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DETERMINING FEATURES IN THE WEAR RESISTANCE CHARACTERISTICS OF TRIBOCOMPOUNDS WITH A TEXTURED HOLE SURFACE UNDER CONDITIONS OF BOUNDARY FRICTION

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The influence of surface texture in the form of pits on the wear resistance of tribocompounds under conditions of limit friction was investigated. At the first stage of research, the mechanism of lubricant behavior between the contacting surfaces and inside the holes was modeled. The limiting condition of the rotation frequency of the sample (n>27) was established, under which a drop of lubricant "leaves" the hole in the upper position of the sample and remains in the space between the sample and the surface of the counterbody, ensuring the regeneration of the boundary lubricating film on the surface of the tribocontact when it is destroyed. When the rotation frequency of the sample is reduced (n<27), the lubricant droplet remains in the hole and does not affect the processes of the boundary lubricant film. At the second stage, experimental studies of tribocombinations with a textured hole surface under conditions of extreme friction were carried out. It was established that the high wear resistance of the textured hole surfaces is provided by the high protective effect of the texture, as well as the high efficiency of the marginal lubricating film. It has been proven that the strengthening of the surface texture by the method of ion-plasma thermocyclic nitriding additionally increases the wear resistance by 1.7 times due to the high protective effect of surface nitrided layers and their high hardness (up to 9500 MPa). This strengthens the effect of inhibiting the occurrence of defects in the surface layers of tribocontact, ensures a high rate of wetting of the places of actual contact of triboconnections, and speeds up the process of regeneration of the boundary lubricating film. Research results can be used to modify the surface layer of heavily loaded parts operating under extreme operating conditions with limited supply of lubricant under various types of friction and wear

Keywords: wear resistance, coefficient of friction, textured surface, hole, boundary friction, regeneration of lubricating film, lubricant droplet, mathematical model

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1. Introduction

Most of the friction units of machines and mechanisms work under conditions of lubrication of the contacting surfaces. It is generally accepted that the wear of tribonodes during the start and stop modes is so great that it is compared to the wear during basic operation. But the greatest wear occurs during the first start-up and especially at low temperatures – the limit friction mode, which is manifested at a minimum thickness of the lubricating film and at a limited supply of lubricant. The wear mechanism under such conditions is complex and different for most friction nodes. Ensuring the reliability of the nodes' operation at extreme friction consists primarily in the improvement of the surface lubrication mechanism and the use of modern technologies for strengthening the contacting surfaces. Therefore, the lubrication of textured surfaces is an open area of research.

2. Literature review and problem statement

Technological methods for creating textured surfaces, the essence of which is replacing the traditional solid layer of the surface with an intermittent mosaic-discrete structure, open up wide possibilities. The surface texture can be performed both in the form of a protrusion and in the form of dimples (holes), and the latter is more popular, especially under elastohydrodynamic and boundary lubrication regimes, due to advantages in terms of micro lubrication and ease of manufacture [1].

The advantages of using surface texturing are widely known. A first advantage is the storage and subsequent release of oil to prevent lubrication starvation. A second one is in the removal of wear products from the tribocontact zone, preventing their action as an abrasive material. The most noticeable effect for increasing the bearing capacity of a textured surface under lubrication conditions is the mechanism for creating additional hydrodynamic lift due to the presence of cavitation and convergent wedges [2]. Other mechanisms, including the occurrence of local cavitation [3], the effect of inertia [4] and suction at the entrance [5] also explained the increase in bearing capacity during hydrodynamic and mixed lubrication of the textured surface. The specified mechanisms show that the tribotechnical characteristics of textured surfaces are very sensitive to texture and depend on their design and technological parameters of formation, which requires more detailed research. The selection of optimal design parameters of the texture will make it possible to reduce the duration of running-in, to improve the tribotechnical characteristics of tribocompounds. This becomes especially important for responsible and heavily loaded nodes and mechanisms operating under conditions of limited supply of lubricant [6].

The shape and geometric parameters of the texture also affect the tribological properties of the textured surfaces and the lubrication efficiency of the textured surface. Thus, some dimple shapes with different geometric parameters, densities, texture pattern orientations work better if you increase the load. Each micro dimple can serve either as a micro hydrodynamic bearing in cases of full or mixed lubrication, or as a micro reservoir for lubricant in cases of starvation under extreme friction conditions [7]. Thus, the texture of round pits [8] has better tribological characteristics than smooth surfaces. Based on the study of the circular texture, elliptical and triangular forms of textures with different sliding directions were developed [7]. The results showed that the geometric shape and orientation had a significant effect on the bearing capacity of the texture surface. Under the same geometric parameters, the bearing capacity of elliptical pits perpendicular to the sliding direction was the best. It has been found that a square texture with $\theta=90°$ orientation can exhibit better hydrodynamic lubrication characteristics than a circular texture by properly increasing the groove depth when the areal density exceeds 25 % [9]. But the question of the effectiveness of the lubricating effect of textures under conditions of extreme friction with the aim of further practical application of textured surfaces remains unresolved.

Studies of chevron textures have shown that the geometric parameters of depth, length, width, and angle significantly affect lubrication efficiency. In particular, area density has the most obvious effect, while length exerts the least effect. In addition, texture distribution has a significant impact on lubrication performance. The more textures are located along the direction of the lubricant flow, the higher the load capacity and the lower the friction coefficient [10]. One requires a comprehensive study and identification of the interrelationship of the factors that determine the course of the lubricant movement behavior within the texture and on the surface between the textures, their impact on the lubrication performance and the load-bearing capacity of the tribocompound.

Numerical approaches to optimization for a texture shape with better lubricating properties have become widespread. It was found using sequential quadratic programming [11] that a chevron shape with flat fronts is the optimal shape for unidirectional sliding, while the optimal texture for bidirectional sliding was a pair of trapezoidal shapes. The developed geometric model [10] with a parabolic profile made it possible to optimize the parameters of the surface texture. Groove orientation angle, depth, areal density, and textured fraction were confirmed to have significant effects on tribological properties. An effective Navier-Stokes model was built to study the textured surface lubrication of deep textures of moderate length and high oil flow rate [12]. To obtain more realistic modeling results, it is necessary to expand it with the help of a cavitation model.

The wear mechanism of the surface texture is affected by its stress-strain state, the dimensions and configuration of which are set based on the conditions for minimizing the stress-strain state under force (temperature) impact on the surface. This makes it possible to increase its limit state several times [13, 14].

The processes of excitation of internal magnetic fields play an important role in determining the mechanism for the wear of textured surfaces, along with the traditional processes of formation and destruction of secondary structures. An inhomogeneous resulting magnetic field is formed at the edges of discrete areas, which leads to the emergence of a ponderomotive force. The ponderomotive force acts on the wear particles and directs them towards greater induction of the magnetic field – the edge of the hole, which leads to the prevention of unacceptable processes of destruction of the contacting surfaces [15].

Thus, the mechanism of texture wear is complex and multifaceted, which requires more detailed and comprehensive scientific research with the aim of further practical application of textured surfaces. For an effective analysis of the wear mechanism of textured surfaces, it is necessary to identify the interrelationship of the factors that determine the course of the process and represent them in a quantitative form – in the form of a mathematical model that could be used to control the simulated processes.

3. The study materials and methods

The purpose of this work is to determine the characteristics of the wear resistance of tribocompounds with a textured hole surface under conditions of extreme friction, with the construction of a mathematical model of the behavior of the lubricant between the contacting surfaces and inside the holes and conducting experimental studies. This will make it possible to understand the mechanism of action of the lubricant under conditions of extreme friction and to devise measures to improve the mechanism of lubrication of textured surfaces in order to increase the wear resistance of tribocompounds.

To achieve the goal, the following tasks were set:

– to build a mathematical model for evaluating the behavior of the lubricant between the contacting surfaces and inside the holes;

– to conduct experimental studies of tribocompounds with a texture in the form of holes (micro-indentations) during friction with a limited supply of lubricant.

4. The study materials and methods

The object of our research is textured surfaces that were formed:

– by the method of mechanical (vibro-impact) creation of holes with a given texture;

– a combined method that combines the method of mechanical (vibro-impact) creation of holes and the subsequent application of the ion-plasma thermocyclic nitriding (IPTA) method;

– by the method of electro spark alloying.

Experimental studies of tribotechnical characteristics of textured surfaces were carried out at friction with a limited supply of lubricant. Hardened steel 45 was used as the material of the sample, and steel 30HGSA was used as the counter sample. The working surface of the samples and counter-samples was polished to R_a=0.32 µm. The holes were formed on the flat end surface of the counter-samples by plastic deformation of the material under the dynamic action of the indenter using a special device that makes it possible to adjust, depending on the movement of the indenter head, the geometry of the holes, as well as the distance between the holes and the distance between rows of holes. Textured hole surfaces (THS) were additionally subjected to strengthening by the IPTA method, which was carried out at the VIPA-1 installation.

For tests of samples with THS under conditions of extreme lubrication, an installation was used – a M-22M friction machine. The contact of the friction pair took place according to the "disk-pad" scheme. The research was carried out at a sliding speed of 0.625 m/s, a specific load of 10.0 MPa, a distance of 2000 m. I-20A industrial lubricant was used as a lubricating medium in accordance with GOST 20799-75. To ensure the limit friction mode, a lubricating device was used in accordance with the recommendations of GOST 26614-85.

The application of coatings on the working areas of the samples was carried out by the electro spark alloying method on the Elytron-22 installation, and an alloy based on VK8 was used as the anode. Discrete structures were formed on the working surfaces of the samples by applying a modified VK8+M coating.

To study the mechanism of lubricant behavior between the contacting surfaces and inside the holes, we shall consider the problem of the movement of an oil droplet in the hole (Fig. 1). The following forces act on a drop of oil of mass *m*, which is in the hole, during the rotation of the counter sample:

– centrifugal force $F_B = m\omega^2 R$;

– Earth's gravity $F_g = mg$;

– oil surface tension force $F_{s.t.} = \sigma l$.

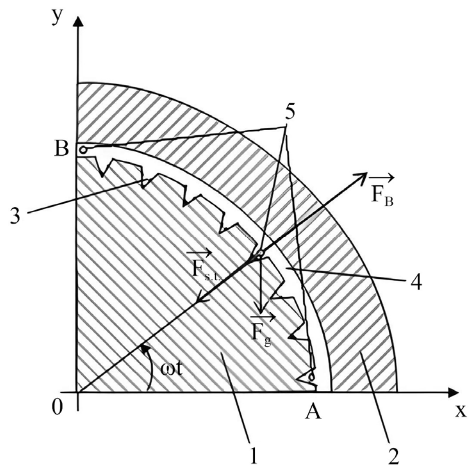


Fig. 1. Movement scheme of a drop of lubricant and the action of forces on it in the process of limit friction: 1 – sample; 2 – counter sample; 3 – hole; 4 – lubricant; 5 – a drop of lubricant

Here:

– $\omega = 2\pi/T$ – angular velocity, rev/s (rad/s);

– $T = 1/n$ – period of rotation, s;

– n – rotation frequency, Hz;

– R – counter sample radius, m;

– g – acceleration of Earth's gravity, m/s^2;

– m – droplet mass, kg;

– σ – surface tension coefficient;

– l – perimeter of the hole, m.

5. Results of mathematical modeling of lubricant behavior and experimental studies of textured surfaces

5. 1. Mathematical model for evaluating the behavior of the lubricant between the contacting surfaces and inside the holes

According to Newton's law:

$$\vec{F} = m\vec{a} = \vec{F}_y + \vec{F}_x + \vec{F}_{s.t.}.$$

In the projections on the *OY* and *OX* axes, we derived the following system of equations:

$$\begin{cases} ma_y = -mg + m\omega^2 R\sin(\omega t) - \sigma l\cos\left(\dfrac{\pi}{2} - \omega t\right); \\ ma_x = m\omega^2 R\cos(\omega t) - \sigma l\sin\left(\dfrac{\pi}{2} - \omega t\right). \end{cases} \quad (1)$$

Dividing by *m* the left and right parts of the equations and taking into account that $a_y = \ddot{y},\ a_x = \ddot{x},$ we built a linear system of differential equations of the second order:

$$\begin{cases} \ddot{y} = -g + \omega^2 R\sin(\omega t) - \dfrac{\sigma l}{m}\sin(\omega t); \\ \ddot{x} = \omega^2 R\cos(\omega t) - \dfrac{\sigma l}{m}\cos(\omega t). \end{cases} \quad (2)$$

By direct integration, we proceeded to the system:

$$\begin{cases} \dot{y} = -gt - \omega R\cos(\omega t) + \dfrac{\sigma l}{m\omega}\cos(\omega t) + C_1; \\ \dot{x} = \omega R\sin(\omega t) - \dfrac{\sigma l}{m\omega}\sin(\omega t) + C_1'. \end{cases} \quad (3)$$

We finally obtained the general solution to the initial system of differential equations (1):

$$\begin{cases} y = -\dfrac{gt^2}{2} - R\sin(\omega t) + \dfrac{\sigma l}{m\omega^2}\sin(\omega t) + C_1 t + C_2; \\ x = -R\cos(\omega t) + \dfrac{\sigma l}{m\omega^2}\cos(\omega t) + C_1' t + C_2'. \end{cases} \quad (4)$$

To determine the constant values C_1, C_2, C_1', C_2', we take into account the initial conditions: at time values $t=0$ (position of the hole at point A) $\dot{x} = 0,\ \dot{y} = 0,$ and $x=R$, $y=0$.

From system (3), we determine C_1 and C_1' at $t=0$. We received:

$$\begin{cases} 0 = -\omega R + \dfrac{\sigma l}{m\omega} + C_1; \\ 0 = C_1'; \end{cases} \quad (5)$$

$$\begin{cases} C_1 = \omega R - \dfrac{\sigma l}{m\omega}; \\ C_1' = 0. \end{cases} \tag{6}$$

According to system (4) at $t=0$, $C_2=0$ and:

$$C_2' = 2R - \frac{\sigma l}{m\omega^2}.$$

Thus, the partial solution to system (4) was written as follows:

$$\begin{cases} y = -\dfrac{gt^2}{2} - R\sin(\omega t) + \\ + \dfrac{\sigma l}{m\omega^2}\sin(\omega t) + \left(\omega R - \dfrac{\sigma l}{m\omega}\right)t; \\ x = -R\cos(\omega t) + \\ \dfrac{\sigma l}{m\omega^2}\cos(\omega t) + 2R - \dfrac{\sigma l}{m\omega^2}. \end{cases} \tag{7}$$

We considered how the drop would move when it rotates 1/4. Let the rotation frequency n=50, the rotation period $\left(T=\dfrac{1}{n}\right) T=\dfrac{1}{50}$ s, R=0.1 m, $\omega=\dfrac{2\pi}{T}=100$ rpm, $l=0.008$ m, $\sigma=26\times10^{-3}$. Let's give time t the following values: t=0 s, $t=\dfrac{1}{600}$ s, $t=\dfrac{1}{300}$ s, $t=\dfrac{1}{200}$ s. Accordingly, we got the coordinates of the drop of oil for these values of t. Similarly, we calculated the coordinates of the droplet for n=40, 35, 30, 25 and entered the obtained data into Table 1.

Analyzing the obtained data (Table 1, Fig. 2), we concluded that the droplet "leaves" the hole in the upper position of the sample (point B, Fig. 1) at n>27 and remains in space between the sample and the surface of the counterbody. This ensures the regeneration of the destroyed limit lubricating film on the surface of the tribocontact when it is destroyed. If the rotation frequency (n value) is changed, then at n<27 (T>1/27) the droplet remains in the hole. Regeneration of the lubricating film does not occur.

Table 1

For R=0.1 and the specified surface tension

n=50 rev/min	t, s	1/200	1/300	1/600	0	Drop leaves the hole
	y_m	0.1412	0.0971	0.0452	0	
	x_m	0.0131	0.0434	0.0872	0.1	
n=40 rev/min	t, s	1/160	1/240	1/480	0	
	y_m	0.1311	0.0952	0.0451	0	
	x_m	0.0072	0.0431	0.0876	0.1	
n=35 rev/min	t, s	1/140	1/210	1/420	0	
	y_m	0.1235	0.0901	0.0427	0	
	x_m	0.0054	0.043	0.0862	0.1	
n=30 rev/min	t, s	1/120	1/180	1/360	0	At n=26.27 rev/min, drop stays for a while in the hole
	y_m	0.1127	0.0841	0.049	0	
	x_m	0.0023	0.0441	0.0847	0.1	
n=25 rev/min	t, s	1/100	1/150	1/300	0	Drop stays in the hole
	y_m	0.1	0.0834	0.048	0	
	x_m	0	0.0467	0.0841	0.1	

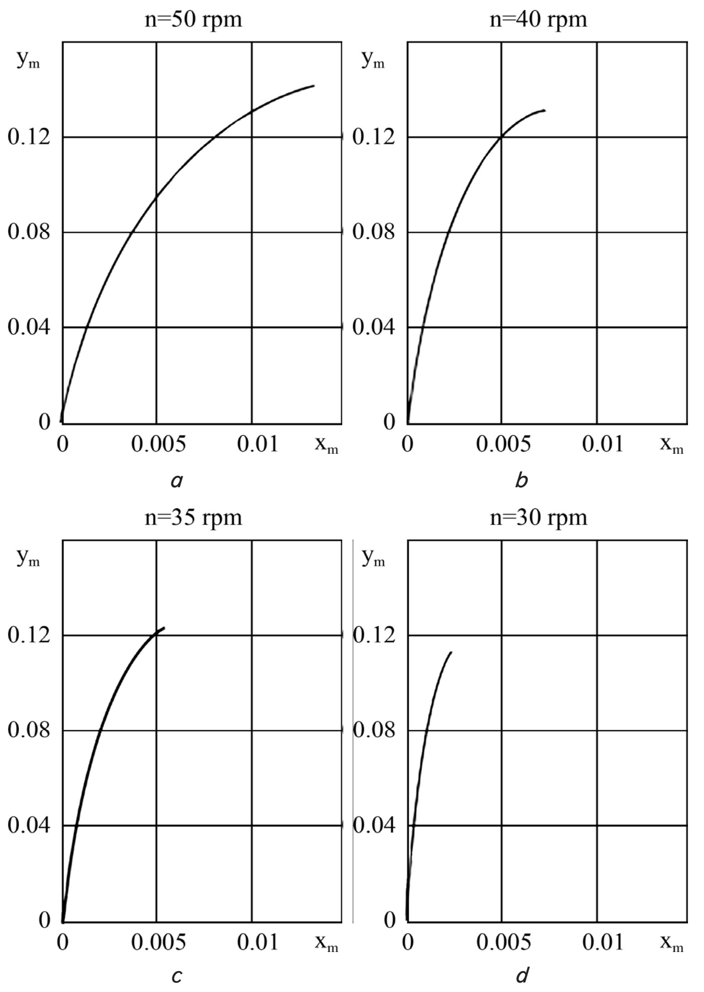


Fig. 2. Trajectory of particle movement at different revolutions per minute: *a* – *n*=50 rpm; *b* – *n*=40 rpm; *c* – *n*=35 rpm; *d* – *n*=30 rpm

Therefore, the high wear resistance of the surface texture with holes is due to the high oil capacity of the holes, in which lubricants will be stored to restore the boundary lubricating film when it is destroyed in the places of tribocontact. Under the condition n>27, the surface of the stationary sample will be constantly lubricated by the flow of lubricant stored in the hole, ensuring the regeneration of the boundary lubricant film on the surface of the tribocontact, which is determined by the time of adsorption filling of gaps in its areas. These processes will improve the tribotechnical characteristics of friction and contribute to reducing the wear of contacting surfaces.

5. 2. Experimental studies of textured surfaces at friction with limited supply of lubricant

Experimental studies of the tribotechnical characteristics of THS during frictional sliding under conditions of extreme lubrication showed that the samples with THS have the highest wear resistance and the lowest coefficient of friction (Fig. 3). The high wear resistance of THS (30HGSA+L) is due to the high protective effect of the surface layers on the one hand, and on the other hand to the high efficiency of the boundary lubricating film.

Fractographic analysis of THS (30HGSA+L) showed that they are smooth with no significant damage and destruction of the surface layer (Fig. 4). This is due to the fact that lubricants under conditions of extreme lubrication have the property of influencing the processes of plastic deformation and destruction of the surface layer of the metal. Under the action of the lubricant, the process of plastic deformation of thin surface layers leads to the diffusion activity of the metal. This significantly affects the physical and chemical processes in the boundary lubricating film, determines the nature of the formation of the dislocation structure in the surface layer of the metal.

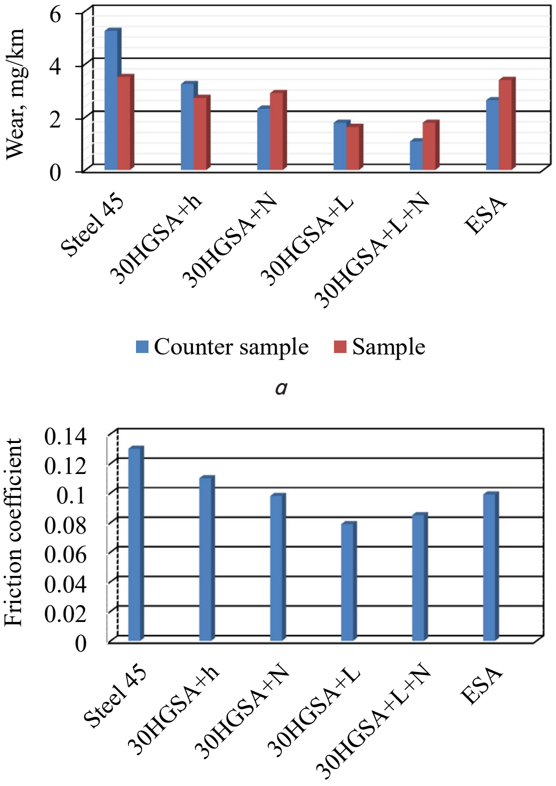


Fig. 3. Tribotechnical characteristics of textured hole surfaces under conditions of extreme lubrication: *a* – wear; *b* – coefficient of friction; h – hardened; N – nitriding; L – holes; ESA – electro spark alloying

In tribocontact, the applied load is perceived by the peaks of micro-uniformities in the interhole space, and the actual contact area will represent the general plane of the deformed peaks of these irregularities. The friction process consists in the deformation of thin surface layers of contacting micro-uniformities, which is accompanied by the destruction of the boundary lubricating film and secondary structures due to repeated loading. This leads to the development of microcracks, their merging, peeling of the film, and the appearance of micropores. This trend is observed on the friction surface in the interhole space, where the size and depth of micropores is 0.5–2.0 μm (Fig. 4, *b*).

The IPTA method was used to strengthen the surface layer of THS. The high wear resistance of THS (30HGSA+L+N) as a whole, as well as individual discrete areas, is due to the high protective effect of surface nitrided layers and their high hardness, which enhances the effect of inhibiting defects in the surface layers of tribocontact. This leads to a decrease in the intensity of the formation of wear products in the surface layer, which is confirmed by the absence of traces of damage from unacceptable wear processes on the friction surface (Fig. 5). In addition, the high hardness of the nitrided layer (up to 9500 MPa) leads to increased wear of the surface layer of the sample and to an increase in the coefficient of friction (Fig. 3, *a*).

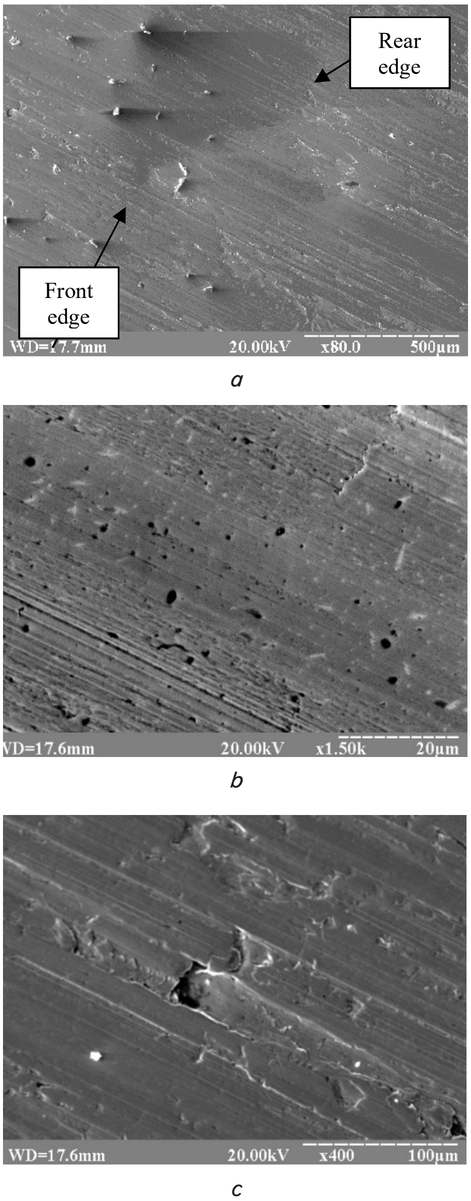


Fig. 4. Photomicrographs of the friction surface of the textured hole surface: *a* – general view of the friction surface with the textured hole surface; *b*, *c* – friction surface in the space between the holes

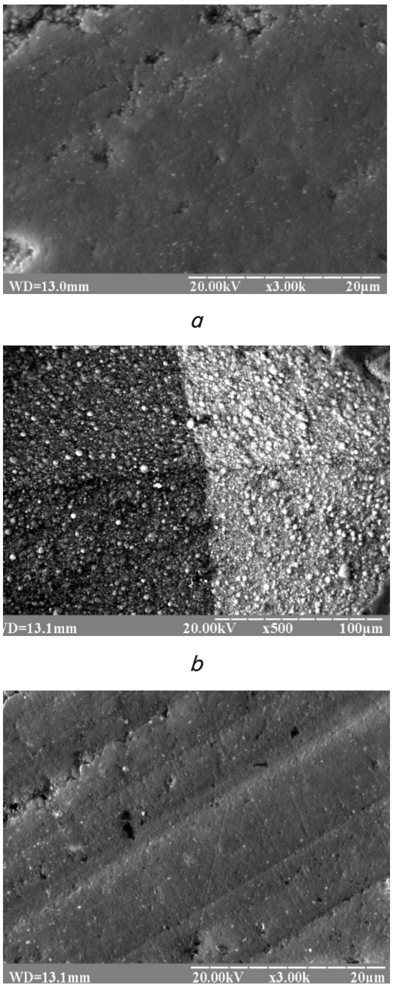
Electro spark coating VK8+M has lower wear resistance (Fig. 3). The friction surface is characterized by a texture in the form of micro-indentations of different sizes with sizes up to 400×150 μm, which were formed after coating in the lubricant medium (Fig. 6). Chemical analysis of the friction surface revealed that 68.32 % of the total number of elements is occupied by iron (Table 2, T.1). This leads to an increase in defects, a decrease in wear resistance, and an increase in the coefficient of friction during the removal of wear products. Wear products will act as an abrasive material on the tribocontact surface.

Four characteristic zones can be distinguished on the friction surface: white, gray, black, and the zone located in the middle of the micro-indentations. The white zone represents the zone of the strengthened layer (Fig. 6, *c*, *d*, T. 3), the basis of which is tungsten (71.94 %) in the form of carbide W_2C, which was formed during the formation of the coating. The formation of W_2C carbide is due to the action of an electric spark discharge when WC monocarbide loses carbon. This zone has a high hardness and will carry the main load during friction under conditions of extreme lubrication and provide high wear resistance of the coating.

Table 2

Elemental composition of the friction surface of the electro spark coating at characteristic points and from the entire surface

Analysis points (area) on the friction surface	Element, %					
	C	N	Cr	Fe	Co	W
T. 1	1.44	0.52	0.45	68.32	3.03	26.24
T. 2	0.24	0.29	0.23	97.34	0	1.91
T. 3	0	0	0.13	21.12	6.8	71.94
T. 4	0.18	0.02	0	99.32	0	0.47
T. 5	0.44	0.16	0.05	58.2	3.79	37.37

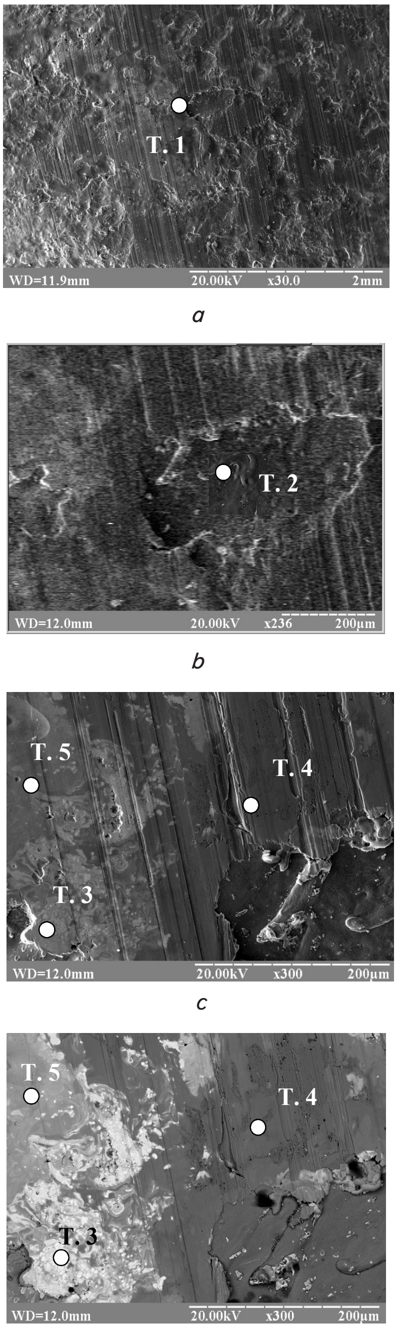


a

b

c

Fig. 5. Photomicrographs of the friction surface of the textured hole surface 30HGSA+L+N under conditions of limit lubrication: *a* — friction surface in front of the hole; *b* — the bottom of the hole; *c* — the friction surface behind the hole



a

b

c

d

Fig. 6. Photomicrographs of the friction surface of the VK8+M electro spark coating under conditions of limit lubrication: *a* — general appearance of the friction surface; *b*, *c* — discrete section; *d* — contrast image

The black zone (Fig. 6, *c*, *d*, T. 4) and the zone located in the middle of the micro indentations (Fig. 6, *c*, *d*, T. 2) have almost the same chemical composition. The main element in these zones is iron – the base material. The basis of the gray zone (Fig. 6, *c*, *d*, T. 5) is iron (58.2 %), tungsten (37.37 %), and cobalt (3.39 %). As in THS, the micro-recesses of the VK8+M electro spark coating will play the role of reservoirs for the storage of lubricant, which will be used to restore the limit lubricant film. In addition, micro-grooves will ensure the removal of wear products from the friction surface. High wear resistance will also depend on the ability of cobalt to retain tungsten carbide particles on the friction surface. Together, these processes will determine the wear resistance of the electro spark coating under conditions of extreme lubrication.

6. Discussion of results of investigating the effect of surface texture on the wear resistance of tribocompounds under conditions of limit friction

The study of textured surfaces was carried out in two stages. At the first stage, a mathematical model of the behavior mechanism of the lubricant between the contacting surfaces and inside the holes was built, which considers one of the main advantages of creating a surface texture. It provides an answer to the question under which boundary conditions of rotation of the sample (Table 1) regenerate the boundary lubricating film upon its destruction. The model built expands the understanding of the mechanism of wear of THS under conditions of limit friction and is a component of the general mechanism. This is explained by the fact that, along with the traditional processes of formation and destruction of secondary structures, other processes play a role in the wear mechanism of THS. In contrast to [15, 16], where the THS wear mechanism is considered from the standpoint of excitation of internal magnetic fields that arise at the edges of discrete areas. As a result, an inhomogeneous resulting magnetic field is formed, which leads to the emergence of a ponderomotive force, which acts on the wear particles and directs them into the holes (greater induction of the magnetic field). Wear particles accumulate in the holes, which leads to the prevention of unacceptable processes of destruction of the contacting surfaces. Under the influence of a magnetic field on the lubricant [16], a dipole-orientational polarization of the lubricant molecules occurs. As a result, the number of diamagnetic lubricant molecules on the surface of the tribocontact increases, a stable lubricating layer is formed, and less energy needs to be spent on the regeneration of boundary lubricating films. These processes retain their activity in the process of friction when lubricant molecules leave the limits of the magnetic field created by the edges of the holes, which has a positive effect on the wear resistance of the surface layer of THS parts. The wear mechanism of THS from the point of view of minimizing the stress-strain state of the texture configuration [13] is ensured by its strengthening of the surface layer by the IPTA method, which eliminates residual tensile stresses, defects on the inner sides of discrete areas, and improves tribotechnical characteristics. Collectively, these processes play an important role in determining the general mechanism of wear of THS and their further practical application. The disadvantage of the constructed mathematical model is that it explains the mechanism of wear only from the point of view of the regeneration of the boundary lubricating film upon its destruction and does not take into account the effect of other factors. This, on the one hand, has certain limitations of its application. On the other hand, the presented model supplements the information about the complex mechanism of wear of THS under conditions of limited supply of lubricant.

At the second stage, the mechanism of THS wear was considered from the point of view of the processes of deformation of thin surface layers of contacting micro-uniformities, which is accompanied by the destruction of the boundary lubricating film and secondary structures due to repeated loading. The high protective effect of the surface layers on the one hand, and the high efficiency of the limit lubricating film on the other hand, provided the best tribotechnical characteristics of THS. Strengthening the texture by the IPTA method made it possible to eliminate defects in the surface layers of THS, to reduce the intensity of the formation of wear products in the surface layer, which is confirmed by the absence of traces of damage from unacceptable wear processes on the friction surface (Fig. 5). Such conclusions can be considered appropriate from a practical point of view since they allow a reasoned approach to the selection of the optimal surface texture, the method of its strengthening, which will lead to a decrease in the wear of THS and, as a result, to an expansion of the range of operation of tribo-joints under conditions of extreme friction.

As in THS, the micro-recesses of the modified VK8+M electro spark coating will play the role of reservoirs for storing the lubricant, which will be used to restore the limit lubricating film. The high wear resistance of VK8+M (Fig. 3) is associated with the technological process of its formation due to greasing the surface of the part with petroleum-based lubricant to replace the conditions of hardening of metal particles in an air environment with the conditions of hardening of metal particles in a liquid environment. As a result, thermal action spreads more slowly to the depth of the part, as a result of which the amount of residual structural stresses and fatigue of the metal decreases, and the wear resistance ultimately increases. The depth and nature of the distribution along the depth of the residual structural stresses depend on the alloying electrode, the material of the part, and processing conditions, which has certain conditions of application of this method for modification of electro spark coatings. From a practical point of view, the technologist decides which alloying electrode is suitable for strengthening the surface of certain friction pairs under certain conditions. We only proposed a technique for modifying the VK8 electro spark coating, which can be applied to other materials of parts. In further work, it is planned to investigate electrodes made of other materials when the electro spark coating is modified using this technology.

7. Conclusions

1. The derived mathematical model expands the understanding of the wear mechanism of THS under conditions of limit friction. It has made it possible to reveal the condition for the effective flow of the tribocontact surface lubrication mechanism during the destruction of the boundary film, namely, the rotation frequency of the sample should be $n>27$. This ensures the transfer of the lubricant from the hole to the problem area, the restoration of the limit lubricant film on the surface of the tribocontact, thereby enabling the smooth operation of a tribocompound.

2. Experimental studies have established a 1.7-fold increase in wear resistance with additional strengthening of THS by the method of ion-plasma thermocyclic nitriding. This is ensured by the high protective effect of surface nitrided layers and their high hardness (up to 9500 MPa), which increases the effect of inhibiting the occurrence of defects in the surface layers of tribocontact and reducing the intensity of the formation of wear products in the surface layer of THS. The established mechanism of the lubricating effect of the texture at sliding friction under extreme operating conditions ensures a high rate of wetting of the places of actual contact of tribocompounds, speeds up the process of regeneration of the limit lubricating film.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

Use of artificial intelligence

The authors used artificial intelligence technologies within acceptable limits to provide their own verified data, which is described in the research methodology section.

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