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## **Wear of Superhard Cutting Tools**

*The paper analyzes mechanisms of wear of cutting tools inserted with superhard cutting elements: monocrystalline (MCD) and polycrystalline (PCD) diamond and cubic boron nitride (cBN). Materials being machined are classified into four groups according to the special features of tool wear. The possibility is shown of controlling polycrystalline cBN tool wear by using gaseous process media.*

**Keywords:** *Diamond, Cubic Boron Nitride, Cutting Tools, Cutting, Wear*

### **1. INTRODUCTION**

The present stage of the industrial development sees an ever-expanding use of structural materials of higher strength, wear resistance, and hardness which cause problems in machining them.

This makes the requirements imposed upon the development of new materials for cutting tools more rigid. Superhard materials (SHM) whose hardness is 2-5 times that of the material being machined meet the requirements placed upon the tools by modern mechanical engineering, instrument making and other industries.

Under the heading of "superhard" materials there come covalent substances whose hardness is above 20,600 MPa [1]. The present paper deals with tools inserted with cutting elements of mono- and polycrystalline diamond and dense modifications of boron nitride: wurtzitic (wBN) and cubic (cBN).

### **2. EXPERIMENTAL PROCEDURES**

The present work uses results of experimental and theoretical studies of SHM tool wear [2, 4-11, 13, 15].

Wear of tools made of BN dense modifications was studied on the following workpiece materials: hard Fe-base faced coatings ЛС-5Х4В3МФС (45-48 HRC; 5% Cr, 0.8% Si, 0.5% C, 3% W, 0.5% V, 2.8% Mo) and ПП-Нп-30Х5Г2СМ (52-58 HRC; 3% Cr, 0.8% Si, 0.5% C, 0.2% Ti, 0.6% Mo, 1.6% Mn), ПГ-10Н-01 hard Ni-base spray-coated (57-62 HRC; 17% Cr, 3.1% B, 4.25% Si, 4.25% Fe, 0.8% C) and ШХ15 bearing steel (60-62 HRC; 1% C, 0.3% Mn, 0.27% Si, 1.45% Cr). The main experiments were carried out using tools made of Kiborit polycrystalline superhard material produced at the Institute for Superhard Materials of the NAS of Ukraine.

Interaction products obtained in model experiments in the case of the process thermoactivation (heating in a

furnace) and products formed in cutting, i.e., for the case of tribothermoactivation were studied.

Products of tool material wear were taken from environment using a mod. 822 aspirator.

Thermochemical properties of SHMs were studied by simultaneous DTA-DTG-TG microthermoanalysis using a mod. MTB 10-8 microanalyzer in air atmosphere at temperature up to 1770 K, the rate of the temperature increase being 10 deg/min. Phase composition of SHMs was studied by X-ray diffractometry on a ДРОН-3 device.

Chemical composition of contact regions of cutting tools was investigated using the Lass 3000 system designed to study a surface, by Auger electron spectroscopy (AES) and secondary ion mass spectrometry (SIMS). Electron energy in the first beam in case of the AES method was 3 keV, the analyzer modulating voltage 2 V. The sample surface was etched with 3 keV Ar<sup>+</sup> ions. In case of the SIMS method a quadrupole mass-spectrometer and a duoplasmatron (as a ion source) were used. To generate a primary beam, oxygen was used with 10 keV O<sub>2</sub><sup>+</sup> ions.

Products of model interaction between a BN-base SHM and a workpiece material (ШХ15 bearing steel) were studied by X-ray spectrum (ИСП-30 quartz spectrograph), energy dispersive X-ray spectroscopic (Link 860), simultaneous thermochemical (MTB 10-8 device) analyses and X-ray diffractometry (ДРОН-3 device). The required amount of a product of the interaction of the tool material with a workpiece and elements of environment was obtained by heating and 1-hour holding in air at 1470 K in an electric furnace.

The processing in gaseous media (argon, nitrogen, air) was performed in a special chamber set upon a machine-tool. The gas was fed into the chamber at the excess pressure of 0.01 MPa.

### **3. RESULTS AND DISCUSSION**

Wear resistance of superabrasive tools varies with materials being machined, which are arbitrarily divided into four groups.

#### *a) Diamond tool (MCD, PCD)*

When machining materials of the first group (copper, brass, magnesium, precious metals, bronze,

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aluminum, polymeric composites with no abrasive inclusions, etc.) the tool fails due to both a longterm adhesive wear and accidental causes (dynamic action of vibration and impacts, effect of material inclusions, etc.).

Machining materials of the second group (copper and aluminum-base alloys, polymeric composite materials which contain hard and abrasive particles, etc.) is accompanied by a slow tool wear due to abrasive and adhesive interaction of materials in contact. In this case, tool wear is almost independent of temperature in the cutting zone and is determined by the cutting length. Thus, in case of machining copper, the following relation was obtained [2]:

$$VB = 0.00042 L^{0,537},$$

where  $VB$  is the tool flank wear,  $\mu\text{m}$ ;  $L$  is the cutting length,  $\text{km}$ .

The third group of materials includes titanium, zirconium and alloys based on them, tungsten, cemented carbides. The machining of these materials is accompanied by high temperatures in the cutting zone. Iron, nickel, cobalt and other metals which react vigorously with carbon or in which carbon dissolves, form a special group of materials.

Diamond cutting tools fail by the following scheme: at first on a cutting edge there form microcracks, then microparticles of the material being machined enter the microcrack, accumulate there and produce a cleaving effect thus expanding it. This, in turn, causes further accumulation of metal microparticles at the cutting edge. Fragments of buildups break away as they reach definite sizes. The removal of the buildup from the tool face, at regular intervals, determines the stress redistribution in the tool surface layer.

Under impact, the rate of microcrack and chip formation on a tool cutting edge increases by a factor of 10 and more. Under these conditions, the chipping of the cutting edge due to the effect of shock loading, rather than due to adhesion becomes dominant.

When machining metals of the first and the second groups, tool wear is due to a rather weak adhesive and abrasive interaction as well as by spalls and microcracks formation on the tool cutting edge, while in machining materials of the third and the fourth groups, tool wear is characterized by an intensive adhesive interaction as well as by carbon diffusion into the material being machined. In high-speed machining of metals of the fourth group a specific type of wear, i.e. eutectic wear, is of particular importance.

It should be noted that the wear behaviour of the fourth group metals depends on the structure of the material being machined. Thus, when turning austenitic metals the tool flank wear ( $VB$ ) is observed which is accompanied by a high adhesion of the materials in contact. When cutting pearlite-ferritic steels the tool shows both face and flank wear.

Abrasive or other hard inclusions in the materials being machined add to the intensity of the tool cutting edge spalling and contribute to its rounding.

In cutting, a diamond tool undergoes a variety of

wear mechanisms (adhesive, abrasive, diffusive and eutectic) depending on the properties of the material being machined and cutting conditions.

In view of the fact that temperatures which arise in machining non-ferrous metals change the diamond hardness only slightly, an abrasive component of wear is at a minimum. The reverse situation is observed when turning materials having hard abrasive inclusions and, specifically, cemented carbides.

According to the degree of the adhesive interaction with diamond, the materials being machined are divided into two groups [3]. The first group, which is characterized by rather low initial adhesion temperatures ( $0.4-0.5 T_{melt}$ ), includes metals reacting with carbon and metals which dissolve carbon (Fe, Ni, Co, etc.).

Metals, specifically, those of the 1b group of the periodic table (Cu, Ag, etc.) which are inactive to carbon, form the second group of materials. The initial adhesion temperature for these materials is on the order of  $0.7 T_{melt}$ .

Diffusive wear shows up as a smooth polished contact flat. When machining iron, nickel and cobalt, a considerable heat generation is observed in the cutting zone, and the resultant contact temperatures suffice to activate carbon diffusion into the material being machined.

In view of the fact that the main diffusion law consists in the parabolic growth of a diffusion layer, the time of contact between the tool and particular regions of material being machined suffices to maintain the intensive diffusion. By virtue of the fact that carbon dissolves in  $\alpha$ - and  $\gamma$ -irons in different ways, diffusion wear varies over a wide range when machining iron-base materials.

Loladze [4] has proposed the following relationships to measure cutting tool durability when cutting austenite

$$T = \frac{5.11 \cdot 10^{-3} e^{32840/Q}}{C_1 v^{0,5}},$$

and ferrite

$$T = \frac{1.34 \cdot 10^{-2} e^{20110/Q}}{C_1 v^{0,5}},$$

where  $C_1$  is the weight fraction of the diffused element,  $Q$  is the cutting temperature.

Calculations by the above formulas show that with cutting speed  $v = 8-9$  m/s the diamond tool durability when turning austenite is by a factor of 25 lower than in turning ferrite.

Carbon dissolves in titanium in a lesser amount than in iron. This fact is responsible for a smaller diffusion component of wear when turning titanium at similar temperatures. Its calculated durability is more than 110 times that for turning ferrite.

When turning copper, zinc, aluminum and alloys based on them which do not dissolve carbon, diamond tool diffusion wear does not occur, this is supported by the efficiency of the application of these cutting tools.

One of the mechanisms of the material interaction at high temperatures is a contact eutectic melting [3], which resides in the fact that in any system having component boundaries which make up an eutectic pair, or in the system having the state diagram with limitless dissolubility with a minimum, just at this boundary a liquid phase appears as eutectic temperatures are reached.

Materials entering into the triad of ferrum when reacting with carbon form eutectic alloys, whose melting temperatures are well below those of the metals themselves (eutectic melting temperatures are as follows: 1420 K for Fe-C, 1591 K for NiC and 1582 K for Co-C).

In view of the fact that at high cutting speeds temperatures above 2000 K can develop on local contact regions of a tool [5] one may conclude that there occurs contact eutectic melting of the tool material.

The interaction of carbon with non-ferrous metals and alloys is characterized by other diagrams of the systems, so high cutting temperatures do not develop, as a result of which the above mechanism is not implemented and is true only for the metals under consideration.

Thus, monocrystalline diamond cutting tool wear in machining non-ferrous metals and alloys and polymeric materials depends on adhesion, abrasive interaction and microfracturing of materials due to dynamic loading. When machining polymeric composite materials, the interaction between diamond carbon and destruction products of the material being machined, i.e. macroradicals of polymer chains is of a certain importance. Data are available on the diamond failure intensification in the presence of components of polymeric materials [6]. Cutting ferrous metals is also accompanied by diffusive dissolution and contact eutectic melting to remove interaction products from working surfaces.

A high wear resistance of polycrystalline diamond cutting tools as compared with those made of diamond single crystals is explained by the difference between their structures. A cutting edge of a monocrystalline diamond tool exhibits cracks due to fatigue-mechanical loading, which may be of large sizes. In a polycrystalline diamond, cracks are retarded and arrested by crystal boundaries. Just this fact is responsible for their higher (by a factor of 1.5-2.5) wear resistance.

#### *b) Cutting tool of boron nitride dense modifications (wBN, cBN)*

Based on electron microscopical studies and X-ray spectral microanalysis a number of researchers [7] make a conclusion that tools of BN-base polycrystalline superhard materials fail by the abrasive-mechanical mechanism. It is thought in this case that wear rate increases at temperatures close to those of cBN→hBN phase transition, and that hBN starts to form at grain boundaries thus making a polycrystal more soft. Other researches [3] develop the theory of tool diffusion wear and emphasize that this wear mechanism shows up most vividly at high cutting speeds. Hitchiner H. et al. [8] and

Kramer B.M. [9] point to the presence of the chemical interaction in the contact zone between the BN-base tool material and the material being machined. In this case the wear rate is defined by the mutual diffusion of elements being in contact.

Experimentally supported is the adhesive mechanism of BN-base PSHM tools wear when cutting iron-carbon alloys [10].

Because of a high hardness of BN particles, abrasive wear of cutting tool depends on a binder content of a PSHM. The highest abrasive wear is observed in cases of low contents of cBN or wBN, and when a soft binder component is used or its hardness decreases with temperature rise more intensively than that of abrasive particles in a workpiece material.

Abrasive cutting-tool wear is intensified due to the chemical interaction of a tool material with a workpiece and elements of surroundings, specifically, with atmospheric oxygen. Rather soft resulting compounds are easily removed from tool contact regions by particles of the workpiece material. This mechanism of wear may be considered as an abrasive-chemical one.

Abrasive cutting-tool wear can be related to a "self-wear" phenomenon. Because of abrasive and adhesive fracture, individual particles pull out from polycrystals and contribute to the intensification of the abrasive interaction in contact regions of a cutting tool due to "self-wear".

Chemical processes proceeding in a cutting zone play an important part in BN-base polycrystal wear. Thermochemically permissible are chemical reactions of BN with Ti, Cr, Zr and some other elements in a wide temperature range. The value of the Gibbs potential  $\Delta G$  for the reaction with iron is positive up to 1500 K [11] which discards the probability that they proceed.

It should be borne in mind that the  $\Delta G$  value has been calculated for the case of thermoactivation of a "perfect" system, while in cutting, thermotriboactivation of real materials is implemented. The mechanical activation including that with shear stresses applied in contact regions, is known to allow chemical reactions of interaction to be implemented, the latter being characterized by a positive  $\Delta G$  value [12]. Chemical reactions similar to those between BN and workpiece materials are to be allowed for other tool material components.

Tables 1 and 2 summarize the results of analysis of chemical composition of contact surfaces of a cutting tool and a workpiece of a hardfaced steel.

Auger spectra from surfaces of PSHM after contacting with a workpiece material do not show lines due to boron and nitrogen because of the material deposition on tool. Even a prolonged etching of a worn-out contact tool surface with Ar<sup>+</sup> ions (130 min) does not remove an iron-containing layer from its surface.

As-machined surface etching with O<sub>2</sub><sup>+</sup> iron changes the shape of spectra from positive secondary ions, which shows up in the lowering of intensity of lines due to BN<sup>+</sup>, MeO<sup>+</sup>, MeC<sup>+</sup>, MeB<sup>+</sup>, MeN<sup>+</sup> ions and in the increasing of intensity of lines due to Cr and Fe.

A spectrum of mass negative secondary ions taken from the surface of a workpiece machined with a BN-

base PSHM tool as well as from the cutting tool surface shows peaks which are due to  $TiB^-$  (59),  $TiN^-$  (62),  $TiB_2^-$  (70) and  $TiN_2^-$  (76), the fact that points to the proceeding of the reaction between BN and Ti (III-Hn-30X5Г2CM).

**Table 1. Composition of specimen surfaces**

Material	Surface	Content, %, of			
		C	O	Cr	Fe
JIC-5X4B3MΦC	Initial	18	11	5	66
	As-machined	10	6	7	77
Tool	After contact with metal	73	18	-	9
	As-etched with $Ar^+$ for 130 min	21	36	-	43

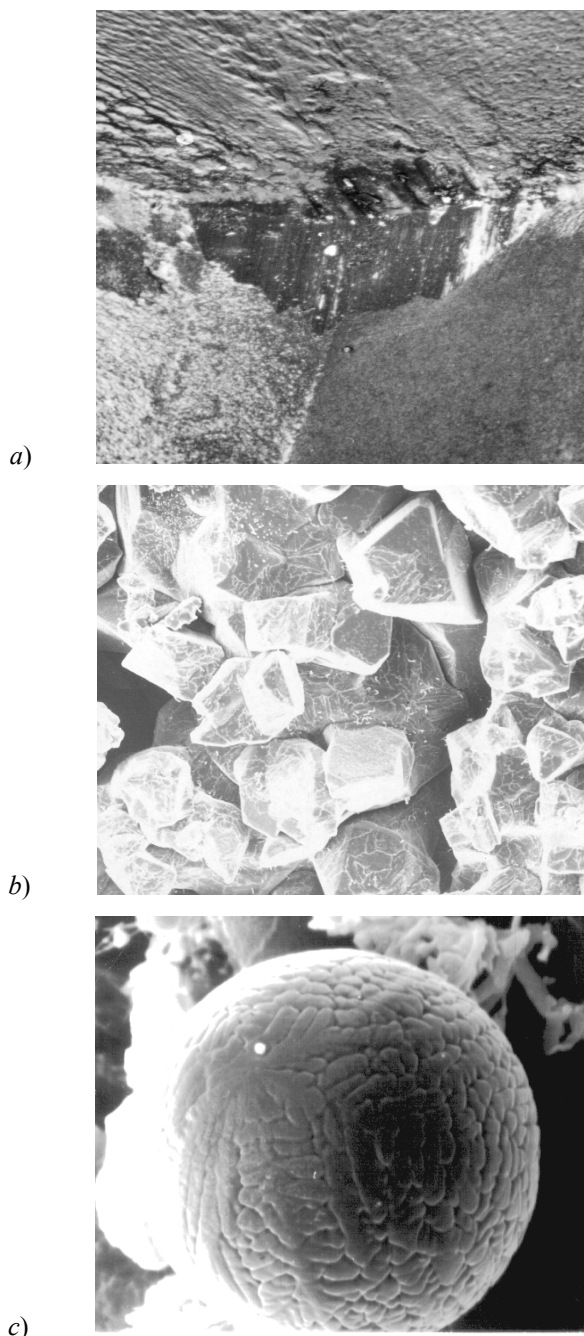
Note: Elements in amounts less than 3 at.% (Si, Mn, Mo, W, V, and Ti) were not revealed by Auger spectroscopy. Turning conditions:  $v = 0.83$  m/s;  $f=0.11$  mm/rev;  $a=1$  mm.

**Table 2. Intensity ratio of lines in the secondary ion spectrum or the machined surface of workpiece JIC-5X4B3MΦC**

Surface	After contact with cBN	As-etched with $O_2^+$ for 30 min
$\frac{52Cr^+}{56Fe^+}$	0.77	0.71
$\frac{52Cr^{11}B^+}{56Fe^+}$	0.77	0.09
$\frac{52CrN^+}{56Fe^+}$	0.29	0.07
$\frac{56FeO^+}{52CrO^+}$ $\frac{56Fe^+}{56Fe^+}$	0.63	0.15
$\frac{56Fe^{11}B^+}{56Fe^+}$	0.62	0.15
$\frac{56FeN^+}{56Fe^+}$	0.12	0.04
$\frac{11BN^+}{56Fe^+}$	0.38	0.11

In the polycrystal-workpiece contact zone chemical reactions proceed to form nitrides, borides, oxides and, very likely, more complex compounds like hydroxyborides of elements entering into a workpiece material.

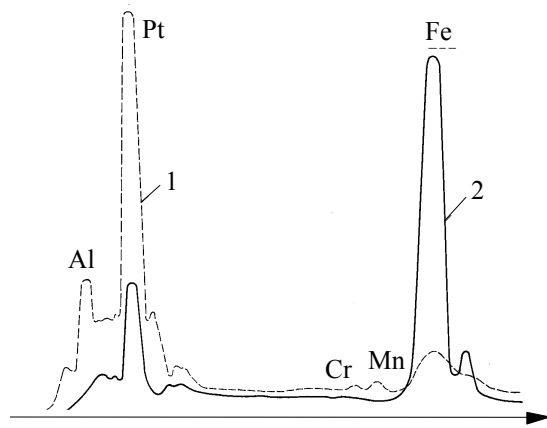
Analysis of our findings and micrographs of the worm-out part of a cutting tool allows a conclusion that in addition to the intertransfer of workpiece and tool materials and changes in chemical composition of surface layers of the cutting tool contact surfaces, the changes in the surface layer composition are also observed on its non-contact regions. This shows up as a coating formed on cutting tool face and flanks or on their sections (Fig. 1a) [13].



**Fig. 1. A coating on a non-contact tool surface (a), a product of tool-workpiece materials interaction in model experiments (b), a spherical particle from environment (c); cBN and IIIХ15 steel are tool and workpiece materials, respectively**

A comparison between energy spectra from the contact surface and the coating surface (Fig.2) shows that they are of a similar composition.

The cutting process is accompanied by the formation of a liquid phase layer on the tool contact surfaces due to the effect of contact melting at the tool-workpiece interface (the interaction may occur both due to free boron which is always found in the tool material and with the participation of boron which has appeared due to BN destruction) as well as due to oxidation of BN to  $B_2O_3$  followed by its interaction with components of a workpiece material.



**Fig. 2. Energy spectrum from a contact surface of a tool (1) and a coating surface (2); Kiborit – IIIX15;  $v = 0.5$  m/s,  $VB = 0.4$  mm**

Analysis of thermograms of polycrystalline BN oxidation shows that the oxidation initiation corresponds to 970 K and is accompanied by an increase in mass with a modest reaction rate. In the temperature range 1370-1470 K the rate of the interaction with atmospheric oxygen increases and oxygen dissolves in  $B_2O_3$ . At 1470 K the mass diminution begins whose rate increases drastically with increase in temperature up to 1730 K. This phenomenon is due to evaporation or reduction of boron anhydride.

In view of the fact that complex compounds (e.g., ternary compounds) may develop at contact points, their melting temperature might be even lower.

It has been found in model experiments that in the system under study at temperatures between 1073 and 1573 K there occur changes caused by the interaction of materials in contact. Heating and cooling specimens of IIIX15 steel and Kiborit PSHM in air cause new chemical compounds to form which contain Fe, Cr, O, Al, B and N. When analyzing the state diagram of Fe-B [14] one would suppose that at 1450 K the Fe-FeB eutectic forms in the contact region. It should be noted that the resultant interaction product, when cooled, is like a combination of individual crystals of various shapes, the fact that points to its crystallization from the liquid phase (Fig. 1b).

The results of chemical analysis of the specimen interaction products agree with data [15] which show that the interaction between BN and steel starts at 1473 K to form the Fe- $Fe_2B$  eutectic on the steel specimen surface, while that between BN and chromium-containing steel at 1273-1373 K to form  $Cr_2B$  and  $Fe_4N$ . Interaction with Ti and Cr is possible at temperatures 200-300 K below those in case of Fe. An increase in pressure in the contact region lowers the initial interaction temperature by 250 K. In this case, nitrogen diffusion in steel increases considerably.

Element composition of the substance produced in a model experiment corresponds to that of the above-considered substance of the tool-workpiece interface obtained in cutting. It should be noted, however, that in spite of the fact that the substances prepared by thermo-activation and tribothermoactivation of the interaction reaction are of the same element composition, the resulting compounds may differ [12].

Analysis of the interaction products on the tool contact surfaces shows that the thickness of new chemical compounds on a tool is at least by an order of magnitude that on an as-machined steel specimen surface. This is attributed to the fact that at the moment of breaking a contact the liquid phase crystallizes more readily on the surface of a polycrystal having much higher thermal conductivity and surface energy as compared with a workpiece material.

Obviously, the liquid phase particles discharged from contact zones to environment acquire a spherical shape by action of gravity and surface tension. In our case in the filter surface region  $10^{-5}$  m<sup>2</sup> in area, particles in sizes from fraction of a micron to 20-30  $\mu$ m deposited with the rate of 2-3 pcs/min which provides support for the significance of the effect under study.

Well-defined are morphological features of the particles found: spherical particles have a pronounced dendritic structure of a cast material (Fig. 1c).

Photospectrum and X-ray spectrum analyses of chemical composition of spherical particles have revealed elements which are found in materials being in contact as well as in environment (B, N, O, C, Fe, Cr, Si, Al, etc.). This fact agrees with the above results.

Thus, BN tool wear at low cutting speeds is due to both adhesive-fatigue phenomena and "self-wear" (i.e. abrasive action of workpiece material) which accompany them.

As the cutting speed increases, so does the contact temperature. This results in the prevailing softening of the workpiece material, reduction in abrasive and adhesive fracture of the tool material, and rise of chemical interaction rate. In contact regions of a tool the role of a liquid friction increases. As a specific thickness of the liquid phase layer is achieved which corresponds to the friction system state, when the abrasive and adhesive wear components become less intensive, and the intensity of the chemical interaction does not still prevail in wear, the highest tool efficiency is realized.

Further increase in cutting speed causes the rate of tool wear due to the development of a liquid phase and removal of it from contact zones to increase constantly, and under the conditions, which correspond to the lower section of the right branch of the  $T=f(v)$  diagram, it completely determines the lowest service life.

A way to improve the BN-base PSHM tool efficiency is to use cutting cooling media (liquid or gaseous).

It is shown in [16] that oil media with high pressure additives are efficient in this case. Thanks to the reaction with BN, which causes a solid lubricant film to develop on the tool surfaces, the oil media prevent the BN from becoming brittle under the action of heating a cutting edge in cutting followed by cooling in a liquid medium or in air. Sulfur and chlorine gas are the additives used.

Gaseous media which prevent the atmospheric oxygen from arriving at the tool contact surfaces also contribute to the improvement of its performance (Fig. 3).

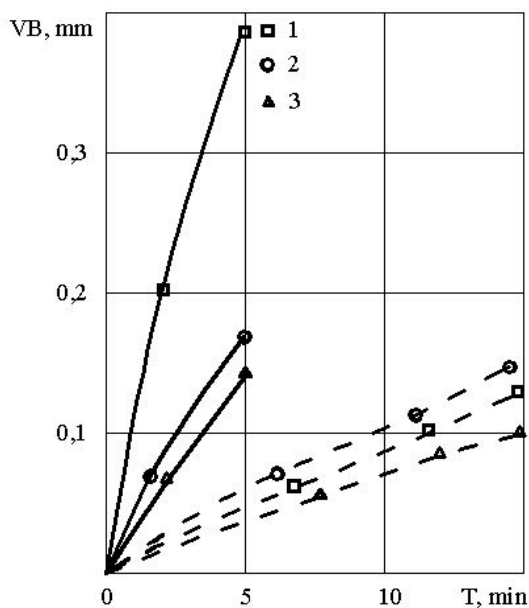


Fig. 3. Effect of cutting cooling media and cutting speed on Kiborit tool wear when turning ПГ-10Н-01 coating: 1- air, 2-argon, 3-nitrogen; cutting speeds: 3.01 (solid line) and 0.75 (dash line) m/s

#### 4. CONCLUSIONS

The highest efficiency of cutting tools made of diamond and dense BN-base superhard materials is realized in a variety of applications: for diamond it is realized in machining non-ferrous metals and alloys, polymeric composite materials, for boron nitride in machining steel, iron, hard-faced and sprayed coatings on the base of ferrous metals. The area of the tool application is dictated by differences in mechanisms of their wear.

In this case, the main prerequisite to the tool application is the realization of high and superhigh cutting speeds, which under otherwise identical conditions ensures higher machining efficiency, accuracy and quality of pieces.

Further investigations into the tool wear peculiarities and the development of new tool materials will contribute to the expansion of SHM tool applications and enlargement of their volumes.

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#### ХАБАЊЕ СУПЕРТВРДИХ РЕЗНИХ АЛАТА

С. А. Клименко, М. Ј. Копејкина, Љ. Тановић

У раду су анализирани механизми хабања резних алата израђених од супертвердих резних сегмената: монокристалног (МCD) и поликристалног (PCD) дијаманта и кубног борнитрида (сBN). Материјали за обраду су класификовани у четири групе према специјалним феноменима хабања алата. Приказане су могућности контролизованог хабања поликристалног сBN у процесима реализованим у гасовитим срединама.