer composite coatings, tool life, carbide cutting tool, crack formation, filtered cathodic vacuum arc deposition

1. Introduction

The efficiency of the cutting tool is a function of the complex processes of contact interaction between the tool material and the material being machined. This efficiency is determined by various factors, including: (i) the crystal-chemical, thermal-physical, and mechanical properties

of the material being machined and the tool material. Depending on the conditions of their contact, for example, dry cutting, cutting with CF (define CF) and type of machining operation, the level of thermomechanical loading on the cutting part of the tool may be influenced; and (ii) the geometrical dimensions of the cutting part of the tool, machining conditions, and the kinematics of motion of interacting tool and workpiece surfaces.

In accordance with the above, during the cutting process, the contact areas of the coated tool are exposed to a combination of factors that trigger their wear and fracture. Such factors usually include (i) an abrasive effect between the material being machined and the coated tool material; (ii) adhesive and adhesive-fatigue processes at the boundaries of the contact between the coated tool material and the material being machined, resulting in "ultimate fatigue" of local volumes, the tool material coating, the formation of cross cracks from fatigue, delamination, and finally the removal of fractured fragments of coating and damaged volumes of tool material (substrate) with trailing chips; (iii) macro- and microchips, as well as brittle fracture of local volumes of the tool material coating, resulting from exposure to pulsed shock loads; (iv) fracture of macrovolumes of the tool material and the material being machined as a result of the combined effect of alternating mechanical and thermal stresses; (v) corrosion and oxidation processes; and (vi) diffusion interaction between the tool material and the material being machined.

Depending on the cutting conditions, the above factors may become either dominant or play a secondary role. Until recently, many of the factors with strong influences on the wear and failure of coated tools were not well known. Therefore, a brief analysis of the publications devoted to research of mechanisms of wear/fatigue processes of cutting tools with complex composite coatings, formed with the use of the vacuum-arc technologies (arc-PVD), is presented below.

Harry et al. [1] studied the mechanism of cracking in tungsten-carbon–based multilayered coatings. The analysis of cracking probability showed a significant effect of the number and thickness of the elementary layers on the fracture resistance of the multilayered coatings. Mo et al. [2] and Birol [3] presented studies of coatings based on CrN, AlCrN, and AlTiN. Impact wear tests were performed to investigate the impact resistance of the coatings. There was no visible crack formation for all three coatings during the impact tests. The AlCrN coating exhibited the best impact wear performance. Nohava et al. [4] studied the properties of AlTiNAlCrN, AlCrON, and α-$(Al,Cr)_2O_3$ coatings. The main wear mechanisms at high temperature were oxidative attack accompanied by gradual material removal. Aihua et al. [5] studied the properties of the coatings TiN, TiAlN, AlTiN, and CrAlN. The wear mechanism of TiAlN was a combination of abrasive wear, oxidation, partial fracture, and microgroove formation. The AlTiN coating was worn by plowing and mechanical-dominated wear, and the damage was caused via a brittle failure mechanism. CrAlN coating presented the best properties of antispalling and antiadhesion. Antonov et al. [6] focused on the properties of gradient and multilayer coatings (AlTiN-Si_3N_4 and also TiN, TiCN, TiAlN, AlTiN). Erosive, abrasive, and impact wear tests were conducted. Henry et al. [7] studied the properties of six titanium aluminum nitrides $Ti_{1-x}Al_xN$ ($0 \leq x \leq 1$). Ti-rich and Al-rich films present two different wear mechanisms related to their toughness values.

To study the properties of coatings, a number of the papers used the method of nanoimpact testing. In particular, in the paper prepared by Beake et al. [8], this method was used to study the coatings $Ti_{1-x}Al_xN$ (x = 0.5 and 0.67). Skordaris et al. [9] studied multilayer TiAlN coatings with an Al/Ti ratio of 54/46. The coatings consisted of one, two, or four layers. Beake et al. [10] studied wear performance of end mill tools with AlCrN monolayer and AlCrN–TiAlN bilayer coatings. The impact fatigue fracture resistance of the AlCrN monolayer coating was lower than AlTiN and AlCrN–TiAlN bilayers (by nanoimpact test). In Ning et al. [11], a number of nanomultilayered $TiAlCrN/M_{ex}N$ coatings (where M_{ex} are transition metals such as Nb, Ta, Cr, W) and monolayer TiAlCrN coatings were tested during dry, high-speed end milling of hardened AISI H13 (HRC 55–57). The dominant wear mechanism for the worn coating zones was abrasion wear. The studies presented by Fox-Rabinovich et al. [12] were focused on the properties of the coatings on the basis of systems TiAlCrN, TiAlCrN/TaN, TiAlCrN/CrN, TiAlCrN/WN, and TiAlCrN/NbN nanomultilayered coatings. In another study, Fox-Rabinovich et al. [13] studied the properties of AlTiN and TiAlCrN PVD coatings. According to the authors [12], in many cases, the hardness of coatings can be a marginal property where the major properties are the plasticity and impact fatigue fracture resistance; a surface with these characteristics is able to dissipate energy by means of plastic deformation and thus surface damage and wear rate are reduced.

The wear propagation of a TiAlN coating during the impact test at temperatures up to 400°C was monitored by Erkens et al. [14] in terms of the coating fracture ratio (FR) versus the applied impact force. Beake and Fox-Rabinovich [15] applied high-temperature nanomechanical testing to the study of PVD coatings (AlTiCrSiYN, AlTiCrN, AlTiN, AlCrN, among others), to help explain why certain coating compositions work well in some applications, but not others. The hard-to-cut materials were being machined during high-speed machining tests. A recently developed multilayer coating, AlTiCrSiYN-AlTiCrN, with a combination of mechanical properties and microstructure can minimize crack formation and dissipate energy by crack deflection along interfaces. The studies were also focused on different mechanical properties of coatings such as (Ti, Cr, Al, Si)N [16], (Al,Cr,Ta,Ti,Zr)N [17], (Al,Si,Ti)N [18], Ti-TiN-(TiCrAl)N [19, 20], Zr-(Zr,Cr)N-CrN and Ti-TiN-(Ti,Cr,Al)N [21], and Ti-(AlCr)N-(TiAl)N, Ti-(AlCr)N-(TiCrAl)N, and Zr-(AlCr)N-(ZrCrAl)N [22].

The review prepared by Bouzakis et al. [23] presents a detailed overview of the available methods to control basic properties of wear-resistant coatings, including control over crack resistance. It should be noted that cracking of the coatings has a decisive influence on failure mechanism and performance of the cutting tool. Meanwhile, only a small number of papers are focused on the study of cracking in the coatings and their influence on performance of the tool. In particular, Tabakov et al. [24, 25] discuss the cracking mechanisms with regard to monolayered macrosize coatings on the basis of systems TiN, TiCN, (Ti,Zr)N, and (Ti,Zr)CN. It was found that the coatings of complex composition of (Ti,Zr)N and (Ti,Zr)CN types better resisted intense cracking in the coating material. Tabakov et al. also studied the multilayered coatings with macrosize structure, in particular, on the basis of systems TiCN-(Ti,Zr)N-TiN, TiN-(Ti,Zr)N-TiN, TiCN-(Ti,Al)N-TiN, and TiCN-(Ti,Mo)N-TiN [26]. The conducted studies have revealed that the introduction of zirconium nitride in the coating composition sufficiently reduced the tendency of cracking. These data were obtained from the study

of wear mechanisms of coated tool in milling of different materials under different conditions of cutting. The problems of cracking and brittle fracture of coatings Ti-TiN-(TiCrAl)N, Zr-(Zr,Cr)N-CrN and Ti-TiN-(Ti,Cr,Al)N; Ti-(AlCr)N-(TiAl)N, Ti-(AlCr)N-(TiCrAl)N, and Zr-(AlCr)N-(ZrCrAl)N were also discussed elsewhere [27–29].

The actual area of the surfaces of the material being machined and the tool material (including coated tool) in contact during the cutting process is less than their nominal contact area, which is predetermined by contact of vertical deviations of roughness. In the areas of actual contact, local specific pressure reaches a value at which plastic flow of metal occurs and thus the adhesion between the contacting materials dramatically increases. The initiation and failure of the adhesive bond bridging occur at high frequency of up to several thousand of failure per minute [30]. It is found out that the sizes of some adhesive spots vary from several micrometers up to several hundredths of a millimeter, and the actual contact area can reach 10–60% of the nominal contact area, while on a meter of cutting path, each contact point is exposed to shear stresses. Thus, this process determines the alternating loading of contact areas on front and flank faces of the tool and adhesive-fatigue nature of their macro- and microfracture (wear).

Tool materials are anisotropic and have various defects (inhomogeneity of structure, presence of pores, cracks, uneven distribution of residual stresses, inhomogeneity of chemical composition, etc.). Consequently, during the cutting process, along with the cut and separation of the material being machined, separation of fragments of the tool material particles also occurs. This separation is intensified as a result of the fatigue processes mentioned above and is defined as adhesive and adhesive-fatigue wear.

The most effective way to reduce these types of tool wear is to improve physical and mechanical properties of the tool material and, above all, its hardness by deposition of wear-resistant coatings. Furthermore, coatings with less physical and chemical affinities with respect to the materials being machined reduce the intensity of adhesion processes and significantly increase the wear of tool contact areas.

In an explanation of wear by the theory of adhesive-fatigue process, the separation of fragments from harder tool metal occurs, like in adhesive wear, because of presence of cracks. Cracks are formed because of the influence of two key factors: (i) repetitive mechanical stresses of a cyclical nature; and (ii) thermal stresses in the tool material characterized by different value depending on the distance from the surface of the tool contact areas. At periodic strain and compression of the upper layers of the tool material caused by mechanical or thermal influence, fatigue microcracks appear; further development then results in the growth and coalescence of microcracks, which causes separation of the fragment of the tool material and its subsequent failure.

The foregoing assumptions related to mechanisms of tool wear can serve as the basis for the formation of following requirements for coatings for cutting tools: (i) coating for a cutting tool should be structured in such a way that they form residual compressive stresses, which may act as a barrier for crack growth; (ii) coatings should have a multilayered structure so that their boundaries serve as additional barriers to crack growth; and (iii) the processes of formation of the coatings should contribute to formation of nanoscale grains and thicknesses of

coating sublayers, creating an optimum combination of high hardness and thermal resistance at sufficiently high fracture toughness.

2. Materials and methods

For the deposition of nanostructured carbide insert (CI) Scanning electron microscope (SEM) multilayered composite coatings (NMCC), a vacuum-arc VIT-2 unit was used, which was designed for the synthesis of coatings on substrates of various tool materials. The unit was equipped with an arc evaporator with a filtration of vapor-ion flow, which in this study was named as filtered cathodic vacuum arc deposition (FCVAD) [16–19] and was used for deposition of coatings on tool in order to significantly reduce the formation of the droplet phase during the formation of coating. The use of FCVAD process does not cause structural changes in carbide. Also it provides (i) high adhesive strength of the coating in relation to the carbide substrate; (ii) 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 (iii) formation of the nanoscale 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^{-1}.

When choosing the composition of NMCC layers, forming the coating of three-layered architecture, the Hume-Rothery rule was used, which states that the difference in atomic dimensions in contacting compounds should not exceed 20% [31]. The parameters used at each stage of the deposition process of NMCC are shown in **Table 1**. An uncoated carbide tool and a carbide tool with "reference" coating TiN, deposited through the use of standard vacuum-arc technology of arc-PVD, were used as objects for comparative studies of tool life.

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

Process	p_N (Pa)	U (V)	I_{Al} (A)	I_{ZrNb} (A)	I_{Ti} (A)	I_{Cr} (A)
Pumping and heating of vacuum chamber	0.06	+20	120	80	65	75
Heating and cleaning of products with gaseous plasma	2.0	100 DC/900 AC f = 10 kHz, 2:1	80	–	–	–
Deposition of coating	0.36	−800 DC	160	75	55	70
Cooling of products	0.06	–	–	–	–	–

I_{Ti} = current of titanium cathode, I_{Al} = current of aluminum cathode, I_{ZrNb} = current of zirconium-niobium cathode, I_{Cr} = current of chromium cathode, p_N = gas pressure in chamber, U = voltage on substrate.

Table 1. Parameters of stages of the technological process of deposition of NMCC.

use of the same raster electron microscope. To perform X-ray microanalysis, the study used characteristic X-ray emissions resulting from electron bombardment of a sample.

The hardness (HV) of coatings was determined by measuring the indentation at low loads according to the method of Oliver and Pharr [32], which was carried out on micro-indent-ometer Micro-Hardness 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 studied on a Nanovea scratch-tester, which represents a diamond cone with apex angle of 120° and radius of top curvature of 100 μm. The tests were carried out with the load linearly increasing from 0.05 to 40 N. Crack length was 5 mm. Each sample was subjected to three 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.

The studies of cutting properties of the tool made of different grades of carbide with developed NMCC were 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. The study was carried out at the following cutting modes: $f = 0.2$ mm/rev; $a_p = 1.0$ mm; and $v_c = 250$ m/min. Flank wear-land values (VB_c) were measured with toolmaker's microscope MBS-10 as the arithmetic mean of four to five tests and a value of $VB_c = 0.45–0.5$ mm was taken as failure criteria.

3. Results and discussion

3.1. Determination of basic properties of NMCC under study

The study was focused on the NMCC containing nitrides of Ti, Al, Cr, Zr, and Nb in its composition. For the detailed studies of various properties, NMCC were selected based on the following conditions: (i) if earlier studies showed a significant increase in cutting properties and reliability of the tool [19–22, 27–29] and (ii) if the thermodynamic criterion ΔG_r (Gibbs free energy change per mole of reaction) favored the formation of the NMCC.

In order to meet the research tasks, NMCC of various compositions were selected to meet the above conditions. NMCC Cr-CrN-(TiCrAl)N, Zr-ZrN–(NbZrTiAl)N, Zr-ZrN-(ZrCrAl)N, and Ti-TiN-(ZrNbTi) were deposited using the FCVAD technology. The thicknesses of the coatings used in the studies were 2.44–3.55 μm, and a wide range of thicknesses were selected to study the effect of coating thickness on the nature of cracking. The basic properties of the NMCC under study are presented in **Table 2**. Curves obtained by mathematical processing of the experimental data are shown in **Figure 1**.

It was found out that for longitudinal turning of steel under preset cutting conditions, the carbide tools with the NMCC under study had fairly close values of tool life of about 31–37 min,

#	Composition of NMCC	Tool life T_c (min) VB = 0.4 mm	Sublayer thickness (nm)	Total thickness (μm)	Adhesion, L_{C2}, N	Hardness, HV, GPa
1	Uncoated	8	–	–	–	18
2	TiN	18	–	2.85	31	30
3	Cr-CrN-(TiCrAl)N	31	30–45	2.75	>40	38
4	Ti-TiN-(NbZrTiAl)N	35	45–60	3.30	>40	34
5	Zr-ZrN-(ZrCrAl)N	37	15–45	2.44	39	36
6	Ti-TiN-(ZrNbTi)	38	55–75	3.55	32	35

Table 2. The basic properties of the NMCC.
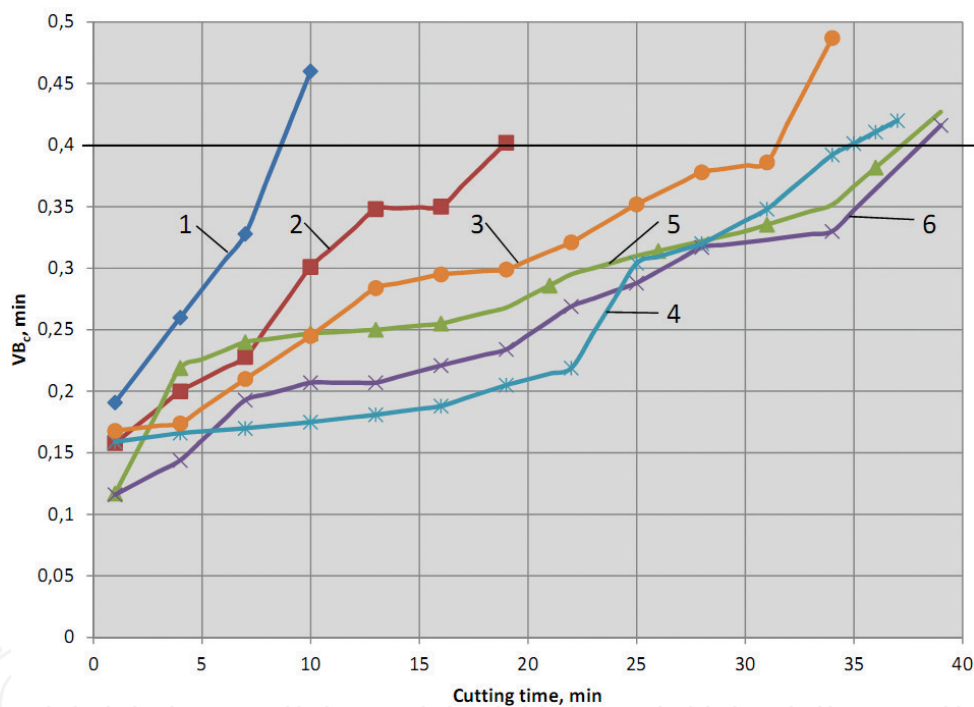
Figure 1. Dependence of wear VB on cutting time at dry turning of steel C45 at a_p = 1.0 mm; f = 0.2 mm/rev; v_c = 250 m min^{-1}. 1—Uncoated; 2—TiN; 3—Cr-CrN-(TiCrAl)N; 4—Zr-ZrN–(NbZrTiAl)N; 5—Zr-ZrN-(ZrCrAl)N; 6—Ti-TiN-(ZrNbTi).

while the nature of wear of the carbide tools with the different NMCCs under study had significant differences. In particular, NMCC Zr-ZrN-(ZrCrAl)N provided the greatest increase in tool life, reaching 37 min at stable kinetics of wear on the stages of running-in, steady, and catastrophic wear (see **Figure 1**). Almost the same stable kinetics of wear was shown by tools with NMCC Zr-ZrN–(NbZrTiAl)N, which had slightly shorter tool life of 35 min (see **Figure 1**). The tools with NMCC Ti-TiN-(ZrNbTi) also showed a long tool life of 38 min. Meanwhile, the tests showed less uniform kinetics of tool wear, which had the following specifics. It was

shown that, if during 25 min of cutting (running-in and steady stages of wear) the tool wear rate of tool with NMCC Zr-ZrN–(NbZrTiAl) was lower than for the tool with NMCC Zr-ZrN-(ZrCrAl)N and Ti-TiN-(ZrNbTi), then after 25 min of cutting the wear of the tool with NMCC Zr-ZrN–(NbZrTiAl)N was sharply intensified (see **Figure 1**). The tool with NMCC Cr-CrN-(TiCrAl)N had the shortest tool life among the group of tools under study, for which 31 min of fairly uniform wear was followed by obvious intensification of wear of the tool.

3.2. Study of mechanism of adhesive-fatigue wear of carbide tool with developed NMCC

During the research of the mechanism of adhesion-fatigue wear of the carbide tool with developed NMCC, special attention was paid to the study of cracking. It was found out that the cracks under study usually had a width of several nm to 1 μm, so it is not possible to visually detect such cracks on the working surfaces of the tool by standard optical instruments. Therefore, such microcracks were detected and studied on cross-cut sections with the use of a SEM. Three main types of formed cracks were identified: (i) cross cracks; (ii) cross cracks combined with longitudinal cracks (delamination), including transformation of cross cracks into longitudinal ones, resulting in stop of crack growth; and (iii) longitudinal cracks (delamination). It is found out that the mechanism of formation and growth (branching) of cross cracks usually includes three to four basic stages (**Figure 2**):
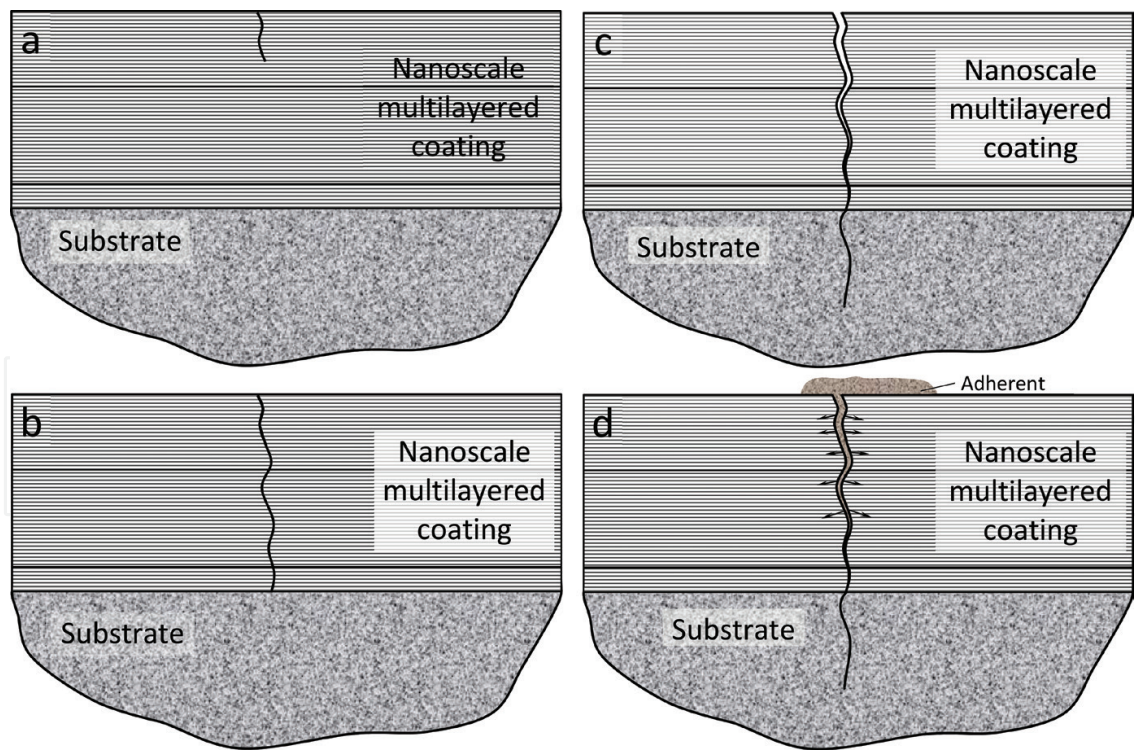

Figure 2. Stages of formation of a cross crack in multilayered nanostructured coatings: (a) initiation of a crack, (b) crack growth throughout the thickness of the coating, (c) "crack opening," (d) penetration into the crack of a fragment of the material being machined, resulting in "wedging" and increasing the width of the crack by up to 1 μm.

- Stage "a" is characterized by initiation of microcracks (see **Figure 2a**) caused by bending (usually alternating) mechanical and thermal stresses. An important role in initiation of a crack may be played by such concentrators of stresses as micro-drops (both embedded in the coating structure and superficial ones) (see **Figure 3a**), surface coating defects (craters, rough spots, etc.), inhomogeneity of mechanical properties of the coating, etc.

- Stage "b" is characterized by the growth of cracks, which can be inhibited by various obstacles, including: "bridging" of particles of more ductile phase, embedded in brittle phase; phase transformations of thermal nature or occurring as a result of plastic deformation in the development of crack tip; change in the direction of crack formation during passage of grain boundary [33].

- On the "c" stage, there is implementation of cracks in the carbide substrate, as well as its "disclosure"

- Stage "d" (typical only for a certain type of cracks) is characterized by penetration of particles into a crack of the material being machined (triggered by high temperatures and contact stresses resulting in thermoplastic deformation and yielding of the material), which has a "wedging" effect and stimulates further growth of the crack (see **Figure 4**). The studied crack development stage may cause separation of a fragment of coating or coated substrate (**Figure 5**). The examples of different cross cracks at different stages of development are shown in **Figures 3** and **4**.

The mechanism of wear of rake face of CI with NMCC Ti-TiN-(ZrNbTi)N has of complicated nature (see **Figure 5**). In particular, at the first stage of the wear process on rake face, the wear-fatigue processes with high frequency of oscillation of contact stresses prevail, and they considerably exceed the stresses acting on flank face of the tool and this results in weakening of local volumes of carbide material. The second stage marks the intensive weakening of local near-surface sections of rake face of CI in the area of crater formation and intensification of the processes of abrasive wear (**Figure 5**).
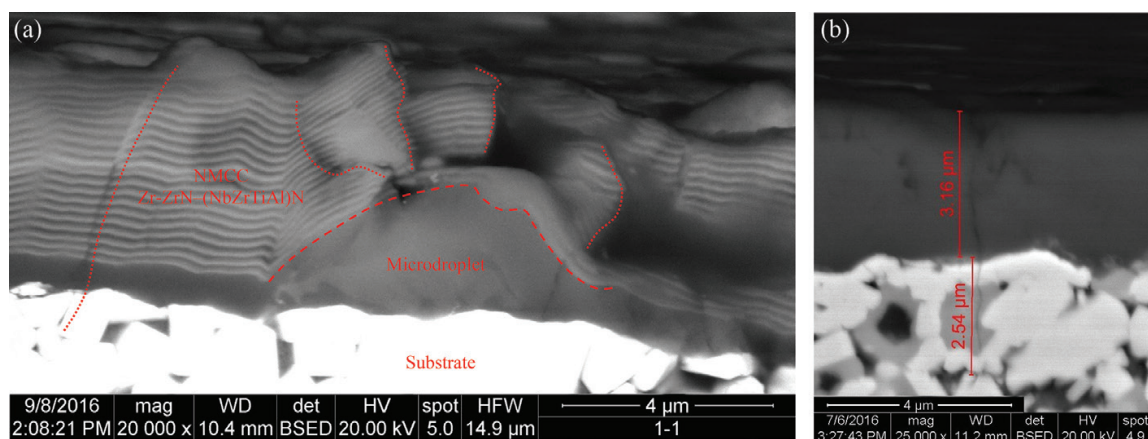

Figure 3. A microdroplet embedded into the structure of NMCC Cr-CrN-TiCrAlN as a factor, causing formation of a crack (a) and development of a cross crack in the coating TiN (b) [34].
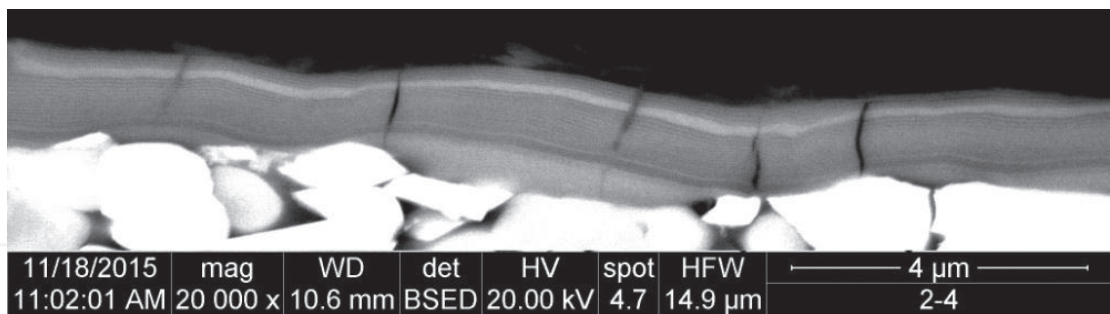
Figure 4. Example of formation of cross cracks in NMCC Cr-CrN-TiCrAlN (with crack thickness of 20–150 nm) [34].
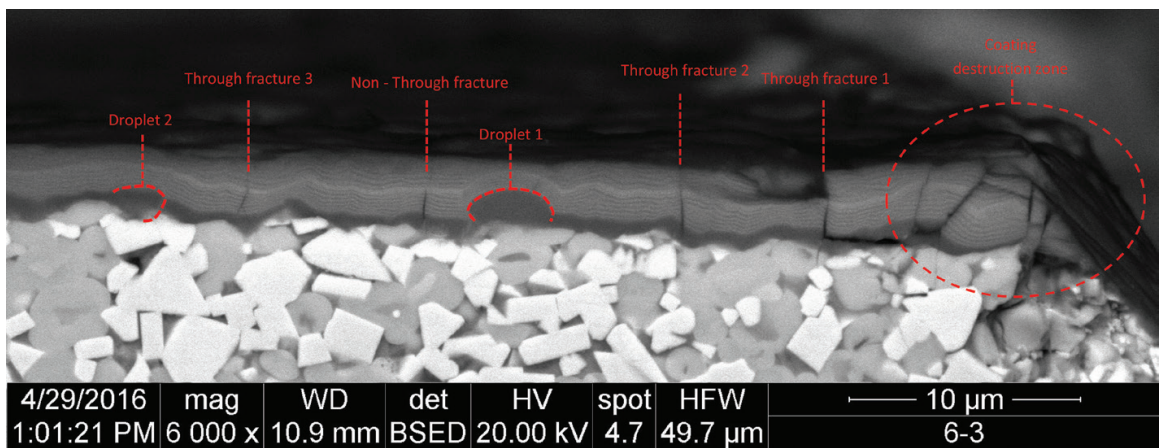

Figure 5. Specifics of wear and failure of NMCC Ti-TiN-(ZrNbTi) on rake face area between the cutting edge and the wear crater [33].

The data presented in **Figure 5** indicate the formation of through and dead-end cracks (1–3), as well as the presence of micro-droplets of cathode material, penetrating in the structure of the coating (1, 2), which contribute to the intensification of tool wear. The area of intense failure of the coating directly adjacent to the tool cutting edge can be characterized by mechanisms of abrasive and adhesion-fatigue wear, which result in active cracking.

Separation of a fragment of coated carbide substrate, occurring because of the final stage of the development of a cross crack is often accompanied by sufficient extensional chipping of the carbide substrate with locking in this area of a build-up of the material being machined (**Figure 6**). Such cracks can be formed in hard, but not sufficiently ductile NMCC, making it prone to brittle fracture. The maximum number of the formed cross-cracks was observed in NMCC Ti-TiAlN-TiAlN and Cr-CrN-TiCrAlN. The nature of such cracks was almost identical to the one usually observed for cracking of solid single-layered coatings of simple composition and architecture (for example, for coating TiN (see **Figure 3b**)).

In the formation of cross cracks in combination with longitudinal ones, three stages of crack development can be observed as follows (**Figure 7**). First, a longitudinal crack (separation) is formed between two fairly closely located longitudinal cracks that typically result in a separation of sufficiently large fragment of the coating (**Figure 8**). Next, the development of a cross
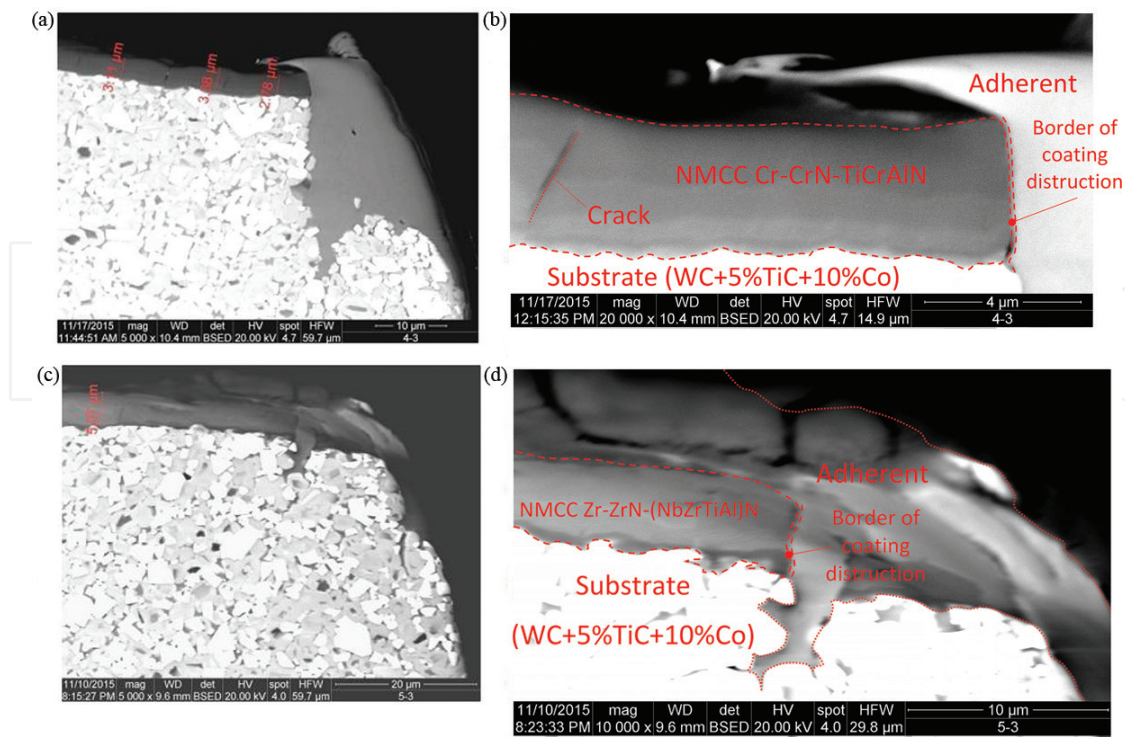
Figure 6. Examples of failure of coating and substrate because of breaking along the formed longitudinal crack. NMCC Cr-CrN-TiCrAlN (a, b); Zr-ZrN–(NbZrTiAl)N (c, d) [34].

crack is inhibited by its transformation into a longitudinal crack (delamination), which ceases its further development (**Figure 9b**, **c**). Finally, the growth of cross cracks that are periodically transformation into a longitudinal crack (delaminations) (**Figure 9a**), which is caused mainly by loss of their development energy.

It is noted that longitudinal cracks (delamination) (**Figure 10**) may occur in connection with violation of adhesive and cohesive bonds between layers and sublayers of the coating and in connection with the presence in the coating structure of different defects, resulting in the concentration of stresses (for example, micro-droplets (**Figure 11**), pores, failed "bridging" of adhesive bonds). The development of longitudinal cracks may result in the initiation of quite extensive internal delaminations without reaching the surface of the coating (this option is more favorable for tool life) and in output the cracks of the coating surface (**Figure 12**) with quite intensive subsequent damage of the coating and removal of the fragments of damaged NMCC by cut chips. The nanoscale layers of more ductile phase inhibit the development of cracks (**Figure 12b**) through formation of crack bridging.

To perform X-ray microanalysis using characteristic X-rays, emitted by the sample as a result of electron bombardment. The studies were conducted using a scanning electron microscope FEI Quanta 600 FEG. Following the analysis of the data presented in **Figures 13** and **14**, it is possible to note that the pattern of change in the content of the main chemical elements (N, O, Zr, Nb, Ti, W) in NMCC Ti-TiN-(ZrNbTi) relates to a significant growth of oxygen content and reduction of nitrogen content in the areas of through cracks in zones 1–3 (see **Figure 5**). Meanwhile, the increase in oxygen content and reduction in nitrogen content in the zones
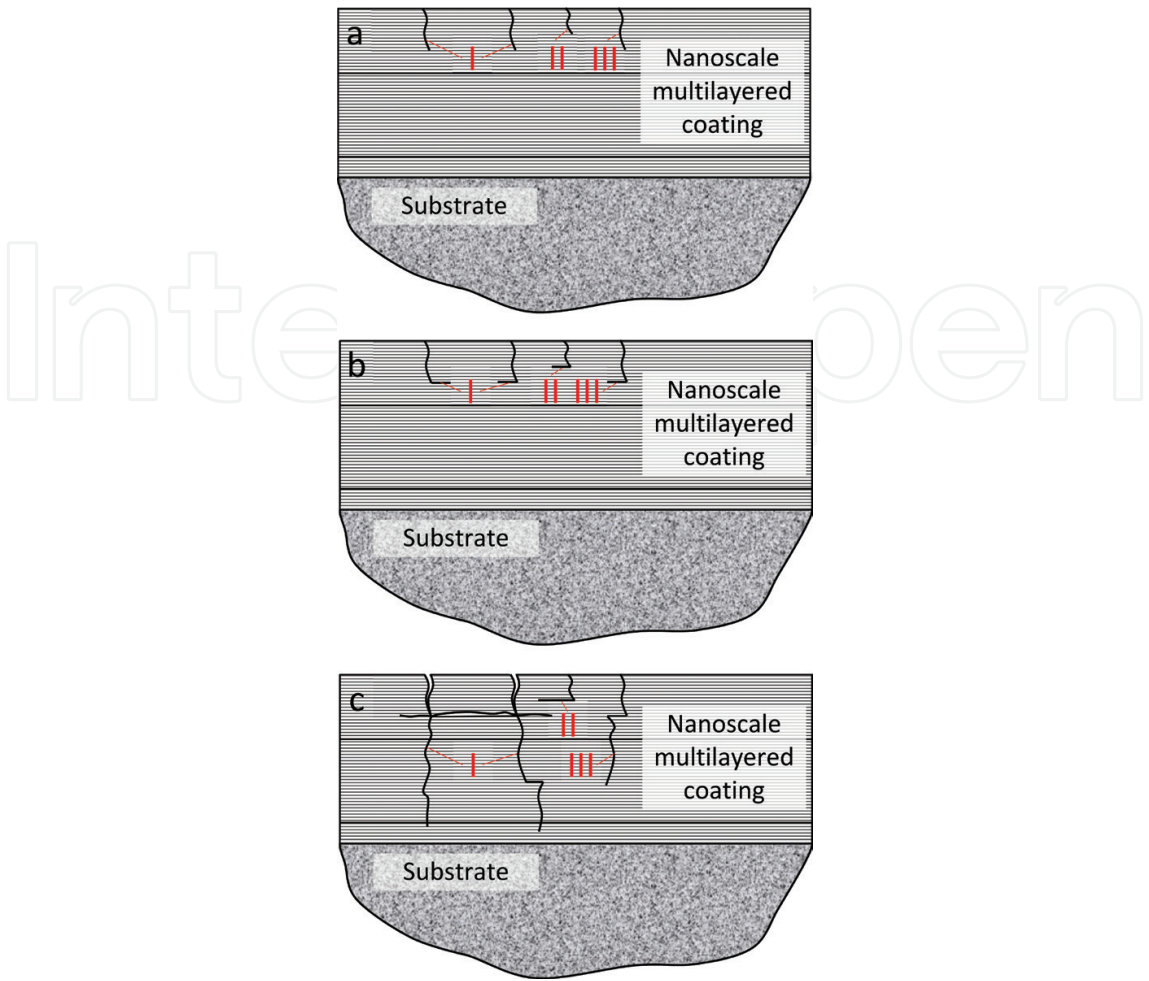
Figure 7. Stages of formation of a cross crack, transforming into a longitudinal crack (delamination) in multilayered nanostructured coating: (a) initiation of a crack, (b) transformation of a cross crack into a longitudinal crack (delamination); (c) creation of a through longitudinal crack between two cross cracks; (d) a tear-out or chipping of a coating segment between two cross cracks.
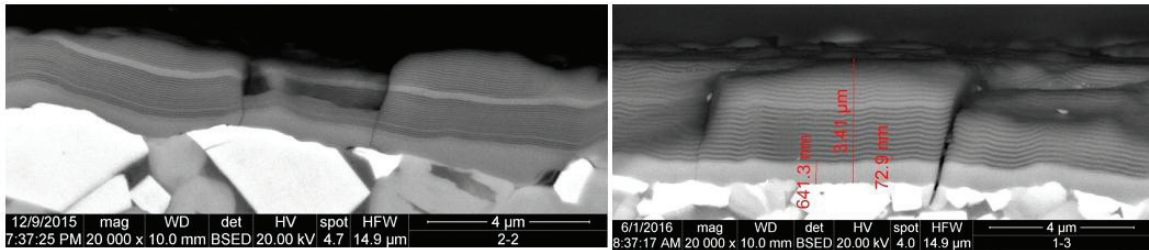

Figure 8. Chipping of coating fragments as a consequence of the formation of longitudinal cracks (delamination) between two cross cracks on the example of NMCC Zr-ZrN-(ZrCrAl)N [34].

through cracks is more noticeable for cracks located close to cutting edge of CI and coating failure zone. The increased oxygen content and reduced nitrogen content are also observed in the coating areas with a high content of microdroplets composed predominantly of α-Ti. Moreover, these processes are more visible for zones with the presence of larger microdroplets
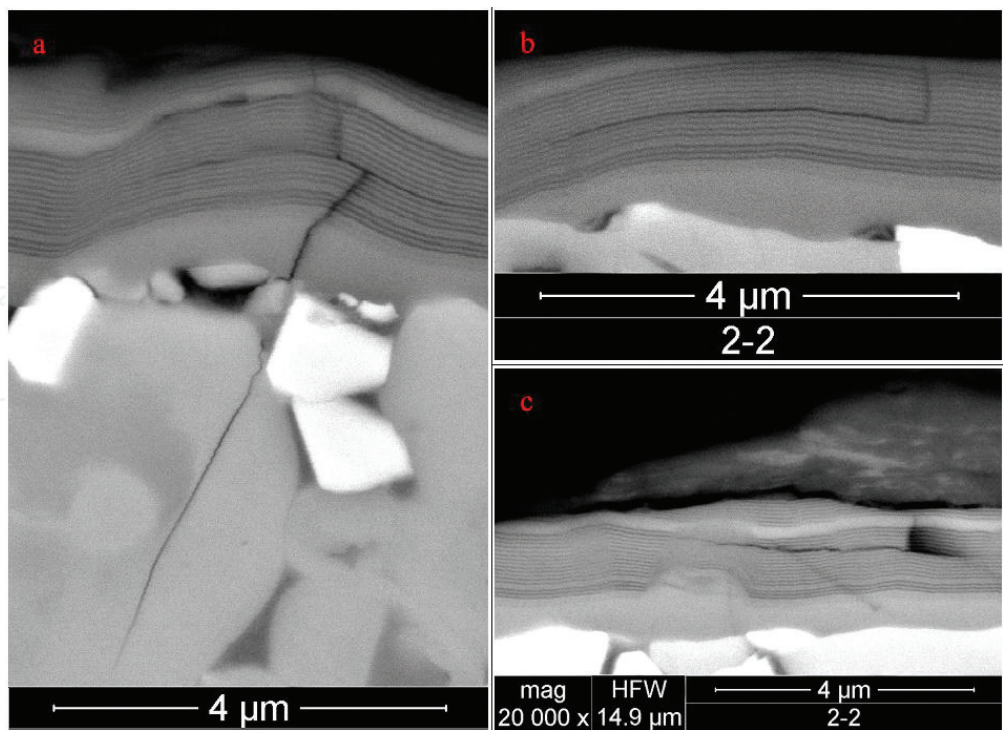
Figure 9. Transformation of cross cracks into longitudinal cracks (delamination) in NMCC Zr-ZrN-(ZrCrAl)N: partial transformation with continuous development of a cross crack (a) and complete transformation with stop of the growth of a cross crack (b, c) [34].
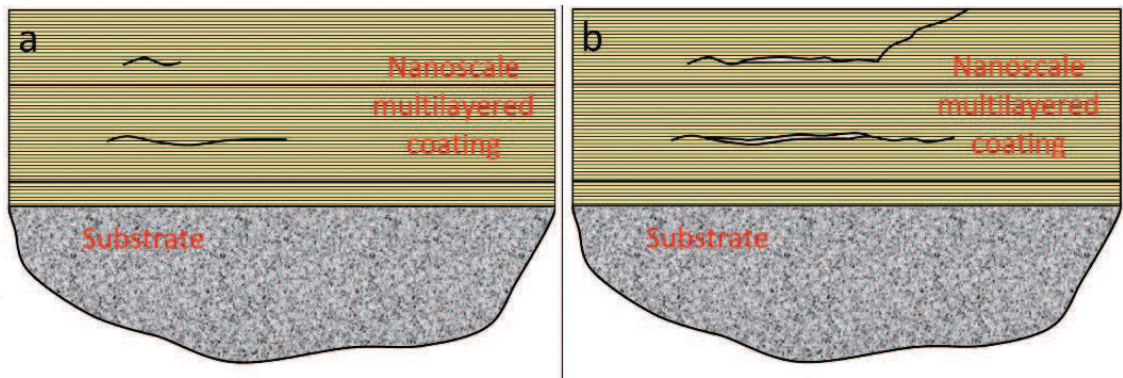

Figure 10. Stages of formation of a cross crack (delamination) in multilayered nanostructured coating: (a) initiation of a crack, (b) development of a crack.

(zone 1, see **Figure 5**). In zone I, associated with active cracking and failure of the coating, it is also possible to note growth of oxygen content and reduction of nitrogen content. Meanwhile, for the NMCC zones containing dead-end microcracks, slight change in the content of nitrogen and oxygen was observed.

The results of the analysis allow noting the partial dissociation of complex nitrides of NMCC and intensification of oxidative processes. Following the analysis of the data obtained, it is possible to note the following. The revealed sharp increase in oxygen content with significant reduction of nitrogen content indicates a high probability of intensive formation of solid and
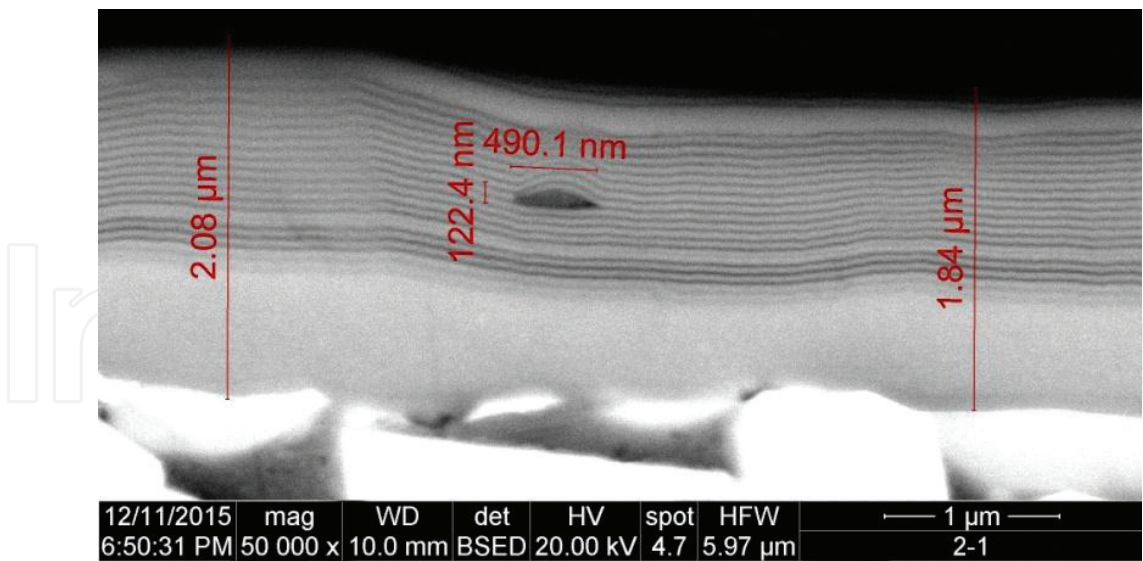
Figure 11. Internal defect of NMCC Zr-ZrN-(ZrCrAl)N (microdroplet), a possible cause of subsequent delamination.

relatively weak oxide formations of TiN_2, Al_2O_3 type, which failure can dramatically intensify the processes of abrasive wear of tool contact areas and reduce the efficiency of coatings deposited on carbide substrates. In this regard, in the use of the arc-PVD processes for the formation
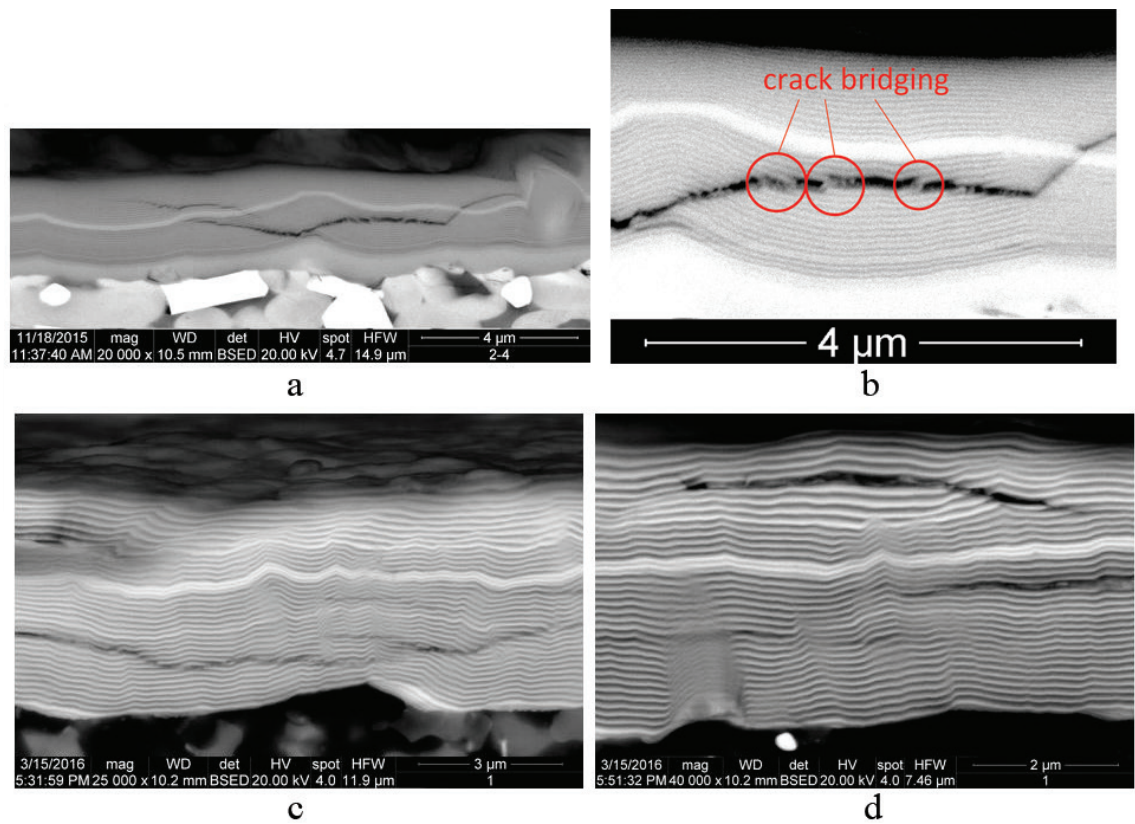

Figure 12. Examples of the formation of longitudinal cracks (delamination) NMCCZr-ZrN-(ZrCrAl)N (a, b) and Zr-ZrN-(ZrNbTiAl)N (c, d).
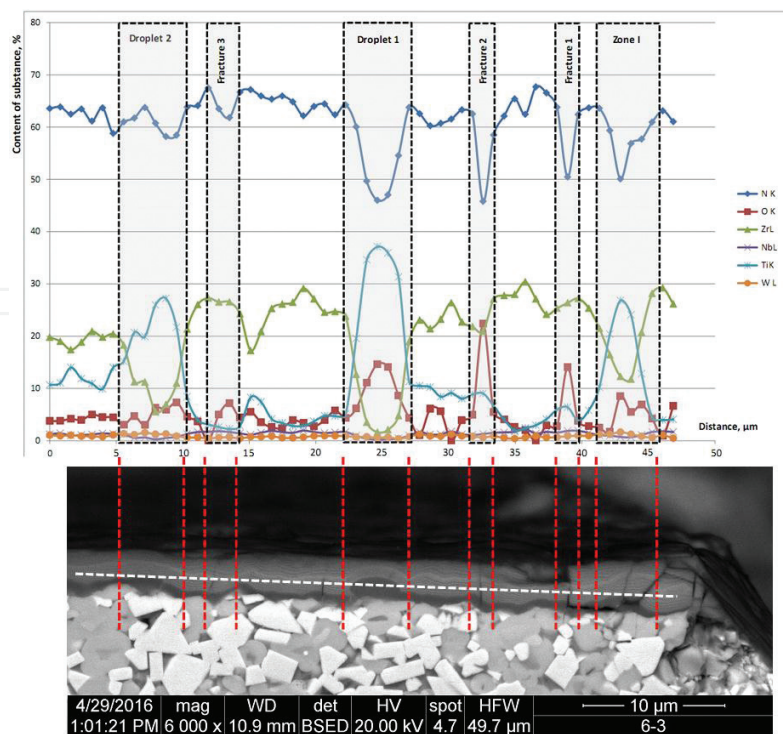
Figure 13. The results of the analysis of chemical element content, including of composition of NMCC Ti-TiN-(ZrNbTi) (N, O, Zr, Nb, Ti, W) at electron beam scanning length of 45 μm from the cutting edge of CI through the depth of NMCC, passing approximately equidistant from the carbide substrate and the outer boundary of NMCC [33].
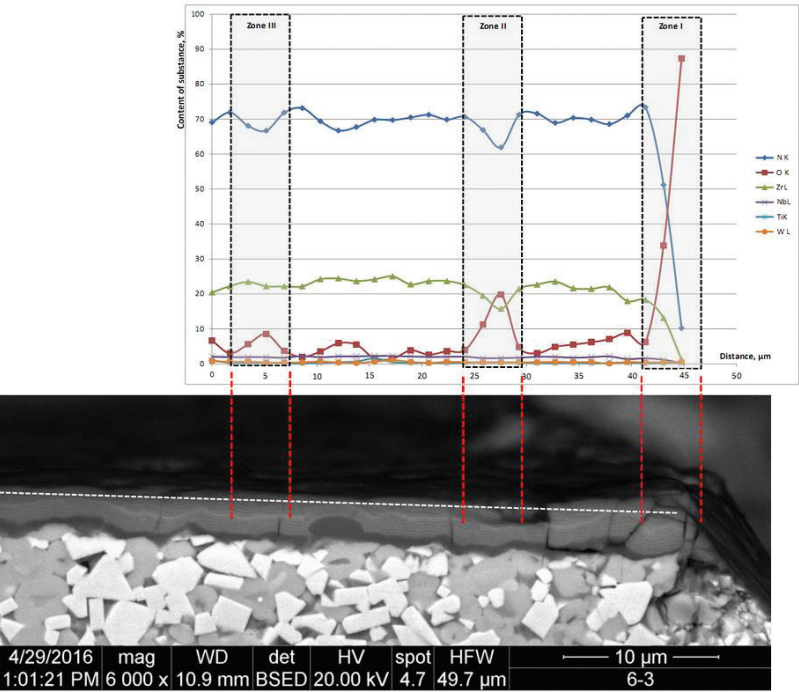

Figure 14. The pattern of change in the content of the main chemical elements (N, O, Zr, Nb, Ti, W) in NMCC Ti-TiN-(ZrNbTi) at the length of 45 μm occurring at the coating failure zone directly adjacent to the outer surface of the coating [33].

of wear-resistant coatings on carbide tools, it is necessary to use filtering systems that block the formation of macro- and microdroplets and that will result in significant improvement of the efficiency of coatings for various cutting operations.

4. Conclusions

Mechanisms of cracking in nanoscale multilayered composite coatings (NMCC) were considered. The studies were focused on NMCC of Zr-ZrN-(ZrCrAl)N, Cr-CrN-(TiCrAl)N, and Zr-ZrN-(ZrNbTiAl)N and Ti-TiN-(ZrNbTi) deposited through FCVAD technology. The thickness of the NMCC under study reached 2.44–11.7 μm. An uncoated carbide tool and a carbide tool with a "reference" TiN coating were selected as objects for comparison. Preliminary studies have shown that the NMCCs under study are characterized by high adhesion to substrate and high hardness (34–38 GPa). The tests of cutting properties carried out at longitudinal turning of steel C45 (HB 200) at the following cutting modes: f = 0.2 mm/rev; a_p = 1.0 mm; v_c = 250 m min^{-1} have shown that all NMCC under study sufficiently improve tool life (by 3–4 times in comparison with uncoated tool, and by 1.5–2 times in comparison with the tool with the TiN "reference" coating). Meanwhile, the nature of wear of NMCC with harder and less ductile wear-resistant layers ((TiCrAl)N and (TiAl)N) was considerably different from the mechanism of wear of NMCC with less hard and more ductile wear-resistant layers, which included zirconium nitrides ((ZrCrAl)N and (ZrNbTiAl)N) compositions. The tools with harder and less ductile NMCC showed less steady kinetics of wear, characterized by sharp intensification of wear and failure in transition from "steady" to catastrophic wear, i.e., at the end of the tool life period. The microstructural studies carried out at cross-cut sections of carbide samples with the NMCC under study with the use of a SEM revealed the nuances and mechanisms of formation of different types of cracks in the various NMCCs studied.

The X-ray microanalysis showed the considerable increase in oxygen content and reduction in nitrogen content in the following coating zones: (i) areas of through transverse cracks in the coating; and (ii) areas adjacent to micro-droplets embedded in coating structure.

Acknowledgments

Nomenclature

FCVAD - filtered cathodic vacuum arc deposition

CF – cutting fluid

PVD - physical vapour deposition

NMCC - nanostructured multi-layered composite coating

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References

[1] E. Harry, M. Ignat, Y. Pauleau, A. Rouzaud, P. Juliet. Mechanical behavior of hard PVD multilayered coatings. Surface and Coatings Technology. 2000;**125**:185-189.

[2] J.L. Mo, M.H. Zhu, A. Leyland, A. Matthews. Impact wear and abrasion resistance of CrN, AlCrN and AlTiN PVD coatings. Surface & Coatings Technology. 2013;**215**: 170-177.

[3] Y. Birol. Sliding wear of CrN, AlCrN and AlTiN coated AISI H13 hot work tool steels in aluminium extrusion. Tribology International. 2013;**57**:101-106.

[4] J. Nohava, P. Dessarzin, P. Karvankova, M. Morstein. Characterization of tribological behavior and wear mechanisms of novel oxynitride PVD coatings designed for applications at high temperatures. Tribology International. 2015;**81**:231-239.

[5] L. Aihua, D. Jianxin, C. Haibing, C. Yangyang, Z. Jun. Friction and wear properties of TiN, TiAlN, AlTiN and CrAlN PVD nitride coatings. International Journal of Refractory Metals and Hard Materials. 2012;**31**:82-88.

[6] M. Antonov, I. Hussainova, F. Sergejev, P. Kulu, A. Gregor. Assessment of gradient and nanogradient PVD coatings behaviour under erosive, abrasive and impact wear conditions. Wear. 2009;**267**:898-906.

[7] P. Henry, M.J. Pac, C. Rousselot, M.H. Tuilier. Wear mechanisms of titanium and aluminium nitride coatings: a microtribological approach. Surface & Coatings Technology. 2013;**223**:79-86.

[8] B.D. Beake, J.F. Smith, A. Gray, G.S. Fox-Rabinovich, S.C. Veldhuis, J.L. Endrino. Investigating the correlation between nano-impact fracture resistance and hardness/modulus ratio from nanoindentation at 25-500°C and the fracture resistance and lifetime of cutting tools with Ti1−xAlxN (x = 0.5 and 0.67) PVD coatings in milling operations. Surface & Coatings Technology. 2007;**201**:4585-4593.

[9]   G. Skordaris, K.D. Bouzakis, P. Charalampous. A dynamic FEM simulation of the nano-impact test on mono- or multi-layered PVD coatings considering their graded strength properties determined by experimental–analytical procedures. Surface & Coatings Technology. 2015;**265**:53-61.

[10] B.D. Beake, Li Ning, Ch. Gey, S.C. Veldhuis, A. Komarov, A. Weaver, M. Khanna, G.S. Fox-Rabinovich. Wear performance of different PVD coatings during hard wet end milling of H13 tool steel. Surface & Coatings Technology. 2015; 279: 118-125 doi: 10.1016/j.surfcoat.2015.08.038

[11] L. Ning, S.C. Veldhuis, K. Yamamoto. Investigation of wear behavior and chip formation for cutting tools with nano-multilayered TiAlCrN/NbN PVD coating. International Journal of Machine Tools & Manufacture. 2008;**48**:656-665.

[12] G.S. Fox-Rabinovich, K. Yamamoto, A.I. Kovalev, S.C. Veldhuis, L. Ning, L.S. Shuster, A. Elfizy. Wear behavior of adaptive nano-multilayered TiAlCrN/NbN coatings under dry high performance machining conditions. Surface & Coatings Technology. 2008;**202**: 2015-2022.

[13] G.S. Fox-Rabinovich, A.I. Kovalev, M.H. Aguirre, B.D. Beake, K. Yamamoto, S.C. Veldhuis, J.L. Endrino, D.L. Wainstein, A.Y. Rashkovskiy. Design and performance of AlTiN and TiAlCrN PVD coatings for machining of hard to cut materials. Surface & Coatings Technology. 2009;**204**:489-496.

[14] G. Erkens, R. Cremer, T. Hamoudi, K.D. Bouzakis, J. Mirisidis, S. Hadjiyiannis, G. Skordaris, A. Asimakopoulos, S. Kombogiannis, J. Anastopoulos. Super nitrides: a novel generation of PVD hard coatings to meet the requirements of high demanding cutting applications. CIRP Annals–Manufacturing Technology. 2003;**52**(1):65-68.

[15] B.D. Beake, G.S. Fox-Rabinovich. Progress in high temperature nanomechanical testing of coatings for optimizing their performance in high speed machining. Surface & Coatings Technology. 2014;**255**:102-111.

[16] H. Ezuraa, K. Ichijoa, H. Hasegawab, K. Yamamotoc, A. Hottaa, T. Suzukia. Microhardness, microstructures and thermal stability of (Ti, Cr, Al, Si)N films deposited by cathodic arc method. Vacuum. 2008;**82**:476-481.

[17] C.H. Lai, K.H. Cheng, S.J. Lin, J.W. Yeh. Mechanical and tribological properties of multi-element (AlCrTaTiZr)N coatings. Surface & Coatings Technology. 2008;**202**:3732-3738.

[18] M.G. Faga, G. Gautier, R. Calzavarini, M. Perucca, E. Aimo Boot, F. Cartasegna, L. Settineri. AlSiTiN nanocomposite coatings developed via Arc Cathodic PVD: evaluation of wear resistance via tribological analysis and high speed machining operations. Wear. 2007;**263**:1306-1314.

[19] A.A. Vereschaka, M.A. Volosova, S.N. Grigoriev, A.S. Vereschaka. Development of wear-resistant complex for high-speed steel tool when using process of combined cathodic vacuum arc deposition. Procedia CIRP. 2013;**9**:8-12.

[20] A.A. Vereschaka, M.A. Volosova, A.D. Batako, A.S. Vereshchaka, B.Y. Mokritskii. Development of wear-resistant coatings compounds for high-speed steel tool using a combined cathodic vacuum arc deposition. International Journal of Advanced Manufacturing Technology. 2016;**84**:1471-1482.

[21] S.N. Grigoriev, A.A. Vereschaka, A.S. Vereschaka, A.A. Kutin. Cutting tools made of layered composite ceramics with nano-scale multilayered coatings. Procedia CIRP. 2012; **1**:318-323.

[22] A.A. Vereshchaka, A.S. Vereshchaka, O. Mgaloblishvili, M.N. Morgan, A.D. Batako. Nano-scale multilayered-composite coatings for the cutting tools. International Journal of Advanced Manufacturing Technology. 2014;**72**(1):303-317.

[23] K.D. Bouzakis, N. Michailidis, G. Skordaris, E. Bouzakis, D. Biermann, R. M'Saoubi. Cutting with coated tools: coating technologies, characterization methods and performance optimization. CIRP Annals—Manufacturing Technology. 2012;**61**:703-723.

[24] V.P. Tabakov. The influence of machining condition forming multilayer coatings for cutting tools. Key Engineering Materials. 2012;**496**:80-85.

[25] V.P. Tabakov, A.V. Chikhranov. Research of developments of cracks in wearproof coverings of cutting tool. Vestnik TSU. 2013;**18**(4):1916-1917 (in Russian).

[26] V.P. Tabakov, M.Y. Smirnov, A.V. Tsirkin. Productivity of end mills with multilayer wear-resistant coatings. Ulyanovsk: UlSTU. 2005 (in Russian).

[27] A.A Vereschaka, A.S. Vereschaka, J.I. Bublikov, A.Y. Aksenenko, N.N. Sitnikov. Study of properties of nanostructured multilayer composite coatings of Ti-TiN-(TiCrAl)N and Zr-ZrN-(ZrNbCrAl)N. Journal of Nano Research. 2016;**40**:90-98.

[28] A.A. Vereschaka. Development of assisted filtered cathodic vacuum arc deposition of nano-dispersed multi-layered composite coatings on cutting tools. Key Engineering Materials. 2014;**581**:62-67.

[29] A.O. Volkhonskii, A.A. Vereshchaka, I.V. Blinkov, A.S. Vereshchaka, A.D. Batako. Filtered cathodic vacuum Arc deposition of nano-layered composite coatings for machining hard-to-cut materials. International Journal of Advanced Manufacturing Technology. 2016;**84**:1647-1660.

[30] S. Kumar, W.A. Curtin. Crack interaction with microstructure. Materials Today. 2007;**10**(9):34-44.

[31] W. Hume-Rothery, Atomic theory for students of metallurgy. London: The Institute of Metals. 1969 (fifth reprint).

[32] W.C. Oliver, G.M.J. Pharr. An improved technique for determining hardness and elastic modulus using load and displacement sensing indentation. Journal of Materials Research. 1992;**7**:1564-1583.

[33] A.A. Vereschaka, B.Y. Mokritskii, N.N. Sitnikov, G.V. Oganyan, A.Y. Aksenenko. Study of mechanism of failure and wear of multi-layered composite nano-structured coating based on system Ti-TiN-(ZrNbTi)N deposited on carbide substrates. Journal of Nano Research. 2017;**45**:110-123.

[34] A.A. Vereschaka, S.N. Grigoriev. Study of cracking mechanisms in multi-layered composite nano-structured coatings. Wear. 2017;**378-379**:43-57. DOI:10.1016/j.wear.2017.01.101.