ISSN 2079–1836
2022, вип. 35

DOI 10.15421/4222220
UDC 621.9:539.3

A. S. Kairov, Dr. Sci. (Tech.), V. Ya. Oshovsky, PhD (Tech.), V. A. Kairov, PhD (Tech.)

INVESTIGATION OF THE EFFECT OF NANOCOATINGS ON THE WEAR-RESISTANCE OF SOCKET CARBIDE MILLS

The results of studies of the wear-resistance of socket mills made of hard alloys in the processing of hard-to-process structural chromium steels are presented. The technology of hardening of cutting teeth with a wear-resistant coating obtained by the Physical Vapour Deposition method is considered. The influence of the structure of the hardening composite coating based on titanium nitrides and carbonitrides on the mechanical characteristics and working capacity of the tool is shown. The nature of wear and brittle destruction of the working surfaces of the tool under intermittent cutting conditions and the influence of wear-resistant coatings on the thermal and stress state of the cutting wedge in the contact zone are investigated.

Keywords: *carbide cutting tools; socket mill; milling; cutting modes*; *nano-coating*; *titanium carbo-nitrides; wear-resistance; endurance*; *hardness of the material*; *contact stresses*; *working capacity.*

Introduction. The efficiency of mechanical processing of hard-to-process structural alloy steels with high chromium content largely depends on the wear-resistance of the cutting tool. This significantly affects the increase in its working capacity. The most acute problem of intensive wear and brittle destruction in the form of chipping and chipping of the cutting edges is manifested in socket mills made of carbide material, which operate at high speeds under intermittent cutting conditions, shock loads, high contact stresses and temperatures [1, 6–9, 12].

One of the effective ways to solve this problem is the application of wear-resistant composite coatings on the working surfaces of the cutting tool using nano-technologies. This makes significantly it possible to working capacity improve the performance, fatigue strength, corrosion resistance of the tool and intensify cutting modes by modifying the physical and mechanical properties of the cutting teeth, their surface and volumetric hardening [2–5, 7, 11, 14]. Composite coatings based on compounds of refractory metals (carbides, nitrides, borides, oxides and their compounds) are more often used. The technologies for applying multilayer coatings are given in [4–7, 11, 14].

Currently, the physical nature of wear during cutting of hard-to-process materials has not been sufficiently studied due to the exceptional complexity of contact processes on the front and rear working surfaces of the tool, as well as the cutting edges of the blade. Therefore, this research is relevant.

The aim of this paper is to study the effect of a hardening composite coating of working surfaces on increasing the wear-resistance of the cutting teeth of socket mills made of solid alloys under intermittent cutting conditions when processing hard-to-process chromium structural steels.

Presentation of the main material. Experimental studies of the wear resistance of the cutting tool were carried out under intermittent cutting conditions when processing chromium steel 20X13 according to the counter milling scheme with socket cutters ∅160 mm equipped with pentahedral replaceable plates made of metal-ceramic hard alloy T5K10. Milling was performed without cooling on a vertical milling machine model 6M12P in the range of cutting modes: $V = 50 \ldots 250$ *m/min*, $S_Z =$ 0.05÷0.3 *mm/catt*, $t = 1 \div 3$ *mm*, $B = 150$ *mm*.

The processing was carried out with uncoated cutters and with coatings of nitride (TiN), carbide (TiC) and titanium carbo-nitride (TiCN), as well as a multilayer structure based on these compounds. The maximum linear wear of the chamfer along the main rear surface of $h_3 = 0.3$ *mm* is taken as the criterion of wear of the cutting plate. The frequency of cyclic thermal force loading of the working surfaces of the tool was provided by adjusting the speed of rotation of the milling cutter. Wear control was carried out both in the initial and in the main periods of operation of the tool.

Coatings made of titanium carbide TiC and titanium nitride TiN were applied to plates made of hard alloys at the vacuum ion-plasma installation «Bulat-3T». The study of the topography of the surface layer of the cutting plates and the microstructure of the applied coatings before and after wear was carried out by X-ray spectral analysis using a scanning electron microscope-microanalyzer REMMA-102-02, electron microscopes REM-100U, Jeol-772 and metallographic microscope MIM-7. The X-ray diffraction analysis of coatings has performed on a DRON-1 diffractometer. The thickness of the coating was measured by the MT-20N device, and its hardness was controlled by the TK-2M and PMM-3 devices. Modern methods of surface research are given in the works [4–7, 11, 14].

Fig. 1 shows a fractogram of the microstructure of the surface of the titanium nitride coating TiN deposited on a base of a hard alloy T5K10.

Wear-resistant coatings TiN, TiC, TiCN, obtained on the basis of refractory metals, were applied to the cutting plates by the method of Physical Vapour Deposition (PVD) using special ion-plasma technology [5, 13, 15]. Together with single-layer coatings, multilayer coatings TiC-TiCN-TiN, TiCN-Al_2O_3-TiN, TiN-TiCN-TiN were also used.

The application of a wear-resistant surface layer was carried out using an arc discharge in a vacuum chamber in a reactive gas atmosphere: nitrogen for titanium nitride (TiN), acetylene for titanium carbide (TiC). The formation of the surface layer occurs by adsorption of ions of the coating material (Ti) in the form of a low-temperature plasma stream on the surface of a hard alloy substrate. At the same time, the crystal lattice of the tool material is completed. Microcracks and pores of the working surfaces are filled with the coating material, which contributes to an increase in the adhesive strength of the connection of the surface with the coating.

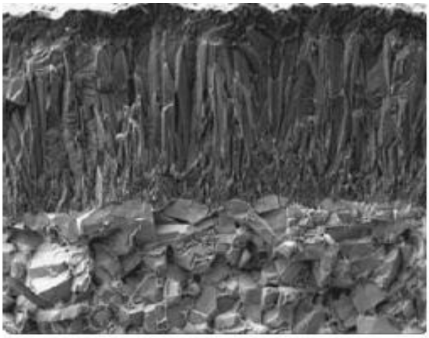


Fig. 1 – **Microstructure of the surface of a TiN coated carbide cutting plate**

The process of forming coatings with certain physical and mechanical properties, thickness, structure and phase composition depends on various factors: reference voltage, arc discharge current of the evaporator, pressure of the reaction gas in the working chamber, substrate temperature, deposition flux density and energy of metal plasma ions TiN, TiC, TiCN, duration and rate of adsorption.

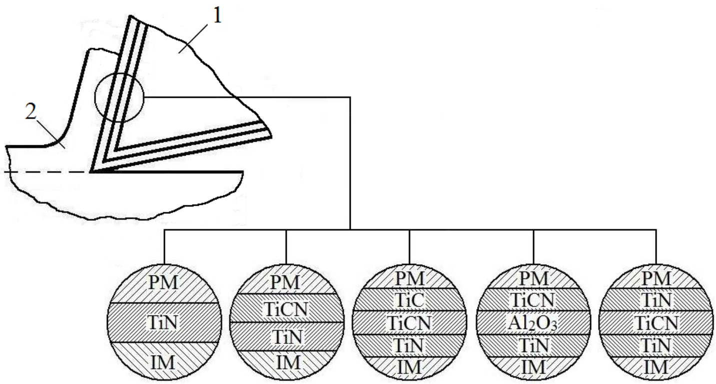
The characteristics of the microhardness, structure and phase composition of the coatings were provided by varying the three main parameters of the condensation mode using PVD technology – the arc discharge current of the evaporator i_o = 90…150 A, the pressure in the reaction chamber of the reagent gas installation $P_\alpha = (2.5 \div 7.9) \cdot 10^{-2}$ *Pa* and the reference voltage on the substrate U_o = 150÷210 *V*. The condensation temperature was maintained in the range of 460÷540°*C*.

As a result of X-ray spectral analysis of the microstructure of the surface of the cutting plates, optimal modes of synthesizing a coating have been established: U_o = 200 *V*; i_o = 110÷120 *A*; $P_\alpha = (2.6 \div 5.3) \cdot 10^{-2}$ *Pa*; θ = 460÷500º*C*. With an increase in the arc discharge current, the condensation rate increases.

X-ray spectral analysis of the microstructure of the obtained coatings showed that under this synthesis mode, the main phase of the condensed layer consists of TiN and TiC with crystallite sizes from 0.004 to 0.033 microns without the presence of free titanium.

Due to the low coefficient of thermal expansion of titanium oxide and carbide and the tendency of thick coatings to crack at high temperature, coatings with a thickness of 5...8 microns were synthesized on the surface of the cutting plates, and their microhardness was 23÷26 *GPa*.

To increase the reliability and durability of replaceable polyhedral cutting plates, multilayer coatings are used (Fig. 2), which can significantly increase the tool wear resistance and processing performance compared to single-layer ones. Each layer of such a composite coating has its own functional purpose.



1 – cutting tool; 2 – billet; PM – processed material; IM – instrumental material

Fig. 2 – **Structural scheme of coatings**

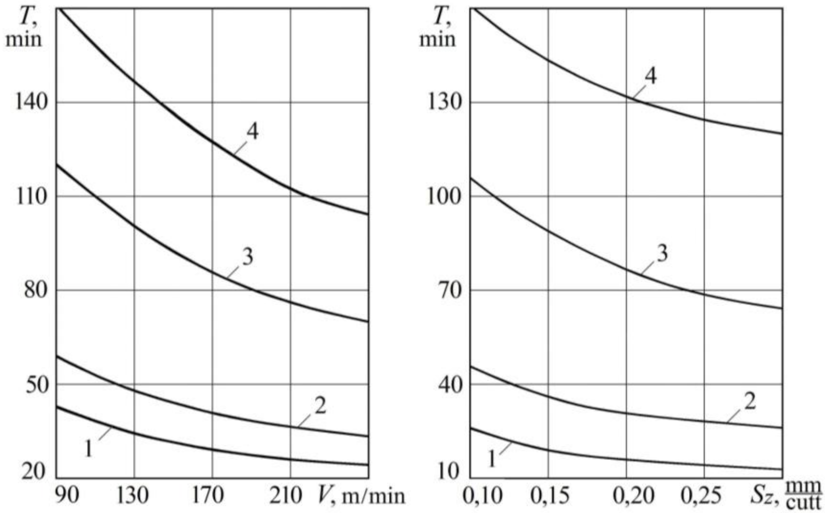
Research results. A feature of milling the chrome-plated steels with socket mills in intermittent cutting conditions is the impact at the entrance and exit of the cutting teeth in contact with the workpiece. Compression stresses are transformed into tensile. This determines the cyclical nature of the thermomechanical load and leads to a sharp increase in wear and brittle destruction of the tool in the form of microcracks and chips.

High physical and mechanical properties and low thermal conductivity of chromium steels impair their machinability. Therefore, the cutting forces are 3…4 times higher than the forces that occur during the processing of carbon steels. The specific pressure during cutting reaches 400÷1200 *MPa*, and low thermal conductivity increases the cutting temperature by 30÷50%. The resistance of the tool due to brittle destruction in the form of chips and wear of the cutting edges is reduced by 1.5÷3 times. As a result, a complex stress state occurs in the cutting wedge of the working part of the cutter with simultaneous interaction of normal and tangential stresses.

Compression stresses arise in the surface layer of the tool material under the action of normal forces and elastic-plastic deformation occurs. The front and main rear working surfaces along the entire width of the slice due to adhesion outgrowth are covered with a smeared thin layer of the processed material already in the initial processing period. The analysis of the elements of the outgrowth on the rear main surface of the cutting teeth during the processing of steel 20X13 showed that the main components of the surface layer of the tool are iron (Fe) and chromium (Cr), corresponding to the chemical composition of the processed material. The concentration of these elements is: iron Fe ~ 85÷86%, chromium Cr ~ 13÷15%, carbon C ~ 0.16÷0.25%. Similar results were obtained for other processing materials.

This causes the need for hardening the working surfaces of the tool with wear-resistant coatings. The hardening coating, having high hardness and wear resistance, protects the tool material for the entire period of its operation.

The dependence of the influence of the cutting speed V and feed S_Z on the resistance T of cutters made of T5K10 hard alloy with various hardening coatings during socket milling of workpieces made of 12X13 steel is shown in Fig. 3 for the parameters of the cutting modes: a – $S_Z = 0.2$ *mm/cutt*; b – $V = 236$ *m/min*; $t = 1.5$ *mm*, $B = 150$ *mm*.



a) b)

1 – T5K10; 2 – TiN; 3 – TiCN-TiN; 4 – TiCN-Al_2O_3-TiN

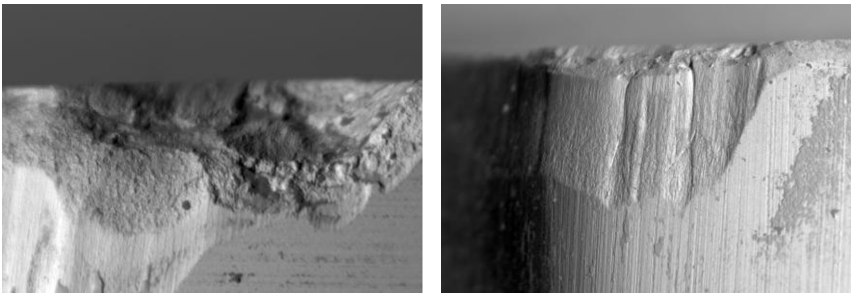
Fig. 3 – **Influence of cutting speed *V* (*a*) and feed S_Z (*b*) on the period of working capacity of cutting plates made of hard alloy with wear-resistant coating during socket milling of workpieces made of steel 12X13**

The obtained results of the study showed a high efficiency of the effect on the wear and resistance of milling cutters of various coating materials and their combinations based on titanium nitride and carbide. Wear-resistant coatings significantly reduce the adhesive interaction of the processed steel with the contact surfaces of the cutting teeth in almost the entire range of cutting modes. Friction, cutting forces and sticking of the processed material are reduced, as well as the heat generated at the same time. The effectiveness of the coatings differed significantly both in magnitude and in the nature of the interaction of the contacting pair.

It was found that the cutting temperature of socket mills T5K10 with nitridotitane coating is 11÷18% lower compared to mills without coatings. The low thermal conductivity of titanium nitride changes the nature of heat removal from the cutting zone, prevents heat removal into the tool and contributes to an increase in heat removal into the chips.

Durability of the tool takes the highest values at low cutting speeds, and the lowest – at high speeds. The effect of the coating is especially manifesting in the initial period of operation, when tool wear increases. When finishing, the effectiveness of influence of the coating on the wear intensity is 1.5÷2.5 times higher compared to the black treatment.

Fig. 4 shows the wear topography of the main rear surface of a pentahedral carbide cutting plate made of T5K10 hard alloy without hardening and with TiN coating when milling 20X13 chrome steel for cutting mode parameters: $V =$ 148.4 *м/мин*, $t = 1.5$ *mm*, $V = 0.15$ *mm/cutt*. Milling width $B = 150$ *mm* and period of work $\tau = 60$ *min*.



a) b)

Fig. 4 – **The nature of brittle fracture and wear of the contact pad of the main back surface of the T15K6 hard alloy cutting plate: a) wear and chipping of the uncoated surface; b) wear of the coated surface**

In the given Fig. 4,a visible formed on the cutting edge of the ledge and wear on the main back surface of the uncoated cutting tooth. The ledge is formed in the zone of brittle fracture during the movement of the swarf and reaches its maximum size in the initial period of cutting. The brittle destruction of the cutting edge occurs in the form of chips from the side of the main back surface. In this zone, there is a transition from the elastic-stressed area of the incisor to the unloaded one. Therefore, there are tensile stresses that lead to brittle destruction. The destruction under intermittent cutting conditions begins with the formation of longitudinal cracks on the front surface of the tool, perpendicular to the main cutting edge, which grow towards the rear surface. The process of wear of the front surface of the teeth of the cutters is accompanied by the formation of the pit. The characteristic signs of intensive adhesive interaction of the chip material with the surface of the milling cutter tooth are observed in the form of a wear field along the main back surface. Further wear occurs in the form of mechanical abrasion along the main back surface up to the accepted blunting criterion.

Fig. 4,b shows the wear topography of the rear tooth surface of TiN coated milling cutter. The coating reduces the rate of the pits formation and the intensity of the wear, both the front and the main back surface. There is practically no chipping formation due to the hardening of the front surface.

Due to high specific loads, temperature and significant plastic deformations in the cutting zone at the contact pads of the tool and the workpiece, the processed material passes into a plastic state, filling the volume of the ledge, pits, cracks, grooves. As a result, a modified cutting wedge is formed and the wear process takes the form of abrasive-mechanical wear.

Further wear occurs in the form of mechanical abrasion on the main rear surface. A layer of steel of the workpiece, smeared on the main back surface of the tool, protects it from wear.

Thus, the hardening of the cutting teeth of milling cutters with nitrido- and carbidotitane coatings TiN, TiC, TiCN allows to significantly reduce the intensity of their wear and chipping, avoid brittle destruction of the cutting edges and increase the resistance of the tool depending on cutting modes. At the same time, cutting forces are also reduced by 10÷20%, and the heat generated by 50÷90°*C* due to a change in the nature of contact processes, a decrease in friction and plastic deformation of the metal being slice. The use of multilayer coatings allows several times to increase the wear resistance of the tool and the productivity of the processing compared to single-layer.

Conclusions. The use of composite coating significantly increases the operability and productivity of carbide socket mills, enlarges tool resistance by 2.3÷2.9 times, which makes it possible to expand the field of their application when milling hard-to-process structural steels and cast iron.

It is revealed that the application of a hardening surface layer on the working surfaces of the tool leads to a significant change in the nature of contact processes, a decrease in the intensity of wear and the impact of shock loads on the cutting teeth of mill, an increase in their resistance to brittle fracture under intermittent cutting conditions.

REFERENCES

1. ***Buckley D.*** Surface phenomena during adhesion and friction interaction. Moscow: Mashinostroenie, 1986. 360 p. (in Russian).

2. ***Ducros C.***, *Benevent V.*, *Savchette F.* Deposition, characterization and machining performance of multilayer PVD coatings on cemented carbide cutting tools. Surface and Coatings Technology. 2003. Vol. 163–164. P. 681–88.

3. ***Gleiter H.*** Nanostructured materials: basic concepts and microstructure // Acta mater. 2000. Vol. 48. P. 1–29.

4. ***Grigor'ev S. N.*** Methods of increasing the durability of cutting tools. Moscow: Mashinostroenie, 2009. 368 p. (in Russian).

5. ***Hawking M.***, *Vasantasri V.*, *Sidki P*. Metal and ceramic coatings: Production, properties and application. Moscow: Mir, 2000. 518 p. (in Russian).

6. ***Kairov A. S.***, *Lymar A. A.*, *Oshovsky V. Ya*. Influence of carbidotitane coatings on wear resistance of high-speed steel end mills // Problems of computational mechanics and strength of structures: Col. of sci. art. Dnipro: Lira, 2021. Vol. 33. P. 76–85.
7. ***Loladze T. N***. Strength and wear resistance of the cutting tool. Moscow: Mashinostroenie, 1982. 320 p. (in Russian).
8. ***Morozov E. M.***, *Zerin M. V*. Contact problems of fracture mechanics. Moscow: Mashinostroenie, 1999. 554 p. (in Russian).
9. ***Ostaf'ev V. A.*** Calculation of the dynamic strength of the cutting tool. Moscow: Mashinostroenie, 1979. 168 p. (in Russian).
10. ***Okumiya M.***, *Gripentrog M*. Mechanical properties and tribological behavior of TiN-CrAlN and CrN-CrAlN multilayer coatings // Surface and Coating Technologies. 1999. Vol. 112. P. 123–128.
11. ***Tabakov V. P.*** Formation of wear-resistant ion-plasma coatings of cutting tools. Moscow: Mashinostroenie, 2008. 311 p. (in Russian).
12. ***Talantov N. V.*** The physical basis of the cutting process, wear and destruction of the cutting tool. Moscow: Mashinostroenie, 1992. 240 p. (in Russian).
13. ***Umanskyi Ya. S.***, *Skakov Yu. A.*, *Ivanov A. I*. Crystallography, radiography and electron microscopy. Moscow: Metalurgia, 1982. 632 p. (in Russian).
14. ***Vereshchaka A. S.***, *Tabakov V. P.*, *Vakhmintsev V. P*. Carbide tools with titanium nitride coatings. Moscow: Machines and tools. 2003. 394 p. (in Russian).
15. ***Woodrof D.***, *Delgar T*. Modern methods of surface research. Moscow: Mir, 1989. 564 p. (in Russian).

УДК 621.9:539.3

О. С. Каіров, д-р техн. наук,
ORCID ID: 0000-0003-3051-9690

В. Я. Ошовський, канд. техн. наук,
ORCID ID: 0000-0002-8065-907X

В. О. Каіров, канд. техн. наук
ORCID ID: 0000-0003-0502-7942

ДОСЛІДЖЕННЯ ВПЛИВУ НАНОПОКРИТТІВ НА ЗНОСОСТІЙКІСТЬ ТОРЦЕВИХ ТВЕРДОСПЛАВНИХ ФРЕЗ

Наведено результати досліджень зносостійкості торцевих фрез з твердих сплавів при обробці важкооброблюваних конструкційних хромистих сталей. Розглянуто технологію зміцнення ріжучих зубів зносостійким покриттям, отриманим методом фізичного осадження парів. Показано вплив структури зміцнюючого композитного покриття на основі нітридів та карбонітридів титану на механічні характеристики та працездатність інструменту. Досліджено характер зносу і крихкого руйнування робочих поверхонь інструменту в умовах переривчастого різання і вплив зносостійких покриттів на тепловий і напружений стан ріжучого клина в зоні контакту.

Ключові слова: *твердосплавний ріжучий інструмент; торцеві фрези; фрезерування; режими різання; нанопокриття; карбонітриди титану; зносостійкість; міцність; твердість матеріалу; контактні напруження; працездатність*.

Ефективність механічної обробки важкооброблюваних конструкційних легованих сталей з підвищеним вмістом хрому в значній мірі залежить від зносостійкості ріжучого інструменту, яка істотно впливає на підвищення його працездатності. Найбільш гостро проблема інтенсивного зношування і крихкого руйнування у вигляді відколів і викришування ріжучих крайок проявляється у торцевих фрез з твердосплавного матеріалу, що працюють на високих швидкостях в умовах переривчастого різання, ударних навантажень, високих контактних напружень і температур [1, 6–9, 12].

Одним з ефективних способів вирішення даної проблеми є нанесення зносостійких композитних покриттів на робочі поверхні ріжучого інструменту з використанням нанотехнологій. Це дозволяє істотно підвищити працездатність, втомну міцність, корозійну стійкість інструменту і інтенсифікувати режими різання за рахунок модифікації фізико-механічних властивостей ріжучих зубів, їх поверхневого і об'ємного зміцнення [2–5, 7, 11, 14].

Найчастіше використовують композитні покриття на основі сполучень тугоплавких металів (карбіди, нітриди, бориди, оксиди та їх сполуки). Технології нанесення багатошарових покриттів наведені в [4–7, 11, 14].

У даний час фізична природа зношування при різанні важкооброблюваних матеріалів вивчена недостатньо внаслідок виняткової складності контактних процесів на передній і головній задній робочих поверхнях інструменту, а також ріжучих крайках леза. Тому дане дослідження є актуальним.

Метою даної роботи є дослідження впливу зміцнюючого композитного покриття робочих поверхонь на підвищення зносостійкості ріжучих зубів торцевих фрез з твердих сплавів в умовах переривчастого різання при обробці важкооброблюваних хромистих конструкційних сталей.

Особливістю процесу фрезерування хромистих сталей торцевими фрезами в умовах переривчастого різання є ударний вплив при вході і виході ріжучих зубів при контакті з заготівлею. Напруження стиснення трансформуються в розтягувальні. Це обумовлює циклічний характер термомеханічного навантаження і призводить до різкого підвищення зносу і крихкого руйнування інструменту у вигляді утворення мікротріщин і відколів.

Для збільшення надійності роботи і довговічності змінних багатогранних ріжучих пластин застосовуються багатошарові покриття, які дозволяють істотно підвищити зносостійкість інструменту і продуктивність обробки в порівнянні з одношаровими. Кожен шар такого композиційного покриття має власне функціональне призначення.

Застосування композитного покриття істотно підвищує працездатність і продуктивність твердосплавних торцевих фрез, збільшує стійкість інструменту в ~2,3–2,9 разів, що дозволяє розширити область їх застосування при фрезеруванні важкооброблюваних конструкційних сталей і чавуну.

Виявлено, що нанесення зміцнювального поверхневого шару на робочі поверхні інструменту призводить до істотного зміни характеру контактних процесів, зниження інтенсивності зносу і впливу ударних навантажень на ріжучі зуби фрез, підвищення їх стійкості до крихкого руйнування в умовах переривчастого різання.

БІБЛІОГРАФІЧНІ ПОСИЛАННЯ

1. ***Бакли Д.*** Поверхностные явления при адгезии и фрикционном взаимодействии. М.: Машиностроение, 1986. 360 с.
2. ***Ducros C.****, Benevent V., Savchette F.* Deposition, characterization and machining performance of multilayer PVD coatings on cemented carbide cutting tools // Surface and Coatings Technology. 2003. Vol. 163–164. P. 681–688.
3. ***Gleiter H.*** Nanostructured materials: basic concepts and microstructure // Acta mater. 2000. Vol. 48. P. 1–29.
4. ***Григорьев С. Н.*** Методы повышения стойкости режущего инструмента. М.: Машиностроение, 2009. 368 с.
5. ***Хокинг М***., *Васантасри В*., *Сидки П*. Металлические и керамические покрытия: Получение, свойства и применение. Пер. с англ. М.: Мир, 2000. 518 с.
6. ***Каіров О. С.****, Лимар О. О., Ошовський В. Я*. Вплив карбідотитанових покриттів на зносостійкість торцевих фрез зі швидкорізальної сталі // Проблеми обчислювальної механіки і міцності конструкцій: зб. наук. праць. 2021. Вип. 33. С. 76–85.
7. ***Лоладзе Т. Н***. Прочность и износостойкость режущего инструмента. М.: Машиностроение, 1982. 320 с.
8. ***Морозов Е. М.****, Зерин М. В.* Контактные задачи механики разрушения. М.: Машиностроение, 1999. 554 с.
9. ***Остафьев В. А.*** Расчет динамической прочности режущего инструмента. М.: Машиностроение, 1979. 168 с.
10. ***Okumiya M.***, *Gripentrog M.* Mechanical properties and tribological behavior of TiN-CrAlN and CrN-CrAlN multilayer coatings // Surface and Coating Technologies. 1999, Vol. 112. P. 123–128.
11. ***Табаков В. П.*** Формирование износостойких ионно-плазменных покрытий режущего инструмента. М.: Машиностроение, 2008. 311 с.
12. ***Талантов Н. В.*** Физические основы процесса резания, изнашивания и разрушения режущего инструмента. М.: Машиностроение, 1992. 240 с.
13. ***Уманский Я. С.***, *Скаков Ю. А*., *Иванов А. И*. Кристаллография, рентгенография и электронная микроскопия. М.: Металлургия, 1982. 632 с.
14. ***Верещака А. С.***, *Табаков В. П.*, *Вахминцев В. П.* Твердосплавные инструменты с нитридтитановыми покрытиями. М: Станки и инструменты. 2003. 394 с.
15. ***Вудроф Д***., *Делгар Т*. Современные методы исследования поверхности: Пер. с англ. М.: Мир, 1989. 564 с.

Admiral Makarov
National University of Shipbuilding,
Mykolaiv, Ukraine

Надійшла до редколегії 07.11.2022