Development of wear-resistant coatings compounds for high-speed steel tool using a combined cathodic vacuum arc deposition

A.A. Vereschaka[1a] , M.A. Volosova[1], A.D.Batako[2] , A.S. Vereshchaka[1]; B. Y. Mokritskii[3]

[1]Moscow State University of Technology (MSUT "STANKIN"), Russian Federation

[a](**Corresponding author,** ecotech@rambler.ru, +7 9169100413

[2]Liverpool John Moores University, UK, a.d.batako@ljmu.ac.uk

[3] Komsomolsk-na-Amure State Technical University, 27, Komsomolsk-na-Amure 681013, Russian Federation

Abstract

The article presents the results of working out for a wear-resistance complex (WRC), formed on the working surfaces of the HSS tools, in order to increase their efficiency. Wear-resistant complex includes nitride layer, which increases the plastic strength of the HSS tool cutting wedge and cutting tool wear resistance, as well as a three-layer nanostructured composite coating, increases lifetime of a HSS tools. Equipment combining the processes of ion nitriding in the gas plasma and the formation of nanostructured multilayer composite coatings in the filtered metal-gas plasma cathode vacuum arc discharge has been developed. Particular attention is paid to the study of the regularities of formation of the nitride layer and optimization of its parameters and structure, as well as the study of the properties and structure of functional coating layers, depending on the parameters of the deposition process. The parameters of the combined cathodic vacuum arc processing (CCVAP), provides a minimum intensity of tool wear during the cutting process. Also conducted research certification cutting tool properties of HSS with WRC, which made it possible to determine the optimal parameters WRC, which gives the maximum increase in tool life for a variety of cutting conditions as compared to uncoated HSS tool, as well as with standard commercial coatings.

Keywords: Arc-PVD processes, wear-resistant complex, HSS tool life

1. Introduction

Modern machining and metal cutting increasingly uses high-efficiency cutting tools made of HSS with wear-resistant coatings, which are obtained using cathode vacuum arc synthesis techniques (arc-PVD). HSS cutting tools with vacuum-arc coating significantly increase the efficiency of a wide range of manufacturing operations with intermittent and heavy cutting. The performance, accuracy and quality of machining are increased with subsequent reduction of consumption of expensive tool materials, improved environmental aspects in dry cutting without use of cutting fluids [1]. However, HSS cutting tools are still the weakest link in the technology of metal cutting. This is true for HSS-tools with complex geometric profile, which are currently widely used for various cutting operations [1-8].

Arc-PVD processes has a significant application in manufacturing of cutting tools made of different materials, especially HSS, which is characterized by relatively low heat resistance, since Arc-PVD processes are implemented in temperature range of 200-800°C [1, 4, 7, 8, 10, 19]. Arc-PVD processes provide a range of opportunities for the formation of multi-layered composite coatings with nano-scale structure based on single- and multi-carbides, nitrides, oxides, borides and their mixtures with elements of IV-VI refractory metals of the Periodic Table of Elements, including those alloyed with the various elements (Al, Si, Cu, etc.) to improve structure and properties [4, 5, 6]. The possibility of forming such coatings with crystallite sizes and thicknesses in the range of tens of nanometers, allow reducing defects of crystallites in super-thin layers and bringing their strength to a possible "theoretically level ". In addition, it is possible to produce coatings with optimum balance of the major characteristics i.e. hardness and toughness, along with high wear resistance of the tool. This allows maximizing crack resistance of coatings, increasing durability of coating in the contact areas of the tool with the machined part even under considerably heavy thermoplastic loads [9, 10, 11, 12].

An analysis of the trends to improve HSS tool with wear-resistant coating [1, 4, 7, 8] shows that this improvement is related to the development of various types of coatings with nano-dispersed structure and multi-layered compositional architecture formed using PVD technologies. The combined methods of synthesis of coatings are increasingly used, since they integrate advantages of chemical-thermal and ion-plasma technologies or combine different types of physical and chemical effects on working surface of the tools [5, 6, 7, 8, 11]. In particular, to produce targeted modification of surface properties of the tool material, coating deposition is accompanied or assisted by simultaneous action on the deposited condensates and tool surface with low and medium energy plasma (stimulated thermo-chemical treatment by inducing ion energies of 0.3-10 keV), high energy ion beams with energies of up to 40-500 keV (ion implantation). The techniques to combine ion-plasma coating synthesis with laser action [1, 8] are noticeably used, and these techniques allow a better management of the process of metal arc evaporation and homogeneity of plasma flow. Additionally, these techniques provide an opportunity of targeting action on surface coating defects directly during the synthesis or after the completion of coating formation, and that allows improving significantly the quality of coating tool and tool performance.

The analysis of the properties of some refractory compounds that are most suitable for wear-resistant coatings for cutting tools, from the point of view of thermodynamics and the conceptual dual "nature" of coating as an "intermediate processing medium" between tool and the machined material, the coatings secure simultaneously an increase resistance to wear at the contact areas and a reduced operational thermo-mechanical stresses that initiate wear [1, 8, 10]. This analysis suggests that the use of mono-layered coatings consisting of one metal compounds (for example, TiN) does not meet the basic requirements for wear-resistance. Therefore, in practice, tool manufacturers increasingly apply nano-structured multi-layered composite coatings with varying chemical composition and properties [9, 10, 11, 12-19].

Thus, the increase the performance of the complex profile HSS tool for a variety of cutting conditions on the basis of the development of wear-resistant complexes applied to its surface, creating a combined equipment and combined cathodic vacuum arc processes (CCVAP) is the main focus of this study.

2. Theoretical background

The analysis of the causes of intense fracture of coatings at contact areas of HSS tool and the studies of the kinetics and mechanisms of tool wear with different coatings [1,2,5, 8,9] show that, despite the significant positive contribution of coating to the reduction in wear intensity in contact areas, their performance is much lower than expected. In particular, the durability of different coatings at contact areas of HSS tool is 0.5-20% of the lifetime of tool to complete failure (Table 1).

Table 1. The ratio of operating time of the HSS tools before the destruction of the TiN coating to the tool life in percent

According to the data [1, 4, 5, 8, 9], different types of HSS-tools (drills, shaping cutters, worm and end milling cutter, cutting inserts) are characterized by the durability of standard types of coatings (such as TiN and TiAlN) not exceeding 0.5-20 % of tool life.

Tables 1 characterize the relation of an operating time of a coating before destruction concerning the period of tool life for various HSS tools in percentage

The results of the studies of the efficiency of coatings on HSS-tools showed that the immediate cause of reduction of plastic strength of cutting tool with coating and subsequent intensive brittle fracture of coatings at the contact areas is the transformation of contact stresses on working surfaces of tool and the shift of isotherms of maximum temperatures directly to cutting edge. This effect is illustrated in Fig. 1 [1].

Figure 1.

The critical stresses appear at the borders of "HSS-coating" section, and their magnitude is largely dependent on the difference in thermo-physical and physical-mechanical properties of the coating material and HSS [1, 8], micro-stresses in surface layers of tool material after full thermal treatment and sharpening, as well as on the stresses generated at the border of HSS and coatings, especially with a low adhesive strength between the two surfaces. This fact means that there is a need in the development of new coating compositions for HSS-tool with improved properties. In this study, M2 tool steel is considered as base material for HSS tool to be coated. These new coatings should secure a low tendency of seizure between the tool material and the machined material. In addition, these coatings should improve the performance of contact processes and chip formation, and a low frictional energy. This in its turn will lead to an increase the predisposition of cutting edges to elastic-plastic bending, a reduction of plastic strength factor of the tool and an increase of the probability of intense brittle fracture of surfaces. These tendencies increase with the increase in strength and hardness of machined material, as along with the predisposition of the machined material to physical-chemical interaction with tool material, and the increase in depth of cutting.

Let us consider the problem of estimating the plastic strength factor of tool with coating. According to the theory of Huber-Mises-Hencky, the plasticity condition, for a perfectly plastic tool material, the equivalent stress in the cutting part of the tool in a model of plastic strain in cutting with a single shear plane can be determined using the following relationship:

$$\sigma_E = \sqrt{\sigma_y^2 + \sigma_z^2 - \sigma_y \sigma_z + 3\tau_{yz}^2}, \qquad (1)$$

where σ_y, σ_z and τ_{yz} are stresses.

In free plastic orthogonal cutting, the conditions for a plastic metal flow are as follows $\sigma_{eq\ max}=\sigma_{yi}$, where σ_{yi} is the yield point of tool material. In this case, the tool plastic strength factor n can be calculated as:

$$n = \frac{\sigma_{yi}}{\sigma_{E\ max}}. \qquad (2)$$

Since the strain state of contact layers along the rear surface approaches the state of simple shear, the equivalent stresses can be expressed in terms of contact stresses acting on the front and back surfaces of the tool [2]:

$$\sigma_E = \sqrt{3(\sigma_\alpha + \tau_\alpha)^2 + \sigma_\gamma^2}, \qquad (3)$$

Where σ_α, τ_α are normal and shear stresses on flank face; σ_γ is a normal stress on rake face of cutting tool, respectively.

With respect to equation (3), the plastic strength factor of the tool can be determined from the following expression:

$$n = \frac{\sigma_T}{\sqrt{3(\sigma_\alpha + \tau_\alpha)^2 + \sigma_\gamma^2}} \qquad (4)$$

Analysis of relationship (2)-(4) can be noted that the higher the yield stress σ_{yi} relatively equivalent tension $\sigma_{eq\ max}$, the higher the safety factor for plastic strength of tool material and less the probability of a plastic change of the cutting wedge tool.

Analysis of the reasons for the lower efficiency of coatings on HSS tools compared with the efficiency of coatings on carbide tools showed the following [1,5,6,7,8,9]. The main reason for increasing the intensity of distraction of coatings on HSS tools is a high probability of plastic changing the shape of the cutting tool wedge that leads to rapid distraction of coatings [1].

On the basis of the results obtained, the principles of improving durability of wear-resistant coatings at the contact areas of HSS-tool were developed. According to these principles, an increased durability of coatings on working surfaces of complex HSS-tool can be achieved by increasing the plastic strength of the cutting wedges of HSS-tool [1]. This was implemented by depositing on working surfaces of HSS-tool four-component wear-resistant complex (WRC). These (WRC) consisted of a thermo-stabilizing layer (TSL), an adhesive underlayer (AU), a transition layer (TL) and wear-resistant layer (WRL). This structure is illustrated in (Fig. 2).

Figure 2

Each of the elements of wear-resistant compound performs a specific technological role. The thermo-stabilizing (reinforcing) layer provides the increase of plastic strength and stiffness of cutting wedge of HSS-tool. The wear-resistant layer enhances the durability of contact areas of HSS-tool due to their increased hardness, with a physical and chemical passivity in relation to the machined material and a high thermodynamic stability. The adhesive underlayer provides an increased adhesive strength between the wear-resistant coating and HSS-substrate due to an increased crystal-chemical compatibility of their properties. The transition layer provides a high adhesive strength between the wear-resistant layer and the adhesive underlayer.

The flow limit of thin surface layers (20-100 microns thick) on the working surfaces of HSS-tool can be increased by means of preliminary surface hardening using additional processes. However, it is more cost effective to carry out the combined ion-plasma treatment of HSS-tool in one technological cycle. For this purpose, a multi-purpose vacuum arc station VIT -4 was developed (see illustration in Fig. 3.). This experimental rig was used to deposit the wear-resistant coating by combining vacuum arc treatment with the stimulated thermo-chemical treatment (ion nitriding) to generate the thermo-stabilizing layer. The filtered cathodic vacuum arc deposition (FCVAD) was used to form of the adhesive underlayer, intermediate and wear-resistant layers .

Figure 3.

3. Experimental

3.1. Deposition of wear-resistant complex (WRS)

A combined ion-plasma process on installation VIT-4 was used to deposit the wear resistance complex –WRS on the HSS-substrates with the following phases.

In the first phase, the thermo-stabilizing layer (TSL) was formed. The target 1 of titanium was evaporated by cathode spots of vacuum arc and used as a cathode for arc discharge. The special screen 4 located between cathode 1 and anode 2 divides the chamber 5 into two zones filled with the metal-gas plasma (on the left side of the screen) and gas plasma (on the right side). This screen is impermeable to micro-droplets, neutral atoms 6 and ions of metal 7 emitted by the cathode spots from the surface of target 1. Only electrons 8 penetrate through the screen 4, and on their way toward the anode 2, they ionize gas which is fed into the chamber and subsequently generate gas plasma which is almost free of metallic particles. The HSS-samples 8 located in plasma were first exposed to positive potential and heated by electrons, and then, when fed with a negative potential, they were subjected to ion nitriding.

Upon completion of the procedure of full formation of the thermo-stabilizing layer, the screen 3 was shifted aside, and as soon as the ions evaporating from the surface of the cathodes (Ti, Cr, Al) reached the surface of the HSS-samples 8, of the layers of the coating were deposited in the following sequence: adhesive underlayer, intermediate layer and и wear-resisitance layer.

During nitriding, the process modes were varied as follows: the temperature was between 420...510°C, the concentration of N_2 in gas mixture with argon was around 10...100% atm.; the nitriding time was in the range of 40...100 min. Since the pressure range at which the vacuum arc discharge is obtained, is sufficiently narrow, in all cases, the nitriding process was carried out at a pressure of $9.75 \cdot 10^{-1}$ Pa. In the process of identifying optimal parameter of depositing the wear-resistant coating, Ti was used as an adhesive underlayer, TiN was used as an intermediate layer and TiCrAlN was used for the wear-resistant layer, nitriding layer was used as the thermo-stabilizing layer. The time of deposition of the thermo-stabilizing layer varied between 40 and 100 min. Other process parameters remained constant in all cases: the temperature was 450-470 °C; the reference voltage was 120V; the arc current on Ti-cathode was 80A, the pressure in the vacuum chamber was $2.6\ 10^{-1}$ Pa, and the ion current density was 0.5 A/mm^2.

3.2. Metallographic studies

Micro cross sections of HSS samples were used for metallographic studies. The cross sections were produced by the standard methods using equipment from "Struhers".

The micro-hardness was measured with a POLYVAR microscope, equipped with the MICRO-DUROMAT 4000 micro-hardness measurement system. The nitride layer, effective and total thickness of the layer was evaluated. The effective thickness of the nitride layer was measured as the distance from the sample surface to the section where hardness became H = 9.8 N/mm^2. The total thickness was assumed as the distance from the sample surface to the section with hardness corresponding to the initial hardness of HSS (H = 8.8 N/mm^2).

The phase composition and structure of the nitride layer were investigated using X-ray crystal analysis with an automated difractometer DRON-4, which was computer-controlled and had a system to record the spectra. Symmetrical recording (filming) of samples reflection was carried out using X-ray tubes with copper and cobalt radiation. This allowed estimating the average phase composition at different depths from the surface down to ~ 7 µm and ~ 2 µm, respectively. In some cases, to determine the phase composition of the thin surface layer of up to 0.5 µm, the method of sliding X-Ray beam (CuKα radiation) with constant angle of entry (α = 5°) was used. Data processing of the spectra was carried out in software.

The following characteristics of the obtained coatings were studied: thickness (method "Calotest", apparatus "Fischer Sindelfingen"), adhesional strength to the substrate material (method "Scratchtest", apparatus "Csem Revetest"), nanohardness and modulus E1 (method "NanoTest", apparatus "Micromaterials Ltd.Wrexam"). Studies on nanoindentometer were carried out using Berkovich indenter by standard methods. For each sample of carbide with obtained coating, research of nanohardness was carried out at 25 measurements on a square of 100x100 µm^2.Studies of crystal-chemical properties of NMCC, obtained on the working surfaces of carbide inserts, were carried out using a scanning electron microscope (SEM) JSM-6700F with an attachment for spectral dispersion spectrometry (EMF) JED-2300F, manufactured by the Company "Jeol". The study of residual stress in the coating was carried out using the method of *X*-ray diffraction (XRD) using *CoKα* radiation based on *X*-ray analysis discussed in detail in reference [8].

3.3. Cutting performance of HSS-tools with wear-resistant coatings

Here standard square HSS inserts (18 x 18 x 6 mm) made of M2 SS tool steel (6% W, 5% Mo) with radius r = 1.2 mm, subjected to standard thermal treatment, were used for turning and symmetric face milling.

The experimental tests for the HSS tools with the developed wear-resistant coating were carried out under continuous traverse turning on a lathe with thyristor drive, which allowed maintaining constant cutting speed when machining workpieces with different diameters.

The interrupted cutting in symmetric face milling was also undertaken. To exclude the influence of radial motion variation of cutting teeth on tool wear, the tests were carried out with single-tooth cutters. Standard steel HB 200 was the material machined and the tests were carried out with the following machining parameters:

Traverse turning: cutting speed v = 82 m/min, feed f = 0.2 mm/rev, depth of cut a_p = 1.5 mm;

Face milling: cutting speed v = 89 m/min, feed f_Z = 0.15 mm/teeth, depth of cut a_p = 1.5 mm, milling width B = 45 mm.

The cutting period at which the tool was changed was T = 60 min. In this study, the maximum allowable flank wear of HSS-tool was set to be VB_{max} 0.45-0.5 mm.

The flank wear land VB_{max} was measured using a microscope BMS-1C. Experimental works were repeated 3-5 times to ensure sufficient repeatability and reliability of the results.

The optimization of for the vacuum plasma treatment of samples was carried out analytically using the mathematical model suggested by [6]. To construct mathematical relations to reveal connection between time of nitriding (τ_N), temperature of nitriding (Θ_N), nitrogen fraction in gas mixture with argon during nitriding (K_N), coating deposition time (τ_C) and their influence on wear of HSS-tool in traverse turning and face milling, the following mathematical model with exponential power was used:

$$\mathrm{VB} = c\Theta_N^{a_1} K_N^{a_2} \tau_N^{a_3} \tau_C^{a_4} \exp[b_1\Theta_N + b_2\, K_N + b_3\, \tau_N + b_4\tau_C] \qquad (6)$$

The unknown parameters (c, a_1 ... a_n, and b_1 ... b_n) were defined using experimental data, which were processed in a software package called "MODELUNI". A function $h_3 = f(\Theta_N, R_N, \tau_N, \tau_C)$ was defined and differentiated using partial derivatives. The desired optimal modes for vacuum plasma treatment were obtained by solving the first derivative of h_3

The unknown parameters (c, a_1 ... a_n, and b_1 ... b_n) were defined using experimental data, which were processed in a software package called "MODELUNI". A function $VB = f(\Theta_N, R_N, \tau_N, \tau_C)$

was defined and differentiated using partial derivatives. The desired optimal modes for vacuum plasma treatment were obtained by solving the first derivative of *VB.*

4. Results

4.1. Structure and properties of wear-resistant complex

The studies carried out have shown that during the formation of the thermo-stabilizing layer of the wear-resistant complex on the HSS-samples, the composition of gaseous medium, its temperature and the time have profound effect on its structure, properties (Table 2)

Table 2.

It was revealed that the surface TS-layer of nitride HSS-samples with 100% N_2 contained in excess: ε-phase of $(Fe,Me)_2N$, nitrides of alloying elements Mo_2N (W_2N), carbides (or carbonitrides) of $Fe_3(W,Mo)_3(C, N)$. In Addition to this, α-phase as a solid solution of carbon and nitrogen in Fe_α (martensite) were detected in the M2 tool steel substrate surface layer. Recording (filming) using the method of sliding X-ray beam shows that at depths of up to ~ 1 μm, there was continuous layer of nitride in the form of ε-phase in case of nitriding with pure nitrogen. In the formation of nitride layer in gas mixtures such as N_2/Ar, the formation of ε-phase is blocked while molybdenum Mo_2N nitrides in the surface layer are maintained, and their volume decreases from ~ 5.6-5.5% (at depth of up to~ 2 μm) up to 1% (at depth of ~ 7 μm).

X-ray diffraction data are in good agreement with the results metallographic investigations. In the microstructure of the surface layer samples nitrided in an atmosphere of 100% N_2, as well as a high content of nitrogen in admixture with argon gas (80% N_2) revealed good solid nitride layer having a thickness of 0.5 to 1.5 mm (Fig. 4a). In case of nitriding in the gas mixture with a nitrogen content of less than 60-80% of the surface nitride layer is absent (Fig.4 b,c). Dark herb layer has a higher hardness (more than 9.8 kN/mm^2) and corresponds approximately effective thickness of the nitrided layer HSS steel M2. The high hardness of this layer due to the fact that, apparently, it consists of a nitrogenous martensite and dispersed nitrides - ε and γ-phase, and nitrides of the alloying components Mo, W, Cr, V. However, γ-phase and a chromium nitride and vanadium not detected X-ray analysis is possible due to their dispersion and small quantity. Follow the dark area wide transition zone where the hardness remains increased due to the presence of nitrogen in the α-solid solution, the grass is almost as a core (base).

The tests of the strength of adhesive bond of wear-resistant complex with HSS-samples, formed in gas mixtures of N_2 and Ar, showed a high adhesive strength of the wear resistant complex and almost complete absence of flaking of the coating and crack formation. This was observed as a characteristic for nitride HSS-samples in 100% N_{2}. The main coatings parameters i.e. microhardness, thickness, strength of adhesion of "coating-substrate" and surface morphology were studied. The composition of the layered structure of Ti, Cr, Al composite was investigated and controlled. The results of the main parameters, surface, structure and morphology of developed functional coatings Ti-TiN-TiCrAlN are presented in Table 3.

Table 3.

The analysis of the data in Table 3 showed that the wear resistant layer Ti-TiN-(Ti,Cr,Al)N has a multilayered structure with the thickness of sublayers down to 15-25 nm. The mean ratio of Ti, Cr and Al in the wear-resistant layer of TiCrAlN was 0.25, 0.25, 0.15 respectively. $Ti_{0.2}Cr_{0.2}Al_{0.15}N_{0.35}$ layer had a columnar structure oriented perpendicularly to the plane of TiN-underlayer. The thickness of the sublayers in the intermediate TiN-layer was in the range of 25 nm as illustrated in Fig. 5, and for this reason, the multilayered composite coating are considered as nano-scale coating

Fig.5

4.2. Investigation into cutting performance

The experimental work conducted HSS cutting tools coated using the combined cathodic vacuum arc treatment revealed the parameters with dominant influence on the cutting properties of tool. These parameters were the temperature (Θ_N), the duration of the nitriding process (τ_N), fraction of nitrogen in gas mixture of argon (K_N) and the time of subsequent application of wear-resistant coatings (τ_C).

Fig. 6 a,b show the effect of parameters of combined vacuum plasma treatment on the wear rate of HSS-tool in traverse turning and face milling of steel. Here J is the wear out rate expressed as $J = VB/(v \cdot T)$, where VB – flank wear land, *v* – Cutting Speed, T- tool life.

Figure 6 a,b

It indicates that in all cases, the tool wear as function of modes of vacuum plasma process has a local minima. The process of the experimental data allowed building a model showing the relationship of flank wear rate of coated tools with the modes of vacuum plasma process.

$$VB_{max} = \frac{0{,}38 \exp[0{,}003\ \Theta_N + 4{,}4K_N + 2{,}21\tau_N + 1{,}3\tau_C]}{\Theta_N^{1{,}38} K_N^{1{,}32} \tau_N^{0{,}73} \tau_C^{0{,}9}} \quad (7)$$

$$VB_{max} = \frac{2{,}74 \exp[0{,}0032\ \Theta_N + 1{,}73K_N + 1{,}075\tau_N + 0{,}82\tau_C]}{\Theta_N^{1{,}6} K_N^{1{,}04} \tau_N^{0{,}72} \tau_C^{0{,}82}} \quad (8)$$

Using these relationships allowed defining the numerical values for optimum process parameters of vacuum plasma modes which secure a minimum wear tool rate in turning (eq.7) and milling (eq.8), as presented in Table 4.

Table 4.

The metallographic studies showed that the wear-resistant complex (WRC) emerged from the modes of combined vacuum plasma treatment had a minimal tool wear rate, and was characterized by the following observations:

- In a uninterrupted turning: the effective thickness of the TSL-layer - h_N = 50-55 μk, microhardness 11,9 ... 12,1 kN / mm^2 at a thickness of the outer coating layers (Ti-TiN-TiCrAlN) h_C = 6 μk;
- In interrupted milling: effective thickness of the TSL-layer - h_N = 30-35 microns, microhardness 10,5 ... 10,7 kN / mm^2 at thickness of the coating layer (Ti-TiN-TiCrAlN) h_C = 4 μk.

To evaluate the performance and reliability of HSS-tool with developed wear-resistant coatings, laboratory and industrial tests were conducted. For the research purpose, a batch of HSS-tools was manufactured and coated with the wear-resistant compound developed on the basis of N-Ti-TiN-TiCrAlN system with relevant parameters as defined and recommended by this work.

Considering that cutting temperatures have a strong softening effect on the HSS-tool with new coatings, which is related with γ to α transformations in HSS, the effect of machining time on the structure along with the magnitude of residual austenite was studied (see Table 6). These machining tests were undertaken for tools with various coating. In addition, the changes in micro-hardness of the cutting edges was investigated. This is illustrated in Fig. 6.

Table 6.

Figure 6.

As illustrated in Table 6 and in Fig. 6), during the unset of wear (cutting time around 280 seconds), the surface layer of the tool with new coating at a depth of up to 10 μm undergoes some hardly noticeable changes in comparison with uncoated HSS-inserts or HSS-inserts with standard coatings.

The difference is especially visible in the surface layers at a depth of 2.5 μm as portrayed in Table 6. In particular, for inserts with the wear-resistant coating, the tests revealed a smaller volume of residual austenite and a decrease in the parameter β (211), which characterizes the distortion of the crystal lattice in HSS-steel. At the same time, the tests showed a lower softening in local volume of tools with new wear-resistant coating during in the unset of wear and especially during rapid wear compared with the reference HSS-inserts (see Fig. 6).

In the rapid wear phase, the tests showed satisfactory conditions of surface layers of the tools with the new wear-resistant coating, despite considerably longer cutting time (up to 820 s) compared to the reference samples which secure only 280 s and samples with standard coating secured up to 680 s.

Thus, the thermo-stabilizing layer as an element of the wear-resistant compound had an extremely important contribution to the enhancement of plastic strength of cutting edges of HSS-tool and to the increase of its resistance to thermal softening under the thermo-mechanical loads generated during the cutting process. This finding allows predicting with confidence the increase in the durability of tool due to wear-resistant coating and its positive contribution to improving the performance of HSS-tool.

The tests also included an investigation into the compositions of the coatings which were developed for different cutting conditions. These results are presented in Fig. 7 and 8, which lead to the following observations.

The developed coating, (e.g. N-Ti-TiN-TiCrAlN) increases the wear resistance of HSS-tool up to 10 times compared with the reference uncoated tools and up to 1.5-8 times compared with tools with standard coatings (Fig. 7 and Fig. 8).

Figure 7.

Figure 8.

With the increase in cutting speed, the performance of tool with the new coatings increases significantly. This is shown in Fig. 7, curves 1-3 versus curves 4 and 5. This indicates the significant contribution of the thermo-stabilizing layer which enhanced the plastic strength of cutting edges of HSS-tools and increased in the durability of coatings at the contact areas of the tools. It was found that the feed rate and especially the depth of cut had the same influence on the performance of the newly coated as on the tools with standard coatings. Fig. 9 illustrates some samples of coated tools and the experimental configurations for laboratory tests in interrupted face milling and traverse turning.

5. Discussion

The results obtained prove that the formation of the thermo-stabilizing layer in 100 percent clean nitrogen significantly limits the performance that could be achieved by the application of wear-resistant coatings. This fact is related to the formation of nitride zone on the thermo-stabilizing layer surface consisting of high-nitrogen ε-phases characterized by an increased hardness and brittleness. It is known [1] that the presence of ε- phase does not reduce the strength of the adhesive bond between the coating and HSS-substrate, and that is one of the most important conditions for the successful operation of tool with coatings.

The analysis of the results of the industrial tests conducted with HSS-tools with the new coatings showed that for the inserts operating under intermittent cutting conditions or continuous cutting with large depth of cut, the formation of thin solid nitride zone (ε-phase) on the thermo-stabilizing layer surface leads to chipping of cutting edges already in the first minutes into the machining process. This is related to the fact that during the formation of continuous layer of brittle ε-phase, the plasticity of the thermo-stabilizing layer greatly reduces. The optimal structure of the thermo-stabilizing layer for milling should be more viscous and resistant to varying loads. This provides solid solutions of nitrogen in the martensite under insignificant volume of dispersed nitrides of alloying elements. This structure also provides greater strength of the adhesive bond between the outer layer coat and HSS-substrate.

For HSS-tool, operating under conditions of continuous cutting e.g. traverse turning, the optimal structure is represented by nitrous martensite with small amount of ε (γ′)-phase and nitrides of alloying elements (W, Mo, Cr, V). This structure provides an improved strength of the adhesive bond between the outer coat and the substrate, higher resistance to plastic strain and heat resistance.

The X-ray analysis allowed observing that, during the formation of the thermo-stabilizing layer, its phase composition, structure and properties can be controlled depending on the targeted operating conditions of cutting tool by varying the ratio of nitrogen and inert gas. For example, for continuous cutting, the optimum structure for the thermo-stabilizing layer contained solid nitrogen solutions in martensite without formation of ε-phase.

It was found that during the processes of the combined cathodic vacuum arc deposition of the coating on HSS-substrates, the structure, hardness and thickness could be controlled during the formation of the thermo-stabilizing layer by varying process parameters, such as temperature, duration and composition of gas mixture.

When optimizing the parameters of the cathode vacuum arc treatment of HSS-tool, not only the parameters of the process of the thermo-stabilizing layer formation, but also the parameters of subsequent deposition of other layers (adhesive under layer, transition layer, wear-resistant layer) should be taken into consideration.

Based on these studies conducted, the mathematical models were developed, revealing the relationships between the most important parameters of the combined cathodic vacuum arc treatment and wear of HSS-tool for different processing conditions.

5. Conclusion

In the modern metalworking industry are widely used profiled HSS tools with wear-resistant coating or chemical-thermal treatment, but the effectiveness of such HSS tools still substantially below the required modern technological processes. In this connection, the further improvement of HSS tools will be important scientific task.

The paper presents the results of studies related to the development of processes, technologies and equipment for the combined cathodic vacuum arc forming a wear-resistant complex (WRC) on the working surfaces of HSS tools in order to improve its effectiveness. Wear-resistant complex (WRC) includes thermo-stabilizing layer (TSL) and three-component nanostructured layers: AU-adhesive layer; IL-intermediate layer, WRL –wear resistance layer.

Among elements of a wear-resistance complex (WRC) the important role is carried out by the thermo-stabilising layer raising plastic durability of cutting part of the HSS tool, durability of a wear-resistance coating and its positive influence on contact processes at cutting and life time of the HSS tools. For the formation of thermally stabilizing layer developed in the process of nitriding nitrogen-argon gas plasma vacuum arc discharge, which allows you to control the phase composition and properties of the nitrided layer (TSL), depending on the operating conditions of the HSS tools.

It is established that at formation of a TSL by nitriding in the gas environment containing 60%N_2 and 40%Ar bloking up formation of fragile ε - phases and is provided high enough plastic durability of the HSS tool cutting part that, promotes efficiency increase for nano-scale coatings Ti-TiN-TiCrAlN and as much as possible reduces intensity of wear process of the HSS tools at uninterrupted cutting (turning, drilling, threading, etc.).

At formation of a TSL in the gas environment containing 30% N_2 and 70% Ar, formation ε - phases also is blocked, and the layer consists, mainly, from nitrogenous martensit that also provides high plastic durability of a cutting part of the HSS tool and efficiency of coating Ti-TiN-TiCrAlN. Such structure is optimum and provides the maximum lifetime of the HSS tools at interrupted cutting (milling, planning, gear shaping, etc.).

Designed as wear-resistant coating composition having a ternary architecture, comprising an AU, an IL and a WRL, which is deposited on the working surface of the HSS tool after forming thermo-stabilizing layer. Structures, parameters and conditions of coating deposition for all coating layer were optimized. It has been established that all coating layers have a thin multilayer substructure with thickness of sublayers of 15-25 nm, and the size of grains did not exceed 5-10 nm.

The process parameters of vacuum-plasma treatment are interconnected in a complex dependence and should comprehensively optimized for specific operating conditions of the HSS tools. The greatest influence on the wear of HSS tools provide: - nitriding time, - nitriding temperature, - the concentration of nitrogen in the gas mixture of argon and parameters coating deposited after the formation of thermally stabilizing layer: - composition; - deposition time; - the thickness of the coating layers and sublayers.

Study the cutting properties of HSS cutting tools with developed WRC for various machining operations (turning, drilling, milling) showed significant benefits of such a tool as compared to the nitrided HSS tools and a tools with a multilayer composite coatings.

6. References

[1] Vereschaka, A.S. 1993. Efficiency of the cutting tool with wear resistant coating. - Mashinostroenie, Moscow, 336 p.
[2] Loladze T.N. 1980. The strength and wearresisnance of the cutting tool. - Mashinostroenie, Moscow, 320 p.

[3] Alami J, Persson P.O.A., Music D, Gudmundsson J.T, Bohlmark J ,Helmersson U (2005) On-assisted Physical Vapor Deposition for Enhanced Film Properties on Nonflat Surfaces. Journal of Vacuum Scienceand Technology A Vacuum Surfaces and Films 23(2): p. 278–280.
[4] Biermann D. (2007) Influence of the Coating on the Maximum Width of Flank Wear Land by Turning the Austenitic-ferritic Steel X2CrNiMoN 22-5-3. Proceedings of the 6th International Conference THE Coatings, p. 97–106.
[5] Lierat F., Vereschaka A. 1999."Entwicklungsstand und - trends der Hartstoffbeschichtung. Tagungsband Magdeburger Produktionstechisches Kolloquium MPK'99. Die Wissensintensive Production, ISBN 3-00 - 004180-x) .7.
[6] Sablev L.P., Andreev A.A., Grigoriev S.N., Metel A.S. US Patent №5,503,725, Europatent №0583473, DE Patent № 69227313T2.
[7] Lierat F. Vereschaka A.S., Pankov A., Lapin V. DE Patent 19733517 A1, C23 C 30/00.
[8] Gorovoy A.P., Fegorov S.V. Volosova M.A. 2001. Influence of plasma nitriding process two-stage vacuum-arc discharge on the structure of the surface layer of high-speed steel / / The interaction of ions with the surface: Proceedings of the XV International Conference. T.2. M.: MAI, p. 318 – 320.
[9] Lierat F., Vereschaka A. 1998. The main trends of Vacuum-ARC technology synthesis of multi-layered coatings for cutting tool perfection. IX Internationales Productionstechnisches kolloquium PTK-98 Berlin, , p.211-225.
[10] Loladze T.N. 1980. The strength and wearresisnance of the cutting tool. - Mashinostroenie, Moscow, 336 p.
[11] Grigoriev S.N., Vereschaka A.A., Vereschaka, A.S., Kutin A.A. 2012. Cutting tools made of layered composite ceramics with nano-scale multilayered coatings. Procedia CIRP 1 (2012), p.318 – 323.
[12] A.S. Vereshchaka, B. Karpuschewski, L. Dubner. 2008. Development of the method of obtaining nanostructured functional coatings. Proceedings of the Intern. Scient. Conf. “Production. Technology”. V.1. p. 62-68.
[13] 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 61 (2012) p.703–723.
[14] F. Sanchette, E. Damond. Single cycle plasma nitriding and hard coating deposition in a cathodic arc evaporation device. Surface & Coating Technology. 1997, p. 261 – 267.
[15] Vereschaka A. A., Volosova M. A., Grigoriev S. N., Vereschaka A. S. Development of wear-resistant complex for high-speed steel tool when using process of combined cathodic vacuum arc deposition. Procedia CIRP 9 (2013) p.8 – 12.
[16] Vereschaka A. A. Development of Assisted Filtered Cathodic Vacuum Arc Deposition of Nano-Dispersed Multi-Layered Composite Coatings on Cutting Tools. Key Engineering Materials Vol. 581 (2014) Trans Tech Publications, Switzerland p. 62-67
[17] Vereschaka A.A. Improvement of working efficiency of cutting tools by modifying its surface properties by application of wear-resistant complexes. Advanced Materials Research Vols. 712-715 (2013) Trans Tech Publications, Switzerland p. 347-351
[18] Vereshchaka, A.A., Vereshchaka, A.S. , Mgaloblishvili, O., Morgan, M.N., Batako, A.D. Nano-scale multilayered-composite coatings for the cutting tools. International Journal of Advanced Manufacturing Technology, Springer-Verlag, 2014, p. 1-15.
[19]. Grigoriev S.N. The technology and equipment for the complex ion-plasma processing of the cutting toosl. STIN. - №2, 2000. P.12 -16

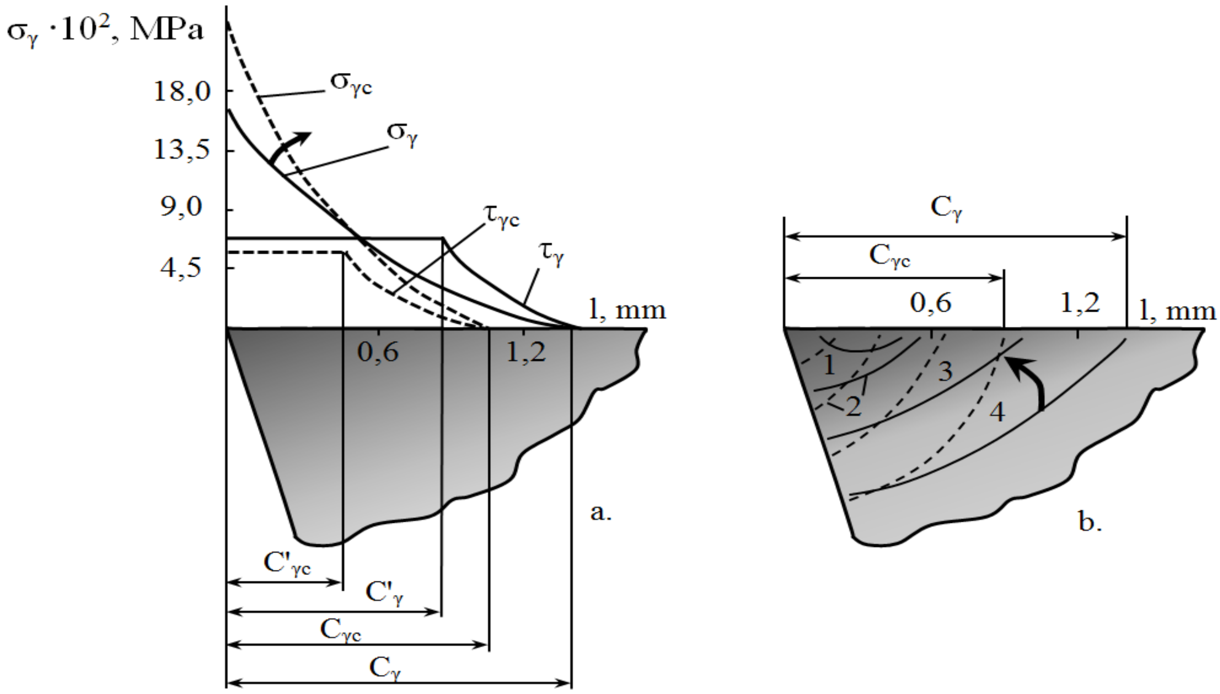


Figure 1. Transformation of contact stresses (a) and isotherms (b) for HSS-tools with coating [1]: 1 620°C; 2 415°C; 3 365°C; 4 230°C (for M2 and M2-TiN arc-PVD) when turning steel 40X; with $v = 50$ m/min; t = 2 mm; Cγ, Cγc is the full length of contact between chip and front surface of tool without and with coating; $\dot{C}'_{\gamma}$, C′γc is the length of tight (plastic) contact for tool without and with coating; σ_{γ}, $\sigma_{\gamma c}$ is the normal contact stress for tool without and with coating; τ_{γ}, $\tau_{\gamma s}$ is the shear stress on front surface for tool without and with coating; contact between chip and front surface of tool without and with coating, respectively.

The solid line is for tool without coating; dashed line is for tool with coating; arrows indicate the direction of change in stresses and isotherms.

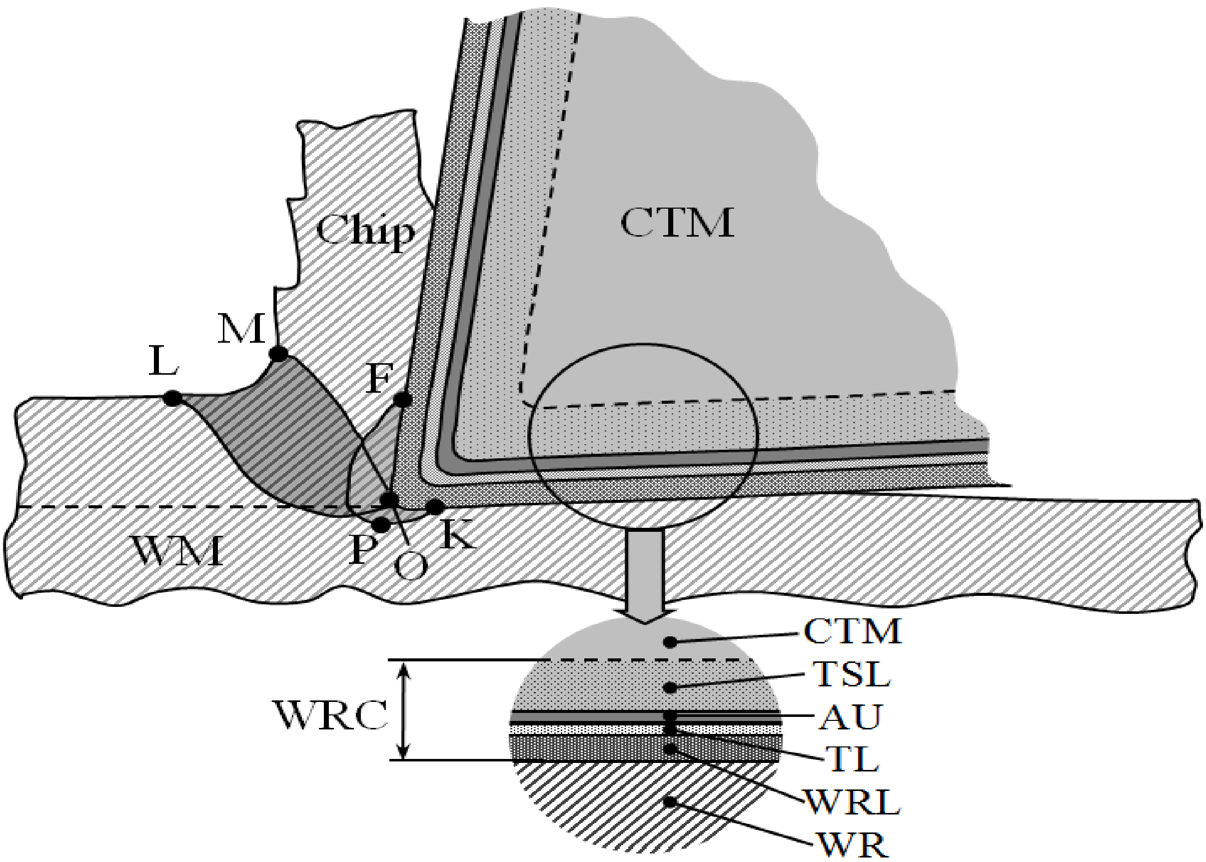


Figure 2. Schematic diagram of wear-resistant coatings formed on working surfaces of complex HSS-tool:

WRC is the wear-resistant compound; TSL is the thermostabilizing layer, AU is the adhesive underlayer; TL is the transition layer; WRL is the wear-resistant layer; CTM is the cutting tool material (HSS); WR is the workpiece material; OLM is the area of principal strains; FPK is the area of additional strains.

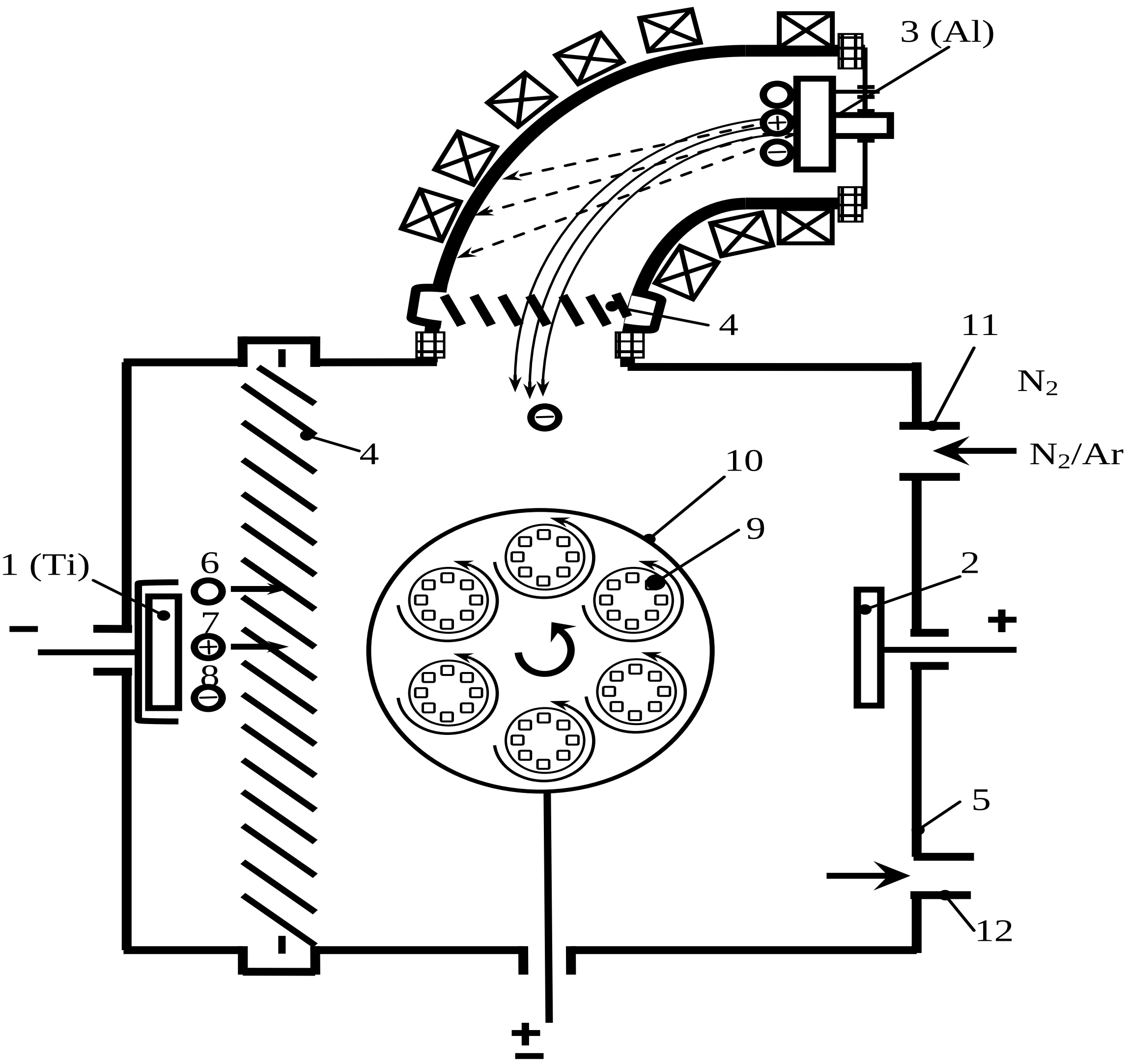


Figure.3. Principle layout of multi-functional cathodic vacuum arc rig VIT-4:

1- titanium target (cathode); 2- anode; 3 - aluminum target (cathode) with filtration of droplet component; 4 - special screen; 5 - vacuum chamber of the installation; 6,7,8- microdroplets, metal ions and electrons; 9 – tool samples carrying planetary motion in the chamber; 10 – turning table with mounted tool samples, 11 - gas inlet valve, 12 - vacuum pumping system.

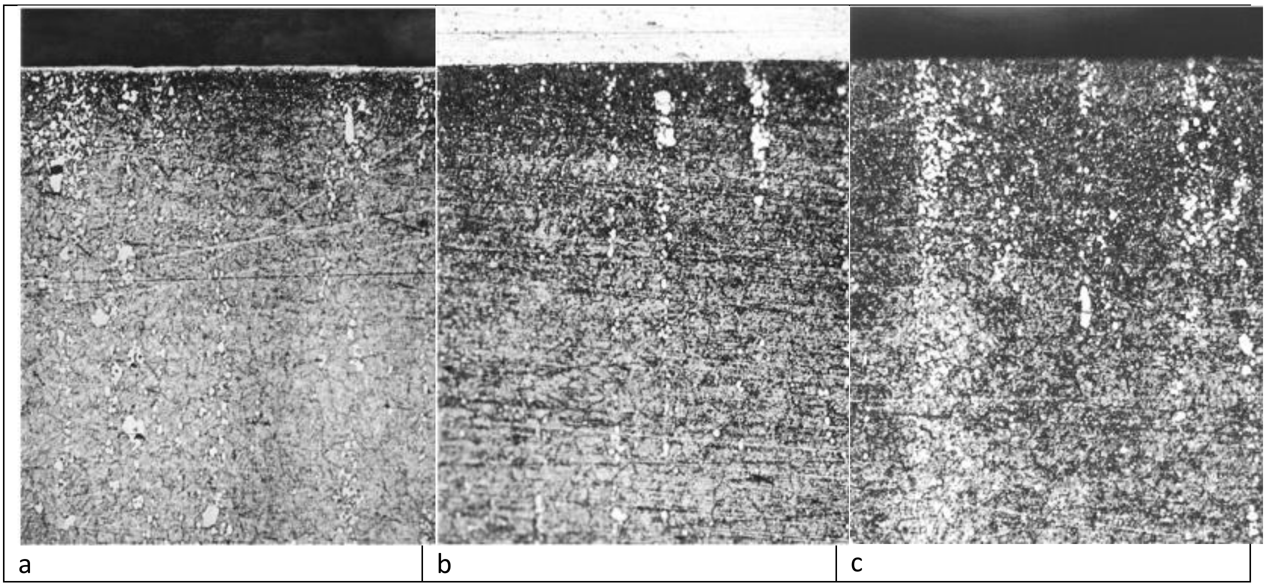


Figure. 4. The microstructure of the samples after nitriding steel R6M5 with using different gas mixtures (× 800): 100% N2 (a), 40% N2 + 60% Ar (b) 10% N2 + 90% Ar (c)

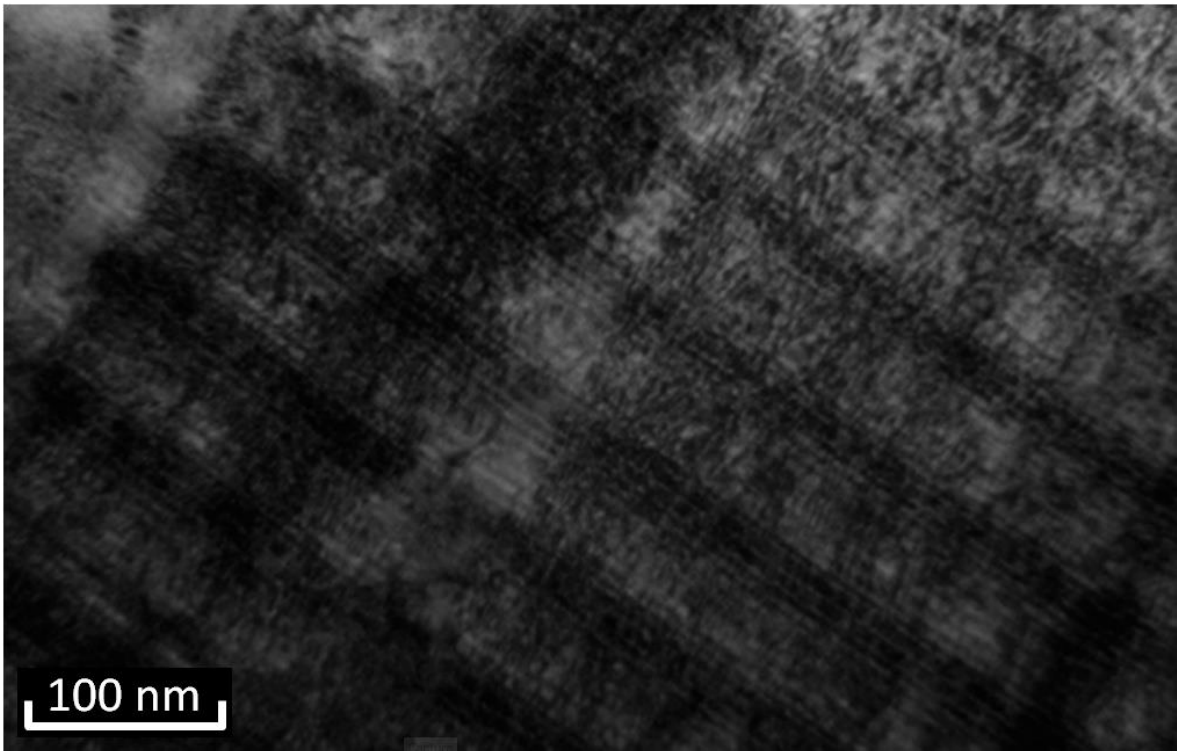
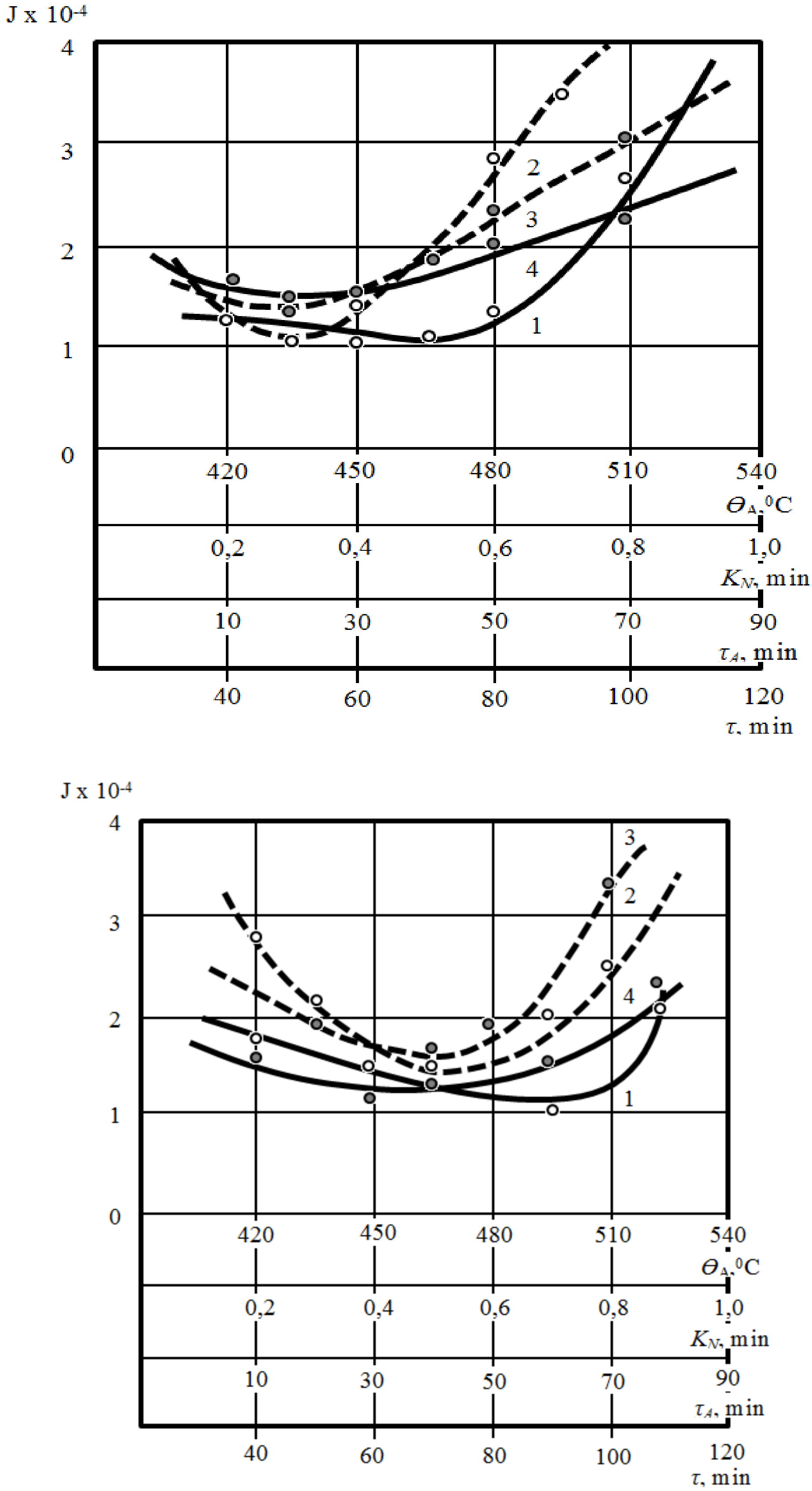


Figure 5. Structure of a wear resistant layer of *NMCC* produced by FCVAD processing.



a

Figure 6. Effect of vacuum plasma treatment on flank wear rate: (a) face milling; (b) traverse turning.

1 the temperature of thermo-stabilizing layer formation (nitriding) (Θ_N); 2 the duration of nitriding (τ_N); 3 the fraction of nitrogen in gas mixture with argon (K_N); 4 the duration of the process of coating application (τ_C).

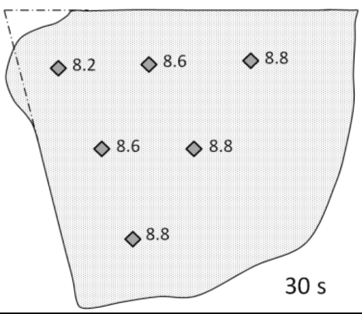
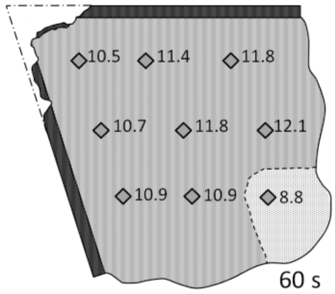
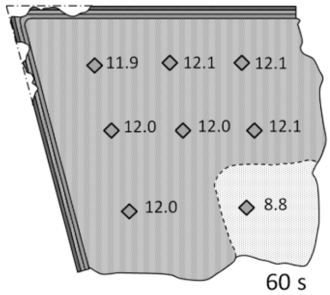
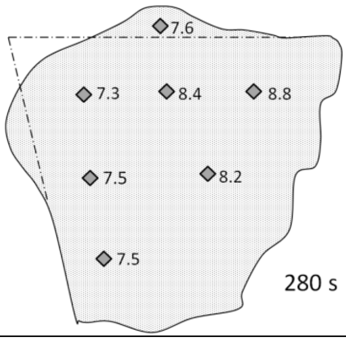
<table>
<tr><th>Wear stage s</th><th>HSS (M2)</th><th>M2-N-TiAlN</th><th>M2-N-(Ti-TiN-TiCrAlN)</th></tr>
<tr><td>Stage of the running tool wear</td><td></td><td></td><td></td></tr>
<tr><td>Stage of the catastrophic tool wear</td><td></td><td></td><td></td></tr>
</table>

Figure 7. Schematization of microhardness fields for cutting HSS-inserts depending on phase of tool wear

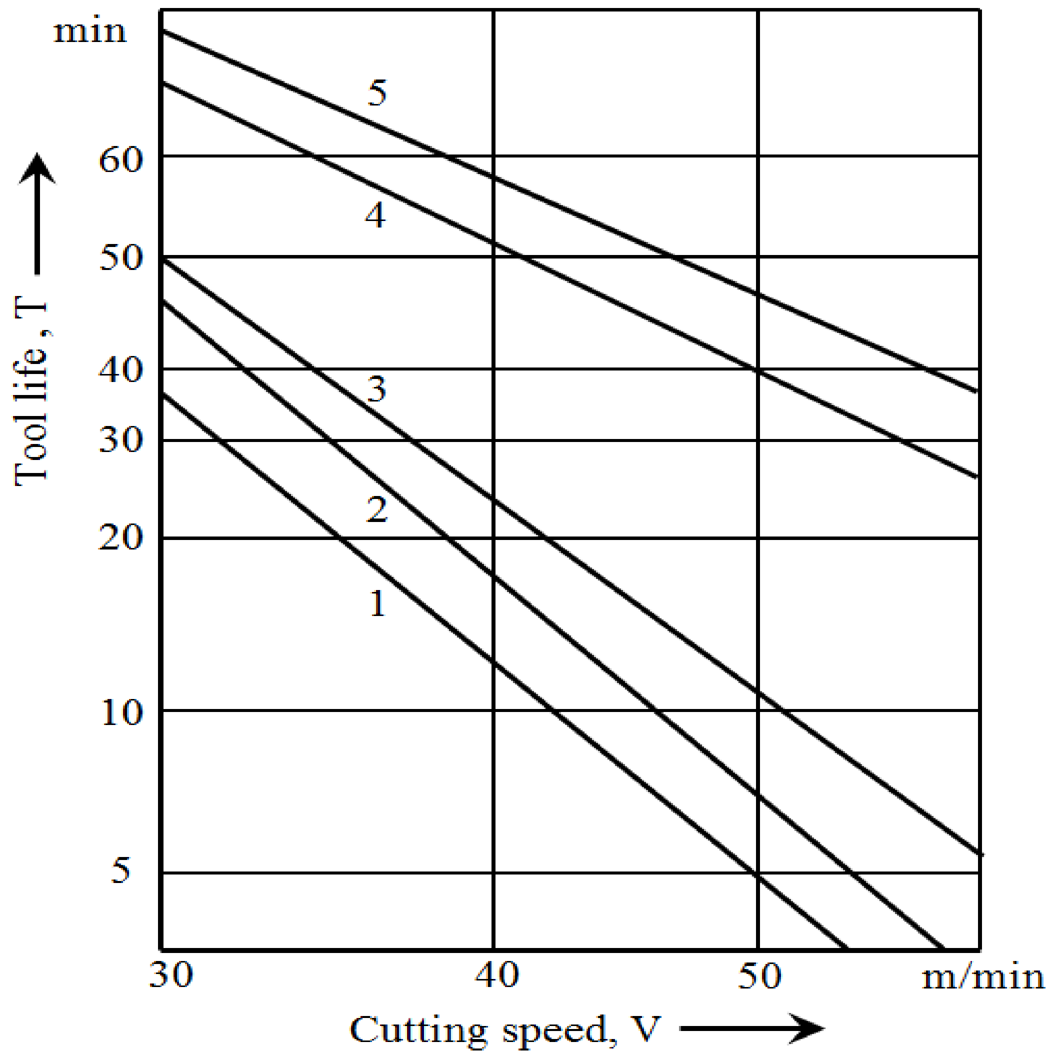


Figure 8. Influence of cutting speed on wear resistance of tool equipped with cutting HSS-inserts with different options of hardening treatment under turning of 45 steel with f = 0.2 mm/rev; a_p= 1.5 mm:

1 HSS inserts; 2 HSS-N; 3 HSS-TiN; 4 HSS-N-TiAlN4, 5 HSS-Ti-TiN-TiCrAlN.

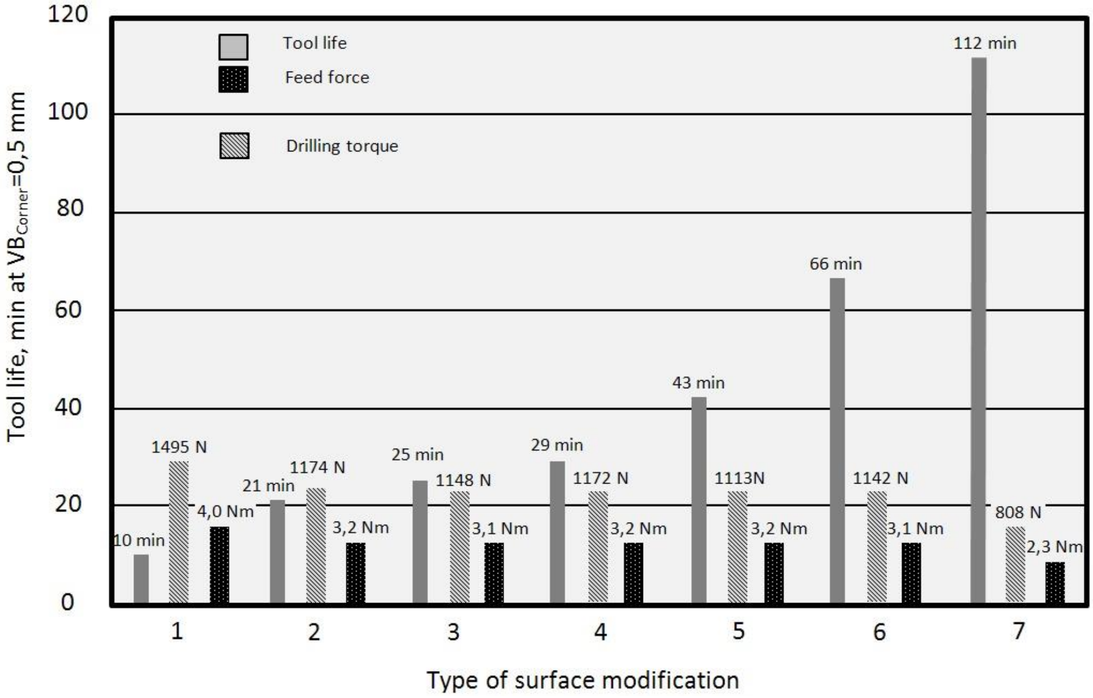


Figure 9: Tool life test for twist drills ∅ 6.8 mm, DIN 338 with various types of surface modification

Tool material: HSS; Workpiece: C 45 (HB 200)	1 - uncoated	4 - N-Ti-TiN-TiCN
Cutting parameters: v_c=35 m/min, f=0.1 mm	2 - TiCN	5 - N-Cr-(Ti,Cr)N
Depth of drilling l_d=30mm	3 - TiN	6 - N-Ti-TiN
Dry cutting		7 - N-Ti-TiN-(Ti,Cr,Al)N

Table 1. Operating time of coating without fracture of complex HSS-tool

Type of HSS-tool	Ratio of wear-resistance period of HSS-tool to operating time of TiN coating to fracture, %
Drills	2.0-5.0
End milling cutters	1.5-2.0
Cutting taps	2.0-10.0
Shaping cutters	0.5-2.0
Worm milling cutters	1.0-4.0
Broach tools	15.0-20.0

Table 2. Effect of temperature and gas composition and thickness microhardness of the TS-layer (nitriding time - 50 minutes).

Nitriding temperature	The concentration of N_2 in the gas mixture with Ar	Microhardness, kN/mm^2	Effective thickness, μк	Total thickness, μк
420	10	10	10	450-500
	20	10	30-40	200-250
	40	10,3	25-30	180-210
	80	10,6	10- 15	150-200
	100	11,2	8,0	80-90
510	10	10,8	175	450
	20	11,2	90-100	300-350
	30	11,1	85	450-500

Table 3. The composition and properties of wear resistant complex (WRC)

Coating layers	Phase contents	Phase characteristics				
		Grains sizes, μm (nm)	Layer and sublayers thickness, μm (nm)	HV, GPa	F**, N	ΔP*, mg/cm^2
TSL	Fe_2N; Mo_2N, $Fe_3(W,Mo)_3$, $Fe_\alpha(C,N)$	1.5-2.0 μm	40-60 μm	12.50	-	54.9
AU	α-Ti	2.0-3.0 μm	0.7-1.1	-	-	-
TL	$Ti_{0.25}N_{0.75}$	25-30 nm	h_c = 2.5-3.0 μm h_{sl} = 20-25 nm	25-30	80-100	14.7
WRL	$Ti_{0.25}Cr_{0.25}Al_{0.15}N_{0.35}$	5.0-15.0 nm	h_c =2.8 μm h_{sl} = 20-25 nm	31-32	120-130	15.7

ΔP*-oxidation on air at 900 °C within 1 hour; F ** - the critical to the indenter at scratch test on coating surfaces (criterion of adhesion)

Table 4. Effect of temperature and composition of gas mixture on thickness and microhardness of TSL (nitride) layer (nitriding time is 50 minutes).

Temperature of nitriding, °C	Fraction of N_2 in gas mixture with Ar	Microhardness, kN/mm^2	Effective thickness, μm	Total thickness, μm
420	10	10.0	70	450-500
	20	10.0	30-40	200-250
	40	10.3	25-30	180-210
	80	10.6	10-15	150-200
	100	11.2	8	80-90
510	10	10.8	175	450
	20	11.2	90-100	300-350
	40	11.1	85	450-500

Table 5. Values of optimal parameters to form TSL of wear-resistant complex WRC for cutting inserts made of HSS

Parameters for TSL-layer formation	Optimal values under turning	Optimal values under milling
Temperature of nitriding Θ_N, °C	500	460
Fraction of nitrogen in gas mixture, K_N	0.6	0.3
Time of nitriding τ_N, hour	0.67	0.33
Time of WRC layer formation: AU,TL,WRL, hour	1.0	0.7

Table 6. Influence of cutting time on volume of residual austenite and lattice distortions

Tools	Distance from surface, µm																			
	Before cutting										After 65 s cutting									
	β (211)·10^{-3},rad					A,%					β (211) ·10^{-3},rad					A, %				
	0	2,5	5	7,5	10	0	2,5	5	7,5	10	0	2,5	5	7,5	10	0	2.5	5	7,5	10
M2 steel	32	41	46	46	44	8	12	13	14	14	22	30	34	36	36	10	8	7	6,5	6,5
M2-N	24	30	30	35	36	8	7,5	7,5	7	7	20	18	17	16	16	10	6	5	4	4
M2-N-Ti-TiN-(TiCrAl)N	20	28	33	40	40	8	7,5	7	7	6,5	18	17	17	17	17	8	5	4	3	4