Application of nanostructured multilayer wear-resistant coating - Features improving operational properties of cutting ceramics.

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Abstract

This paper presents the results of development of nano-scale multi-layered composite coatings, that modifies contact processes of ceramic cutting tools in order to reduce the brittle fracture of cutting edges and to ensure balance wear of tool contact areas during dry high-speed cutting of hardened steels. The technology of filtered cathodic vacuum arc deposition was used to produce modifying coatings. This technology provided the possibility to form nano scale multi-layered composite coatings (NMCC) with improved physical and mechanical properties and adhesion strength to ceramic substrate. This work used thermodynamic criteria to evaluate the selected composition of NMCC, and studied crystal-chemical, physical, mechanical and cutting properties and wear mechanisms of NMCC. The Ti-TiAlN-ZrNbTiAlN coating structure was deposited on various ceramic Al_2O_3, Al_2O_3-TiC and Si_3N_4 substrates. It is shown that wear mechanism of a ceramic tool with developed coatings is connected with adhesive-fatigue processes, and the development of wear centres on rake and flank faces of the tool is of balanced nature without typical brittle chips. It was found that during high-speed longitudinal turning of hardened steel X153CrMoV12, the tool life of a ceramic tool of Al_2O_3-TiC –Ti-(TiAl)N-(ZrNbTiAl)N was up to 1.5 times longer than the tool life of uncoated tools and up to 1.3 times longer than the tool life of tools with PVD coating Ti-TiAlN.

Keywords: cutting ceramics; wear-resistant coatings; wear; diamond-like coating; durability

Abbreviations

HSC - high speed cutting
CF - cutting fluids
CC - cutting ceramic
CI - cutting inserts
NMCC - Nano-scale multi-layered composite coatings
FCVAD - filtered cathodic vacuum arc deposition

1. Introduction

The widespread application of the innovative technology of high speed cutting (HSC) in terms of environmentally friendly cutting without cutting fluids (CF) leads the increasing use of tools, equipped with replaceable multifaceted cutting inserts (CI) made of cutting ceramic (CC) [1-3].

CC is characterized by a unique combination of high hardness (HRA 91-94), heat resistance (1200-1450ºC) and wear resistance with extremely low propensity to physical and chemical interaction with the materials being machined (steels, cast irons, etc.). The properties determine the essential advantages of ceramic tools over carbide tools during dry high speed cutting of structural steels. In particular, while the maximum rates of cutting speeds during finish turning of steels with carbide tools are 500-600 m/min, then the rates of cutting speeds used for ceramic cutting tools increase up to 900-1000 m/min [3]. Furthermore, the use of ceramic tools contributes to significant improvement of the economic aspects of machining process, since the composition of cutting ceramic includes no scarce or expensive components (W, Ta, Ti, Co, etc.).

However, CC is characterized by relatively low toughness and bending strength, high brittleness, and low thermal conductivity with a sufficiently high coefficient of thermal expansion. Therefore, ceramic tools are very sensitive to thermal cycling loads and are characterized by an increased tendency to micro/macro-brittle failure at contact stresses higher than 900-1000 MPa, which predetermines the very narrow scope of application (K01-K10, P01-P10) [1, 3].

An effective method for overall improvement of physical and mechanical properties of cutting ceramic is the deposition of modifying functional coatings on the working surfaces [4-18]. Thus allowing a control of contact processes in order to change thermomechanical strain of the cutting edges and the nature of wear. This is connected with the phenomenological dual role of coating, which is manifested in the improvement of the surface properties of the ceramic material to reduce thermomechanical effect on the tool contact areas during cutting while providing high adhesion strength with the ceramic substrate [9-13]. In this respect, large-scale studies are currently undertaken to improve the properties of cutting ceramic through deposition of functional coatings. The wide use of this technology for dry high speed shape-generating machining provides the significant cost-efficiency while reducing negative impacts on the environment and personnel health [14-24].

In contrast to carbide and high-speed steel, for which the use of modifying coatings provides positive effects, the benefits of coatings for ceramic cutting tools are not always obvious. The studies in recent years in increasing the efficiency of ceramic tools through modifying coatings [17-24] have revealed both the possibilities for a significant improvement in cutting properties of ceramic tools.

In particular, papers [17-20] studied the properties of ceramic tools on the basis of Al_2O_3-ZrO_2, Al_2O_3-Ti(C,N), Al_2O_3-TiC and Si_3N_4 with various PVD coatings, e.g. ((Ti,Zr)N-(TiN/ZrN), TiN-(TiAl)N-(TiN/(TiAl)N), TiN-(Ti,Al,Si)N-TiN, TiN-(Ti,Al,Si)N-TiN, TiN-TiAlSiN-AlSiTiN). The tests were carried out fo turning of steels NC6 (HRC 48-52) [17] and C45E [18], gray cast irons EN-GJL-250 [18, 19] and SL-25 (250 HB) [20] at cutting speed of 150-400 m/min, feed, 0.1-0.2 mm/rev and depth of cut 0.5-2 mm. The results showed an increase in tool life for coated tools by 20-80% [17]. Papers [18, 19] found that coatings not only improved ceramic tool life, but in some cases, it led to deterioration. The authors in [18] showed that for CC, the prevailing wear mechanisms are of abrasive and adhesive nature.

The studies in paper [21] expand the results presented in papers [17-20] on the possibilities to improve the properties of ceramic tools with the deposition of complex composite coatings. In particular, paper [21] focuses on the influence of a range of coatings based on TiAlN, TiCN-TiN, TiN-TiAlSiN-TiN, TiN-TiAlSiN-AlSiTiN, including nano-structured ones, formed by PVD and CVD, on cutting properties of mixed ceramic TiC/Al_2O_3. Cutting tests in continuous dry turning of gray cast iron (260 HB) demonstrated an increase of tool life by 1.3 -1.83 times and a lower surface roughness of the machined workpiece

Aslantas et al [22] studied cutting properties of cutting inserts (CI) with mixed ceramic Al_2O_3-TiCN with coating TiN in turning of hardened steel AISI 52100 (HRC 63). It was shown that for uncoated CI, tool failures are caused by the formation of cracks and chips. It was found that temperature in the cutting zone significantly decreased when coated CI was used, and tool failures were determined by a balanced wear of contact areas on the rake and flank faces with formation of typical rake face wear craters [22.

Qin et al [23] investigated longitudinal turning of grey cast iron using various depths of cutting with uncoated silicon nitride (Si_3N_4) and TiN/Al_2O_3 CVD coatings. The prevailing tool wear mechanism was abrasive wear and brittle failure under the influence of adhesive-fatigue processes.

Long et al [24] presented the results of cutting performance of Si_3N_4 ceramic tool with TiAlN-AlCrO composite PVD coating in dry longitudinal turning of grey cast iron HT250 and steel AISI 4340. The studies revealed distinct advantages of Si_3N_4-(TiAlN-AlCrO) over uncoated Si_3N_4 ceramic tool. The failure the Si_3N_4-(TiAlN-AlCrO) occurred due to a combination of abrasive-adhesive wear.

Long et al [25] studied various properties and wear mechanisms of Si_3N_4 ceramic tools with (TiAl)N and (CrAl)N PVD coatings in dry turning of gray cast iron. The tool life of coated tools was up to 2 times higher than the tool life of uncoated tools, and wear of coated tools was characterized by a uniform development of flank wear land with no visible chips and micro-brittle failure of ceramic material.

A number of papers, focused on the improvement of the performance properties of the coatings by making its elemental composition more complicated. In particular, studies are focused on different properties of the coatings CrAlN-TiN and CrAlN-ZrN [26] that show a significantly inferior oxidation resistance than CrAlN coating. **Fox-Rabinovich** et al [27] studied the properties of TiAlCrN, TiAlCrN-TaN, TiAlCrN-CrN, TiAlCrN-WN and TiAlCrN-NbN nano-multilayered coatings. The TiAlCrN/NbN coated tool had the longest tool life compared to the other transitional metal nitrides – content nano-multilayered coated tools. The results obtained showed that the tribo-oxides formed during friction of TiAlCrN/NbN coatings under high performance cutting conditions work in synergy by protecting the surface (like alumina tribo-films), lubricating the cutting zone (like Cr–O tribo-films) and dissipating energy (as Nb–O films). **Li Chen, et al** [28] focused on the properties of the coating CrAlNbN. They found that the presence of Nb in the composition of coating increases its hardness and oxidation resistance. The higher (more than 15%) of Nb content in the coatings is, the lower their oxidation resistance and hardness is.

Following the analysis of the publications focused on the influence of coatings on different properties of the ceramic tool, it is possible to note the following. Unlike the influence on the carbide tools, for which the application of wear-resistant coatings provides clear positive effect (significant increase in tool life and reliability of the tool, possibility to significantly increase the cutting speed, improvement of quality and accuracy characteristics of the surface layer of the machined workpieces), the influence of the coatings on the properties of ceramic tools is not so clear. While some studies revealed significant improvement of tool life of a ceramic tool (up to 2-3 times), other studies found only small increase in tool life by 20-30% or even complete absence of any influence of coatings.

Based on the analysis of the above mentioned studies focused on the influence of coatings, and their properties, it is observed that there is no targeted approach to the selection of compositions and architectures of coatings. This is important to positively modify the properties of ceramic tools in order to improve their cutting performance. For identifying the causes of the sudden (unpredictable) failure, occurring in brittle fracture of the cutting edge of the ceramic tool, it is necessary to understand means influencing the causes of such failure.

The most acceptable possibility to eliminate the causes of brittle fracture of contact areas of the ceramic cutting tool is to develop the means providing targeted control over the contact processes to ensure fine-balanced wear of contact areas for a gradual, predictable failure. Such means are nano-scale multi-layered composite coatings (NMCC) with functional properties, the composition and properties of which may be varied to ensure direct control over the contact processes and the most important surface properties of ceramic tools. Such properties include: - adhesion activity of the ceramic material in relation to the material being machined, influencing the coefficient of chip friction on rake face of the tool, length of complete, dense and discrete contact of chips on rake face of the tool, power of frictional heat sources, contact stresses, specific thermal-mechanical stresses on the cutting edge of the ceramic tool.

Studies carried out earlier had identified the following [17-21, 24]:

- increased efficiency of NMCC with nano-structured wear-resistant (outer) layer, which combines high hardness and enhanced resistance to brittle fracture;
- high corrosion and oxidation resistance of wear-resistant layer of NMCC, alloyed nitrides Zr and Nb, with content of Nb, not exceeding 15%;
- substantial or complete absence of the data on the application of NMCC, containing multi-component nano-structured wear-resistant layers for ceramic cutting tool illustrating positive effect on the use of multi-component coatings, comprising nitrides of Zr, Nb, Ti, Al;
- there is also a considerable amount of the results of the use of multi-layered coatings, comprising nitrides of such metals as Zr, Nb, Ti, Al, Cr, in order to increase the tool life of carbide tools [8, 27, 29];
- **Ning et al** [29] found that AlO films protected the substrate by insulating it from thermal impact; NbO films served to dissipate energy and thereby reduced cutting edge and surface damage. The influence of zirconium oxides of the coatings on the parameters of the cutting process was much less studied.

Preliminary studies of the ceramic cutting tool with developed NMCC on the basis of Zr-ZrN-(ZrCrAl)N, Ti-TiN-(NbZrTiAl)N, Ti-TiN-(NbZrAl)N, Ti-TiAlN-(ZrNbTiAl)N), conducted by the authors of this paper in longitudinal turning of HVG hardened steel (analog DIN 1.2419, HRC 58-60) and X153CrMoV12 hardened steel, have shown that the highest wear resistance was achieved by the ceramic tools with NMCC on the basis of Ti-TiAlN-(ZrNbTiAl)N.

The criterion for this selection was the thermodynamic criterion "Gibbs energy ΔG of the reaction". This was done by valuating the interatomic two-dimensional space between the boundary layers "coating-ceramics" and contacting layers "machined material - wear resistant layer." In selecting the composition of the layers NMCC and forming the coating-layer architecture, the Hume-Rothery rule (difference in atomic dimensions of contact compounds must not exceed 20%) was used.

Thus, further detailed studies of wear mechanisms of the tools made of mixed cutting ceramic Al_2O_3/TiC were conducted with the application of NMCC on base system Ti-TiAlN-(ZrNbTiAl)N. For the comparative tests, the Ti-(TiAl)N coating was selected as reference, which was deposited on the ceramic substrate using standard arc-PVD and which is currently widely used, including cutting ceramic.

2. Experimental studies

2.1. Deposition method

Nano-scale multi-layered composite coatings were generated using filtered cathodic vacuum arc deposition (FCVAD) which was fully described in [2, 3, 4]. The FCVAD technology was developed as a way to obtain NMCC with high adhesion strength with regard to substrate, high density and nano-scale structure, contributing to improvement of cutting properties of ceramic cutting tool. Following a preliminary chemical and mechanical processing (ultrasonic cleaning, rinsing, and drying), ceramic CI were placed into the chamber of the unit VIT-2, in which the inserts were subjected to additional ion cleaning and processing to heal surface defects formed during manufacture and then the deposition of NMCC [10,11]. In the process of deposition of NMCC, the ceramic CI were given a planetary movement in the chamber of the VIT-2, which allowed obtaining coatings of uniform thickness.

The use of FCVAD process did not cause structural changes in ceramic material and provided:

• high adhesive strength of the coating in relation to the ceramic substrate;

• control of the level of the "healing" of energy impact on surface defects in ceramic in the form of micro-cracks and micro-pores and formation of desirable compressive residual stresses in the surface layers of the ceramic material;

• 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 ceramic material at an extremely high rate of about 10^{14} K/s.

The parameters of the process of deposition of NMCC are presented in Table 1.

Process	τ, min	p_N, Pa	U, V	I_{Al}, A	I_{ZrNb}	I_{Ti}, A
Pumping and heating of vacuum chamber	20	0.06	+20	120	80	65
Heating and cleaning of products with gaseous plasma	10	2.0	100 DC / 900 AC f = 10kHz, 2:1	80	-	-
Deposition of coating	40	0.36	-800 DC	160	75	55
Cooling of products	90	0.06	-	-	-	-

where I_{Ti} – current of titanium cathode, A,

I_{Al} – current of aluminum cathode, A

I_{ZrNb} – current of zirconium-niobium cathode, A

p_N – gas pressure in chamber, Pa,

U – voltage on substrate, V

During the process of coating deposition, the following cathodes were used:
Ti 99.8%, Al 99.9%, (Zr 80%+Nb19,5%)

2.2. Microstructural research and chemical analysis

The microstructural research and chemical analysis of samples were carried out with the use of a raster electron microscope (REM) FEI Quanta 600 FEG. The pictures were taken at accelerating voltages of 20 and 30 kV. The area under study was exposed to a finely focused electron beam, which formed a raster pattern on the surface. Secondary electrons and/or reflected (back-scattered) electrons were used to obtain the information about the surface structure. The Everhart-Thornley detector, providing selective detection of electrons with energy less than 50 eV, was used for the study of secondary electrons. Back-scattered electrons were registered by a solid-state detector, which was mounted under the polar tip and optimized to work with low accelerating voltages (up to 3 kV).

For chemical analysis, the research included the characteristic X-radiation, emitted as a result of electron bombardment of a sample. The analysis of the characteristic X-radiation, emitted from the area, in which a beam of electrons falls, provides both qualitative and quantitative information about the elemental composition of an object.

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For the microanalysis, the characteristic X-radiation, emitted as a result of electron bombardment of a sample, was of primary interest. The analysis of the characteristic X-radiation, emitted from the area, in which a beam of electrons falls, provides both qualitative and quantitative information about the elemental composition of an object.

2.3. Tribological characteristics

Tribological characteristics of the coatings were examined using the standard procedures of ASTMG99-95a on TetraBasaltN_2 test station with the use of "Ball-on-disc" method; the roughness of the coated and uncoated samples did not exceed 0.35…0.4 Ra; the tested characteristics of friction on the samples of cutting ceramic with coatings most adequately matched the friction conditions occurring in the cutting zone, 6-mm-diameter balls of hardened steel AISI 52100 were used as a counter-body, the distance of the ball run across the surface of the ceramic samples was 500 m. Hold-down load of the ball to the friction surface was controlled by the installation system and reached 20 N.

2.4. Coating adhesion

Adhesion tests were conducted to study adhesive strength of the system "ceramic substrate-coating" with the help of the standard methods of ASTMC1624, ISO 20502, and ISO 1518 (method "Scratchtest", apparatus "CsemRevetest"). Panoramas of tracks of scratches, even at extreme loads on the indenter of up to 40 N, have demonstrated a high adhesion of NMCC to ceramic substrate. Moreover, acoustic emission signal curves had no sharp peaks, associated with delamination of the coating from the substrate at the maximum load applied.

2.5. Hardness (HV) of coatings

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 micro-indenter 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.

2.6 . Cutting test

This test used the cutting tools equipped with coated and uncoated ceramic inserts with dimensions of 12.5 x 12.5 x 4.75 mm (SNUN ISO). Tools had following value of geometrical parameters of the tool cutting part: rake angle $\gamma = - 8^0$; clearance angle $\alpha = 6^0$; tool cutting edge angle $k = 45^0$, an corner radius r = 0.8 mm.
The experiments were carried out in longitudinal turning of HVG hardened steel (analog DIN 1.2419, HRC 58-60) and X153CrMoV12 hardened steel on a universal machine 16K20 with stepless thyristor drive, which allowed to maintain the required cutting speed when changing workpiece diameter at v = 80-350 m/min; f = 0.1-0.25 mm/rev: a_p = 0.5-1.0 mm. A large tool microscope BMI-1C was used for registration of flank wear land VB_{max} of ceramic tool.
The efficiency of ceramic tools with the developed NMCC was evaluated by the time they reached a maximum flank wear VB_{max} = 0.3-0.4 mm.

3. Result and discussion

3.1. Coating architecture, hardness measurement

The analysis of the coating architecture revealed the following characteristics of developed NMCC (Fig. 1.):

- thickness of adhesive layer reached about 100-300 nm and is not constant along the section of cut;

- thickness of intermediate layer is about 2.4 μm;

- thickness of wear-resistant layer is about 1.8 μm;

- intermediate and wear-resistant layers of NMCC are characterized by nano-structure, and thicknesses of nano-layers reach 45-70 nm.

Hardness of (HV) NMCC Ti-TiAlN-(ZrNbTiAl)N, according to the method of Oliver and Pharr, reached 36 GPa.

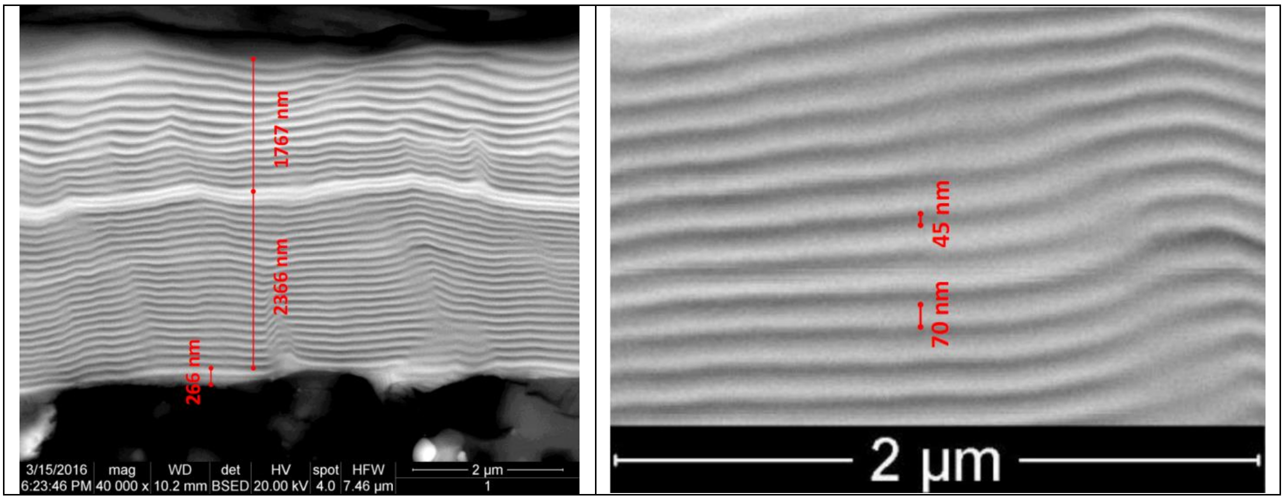
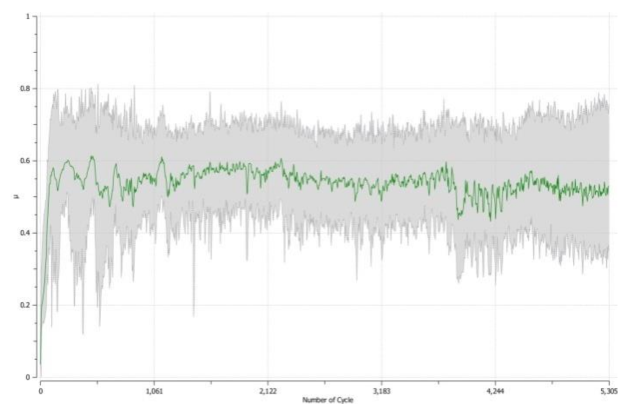
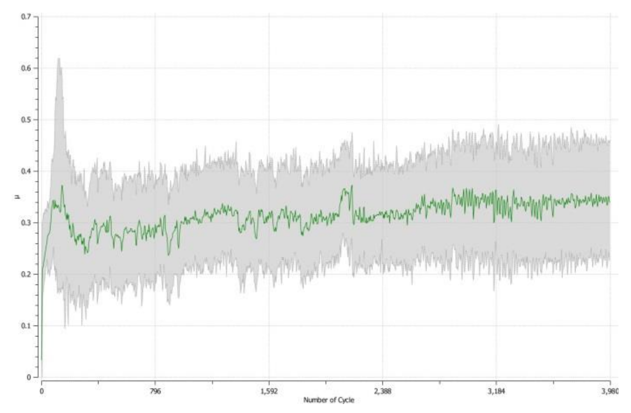
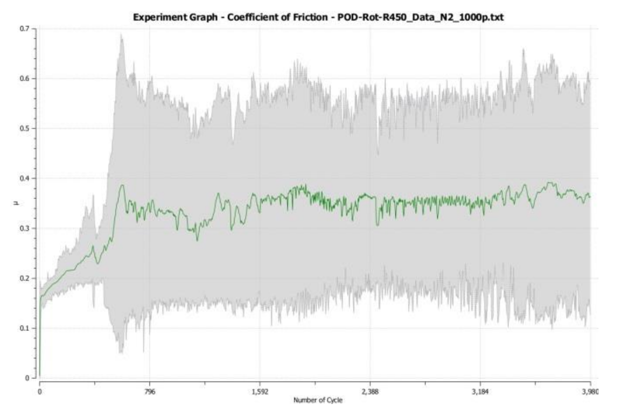
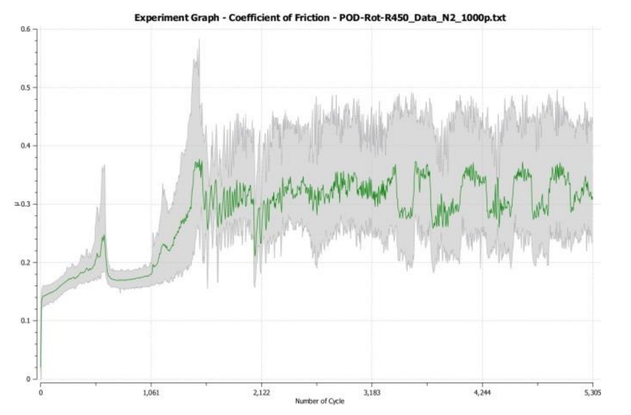


Figure 1.The micro (a) and nano (b) structure of thecross-sectionfor cutting ceramic inserts Al_2O_3 – TiC with **NMCC**Ti-TiAlN-(ZrNbTiAl)N.

3.2. Influence of NMCC on tribological properties

The results of the tests of tribological properties of ceramic inserts on the basis of the systems Al_2O_3-TiC and Al_2O_3-SiC_w with NMCC Ti-(TiAl)N-(ZrNbTiAl)N are presented in Fig. 2.
The study results have revealed the following. The CI on the base of Al_2O_3-TiC and Al_2O_3-SiC_w with NMCC showed a decrease in friction coefficient down to 0.3-0.4 (Fig. 2). In particular, with friction along the surface of the sample based on mixed ceramic Al_2O_3-TiC with NMCC of Ti-(TiAl)N-(ZrNbTiAl)N (Fig. 2, c), in steady state after two thousand cycles, the friction coefficient μ decreased down to 0.4. The Al_2O_3-SiC_w-based samples with NMCC of Ti-(TiAl)N-(ZrNbTiAl)N (Fig. 2, d) showed gradual increase in the friction coefficient μ from 0.2 down to 0.3, which was two times lower than on uncoated samples. ???

Al$_2$O$_3$-TiC	Al$_2$O$_3$-SiC$_w$
	
a. Uncoated	b. Uncoated
	
c. NMCC Ti-(TiAl)N-(ZrNbTiAl)N	d. NMCC Ti-(TiAl)N-(ZrNbTiAl)N

Alex what is the green line? For clear comparison vertical axis must be of same magnitude; put all on 0.7

Figure 2. Dependence of friction coefficient on the number of cycles, committed by counter-body on the base of Al$_2$O$_3$-TiC and Al$_2$O$_3$-SiC$_w$: without coating (a, b), with NMCC Ti-(TiAl)N-(ZrNbTiAl)N (c, d)

3.3. X-ray diffraction microanalysis of the elaborated NMCC

Results of X-ray diffraction chemical analysis of Ti-TiAlN-(ZrNbTiAl)N both on the surface and cross section, as well as - in the «bevel cut», formed as a result of wear on the rake face are shown in Fig. 3.

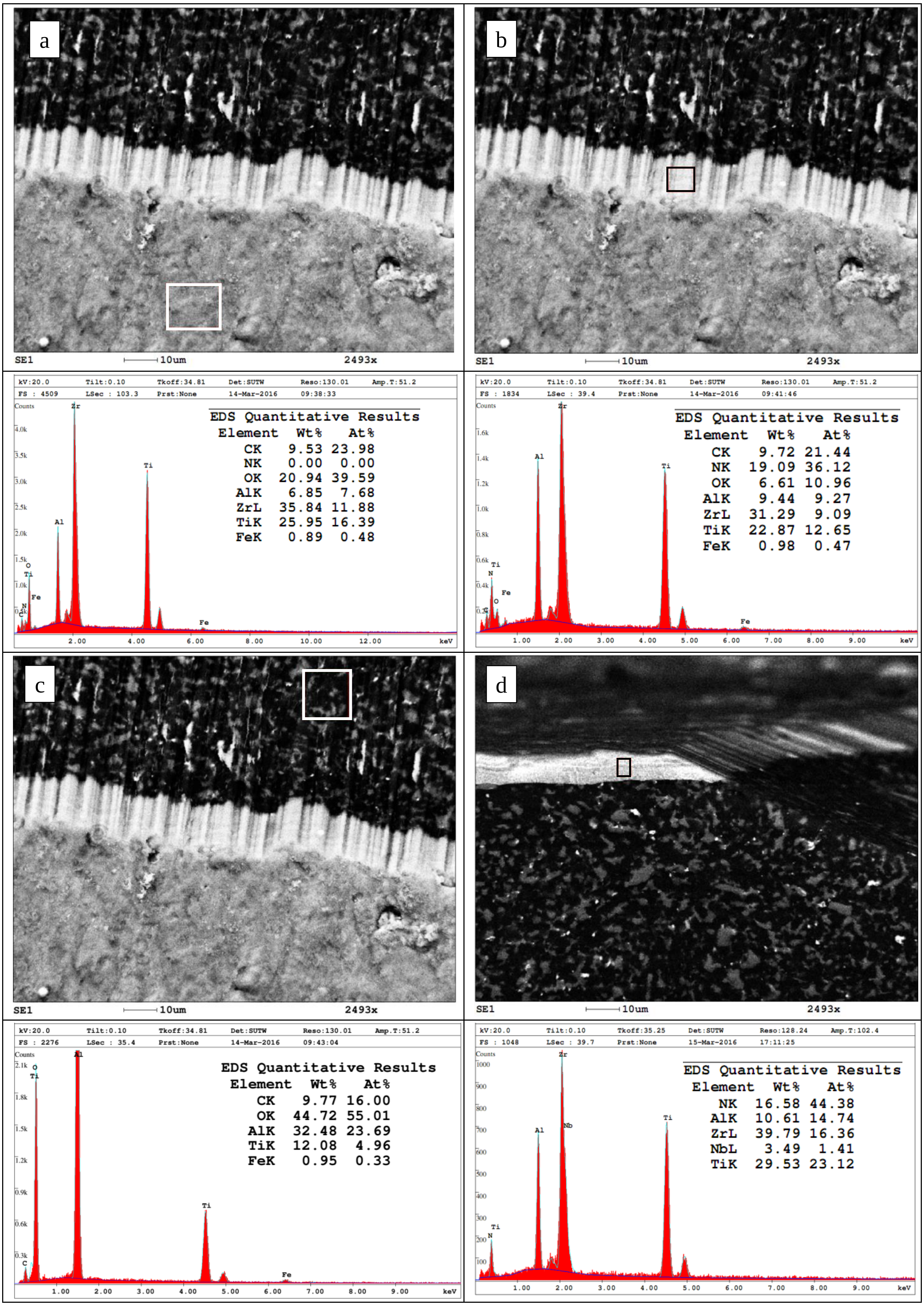

a
SE1
10um
2493x
kV:20.0 Tilt:0.10 Tkoff:34.81 Det:SUTW Reso:130.01 Amp.T:51.2
FS : 4509 LSec : 103.3 Prst:None 14-Mar-2016 09:38:33
EDS Quantitative Results
Element Wt% At%
CK 9.53 23.98
NK 0.00 0.00
OK 20.94 39.59
AlK 6.85 7.68
ZrL 35.84 11.88
TiK 25.95 16.39
FeK 0.89 0.48
b
SE1
10um
2493x
kV:20.0 Tilt:0.10 Tkoff:34.81 Det:SUTW Reso:130.01 Amp.T:51.2
FS : 1834 LSec : 39.4 Prst:None 14-Mar-2016 09:41:46
EDS Quantitative Results
Element Wt% At%
CK 9.72 21.44
NK 19.09 36.12
OK 6.61 10.96
AlK 9.44 9.27
ZrL 31.29 9.09
TiK 22.87 12.65
FeK 0.98 0.47
c
SE1
10um
2493x
kV:20.0 Tilt:0.10 Tkoff:34.81 Det:SUTW Reso:130.01 Amp.T:51.2
FS : 2276 LSec : 35.4 Prst:None 14-Mar-2016 09:43:04
EDS Quantitative Results
Element Wt% At%
CK 9.77 16.00
OK 44.72 55.01
AlK 32.48 23.69
TiK 12.08 4.96
FeK 0.95 0.33
d
SE1
10um
2493x
kV:20.0 Tilt:0.10 Tkoff:35.25 Det:SUTW Reso:128.24 Amp.T:102.4
FS : 1048 LSec : 39.7 Prst:None 15-Mar-2016 17:11:25
EDS Quantitative Results
Element Wt% At%
NK 16.58 44.38
AlK 10.61 14.74
ZrL 39.79 16.36
NbL 3.49 1.41
TiK 29.53 23.12
keV

Figure 3. Analysis of the chemical composition of NMCC based on Ti-TiAlN-(ZrNbTiAl)N at the surface (a), in the «bevel cut», formed as a result of wear of NMCC on the rake face (b), the area of the ceramic substrate wear (c) and cross section of NMCC (d).

Based on the content of elements on the surface and cross section, as well as in the bevel cut, formed as a result of wear on the rake face, one can state the following:

1. The content of Zr and Ti in NMCC on the basis of Ti-TiAlN-(ZrNbTiAl)N is relatively high in the analysis of cross section of coating . It is to notice that the cuts were done with a diamond grinding wheel. These figures are most close to the content of the above elements in the coating structure (39.79 and 29.53%, respectively). On the surface of the coating, in the area of contact with the rake face of the ceramic substrate, both elements are registered in smaller amounts (35.84 and 25.95%, respectively).The lowest concentration of these elements is registered in the "bevel cut" zone, formed as a result of wear on the rake face (31.29 and 22.87%, respectively). The above can be apparently associated with diffusion processes in the cutting zone and chemical interaction of NMCC with ceramic substrate Al_2O_3-TiC. Meanwhile, Nb, detected in the tests of cross section of NMCC, was not registered in these tests of its contact areas.

The content of Al is also higher in the analysis of cross section of coating (10.61%); however, its content in the "bevel cut" zone, was higher (9.44%) than on the outer face of coating (6.85%). This can be explained by a combination of inter-diffusion processes between the material being machined (resulting in a reduction in Al content) and ceramic substrate Al_2O_3-TiC. This may result in some increase in the content of Al due to its diffusion from the ceramic substrate.

2. On all contact areas, the tests registered a small content of Fe (0.89-0.98%) due to the diffusion from the material being machined.

3. The content of O was considerably higher on the coating face (20.94%) than in the "bevel cut" zone, (6.61%). This was associated with the active "failure" of oxide films in the area of secondary deformations, i.e., in the area of the tight contact between NMCC and the material being machined.

3.4. Coating adhesion

During the studies of adhesion strength of the NMCC Ti-TiAlN-(ZrNbTiAl)N, deposited on the ceramic substrates Al_2O_3-TiC, a normal load F_n was applied to operating indenter, and the depth of indenter penetration P_d was registered with a simultaneous determination of friction coefficient. A fragment of the results of the studies of adhesion strength of coatings is presented in Fig. 4 .

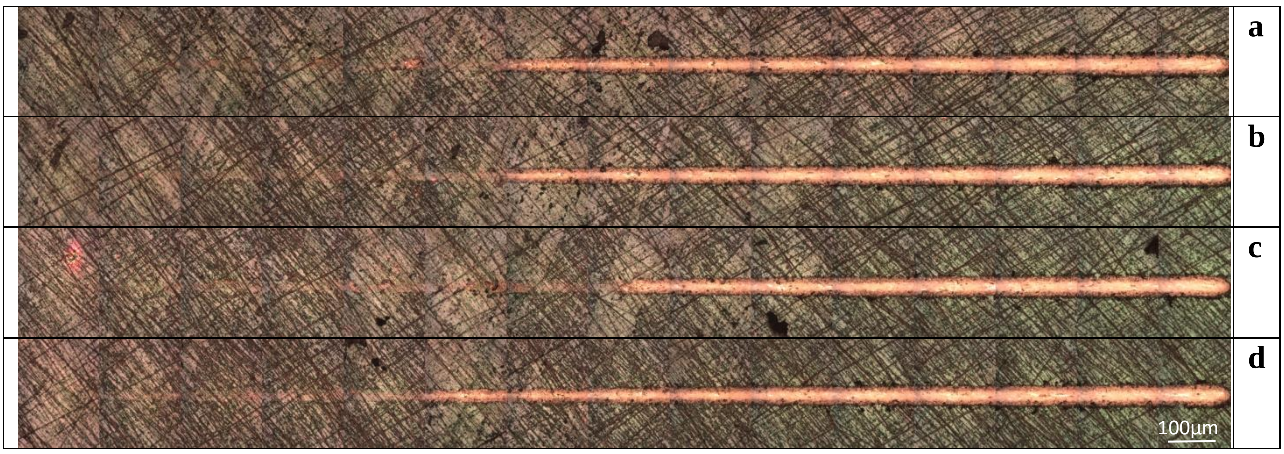


Figure 4. tracks of scratches on the surface of the Al_2O_3-TiC-based samples of CC with ***NMCC*** of Ti-TiAlN-(ZrNbTiAl)N under loads: 1- 5.0 N (*a*), 1 - 10 N (*b*), 1-20 N (*c*), and 1 - 40 N (d).

As it can be seen from the data shown in Fig. 4, no delamination of coating Ti-TiAlN-(ZrNbTiAl)N was observed along a scratch within the whole range of changes of the load F_n on indenter up to 40 N, and that proves high adhesion strength between coating Ti-TiAlN-(ZrNbTiAl)N and ceramic substrate Al_2O_3-TiC.
It should be noted that during the scratching of the surface of ***NMCC*** of Ti-TiAlN-(ZrNbTiAl), the registered acoustic emission signal generated no sharp peaks and showed no delamination of ***NMCC*** from ceramic substrate even at critical loads of up to 40 N on the scratching indenter.

3.5. Influence of coating properties on cutting performance

Cutting properties of coated ceramic tool

Fig. 5 presents samples of a large-scale studies of cutting properties of ceramic inserts of mixed ceramic Al_2O_3-TiC and Al_2O-SiC_w without coatings (1) and with coatings Ti-(TiAl)N (2) and NMCC of Ti-TiAlN-(ZrNbTiAl)N (3).
The analysis of the results of the studies of cutting properties of coated tools, the following can be noted. In longitudinal turning of hardened steel X153CrMoV12, the wear rate for ceramic tools of mixed ceramics Al_2O_3-TiC and Al_2O-SiC_w strongly depended on the composition of coating. In particular, the maximum increase in the tool life was provided by NMCC system Ti-TiAlN-(ZrNbTiAl)N, which for VB=0.4 mm the increase of tool life was up to 1.5 times of the uncoated tool and 1.3 times as compared with the tool life of a tool with standard coating Ti-(TiAl)N. The differences in cutting time for different types of coatings and uncoated ceramic tool increase with the increase in cutting speed from 250 up to 300 m/min.

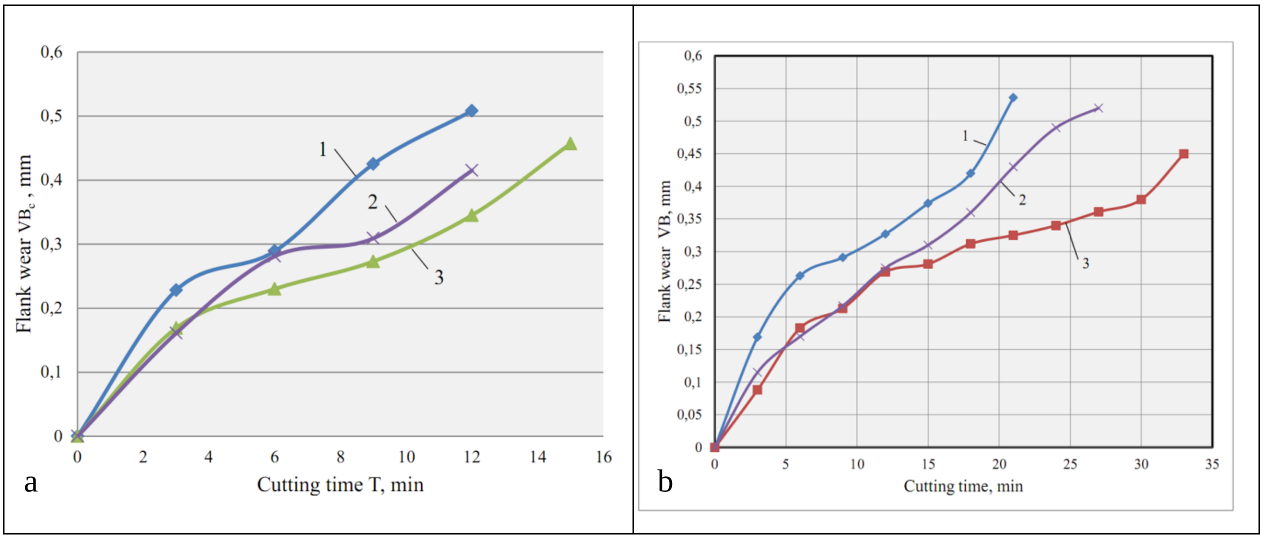


Figure 5. Dependence of wear VB_{max} on cutting time for: uncoated inserts (1), with coating Ti-(TiAl)N (2) and NMCC Ti-TiAlN-(ZrNbTiAl)N (3), in longitudinal turning of hardened steel X153CrMoV12 at v_c=250 m/min, f =0.05 mm/rev, a_p=0.5 mm, inserts made of Al_2O_3-TiC (a) and Al_2O_3-SiC_w (b) at v_c=300 m/min, f =0.1 mm/rev, a_p=0.5 mm, inserts made of Al_2O-SiC_w (b).

The wear mechanism of the coated ceramic tool

The most probable mechanism of failure of a ceramic tool is brittle fracture of cutting wedge [1-4, 12-15]. This occurs because of the lower brittle strength of the ceramic tool material as compared with the corresponding characteristics for carbide material. In this case, the tendency of the ceramic tool to stochastic brittle fracture is also caused by the higher contact stresses, particularly normal ones. These contact stresses are generally higher than the corresponding values for the carbide tool because of the considerable reduction of the total length of chip contact with rake face of the ceramic tool at small decrease in the normal load.

The nature of the development of wear centres on rake and flank faces of Al_2O_3 – TiC ceramic cutting insert with coating Ti-(TiAl)N and NMCC Ti-TiAlN-(ZrNbTiAl)N in longitudinal turning of hardened steelX153CrMoV12 was balanced with no visible chips and microchipping. The above process is also characterized by undisturbed residues of coatings at the edges of wear centres both on rake and flank faces of the ceramic cutting insert (Fig. 6, a, b).

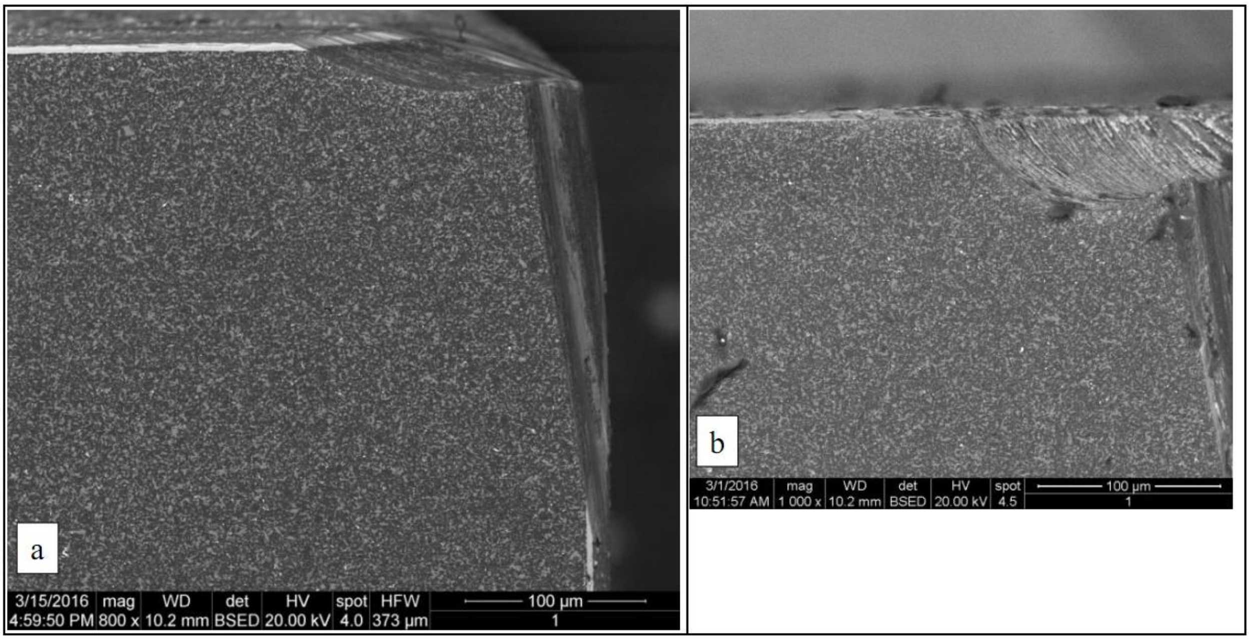


Figure 6.The nature of wear after 25 minutes in longitudinal turning of hardened steel X153CrMoV12 at v_c=250 m/min, f =0.05 mm/rev, a_p=0.5 mm for cutting inserts made of Al_2O_3 – TiC with NMCC Ti-TiAlN-(ZrNbTiAl)N (a) and coating Ti-(TiAl)N (b).

The wear mechanism for NMCC, both along the rake and flank faces of a tool, was similar to the wear mechanism for ceramic substrate and showed a predominantly abrasive interaction with the material being machined. It is important to note that NMCC and substrate operate as an integrated system, with virtually no scratches and chips (Fig. 6). No adherence of the material being machined was observed on the surface of NMCC, and this fact is connected with low adhesion between outer (wear-resistant) layer of NMCC and the material being machined.

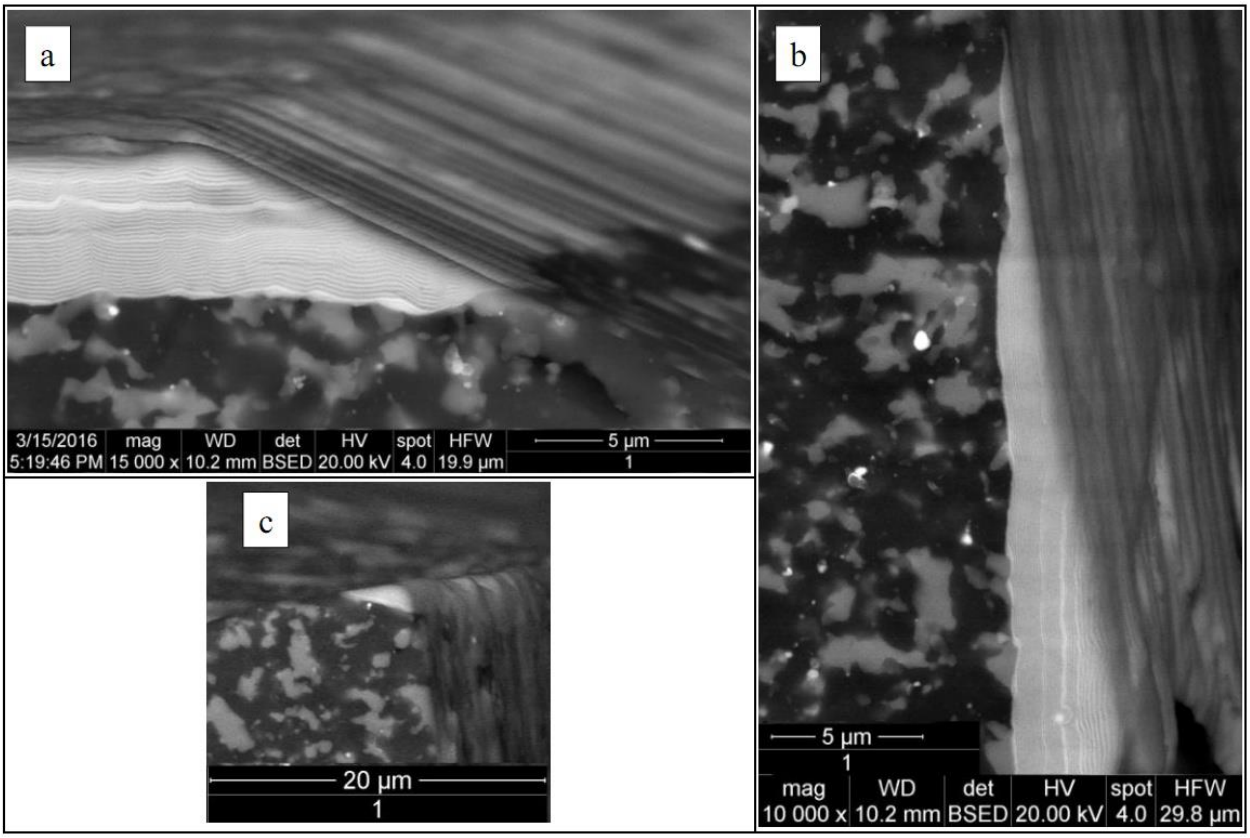


Figure 7. Nature of wear of: rake face (a), flank face (b) and corner (c) of ceramic insert Al_2O_3 – TiC with NMCC Ti-TiAlN-(ZrNbTiAl)N after 15 minutes cutting.

During the testing, a good adhesion was maintained between NMCC and ceramic substrate (Fig. 7). A typical mechanism of failure of NMCC means the formation of longitudinal cracks in the areas, directly adjacent to the cutting zone (Fig. 7a). However, such cracks, associated with "delamination" of NMCC under the influence of compressive residual stresses, are considerably less dangerous than cross cracks, which are often formed in the coatings of "traditional" type (Fig. 8).

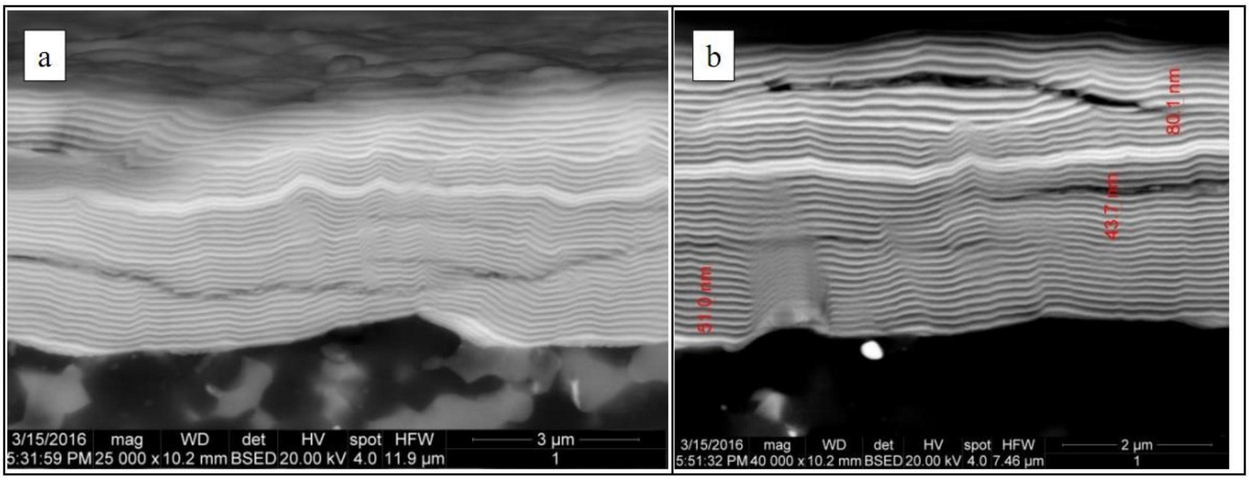


Figure 8. Ceramic insert Al_2O_3 – TiC with NMCC Ti-TiAlN-(ZrNbTiAl)N. Find machining conditions in Fig. 6.

During cutting with coating Ti-(TiAl)N, a mass adherence of the material being machined was observed, both along the rake and flank faces of the tool (Fig. 9). The mechanism of tool wear here was connected with adhesive-fatigue processes, as proved by the nature of failure of the coating with distinct "tear-outs" of the coating elements (see Fig. 9).

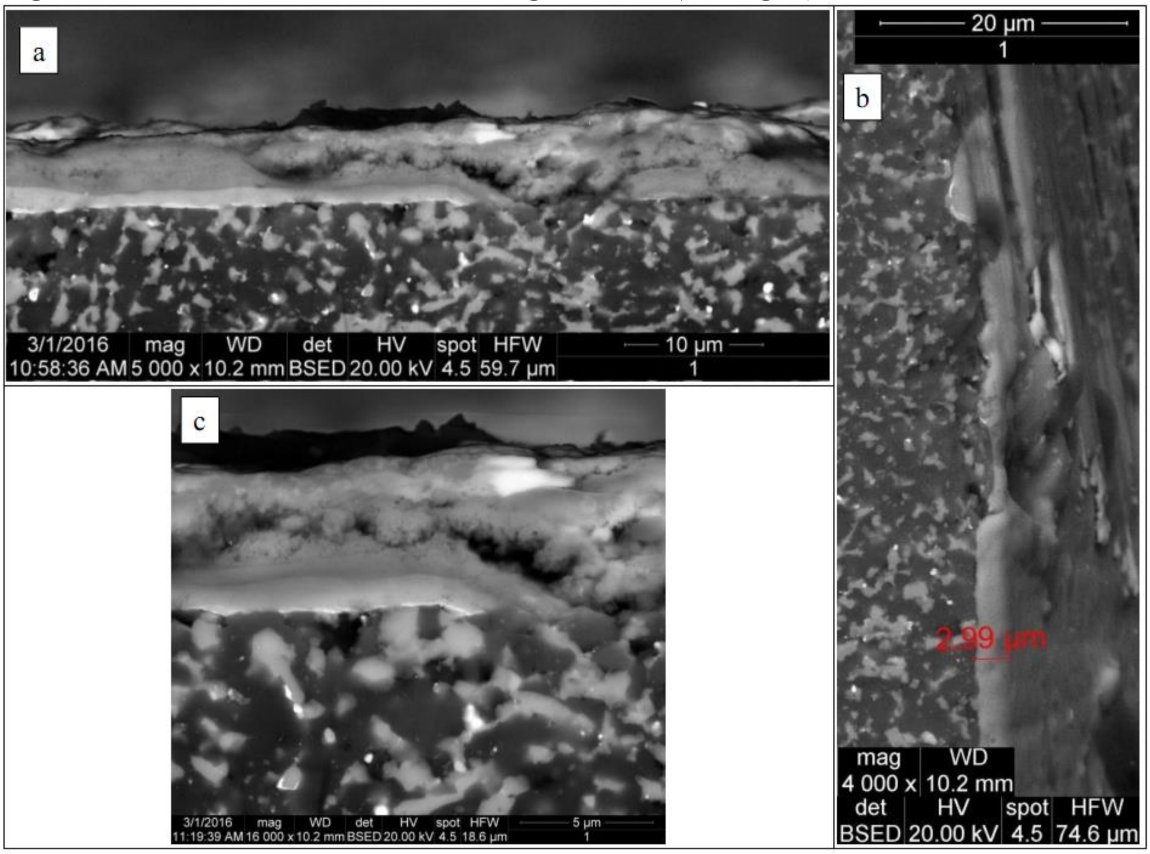


Figure 9. Wear of rake face of ceramic insert of Al_2O_3 – TiC with: coating Ti-(TiAl)N (a) and nature of wear of flank face of insert with particles of the material being machined (b) after 20 minutes cutting in longitudinal turning of hardened steel X153CrMoV12 at v_c=250 m/min, f =0.05 mm/rev, a_p=0.5 mm.

It was found that the uncoated CI made of Al_2O_3/TiC showed the most intensive wear accompanied with active cracking and brittle fracture of the tip. The tests discovered the presence of brittle cracks with length of up to 15-35 µm and width of up to 30-250 nm. Practically along the entire crack length, the tests have detected the presence of iron, embedded from the material being machined. The tests have also detected in the cracks the high content of oxygen, which is associated with increased oxidative activity during the cutting process.

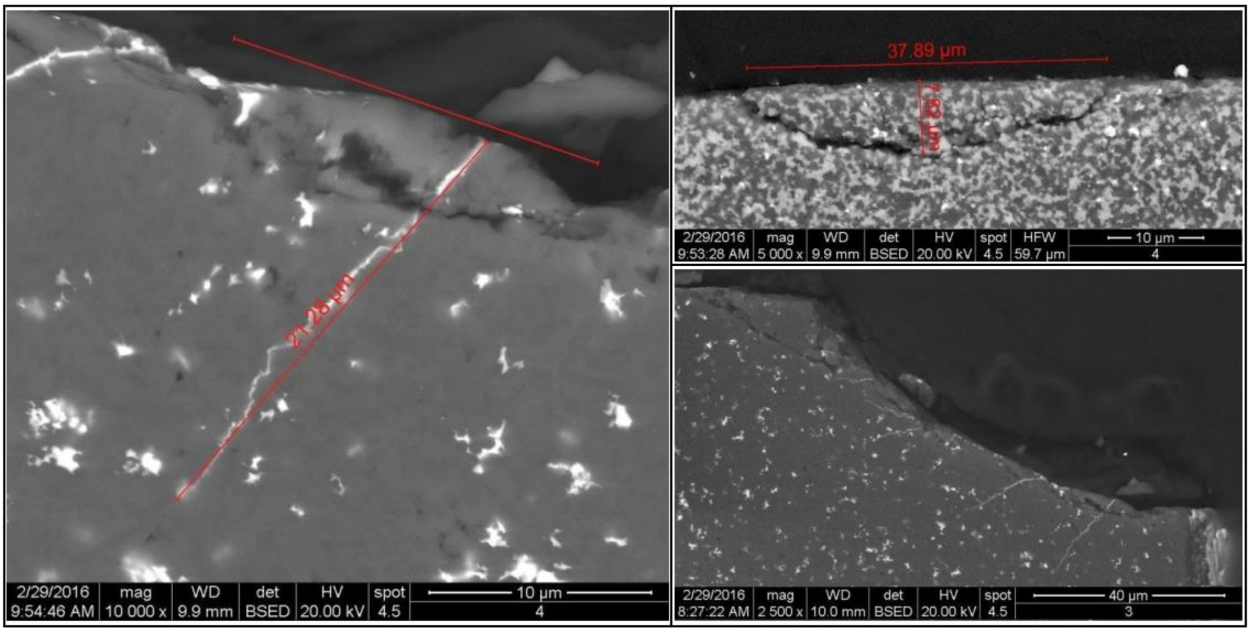


Figure 10. Uncoated ceramic insert Al_2O_3 – TiC after 12 minutes cutting. Find machining conditions in Fig. 6.

Thus, the conducted studies found that the ceramic cutting inserts of Al_2O_3 – TiC: uncoated, with coating Ti-(TiAl)N and with NMCC Ti-TiAlN-(ZrNbTiAl)N demonstrated three different mechanisms of wear:

- for the ceramic tool with NMCC Ti-TiAlN-(ZrNbTiAl), the tests have detected clear abrasive wear, without formation of adhered particles of the material being machined with virtually no cracks and brittle fracture;

- the ceramic tool with coating Ti-(TiAl)N was characterized by wear, combining adhesive and adhesion-fatigue mechanisms of wear with formation of massive adhered particles of the material being machined and removal by the cut chips of the fragments of the coating subjected to brittle fracture, formed as a result of adhesive interaction with the material being machined; meanwhile, no cracking and brittle fracture of the surface layer of the ceramic tool were discovered; the wear of the uncoated mixed ceramic Al_2O_3 – TiC was accompanied with active cracking, resulting in intensive brittle fracture of the surface layer of the tool.

Conclusion

The architecture of a nano-structured multi-layered composite coating for ceramic tool was designed using the concept of the dual nature of coatings as a process medium between the material being machined and the ceramic substrate. The outer wear-resistant layer of NMCC in contact with the material being machined intended to reduce the normal and tangential (shear) stresses and increase brittle strength of cutting wedge of a tool. The adhesive layer in contact with the ceramic substrate provided high adhesion strength of NMCC to the ceramic substrate, while the intermediate layer increases the adhesion strength between the adhesive and wear-resistant layers of NMCC. The study also focused on crystal-chemical, physical, mechanical and cutting properties of different grades of cutting ceramics with the developed NMCC. The conducted studies show that the developed coatings deposited on contact areas of ceramic cutting tools contribute to:

•the increase in the adhesion strength between the cutting ceramic and the developed NMCC;

•the reduction of the intensity of the thermal effect on structures of the ceramic substrate, due to the improvement of heat dissipation from the cutting zone by increasing the length of plastic contact. This allowed predicting an increase in tool life.

The tools of mixed ceramic with developed NMCC Ti-TiAlN-(ZrNbTiAl)N, provided an increase in the tool life as compared with the tool life of the ceramic tools without coatings and with coating Ti-(TiAl)N. Additionally, the tool life increased with the increase in cutting speed from 250 up to 300 m/min.

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