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Development and research of nanostructured multilayer composite coatings for tungsten-free carbides with extended area of technological applications

Development and research of nanostructured multilayer composite coatings for tungsten-free carbides with extended area of technological applications

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Abstract
This paper discusses aspects of the development of nanostructured multilayer composite coatings (NMCCs) formed using the processes of filtered cathodic vacuum arc deposition (FCVAD) for application to the tungsten-free carbides (cermets) based on TiC-(Ni,Mo) and TiCN-(Ni,Mo) compounds in order to improve cutting properties of tools and to expand the area of their technological application. NMCCs were used not only to improve the physical and mechanical properties of the working surfaces of tools, but also to ensure the control over contact processes during cutting. The study has shown that despite their high hardness, thermal stability and resistance to scaling, low tendency to diffusion with the material being machined, tungsten-free carbides are characterized by relatively low fracture toughness and bending strength, low thermal conductivity. With regard to the above properties, tungsten-free carbides are inferior not only to tungsten WC-Co carbides, but also to WC-TiC-Co carbides with binder content of less than 8% (by weight). Therefore, cutting tools made of tungsten-free carbides have a limited range of technological application in interrupted cutting, machining of hard-to-cut alloys and steels. With respect to this, the paper considers the possibility of directional control over contact processes during cutting with the use of NMCCs to create more balanced properties of tungsten-free carbides with regard to hardness and toughness. This work has developed architecture of three-component nanostructured multilayer composite coatings, the methods for selecting functions and rational component parameters of architecture for tools made of tungsten-free carbides.
The developed compositions of NMCCs have improved cutting properties of tungsten-free carbides and expanded the area of their technological application in cutting of heat-treated steels of increased hardness and machining of heat-resistant carbides.

Keywords: tungsten-free carbides; nanostructured multilayer composite coatings; tool life.

1. Introduction

Carbide is a basic tool material used in modern metalworking industries. There is a widespread use of standard carbides containing scarce and expensive elements such as W, Ta, Nb, Co, and others that substantially increases the production costs. This has stimulated the creation of another group of carbides not containing the above mentioned elements. Such carbides are termed "tungsten-free carbides" or “cermets”. However, the properties and areas of technological application of tungsten-free carbides are inferior to the corresponding properties of tungsten carbides. In this context, the improvement of the properties of tungsten-free carbides and expansion of areas of their technological application are important scientific and practical challenges of modern metalworking industries. According to leading experts, in edge shape-generating machining technologies of the future, the widespread use of tools made of tungsten-free carbides, not containing such deficient elements as W, Ta, Nb, Co, and others, will lead to

significant economic and environmental impact [1-3]. There are a number of works that demonstrate the effectiveness of the use of wear-resistant coatings for tungsten-free carbideas [4-5]. In particular, they studied the coating deposited by the method of PVD- TiAlN [4], TiN, TiC, TiCN and Al_2O_3 [6], also considered properties of the coating TiN, deposited by PACVD [6]. Investigations were carried out to determine coating adhesion, residual stress and machinablity. Face milling experiments showed a substantial increase in wear resistance of coated tool.
Moreover, binary and ternary titanium based hard coatings deposited onto different cermet substrates by PVD processes were examined in interrupted cutting of tempered, case hardened and austenitic steels. PVD (Ti,Zr)N and Ti(C,N) coatings improve tool life in the machining of tempered steel [8]. This study also showed that the thermal conductivity of the cermets is of great importance for performance in interrupted cutting.
Multiple layers of type TiN with mono- or gradient(Ti, Al, Si)N + TiN and TiN with multi(Ti, Al, Si)N + TiN in CAE (cathodic arc evaporations) process (method PVD) [9]were investigated. Results of the continuous machining of the C45E steel showed a significant increase in the durability coated inserts compared with uncoated. Recent studies indicate the possibility of using tungsten-free carbides on a par with traditional tungsten carbides, and in some cases - a superiority over tungsten carbides was observed. In particular, the work [10] has shown that Ti(C,N)-based cermet tool had longer tool life and higher crater wear resistance than coated WC–Co tool in hard turning. The work in [11] examined the coating Ti-TiN-TiAlCrN, Ti-TiN-TiZrCrN and Ti-TiN and an increase in tool life by 2.5-4 times, and by 3-4 times respectively, compared to lifetime of tool without coating and with standard coatings.

This study presented here focuses on the development of the methods to apply coatings on tools of tungsten-free carbides to improve their cutting properties and expansion of the area of their technological application. For deposition of coatings on substrates of tungsten-free carbides, the innovative processes of filtered cathodic vacuum arc deposition (FCVAD) were used, that allowed to form multilayer composite coatings with nano-scale structure [12-17]. The application of coatings of the above type cannot only improve wear resistance of tools made of tungsten-free carbides when exposed to high thermomechanical stresses typical for high-speed processes of dry cutting. Besides, it significantly expands the area of application of the tools and improves the environmental parameters of machining.
The development of tools of tungsten-free carbides with nanostructured multilayer composite coatings (NMCC) is an urgent scientific direction of "engineering" of composite materials with an optimum combination of surface and "bulk" properties in the same geometric body of the product. It should be noted that despite the considerable number of the studies aimed to develop tungsten-free carbides carried out in several technologically advanced countries, layer composite, comprising substrate of tungsten-free carbides and NMCCs, was hardly used as a basis for the development of composite materials.

Symbols

K_a	adhesion coefficient
ρ	density of tool material
F_a	nominal contact area
J	adhesion intensity
σ_a	bending strength at adhesion knots
σ_p	wear resistance of tool material
N_T	number of active centers per unit of contact area, at thermal activation
N_M	number of active centers per unit of contact area, at mechanical activation
ν	frequency of natural oscillations of atoms of valence
T	time

Q_t	thermal activation energy
K	Boltzmann constant
ρ_1	density of dislocations
S	the mean free path of dislocation
b	Burgers vector
V_D	Speed of movement of dislocations
τ	stresses
$n1$	exponent, depending on the hardness of the material
θ	absolute temperature
p_N	pressure of reaction gas (nitrogen)
W_i	ion energy
U_s	voltage on substrate
I_A (I_{Ti}, I_{Cr}, I_{Al}, I_{Zr})	arc current
P_s	adhesion strength to substrate
t	depth of cut
f	feed
v	cutting speed
h_F	flank wear
C_γ	length of full contact on rake face
F	shear angle
μ_γ	friction coefficient on rake face
ξ	shrinkage of chips
P_z, P_y and P_x	tangential, radial, and axial component cutting forces, respectively
$C_{\gamma P}$	length of plastic (thick) contact on rake face
τ_F	tangential stress in conventional shear section
q_F	average tangential stresses on rake face of tool
q_N	average normal contact stresses on rake face of tool
σ_{Nmax}	maximum normal contact stresses on rake face
σ_n	contact stresses on rake face
τ_y	tangential stresses on rake face

2. **Methods of study**

The object of study was represented by inserts that efficiently combined the properties of tungsten-free carbides (high wear resistance and toughness) and multi-component functional coating with multilayer composite architecture and nanoscale structure (desirable transformation of contact processes in cutting, "healing" of surface defects) [1].

The experiments used strong substrates of tungsten-free carbides based on systems of TiC-Ni/Mo and TiCN-Ni/Mo with content of Ni/Mo binder over 10% (by volume), and that gave the composite of "tungsten-free carbide-NMCC" the strength similar to strong classes of carbides (**σ_i** ≅ 1350-1400 MPa). The formation of surface layers in the form of NMCCs based on nanostructured composite multilayer architecture significantly increased the tool life and operational reliability of tungsten-free carbides. Besides, the combined impact on the surface of tungsten-free carbides by average-energy ions of metal-gas plasma followed by synthesis of ion-plasma NMCCs based on compositions of various compounds of refractory transition metals allowed "healing" the most dangerous surface defects (including sub micro cracks, discontinuities, sub micro- and micro pores, surface areas with tensile residual stresses, etc...) that were formed during the manufacturing process. NMCCs were formed on substrates of carbides using conventional physical processes of arc-PVD or MeVVa (Metal Vapor Vacuum Arc), as well as the innovative version of arc-PVD, called "filtered cathodic vacuum arc deposition" (FCVAD) of coatings. The FCVAD processes were implemented using vacuum-arc VIT-2 unit.

At present, the ***MeVVA*** processes are widely used by the leading manufacturers of cutting tools due to their high reliability, flexibility, and possibility to produce coatings of virtually any architecture, composition, and structure. Meanwhile, the MEVVA processes ensure environmental purity as compared with the methods and processes of chemical vapour deposition of coatings (CVD methods).

When analyzing the functional role of coating on contact areas of tungsten-free carbides, the study used the concept of dual nature of coating as "intermediate technological environment" (ITE) between the tool material and the material being machined. The accepted concept determines the role of the coating on the working surfaces of tungsten-free carbides. On the one hand, the coating should directly improve important properties of tool material as physical-chemical inertness (tendency to adhesion) with respect to the material being machined, wear resistance (hardness, thermal conductivity, heat resistance). On the other hand, the coating should influence the contact processes (length of "chips-tungsten-free carbides" contact, contact stresses, temperature fields) and cutting parameters determining wear intensity of the cutting tool. In this case, the coating should have multilayer architecture for full compliance with the requirements to ITE. With regard to the coating as a basis for ITE, the study has formulated the concept of coating as three-component system with nanostructured multilayer composite structure (NMCC) for deposition on tungsten-free carbides (Table 1).

The chemical composition of wear-resistant layer of NMCC was selected in accordance with the accepted assumption that adhesive-fatigue wear was the main mechanism of wear of the cutting tool of tungsten-free carbides. On the basis of the accepted model of wear of tungsten-free carbides, it should be noted that the maximum reduction of adhesive-fatigue wear of the cutting tool is observed at minimum weight loss in tool material, i.e., when *Ma → minimum* [1]:

$$Ma = K_a \cdot \rho \cdot F_a\left(J \cdot \sigma_a/\sigma_p\right), \quad (1)$$

where K_a – adhesion coefficient (by volume); ρ – density of tool material; F_a – nominal contact area; J – adhesion intensity; σ_a – bending strength at adhesion knots; σ_p – wear resistance of tool material. In particular, the adhesion strength was determined by the following relation:

$$J = (N_T + N_M)F_a, \quad (2)$$

where N_T, N_M – are number of active centers per unit of contact area, at thermal and mechanical activation, respectively. N_T was determined as follows:

$$N_T = \nu \cdot T \cdot e^{-Q_t/K\theta}, \quad (3)$$

where ν – frequency of natural oscillations of atoms of valence; T – time; Q_t – thermal activation energy; K – Boltzmann constant; θ – absolute temperature. N_M was determined from the following expression:

$$N_M = \rho_1 \cdot S \cdot b \quad (4)$$

where ρ_1 - density of dislocations; S - mean free path of dislocation; b - Burgers vector.

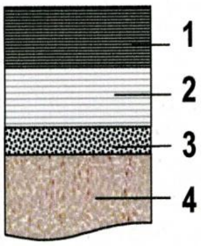
The speed of movement of dislocations can be estimated as:

$$V_D = S \cdot \tau^{n1} \quad (5)$$

where τ - stresses; $n1$ – exponent, depending on the hardness of the material.

A specific feature of the formation of NMCC of tungsten-free carbides was associated with low thermal conductivity and relatively low thermal capacity as compared with standard tungsten carbides. In this regard, ion cleaning (bombardment) and thermal activation (by ions) of carbides inserts was performed with pulsed shear voltage U_s, and that allowed thermal activation at relatively slow heating of the substrate without the risk of formation of thermo-cracks inside the insert surface. The temperature of the thermal activation was 600-650°C.

Table 1. Architecture of NMCC for cutting tool of tungsten-free carbides

Architecture of NMCC layers	**Compositions of NMCC layers**	**Functional area**
	1 - wear resistance (outer) layer with nano-scale sublayers (e.g. Ti,AlN, TiCrAlN, ZrCrAlN, TiCrAlSiN, etc.) 2 – intermediate layer with nano-scale sublayers (e.g. TiN, TiN/AlN, ZrN, CrN, Al_2O_3) 3 – adhesive sublayer (e.g., Ti,Zr,Cr,TiN,CrN) 4 – substrate of tungsten-free carbide (KNT-16; ISO K10-K20; 84% TiCN;12,4%Ni/3,6%Mo)	1. Improvement of wear resistance of substrate of carbides, reduction of physical-chemical and adhesion activity of carbides, control over contact processes. 2. Maintenance of adhesion between layers 1 and 3, barrier functions (with regard to diffusion, thermal flows, etc.). 3. Maintenance of high adhesion strength between layer 3 and ceramic carbide substrate (layer 4).

2.1. Methods to form coatings

The process of NMCC deposition was carried out at optimal combination of key parameters of the FCVAD process at vacuum-arc VIT-2 unit. The system also provided optimal rotation speed of worktable of VIT-2 unit (1.0-10 rpm) and rotation speed of machining attachments with inserts, and that provided a uniform formation of nano-scale thicknesses of sublayers of wear-resistant, intermediate, and adhesive layers, as well as nano-dispersed structure of NMCC.

The analysis of conditions for producing NMCCs with the use of FCVAD processes with regard to their parameters and properties has revealed that the content of nitrogen in nitride of refractory compound and the ratio of "nitrogen-metal" in the NMCC layers being formed are determined by the pressure of reaction gas (nitrogen) p_N and ion energy W_i. The latter parameter highly depends on shear voltage on substrate U_s and arc current I_A at evaporation of cathode (Ti, Zr, Cr, Al, etc.). Therefore, the parameters of the process for synthesis of adhesive (3), intermediate (2), and wear-resistant (1) layers of NMCC have a strong influence on their structure, phase composition, crystal lattice parameter, structural and geometrical defects, and performance properties of NMCC in general.

For the investigation, four types of multilayer composite coatings were selected, including Ti-TiN-TiAlN; Zr-ZrN-ZrCrAlN, Cr-CrAlN-TiCrAlSiN and Ti-TiAlN-TiZrAlSiN. After placement of carbide inserts in the chamber of VIT-2 unit, the chamber vacuum was created at a pressure of 0.01 Pa. Plasma cleaning of the working surfaces of inserts was conducted by Ar ions at increased pressure from 1.5 up to 2.5 Pa. Then, final cleaning and thermal activation of inserts were carried out in non-self-maintained gas discharge (GD) at pressure of 0.5 Pa and maximum shear stress of 1 kW.

Parameters for coating deposition were as follows: I_{Ti} = 80 A; I_{Cr}=70 A; I_{Al}=160 A; U_s=160 V; p_N= 0.5 Pa.

The following characteristics of the coatings were studied: thickness (by method of "Calotest", apparatus of Fischer Sindelfingen), adhesion strength to substrate material (by method "Scratchtest", apparatus of Csem Revetest), nano-hardness and modulus E_1 (by method of NanoTest, apparatus of Micromaterials Ltd.Wrexam). The tests on nano-indenter were carried out using Berkovich indenter in accordance with standard methods. For each sample of carbide with deposited coating, nano-hardness was tested through 25 measurements in area of 100 x 100 µm^2.

Pre-certification confirmation tests of the tool with inserts of KNT-16 with various options of nanostructured multilayer composite coatings have shown that higher results for the tool life were obtained for Ti-TiN/AlN-TiCrAlSiN coating, and thus, the basic studies of functional cutting parameters were conducted with the use of the tool with the above mentioned coating.
Coating of Cr-CrN/AlN-(TiCrAlSi)N used in the experiments was characterized by the following parameters: microhardness $HV_{0.05}$=3.2 GPa; adhesion strength to substrate P_s=120 N; total coating thickness 3.9 µm; grain sizes of coating components 10-12 nm; thickness of sublayers (outer and intermediate layers) 20-25 nm. Further studies were carried out only for inserts of KNT-16 with developed NMCCs formed with the use of the FCVAD technology.

Results materialographic investigation into the microstructure of the coating transverse sections are shown in Figures 1-4. It is important to note that during actual deposition of coatings in some cases between the intermediate and the wear-resistant layer an additional intermediate layer was formed (especially notable in Fig. 1 and 2). This layer is formed as a result of the need for additional heating process products by metal plasma flow and consists of a combination of deposited metals (Ti, Cr, Al, Zr). The thickness of this layer is from 10 to 30 nm. Intermediate and wear-resistant layers in all cases had a thickness of 10-15 nm, at the same time, adhesive layer has nanoscale only when using Cr as the material of the layer (see Fig. 3).
Analysis of metallographic studies (Fig.1-4) confirmed the presence of a kind of circular structure of tungsten-free carbide CST-16 [4].

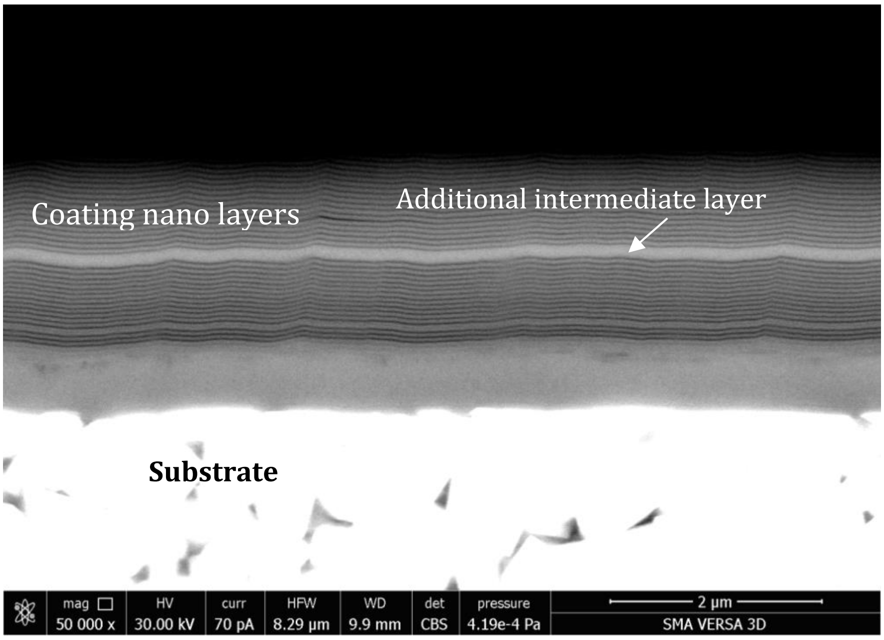


Fig.1. SEM microphotographs of structure for sample of the composite multilayer coating Zr-ZrN-ZrCrAlN on the tungsten-free substrate KNT-16; ISO K10-K20

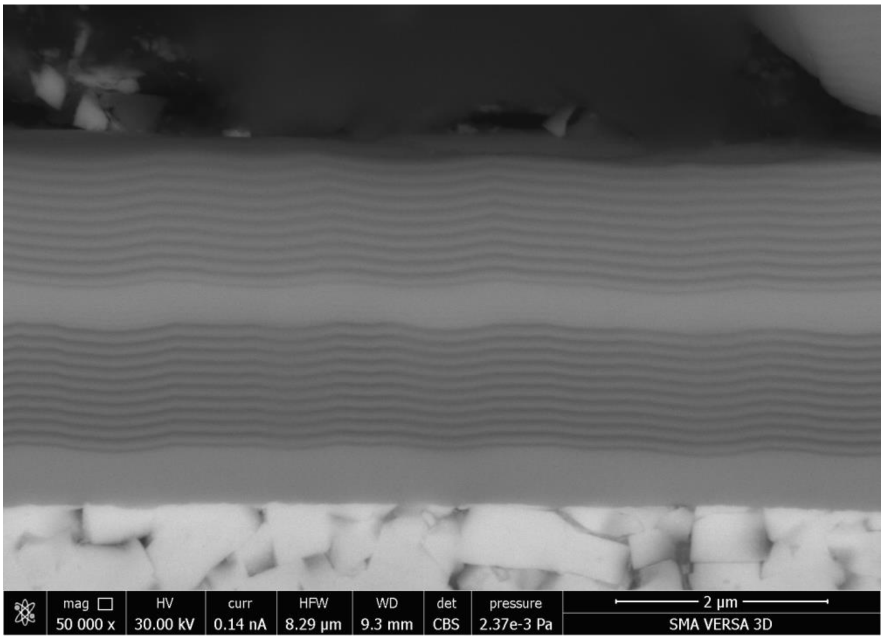


Fig.2. SEM microphotographs of structure for sample of the composite multilayer coating Ti-TiAlN-TiZrAlSiN on the tungsten-free substrate KNT-16; ISO K10-K20

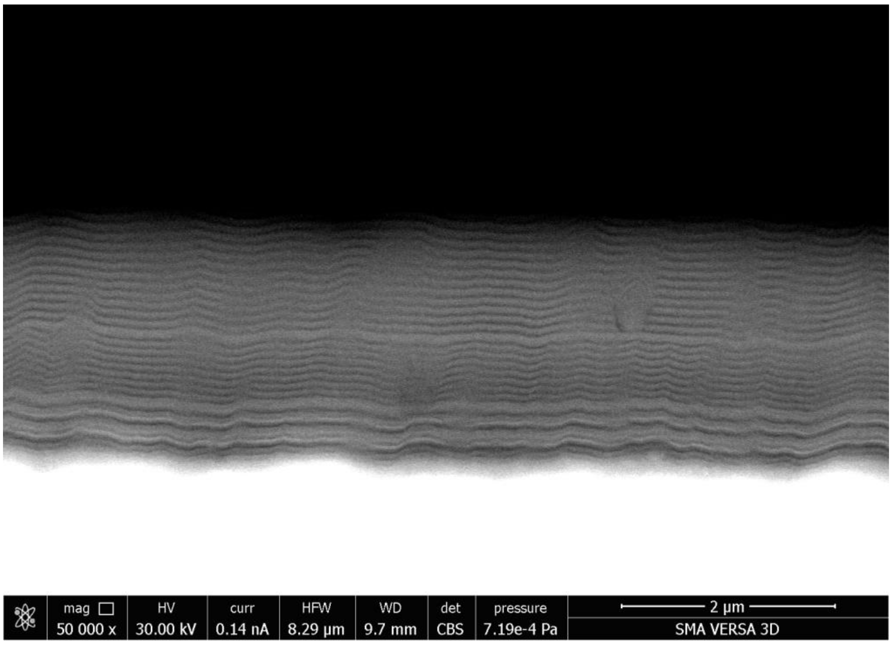


Fig.3. SEM microphotographs of structure for sample of the composite multilayer coating Cr-CrAlN-TiCrAlSiN on the tungsten-free substrate KNT-16; ISO K10-K20

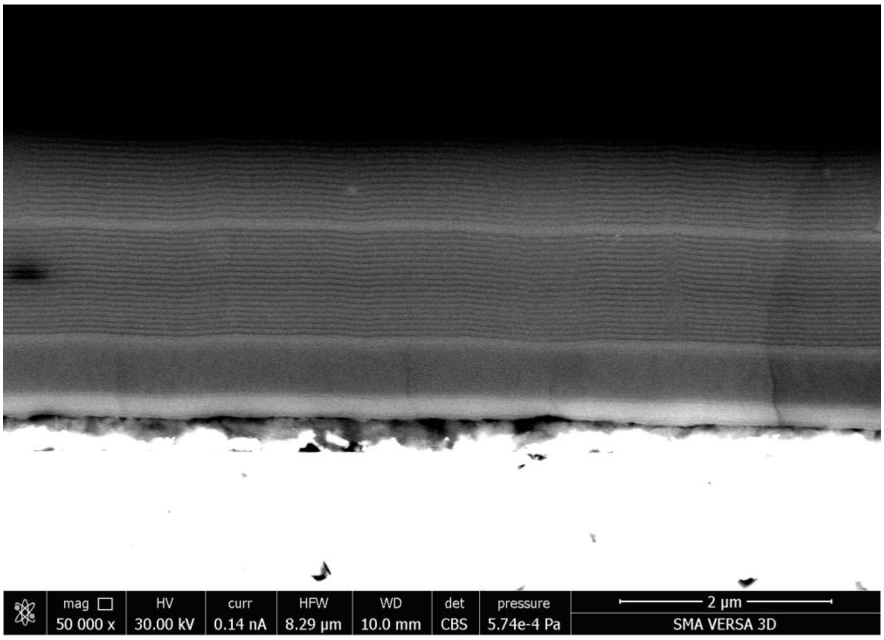


Fig.4. SEM microphotographs of structure for sample of the composite multilayer coating Ti-TiN-TiAlN on the tungsten-free substrate KNT-16; ISO K10-K20

2.2. Study of cutting properties of coated tungsten-free carbides

During testing, square inserts (12.7×12.7×4.75 mm; SNUN - ISO 03111 0363) were used with the following geometric parameters of the cutting edges: $\gamma = -8°$; $\alpha_z = 6°$; $\varphi = \varphi_1 = 45°$; $\lambda = 0$; r = 0.8mm.

Steels 1045 and 107WCR5 (HVG) and chromium-based heat-resistant alloy H65NVFT (Cr - base; Ni – 32%; Ti - 0,5%; V - 0,25%; W - 1,5% were used as machined materials.

The cutting performance of the tools were studied on a lathe, which provided stepless control of spindle speed and thus maintained the desired cutting speed for different diameters of workpieces.

The parameters of the cutting conditions were as follows: - semi-finishing machining of steels: t = 1.0 mm, f = 0.3 mm/rev, v = 250-350 m/min; - semi-finishing machining of heat-resistant carbide: t = 1.0 mm, f = 0.1 mm/rev; v = 20-40 m/min.

The criterion of tool failure was flank wear h_F set to be 0.3-0.35 mm and was measured with a microscope MBS-10.

2.3. Results and discussion

The results of the studies of the functional parameters of cutting and contact characteristics of the process of dry turning of hardened steel 107WCR5 (58-60 *HRC*) with uncoated inserts of and coated inserts with NMCCs of various compositions are shown in Table. 2-3 and in Figure 5.

Table 2. Contact **characteristics** of coated tool type KNT-16

Tool material	Functional parameters of cutting						
	C_γ, mm	F, grades	μ_γ	ξ	P_z, N	P_y, N	P_x, N
KNT-16 - uncoated	0.114	21.6	0.294	1.906	21.018	60.409	9.194
KNT-16– Ti-TiN-TiAlN	0.116	21.4	0.3	1.922	21.45	60.820	9.198
KNT-16– Cr-CrAlN-TiCrAlSiN	0.120	21.3	0.310	1.933	22.124	62.135	9.194
KNT-16– Ti-TiAlN-TiZrAlSiN	0.120	21.6	0.294	1.906	22.124	60.409	6.129
KNT-16– Zr-ZrN-ZrCrAlN	0.141	21.1	0.334	1.961	26.549	63.861	6.129

C_γ – length of full contact on rake face, F – shear angle, μ_γ – friction coefficient on rake face, ξ – shrinkage of chips, P_z, P_y and P_x – tangential, radial, and axial component cutting forces, respectively.

Table 3. Contact characteristics of cutting process

Tool material	C_γ	$C_{\gamma P}$	$\tau_F \cdot 10^{-5}$	$q_F \cdot 10^{-5}$	$q_N \cdot 10^{-5}$	$\sigma_{Nmax} \cdot 10^{-5}$	n
	mm		N/m²				
KNT-16-71 - uncoated	0.114	0.0533	603	248.999	761.751	2103.165	1.639
KNT-16– Ti-TiN-TiAlN	0.118	0.0541	603	248.252	760.005	2107.134	1.652
KNT-16– Cr-CrAlN-TiCrAlSiN	0.120	0.0542	603	243.622	739.220	2055.745	1.668
KNT-16– Ti-TiAlN-TiZrAlSiN	0.120	0.0538	603	240.130	734.616	2028.249	1.639
KNT-16– Zr-ZrN-ZrCrAlN	0.141	0.0538	603	207.285	624.020	1747.627	1.697

$C_{\gamma P}$ – length of plastic (thick) contact on rake face; τ_F – tangential stress in conventional shear section; q_F – average tangential stresses on rake face of tool; q_N – average normal contact stresses on rake face of tool; σ_{Nmax} – maximum normal contact stresses on rake face; *n* – index.

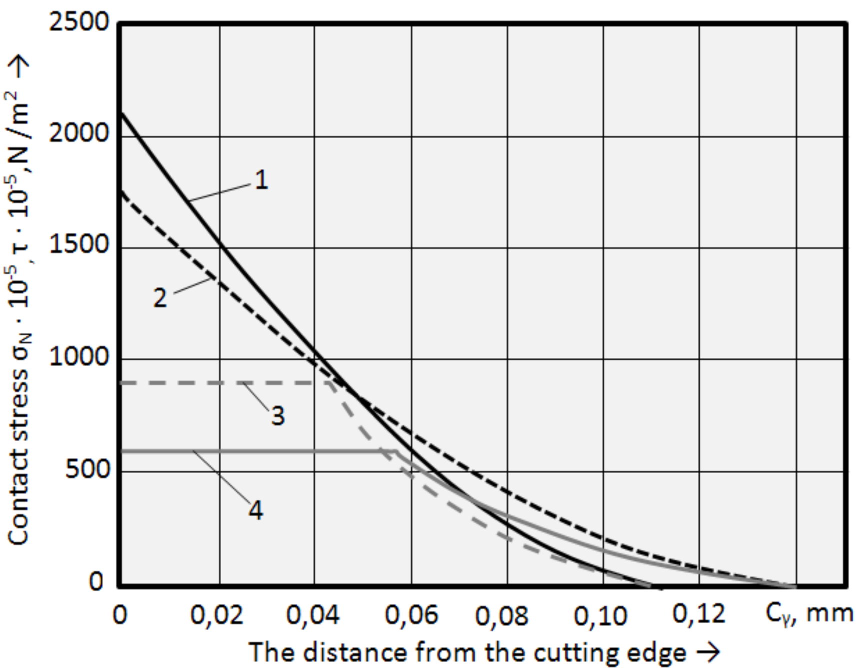


Figure 5: Distribution of normal contact σ_n (1, 2) and tangential τ_y (3, 4) stresses on rake face of cutting inserts of KNT-16 in dry cutting of steel 107WCR5 (HVG) (58-60 HRC) at t=0.1 mm; f=0.15 mm; v=250 m/min (where h is distance from cutting edge):

1, 3 - uncoated inserts of KNT-16; *2, 4* – inserts of KNT-16 with Zr-ZrN-ZrCrAlN coating

The analysis of obtained results revealed that the developed coatings (NMCCs) deposited on contact areas of the tungsten-free carbide led to some increase of friction at the interface of the coating and machined material, and this contributed to increased length of contact of chips with the rake face of tool C_γ. This reduced contact stresses σ_n and τ_γ (see Figure 7), and in combination with improved heat dissipation, this simultaneously reduced specific thermo-mechanical loads on the cutting edge of the inserts and allowed predicting the improvement of tool life.

The results of the comparative studies of the cutting properties of the tool equipped with inserts of KNT-16 with various NMCCs are presented in Figure 6.

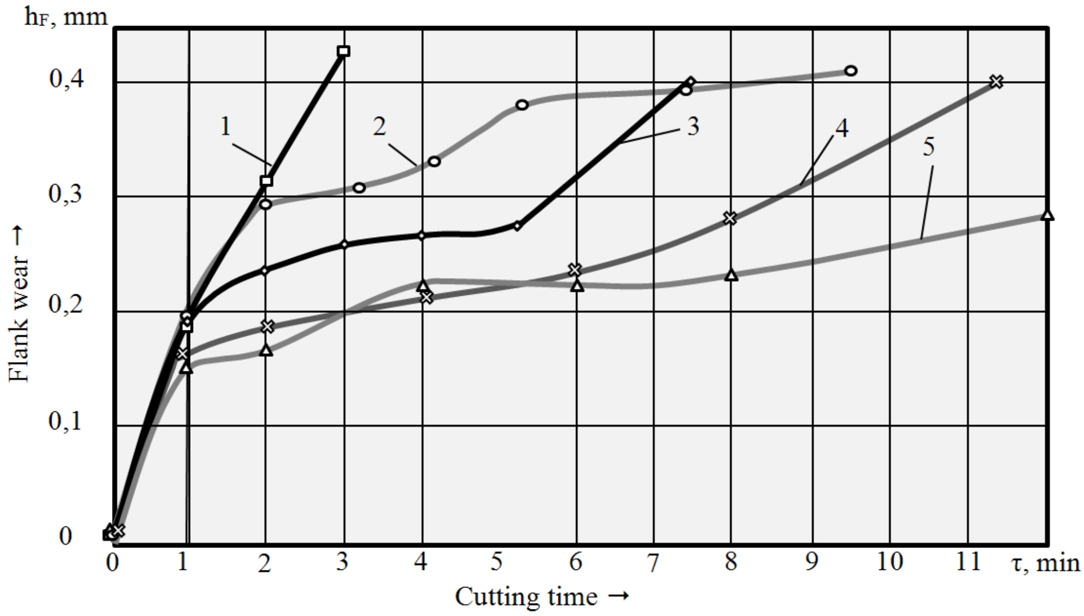


Figure 6. Relation between flank wear h_F and cutting time for inserts of KNT-16 with various NMCCs in turning of steel 107WCR5 (HVG):

1- control inserts of KNT-16; 2 - KNT-16 - Ti-TiN-TiAlN; 3 - KNT-16- Cr-CrAlN-TiCrAlSiN; 4 - KNT-16-Zr-ZrN-ZrCrAlN; 5 -KNT-16-Ti-TiAlN-TiZrAlSiN

The analysis of the nature of the "wear-time" curves depicting tool wear depending on cutting time revealed the standard form of the obtained relations for uncoated and coated tools (Figure 2). The inserts with developed NMCC of optimal composition (Figure 6, Curve *5*) has demonstrated significant reduction of wear rate as compared with the control uncoated tool and the tool with NMCC of suboptimal composition (Figure 6, compare Curves *1-3* and Curve *4*). The study has also revealed the balanced nature of flank wear of coated inserts of KNT-16 (Ti-TiAlN-TiZrAlSiN) without visible macro- and microchipping of cutting edge. The wear resistance of such inserts was 2-2.5 times superior to the tool life of uncoated tool of KNT-16.

The heat-resistant alloy based on H65NVFT chromium, specially developed for use in the aerospace engine industry, was selected as an object to study cutting performance of tungsten-free carbides with developed NMCCs. The H65NVFT is a refractory alloy characterized both by heat resistance and resistance to scaling. Resistance to scaling is achieved due to the formation of dense oxides Cr_2O_3 on surface in contact with oxidizing medium. Chromium-based alloys are resistant to gas corrosion in end products of fuel combustion that contain sulfur and that are significantly cheaper than traditional nickel-based alloys. However, at present, there are virtually no data on the technological properties of these alloys and, in particular, their machinability, which is one of the most important technological characteristics.

The nature of changes in relation of $h_F=f(\tau)$ presented in Figure 7 demonstrates the improvement in cutting properties of insert with NMCC based on Zr-ZrN-ZrCrAlN. Meanwhile, it has been identified that the life of the tool equipped with inserts of KNT-16 with developed NMCC based on Zr-ZrN-ZrCrAlN exceeds the life of the control tool of KNT-16.

Certification tests of the performance of inserts of KNT-16 were carried out in turning of heat-resistant chromium-based alloy at cutting speeds of 20, 30 and 40 m/min. The obtained results showed significant advantages of developed NMCCs based on systems of Ti-TiN-TiAlN (Figure 7, Curve 2), Cr-CrAlN-TiCrAlSiN (see Figure 9, Curve 3), Ti-TiAlN-TiZrAlSiN (see Figure 7, Curve 4) , and Zr-ZrN-ZrCrAlN (see Figure 2, Curve 5). The wear resistance of inserts with developed NMCC was 2-3 times higher than wear resistance of inserts of uncoated KNT-16.

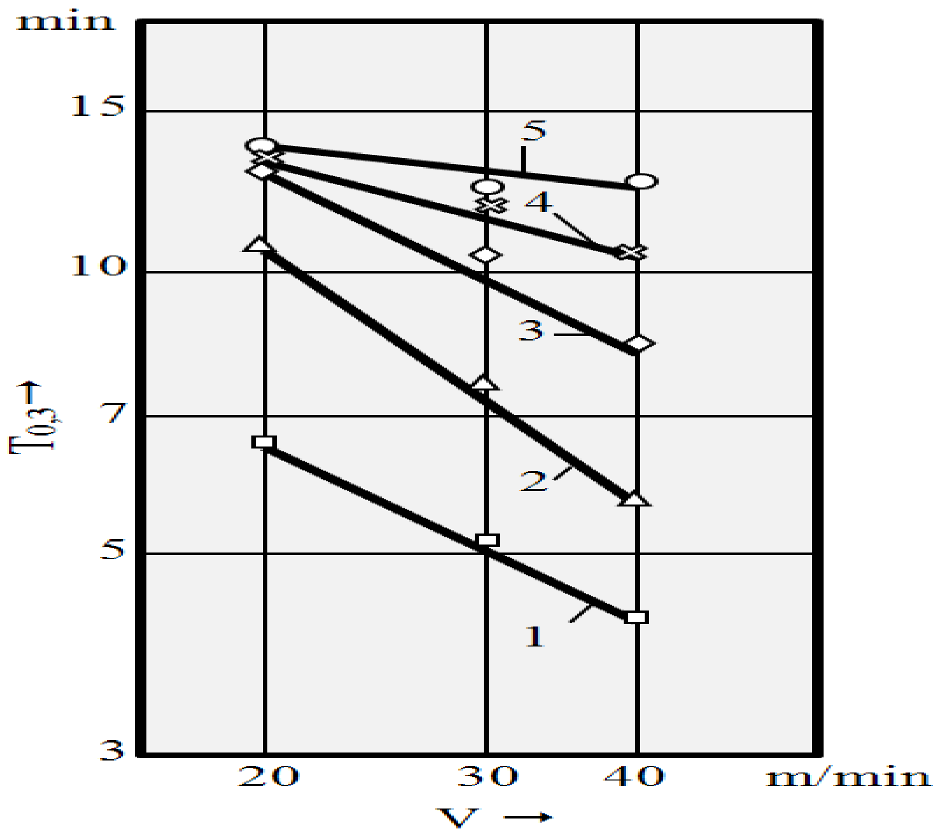


Figure 3: Effect of cutting speed on life span of inserts of KNT-16 with various NMCCs in turning of heat-resistant chromium alloy (H65NVFT), for t = 1.0 mm and f = 0.1 mm/rev:

1 - KNT-16 - uncoated; 2 - KNT-16- Ti-TiN-TiAlN; 3 - KNT-16- Cr-CrAlN-TiCrAlSiN; 4 - KNT-16- Ti-TiAlN-TiZrAlSiN; 5 - KNT-16- Zr-ZrN-ZrCrAlN

The study has revealed the absence of curve extremum for function of $T = f(v)$ for the tested range of cutting speeds for uncoated inserts of KNT-16 and for tools with developed NMCCs, and that confirms the above accepted concept on prevailing influence of adhesive-fatigue processes on wear of the tools of tungsten-free carbides with NMCCs and the stability of thermo-mechanical stresses in the contact area of coatings (NMCC) and H65NVFT alloy for the tested range of cutting speeds (v = 20-40 m/min).

It was identified that for the cutting process with tungsten-free carbides inserts with NMCC, the likelihood of sudden tool failure associated with micro-flaking and chipping of local volumes of

cutting edge was reduced and that had a positive effect on the tool life and produced high-quality machined surface of workpieces.
Coatings based on Zr-ZrN-ZrCrAlN are especially effective in machining of H65NVFT carbide. It was shown that in this case inserts with Ti-TiAlN-TiZrAlSiN coatings had the lowest wear rate with the increase of cutting speed. It should be noted that the developed systems of Ti-TiAlN-TiZrAlSiN and Zr-ZrN-ZrCrAlN deposited on inserts of KNT-16 with the use of the FCVAD process provided an increase of tool life up to 2-3 times as compared to uncoated tools. In machining of steel 1045, the same NMCC had no advantages against uncoated tool within the entire range of changes in cutting conditions. This suggests that at present, there are no universally operating coatings for cutting tools, and each particular cutting option needs specially developed coatings with special structure, composition, and architecture.

Conclusion

This work developed new methods for rational selection of functions and component parameters of architecture of multilayer composite nano-dispersed coatings formed by filtered cathodic vacuum arc deposition for the tools made of tungsten-free carbides that significantly improved cutting performance of the tools in machining structural steels and heat-resistant carbides.
The conducted tests have confirmed the possibility for improvement of cutting properties of tools of tungsten-free carbides through the control of the contact processes with the use of nanostructured multilayer composite coatings of optimum composition and properties in finishing and semi-finishing machining of steels and hard-to-cut chromium-based carbides, and that indicates the possibility for expansion of the area of technological application of the tools of tungsten-free carbides.
In longitudinal turning of 107WCR5 (HVG) steel with hardness of 58-60 HRC, KNT-16 inserts with the developed NMCC of Ti-TiAlN-TiZrAlSiN of optimal composition provided an increased cutting of efficiency (increases the area of metal removal from surface of workpiece) up to 2-2.5 times as compared with similar tools without coating.
It was shown that tungsten-free carbides were characterized by lower resistance to "tear-out" of carbide grains from the binder as compared with their wear resistance, leading to the "failure" of bending strength arising from the increased temperatures in cutting. This may be one of the reasons for transition to intensive wear, in machining smooth carbides or titanium carbonitrides where wear was unevenly distributed on surface, reducing further the wear resistance. In this regard, the application of multilayer composite nano-dispersed coatings, reduced the tendency to adhesion and frictional heat sources, largely eliminating the organic disadvantages of conventional tungsten-free carbides and improving their wear resistance.

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