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EFFECT OF COMPOSITE NANOCOATINGS ON WEAR-RESISTANCE AND PRODUCTIVITY OF SOCKET MILLS

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Abstract- The study of the wear resistance of cutting tools is of paramount importance due to their wide application in the machining of parts in mechanical engineering and other branches of technology. Therefore, the problem of increasing the strength characteristics and operability of cutting tools is important. The paper presents the results of experimental studies of the wear resistance of socket mills made of high-speed steels and hard alloys in the processing of hard-to-process structural chromium steels. The method of experimental research of wear resistance is generated. The technology of hardening the cutting teeth with a wear-resistant coating using the PVD method has been developed. The influence of the structure of a composite coating based on titanium nitrides and carbides on the mechanical characteristics and working capacity of the cutting tool is shown. The results of an experimental study of the effect of hardening coatings of the cutting teeth of socket mills on wear resistance are obtained. The nature of wear and brittle destruction of the working surfaces of the tool under intermittent cutting conditions and the effect of high-strength coatings on the thermal and stress state of the cutting edge in the contact zone are investigated. The dependences of the resistance of the cutting teeth of socket mills on the cutting speed and infeed during the processing of workpieces made of hard-to-process chromium steels are given. X-ray spectral analysis of the chemical composition of the surface layer of the cutting plates was performed. The structure of the wear surface and brittle fracture of the cutting teeth is presented.

Keywords: Socket Mill, Wear-Resistant Composite Coatings, Cutting Modes, Solidity and Hardness of the Material, Contact Stresses, Titanium Carbides and Nitrides, Working Capacity.

1. INTRODUCTION

The efficiency of mechanical processing of hard-to-process structural alloy steels and alloys with a high chromium content largely depends on the wear resistance of the cutting tool. The most acute problem of intensive wear and brittle destruction in the form of chipping and crumbling of the cutting edges is manifested in socket mills operating at high speeds under conditions of intermittent cutting. At the same time, they are affected by cyclic shock loads, high contact stresses and temperature, which leads to premature wear. The main working elements of socket mills are cutters with cutting plates. High-speed steels and hard alloys are widely used as tool materials for the manufacture of cutting plates [1-4]. The issues of destruction and strength of tool materials are considered in [4-13]. Thermal and tribological processes at the interface between the working surface of the tool and the chip during machining are considered in [4-7, 13-15].

One of the most effective ways to raise the working capacity of cutting tools is to apply wear-resistant coatings to work surfaces. Protective coatings increase fatigue strength, hardness, heat resistance, residual compression stresses and corrosion resistance of work surfaces. This makes it possible to significantly improve the working capacity of the tool and intensify the machining modes. Composite coatings based on compounds of refractory metals (carbides, nitrides, borides, oxides and their compounds) have been most widely used. They have higher wear resistance and solidity compared to other tool materials. The problems of using modern composite materials for reinforcing protective coatings are discussed in publications [2, 3, 8, 14, 16-27]. Coating technology is of great practical importance [18-22, 26-30, 32, 33]. By varying the technology of their application, it is possible to adjust the composition, structure, as well as the thickness and hardness of the protective layer.

Currently, the physical nature of wear during cutting of difficult-to-process materials has not been sufficiently studied due to the exceptional complexity of the contact processes on the front and rear working surfaces of the cutter teeth, as well as the cutting edges of the blade. Therefore, the study of the effect of reinforcing coatings on the working surfaces of socket mills in order to increase their wear resistance and cutting ability in conditions of intermittent cutting of chrome-plated structural steels is an

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urgent task and is of practical importance for improving the efficiency of mechanical processing. The purpose of this work is an experimental study of the effect of the hardening composite coating on the wear resistance of cutting blades of socket mills made of high-speed steels and hard alloys in the processing of hard-to-process chromium steels.

2. EXPERIMENT TECHNOLOGY

Experimental studies of the wear resistance of the cutting tool were carried out under conditions of intermittent cutting according to the counter milling scheme when processing chrome-plated structural alloy steels. As a cutting tool, socket mills of ∅160 mm (Figure 1) was used, equipped with pentahedral interchangeable plates made of high-speed steels and metal-ceramic hard alloys. Cutting plates without coatings and with reinforcing coatings of TiN nitride, TiC carbide and titanium carbonitride TiCN, obtained on the basis of refractory metals, were used. Together with single-layer coatings, TiC-TiCN-TiN, TiCN-Al_2O_3-TiN, TiN-TiCN-TiN multilayer coatings were also used. Milling was performed without cooling on a vertical cantilever milling machine model 6M12P in the range of cutting modes: speed $V = 31...250$ m/min, infeed per tooth $S_Z = 0.05...0.3$ mm/tooth, cutting depth $t = 1...3$ mm, milling width $B = 100$ mm. As a criterion for blunting the cutting plate, its maximum linear chamfer wear along the main back surface of the cutting teeth $h_o = 0.3$ mm is adopted. 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. Tool wear monitoring was carried out both in the initial period of time and during operation.

Figure 1. Socket mill with replaceable cutting plates

Wear-resistant coatings TiN, TiC and TiCN were applied to the cutting plates by the method of Physical Vapour Deposition (PVD) of coatings using special ion-plasma technology [12, 27]. In this case, the technology of condensation of refractory materials from the plasma phase in vacuum with ion bombardment (CIB) was used, based on the generation of matter by a cathode spot of a vacuum arc of a low-voltage high-current discharge. Schemes of devices implementing PVD processes are presented in [3]. The advantage of this method is the high deposition rate of the coating and the relative simplicity of the technical implementation. The application of a wear-resistant surface layer was performed in the Bulat-3T vacuum plasma installation using an arc discharge in a vacuum chamber in an atmosphere of a reagent gas: nitrogen N_2 for titanium nitride (TiN), acetylene C_2H_2 for titanium carbide (TiC). The metal body of the camera serves as an anode. The cathode is a refractory material subject to evaporation. Due to the plasma chemical reaction of the ionized flow of metallic plasma and reagent gas, the coating condenses on the surface of the tool.

The process of forming ceramic coatings with specified physical and mechanical properties depends on various factors: reference voltage, arc discharge current of the evaporator, the pressure of the reagent gas in the working chamber, temperature of the reinforced plate, the density of the deposition flux and energy of metal plasma ions, duration and rate of absorption. The formation of the surface layer occurs by adsorption of ions of the coating material in the form of a low-temperature plasma stream on the surface of the cutting plates. In this case, microcracks and pores of the working surfaces of the cutting plate are filled with the coating material, which helps to increase the adhesive strength of the surface connection with the coating.

Due to the low coefficient of thermal expansion of titanium nitride and carbide and the tendency of thick coatings to crack at high temperatures, coatings with a thickness of 5...8 microns were synthesized on the surface of the cutting plates, and their microhardness was 23...26 GPa. The quality of ion plasma coatings depends on various factors: the coating structure (number of layers, their thickness, alternation, etc.), technological modes (temperature, application duration, etc.), operating conditions [2].

The specified characteristics of microhardness, structure and phase composition of ceramic coatings of cutting plates were provided by varying three main parameters of the condensation mode: the arc discharge current of the evaporator is $I_o = 90...140$ A, the pressure in the reaction chamber of the reagent gas installation $P_\alpha = (2.5...7.9) \times 10^{-2}$ Pa and the reference voltage $U_o = 150...200$ V on the hardened plate. The condensation temperature was maintained within $\theta = 450…540$ ºC. 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 with this technology, the crystallite sizes of the synthesized layer range from 0.004 to 0.033 microns.

The topography of the surface layer of the cutting plates and the microstructure of the applied coatings before and after wear were studied 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. X-ray diffraction analysis of coatings was 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 PMT-3 hardness meters. Modern methods for studying the surface of plates are given in publications [21, 31]. Figure 2 shows a fractogram of the microstructure of the surface of the titanium nitride coating TiN deposited on a plate made of T5K10 hard alloy.

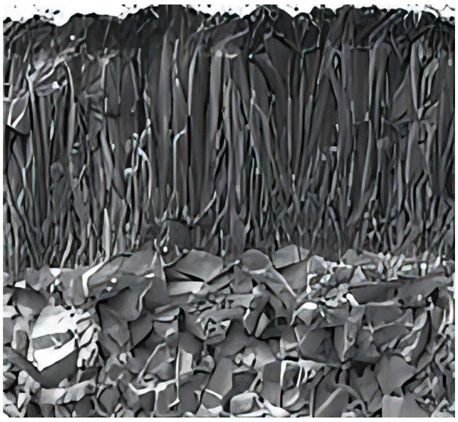


Figure 2. Microstructure of the surface of carbide cutting plates with TiN coating (×1800)

Titanium carbonitride coatings Ti (C, N) have a columnar structure, elongated towards growth, with an average column's width of 260 nm. This coating has a high Vickers hardness is $H_{\mu} = 22...25$ GPa and has a low coefficient of friction on steel is 0.25…0.3. The permissible maximum cutting temperature is 600 °C. The TiCN material is used as an independent coating, as well as as its separate layers. Its hardness reaches $H_{\mu} = 27...30$ GPa, the coefficient of friction on steel is 0.3, the maximum cutting temperature is 400 °C.

3. RESEARCH RESULTS AND THEIR DISCUSSION

A feature of the milling process of chromium steels in intermittent cutting conditions is the hit action at the entrance and exit of the cutting teeth in contact with the workpiece. As a result, a complex stress state occurs in the cutting wedge of the working part of the tool with simultaneous interaction of normal and tangential stresses. Under the action of normal forces, compression stresses occur in the surface layer of the tool material of the cutting edge and elastic-plastic deformation occurs. At the moment of the exit of the milling cutter tooth from the workpiece, the load is relieved, and under the action of elastic deformation, the sign of internal stresses changes. The compression voltage is transformed into a tensile one.

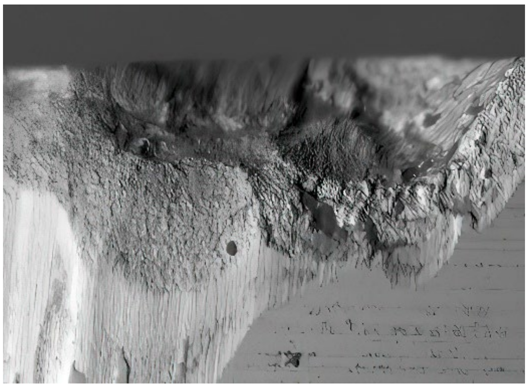
As a result of the action of tensile stresses, when the limit value of the tensile strength is reached σ_B, brittle destruction of the deformed surface of the tool occurs. In this case, part of the mechanical energy is transformed into thermal energy. This causes the cyclical nature of the thermomechanical load and leads to a sharp increase in wear and brittle destruction of the cutting plates with the formation of microcracks, chips and crumbling.

The abrasive wear of the tool occurs under conditions of active interaction of the swarf of the cut material with the cutting plates of the cutter. As a result of contact friction and significant plastic deformations of the swarf on the front and main rear working surfaces of the cutting teeth, adhesion of the cut metal is formed, the formation of holes on the front surface, chipping of the cutting edges and a decrease of the tool durability period. Subsequently, in the cutting zone, due to high specific loads and temperature, the workpiece material passes into a plastic flow, filling the volume of the ledge. Holes, cracks and grooves are filled with the material of the workpiece. 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 back surface.

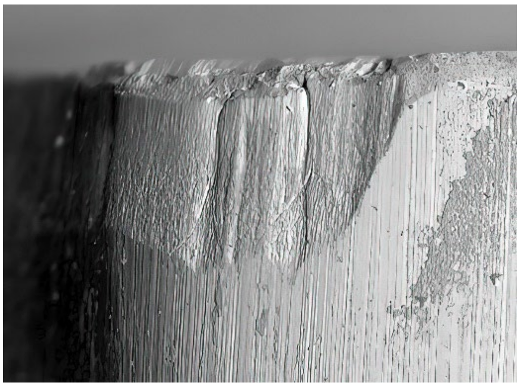
For example, when processing 20×13 steel, analysis of the adhering elements on the rear main working surface of the cutting teeth showed that the main components of the surface layer of the tool are iron (Fe) and chromium (Cr), corresponding to the chemical composition of the processed material. The 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.

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%. Tool durability is reduced by 1.5...3 times due to brittle fracture in the form of chipping and breakouts of the cutter material particles from the cutting edges.

Figure 3 shows wear structure of the main back surface of a pentahedral cutting plate made of T5K10 hard alloy without hardening and with TiN coating during processing of 20×13 chrome steel. Cutting mode parameters: $V = 158.4$ m/min, $t = 1.5$ mm, $S_Z = 0.15$ mm/cutter, and milling width of $B = 100$mm and working period $\tau = 60$ min.



(a)



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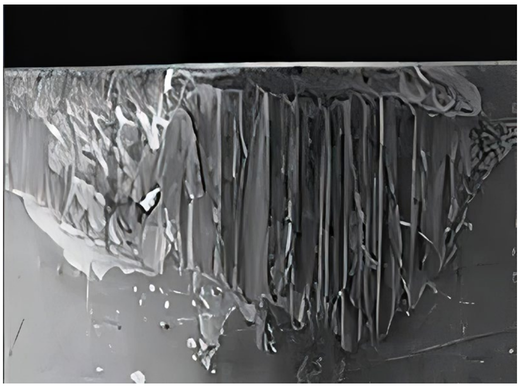


(c)

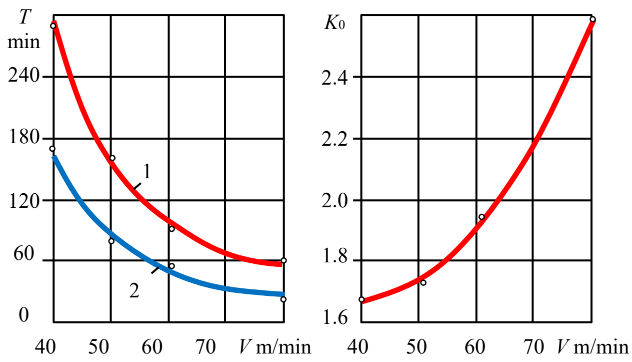
Figure 3. The wear structure on the back surface of the cutting teeth of high-speed steel cutters P6M5 when milling steel 20×13 (×200)

The topography of the worn surface (Figure 3a), obtained on a scanning electron microscope, has a relief in the form of an excrescence due to the presence of a large number of deformed protrusions, representing particles of the workpiece material smeared on the cutting surface of the plate. The above image of the uncoated cutter shows the build-up formed on the main front surface near the cutting edge and wear on the main back surface. This indicates significant plastic deformations in the cutting area at the contact pads of the tool and the workpiece. The projections and the grooves separating them are located in the direction of chip movement. Wear occurs in the form of mechanical abrasion along the main back surface to the accepted blunt criterion. The process of wear of the front surface of the teeth of the cutters is accompanied by the formation of a holes. During operation, a ledge is formed in the zone of brittle destruction of the cutting edge as a result of tearing the particles of sharp edges, protrusions and wear of the cutter material that prevent the movement of the descending chips.

Brittle destruction of the cutting edge in the form of chips from the side of the main back surface is shown in Figure 3b. The wear along the length of the cutting-edge proceeds unevenly and reaches the highest value along the radius transition from the main back surface to the auxiliary one. In this area, the most difficult working conditions of the tool are created, which increases the intensity of wear and leads to chipping. A characteristic feature of chipping is that they are located on the peripheral section of the main cutting edge. Here there is a transition from an elastically stressed area of the incisor to an unloaded one and there are significant tensile stresses, leading to brittle fracture of the cutter along the cutting edge. Failure under intermittent cutting conditions begins with the formation of longitudinal cracks on the front surface of the plate, perpendicular to the main cutting edge, which grow towards the rear surface. The wear-resistant coating significantly reduces the intensity of wear and setting on both the front and main back surfaces

Increasing the durability period of the tool makes it necessary to strengthen its working surfaces with wear-resistant coatings. The reinforcing coating, having high hardness and wear resistance, protects the tool material for the entire period of its operation. Figure 3c shows the wear topography of the rear tooth surface of a TiN coated milling cutter. Characteristic signs of intensive adhesive interaction of the chip with the surface of the milling cutter tooth are observed in the form of a wear place along the main back surface. The reinforcing coating reduces the rate of hole formation and the intensity of wear on both the front and main back surfaces. At the same time, there is practically no chipping and the temperature in the cutting area decreases.

The effect of the composite coating of the cutting plates on the durability period of the milling cutter when processing 20×13 chrome steel is studied below. The dependences of the durability period T and the coefficient K_o of relative in the durability mills from a high-speed steel P6M5 on the cutting speed are shown in Figure 4 for the parameters of the cutting mode: $S_Z = 0.1$ mm/cutter; $t = 1.5$ mm. The coefficient $K_o = T_1 / T_2$ is defined as the ratio of durability period T_1 of mills with titanium carbide coatings to the durability period T_2 of uncoated mills.



(a) (b)

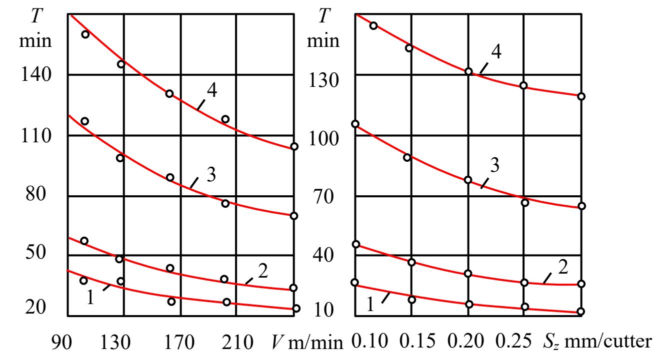
Figure 4. Dependences (a) of the durability period T and (b) the coefficient of relative in the resistance K_o of socket mills made of high-speed steel on the cutting speed - 1) with a coating TiC; 2) uncoated

The coefficient K_o value increases by 2.61 times at $V = 80.4$ m/min and with a decrease in speed to $V = 40.2$ m/min, the coefficient K_o value decreases to 1.67. The effect of the coating is especially evident in the initial period of operation, when tool wear increases and the coefficient K_o of relative increase in durability reaches a value of 3...8. With a decrease in the amount of wear, the value K_o decreases to 1.5...3.5. When cutting with uncoated plates, the front surface of the teeth of the mills along the entire width of the cut, due to adhesion setting, was covered with growths already in the initial processing period. Growths occurred over the entire cutting speed range $40.2 \le V \le 80.4$ m/min. The results of a study of the operability of socket mills with TiC coatings in the processing of chrome-plated structural alloy steels and carbon steel are presented in Table 1.

Table 1. Results of the study of the operability of socket mills with TiC coatings

Instrumental material	Processable material	Coating thickness	Cutting modes			The coefficient of increase in durability
			V, m/min	S_{ze}, mm/cutter	t, mm	
P6M5	Steel 45	6-7	75.4		2	2.2-2.7
P9K5	Steel 45	5-7	75.4		2	2.3-2.8
P18	Steel 45	5-7	75.4		2	2.5-3.2
P6M5	38XH3MA	6-7	29.6-75.4		1.5	1.8-2.7
P18	38XH3MA	6-8	29.6-75.4		1.5	1.9-3.1
P6M5	18X2H4MA	6-7	29.6-75.4	0.1	1.5	1.7-2.5
P9K5	18X2H4MA	6-7	29.6-75.4		1.5	1.8-2.6
P6M5	20×13	5-7	29.6-75.4		1.5	1.6-2.6
P9K5	20×13	5-7	29.6-75.4		1.5	1.7-2.6
P18	20×13	6-7	29.6-75.4		1.5	1.8-2.8

The dependence of the influence of cutting speed V and feed S_Z on the durability period T of T5K10 hard alloy cutters with various reinforcing coatings during face milling of 12×13 steel workpieces is shown in Figure 5 for the parameters of cutting modes: a- S_Z = 0.2 mm/cutter, b- $V = 251.3$ m/min, $t = 1.5$ mm, $B = 100$ mm.



(a) (b)

Figure 5. The effect (a) of the cutting speed V and (b) feed S_z on the durability period of hard alloy cutting plates with a wear-resistant coating during face milling of steel workpieces
1) uncoated, 2) TiN, 3) TiCN-TiN, 4) TiCN-Al_2O_3-TiN

It has been established that high physical and mechanical properties, low thermal conductivity and a tendency to hardening worsen the workability of chromium steels. Therefore, the cutting process is accompanied by a significant thermal and force load.

The obtained results of the study showed a high efficiency of the effect on the wear and durability period of milling cutters of coatings of cutting teeth with alloys based on titanium nitride and carbide. Wear-resistant coatings significantly reduce the adhesive interaction of the contact surfaces of the cutting teeth with the processed material in almost the entire range of cutting modes. Friction, cutting forces, wear and sticking of the processed material are reduced, as well as the heat generated during this process. The effectiveness of the coatings differed significantly in magnitude and in the nature of the interaction of the contacting pair.

It was found that the cutting temperature of T5K10 and P6M5 coated plates is 11...18% lower compared to uncoated plates. The low thermal conductivity of titanium nitride and carbide changes the nature of heat removal from the cutting zone, prevents heat removal into the tool and contributes to an increase in its removal into the chips. The tool durability period takes on the highest values at low cutting speeds, and the lowest values at high speeds. The effect of the coating is especially manifesting in the initial period of operation, when tool wear increases. During finishing, the effectiveness of the coating effect on the wear rate is 1.5...2.5 times higher compared to roughing.

Thus, the hardening of the cutting teeth of milling cutters with nitrido- and carbidotitane coatings TiN, TiC, TiCN according to the proposed method can 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. The reinforcing coating, while maintaining the mechanical properties and strength of the cutting plate and having high hardness and wear resistance, protects the tool material throughout its operation. At the same time, by reducing friction and plastic deformation of the catted metal the cutting forces are reduced by 10 ...20%, the chip shrinkage coefficient by 8...16%, and the heat generated by 50...90 °C. The use of multilayer coatings allows to increase the wear resistance of the tool and processing performance compared with single-layer. The greatest improvement in the performance of the tool is provided by three-layer coatings TiCN-Al_2O_3-TiN. The coefficient of increasing the tool durability period with such coatings is 2.9...4.4 and higher, depending on the cutting modes.

4. CONCLUSIONS

A methodology for the experimental study of the wear resistance of socket mills made of high-speed steels and hard alloys in the processing of hard-to-process structural steels has been developed. Hardening of the cutting teeth with a wear-resistant coating is performed by the PVD method. The use of a composite coating significantly raises the operability and productivity of the tool, increases its resistance period by 1.7...2.4 times from high-speed steels and 2.3...2.9 times from carbide materials. This makes it possible to expand the scope of application of socket mills for milling hard-to-work steels.

The structure of wear and brittle destruction of the working surface of the cutting teeth is shown. The dependences of the resistance period of the cutting plates of the teeth on the cutting speed and infeed when processing workpieces are constructed. The patterns of wear and the period of durability of socket mills with a wear-resistant composite coating under conditions of intermittent cutting of chrome-plated structural steels have been established, allowing to increase processing productivity. It is revealed that the hardening composite layer on the working surfaces of the tool leads to a significant change in the nature of contact processes, to a decrease in the intensity of wear and brittle fracture of the cutting teeth. Their contact solidity also increases and the surface temperature in the cutting area decreases, which increases the durability period of the tool.

In future studies, it is supposed to consider in more detail the wear resistance of cutting tools with multilayer coatings with various combinations of component layers for other tool materials and cutting conditions. The results of this study can be used in tool production in the manufacture of socket mills with heightened wear resistance to increase labor productivity during machining. The proposed coatings also have practical use for other types of cutting tools.

5. NOMENCLATURES

Symbols / Parameters

V : the cutting speed during milling

S_Z : the infeed to the milling cutter tooth

t : the cutting depth

B : the milling width

h_o : the maximum chamfer wear along the main back surface of the cutting teeth

I_o : the current strength of the arc discharge of the evaporator of refractory metals

P_α : the pressure of the reagent gas in the working chamber

U_o : the reference voltage on the reinforced plate

θ : the condensation temperature of ion-plasma coatings in the working chamber

H_μ : a hardness of the cutting plate coating according to Vickers

T : the tool durability period

τ : the period of operation of the milling cutter

K_o : the coefficient of relative increase in the durability period of socket mills

T_1 : the durability period of mills with titanium carbide coatings

T_2 : the durability period of uncoated mills

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