Наносистеми, наноматеріали, нанотехнології
Nanosistemi, Nanomateriali, Nanotehnologii
2021, т. 19, № 3, сс. 547–558

PACS numbers: 62.20.Qp, 68.37.Hk, 79.40.+z, 81.15.Jj, 81.40.Pq, 81.70.-q

Hardening of Thin-Walled Knives by Nanostructured Coating and Their Operating Resistance

T. S. Skoblo[1], S. P. Romaniuk[1], V. M. Romanchenko[1], E. L. Belkin[1],
T. V. Maltsev[2], and R. M. Muratov[3]

[1]*Kharkiv Petro Vasylenko National Technical University of Agriculture,*
44, Alchevskykh Str.,
UA-61002 Kharkiv, Ukraine
[2]*State Enterprise 'Malyshev Plant',*
126, Plekhanivska Str.,
UA-61037 Kharkiv, Ukraine
[3]*National Science Centre 'Kharkiv Institute of Physics and Technology',*
1, Akademichna Str.,
UA-61108 Kharkiv, Ukraine

A new technological process of hardening thin-walled knives with a thickness of 0.64 mm and with a cutting edge of 0.1 mm, which are used in confectionery production, is proposed. For the hardening of them, the ion-plasma method of applying a nanostructured multilayer TiN coating is used. Statistical studies of the operational resistance of such a tool in industrial production when crushing nuts are carried out. The analysis of the obtained results shows that their operational resistance varies within a wide range from 10 to 210 work shifts. At the same time, the surface hardening coating applied with a thickness of 3.3 microns does not completely wear out. The main reasons for the failure of such a tool in operation are low quality of the metal products and processed products, which is caused by pores and cracks, the intensification of diffusion processes, and the formation of zones of heterogeneity in phase-components' distribution. The kinetics of changes in the structure, the degree of its heterogeneity in the working layer during diffusion processes, which occur during operation and are responsible for the formation of defects and structural degradation, are investigated. Experimental and theoretical methods for describing structural changes on the friction surface of knives revealed the nature of the development of their damageability based on the formation of zones with different densities of alternating fragments (compression and vacuum zones).

Запропоновано новий технологічний процес загартовування тонкостінних ножів товщиною у 0,64 мм з різальним пругом у 0,1 мм, що використовуються у кондитерському виробництві. Для загартування їх був використаний йонно-плазмовий метод нанесення наноструктурованого багатошарового покриття TiN. Проведено статистичні дослідження експлуатаційної стійкости такого інструменту у промисловому виробництві для подрібнення горіхів. Аналіза одержаних результатів показала, що їхній експлуатаційний опір коливається в широких межах від 10 до 210 робочих змін. У той же час поверхнево-зміцнювальне покриття, нанесене товщиною у 3,3 мкм, не повністю зношується. Основними причинами виходу з ладу такого інструменту в роботі є низька якість виробів з металу та продуктів оброблення, що викликають пори та тріщини, інтенсифікація процесів дифузії й утворення зон неоднорідности розподілу фазових компонентів. Досліджено кінетику змін структури, ступінь її неоднорідности в робочому шарі під час дифузійних процесів, що відбуваються під час роботи та відповідають за утворення дефектів і деґрадацію структури. Експериментально-теоретичні методи опису структурних змін на поверхні тертя ножів виявили характер розвитку їхньої пошкоджуваности на основі утворення зон з різною щільністю осколків (зони стиснення та вакууму), що чергуються.

Key words: nanostructured coating, thin-walled tool, operational resistance, heterogeneity, diffusion of components, defects.

Ключові слова: наноструктуроване покриття, тонкостінний інструмент, експлуатаційний опір, гетерогенність, дифузія компонентів, дефекти.

(Received 22 October, 2020; in revised form, 26 October, 2020)

1. INTRODUCTION

The main condition for increasing the wear resistance of products is the quality and properties of their working surfaces. If, in the field of traditional industries, there are well-established, well-studied and substantiated methods of hardening such products in various industries, then, with the development of science in mechanical engineering and electronics, new directions with the use of nanotechnology attract special attention.

It is especially difficult and sometimes ineffective to use such technological processes in mechanical engineering, since, for each specific case of operation, there are special requirements, which must provide the necessary technical conditions. In addition, the properties of the metal of the hardened and mating parts or working environment are also important factors. Therefore, to control the processes of applying a hardening coating, we ensured its necessary working capacity by using an integrated approach to identify the features and patterns of structure formation in order to ensure the stable operation of parts.

Studies [1] found that thin-walled knives used in confectionery machines for crushing nuts are characterized by low operation resistance associated with wear and damage of the cutting edge as well as with the destruction of its main part due to violation of flatness, fatigue damage.

Thin-walled knives, most often possibly due to design features, are not subjected to high-temperature hardening treatments.

Considering this, an attempt was made to surface such a tool with nanostructured coatings with a CrN and WC composition. The wear resistance of the hardening knives increased only from 11 to 45 shifts [2, 3], which did not significantly ensure the economic efficiency of such a process due to the high cost of consumables.

At the same time, based on this experience, it was found that nanostructured coatings not only reduce damage, but also prevent fatigue failure as well as the need for its periodic sharpening with an increase in service life. The self-sharpening effect was achieved by hardening the knife on one side.

TiN is a cheaper nanostructured coating that provides the highest hardness; however, the technological process of applying such a composition is accompanied by a higher temperature, which requires the development of hardening parameters for a thin-walled tool that differ from the previously used ones.

The purpose of this work was to develop an effective technological process for applying a nanostructured coating with a TiN composition for hardening thin-walled knives used in confectionery production.

2. OBJECT, MATERIALS, AND RESEARCH METHODS

Thin-walled knives with a diameter of 75 mm and a cutting edge of 3.0 mm, made of cold-rolled sheet steel 65G, corresponding to the thickness of the product, were subjected to hardening.

Tests were performed on a Model CD-A Dicer nut cutter and chopper manufactured by 'Urschel Laboratories, Incorporated'. During operation, 48 knives were used simultaneously.

The coating was applied on 'Bulat-6' type equipment with the special devices developed at the Institute of Plasma Physics, NSC 'KIPT' (Kharkiv). The TiN coating was applied by a vacuum arc method using a high-frequency (HF) discharge. To clean the surface of the instrument with a high-frequency discharge in a vacuum chamber, an argon pressure of $P = 1\cdot10^{-1}$–$9\cdot10^{-2}$ Pa was created. The negative bias on the substrate was $U = -500$ V. The tool was cleaned with an HF discharge for 10 min. An underlayer of pure Ti was applied for 3 min at a pressure of $P = 2\cdot10^{-1}$ Pa, $I_{arc} = 110$ A, $I_{focus} = 0.65$ A and $U = -100$ V. To obtain a TiN nanocoating, the vacuum chamber was also filled with nitrogen of 99.99% purity up to a pressure of $P = 1\cdot10^{-1}$ Pa. The negative bias on the substrate was $U = -100$ V; the parameters of the vacuum arc are as follow: $I_{arc} = 110$ A, $I_{focus} = 0.65$ A. Considering the fact that the temperature of formation of the TiN composition is higher than the previously used CrN and WC coatings by 230–250°C, there was a problem of overheating of both the cutting edge and the main part of the knife, which manifested itself on the unhardened surface with discoloration. In such knives, during operation, the flatness of the main part was violated; the edge of the cutting edge was deformed and bent. Taking this into account, a special method of applying a multilayer coating was developed [4], which provided the required quality of such a technological process. To prevent overheating of the instrument, pauses with multiple time parameters of formation of each layer were used.

The quality of hardened knives and their wear resistance were evaluated in production conditions when crushing nuts at the confectionery factory 'Kharkivchanka'.

The studies were carried out on a statistical sample—50 knives.

A set of techniques and new approaches to assessing the structural variability of coatings during operation were used for research. These are traditional research methods: metallographic optical and electron microscopies, local spectral analysis, and thermionic emission distribution of components, estimations of the magnetic parameter— coercive force.

The developed method using a new approach to assessing the phase distribution includes an optical-mathematical method for describing structural changes, the degree of its heterogeneity [5, 6].

The nature of the damageability of knives, their operating time was assessed on products of various production batches.

3. RESEARCH RESULTS

By analysing the operational resistance of knives in production conditions, it was found that their operating time varied from 10 to 210 shifts.

To assess their structural state and damageability after operation at the first stage, we used a non-destructive magnetic method based on the coercive force and visual assessment of the friction surface, as well as optical microscopy.

In this case, the state of the knives was evaluated by four zones of its base (corresponding to the areas of initiation and development of cracks), which were located equidistant from each other.

Table 1 shows the results of the operational resistance of 50 knives, their operating time, and the nature of failures during visual assessment.

TABLE 1. Indicators of the operational resistance of knives hardened with a nanostructured multilayer tin coating.

Conditional knife number	Resistance indicators, number of shifts	Reasons of failures in the analysed knife number
1–3	10	1—damage
4–7	11	4, 7—damage; 5, 6—cracks
8–16	20	11, 13—cracks; 9, 10, 12, 14–16—damage
17–22	23	20—cracks; 21—loss of flatness; 22—damage
23	27	—
24	30	—
25	33	—
26	34	26—fatigue destruction
27–30	36	28, 30—damage; 29—fatigue destruction
31–33	37	31, 33—damage; 32—cracks
34	38	34—damage
35–37	40	35, 36—cracks; 37—destruction
38	41	—
39	46	—
40	51	—
41–43	55	42—damage
44–49	59	44, 46, 47, 49—cracks
50	210	—

The performed analysis of the friction surface showed a wide spread in the readings of the operational resistance of the knives (from 10 to 210 shifts). The main reasons for failures during visual inspection of such knives are their damageability, fatigue damage (along the ring of the main part), deformation and bending of the cutting edge. Almost all tested knives retained a hardening coating. The exception is a knife that has served 210 shifts, which lacked coating only on the cutting edge. However, no visible defects were found on this instrument, and the colour of the coating remained yellow.

The revealed damageability of knives is largely associated with the quality of the processed products (with increased hardness, the degree of moisture content of nuts, and the presence of abrasive in the raw material—solid inclusions).

During the operation of hardened knives, a violation of flatness was revealed only in one case. Of the entire tested batch, only 10 knives were taken out of operation without damaging the main part (only the blade), and they worked a different number of shifts: 27–33, 41–51, 210 that confirms the main reasons for knives out of operation noted above.

The evaluation of the knives state after operation was carried out in the same zones as the visual analysis, by the magnetic method according to the coercive force H_c, based on the available experience [7]. It was planned to identify degradation zones in the metal, as well as local stresses in the knives after operation. Figure 1 shows the measurement results of tested knives in production.

From the data obtained, it can be seen that the readings of the coercive force on such knives vary over a wide range from 16.9 to 41.8 A/cm. At the same time, in some knives, the difference in readings reached 50%. These are knives No. 4, 7, 9, 10, 12, 14, 28, 33, 34, 42, which have defended the number of shifts in operation: 11, 11, 20, 20, 20, 20, 36, 37, 38, 42, respectively. This information indicates that the most intensive development of local deformation in knives occurred during their operation in two sets that operated for 11 and 20 shifts, which may be the result of low-quality processed products. Single cases of an increase in the coercive force indicated can be the result of the ingress of solid inclusions (pebbles, shells).

The knives, on which, after operation, during visualization, no defects (damageability, local deformations) were detected, differed in closer readings, which, on average, varied from 18.8 to 21.1 A/cm. The difference did not exceed 2.3 A/cm, and the share of such knives was 36%. In the presence of defects, the scatter of readings varied over a wider range from 16.9 to 41.1 A/cm, and the average deviations of the values from these measurements amounted to a significantly larger spread of readings up to 24.4 A/cm.

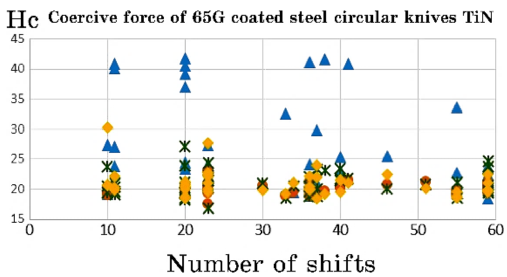


Fig. 1. The results of evaluating the coercive force of thin-walled knives after different operating time (▲, ●, ✳, ◆—measurements in 4 different zones of the knife).

Based on the results obtained, it can be concluded that this characteristic cannot objectively separate the degradation of the structure of knives that occurs during operation, as well as the presence of damage and local deformations in them.

To determine the nature of the destruction and degradation of the metal, an integrated approach was used in investigation, according to the methods of optical and electron microscopies, thermionic emission, and an optical-mathematical description of structural changes on the friction surface.

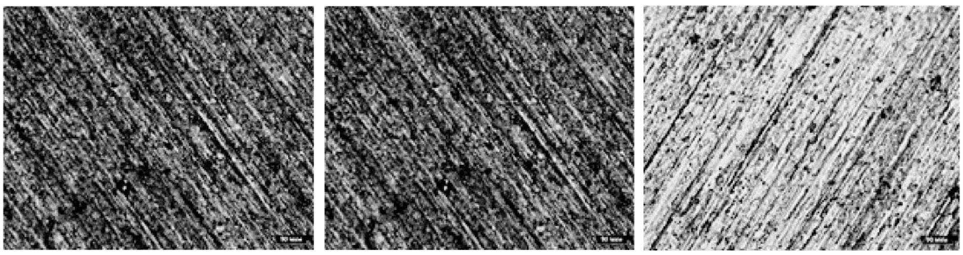
At the first stage, optical photographs were comparatively analysed.

Figure 2 shows the microstructures of the friction surface of knives that have served different service lives: 10, 20, and 210 shifts.

From the comparative analysis, it follows that all the options considered, differing in different knife resistance, are characterized by the structurization of the friction surface, and to a greater extent, it manifests itself in a knife that has worked 10 shifts, and to a lesser extent, 210 shifts, that may be the result of significant wear of the last one. In this case, a large proportion of white zones appear, and in the first, an increased density of dark zones is noted.

In all analysed cases, with additional computer magnification, very small cracks (tears) are visible, which are formed both along and across the friction strips, and they are especially clearly visible on the light stripes. Such damageability is more typical for knives after 10 and 20 shifts of operation, which are characterized by a high level of coercive force index up to 30–40.8 A/cm compared to the rest ones of 16.9–24 A/cm.

Based on this, we can conclude that a significant increase in local stresses in the knives contributes to the formation of microtears and damage.



a *b* *c*

Fig. 2. Microstructure of the friction surface of knives with different operational resistance: *a*—10 shifts; *b*—20 shifts; *c*—210 shifts.

Local changes in structures and the formation of defects on the friction surface were determined comparatively after 10 and 210 operating shifts. In knives with a lower operation resistance, cracks, tears, and pores were revealed (Fig. 3).

Cracks in this case are located along white stripes, and their boundaries with dark ones. At the same time, tears are detected in such zones, which are located both across and parallel to the already formed cracks. At the same time, pores and transverse cracks are oxidized to a greater extent. The proportion of oxygen in them reaches 11.37–31.22% (Table 2). In the damaged areas, there is an increased concentration of carbon, which diffuses from the base metal of the knife, and the appearance of a number of components in small amounts is determined by the deposition of processed raw materials.

The pores contain different proportions of titanium and nitrogen that indicates that they belong to the droplet phase of the hardening coating. Previous studies have shown that, along the boundary

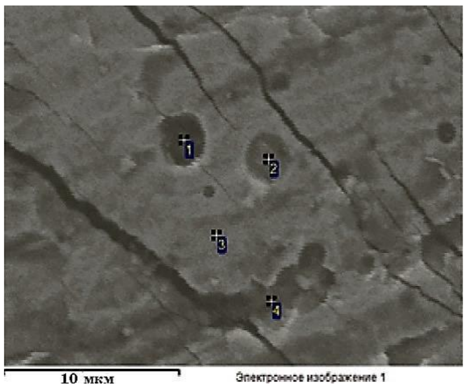


Fig. 3. Defects on the hardened friction surface of the knife after 10 shifts operation.

TABLE 2. Micro-x-ray spectral analysis of the working surface of the hardened knife after 10 shifts of operation (measurement zones see in Fig. 3).

Spectrum	C	N	O	Al	Si	Ca	Ti	Fe	Result
1	16.64	5.16	31.22	0.17	0.28	3.50	41.96	1.07	100.00
2	8.85	24.84	11.14				54.11	1.06	100.00
3	4.85	31.85					62.40	0.90	100.00
4	11.33	16.55	11.37		0.19		60.56		100.00

of the droplet phase containing titanium, it is saturated with nitrogen in the form of a TiN film covering it, which, under local deformations under friction conditions, partially (along the boundaries) destroys and increases the accumulation of oxygen, carbon, and other components in such pores.

Because such a droplet phase is destroyed to varying degrees, the concentration of components in these zones can vary significantly.

Thermionic emission confirmed the diffusion of carbon from the substrate and revealed its increased concentration in the transition zone of the coating—base metal and in defects (Fig. 4).

Significant heterogeneity of nitrogen is revealed. Its minimum proportion is found in defects—cracks, pores, and in a number of droplets.

In the knife, which was operated for 210 shifts, the above defects were not revealed, however, the zones of stretching (energy release) and the droplet phase, which do not contain nitrogen and are characterized by a reduced proportion of titanium in the pores and at the same time are significantly saturated with carbon, are more clearly manifested, which may indicate their varying degrees of heterogeneity prior to destruction. According to the revealed intense diffusion of carbon, the degree of inhomogeneous distribution of components—nitrogen and titanium (Fig. 5) can be judged about not only the degree of degradation of the working surface, but also about its significant wear.

To determine the degree of inhomogeneity of the phases' distribution on the friction surface, an optical-mathematical method was used to describe them. As it was established by preliminary studies, the most reliable information on the degree of phase inhomogeneity during operation is provided by an analysis of 20 or 25 pixels. Therefore, digitization was carried out at 25 pixels. All images in electron-microscopic photographs of the structure were divided into 19 intervals in both vertical and horizontal directions, and each of them from 1/19 to 19/19 characterized the variability of the degree of the formed inhomogeneity from the maximum to the minimum.

The knife, which was taken out of operation after 10 shifts of use, differed in maximum intervals of inhomogeneity from 2/19 to 12/19, which is associated with the intensive structurization of the friction surface, with a clear identification of compression and stretching bands formed during friction. In the intervals 13/19–19/19, the structurization is insignificant and differs in a more uniform distribution of phases (Fig. 6).

An analysis of the degree of the knife heterogeneity after 210 operating shifts shows that it is significantly higher in the intervals 2/19–7/19, and, in the rest, it is manifested to a lesser extent, which can be explained by a more significant wear of the hardened

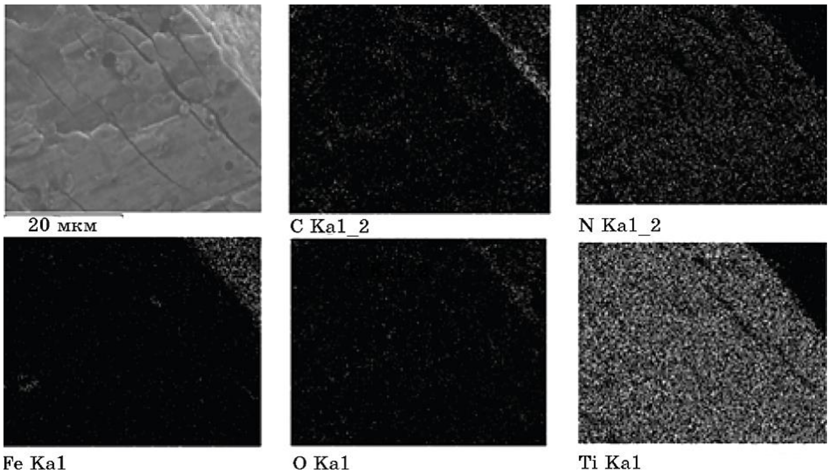


Fig. 4. Distribution of components on the working surface of the hardened knife after 10 operating shifts. Thermionic emission.

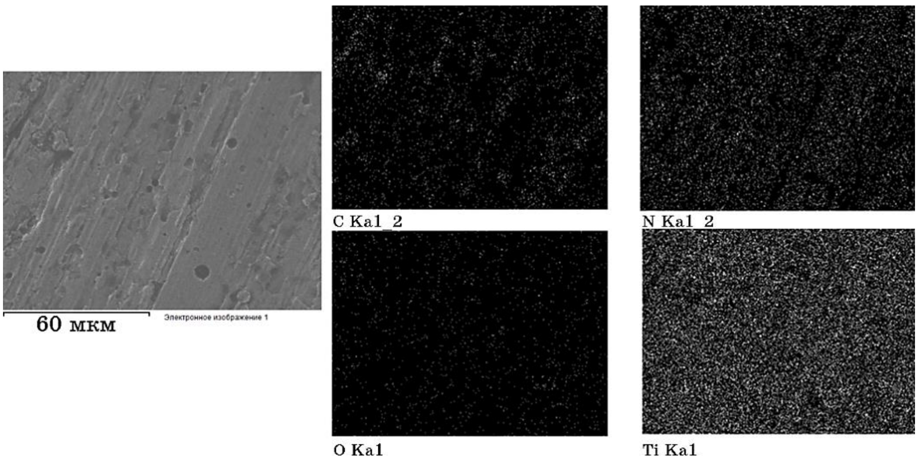


Fig. 5. Distribution of components on the working surface of the hardened knife after 210 operating shifts. Thermionic emission.

working surface (Fig. 7).

4. CONCLUSIONS

As a result of the performed complex analysis, the possibility of using a nanostructured coating on thin-walled knives with a TiN composition has been shown. It is shown that such a hardening coating applied on one side can increase the tool life up to 210 times. It has

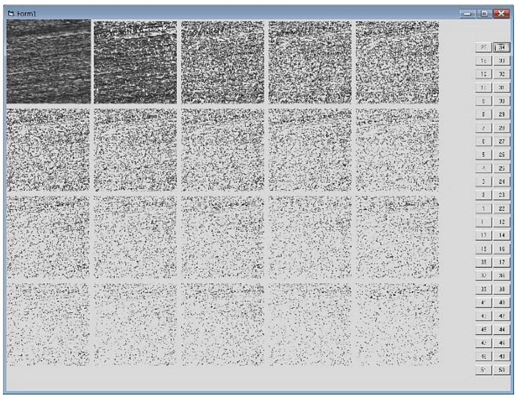


Fig. 6. Inhomogeneity of the phase distribution on the working surface of the hardened knife after 10 operating shifts. The first photo on the left is the original photo, and then, along the first, second, third and fourth frames, in the same order, the analysed intervals are shown according to the heterogeneity of the phase distribution from 1/19 to 19/19.

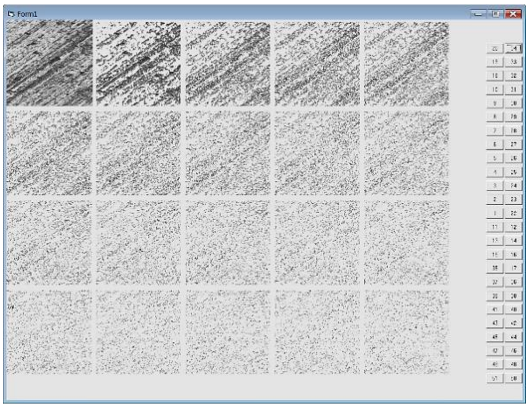


Fig. 7. Inhomogeneity of phase distribution on the working surface of the hardened knife after 210 operating shifts.

been established that the hardening of knives with the application of a multilayer TiN coating using a special technology by the ion-plasma method provides a self-sharpening effect, is economically feasible, and prevents the destruction of the tool and its entry into the processed product.

On the basis of complex studies using methods of non-destructive quality control, optical and electron microscopies, the method of local spectral analysis, thermionic emission, and an optical-mathematical description of structural changes (degree of phase inhomogeneity) during friction, the nature and causes of damage have been revealed that will allow them to be taken into account in production. The research was carried out on 50 knives, which have been used in production conditions.

REFERENCES

1. T. S. Skoblo and S. P. Romaniuk, *Khranenie i Pererabotka Selkhozsyr'ya*, Iss. 7: 46 (2013) (in Russian).
2. T. S. Skoblo, A. I. Sidashenko, and S. P. Romaniuk, *Konstruyuvannya, Vyrobnytstvo ta Ehkspluatatsiya Silskogospodarskykh Mashyn*, **45**, No. 1: 96 (2015) (in Russian).
3. T. S. Skoblo, A. I. Sidashenko, S. P. Romaniuk, and R. M. Muratov, *Metaloznavstvo ta Termichna Obrobka Metaliv*, **3**, No. 70: 44 (2015) (in Russian).
4. S. P. Romaniuk, O. I. Sidashenko, T. S. Skoblo, Yu. M. Nezovybatko, I. Ie. Harkusha, and V. S. Taran, *Sposib Pidvyshchennya Ehkspluatatsiynoyi Stiykosti Tonkostinnogo Rizhuchogo Instrumentu* [The Method of Increasing the Operational Stability of Thin-Walled Cutting Tools] (Patent 101699 UA. C23C 14/48, C23C 14/16) (Korysna Model', 18) (2015) (in Ukrainian).
5. S. P. Romaniuk, *Problemy Mashinobuduvannia* [Journal of Mechanical Engineering], **22**, No. 4: 67 (2019); https://doi.org/10.15407/pmach2019.04.067
6. T. Skoblo, O. Klochko, E. Belkin, and A. Sidashenko, *International Journal of Mineral Processing and Extractive Metallurgy*, **2**, Iss. 3: 34 (2017); DOI: 10.11648/j.ijmpem.20170203.12
7. T. S. Skoblo, S. P. Romaniuk, A. I. Sidashenko, I. E. Garkusha, V. S. Taran, A. V. Taran, and N. N. Pilgui, *Journal of Advanced Microscopy Research*, **13**, No. 3: 333 (2018); https://doi.org/10.1166/jamr.2018.1399