STUDY OF DEGRADATION MECHANISM OF METAL-CUTTING TOOLS AND THEIR HARDENING BY ZrN PVD COATINGS

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The wear behavior of packaging knives made from high-alloy steel of X205Cr12KU type used in wrapping machines of MC1DT-T type (MC Automations, Italy) has been investigated. ZrN nanostructured coatings deposited by physical vapor deposition (PVD) with RF discharge mode have been employed to act as protective coatings on such knives due to their high hardness and chemical stability. The chemical composition, microstructure, and physical-mechanical characteristics of the ZrN coating have been studied by means of optical microscopy, scanning electron microscopy (SEM), X-ray diffraction (XRD), energy dispersive spectrometry (EDS) and nanoidentation method. The maximum nanohardness of the ZrN coating reached 32.05 GPa, which was 3.4 times higher than the tool matrix and was 57.65 % higher than that of the base metal spec-carbide phase. The application of coatings allowed stabilizing the working surface layer under deformation and to prevent the carbide phase from being crushed. Due to ZrN coating an increase in wear resistance by 3 times under production conditions was achieved.

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INTRODUCTION

Wrapping machine of MC1DT-T type (MC Automations) is used in food industry for cutting of packaging film and further wrapping of sweets. The operational properties of such devices, on large extent, depend on the durability of the blade tool used in this machine. During operation, damageability and destruction of such tools took place. In so doing, a comprehensive complex control of cutting-tool properties and wear behavior during operation as well as utilization of various hardening methods is a key solution for preventing degradation of tools surface increasing their service-life.

The physical and mechanical characteristics of the surface working layer can be improved by chemical-thermal treatment or application of wear-resistant coatings using various PVD methods [2, 3]. Standard heat treatment and quenching in oil with heating up to 960…980°C and subsequent low tempering at a temperature of 180°C is used to partially relieve the stresses formed during quenching and achieve high hardness (at least 62 HRC) [1]. The hardness level can be increased correcting the tempering temperature (Fig. 1).

The research was performed in two stages: in the first stage, the cutting knives were characterized regarding their wear behavior, degradation mechanism, chemical composition and structure using optical microscopy, scanning electron microscopy (SEM), X-ray diffraction (XRD), and nanoidentation, respectively. During the second stage, ZrN coatings were applied on such knives by means of vacuum-arc evaporation with RF discharge and industrial tests were carried out.

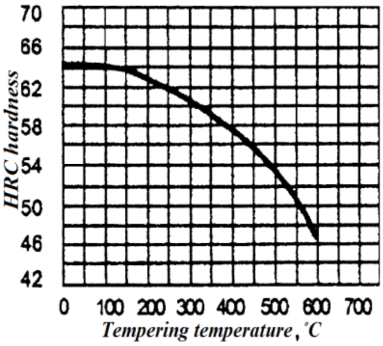

Fig. 1. HRC hardness as a function of tempering temperature

1. EXPERIMENTAL SETUP

Packaging knive made of X205Cr12KU high-alloy steel has four cutting edges and turns over during operation in order to use a sharper blade. Tool sharpening is carried out after all four corners cease to perform their cutting functions. Sharpness of the edge is restored by rectifying two end planes of the tool.

To improve wear resistance and durability of such knives, ZrN coatings were applied by vacuum arc method with the use of high-frequency discharge (RF) in the Bulat-6 type installation. Bias potential was applied to the substrate from RF generator, which produced impulses of oscillations at 5 MHz frequency. Chemically pure zirconium (99.999) was used as a cathode material. Nitrogen at a purity of 99.999 % was used as an active gas. The surface cleaning in RF discharge took place in argon plasma in order to make substrate degreasing and remove impurities for 15 min (U_{bias} = -1000 V, P(Ar) = 6 × 10^{-1} Pa). In order to improve the coating adhesion, a thin 20 nm Zr buffer

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layer was deposited before the nitride coatings. Application parameters: I_{arc} = 110 A, U^{RF}_{bias} = -200 V, base pressure $P = 5\times10^{-4}$ Pa. Time 25 min. The thickness of coating was 4.4 μm. Deposition rate was 34 μm/h.

The study of the structure and chemical composition was carried out using scanning electron microscope JEOL JSM-6390LV at an accelerating voltage of 10 kV equipped with EDS analyzer. X-ray diffraction (XRD) studies were performed using DRON-3M device, under Cu-Kα radiation. To analyze the mechanical properties the Nanoindentor G200 and the CSM method with automatic continuous recording of the loading and unloading diagrams were used. The amount of the carbide phase, as well as its distribution on the surface were calculated using the computer program Thixomet Pro.

2. RESULTS AND DISCUSSION

2.1. TOOL DEGRADATION MECHANISM

Fractured tool surface with fatigue wear resulted from cyclic loads is shown in Fig. 2. Some micro pores and microcrack were found to form during plastic deformation and destruction of the carbide phase.

a

b

Fig. 2. Tool surface with fatigue wear resulted from cyclic loads

The origin and further spread of microcracks began from the edge of the working surface (Fig. 3). In addition, micropores and nonmetallic inclusions are locally found in the tool metal structure, which serve as stress concentrators. All this contributed to futher destruction of the tool (see Fig. 2).

According to XRD data, the main matrix of metal knife consists of martensitic tempering phase and Cr_7C_3 special carbide phase.

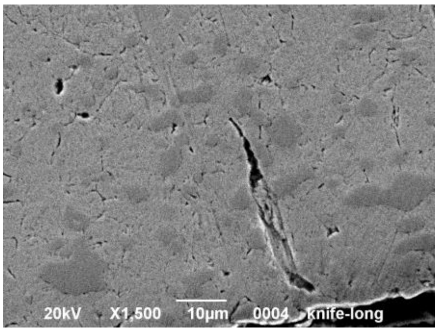


Fig. 3. SEM image of the tool working layer with microcracks

Analysis of the optical microscopy images from individual zones of the tool with the help of the Thixomet Pro program revealed that the number of doped special carbides was different. A decrease of special carbides in the working surface layer by 43.7 % contributed to a significant decrease in the wear resistance of the tool. This is determined by the degradation of the material during operation. The total amount of carbides was 14.4 % of the metal matrix in the middle of the tool, and at the edge of the working surface it did not exceed 8.15 %.

It was established that tool degradation mechanism is preceded by the following stages: destruction of carbides and diffusion of their components, fragmentation of small carbides during deformation, aligning them in chains and along grain boundaries, the appearance of a more decarburized light zone along the working surface during operation, and the formation of cracks. In the subsequent operation, chains of small carbides are located at an angle of 45° (corresponds to the effect of compressive stresses). The working surface is destroyed from the formed cracks.

The nanohardness of special carbides was 2.2 times higher than that of the base metal of the matrix. The hardness of the steel matrix was 9.19 GPa. The data spread obtained from the results of the 7 measurements was 4.35 %. The average nanohardness of special carbides reached 20.33 GPa. Spec-carbides have higher elastic properties. The modulus of elasticity of the steel matrix is 246.4 GPa with the data spread 5.0 %. The average value of elastic modulus for special carbides was 275.87 GPa with a minimum data spread of of 1.6 %.

2.2. STRUCTURE, COMPOSITION AND MECHANICAL PROPERTIES OF ZRN COATING

The general wiev of the cutting tool reinforced with ZrN coating is shown in Fig. 4.

Fig. 4. Cutting knife with ZrN coating

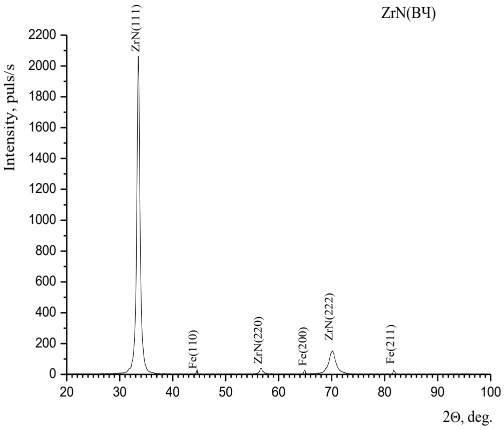


Fig. 5. XRD spectra from ZrN coating

Typical XRD pattern of ZrN coating obtained in RF regime is presented in Fig. 5. All angels of diffraction peacks with (111), (222), and (220) main reflections were indexed as ZrN phase with a crystal structure of B1 NaCl cubic lattice type (according to JCPDS 35-0753, *a* = 0.4577 nm lattice constant). XRD data revealed the formation of finecrystalline structure with the grain size of 20 nm.

From Fig. 6, we can conclude that components Zr and N, forming superdispersed nitrides ZrN, distribute evenly across the surface. Results of EDS analysis are shown in Table.

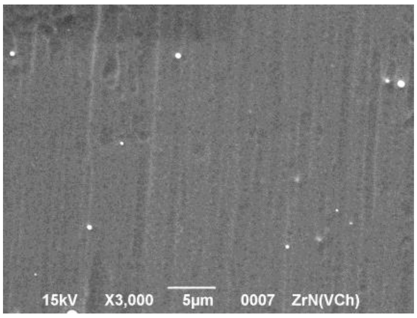


Fig. 6. Surface morphology of ZrN coating

Distribution of chemical components (EDS microanalys)

Element	Conc.	Intensity	Wt %	At %
C	0.42	0.7480	3.89	13.22
N	0.29	0.1461	13.33	38.86
O	0.36	0.4829	5.07	12.93
Fe	0.09	0.9833	0.66	0.48
Zr	10.54	0.9330	77.06	34.50

On the basis of the obtained load/unload diagrams, the elastic recovery of the ZrN coating was evaluated (Fig. 7). The measurements were carried out at a load of up to 80 mN and the penetration depth of the indenter of 523 nm. The elastic recovery reached 36.8%.

It was established that all physical and mechanical characteristics of the ZrN coating are significantly higher in comparison with the initial metal tool (Fig. 8). The maximum nanohardness of the ZrN coating reached 32.05 GPa, which is 3.4 times higher than the knife matrix and 57.65 % higher than that of the base metal special carbides. The high level of nanohardness of the ZrN coating made it possible to increase the wear resistance of the working surface layer and to increase the time between the repair periods by re-grinding.

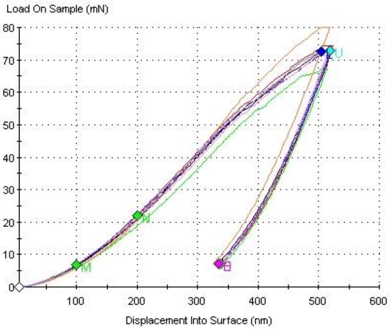
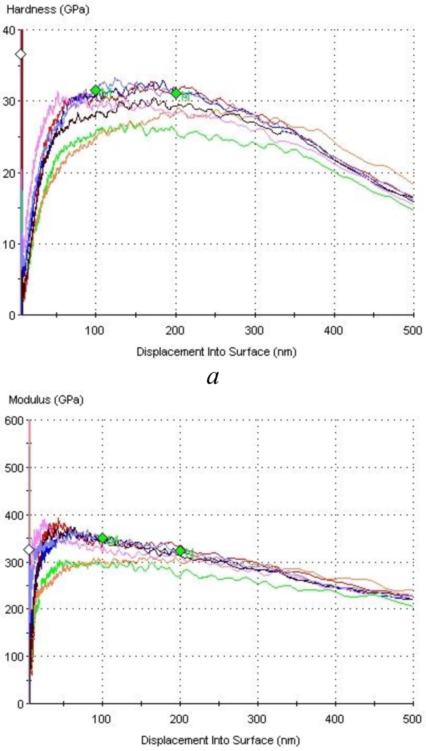


Fig. 7. Load/unload diagram of ZrN coating



a

b

Fig. 8. Nanohardness of ZrN (a) elastic modulus (b) as a function of indenter depth

The average value of the elastic modulus for the ZrN was 320.81 GPa. The spread of the data obtained does not exceed 10.04 %.

The shear modulus G was calculated using the formula:

$$G = \frac{E}{2} * (1 + \mu) . \qquad (1)$$

Where, E is elastic modulus (GPa), μ is Poisson's ratio. The maximum resistance to shear stress during operation for the ZrN coating reached 210.77 GPa. This allowed stabilizing the working surface layer of the tool during deformation and reducing the propensity to develop diffusion processes.

The tensile strength of the working surface was calculated using the equation:

$$\sigma_в = 0.333 * H_{max} , \qquad (2)$$

where H_{max} is the maximal hardness (GPa).

As a result of the theoretical calculation it is established that the maximum tensile strength that is capable of withstanding the ZrN coating comprised 10.67 GPa, above which the probability of its destruction may increase.

The ability of the material to resist the elastic deformation was evaluated by the H/E ratio. It was found that the maximum elastic fracture deformation for the ZrN coating does not exceed 0.095.

The plastic deformation resistance coefficient was calculated as the ratio H^3/E^{*2}, where E^{*2} is effective Young's modulus, which was calculated from the ratio:

$$E^* = \frac{E}{1-\mu^2}, \quad (3)$$

The coefficient of resistance to plastic deformation H^3/E^{*2} for the ZrN coating reached 0.254.

Industrial test results showed that the hardening of the knives by the ZrN coating according to the proposed technology provides a 3 times increase in durability during operation.

CONCLUSIONS

The wear behavior of packaging knives made from high-alloy steel of X205Cr12KU type used in wrapping machines of MC1DT-T type (MC Automations, Italy) has been investigated. ZrN coating was applied on such a knife by vacuum arc deposition with the use of high-frequency discharge. XRD data revealed the formation the formation of stoichiometric ZrN phase of cubic modification with average grain size of 20 nm. The maximum nanohardness of the ZrN coating reached 32.05 GPa. The modulus of elasticity reaches 320.81 GPa, and the tensile strength was 10.67 GPa. The application of such a coating provides an increase in mechanical properties, allows stabilizing the working surface layer under deformation, preventing the carbide phase from being crushed and the development of diffusion processes. The conducted tests showed that hardening of knives with ZrN coating provides an increase in wear resistance by 3 times.

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ИССЛЕДОВАНИЕ МЕХАНИЗМА ДЕГРАДАЦИИ МЕТАЛЛА РЕЖУЩЕГО ИНСТРУМЕНТА И ЕГО УПРОЧНЕНИЕ PVD ПОКРЫТИЕМ ZrN

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Проведено исследование износостойкости упаковочных ножей из высоколегированной стали марки X205Cr12KU, используемых в машинах типа MC1DT-T (MC Automations, Италия). Наноструктурные покрытия ZrN, полученные физическим осаждением из газовой фазы (PVD) с применением ВЧ-разряда, благодаря высокой твердости и химической стабильности использовались для защиты поверхности таких ножей. Химический состав, микроструктура и физико-механические характеристики покрытия ZrN изучались с помощью: оптической микроскопии, сканирующей электронной микроскопии (SEM), рентгеновской дифрактометрии (XRD), энергодисперсионной спектрометрии (EDS) и метода наноидентирования. Максимальная нанотвердость покрытия ZrN достигала 32,05 ГПа, что в 3,4 раза больше, чем твердость матрицы инструмента, и на 57,65 % выше, чем у карбидной фазы основного металла. Применение покрытий позволило стабилизировать рабочий поверхностный слой при деформации и предотвратить измельчение карбидной фазы. Благодаря покрытию ZrN было достигнуто повышение износостойкости в производственных условиях в 3 раза.

ДОСЛІДЖЕННЯ МЕХАНІЗМУ ДЕГРАДАЦІЇ МЕТАЛУ РІЖУЧОГО ІНСТРУМЕНТА ТА ЙОГО ЗМІЦНЕННЯ PVD ПОКРИТТЯМ ZrN

Т.С. Скобло, С.П. Романюк, А.І. Сидашенко, І.Є. Гаркуша, В.С. Таран, А.В. Таран, С.В. Демченко

Проведено дослідження зносостійкості пакувальних ножів з високолегованої сталі марки X205Cr12KU, які використовуються в машинах типу MC1DT-T (MC Automations, Італія). Наноструктурні покриття ZrN, отримані фізичним осадженням з газової фази (PVD) за допомогою ВЧ-розряду, завдяки високій твердості та хімічній стабільності використовувалися для захисту поверхні таких ножів. Хімічний склад, мікроструктура та фізико-механічні характеристики покриття ZrN вивчалися за допомогою: оптичної мікроскопії, скануючої електронної мікроскопії (SEM), рентгенівської дифрактометрії (XRD), енергодисперсійної спектрометрії (EDS) та методу наноідентування. Максимальна нанотвердість покриття ZrN досягала 32,05 ГПа, що в 3, 4 рази більше, ніж твердість матриці інструмента, і на 57,65 % вище, ніж у карбідної фази основного металу. Застосування покриттів дозволило стабілізувати робочий поверхневий шар при деформації і запобігти подрібненню карбідної фази. Завдяки покриттю ZrN було досягнуто підвищення зносостійкості у виробничих умовах в 3 рази.