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APPLICATION OF WEAR-RESISTANT COATINGS FOR INCREASING EFFICIENCY OF ELEMENTS OF HYDROCUTTING DEVICES

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ЗАСТОСУВАННЯ ЗНОСОСТІЙКИХ ПОКРИТТІВ ДЛЯ ПІДВИЩЕННЯ ПРАЦЕЗДАТНОСТІ ЕЛЕМЕНТІВ ГІДРОРІЗАЛЬНИХ ПРИСТРОЇВ

In this work the question of investigating the stability of coatings TiN, the nitrided layer and the combined coverage of the nitrided layer and TiN under conditions of high hydro-cavitation wear are cosidered. Received regression equation resistance of coatings deposited on the basis of hard alloy VK 8 type of conditions of leakage of a fluid. The possibilities of functionally-oriented approach to the formation of the surface layer parts channel elements of hydrocutting devices are shown, increasing of their worktime is proved .
Keywords: coatings, hydrocutting devices, hydro-cavitation wear.

Introduction. The appearance and widespread using in industry of new structural materials, especially composites, and new high-tech products, makes the need for new methods of treatment. One of these methods is hydroabrasive cutting.

The use of hydroabrasive cutting justifies itself especially where use of traditional methods does not give a satisfactory quality. Additional costs for works or reducing of the production rate go into oblivion. An additional advantage of this method is its cleanliness and environmental friendliness. Modern systems of hydroabrasive cutting provide continuous optimization of production and quality in manufacturing. The need for high processing results requires sustainability and compactness of jet-abrasive stream.

Using of hydroabrasive processing enables significantly improve the quality of machined surface and cutting performance, which requires the development of promising new layout tools for combined treatment.

Among the trends of hydroabrasive treatment the improving of the accuracy and efficiency of processing equipment is allocated. Effectiveness can be enhanced by increasing fluid pressure (600 MPa) and the number of concurrent working heads [1, 2]. However, increasing of working pressure leads to intensification of systems of wear of hydrocutting equipment, including calibration tubes (Fig. 1), which in turn reflected in the cost of processing.

Objective. Calibration tube is one of the most important elements of hydrocutting system, which affects the technological and economic characteristics of the cutting. Industrial observations suggest that most functional failures in the implementation of hydroabrasive cutting occurs due to sudden changes in geometry of jet-forming elements (nozzle and calibration tube). The tube is exposed to constant wear, resulting in internal diameter increases, which determines the wear tube. Usually firmness of tube presents 10...15 hours, and its cost arrives at 20...50 $ [2].

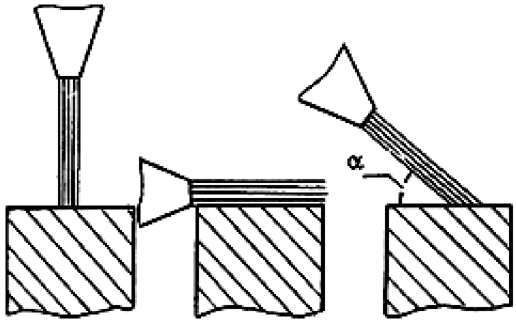
In this regard, an urgent task is improving the stability of calibration tube using the functional-oriented approach.

To determine the peculiarities of wear of calibration tube, the impact of movement abrasive grains and species destruction are analyzed.

The research. It is known that in the motion of two-phase flow "liquid - solid particles" through the calibration tube there is chaotic action on the walls of the tube of some abrasive particles at different angles of attack and with different power of hit [3].

Abrasive destruction of surface of the tube depends on the nature of action of the abrasive grains on its surface. Depending on the direction of action of the abrasive jet to the surface there are the following schemes of action: the destruction with a shock jet , when the angle of attack $\alpha = 90$ (Fig. 2 *a*), with sliding jet, when $\alpha = 0$ (Fig. 2 *b*), with oblique jet, when $0 < \alpha < 90$ (Fig. 2 *c*) [4, 5].

Fig. 1. Calibration tubes, collet mixing chamber and sapphire nozzle inserts by firm SynergicInc., (Provider – ELFIHmbH. Austria)



a *b* *c*

Fig. 2. Scheme of action of the abrasive jet to the surface

If on the flat surface of the material affects the flow of hard abrasive particles that fly at the speed v_u at an angle α to the surface, each share with a punch, elastically deforms the work surface and slip on it with friction [6].

Assumed that the normal component of velocity v_0 makes only elastic deformation of the material, and tangent v_0 is partially or completely extinguished and does the work of cutting, engaging in frictional contact with the surface. With the reduced turns out that the largest processing performance theoretically should be at an angle of attack α = 45, which is confirmed by many authors [6 - 9].

The intensity of wear in the abrasive flow is defined as the result of multiple impacts of solid particles on the surface wear at different angles of attack. Initial period of destruction of the metal is characterized by the introduction of abrasive particles in the surface layer at some depth, the second - of continuous movement of particles of the material along surface layer at some distance at which the displacement of microvolumes of the metal in layer occurs in the direction of introduction of particles and their separation from the array [10] .

In implementing of the abrasive particle in the surface layer of metal in a free kick there is deformation near the contact zone, resulting in this layer there is a complex inhomogeneous stress-strain field with a variable limit. Stresses and strains arising from the introduction of abrasive particles in the metal depend on complex factors that characterize the parameters of the flow of particles and resistance of the metal to elastic-plastic deformations.

Elastic and plastic deformations will develop in the contact zone, which will assist to metal collapse under the particle in the radial direction and subsequent tangential changes in the direction of motion of the relative particles to the surface.

Depth introduction of the particle and its tangential displacement associated with the mechanical properties of the abrasive and of material of wearing surface, particles size, and deformation of the metal.

At small angles of attack due to the predominance of tangential velocity impact, the main process of destruction of the surface layer is the tangential displacement microvolumes of metal in the direction of implementation, i.e. microcutting.

At the angles of the attack close to 90 º,mechanism of destruction of the surface layer of metal in a stream of abrasive particles takes a polydeformational striking character due to the predominance of the normal velocity.

Destruction of structural materials under the action of abrasive particles contained in the flow of fluid is very complex and may be semifluid, brittle, polydeformational or acquires fatigue character and is complicated with phenomenon of cavitation [10].

Thus, the parameters of the internal profile of tube should ensure the following conditions of flow [3]:

1) the minimum thickness of the boundary layer flow inside the tube, turbulent layer of output free jet, which reduces the thickness and the interaction of jet with the environment;

2) reducing of the possibility of separation of boundary layer of jet, helping to reduce excitation of central flow;

3) reducing of the possibility of cavitation, which provides an exception of formations of low pressures inside the tube to avoid formation of bubbles and destruction of tube.

The physical and mechanical properties of the material, which facing the particle, also have impact on the efficiency of processing.

The theoretical dependence given in [6, 7, 10] help to assess of the impact angle of attack on the intensity of wear only qualitatively. Therefore, to analyze the phenomena that occur in calibration tube during the formation of liquid abrasive flow the software package Flow Vision was used. When modeling the problem of detection of conditionality of diagrams load on the cross-section of calibration tube with microhermetic parameters of jet erosion was treated, establish the role and activity of wave processes occurring in streams and exert force on the inner diameter of the calibration tube.

The core package is a unit of the numerical solution of equations of fluid motion in the orthogonal coordinate system (Navier-Stokes equation (1)) that for certain initial and boundary conditions defined by the user, provides a diagram of distribution of velocities and dynamic pressures at the point of contact with the jet or other surface:

$$\begin{cases} \frac{\partial v_r}{\partial t} + v_r \frac{\partial v_r}{\partial r} + \frac{v_\phi}{r}\frac{\partial v_r}{\partial \phi} + v_z \frac{\partial v_r}{\partial z} - \frac{v_\phi^2}{r} = f_r - \frac{1}{\rho}\frac{\partial \rho}{\partial r} + v\left(\frac{\partial^2 v_r}{\partial r^2} + \frac{1}{r^2}\frac{\partial^2 v_r}{\partial \phi^2} + \frac{\partial^2 v_r}{\partial z^2} + \frac{1}{r}\frac{\partial v_r}{\partial r} - \frac{2}{r^2}\frac{\partial v_\phi}{\partial \phi} - \frac{v_r}{r^2}\right); \\ \frac{\partial v_\phi}{\partial t} + v_r \frac{\partial v_\phi}{\partial r} + \frac{v_\phi}{r}\frac{\partial v_\phi}{\partial \phi} + v_z \frac{\partial v_\phi}{\partial z} - \frac{v_r v_\phi}{r} = f_\phi - \frac{1}{\rho r}\frac{\partial \rho}{\partial \phi} + v\left(\frac{\partial^2 v_\phi}{\partial r^2} + \frac{1}{r^2}\frac{\partial^2 v_\phi}{\partial \phi^2} + \frac{\partial^2 v_\phi}{\partial z^2} + \frac{1}{r}\frac{\partial v_\phi}{\partial r} - \frac{2}{r^2}\frac{\partial v_\phi}{\partial \phi} - \frac{v_\phi}{r^2}\right); \\ \frac{\partial v_z}{\partial t} + v_z \frac{\partial v_\phi}{\partial r} + \frac{v_\phi}{r}\frac{\partial v_z}{\partial \phi} + v_z \frac{\partial v_z}{\partial z} = f_z - \frac{1}{\rho r}\frac{\partial \rho}{\partial z} + v\left(\frac{\partial^2 v_z}{\partial r^2} + \frac{1}{r^2}\frac{\partial^2 v_z}{\partial \phi^2} + \frac{\partial^2 v_z}{\partial z^2} + \frac{1}{r}\frac{\partial v_z}{\partial r}\right). \end{cases} \quad (1)$$

where f_r, f_φ, f_z – voltages of mass forces along the respective axes;; r, φ, z, v – kinematic viscosity; $\frac{\partial v_r}{\partial r};\frac{\partial v_r}{\partial \phi};\frac{\partial v_r}{\partial z};\frac{\partial v_\phi}{\partial \phi};\frac{\partial v_\phi}{\partial z};\frac{\partial v_z}{\partial \phi};\frac{\partial v_z}{\partial z}$ – components of the strain rates of elementary volume of fluid (the same name derived describes the strain rate compression or stretching of line elements of the selected volume, and dissimilar – the rate of change of the angles between them); ρ – mass density of fluid; v_r, v_φ, v_z – speeds of the elementary volume of the respective coordinates.

Found stresses values of mass forces along the respective axes provided continuity $\frac{\partial(v_r r)}{\partial r} + \frac{\partial v_\varphi}{\partial \varphi} + r\frac{\partial v_z}{\partial z} = 0$ determines mass force acting on the volume of liquid, which is considered:

$$F = \int_W f\rho dW,$$

where W – elementary volume.

Initial conditions are determined by geometrical profile nozzle orifice, by the pressure of liquid p_b and its properties. Boundary conditions determine the leakage of jet to the surface, which is an internal cylindrical surface of the calibration tube.

Mass transfer was determined by (2) based on the Stokes equation, which determines the strength of resistance in a stream of particles:

$$F_c = \frac{18\mu\Delta w}{d^2{}_s}, \quad (2)$$

where μ – rate of fluid flow through the nozzle; d_s – diameter of tube.

Three-dimensional model of free jet was created to determine the parameters of the system and using the software package Flow Vision was determined the pressure and velocity in the jet.

For the model studies was considered the problem of leakage of jet fluid that flows out of the hole diameter of 1 mm. In order to determine pressure and velocity of fluid in the jet the problem with free surface was created and solved.

Were given the following physical parameters:

- The initial parameters;
- Basic values - temperature 273 K, pressure 101 000 Pa;
- Parameters of the model - the density of liquid 1000kh/m^3;
- Liquid 0 - clear water;
- Adaptation of the grid up to level 2.

Boundary conditions for the elements (walls, entrance, exit) and the degree of adaptation for each of them are given. Speed jet at the inlet is 300 m/s.

Initial mesh with 25652 cells where 21168 of them solidified it in the area of the exit from nozzle and at the surface of leakage is given.

The general model parameters and time course of the calculation in the range from 0 to 5 • 10^{-5} are given, the calculation is standard.

The calculation results derived in the form of diagrams (Fig. 3, *a, b*) fill – pressure in the range of 3,5•10^5 Pa to 7,579•10^7 Pa; rate – isolines, from 0 to 300 m/s [11].

Researches showed that most loaded from the point of view of abrasive wear are places of entrance of liquid-abrasive mixture and on an exit from a tube (Fig. 3). In these areas transversal pressure caused by wave processes maximally influences on the mobile particles of abrasive.

Submitted photomicrography of the edge of nozzle shows that the destruction takes place on that part of that perceived maximum hydrodynamic load (Fig. 4) caused with a back wave in time of leakage jet on an obstacle - the work surface. Thus, the picture of the damage of tube corresponds to parameters of simulated pressure diagram in the longitudinal and end sections nozzle channel. Obtained in Fig. 5 oscillogram shows a periodic increase pressure on the edge of the nozzle with amplitude from 3,89 • 10^8 Pa to 7,579 • 10^7 Pa and frequency 2 • 10^{-6} s, which indicates the presence of wave processes in the body of the jet.

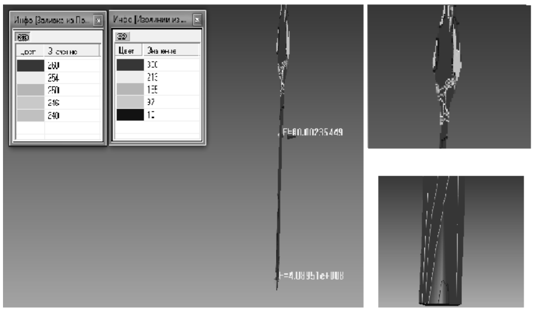


Fig. 3. The results of modeling of liquid-abrasive mixture with the walls of the calibration tube

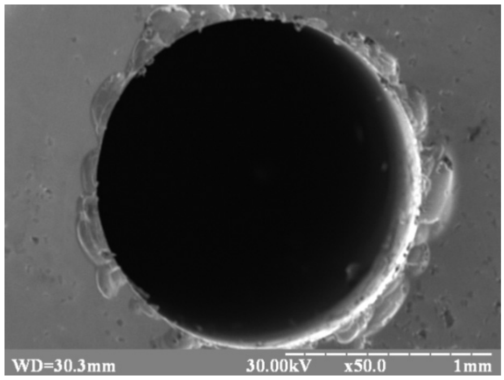


Fig. 4. The photomicrography of the worn edges of the tube

Durability σ_w of materials calibration tubes with hydroabrasive wear is a complex and ambiguous function of the conditions of interaction of material with abrasive particles and the environment [4]:

$$\sigma_w = f(T; \Pi; d; K_m; K_\phi'; v; \alpha; \chi),$$

where T — duration of wear; Π — concentration of abrasive particles in a liquid; d — size of particles; K_m — coefficient of hardness equal to the ratio of hardness of material to hardness of abrasive particles; K_ϕ' — coefficient that describes the shape of the particles; v — velocity of abrasive particles in the moment of impact with the details surface; α — angle of velocity vector of particle to wearing surface (angle of attack); χ — coefficient characterizing the decrease of mechanical properties of material resulting softening physical-chemical action environment.

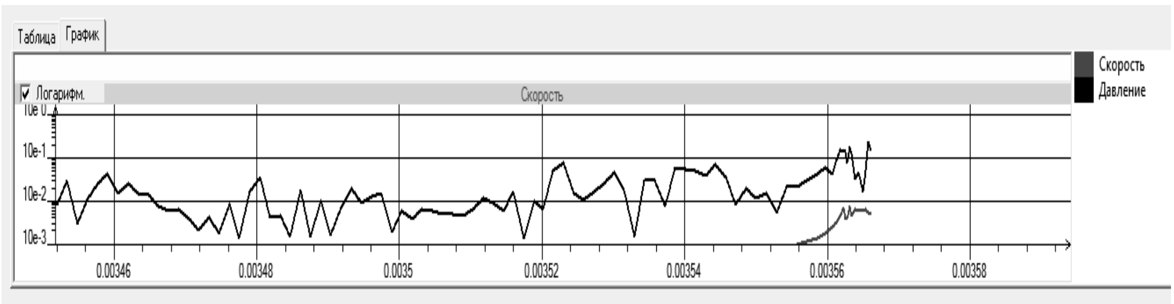


Fig. 5. Graph of velocity and pressure under leakage of jet on the walls of the calibration tube

Total volume of material seized in the interaction with the walls of hydroabrasive stream gauge tube will be:

$$w_{i\Sigma} = w_1 + w_2 = \frac{\pi\delta^2 n(3r - \delta_n)}{3} + \frac{\delta_n(6a + 18b)}{15}\delta_a, \quad (3)$$

hole depth δ_n and its length δ_a as a function of process arameters:

$$\delta_n = \frac{mv^2{}_n}{2}\frac{R_a}{k_n z_n HB}; \delta_a = \frac{mv^2{}_a}{2}\frac{z_n}{k_a\sigma_b R_a} - \frac{k_a T^2{}_p \sigma_b R_a}{2mz_n} \quad (4)$$

where m – mass of abrasive particles; v_n, v_a – normal and tangential component of particle impact velocity with the treated surface; Ra, HB, σ_b – parameters of roughness, hardness and strength of surface; z_n – granularity of abrasive particles; T_p – constant, taking into account the inertia of the process microcutting; k_n, k_a – constant coefficients.

Since the calibration tube takes hydrodynamic and mechanical loading from fast moving abrasive particles inserted in the flow of fluid from the nozzle cut, the reason for its withdrawal from the calibration aperture D_k growth over the limit and split of individual elements, thus changing the geometry formed by grooves cut (Fig. 6). This damage is caused with wearing phenomena. It is logical increase firmness of the calibration tubes by causing protective coatings.

The use of special wear-resistant coatings can significantly improve the time of stability of materials in aggressive environments, improve the stability of the process due to less intensive changes in the dynamics of initial geometrical parameters of the channel. However, currently there are no clear guidelines regarding the type of coatings that can be used in this practice and rational technologies application of such coatings on the inner surface of the channel.

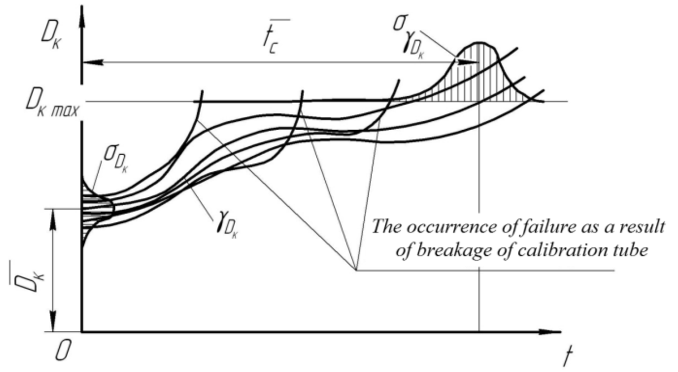
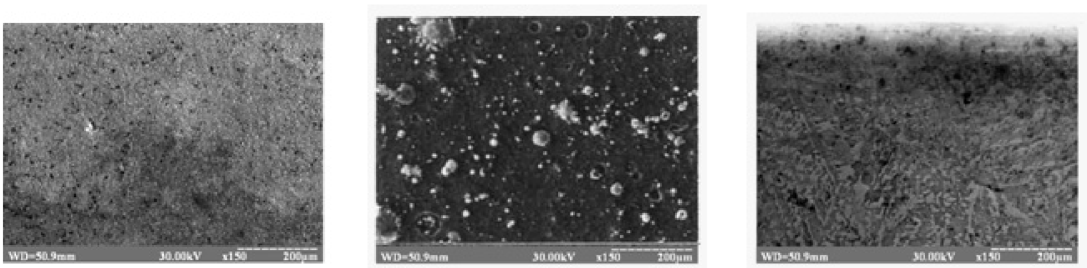


Fig. 6.The dependence of change of the calibration opening on run-in time

To address the question of whether the use of certain surface coatings on hydroabrasive resistance the samples with size 40x10x5 mm from titanium alloy VK8 were tested, which is instrumental material of elements of hydroabrasive processing, as no cover, so with a vacuum-plasma coating TiN, with the nitrided layer and the combined coverage of the nitrided layer and TiN (Fig. 7). Modes of coating are given in Table1.

To microelectronic studies of these, coating were deposited considering functional-oriented approach to flat plates, which were established for research under certain angles to leakage jet (Fig. 8).

Functionally-oriented approach involves the production of calibration tube by special technology, which is based on strict topologically oriented implementation of the required set of algorithms of technological performance of processing in required micro and macro zones and parts of the product that meet the functional requirements of their operation in each of its zone.



a *b* *c*

Fig. 7. Microelectronic researches of alloy VK8:
***a* – without coating; *b* – with coating TiN; *c* – with the nitrided surface layer**

Table 1

Modes of coating

Parameters	**Vacuum-plasma spraying TiN**	**Ionic-plasma thermocyclic nitriding**
Working pressure P	$2{,}2\bullet10^{-3}$ mmHg	100 Pa
Arc current Iд, A	100	10
Temperature T, ºC	520	550
Voltage U, V	500	600
Time, min	40	360

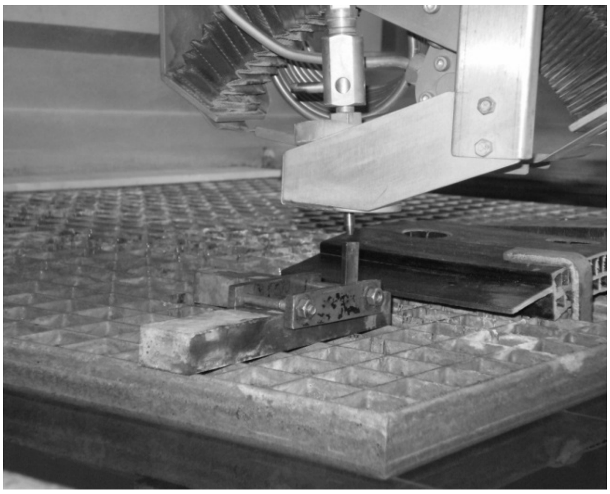


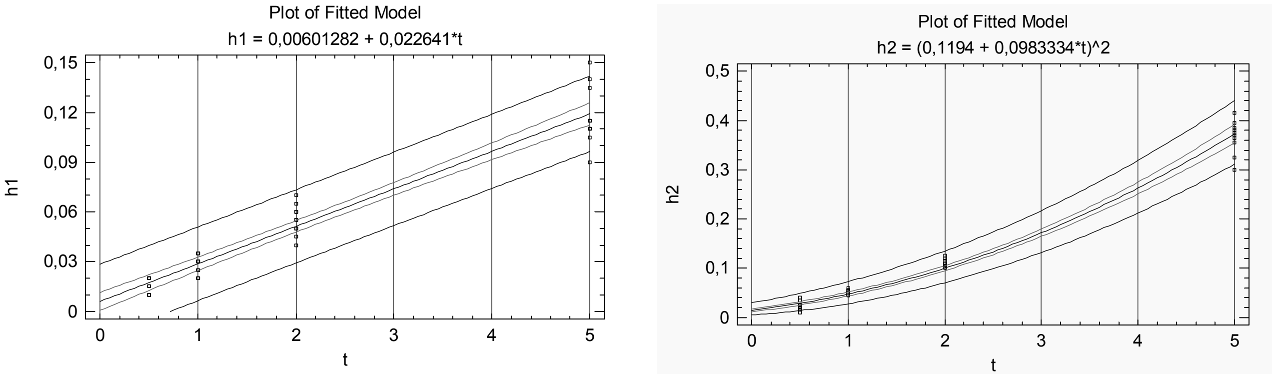
Fig. 8. Installation of a test piece on desktop of hydrocutting machine LSK-5-400

For a comparative analysis all experimental studies were made at the same processing parameters, which were adopted: leakage pressure – 280 MPa, volumetric concentration of abrasive in suspension – 0.6 kg/min, processing time – 10.5 minutes.

Weighing samples before and after processing was made on the analytical scales VLR-200 with accurate weighing to 0.0001 g.

Investigation of angle of attack for wear of samples were carried out using a garnet sand from grit 30 mesh as an abrasive in suspension. The distance between the initial section of ejecting adjutage of ink-jet apparatus and the sample was 80 mm.

In Fig. 9 there are comparative diagrams of coating TiN and combined coating wearing, presented as the depth of damage layer, measured relative to the plane undamaged surface. Angle of leakage of samples is 15^{0} ($\pi/12$).



a *b*

Fig. 9. The comparative diagrams wear of coating TiN (*a*) and combined coating nitrided + TiN (*b*)

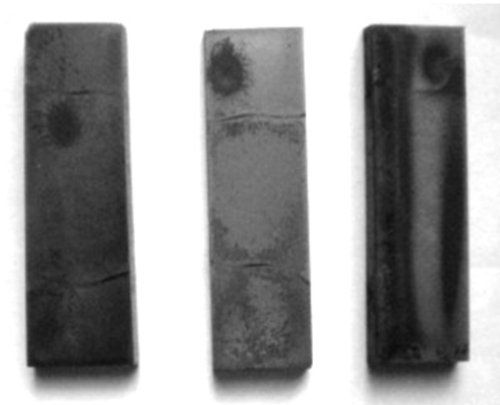


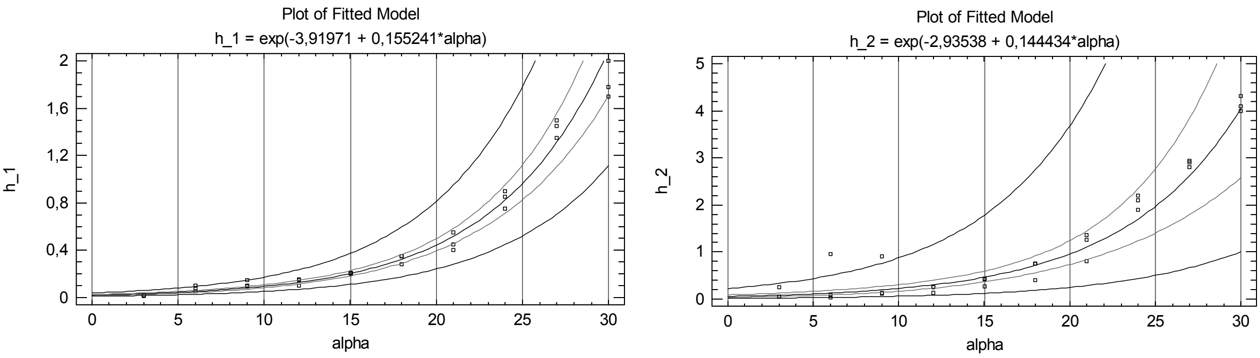
Fig. 10. Samples after testing

Found that the dynamics of damage protective coatings is fundamentally different: coating TiN weared more rapidly and in 3 minutes damage reached its maximum. After that damage rate declined, and on the samples were observed area almost its complete removal. Further active destruction of substrate material began (Fig. 10).

The of combined coating was more resistant to liquid cavitation abrasive wear (almost 3 times). This wear was evenly without forming complete detachment areas.

In the following diagrams the dependence of the degree of damage is presented (like a deep hole that is formed on the surface (h) for a fluid time). Dependence of change of depth hole formed in function of the angle jet of leakage α is given.

Impact angle of leakage boost on the speed of removal of coating was determined by measuring the penetration of the jet in the specimen at a time equal to 1 min. Measurements performed in the range of angles from 3^0 ($\pi/60$) to 30^0 (a further increase in angle leads to complete destruction of coating and base and a groove about 3-4 mm).



a *b*

Fig. 11. Dependence of wear coating TiN (*a*) and combined coating on the corner of accumulating (*b*)

The adequacy of the obtained models – 0.95.

According to the obtained data it is easy to conclude that most works better coverage at the tangent jet of leakage. The operation time in 1 min is not exponential, because this time is necessary to establish to ensure comparability of measurements of the dynamics of wear at the big corners of leakage.

Conclusion. Comparison of the stability of samples with coating and without coating shows that the coating provides a two-band dynamics of growth of the outlet calibration tube: the time of operation and cover with work of tube is worn surface.

Thus, comparative experimental tests have shown that depending on the modes of technological processing, samples with a combined surface of the nitrided layer and TiN wearless intense than the samples without coating when exposed hydroabrasive stream. With all the parameters – D_k, σ_{Dk}, γ_{Dk}, λ_{Dk}, deposition of functional coatings helps to reduce γ_{Dk}, thereby increasing lifetime of the tube to the predicted onset of failure as $T_3 = \dfrac{D_к - D_i}{\gamma_D}$.

The functional dependence of wear of calibration tubes with coating for criteria of hydroabrasive stability complete the overall methodological information base and certainly contribute to the development of the principle properties of the surface layer.

Аннотация. *В работе рассмотрены вопросы исследования устойчивости покрытий TiN, азотированного слоя и комбинированного покрытия из азотированного слоя и TiN в условиях высокоинтенсивного кавитационно-гидроабразивного износа. Получены регрессионные уравнения устойчивости покрытий, нанесенных на основу из твердого сплава типа ВК 8 от условий натекания жидкости. Показаны возможности использования функционально-ориентированного подхода к формированию поверхностного слоя протоковых частей элементов гидрорежущих устройств, доказано повышение их работоспособности.*
Ключевые слова:покрытия, гидрорежущие устройства, гидроабразивное изнашивание.

Abstract.
Purpose. Among the trends of hydroabrasive treatment the improving of the accuracy and efficiency of processing equipment is allocated. Effectiveness can be enhanced by increasing fluid pressure and the number of concurrent working heads. However, increasing of working pressure leads to intensification of systems of wear of hydrocutting equipment, including calibration tubes, which in turn reflected in the cost of processing. In this regard, an urgent task is improving the stability of calibration tube using the functional-oriented approach.
Design/methodology/approach. To analyze the phenomena that occur in calibration tube during the formation of liquid abrasive flow the software package Flow Vision was used. When modeling the problem of detection of conditionality of diagrams load on the cross-section of calibration tube with microhermetic parameters of jet erosion was treated, establish the role and activity of wave processes occurring in streams and exert force on the inner diameter of the calibration tube. To address the question of whether the use of certain surface coatings on hydroabrasive resistance the samples with size 40x10x5 mm from titanium alloy VK8 were tested, which is instrumental material of elements of hydroabrasive processing, as no cover, so with a vacuum-plasma coating TiN, with the nitrided layer and the combined coverage of the nitrided layer and TiN.
Findings. comparative experimental tests have shown that depending on the modes of technological processing, samples with a combined surface of the nitrided layer and TiN wearless intense than the samples without coating when exposed hydroabrasive stream.
Originality/value. The functional dependence of wear of calibration tubes with coating for criteria of hydroabrasive stability complete the overall methodological information base and certainly contribute to the development of the principle properties of the surface layer.
Keywords: coatings, hydrocutting devices, hydro-cavitation wear.

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