DOI: https://doi.org/10.26642/ten-2025-2(96)-38-45
UDC 620.1:621.951:664.02

V.I. Osypenko, Doctor of Technical Sciences, Prof.
L.D. Mysnyk, PhD in Engineering, Assoc. Prof.
N.V. Filimonova, PhD in Engineering, Assoc. Prof.
M.V. Khandyuk, Senior Lecturer
Cherkasy State Technological University
L.G. Polonsky, Doctor of Technical Sciences, Prof.
Zhytomyr Polytechnic State University

Analysis of the functional parameters of the head design for drilling out onion rhizomes and improving the efficiency and reliability of a spade bit

The paper presents the results of analyzing the functional parameters of the design of a head for drilling out onion rhizomes. On that basis, it is proposed to increase the durability of the drill head by forming a wear-resistant and corrosion-resistant coating based on titanium nitride on its cutting surfaces by plasma spraying. The results of studying the microgeometry of coated and uncoated samples using scanning electron and atomic force microscopy are presented. The parameters of low-energy electron beam treatment were determined, which significantly improved the surface structure of the TiN coating formed by gas-phase deposition. The nature of wear and fracture of coated and uncoated samples during long-term operation when drilling onion rhizomes was determined. The value of the critical load at which the first chips and delamination of the titanium nitride coating appeared was obtained by sclerometric studies. A regression equation was obtained that relates the wear time of the sample to the values of residual microroughness and the number of microdefects on the cutting edge. The equation allowed us to establish that the number of microdefects has a much greater influence on the wear time of the sample than the increase in the values of residual microroughness. In this case, the wear time of the sample depends on the linear dimensions of the residual microdefects on its surface. Experimentally confirmed the increase in the service life of the coated tool up to 2200 hours compared to the uncoated drill up to 800 hours.

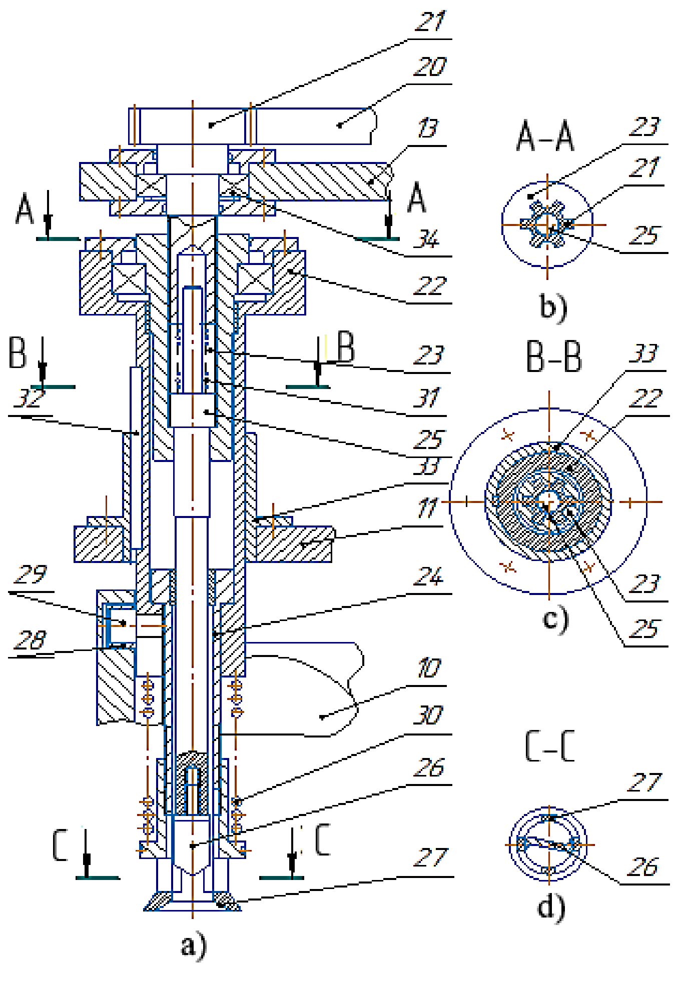
Keywords: *drilling head; spade bit; gas-phase deposition in vacuum; titanium nitride; scanning electron microscopy; atomic force microscopy.*

Problem statement. The food industry includes many different types of production: flour milling, bakery, pasta, confectionery, production of meat, dairy products, sugar, vegetable oil and other products [3, P. 3]. The canning industry is one of the main branches of the food industry, which allows for reducing the time spent on cooking at home, to diversify the diet of public catering, to provide the population with products from raw materials that grow only in a certain period of the year [1, P. 4]. In modern production, the problems of increasing the reliability and durability of machinery and equipment are particularly relevant. The costs of maintaining the performance of various technical facilities and systems are constantly increasing [2, P. 7]. An analysis of equipment repair data in the food and processing industry shows that the main causes of technical facility failures, such as wear and tear, fatigue failure, corrosion, etc., should be carefully studied and eliminated if possible. Loss of product performance due to failures leads to downtime, significant costs for repairs and spare parts [2, P. 7]. A significant factor in resource consumption is wear and corrosion of the working bodies of machinery and equipment. In most cases, the durability of technical facilities is associated with the problem of wear and tear of their individual parts and components. Therefore, increasing the wear resistance of the friction units of machines and protection against corrosion and premature wear of the most vulnerable structural elements of the devices is one of the main directions of increasing the reliability and durability of the industry's equipment [2, P. 7]. Even today, the wear of tools in the processing of various food products is a complex, specific problem [2, P. 9].

Analysis of recent research and publications. It should be noted that S.Maikov, O.Vivcharuk, and I.Romashko considered the issue of promoting healthy eating through the prism of innovation and sustainable economic development of Ukrainian enterprises [4, P. 120–129]. Similar issues in the context of the development of vegetable caviar with increased nutritional value were dealt with by N.Dudenko and V.Olkhovska [5, P. 116–122]. Sokolov A.Y. noted that the working bodies of technological equipment in the food industry should have particularly high wear resistance, because wear products can get into food and make it unsuitable for food and feed purposes [2, P. 10]. One of the first studies of the wear of parts of machinery and equipment in the food and processing industry was conducted by scientists of the NUFT, where the Department of Materials Science and Engineering Technology obtained important scientific results and developed sound recommendations for improving the reliability and durability of these facilities. Professors G.O. Preis and M.A. Sologub were at the origins of the research area. Their work was continued by their students – Professors O.I. Nekoz and Y.G. Suhenko, Associate Professors B.M. Zimko, K.O. Ipatov, O.I. Slynko, I.K. Ipatov, O.I. Bezykornov, V.I. Bilyi, O.E. Novytskyi, O.A. Lytvynenko and others. The issues of corrosion protection in NUFT were dealt with much less. But we should also note the work of V.G. Kryuchek, performed together with the Titanium Institute, aimed at using this corrosion-resistant metal in the food and processing industry, as well as the work of M.I. Krasnopolsky, dedicated to increasing the corrosion resistance of equipment of alcohol plants, V.Y. Suhenko, aimed at researching the corrosion inhibitor protection of equipment in the industry [2, P. 10–11]. Despite such significant developments, the problems of increasing the wear resistance and corrosion resistance of working tools when processing a particular food product remain relevant.

Objective. To analyze the functional parameters of the head for drilling out onion rhizomes, to increase the efficiency of cutting tool operation by forming wear-resistant coatings based on titanium nitride on the cutting surfaces by plasma spraying, followed by studying their microgeometry using scanning electron microscopy (SEM) and atomic force microscopy (AFM). To develop an adequate regression model for assessing the significance of the influence of wear parameters on the service life of a cutting tool.

The main material of the study. A machine has been developed for drilling rhizomes and cutting the stems of onions [6, P. 196–197, 7, P. 62–67]. Figure 1 shows the basic unit of the machine: a drilling head for drilling the rhizome and cutting the onion stem.



10 – copier; 11 – lower disk; 13 – upper disk; 20 – central gear; 21 – gear wheel; 22 – cup; 23 – spline coupling; 24 – rod; 25 – spindle; 26 – spade bit; 27 – holder; 28 – roller; 29 – finger; 30 – spring; 31 – spring; 32 – key; 33 – hub; 34 – bearing

Fig. 1. Drilling head of the machine for drilling onion rhizomes: a) section of the drilling head; b), c) and d) cross sections of the drilling head

The drawings (fig. 1) show that only the spade bit 26 rotates, and the other parts of the head for drilling the rhizome of the bulbs reciprocate due to the presence of a key 32 and a pin 29, which prevent the rotation of the cup 22 and the rod 24. The correct position of the drilling head is ensured by the lower disk 11, the upper disk 13 and the bearings 34 and the hub 33. The drilling is performed by the interaction of the copier 10 and the roller 28, which gradually lowers the cup 22, and the holder 27 contacts the bulb and rises up with the rod 24, compressing the spring 30. Next, the bulb meets the rotating spade bit 26, which receives rotation through the gearing 20, 21 from the central shaft and then through the spline coupling 23 and spindle 25. The threaded connections of the holder 27 and rod 24, as well as the drill 26 and spindle 25, allow the drilling head to be adjusted to any size of bulb within certain limits (for example, to a size difference between 25 mm and 30 mm). Due to the presence of springs 30 and 31, the rhizome drilling process is carried out without damaging the bulbs.

Thus, due to the well-designed kinematics of this drilling head, the cutting tool, the spade bit, is the most worn part. The reliability and durability of a spade bit are largely dependent on the quality of the surface layer of the cutting surfaces. The parameters of this layer determine the operational properties, such as fatigue resistance, wear resistance, corrosion resistance, resistance to contact fatigue, etc. Due to the intensification of operational processes, an increase in the speed of movement of working bodies, an increase in temperature and pressure, the role of the quality of the surface layer is significantly increasing [8, P. 62–65]. In modern conditions, the following design of a spade bit is usually most often offered for drilling onions: body/base made of AISI 304, and the cutting edge is hardened AISI 420.

To increase the service life and reliability of the spade bit, modern methods of studying the microgeometry of the cutting surface parameters by promising methods of scanning electron microscopy (SEM) and atomic force microscopy (AFM) [9, P. 83–87], which are fast, precise, and have nanometer spatial resolution, were used.

The relationship between the characteristics of the quality of the surface layer and the operational properties of parts indicates that the optimal (in terms of improving the operational properties of parts) surface should be hard enough, have compressive residual stresses, a finely dispersed structure, a smoothed shape of micro-irregularities with a large bearing surface area [10, P. 11–13]. Widely used finishing methods (grinding, finishing, etc.) create the required shape of parts with a given accuracy, but often do not ensure the optimal quality of the surface layer.

Considering the above, the objects of study were samples cut on an EDM cutting machine from the cutting edges of a spade bit in the form of disk sectors made of hardened stainless steel AISI 420, 3,5 mm in diameter and 2 mm thick, which were divided into two groups:

- samples without *TiN* coating;
- samples with a layer of *TiN* coating (up to 13 microns).

The coated samples were obtained using the chamber vacuum ion-plasma unit ННВ-6,6 I1 by deposition of *TiN* coating on the substrate (PVD method (Physical Vapor Deposition – application of thin coatings on various parts in a vacuum by condensation of the material vapor to be sprayed on the treated surface), to be sputtered onto the surface to be treated) in the appropriate technological mode (coating deposition rate from 13 μm/h to 40 μm/h, deposition time from 2 min to 20 min, substrate power supply current – 8 A, residual pressure in the vacuum chamber $1{,}5 \times 10^{-3}$ Pa) followed by low-energy electron beam treatment (EBT).

EBT treatment was carried out using a Pierce tape electron gun on a modified vacuum installation УВН-71 in the following modes: electron flux current I_{flux} = 450 mA; voltage accelerator U_{accel} = 6,5 kW; electron beam processing speed V_{mach} = 1,5 kW; electron beam processing time t = 5 ÷ 8 s; residual pressure in the vacuum chamber $t = 5{,}5 \times 10^{-5}$ Pa.

The surface topography and the kinetics of the coating layers development were studied by scanning electron microscopy (JEOL JSM-6700F scanning electron microscope (Japan).

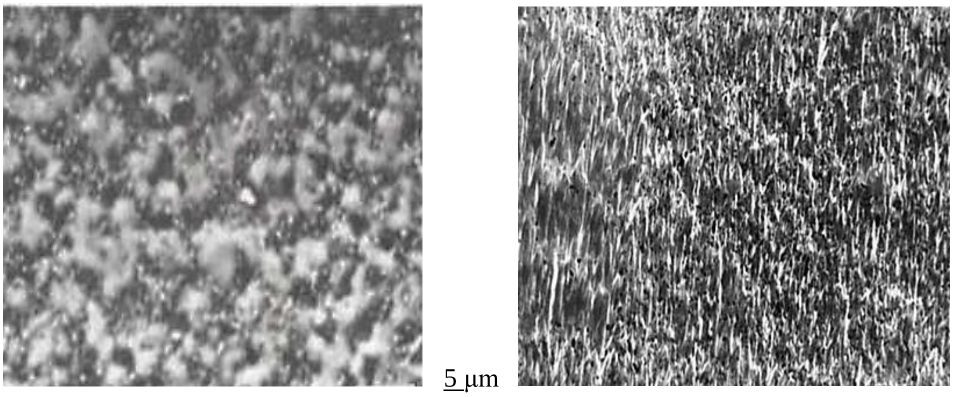
The microgeometry of the surfaces of objects from both groups was studied by scanning AFM on an NT-206V microscope (manufactured by Microtestmashina ALC) using Ultrasharp CSC12 silicon probes (manufactured by Mikromasch, Germany). In order to increase the reliability of the results, the studies were carried out on 9 areas of 13x13 microns on the surface of each sample.

The selection of the required area on the sample surface was carried out by a micropositioning system and a built-in Logitech optical long-focus microscope (manufacturer: Logitech Inc., USA).

The study of the interface between the coating material and the tool base was carried out on a JEOL JSM-6700F scanning electron microscope at the Tokyo-Boechi Cooperative Use Center (Kyiv), and its results allow us to judge the nature of the interaction between the base material and the coating material.

Samples were studied by atomic force microscopy as follows: after ultrasonic cleaning of the sample under study in ethyl alcohol, it was placed on a magnetic slide. The use of a built-in long-focused microscope and a micro-positioning system allows for determining the area of the sample whose surface was studied with an accuracy of ±2,5 μm. The static mode of AFM operation was chosen as the working mode, which has lower accuracy compared to the dynamic mode, but allows you to study the surface of the object itself, ignoring the presence of moisture and residues of organic substances (alcohol, fatty acids, etc.). To increase the accuracy and reproducibility of the study results, measurements were performed on 6 samples from each group. After the measurement process was completed, the AFM measuring head was moved to the next section using the micropositioning system. The measurement results were recorded in the memory of a personal computer, which is part of the diagnostic complex of the atomic force microscope for further visualization, research and analysis.

Figures 2, *a*, *b* show microphotographs of the surface of refractory gas-phase coatings based on titanium nitride before and after low-energy electron beam treatment.



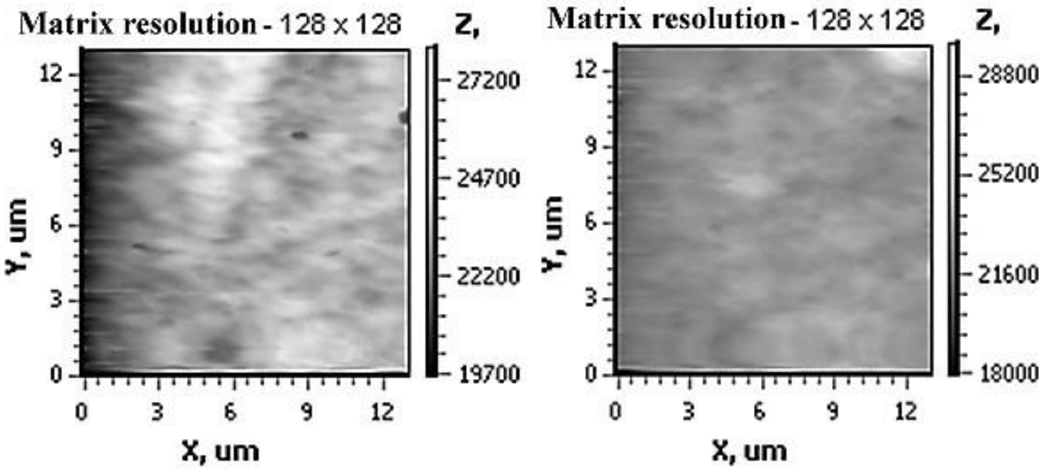
a) *b)*

Fig. 2. SEM images of the surface of TiN gas-phase coating on AISI 420 steel (deposition time 15 min (a) and subsequent EBT for 7 s (b))

As can be seen from figure 2, *a*, as a result of the deposition of gas-phase coatings based on titanium nitride, porous coatings are formed with structural formations of the order of 3 µm to 8 µm. The structure of such coatings, considering the impact load on the tool, does not significantly improve their reliable service life, which ranges from 900 hours to 1020 hours (compared to 800 hours of operation of such an uncoated tool) at a force of 186 N on the spade bit. At the same time, with further electron beam modification of the deposited *TiN* coatings (fig. 2, *b*), a decrease in their porosity is observed, and the crystallites of the formed formations have a needle-like shape with a clearly defined direction of their formation along the direction of the electron flow of the tape form. This electronic action significantly improved the surface structure of the *TiN* coating formed by gas phase deposition. At the same time, increasing the EBT time beyond 10 s leads to significant evaporation of the coating material, which significantly worsens its performance characteristics (micro-irregularities increase from 50÷60 nm to 325÷512 nm, the integrity of the coating is disrupted, and in some places it separates from the base material), while reducing the time to 3 s does not lead to obvious surface structuring.

The adhesion properties of *TiN* coatings after EBT were studied using the sclerometric method (scratching method). As a result of these studies, it was found that the critical load at which the first chips and peeling of the coating appeared ranged from 135 N to 165 N, which significantly exceeds the critical impact load of 10 N/mm^2 that occurs when operating a spade bit of a machine for drilling out the rhizome and cutting the stem of onions. The profiles of the uncoated and *TiN*-coated AISI 420 spade bits obtained by the AFM method using the NT-206V device after EBT indicate high coating continuity even after its long-term operation, which is from 1,35 times to 1,5 times higher than the service life of the uncoated spade bits under the same conditions.

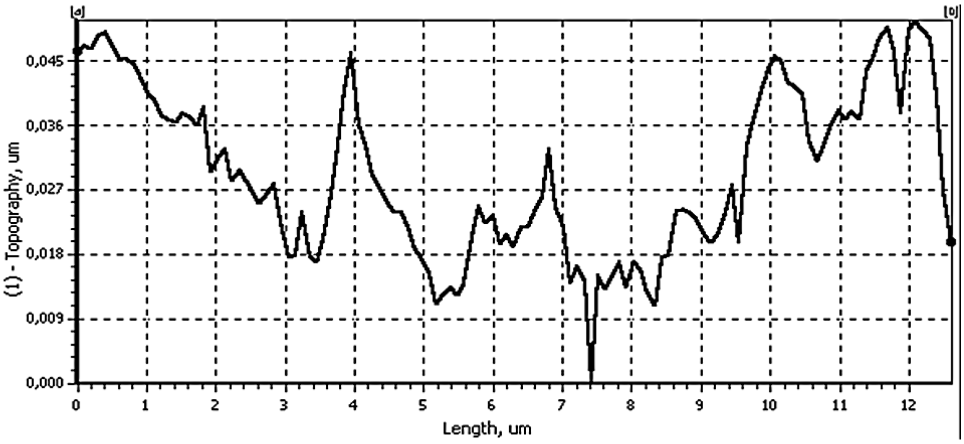
Figure 3 shows the results of the AFM study of the cutting edges of the spade bits without (*a*) and with *TiN* coating (*b*) after EBT, after their operation for 2200 hours at a force of 186 N on the spade bit).



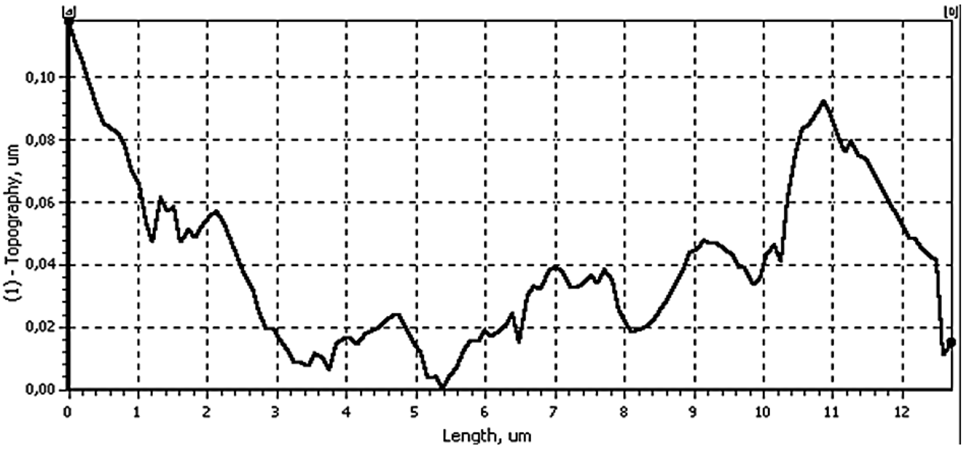
a) *b)*

Fig. 3. Topography of the surface in the laser deflection mode: a) without TiN coating; b) with TiN coating

Figure 4 shows the results of profilograms along the main diagonal on the scanned surface of the cutting edges of the spade bits of samples without (*a*) and with TiN coating (*b*).



a)



b)

Fig. 4. Profilogram along the main diagonal on the scanned surface: a) without TiN coating; b) with TiN coating

The analysis of the results of surface topograms in the laser deflection mode and the profilograms of uncoated samples (fig. 3, *a*, 4, *a*) made it possible to establish that during long-term operation (800 hours), the destruction of working surfaces occurs (increase in micron irregularities from 60 nm to 280÷350 nm, appearance of microcracks, chips and other microdefects), which leads to a sharp decrease in the functional properties and performance of the spade bit in general.

At the same time, no microdefects were observed on the *TiN*-coated samples (fig. 3, *b*, 4, *b*) obtained at the ion-plasma installation HHB-6,6 I1 with subsequent EBT, and micron irregularities during the same operating time increased from 50...60 nm only to 85...130 nm, which are not significant.

Mathematical processing of the experimental results. The analysis of the research data obtained by atomic force microscopy of coated samples was carried out by planning a two-factor experiment [5], where the increase in the values of residual micron irregularities (%) and the number of microdefects on the surface of the sample during its wear at a critical impact load of 10 N/mm^2 were chosen as input variables.

The sample wear time (h) was chosen as a response. Significant coefficients at X_1 and X_2 were obtained using the Statistik software for statistical processing of experiments. The results of the experiment are presented in the form of a regression equation:

$$Y = 1328 - 0{,}71X_1 - 63X_2, \quad (1)$$

where Y – the response, the wear time of the sample (h);

X_1 – the increase in the values of residual microroughness (nm);

X_2 – number of microdefects (nm).

The obtained regression equation allows us to establish that the number of microdefects has a much greater influence on the wear of the sample than the increase in the values of residual micron-irregularities. At the same time, it has been experimentally established that the wear time of a sample depends on the linear dimensions of residual microdefects on the sample surface and their nature (microcracks, porosity, chipping, etc.). For example, microcracks up to 15 microns long have almost no effect on the wear time of the sample and are healed by 96 % during the EBT process, while microcracks from 25 microns to 30 microns long reduce the wear time of the sample by 18 to 20 %.

Comparison of the calculation results from the linearized model with experimental data showed that the relative error ε in determining the time between failures of the working part of the spade bit does not exceed 8 %.

As a result of the studies, it was found that adsorption of active molecules with their thermal decomposition and interaction of active titanium and nitrogen atoms occurs on the surface of the spade bit during the coating process. The formation of a *TiN* nucleus on stainless steel AISI 420 can be represented as follows: defects associated with coating delamination are observed more in intermetallics formed on a chromium matrix with a more complex structure. The titanium phase, which is mainly in a liquid state during the formation of intermetallics, has fewer defects in its structure.

Thus, the number of *TiN* nuclei on the titanium phase should be higher, which would lead to the preferential growth of the coating. However, the peculiarities of the formation of nanostructured titanium nitride coatings on working tools by the combined PVD method with subsequent low-energy electron beam treatment are the adsorption of active molecules of titanium and nitrogen atoms with the base material, namely, the titanium phase.

This is because the formation of *TiN* molecules is followed by the stage of interaction of these molecules with the lattice of the substrate. This process is aimed at reducing the free surface energy and is carried out during the crystallization of titanium nitride with the least distortion in the crystal lattice. As a result of the catalytic action of the base metals, the energy of the molecules at the interface differs from the molecules in the coating volume. Thus, during the coating process, the heated surface of the steel (titanium phase) activates the *TiN* formation process.

Conclusions.

1. The analysis of the functional parameters of the design of the head for drilling out onion rhizomes has shown that, due to well-designed kinematics, the most–worn part of the cutting tool is the spade bit. It is proposed to increase the efficiency of operation of the cutting tool (hardened stainless steel AISI 420) by forming corrosion-resistant and wear-resistant coatings based on titanium nitride on the cutting surfaces by plasma spraying, followed by studying their microgeometry using the methods of scanning electron microscopy (SEM) and atomic force microscopy (AFM).

2. The peculiarities of the formation of nanostructured titanium nitride coatings on cutting surfaces by the combined PVD method followed by low-energy electron beam treatment have been established. The peculiarities of such an action are the adsorption of active molecules of titanium and nitrogen atoms with the base material, which leads to the growth of the coating on the titanium phase due to the interaction of these molecules with the crystal lattice of the base.

3. Analysis of the sample surfaces showed that during prolonged operation (more than 2000 hours), they undergo destruction (an increase in micro-irregularities from 60÷90 nm to 280÷350 nm, the appearance of microcracks, chips, and other microdefects), which leads to a sharp decrease in the functional properties of these coatings and the performance of the tool as a whole. At the same time, on samples with a *TiN* coating obtained by the PVD method followed by EBT, no microdefects were observed, and micro-irregularities during the same period of operation (800 hours) increased from 50÷60 nm to 85÷130 nm, which is not critical for the surface condition.

4. As a result of sclerometric studies, it was found that the critical load at which the first chips and peeling of the titanium nitride coating appeared was 135÷165 N, which significantly exceeds the critical impact load of 10 N/mm^2 when operating a spade bit for cutting the stem and rhizome of onions.

5. The results of the study of the spade bit of the machine for cutting the ends of onions and drilling the core without coating and with *TiN* coating made it possible to increase the service life of the coated tool to 2200 hours (55 working days of operation) compared to the uncoated drill to 800 hours (20 working days of operation) at a force of 186 N on the spade bit.

References:

1. Olabodi, O.V. (2020), «Canning industry: traditions and innovations», *Domestic and world experience*, National University of Food Technology, Scientific and Technical Library, Kyiv, 265 p., [Online], available at: scientific and auxiliary bibliographic index
2. Suhenko, Y.G., Palamarchuk, I.P., Zheplinska, M.M. et al. (2019), «Reliability of food industry equipment», *Study guide*, CP «COMPRINT», Kyiv, 375 p.
3. Boiko, V.S., Samoichuk, K.O., Tarasenko, V.H. and Lomeiko, O.P. (2020), *Protsesy i aparaty kharchovykh vyrobnytstv. Teploobminni protsesy*, pidruchnyk, Melitopol, 300 p.

4. Maikova, S.V., Vivcharuk, O.M. and Romashko, I.S. (2020), «Improvement of national dishes and their adaptation for modern restaurant business establishments», *Bulletin of the Lviv Institute of Economics and Tourism: a collection of scientific articles*, Ministry of Education and Science of Ukraine, Lviv Institute of Economics and Tourism, LIET, Lviv, No. 15, pp. 20–129.
5. «Mathematical modeling of canned vegetables with specified consumer properties» (2013), *Bulletin of NTU «KhPI»*. Series. *New solutions in modern technologies*, No. 1 (977), pp. 116–122.
6. Khandyuk, M.V. (2015), «Improvement of the machine for cutting the ends of onions», *Innovative aspects of the development of equipment for the food and hotel industry in modern conditions*, International Scientific and Practical Conference (Kharkiv – Melitopol – Kyrylivka), September 8–11, KHDUHT, Kharkiv, No. 4, pp. 196–197.
7. Khandyuk, M.V. (2015), «New design of the machine for cutting the ends of onions», *Collection of scientific works of Vinnytsia National Agrarian University*. Series. *Technical sciences*, Issue 1 (89), Vol. 1, pp. 62–67.
8. Zhou, Y., Wu, Y., Wang, Y. and Liu, Y. (2023), «Recent advances and strategies for high-performance coatings», *Progress in Materials Science*, Vol. 136, doi: 10.1016/j.pmatsci.2023.101125.
9. Kucharska, B., Czarniak, P., Kulikowski, K. et al. (2022), «Comparison Study of PVD Coatings: TiN/AlTiN, TiN and TiAlSiN Used in Wood Machining», *Materials*, Vol. 15, Issue 20, doi: 10.3390/ma15207159.
10. Wang, S., Ji, W., Wang, Y. et al. (2022), «Comparative Study of Corrosion Behavior of LPCVD-$Ti_{0.17}Al_{0.83}N$ and PVD-$Ti_{1-x}Al_xN$ Coatings», *Coatings*, Vol. 12, Issue 6, doi: 10.3390/coatings12060835.

Осипенко Василь Іванович – доктор технічних наук, професор, завідувач кафедри проєктування харчових виробництв та верстатів нового покоління Черкаського державного технологічного університету.

https://orcid.org/0000-0002-2166-7766.

Наукові інтереси:

– процеси фізико-технічної обробки матеріалів;
– технології лазерної обробки матеріалів;
– визначення раціональних конструктивно-технологічних параметрів процесів харчових виробництв.

E-mail: v.osypenko@chdtu.edu.ua.

Мисник Людмила Дмитрівна – кандидат технічних наук, доцент, доцент кафедри проєктування харчових виробництв та верстатів нового покоління Черкаського державного технологічного університету.

https://orcid.org/0000-0002-7653-9569.

Наукові інтереси:

– визначення раціональних конструктивно-технологічних параметрів процесів харчових виробництв.

E-mail: l.mysnyk@chdtu.edu.ua.

Філімонова Надія Вікторівна – кандидат технічних наук, доцент, доцент кафедри проєктування харчових виробництв та верстатів нового покоління Черкаського державного технологічного університету.

https://orcid.org/0000-0003-0136-7587.

Наукові інтереси:

– визначення раціональних конструктивно-технологічних параметрів процесів харчових виробництв;
– вивчення та оптимізації процесів переробки м’ясної сировини на м’ясорізальних машинах.

E-mail: n.filimonova@chdtu.edu.ua.

Хандюк Микола Васильович – старший викладач кафедри проєктування харчових виробництв та верстатів нового покоління Черкаського державного технологічного університету.

https://orcid.org/0000-0003-3225-6900.

Наукові інтереси:

– визначення раціональних конструктивно-технологічних параметрів процесів харчових виробництв.

E-mail: nikolay.khandiuk@gmail.com.

Полонський Леонід Григорович – доктор технічних наук, професор Державного університету «Житомирська політехніка».

https://orcid.org/0000-0002-4347-9088.

Наукові інтереси:

– різальний інструмент;
– обробка матеріалів різанням.

E-mail: pol@ztu.edu.ua.

Осипенко В.І., Мисник Л.Д., Філімонова Н.В., Хандюк М.В., Полонський Л.Г.

Аналіз функціональних параметрів конструкції головки для висвердлювання кореневища ріпчастої цибулі та підвищення ефективності і надійності перового свердла

У роботі наведено результати аналізу функціональних параметрів конструкції головки для висвердлювання кореневища ріпчастої цибулі. Запропоновано підвищення довговічності перового свердла шляхом формування на його різальних поверхнях плазмовим напиленням зносостійкого та корозійностійкого покриття на основі нітриду титану. Представлено результати дослідження мікрогеометрії зразків з покриттям та без, здійсненого методами растрової електронної та атомно-силової мікроскопії. Визначено параметри низькоенергетичної електронно-променевої обробки, які дозволили суттєво покращити структуру поверхні, сформованої газофазним осадженням покриття TiN. Встановлено характер зношування та руйнування зразків з покриттям та без у процесі тривалої експлуатації при висвердлюванні кореневища ріпчастої цибулі. Шляхом склерометричних досліджень отримано значення величини критичного навантаження, за якого з'являлися перші відколи і відшаровування покриття з нітриду титану. Отримано рівняння регресії, що пов'язує час зносу зразка зі значеннями залишкових мікронерівностей та кількістю мікродефектів на різальній кромці. Рівняння дозволило встановити, що на час зношування зразка кількість мікродефектів впливає більше, ніж приріст значень залишкових мікронерівностей. При цьому час зношування зразка залежить від лінійних розмірів залишкових мікродефектів на його поверхні. Експериментально підтверджено зростання терміну експлуатації інструменту з покриттям до 2200 год порівняно зі свердлом без покриття до 800 год.

Ключові слова: свердлильна головка; перове свердло; газофазне осадження у вакуумі; нітрид титану; растрова електронна мікроскопія; атомно-силова мікроскопія.

The article was sent to the editorial board on 16.09.2025.