DEVELOPMENT OF COMPLEX TECHNOLOGY OF STRENGTHENING OF THIN-WALLED CUTTING TOOLS

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The complex technology to strengthen thin-walled cutting tools by coating for a long, stable operation of disk knives has been proposed. The cutting tools for crushing nuts used in the confectionery industry made of cold-rolled steel sheet of 65 G and X20Cr13 types were used for coatings application. Two methods of cleaning and strengthening of such tools were proposed and investigated: ion bombardment with titanium ions (PVD) and vacuum-arc method using RF-discharge (RF). The structure and chemical composition of knifes with TiN coating were investigated using scanning electron microscopy and X-ray microanalysis. A new way to strengthen thin disk knives with TiN nanocoating was patented in Ukraine.

PACS: 81.40.-z

INTRODUCTION

Crushers, mills and cutting machines are currently used in processing raw materials in the food industry. Their specific use depends on the process purpose, material properties, the type and the shape of raw materials and the cutting device operating principle. In the confectionery industry one type of tools for mechanical processing of food products is an edge cutting tool. Its operational stability is insufficient; it is no more than 1-2 days (processing to 1.8 t nuts).

The operational stability of a cutting tool can be increased by using specific types of processing, providing durability, fatigue strength, corrosion resistance of parts depending on material and operating conditions. One of promising strengthening methods is the vacuum ion-plasma coating technology [1-4]. In manufacturing process the most widely-spread ion-plasma sedimentation methods are as follows: magnetron sputtering [5]; vacuum-arc [6]. Each of these sedimentation methods has its characteristics determined by natural processes and specific technological parameters.

Ion bombardment allows to obtain surface layers with nanocrystalline structure, characterized by high hardness, strength, durability and others characteristics [7]. Except coating sediments, which have improved characteristics, ion bombardment is used to clean and activate the surface to be coated. Devices as "Bulat" and other various modifications based on them are used for coating products by the vacuum ion-plasma method [8].

The process of coating on the surface of a cutting tool is defined by coating material properties and operating conditions of the instrument as well as specific processes of hardened layer formation. Coating characteristics depend on the method of their application to the work surface, whereas operational stability depends on its thickness and quality.

In the paper, the cutting tools for crushing nuts have been coated by TiN on Bulat-6 type device by means of ion-bombardment of Ti target as well as RF discharge. The structure and chemical composition of the obtained samples were investigated.

1. MATERIALS AND EXPERIMENT

The disk knives were initially subjected to grinding, polishing and ultrasonic pretreatment (within 5 min.) to clean the surface of the disk knives from contamination after their production and activation of the surface in creating optimal conditions for coating adhesion with a cutting tool.

The cutting tools for crushing nuts in the confectionery industry made of cold-rolled steel sheet 65 G (domestic production) and X20Cr13 have been used for coatings application. The blade diameter was 76 mm with 32 mm aperture and 0.64 mm thickness. X20Cr13 steel knives differ structurally. They have thickened rim (along the tool perimeter of the cutting blade) with thickness of 0.9 mm.

TiN coatings are obtained in the "Bulat-6"-type device with production of special tools developed at Institute of Plasma Physics of National Science Center, Kharkov Institute of Physics and Technology [9].

Two methods of cleaning and strengthening of the cutting tool were proposed and investigated: using ion bombardment ions titanium (PVD) end using RF discharge (RF). Strengthening was performed to ensure sharpening effect in operation, on the one hand.

In the first method, TiN coating was obtained by the vacuum-arc method using ion bombardment titanium (PVD). To clean the tool surface in a vacuum chamber it was created pressure no less than $P = 5.3\times10^{-3}$Pa. The negative shift on the substrate was $U_{shift} = -1000$ V, titanium cathode arc current was $I_d = 100$ A, $I_{fok} = 0.3$ A. Cleaning was performed pulsed to avoid overheating of the instrument. For better adhesion of TiN coating with a cutting tool we applied the pure sublayer of Ti (for 1.5 min.) at a pressure of $P = 4\times10^{-3}$ Pa, $I_d = 100$ A, $I_{fok} = 0.3$ A and $U_{shift} = -200$ V. To get TiN nanocoating the vacuum chamber was filled with nitrogen at purity 99.99 % up to pressure P = 4×10^{-1} Pa. TiN nanocoating deposition time was 24 min under the cyclic mode of sedimentation (3 min deposition and 3 min pause). The thickness of the TiN coating was 4 microns.

In the second method, TiN coating was obtained by the vacuum-arc method using RF discharge. To clean the tool surface of RF-discharge in a vacuum chamber it was established argon pressure P = 0.1…0.09 Pa. The negative shift on the substrate was U_{shift} = - 500 V. Tool cleaning with RF-discharge was performed within 10 minutes. Pure Ti underlayer was applied within 3 minutes at a pressure of P = 2×10^{-1} Pa, I_d = 110 A, $I_{fok}U_{shift}$= 0.65 and = - 100 V. To get TiN nanocoating the vacuum chamber was also filled with nitrogen at purity 99.99 % to pressure P = 1×10^{-1} Pa. The negative shift on the substrate was U_{shift} = - 100 V, and vacuum arc parameters: I_d = 110 A, I_{fok}= 0.65 A. Total time TiN coating deposition was 15 minutes at the cyclic mode of sedimentation (5 min deposition with 3 min pauses (cycle 3)). The deposited TiN coating thickness was measured by an interference microscope MYY-4-0 and it comprised 3.3 µm.

2. RESULTS AND DISCUSSION

The exterior surface of the disk knives coated with TiN after PVD is presented in Fig. 1.

Fig. 1. Hardened disk blade surface made from steel X20Cr13 with TiN coating (4 µm)

The exterior surface of the disk knives coated with TiN coating obtained by the vacuum-arc method using RF discharge is presented in Fig. 2.

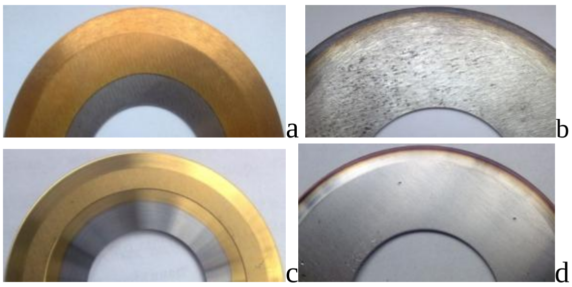


Fig. 2. The design of new reinforced knives from steel 65 G (a) and X20Cr13 (c) coated with TiN 3.3 µm with RF treatment; reverse, not hardened side knife from steel 65G (b) and X20Cr13 (d)

A new way to strengthen thin disk knives with TiN nanocoating was patented in Ukraine [10].

The study of structure and chemical composition heterogeneity of a knife coated with TiN was done in scanning electron microscope JEOL JSM-6390LV. With thermionic emission it was investigated homogeneous distribution of components and composition of the cutting tool surface layer hardened with coating TiN PVD (Fig. 3) and RF (Fig. 4).

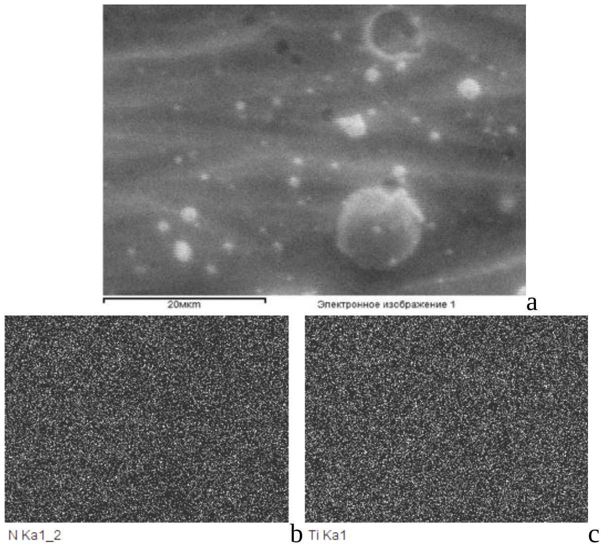


Fig. 3. SEM image (a), distributions: of nitrogen (b) and titanium (c) on knife surface treated with PVD method

The proportion of distributed components on the disk knife surface strengthened with TiN is 71.21 % Titan, 25.59 % Nitrogen, 1.88 % Carbon, 1.32% Oxygen (see Fig. 3).

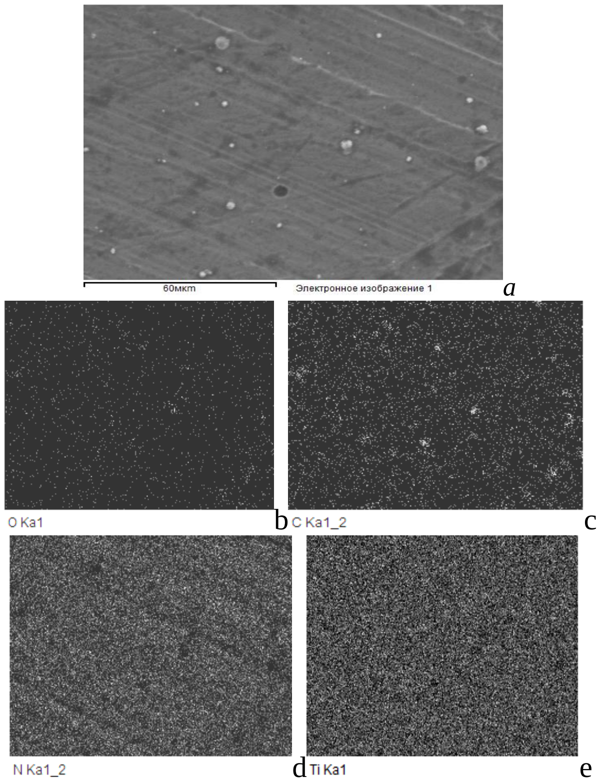


Fig. 4. SEM image (a), distributions: of oxygen (b), carbon (c), nitrogen (d) and titanium (c) on knife surface treated with RF processing

From the findings presented in Fig. 3, we can conclude that components Ti and N, forming superdispersed nitrides TiN, distribute evenly across the surface. However, there is the presence of a droplet phase, reduced the physical and mechanical properties of the coating, which is a weak way of applying ion-plasma coating technology using PVD. For high-tech processes micro particles can be removed using filters. Applying filters reduces productivity of the deposition process, complicates facility operation [11].

The proportion of distributed components on the knife surface strengthened with TiN under RF processing is 63.43 % Titan, 31.76 % Nitrogen, 2.25 % Carbon, 1.84 % Oxygen, 0.03% Silicon and 0.69 % Iron (see Fig. 4).

The initial state of the surface layer of the product significantly affects the quality of strengthening. Tables 1 and 2 present all components that are recognized in local areas on the strengthened surface (Fig. 5).

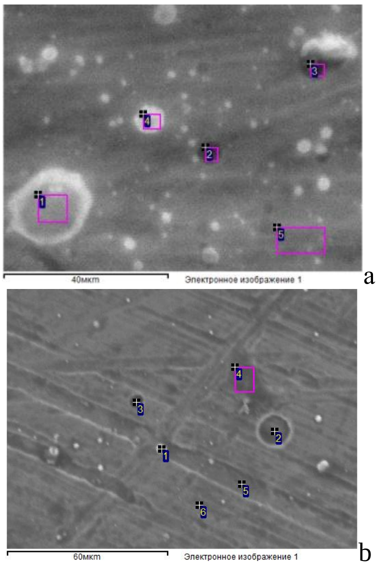


Fig. 5. SEM images of structure of the strengthened surface layer after PVD (a) and RF processing (b)

Through a comparative analysis of the modified TiN coating surface during various deposition technologies, it should be noted that the degree of purification is about the same in both treatments. There is a presence of residual oxides, sulfates, aluminosilicate, covered with TiN coating. Thus, the results are significantly better than the original surface condition (Table 3, Fig. 6). It proves the number of microelements remained under cover. The part of oxides is significantly bigger from the reverse side of the knife (not strengthened). According to the differences in these parameters we can assess the initial surface condition of the tool, purification degree and its efficiency.

Table 1

The results of micro X-ray analysis after PVD (according to Fig. 5,a)

Spec-trum	C	N	O	Al	Si	S	Ca	Ti
1	1.64	25.63	1.82	–	–	–	–	70.91
2	13.47	19.19	10.02	0.21	0.65	0.34	1.57	54.54
3	18.17	21.10	14.29	–	0.64	–	3.87	41.93
4	2.40	20.45	2.26	0.31	–	–	–	74.58
5	1.59	26.16	1.29	0.08	0.08	–	–	70.79

Date analysis shows that the concentration of alloying elements Si and Mn greatly exceed their share according to GOST (Russian: ГОСТ) 14959, characterizing the heterogeneity degree of alloying elements distribution and their diffusion in the process of consolidation.

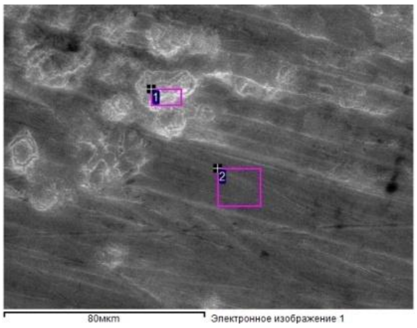


Fig. 6. The structure of the not-strengthened knife surface (back side)

Microanalysis found that brown and blue areas on the back side of the cutting edge of the knife (see Fig. 2) differ in chemical composition. At the edge there are the following: C – 5.74 %, O – 12.48 %, Si – 0.45%, Ti –1.16%, Mn – 4.51%, Fe – 75.66%. In the next area of the cutting edge (blue) there is much less oxygen (almost 2 times: O – 6.25 %), and reduced the concentration of components: 4.84 C %, 0.47 Si%, 4.07 Mn%, 84.38 Fe%.

It should be noted, that due to color variability we can assess the heating temperature of cutting edge tools. These results confirm that maximum heating under cyclic mode of coating on the knife made from steel 65 G is at a depth of 0.3 mm and corresponds to 200…240°C, whereas during the same period of time the ion bombardment leads to overheating of 600°C, not only cutting edge but also the entire blade with thickness 0.64 mm (65 G) and 0.9 (steel X20Cr13).

Table 2

The results of micro X-ray analysis after RF (according to Fig. 5,b)

Spectrum	C	N	O	Na	Al	Si	S	Cl	Fe	K	Ca	Ti
1	4.47	39.32	5.01	0.44	0.03	0.07	–	–	0.43	–	–	50.24
2	5.45	26.40	4.78	0.38	–	0.09	–	0.09	12.2	–	–	50.62
3	35.56	4.73	16.27	5.13	0.04	0.17	0.34	3.13	0.68	0.64	0.43	32.88
4	27.41	8.20	13.96	1.59	0.02	0.07	0.12	0.58	0.43	0.21	0.17	47.23
5	5.71	31.06	5.61	0.57	0.05	–	–	–	0.64	–	–	56.37
6	3.00	32.05	2.13	0.27	–	–	–	–	0.68	–	–	61.85

TiN coating on disc blades made from steel 65 G obtained by vacuum-arc method using titanium ion bombardment led to overheating and loss of tool flatness (they were deformed) in strengthening process.

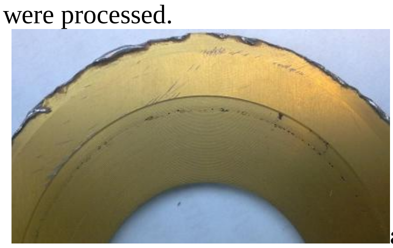
This tool is unsuitable for further use. Overheat of the tool also occurred during strengthening X20Cr13 steel knives, but thanks to their thick rim, flatness was not violated. Lifetime of X20Cr13 steel knives coated with TiN (4 mm) after PVD was 12 days, during which 10.8 t of products (nuts) were processed. Industrial tests were carried out on the equipment for processing nuts – Model CD-A Dicer of Urschel Laboratories, Incorporated in terms of production of JSC "Confectionary" Kharkovchanka". The design of hardened TiN (PVD) coating of cutting tools made from Steel X20Cr13 after operation in processing of 10.8 t nuts is presented in Fig. 7. There is a plastic deformation and a bend of the overheated cutting edge of the knife. This type of damage is also typical for a thin-walled tool without strengthening [12, 13].

Table 3

The chemical composition of not strengthened knife surface

Spectrum	C	O	Si	Mn	Fe
1	4.76	13.98	1.73	3.74	75.78
2	4.16	1.97	0.41	3.88	89.59

Lifetime of X20Cr13 steel knives coated with TiN (3.3 mm) after PVD was 47 days, during which 42.5 t of products were processed.


a


b

Fig. 7. The design of the knife made from X20Cr13 steel coated with TiN (PVD) after operation with a hardened (a) and its reverse (b) side

The study found that the best technology is a vacuum-arc method using RF-discharge. Therefore, further studies are being carried out on the machine that had been strengthened in this way.

To determine physical and mechanical properties of TiN coatings, the method of nanoindenter indentation with recording depth, increasing load and recording diagrams has been applied. We used «Nanoindenter G200» with diamond Berkovich pyramid [14]. The values of nanohardness, modulus of elasticity, material resistance to elastic deformation by destruction (estimated relative hardness to modulus H / E, called plasticity index) and the material resistance of plastic deformation (H3 / E2) are presented in Table 4.

The comparative analysis of loads diagrams during nanoindentationconcludes that the sample coated with TiN all indicators are much higher than the source material. This indicates increase in elastic and plastic properties of the product. Average value of nanohardness for the initial sample was 3.91 GPa. Average value of nanohardness for the sample coated with TiN was 25.66 GPa. According to the test results, mean value of modulus of elasticity of the sample coated with TiN was 389.28 GPa, and data variation reached 27.19 % due to the formation of inclusions containing nitride. Average value of modulus of elasticity for the virgin sample was 203.41 GPa with 9.52 % data spread. Resistance to plastic deformation of the metal knife coated with TiN increased 77 times compared to the original one.

Table 4

Physical and mechanical properties of samples

Sample	№ experiment	Physical and mechanical properties of the samples			
		H, GPa	E, GPa	H/E	H^3/E^2,GPa
Initial	1	3.915	204.382	0.019	0.0014
	2	3.727	204.496	0.018	0.0012
	3	4.084	184.049	0.022	0.0020
	4	3.872	203.588	0.019	0.0014
	5	3.99	205.773	0.019	0.0015
	6	3.61	198.272	0.018	0.0012
	7	3.8	209.751	0.018	0.0012
	8	4.355	217.001	0.020	0.0018
With TiN	1	16.338	283.446	0.058	0.054
	2	28.724	423.457	0.068	0.132
	3	23.694	366.271	0.065	0.099
	4	30.499	451.878	0,067	0.139
	5	24.406	369.622	0.066	0.106
	6	34.314	483.028	0.071	0.173
	7	27.16	401.275	0.068	0.124
	8	20.19	335.307	0.060	0.073

CONCLUSIONS

Two technologies of strengthening a thin-walled TiN coated cutting tool were investigated. It has been shown, TiN coating on thin-walled disc knives made from steel 65 G by vacuum-arc method using titanium ion bombardment leads to overheating and loss of tool flatness in strengthening process. This tool is unsuitable for further use. Strengthening TiN coated knives by vacuum-arc method with HF treatment saves flatness and increased operational stability of thin-walled tools. For industrial production JSC "Confectionary" Kharkovchanka" a new strengthening technology has been developed. It allows to prolong the service life of products in 47 times. Basic physical and mechanical characteristics of the initial sample and the sample coated with TiN were estimated. Comparative data analysis has shown a significant increase of physical and mechanical properties of TiN coating.

REFERENCES

1. V.I. Tereshin et al. Coating deposition and surface modification under combined plasma processing // *Vacuum*. 2004, v. 73, № 3-4, p. 555-560.
2. I.E. Garkusha et al. Properties of modified surface layers of industrial steel samples processed by pulsed plasma streams // *Vacuum.* 2000, v. 58, № 2, p. 195-201.
3. V.I. Tereshin et al. Pulsed plasma accelerators of different gas ions for surface modification // *Review of Scientific Instruments*. 2002, v. 73, № 2, p. 831.
4. V.S. Taran et al. Recent developments of plasma-based technologies for medicine and industry// *Nukleonika*. 2012, v. 57, 2, p. 277-282 (in Russian).
5. J. Musil, H. Hruby. Superhard nanocomposite Ti1-xAlxN films prepared by magnetron sputtering // *Thin Solid Films*. 2000, v. 365, p. 104-109.
6. A.A. Andreev et al. *Vacuumno-dugovie pokrutija*. Kharkov: NCS KIPT, 2010, p. 318 (in Russian).
7. N.N. Belash et al. Vliyanie predvariteloy obrabotki i sostava kompozitsionnyh pokrutij na stojkost' tverdosplavnuh rezushih plastin // J. *Physical surface engineering.* 2003, № 2, p. 23-25 (in Russian).
8. I.I. Aksenov et al. *Vacuum arc: plasma source, deposition of coatings, surface modification.* Kiev: "Naukova Dumka" NAS of Ukraine. 2012, p. 727 (in Russian).
9. I.I. Aksenov et al // *Vacuum plasma technology for high energy*.1980, v. 6, p. 918-924.
10. Patent No. 101699 Ukraine, IPC (2006.01) C23C 14/48, C23C 14/16. Key paviment exploitatio stycast concocting reusage instrumento/ T.S. Skoblo, S.P. Romanyuk, O.I. Stasenko, I. Garkusha, V.S. Taran, Yu.M. Nezovybatko; Savnik patentbureau Romanyuk S. P. No. u201503179. Appl. 06.04.2015.; publ. 25.09.15, Bull. № 18.
11. V.V. Gasilin et al. Application of coatings in the ARC discharges with plasma flow filtration // *Problems of Atomic Science and Technology. Series "Plasma Physics".* 2006, v. 12, № 6, p. 210-212.
12. T.S. Skoblo, S.P. Romanyuk. Statistical analysis of wear of cutting tools in the processing industry // *Storage and processing of agricultural products*. 2013, № 7, p. 46-48.
13. T.S. Skoblo et al. Kinetics of structural changes of the knives in the process of friction in the processing of products // *Scientific review*. 2014, № 4, p. 197-204.
14. T.S. Skoblo, S.P. Romaniuk, A.I. Sidorenko. Study of the properties of nano-coating on the cutting tool by the method of nanoindentation // *Agriculture and energy supply.* 2014, № 4, p. 92-100.

Article received 15.10.2016

РАЗРАБОТКА КОМПЛЕКСНОЙ ТЕХНОЛОГИИ УПРОЧНЕНИЯ ТОНКОСТЕННОГО РЕЖУЩЕГО ИНСТРУМЕНТА

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Предложена комплексная технология упрочнения тонкостенного режущего инструмента с помощью покрытий для обеспечения более длительной стабильной работы дисковых ножей. Покрытия наносили на режущий инструмент, изготовленный из холоднокатаной тонколистовой стали 65Г и 20Х13, для дробления орехов в кондитерском производстве. Предложены и исследованы два метода очистки и упрочнения таких инструментов: ионная бомбардировка ионами титана и вакуумно-дуговой метод с использованием ВЧ-разряда. Исследованы структура и химический состав ножей с покрытием TiN с помощью сканирующей электронной микроскопии и микрорентгеноспектрального анализа. Новый способ упрочнения тонкостенных дисковых ножей нанопокрытиями TiN защищён патентом Украины.

РОЗРОБКА КОМПЛЕКСНОЇ ТЕХНОЛОГІЇ ЗМІЦНЕННЯ ТОНКОСТІННОГО РІЖУЧОГО ІНСТРУМЕНТА

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Запропоновано комплексну технологію зміцнення тонкостінного ріжучого інструмента з допомогою покриттів для забезпечення більш тривалої стабільної роботи дискових ножів. Покриття наносили на ріжучий інструмент, виготовлений з холоднокатаної тонколистової сталі 65Г і 20Х13, для подрібнення горіхів в кондитерському виробництві. Запропоновано та досліджено два методи очищення і зміцнення таких інструментів: іонне бомбардування іонами титану і вакуумно-дуговий метод з використанням ВЧ-розряду. Досліджено структуру та хімічний склад ножів з покриттям TiN за допомогою скануючої електронної мікроскопії та мікрорентгеноспектрального аналізу. Новий спосіб зміцнення тонкостінних дискових ножів нанопокриттям TiN захищений патентом України.