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# Development of modifying compounds for multilayer nano-structured coatings for cutting tools

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**Abstract:** The subject of this study was to research and develop modified multilayer nanostructured wear-resistant coatings (***NWC***) for cutting tools. ***NWC*** are formed through the innovation process of filtered cathodic vacuum-arc deposition (***FCVAD***). The processes of ***FCVAD*** allow forming ***NWCs*** by filtering vapour-ion flow of macro/micro particles in the plasma torch of vacuum arc, using the plasma duct of special structure isolated from the station chamber, when the angle of rotation of the plasma stream is 120°. This work presents the configuration of the system, alongside with the influence of process parameters on the output. The topology of the coatings is presented together with the hardness and a comparison between standard physical vapour deposition (arc PVD) and ***FCVAD*** coating technologies. Machining tests were undertaken in turning of standard HB200 steel and heat resistant nickel alloy. The results are presented in terms of tool flank wear. It is shown that the application of the ***NWC*** secured 2-6 fold extended tool life

**Keywords:** nano-scale multilayer composite coatings; filtered cathodic vacuum-arc deposition; cutting condition; cutting tools.

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**Biographical notes:** ***Dr. Alexey A. Vereschaka*** graduated from Moscow State Technical University STANKIN (Russia) in 1990 as tool production engineer. He successfully obtained his Dr.-Ing. in 2010 and his research interests are in wear-resistant, corrosion-resistant, tribological and modifying coatings. He is engaged in the development of new technologies to improve wear resistance and efficiency of cutting tools (end mills, cutting inserts, HSS tools, carbide and ceramics). He is also researching into the improvement of physical and chemical passivity and biological inertness of coating to improve parts performance in polyfascicular osteosynthesis device in dentistry and joint implants and other critical medical devices. He extends this development to surface modification to improve the resistance and tribological properties of friction pairs. He has published over 100 scientific papers and 2 monographs.

***Dr. Andre DL Batako*** obtained his bachelor degree (Togo) and his Masters degree in Mechanical and Manufacturing technology in former Soviet Union in 1988. He worked about 10 years in automotive industry and return to research activities to obtain his PhD in Dynamics of vibro-impact system at Loughborough University (UK) in 2004. He is current working in Liverpool John Moores University in the UK where he leads a team of researchers in the field of controlled vibration assisted high efficiency machining in the advanced Manufacturing Technology Laboratory. He has published over 65 papers, 2 books and successfully supervised 7 PhD's. He is open to collaboration in hybrid machine tool development for sustainable manufacturing.

***Prof. Anatoly S. Vereschaka*** received the Dr.-Ing. in 1965 and Doctor of Science (DSc) in 1986, He is a full Professor of Engineering Technology, Material Cutting Technology, and Surface Engineering Technology of Moscow State University of Technology (STANKIN), Russia. His research interests are in physics of metal cutting processes, design theory and functional coating for cutting tools. As one of the first in the world (mid-1960s), he began developing arc-PVD technology to improve wear resistance and operational properties of metal-cutting tools. He published more than 300 scientific papers including 8 monographs. He was awarded the State Prize in science for his work on processes and equipment development and the technology for depositing wear-resistance coating on cutting tools. He has supervised over 22 Dr.-Ing. and 4 DSc's in the field of technical sciences of the development of methodology, equipment and technologies for the synthesis of multicomponent nanostructured multilayer coatings for various types of cutting tools.

***Dr. Alexander I. Dodonov*** has his first degree in Physics from Lomonosov Moscow State University. He worked for the Institute of Nuclear Physics focusing on the studies of the interaction of accelerated ions with the solid state surface. He has published more than 60 papers on this subject in leading international scientific journals. Subsequently, he became head of the laboratory in VNIIETO, which that time was investigating into the development of new methods and equipment for surface modification and coating deposition using ion and plasma beams. He is currently Director of "Vacuum Ionic Technologies" and he is author of a number of innovative plasma sources, methods of coating deposition and methods of surface modification using plasma beam.

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## Introduction

Leading manufacturers of coated cutting tools apply several fundamentally different processes for coating deposition, and each of them has its own advantages and disadvantages [1,2-6,8-10]. The processes of physical vapor deposition (arc PVD) are increasingly used in manufacturing of cutting tools. These processes use different sources of sublimation of refractory metals in vacuum with a supply of reaction gases, from which, plasma-chemical reactions result in the synthesis of refractory compounds [1-4, 7-9,11-13].

For arc PVD processes, the ion source was in an electric gas arc excited between electronegative cathode and electropositive anode under low voltage of about 20 V and high intensity current of 100 A. In addition, the arc was excited under low pressure or under vacuum as described in [2,4]. The power of arc discharge is concentrated directly in the crater of cathode arc spot, and it reaches about 109 V/cm$^2$. Since the arc discharge develops exclusively in vapor of the cathode material, the vapor cloud is ionized repeatedly, to produce an ion flow commonly referred to as plasma flow. As a result of these processes, the vacuum space of the chamber generates a strongly ionized plasma flow consisting of ions, neutral particles (atoms), electrons, and it is often called "vapor-ion" flow. The vapor-ion flow includes a small amount of molten micro-droplets of the cathode material with diameter of 0.5-10 µm and solid fragments.

An important role is played by erosion of the cathode surface, its uniformity and stability. Static magnetic fields are used to ensure uniform erosion of the cathode arc spot. The erosion of the cathode surface occurs through uncontrolled (stochastic) cathode spot or cathode spot controlled by certain law. Usually, a stochastically moving cathode spot does not provide the required stability and uniformity of the process of erosion of the cathode surface. Therefore, modern vacuum-arc stations apply "controlled arc", where the combustion stability is provided by an alternating magnetic field. The process of electro-erosion of the cathode surface occurs absolutely uniformly, and that provides almost complete consumption of the working volume of the cathode with stable rate of arcing [1-5].

It should be noted that the micro-droplets and solid fragments of the cathode are highly undesired defects in the coatings, especially if they are located at the surface of a coating or at the borders in-between the coating and substrate. In the first case, the tendency of adhesion between coating and machined material increases significantly, and for the second case, the adhesion strength of the coating with the substrate reduces drastically.

For the processes of vacuum-arc deposition, the density of the ion flow and ion energy is critical for the bombardment of the substrate with subsequent deposition of the coating.

Thus, the main objective of this study is to develop methods and processes of formation of nano-structured multilayer modified compound for cutting tools using vacuum-arc processes.

## Vacuum-arc evaporators as sources of plasma used to form multilayer nano-structured modifying compounds for cutting tools

Processes of vacuum-arc deposition of coatings referred to as Metal Vapor Vacuum Arc (MeVVA) are widely used in tool manufacturing. The processes are characterized by:

- High rate of coating deposition;
- Wide range of temperature (200-900° C) during short process of coating deposition, which eliminates thermal softening of tool materials;
- Maximum adaptability for the implementation of new principles for formation of coatings, consistent with the concepts of nanostructured, gradient, metastable, discrete, multi-element, multilayer, or super-lattice ones;
- Possibility of creating high strength of adhesion between the coating and the substrate in comparison with other physical processes (e.g., magnetron-ion sputtering);
- High repeatability of technological processes of coating formation;
- Ecological cleanness of coating formation.

However, the processes of MeVVA have the following disadvantages:

- When the metal is evaporated by arc spot of high-current discharge, it causes formation of macro/micro-droplets along with particles of the cathode material, especially, in evaporation of metals with relatively low atomic weight and density (Ti, Al, etc.). Macro/micro-droplets are defects reducing operational efficiency of tools with coatings;
- Combined processes of thermal activation (heating) and ion cleaning of tool surfaces prior to coating deposition may lead to electro-erosion of tool cutting edges and degradation of coating surface because of lack of sufficient ion cleaning;
- Effects of "direction" of the plasma flow that allow forming coatings of uniform thickness and density on complex surfaces only when the plasma flow is perpendicular to the tool surface, and that leads to the need of complex (planetary) motion of the tool with reference to the plasma flow in the station chamber.

The analysis of the main features of the vacuum-arc deposition of coatings has allowed choosing a rational process to form coatings on the working surfaces of cutting tools and a method of its implementation.

The VIT-2 system is equipped with source of plasma (Fig. 1) with a function for filtering vapor-ion flow. The source consists of a plasma duct, which is a portion of a torus with an angle of 120º. The inner torus diameter is 200 mm and the inner side of the plasma duct accommodates an electromagnetic coil. At the inlet of the plasma duct, the cathode assembly is placed with a cathode mounted thereon. The cathode is displaced from the center of the plasma duct, and it is located with reference to the torus center at radius of $R_0 = \sqrt{r \cdot R}$ where r and R are the minor and major radii of the plasma duct walls, respectively. An anode of the arc discharge is placed at the opposite end of the plasma duct. The walls of the vacuum chamber can play a role of the above anode. Positive or negative voltage is supplied to the body of the plasma duct.

When current passed through the coil inside the plasma duct, it creates a magnetic field which is uniform along its length. The magnitude of the magnetic field strength at the centre line of the torus is about 600 Oe. The arc discharge is ignited between the cathode and the anode and allows passage of electron current through the plasma arc formed inside the plasma duct. Since the electronic element of plasma is magnetized, then the magnetic field lines crossing the cathode and passing near the axis of the plasma duct take a potential close to the potential of the cathode, and the strength lines near the plasma duct wall have the potential of the walls. Thus, the plasma creates an electric field perpendicular to the walls of the plasma duct.

The electric field moves ions from the wall or to the walls of the plasma duct depending on the polarity and magnitude of the voltage applied to the walls. Thus, the ionized plasma element is transported along the magnetic field lines in the plasma duct to the outlet. At the same time, the micro-particles and the neutral plasma element are deposited on the walls of the plasma duct.

In order to form the modified tool coatings, the study used processes of filtered cathodic vacuum arc deposition (FCVAD) to effectively implement the concept of multi-component, multilayer, nano-structured coatings.

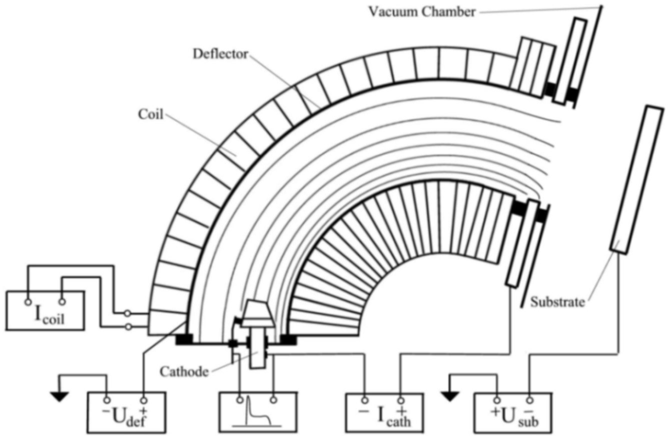


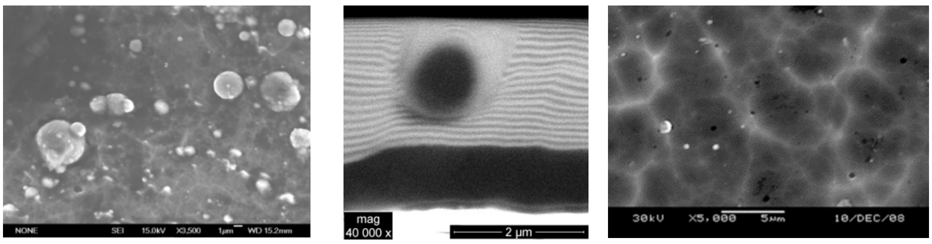

**Figure 1** Scheme of plasma source with function of filtering vapor-ion flow.

## Morphology, structure and properties of *NWC*

Micro droplets can be formed on the surface (Fig. 2.a) or in the volume of coating (Fig. 3. b) as well as on the border connected to the tool material. The droplets are serious defects of coated tools (Fig. 2. a,b). The application of FCVAD processing nearly completely eliminates the formation of micro droplets (Fig. 2. c).

As a result of this study, the structure, morphology and properties of modified multilayer nanostructured wear-resistant coatings (***NWC*** ) on the basis of the systems *Ti-TiN-TiCrAlN* and *TiAlN-ZrNbN-CrN* should be emphasize the following statements.

The morphology of the surface of ***NWC*** produced by FCVAD processing (Fig. 2.c) has much higher quality compared to that of a surface with similar layer produced by standard arc-PVD technology (Fig. 2.a).




a b c

**Figure 2** Morphology of surface of carbide with ***NWCs*** of *Ti-TiN-TiCrAlN* obtained with the use of the standard technology of arc-PVD (a), a droplet in the coating structure (b) and Morphology of surface of carbide with ***NWCs*** of *Ti-TiN-TiCrAlN* obtained with the use of the elaborated technology of *FCVAD (c)*

The ***NWC*** wear resistant layer has nano-dispersed structure with thickness of sub-layers on the order of 70 nm (Fig. 3). The thickness of sub-layers of an adhesion and intermediate *TiAlN-ZrNbN* layers is also on the order of 25 nm that allows classifying the developed ***NWC*** as nano-structural coating.

The developed methodology of formation the ***NWC*** has been used for producing a variety of ***NWC*** compositions with nano-scale structure and may be efficiently employed for various material machining operations.

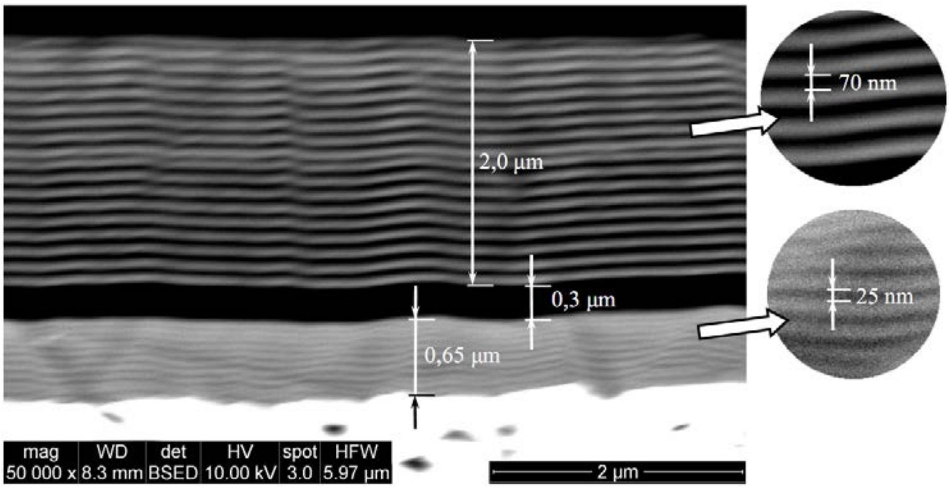



**Figure 3** Micro- and nano- structure of transverse section of carbide with coating of *TiAlN-ZrNbN-CrN* (FCVAD).

## Results of machining tests of cutting properties of carbide inserts with *NWC*

This test used carbide inserts, ISO SNUNISO with a tip radius of 0.8 mm. The produced inserts were divided into three groups, the first of which (without coatings) was used as a control group, the second group of inserts was coated with ***NWC*** *Ti-TiN-TiCrAlN*, and the third party of inserts was coated with ***NWC*** *TiAlN-ZrNbN-CrN* developed in accordance with the principles mentioned above. Longitudinal turning in dry conditions was conducted maintaining the cutting speed at a specified level when the diameter of the workpiece was changed. The machining test were carried out on steel C45 (HB 200) and nickel-based alloy *NiCr20TiAl*.

Cutting inserts with and without coatings had the following geometric configuration: for turning: γ = - 8°; α = 6°; k = 45°; r = 0.8 mm. The efficiency of cutting tools with the developed ***NWCs*** was evaluated by the time they reached a maximum flank wear $VB_{max}$ = 0.4-0.5 mm.

The verification tests of cutting properties of inserts with developed ***NWCs*** were carried out for longitudinal turning (continuous cutting process with constant parameters for cross sections of cut and contact thermo-mechanical stresses during cutting in one pass).

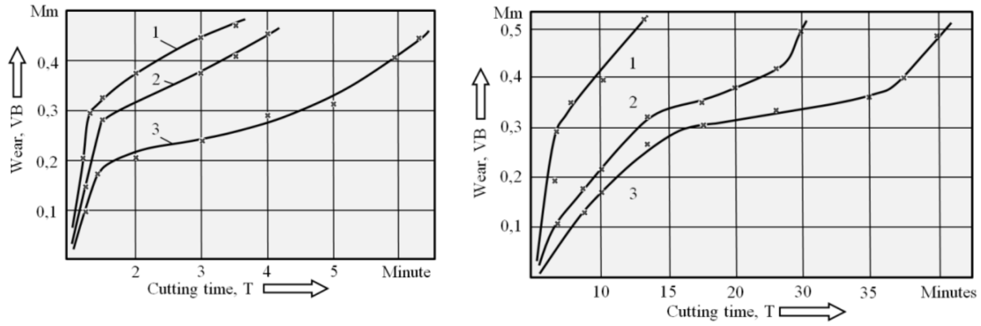
For turning of steel, the study used inserts of carbide without and with coatings based on

system *Ti-TiCrAlN*. The results of verification tests are presented in Fig. 4. The conducted tests have revealed significant advantages of carbide tools with developed ***NWC*** Ti-TiN-TiCrAlN and *TiAlN-ZrNbN-CrN* compared to control uncoated carbide tools.

Comparison of the results of the verification tests of the cutting properties of tools of carbide without coatings with the corresponding data for carbide tools with developed *NWCs* confirmed the validity of the application of the above formulated principles on the formation of nano-scale multilayer composite coatings with the use of the process of the *FCVAD*.

*NWCs* deposited on surfaces of the carbide cutting tools using of the *FCVAD* processes sufficiently improve the tool life compared with the tool life of control carbide tool without coating, with fine structure and sufficiently notable imbalance of hardness and strength for all tested cutting conditions (see Fig. 4). The best results were provided by *NWCs* with balanced hardness and thermal stability, which was reached, for example, by introduction of barrier layer of *ZrNbN* between extremely hard and mutually soluble wear-resistant layers of TiAlN and CrN.

The maximum increase of tool life is shown by inserts with developed *NWCs TiAlN-ZrNbN-CrN* (see Fig. 4 curves 3).




a b

**Figure 4** Dependence of tool wear equipped with inserts made of carbide (curve 1) with *Ti-TiN-TiCrAlN* (curve 2) and with *TiAlN-ZrNbN-CrN* (curve 3) from the cutting period when: turning steel C45 (a) and nickel alloy *NiCr20TiAl* (b) with $a_p$ = 1.5 mm; f = 0.3 mm/rev

## Conclusion

Investigation of the thermal composition and structure of *NWCs* deposited on carbide substrates with the use of the developed process of *FCVAD* allowed classifying the produced *NWCs* as nano-structured. In particular, the example of *NWC* based on the system of *TiAlN-ZrNbN-CrN* reveals that the outer layer *CrN* with thickness of 2.0 µm has a nanolayer structure with thickness of sublayers of about 70 nm, and the intermediate and adhesion layers (*TiAlN-ZrNbN*) with total thickness of about 1.0 µm also has the nano-scale layer structure with thickness of sub-layers of 25 nm.

The studies of the properties of the carbide inserts with developed *NWCs* showed their high efficiency. In traverse turning and face milling of steel C45 and nickel alloy *NiCr20TiAl*, tool life of the carbide inserts with developed *NWCs* based on the system of *Ti-TiN-TiCrAlN* and *TiAlN-ZrNbN-CrN* (FCVAD technology) was increased up to 5-6 times in comparison with the control uncoated inserts.

## Acknowledgements

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