# KAPITEL 1 / *CHAPTER 1* [1]
# THE EFFECT OF A MAGNETIC FIELD ON THE FORMATION OF SECONDARY POINT CONTACT STRUCTURES IN THE ELECTROLYTE

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## Introduction

The technical means with are used now, from simple machines to the operation of aircraft and spacecraft, contain complex tribological mechanisms, the restoration of which costs almost a quarter of the world's GDP.

Intensive operation, even when using modern lubricants, is accompanied by wear to a critical level of tribological pair parts, which reduces the resource and increases operating costs. Most technical devices operate in different environments, at high pressures in a wide range of sliding speeds, as well as high dynamic and temperature loads. The entire range of units requires maintenance and periodic repair and restoration.

Increasing the durability and performance of units through restoration processes significantly increases the cost of the product. The technology of updating the mechanism to working parameters has always consisted of dismantling and restoration with subsequent assembly. The most progressive is the method of non-disassembly service depending on the technical condition of the unit, at which condition is assessed based on the results of technical diagnostics.

In dynamic mechanisms, from passenger cars to multi-ton machines and special industrial equipment, systems are used to perform important functions from motion control to complex technological process control, with the performance of tasks that are beyond human capabilities. Each functional system is based on units that perform booster tasks, the profitability of the entire machine depends on the resource of which. The executive mechanism of the FS is pumps, their high-quality work is based on working elements, a precision pair, the basis of which is the combination of two interacting parts assembled into a tribounit, the manufacture of which is a complex

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[1]***Authors:*** *Svyryd Mykhailo, Sydorenko Oleksandr, Kvach Yuliia, Yakobchuk Oleksandr, Borodiy Viktor*
***Number of characters:*** *55419*
***Author's sheets:*** *1,38*

technological operation that requires high-precision equipment and sufficiently qualified performers. Even with modern, cutting-edge technologies, the manufacture and restoration of worn friction surfaces of parts of complex specialized precision mechanisms largely encounter technological difficulties and significant costs.

## 1.1. Literature review

Even in developed countries, approximately 80% of the total number of workers and the same number of machine tools are engaged in equipment repair.

The founder of the repair base theory [1] noted that the current system of technical maintenance and repair of machines consists of numerous practical recommendations for proper operation and systematized data on the study of their wear, consumption, and patterns of changes in the initial parameters of machines as they are used.

The wear mechanism determines the nature of the destruction and the conditions for the formation of wear particles, their geometric parameters and mechanical properties. The processes of separation of wear products from the surface and their further participation in the creation of surface films are determined by the processes of structural deformation and geometric shapes. This is reflected in the variety of approaches to determining the type of wear [2,3]. From the analysis of damageability, it should be noted that they do not sufficiently take into account the dynamic state of the active layer in the process of friction [4].

Kinetically, tribological effects on chemical transformations in the surfaces of materials differ from thermal effects. Mechanical heating significantly increases internal reactions with overall temperature decreases; the loading parameter of the tribosystem significantly increases the reactivity of the material; the conditions of classical thermodynamics do not fully correspond to the conditions of tribochemical reactions.

The wear process is accompanied by the constant removal of wear products from the surface (surface reactions) with the exposure of fresh areas, which provokes diffusion-free kinetics of mass transfer of materials. Deformation processes during tribological interaction of surfaces activate the mechanical component of thin layers of the surface, which changes the state of the structural component and actively reduces the strength of the surface [5], [6]. The imbalance of the energy state of the surface layer (the appearance of vacancies, interstitial atoms, dislocations, the development of cracks) is accompanied by the mobility of the structure (point and linear defects, intergrain boundaries and cracks) is determined by the wear resistance of the parameters of the coupled friction pairs.

The material properties and the intensity of mechanical action are manifested in the change of the submicrostructure of the surface layer during its mobility during the friction process. At low loads, in the regions of elastic deformation in iron, only a slight acceleration of the cathodic process with hydrogen depolarization was detected [7, 8]. In the case of plastic deformation, an increase in current is observed and the solubility increases approximately 30 times compared to the unloaded material.

The imbalance of the tribojunction due to mechanical loading contributes to an increase in the chemical potential of the surface. In this case, chemical reactions can occur both between the activated solid and the components of the environment, and between solids in contact (setting). Thermodynamic phenomena in [9] metallic bonds of contacts originate from active centers of the material substructure.

Based on the use of triboelectrochemical processes, an energy reparation approach to the regeneration of tribosystem elements has been developed, which allows for the restoration of parts in the process of wear and aging oil during operation.

When studying the dynamics of tribological interaction in real time, it was found [9] that surface destruction begins when the dynamic system passes the bifurcation point. During the tests, dynamic changes in friction processes were systematically monitored; at each stage, two system characteristics were identified: impulse and unitary transition functions.

Frictional wear [10] entails structural and energetic changes on the surfaces of triboconjugates, while the state of the material changes up to the loss of performance.

External friction occurs in the areas of actual contact areas (ACA), which is about 0.1% to 10% (at high loads) of the total working area, with the participation of three

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components of the nature of friction (mechanical, physical and chemical) [11].

The most technologically labor-intensive and repair-intensive pumps in the restoration of precision steam are plunger pumps; the complexity of the design and the variety of materials used complicate the restoration processes in conditions of saturation of the friction surface under the influence of magnetic and electric fields.

The work considers the issue of increasing the wear resistance of parts by applying nano-coatings for conditions of reversible friction. Units of fuel and hydraulic systems of modern machines operate according to reversible schemes - pumps with automatic performance control equipment, as well as power hydraulic cylinders and hydraulic motors with control elements in the form of regulating and distributing devices. Analysis of parts of plunger pumps and study of the topography of working surfaces indicates a rather complex structure of the contact surface. Fig. 1 shows parts of a plunger pump whose working surfaces, after critical operation, have a roughness of more than 5 microns.

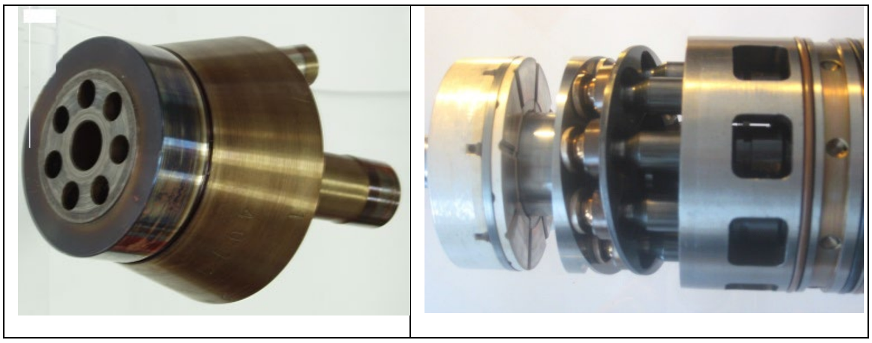

**Figure 1 –** Friction units of plunger pumps

As the precision pair wears out, the precise operation of the fuel pump is disrupted. These disturbances are mainly caused by an increase in the gap between the parts of the plunger pair and distortion of the geometric shape of the plunger head [12].

It has been established that under identical conditions of reversible and unidirectional friction, the parameters of the change of working surfaces are significantly different, and wear increases significantly on the friction surface with a sign-changing sign [13]. The reversibility of friction affects wear not only in dry friction, but also in the presence of lubricant. The author [14] established that in an interactive environment, reversible friction causes wear twice as much as one-way friction. During reversible motion, deformations outside the contact zone not only change sign, but also appear larger than with one-way friction, which leads to an increase in the friction coefficient.

Thus, given that friction is the birth of new surface structures in different conditions and environments, there is an urgent problem of keeping them in working condition. For this, it is necessary to determine the conditions under which there are working modes of maintaining these surfaces or their restoration during operation. The main complexity of such technological operations is the revival of the accuracy of the parameters of the precision mechanism that works more often in oils. The work proposes restoration technologies to reproduce due to the energy of magnetic fields.

## 1.2. Research results

Based on the physical characteristics of the magnetic field related to the properties of materials, it is necessary to determine the conditions for the distribution of its energy across the friction zone of materials.

The priority direction of the presented research is the conditions of service-free maintenance of precision friction pairs during operation. An integral task of the survivability of the operational parameters of the unit is to create conditions under which maintenance of the mechanism can be carried out without disassembly, and better without disconnecting it from the general working system. For this, it is necessary to know the interactions of the elements of the components of the friction unit with the environment and among themselves, to correctly use the flow of energy (or force), which controls the processes of moving auxiliary elements onto an energetically unstable friction surface.

To determine the conditions for the distribution of wear products relative to the friction plane, a tribological complex was manufactured in which the magnetic field acted perpendicularly on the friction plane [15].

The mechanism works most rigidly in conditions of sliding friction without lubrication, structural changes in them are enhanced by the deformation component, which are determined by the rocking of the surface layer. During reversible movement, the friction forces and deformation directions both in the contact and outside its zone change sign and double in comparison with one-sided friction. Which is most noticeable in conditions of sliding friction without lubrication. Therefore, a set of studies on the restoration of precision friction surfaces by a magnetic field is recommended to begin with the interaction of surfaces without the intervention of lubricants. It is known that friction has a molecular-mechanical nature, in which the forces of molecular interaction in places of actual contact are greater between the crystal lattices of compatible friction surfaces. If there is no layer of oil between the friction planes, then molecular forces provoke adhesion. Adhesion is possible between metals and oxide films. Molecular and adhesion forces are directly proportional to the plane of actual contact [16]. In the presence of mutual attraction and adhesion, the relative displacement of the surfaces is accompanied by shear deformation. Friction without a lubricant is accompanied by jump-like sliding of the surface. The coefficient of friction is influenced in two ways by moisture, contamination and oxide films. In the presence of these factors, the forces of molecular attraction between the surfaces can be hundreds of times less than in the case of interaction in pure contact. In addition, the coefficient of friction decreases because the strength of oxides is usually less than the strength of the base metal, so the resistance to shearing of particles during movement, together with the forces of molecular interaction, is significantly reduced. Thick oxide films have lower hardness, and their presence leads to an increase in the area of actual contact, and if this increase occurs faster than the decrease in the mechanical component of the friction force, then an increase in the friction force will occur.

Thus, reversible friction significantly affects the surface and subsurface layers of the metal, compared to the conditions of one-sided contact interaction. At the same time, it affects the internal stress, strengthening, increases the surface energy, and the number of structural defects increases. The interest in studying complex operating conditions does not end with only the reversible movement and strengthening of surfaces; it is much more promising to intervene in the restructuring of the structure during the operation of the friction unit. Therefore, there was a need to conduct research in conditions of hard friction without lubrication under the action of MP, which constantly affects the processes and changes in the places of the FPC. Transformations in the surface layers are actively studied by many authors, so dislocation changes in the structure of the material were noted in [17]. Film formation reduces the friction force and wear intensity, protects the surface from corrosion.

The study of materials during reverse friction was carried out as follows: mechanical preparation of the surface of the working sample by grinding on an abrasive micron skin, after which it was washed with alcohol and weighed on an analytical balance ADV-200M with an accuracy of $10^{-4}$ grams. Next, the working sample was placed in a removable tip of the friction machine and a load of 3.5 MPa was set, with a reciprocating motion speed of 0.12 m/s in the center of the counterbody, the length of which was 40 mm. The working sample material used was steel 45, and the counterbody was LS59-1.

The starting point of the research was the conditions of friction without lubrication during reciprocating motion. The surface deformation processes that arise in this case loosen the surface structure of the working material, which significantly reduces the efficiency of the entire friction unit. Monitoring the processes that occur in a dynamic mode during friction and determining the behavior of wear products is an integral technological operation of modeling the operating conditions of the pair. The basis of the friction process is the formation of protective films on the working surface and the conditions for their existence without being destroyed under the influence of external forces. The load has a predominant effect on the tribological parameters in the tribosystem of interacting surfaces. Environmental elements (air $O_2$, $N_2$), as well as friction materials, interact ambiguously with each other during the operation of the surfaces. From tribological studies (Fig. 2.) it is clear that the wear of the sample is characteristically small.

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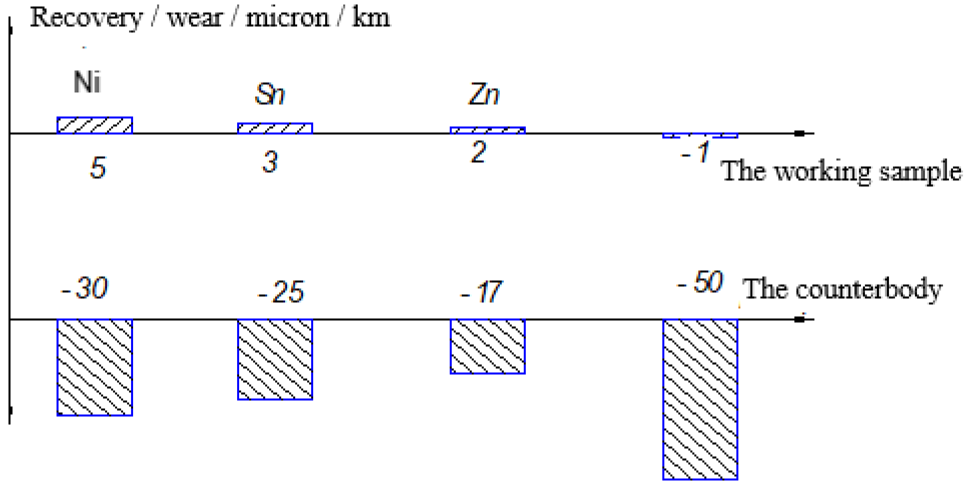



**Figure 2 –** Dependence of recovery/wear of steel 45 (upper histogram) and counterbody LS59-1 (lower histogram) with and without adding modifier powder to the friction zone during friction without lubrication

As for the counterbody, significant wear is noted here, this is explained by the large deformation imbalance of the friction surface of the counterbody due to the deformations obtained during the reciprocating movement of a harder sample (HRC=51.55) along it in the friction zone.

The topography of the friction surfaces (Fig. 3.) indicates significant deformation damage to the surface layers of the metal. The roughness of the counterbody (Fig. 3b) during friction in a pair is determined by a harder steel sample. During the reciprocating movement of the load in the surface layers, in the FPC zones, steel 45 actively interacts with the brass component (copper, zinc) on the friction surface. Brass shifts away from the friction track are visible with their subsequent transfer to the surface of steel 45 (Fig. 3a). A mechanism of accumulation of brass to a critical mass occurs, which is determined by the thickness of the surface film h = 0.02 to 0.04 mm with subsequent breakage and wear. Places of transferred brass are visible on the steel surface (greenish spots on the surface).

Thus, the wear of the steel sample, under conditions of sliding friction without lubrication, is characterized by minimal indicators in comparison with the control sample. In Fig. 2. the total wear of the pair is shown by the last columns of the diagram - which reaches 51 µm/km.

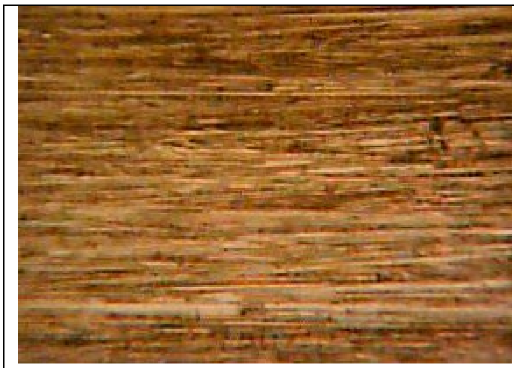
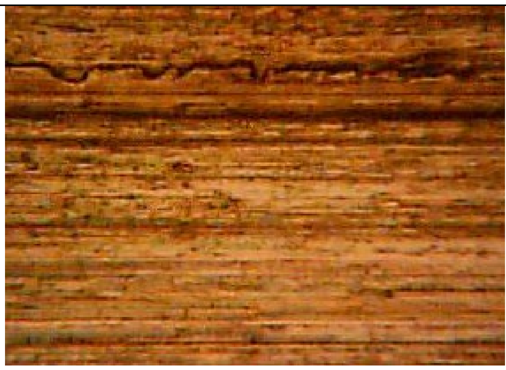
| | |
|---|---|
|  a) Steel 45 |  b) LS59-1 |

**Figure 3 –** Topography of a working sample of steel 45 and a counterbody LS59-1 without lubrication (300X)

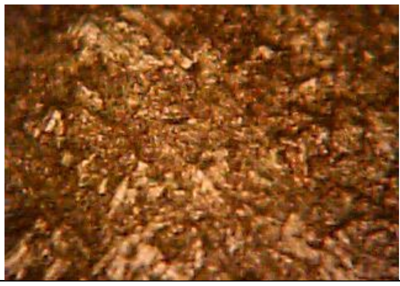
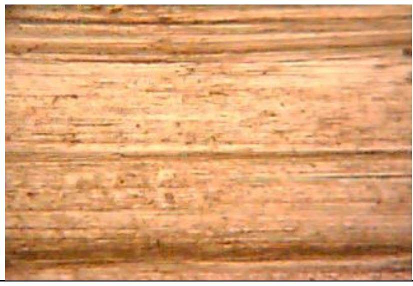
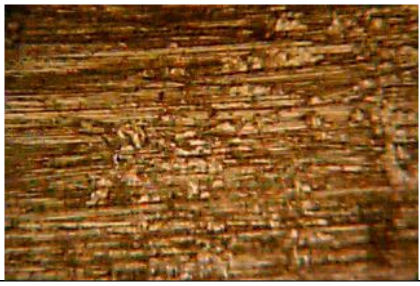
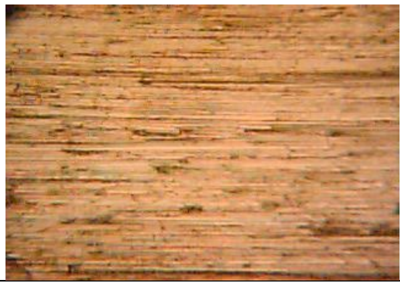
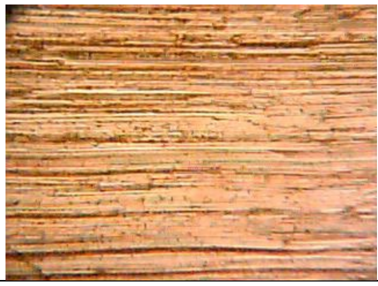
| Powder modifier | Working sample steel 45 | Counterbody LS59-1 |
|---|---|---|
| Ni Ferro-magnetic | a  | b  |
| Zn Diamagnetic | c  | d  |
| Sn Diamagnetic | e  | f  |

**Figure 4 –** Topography of friction surfaces with the addition of powders of different magnetic susceptibility

In accordance with the tasks set in this work and taking into account that in the future it is necessary to study the influence of MP on the friction conditions and the behavior of wear products of various magnets operating in friction units, it is necessary to study their behavior in MP. The technology for studying the conditions of the influence of MP on wear products consists in studying their behavior in MP according to the laws of physics. To accelerate the process of determining and developing a physical model of the conditions for the restoration or transfer of material under the influence of MP, modifying additives of powders of two classes were used in the friction zone, alternately, diamagnetic (Zn - up to 40 μm), diamagnetic (Sn - up to 20 μm) and ferromagnetic (Ni - up to 20 μm).

Tribological parameters (Fig. 2) and the nature of the formed films on the friction surface of steel 45 hardened to martensite, when friction without lubrication with modifying additives in the form of powders are presented in Fig. 4. Studying the topography of the three additives, one common parameter can be noted - sticking of the corresponding modifier powder on the friction surfaces of the sample and counterbody. What is characteristic is that the hardness of the powder does not affect the tribological parameters of the friction pair.

The electrode potential of modifying powders with respect to iron is arranged in the following order: (Zn= - 0.76) < (Fe= - 0.44) < (Ni= - 0.25) < (Sn= - 0.14).

It was not possible to establish a direct relationship between the parameters of electrode potentials and wear. The conditions for material transfer are well explained by the passage of current during friction according to an electrical circuit from a DC source through the friction plane through the FPC locations. The effect of the current, generated during friction, is called triboelectricity, the phenomenon of the appearance of electric charges during friction. It is observed during mutual friction of two metals of different chemical composition. In this case, both bodies are electrified; their charges are the same in magnitude and opposite in sign. Triboelectricity of solids is explained by the transition of current carriers during friction from one body to another. Triboelectricity is due to the transition of electrons from a substance with a lower work function to a substance with a higher one.

The running-in of surfaces during relative movement is characterized by the passage of current through the friction zone. At the initial moment when the modifying powder is added to the friction zone, the current value is maximum (according to Ohm's law) because a large area is not covered by the tribological film. The increase in the area and thickness of the tribological film due to this increases the total electrical resistance. The indicators between the newly created contacts of the tribological film in the places of the FPC and the existing surface are controlled the larger the area of the newly created points, the easier it is for current to pass through the sample-counterbody circuit, which indicates an insufficient number of protective tribological films on the friction surface.

Fig. 5 shows the change in current strength when passing through the contact zone with the addition of nickel (reaches $45\cdot10^{-3}$ ...$48\cdot10^{-3}$ A), tin ($26\cdot10^{-3}$ ...$28\cdot10^{-3}$ A), zinc ($20\cdot10^{-3}$ ...$23\cdot10^{-3}$ A), while the tribological characteristics are ambiguous.

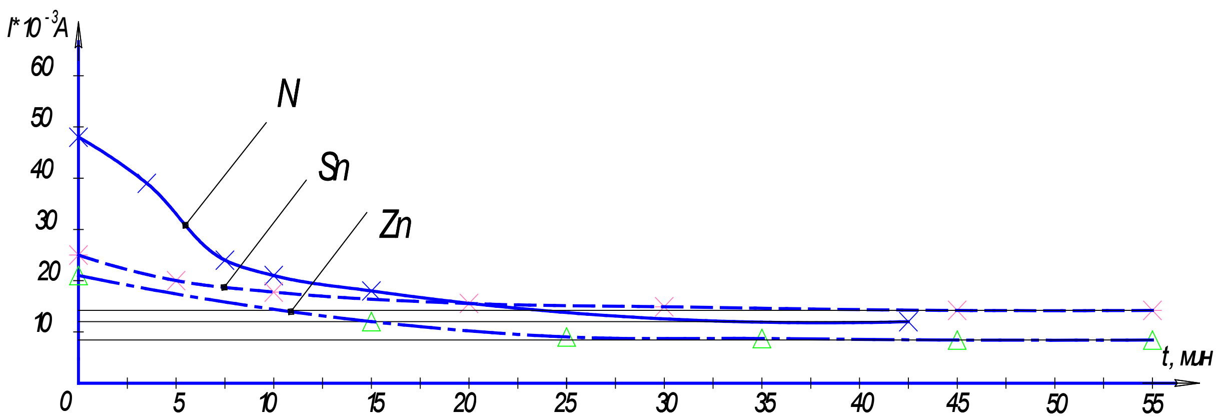



**Figure 5 –** Dependence of the change in current on the time of the friction process when adding finely dispersed powders

A steel sample (steel 45) hardened to tempered martensite undergoes repair processes (Fig. 2), while the counterbody (copper alloy LS59-1) wears out significantly.

The total wear intensity of the friction pair when modified with nickel powder (hardness after deformation according to HB=170) is:

$$\text{With}_{\text{Ni pairs}} = C_{\text{sp}} + C_{\text{ct}} = +5 + (-30) = -25 \ \mu\text{m/km}.$$

When modified with zinc (hardness HB=40…50):

$$With_{Zn} +2 + (-17) = 15 \mu m/km$$

When modified with tin powder (hardness according to HB=5):

$$With_{Sn} +3 +(-25) = 22 \mu m/km$$

The addition of nickel (ferromagnetic material) is characterized by an initial current at the level of $48\ 10^{-3}$ A, which is explained by the hardness of nickel powder at the initial stage of friction, which, filling the surface roughness, somewhat refreshes the surfaces of the sample and counterbody. With further development, the formation of surface tribological films increases the electrical resistance in the contact, due to the formation of oxides from the contact materials, from which a constant current value is established at the level of $12.\ ^{10}-3\ ^{A.}$ In this case, the process of surface modification (stabilization of the formation of tribofilms) ends in 30 minutes (Fig. 5).

The addition of zinc (diamagnetic material) - which has a lower hardness on the HB scale $_{Zn}$ = 15, determines the running-in process for 22 minutes at an initial current I = $21.\ 10^{-3}$ A to a constant current mode of $8\ 10^{-3}$ A. (Fig. 5.)

The addition of tin (a diamagnetic material) softens the initial current (25mA) due to its own hardness ($HB_{Sn}$ = 5.7), but the annealing process is prolonged to 35 minutes, and the stabilization current reaches $15 \cdot 10^{-3}$A. (Fig. 5)

This is explained by the fact that the powder particles are mechanically rubbed into the technological irregularities of the surface of the working sample, while forming oxides that prevent the passage of current in the contact zone. The illustration of the friction surface topography indicates (Fig. 4) the formation of protective films due to transformations between the modifier and the material of the friction surfaces. On the surface, you can see stuck particles of a modifying material of a different color, which are smeared, with a steady process of wear of the counterbody. The total wear in all friction pairs, with the addition of different classes of powders modifying the powders, under conditions of sliding friction without lubrication is the same and varies in the range of 30...20 microns per kilometer of path.

The time of stabilization of the tribocurrent and the formation of surface films from materials located in the friction zone depends on the value of the electrode potential. The more positive the electrode potential, the longer the stabilization of surface tribological films takes. A decrease in the electric current characterizes the running-in of friction pairs, i.e. the formation of protective tribological films.

**Table 1 - Parameters of powder materials used in studies to determine**

| Modifying powders | Cu | Zn | Fe | Ni | Sn |
|---|---|---|---|---|---|
| Electrode potential (V) | 0.34 | -0.76 | -0.036 -0.44 | -0.25 | -0.14 |
| Vickers Hardness (HB) | 77-99 | 15 | 35-45 MPa | 200 | 5 |
| According to Rockwell | | | | | |
| Starting current ($A \cdot 10^{-3}$) | | 21 | - | 48 | 25 |
| Stabilization time (min) | | 22 | - | 31 | 35 |
| Stabilization current ($A \cdot 10^{-3}$) | | 8 | - | 12 | 15 |
| Electron work function eV | 4.4 | 4.24 | 4.31 | 4.5 | 4.39 |

So, according to the graph (Fig. 5) and the electron emission energy for ferromagnets Ni and Fe, it is clear that the faster running-in will occur in the case of adding Ni. Then when adding a diamagnet. This is explained by the hardness of the added powders:

$$150=HB_{Ni} > 20=HB_{Zn} > 5=HB_{Sn}.$$

Harder powders act as an abrasive for the counter body, which explains the high wear of the counter body and the short running-in time.

When studying friction surfaces with admixtures of powder magnets, one common parameter can be noted - sticking of powder of the corresponding modification to the friction surfaces of both the sample and the counter-body. The hardness of the powder significantly affects the surface topography (Fig. 4.) and the change in the nature of the tribological parameters of the friction pair.

To determine the initial influence of the tribological component on the conditions of sliding friction without lubrication, studies were conducted with the addition of each of the powders, with different magnetic susceptibility, to the contact zone of the steel sample and the glass counter-body. The idea of setting up the experiment is based on the perception of the tribo-contact conditions of the sliding friction mechanism in contact without lubrication with impurities depending on the mechanical and chemical properties of the powders. However, according to the classical theory of electrochemical processes, it is impossible to determine the absolute electrode potential, therefore, the zero hydrogen potential is taken as the initial potential of the electrochemical cell. From which, in both directions (negative on the left and positive on the right), metals are placed according to the electrode potential. The series (presented in this work) has the sequence:

$$Zn= - 0.76) < (Fe= - 0.44) < (Ni= - 0.25) < (Sn= - 0.14) < H=0; Cu= + 0.44,$$

This sequence of metals is strictly related to the electrode potential of iron. The experiment involved metals of two main magnetic classes.

Therefore, adding ferromagnetic grade powder (Ni) to the contact zone, compared to steel 45, acts as an anode with a potential difference of +0.19 volts when rubbing against glass.

Tin (Sn) diamagnetic powder works in the mechanism of electrochemical laws as well as steel 45 with a potential difference of +0.3 volts. Under friction conditions, tin powder is much softer, therefore it partially complements the lubricating properties between hard friction surfaces.

Copper Cu diamagnetic powder is the basis of the brass alloy (LS59-1 Cu-57…60%; Zn-37…42).

### 1.3. The energetic nature of the magnetic field during reciprocating motion

Friction conditions are determined by the mechanical movement of planes with a certain surface roughness, which, when interacting, form wear products in the form of small particles of different fractions. Such finely dispersed products actively interact with the magnetic field, obey its directional action, and are displaced in the friction zone onto the plane depending on the direction of the magnetic lines and their density.

In the works [18] it is stated that the influence of MP changes the plastic properties of crystals, causing the magneto-plastic effect (MPE).

The results of the study of the wear intensity of steel 45 on brass LS59-1 under

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the influence of MP under conditions of sliding friction without lubrication with additives of alloying elements of ferromagnetic and diamagnetic class are presented in Fig. 6.

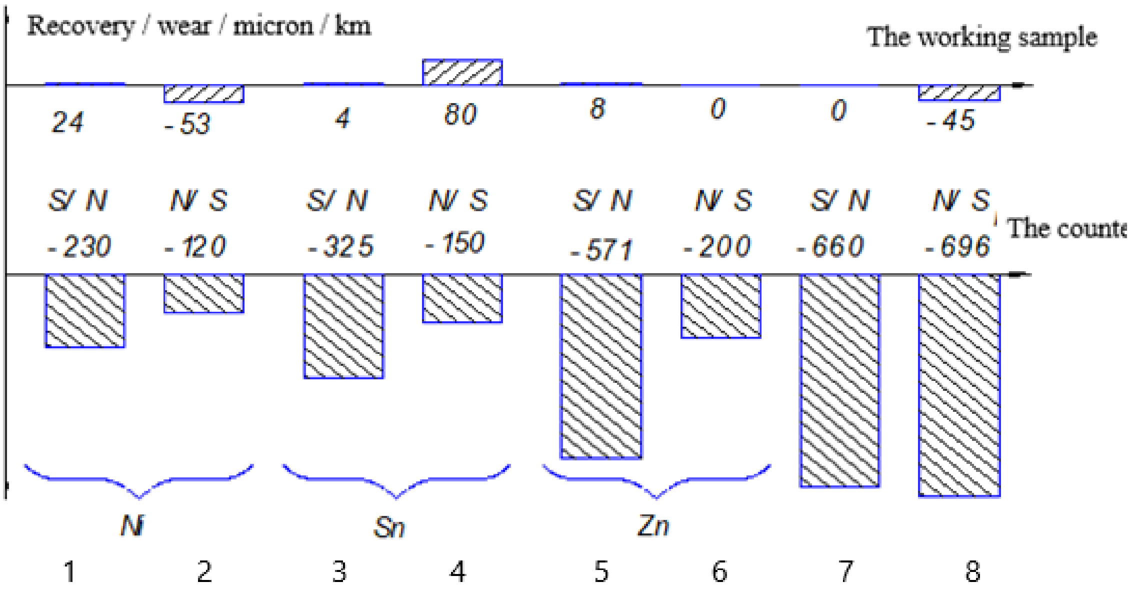



**Figure 6 –** Dependence of wear intensity (recovery) when adding modifying powder to the contact zone during friction without lubrication

The physical characteristics of the magnetic lines of force of the magnetic field directed through the contact zone indicate the direction of movement of the wear products according to the location of the poles. The wear products of the ferromagnetic sample (in the form of a roller with a diameter of 4 mm and a length of 33 mm) are located around the contact zone, performing the restoring functions of the material. Ferromagnetic particles fall on the steel surface, are pressed by a magnetic field, are rubbed on contact due to increased deformation parameters under the action of the magnetic-plastic effect. The wear products of the counterbody LS59-1 made of diamagnetic material, copper and zinc, in a uniform magnetic field are displaced from the friction zone beyond the action of the lines of force towards the negative gradient of the magnetic field, which will lead to the active removal of wear products.

For comparison, studies were conducted without the addition of fine powders in a magnetic field. Fig. 7 (histograms 7,8) shows the topographies of paired friction surfaces (Fig. 7).

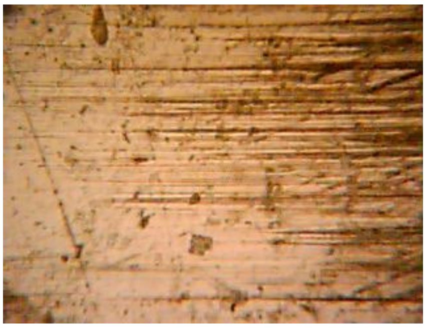
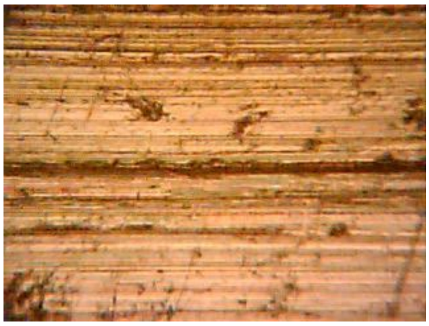
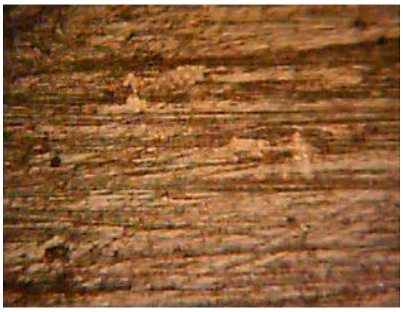
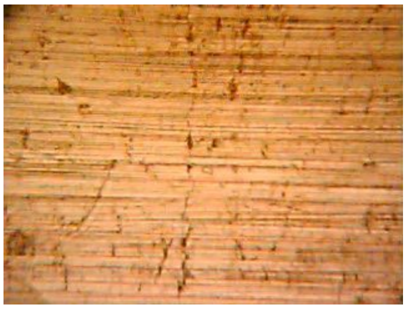
| Field direction | Working sample | Counter-body |
|---|---|---|
| S/N | a  | b  |
| N/S | c  | d  |

**Figure 7 –** Topography of the working sample 45 and the counter-body LS59-1 under the influence of MP. The surface of the working sample and the counter-body of brass is rough, covered with grooves and cracks. 250 $^{X}$

When the external magnetic field is located in the S/N direction (i.e. the input pole on the sample is S and the output pole is N), the working sample did not wear out, unlike the counter-body (Fig. 7a). This is explained by the different hardness of the materials. And also, by the fact that the directions of magnetic induction are directed from N to S, i.e. everything that comes off the counter-body is pressed against the working sample and mechanically rubbed onto its surface (Fig. 7 b).

When the magnet poles are arranged N/S (Fig. 6. histogram. No. 8), that is, the reverse mechanism of the MP action was introduced, which led to wear of both surfaces with deterioration of their topography (Fig. 7 c, d). This is explained by the fact that the magnetic lines of force were directed away from the sample, and the wear products are located near the contact zone and in the abrasive wear mode work in the friction zone. Despite the fact that the ferromagnet is affected by the MPE, its hardness is still quite high compared to brass, so the effect of hardness significantly affects the wear results under friction conditions without lubrication.

Model studies with powder additives (diamagnets Zn, Sn and ferromagnet Ni) allow us to determine the behavior of magnets under the influence of MF on the conditions of their location in the contact surface zone. The experiment was carried out in a perpendicularly directed uniform magnetic field (S/N and N/S) relative to the friction plane.

Considering the results of wear intensity (Fig. 6), the influence of the magnetic field on the contact zone of the ferromagnetic-diamagnetic friction pair is ambiguous:

- so, a working sample of the ferromagnetic class attracts both wear products and powder with appropriate magnetic properties (in this case $\chi_{Ni}$ =110), with a force exceeding the force of the external magnetic field, regardless of the area of the magnetic field;
- diamagnets (**tin:** magnetic susceptibility "$\chi$ = +0.025 $10^{-6}$), (**copper:** $\chi$= -9.63·$10^{-6}$)

(**zinc:** magnetic susceptibility $\chi$= -1.56·$10^{-5}$) weaken the external magnetic field and move towards the negative gradient of the magnetic field, i.e. are pushed out of the field zone.

Thus, if the MP is placed perpendicular to the friction plane, we obtain ambiguous results on the wear of materials. The equipment is equipped in such a way as to determine the behavior of magnets in a uniform parallel MP. Since there are two main classes of materials that, from a physical point of view, are significantly dependent on the direction and state of the MP. In the experiment, the following were selected for the study: from the ferromagnetic class - iron and nickel, from the diamagnetic class - tin and zinc.

When adding ferromagnetic material (Ni) to the friction zone as a modifying ferromagnetic additive, the friction surface is characterized by the formation of tribological films Fig. 8 (a, b, c, d). In the direction of the S/N MP, the wear products are in the friction zone and are directed by the MP force into the sample, in addition, the ferromagnetic additive significantly reduces the wear of the friction pair as a whole (Fig. 6. No.1, 2).

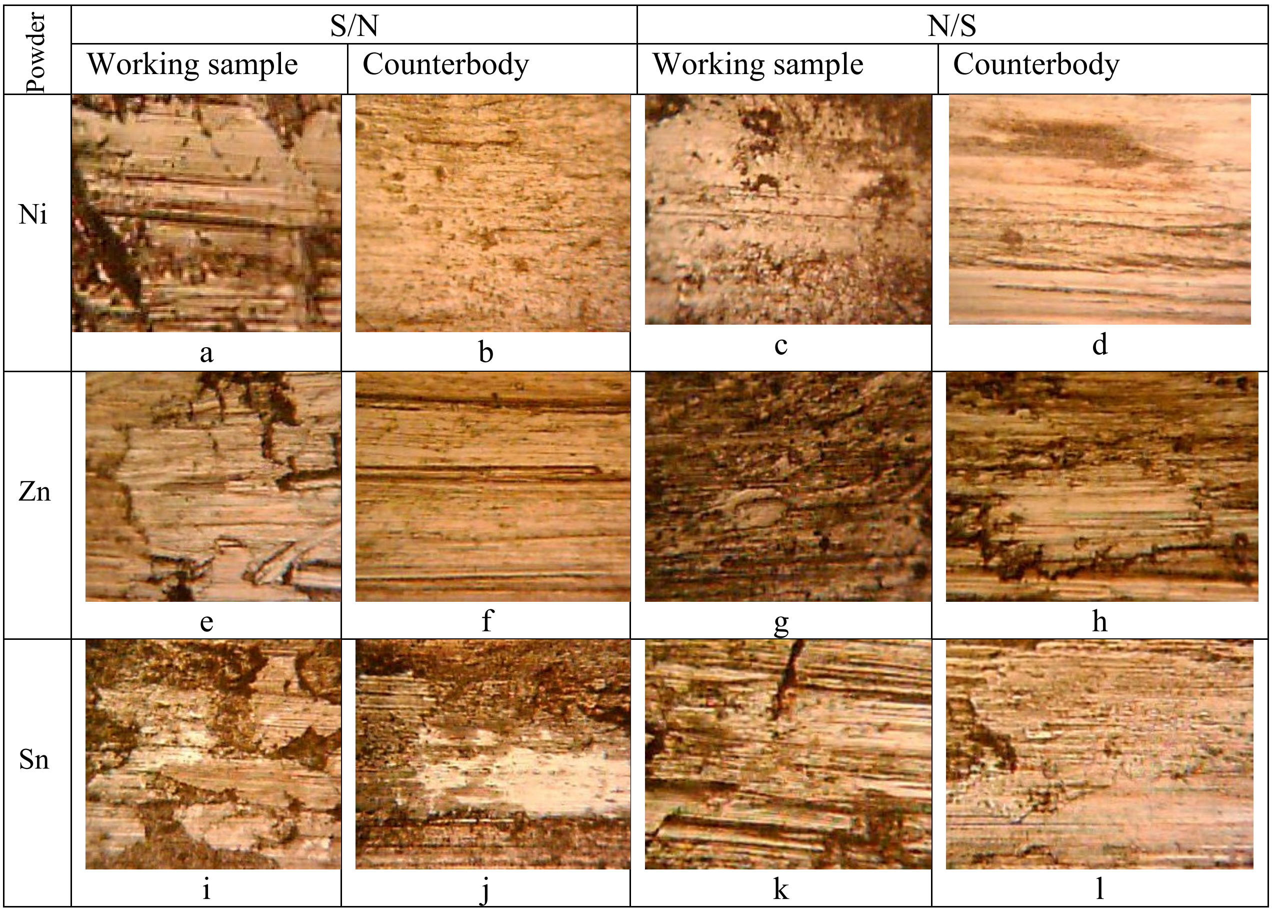



**Figure 8 –** Topography of friction surfaces of a sample of steel 45 on counterbodies LS59-1 with impurities of alloying elements (friction without lubrication)

The friction surface on the sample is densely covered with modified powder, significantly reducing its roughness Fig. (8 (a, b)), although the wear process on the counter body is observed. However, the sample receives an additional increase in size. (Fig. 6 No. 1), due to ferromagnetic nickel.

Changing the direction of the magnetic field leads the tribopair to a state of wear of both surfaces (Fig. 6 No. 2), it should be noted that the roughness on the surfaces of the counterbody and the working sample is significantly reduced compared to the friction surfaces without a magnetic field. This effect is explained by the increased deformation capacity of the surfaces, which is summed up by the influence of the magnetic field, which contributes to the healing of cracks and other defects on the metal surface. The decrease in total wear (-53…-120 = -173 μm/km) when adding ferromagnetic powder to the friction zone can be explained by the structural change of the powder due to the effect of magnetic plasticity in the zone between the friction

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surfaces. In this case, the powder will perform the function of a dry lubricant. Since the magnetic field is directed by lines of force into the counterbody, the wear of the working sample is greater, and of brass is less, than with the direction of the magnetic field S/N (Fig. 8b) The friction surface is shown in Fig. 8 b.

The addition of diamagnetic zinc powder is accompanied by an increase in the size of the sample and a significant decrease in the counterbody (- 571+8) = - 563 μm/km). This is explained by the displacement of diamagnetic material from the friction zone. The largest amount of which is in the counterbody (copper and zinc). But the direction of the S/N magnetic field presses the wear products, as well as the modifier - zinc, to the surface of the sample, which provokes deposition with subsequent smearing of zinc in the friction zone of steel 45 (Fig. 6 No. 5) friction surface (Fig. 8e, f), where large adhesions on the steel surface are visible. Changing the direction of the magnetic field to N/S significantly reduces the wear of the counterbody, but the sample does not increase in size, which is explained by the removal of diamagnetic material from the friction zone and is not directed to the sample (Fig. 6, No. 6).

When adding diamagnetic powder (tin) to the friction zone, the recovery value of the metal sample decreases slightly (Fig. 6, No. 3), despite the adhesion of tin to the surface of the ferromagnetic sample (Fig. 8 i). On the surface of the LS59-1 counterbody, the formation of protective tribological films is observed (Fig. 8 m), due to which the total wear resistance of the friction pair 45 - LS59-1 increases to (- 325+4) = - 321 μm/km). The change of the uniform magnetic field to the N/S direction is accompanied by wear of the friction pair with different parameters from the previous ones. The variable value of wear of the pair when introducing diamagnetic tin material is accompanied by a significant deterioration of the relief of the topography of the friction surface of the brass counterbody (Fig. 8 m). However, the sample increases in size due to the transfer of tin powder to the surface. On the opposite side, diamagnetic components of brass are removed from the friction zone under the action of a magnetic field, which increases the wear of the counterbody.

A significant influence on the parameters of powder gradient transfer between friction surfaces is exerted by the electrode potential of the three-phase system steel - powder-brass. It is known that the electrode potential characterizes the number of free electrons in the metal, which can be used to transfer this element to another "friction" surface where they are lacking. If the movement is performed by a magnetic field, then it is possible to "force" them to move to a given friction surface, thereby changing the structural parameters of the surface. For this purpose, an analysis of the formation of protective films on the friction surface was carried out. Since surface films are oxides and they are dielectrics was passed through the contact zone (Fig. 9).

Fig. 10a shows experimental data with the addition of finely dispersed ferromagnetic nickel powder (Ni), where the current stabilized over time depending on the direction of the magnetic field from 35 minutes to 90 minutes (Table 2). According to studies, it is clear that the initial current and stabilization time do not depend on the directional effect of the magnetic field on the friction unit. This effect is explained by the corrosion resistance of nickel in air and the significant hardness of the powders, which act as an abrasive.

Impurities of diamagnetic tin powder (Sn), the electrode potential of which is closer to "0" is equal to - 0.14 V, while the dependence on the direction of the magnetic field does not affect the rate of stabilization of the formation of protective tribological films (Table 2).

Zinc is the most susceptible to corrosion (along with steel) from the presented series, as indicated by the stabilization results (Fig. 9).

Thus the decisive force in the movement of electric charges in metallic materials is the influence of electric and magnetic forces. The most powerful method for studying the influence of external forces on the structure of materials is the friction of metal surfaces.

It is necessary to choose the mildest (most favorable) conditions for different environments. Thus, the electrolytic medium polyethylene glycol 400 was chosen. This environmentally friendly substance has lubricating properties that dissolve in water.


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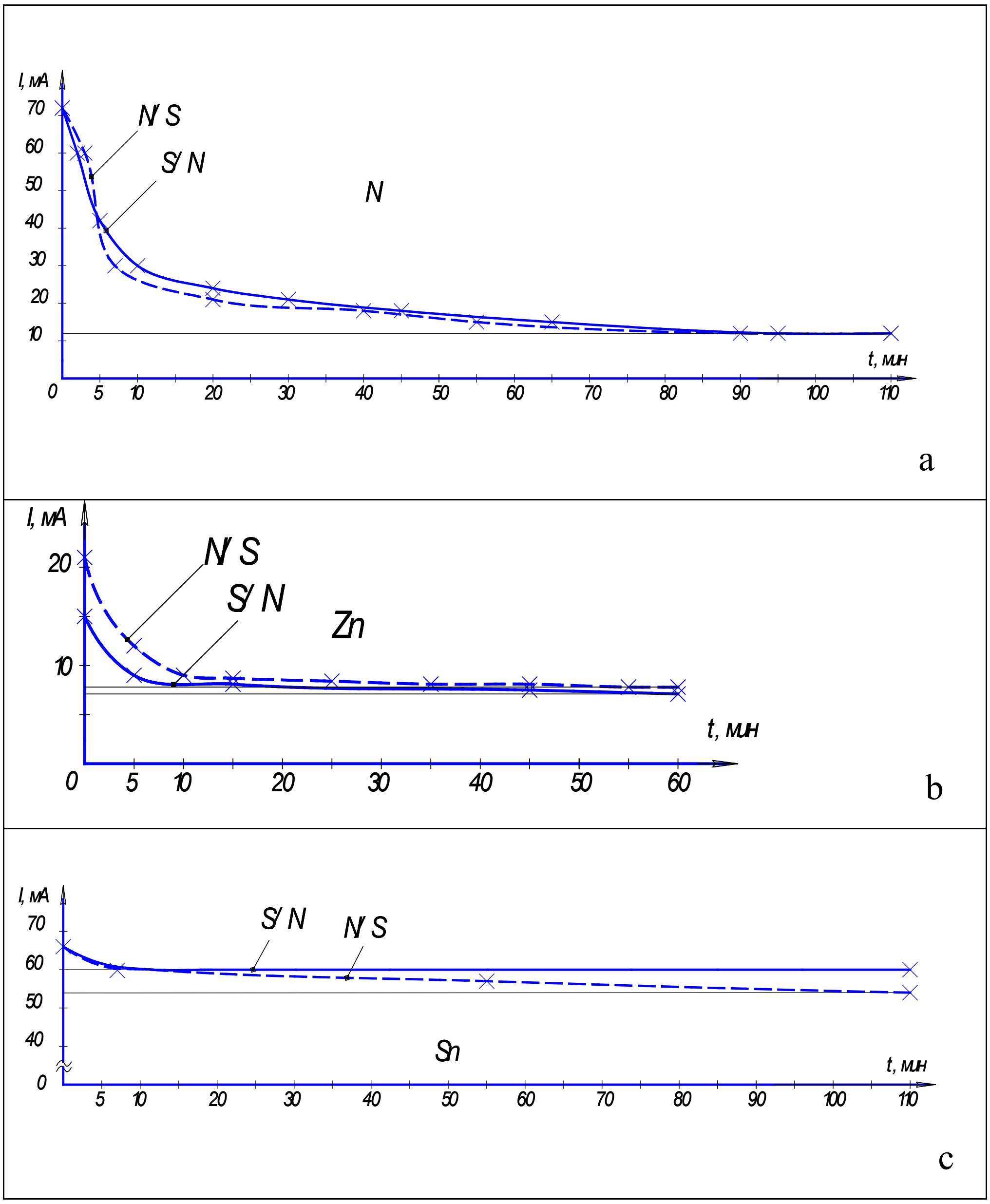


**Figure 9 –** Current dependences on time with the addition of finely dispersed powders in a magnetic field:

**Table 2 – Parameters of powders in the process of friction under the influence of a magnetic field**

| Parameters | S/N | N/S | S/N | N/S | S/N | N/S |
|---|---|---|---|---|---|---|
| Modifying powders | Zn | | Ni | | Sn | |
| Electrode potential (V) | -0.76 | | -0.25 | | -0.14 | |
| Hardness (NV) | 42 | | 200 | | 5 | |
| Starting current (A · 10 $^{-3}$) | 15 | 22 | 72 | 72 | 66 | 66 |

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| Parameters | S/N | N/S | S/N | N/S | S/N | N/S |
|---|---|---|---|---|---|---|
| Stabilization time (min) | 55 | 35 | 90 | 90 | 10 | 11 |
| Stabilization current ($A \cdot 10^{-3}$) | 7 | 8 | 12 | 12 | 66 | 54 |
| Δ Initial/stabilization | 8 | 14 | 60 | 60 | 0 | 12 |
| Electron release energy **eV** | 4.24 | | 4.5 | | 4.39 | |

## 1.4. Tribological characteristics of friction units when tested without the action of a magnetic field during reciprocating motion in a PEG-400 medium

The parameter of the relative movement speed determines the nature of the physicochemical and mechanical interaction of the liquid with the metal during friction. The friction processes occurring on the surfaces, when changing the speed regime, form different schemes of their chemical interaction. At low sliding speeds (0.15 - 0.3 m/s), chemical processes occur, elastic and plastic deformation spreads into the depth of the surface layers of the metal, activation occurs. This contributes to the occurrence of chemical reactions and the formation of secondary structures of great thickness, which are quickly destroyed. New structures are formed on the spot, which leads to intensive wear. The amount of oxygen in the friction zone remains constant at low speeds, therefore chemical processes prevail in the friction zone. At an average sliding speed (0.2 m/s), chemical wear decreases due to small time intervals between active mechanical actions, which lead to the localization of elastic and plastic deformation in a very thin surface layer. When the temperature changes, the properties of the working fluid change, the rate of sorption, diffusion and oxidation processes, and viscosity change.

Lubricating medium modifiers protect metal surfaces from seizing, their composition determines the intensity of wear (microstructural transformations and microhardness). With increasing load, intensive wear of samples occurs, microhardness increases, and secondary structures - carbides and white layers - are formed more intensively.

Regardless of the environment in which the dissolved oxygen is located, there is an effect on the oxidation reactions of the material elements on the surface, which affects the processes of friction and wear. It is known that plastic deformation increases the oxidation rate, therefore, the axial load on the friction pair has an active effect, in which the surface layers are constantly displaced relative to the ground state of the structure, leading it to imbalance.

The microrelief, structure, physical-mechanical and other properties of the surface layers of metals undergo irreversible changes during friction in a liquid medium, as a result of which the residual state of the surface layers is formed. The main physical-chemical processes that occur in the metal and in the working fluid during friction include:

- plastic deformations,
- formation of secondary structures,
- change in the state of the fine crystalline structure,
- change in the properties of the lubricating medium.

All these processes occur simultaneously, prevailing over each other, depending on the experimental conditions and the nature of the materials, structure and composition. An important characteristic of the state of the surface layers of metals is a fine crystalline structure. In which there may be microdistortions of the crystal lattice (stress of the second kind) and dispersion of the structure (the size of the mosaic blocks).

Conditions for the formation of secondary structures: deformation and diffusion. Typical secondary structures are carbides, sulfides, oxides, white, non-etchable layers, and organic products.

Using an alternative energy source, a magnetic field, the research used a lubricating medium PEG400 diluted by 50% with water and samples of structural steel 45 hardened to martensite and a counterbody made of brass LS59-1. The experiment was carried out with the direction of the magnetic field S/N, N/S. In each study, a modifying powder was added to the friction zone: ferromagnetic class - nickel (Ni - up to 20 μm), diamagnetic - tin (Sn - up to 20 μm) and diamagnetic - zinc (Zn - up to 40 μm).

The nature of the tribological parameters of the surface during reciprocating movement in environments modified by powders is presented in Fig. 11. Depending on the mechanical characteristics of the powder, the tribological parameters of wear are determined. The harder the powder, the more active the process of wear of the pair of steel 45 - LS59-1, when adding nickel powder, which is characterized by a hardness that varies from 70 MPa in the tempered state to 200 MPa after deformation, which it receives in the friction process (Fig. 11 – 3-6). The topography is characterized by dense scratches that the nickel powder leaves at the initial hardness.

The addition of zinc reduces the impact of the abrasive component of the friction process. The hardness of zinc is much lower than that of nickel, given that brass has a hardness of 150 MPa, which is much lower than the hardness between the powder and the friction surfaces of the sample and the counterbody, while the total wear is - 48 μm/km. The topography of the friction surface is characterized by the formation of surface films that mix with each other and smear on the surfaces with subsequent oxidation on the surface of the sample.

Modification of the friction unit of the soft component, tin powder (hardness 5 MPa) is characterized by mechanical rubbing into the surface of the brass counterbody (hardness 150 MPa) while healing surface defects. This mechanism can be interpreted as "dry lubrication", the surface Fig. 11 – 5.

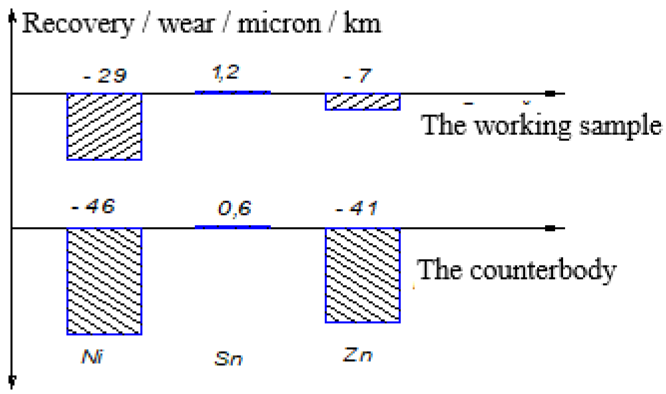


**Figure 10** – Diagram of the dependence of the tribological characteristics of the friction pair 45 on LS 59-1 (without a magnetic field) in a PEG-400 medium 50%

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A significant difference in the hardness of the sample and the powder is determined by the mechanical nature of the rubbing tin (Fig. 11 – 2), where large spots on the friction surface are characteristic, which carry the tribo-load of the mechanism, as can be seen from the photo taken in dynamic mode during the friction process.

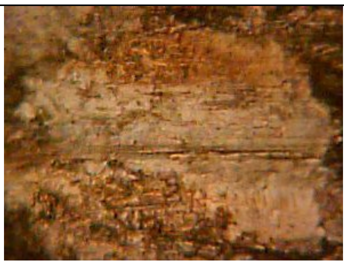
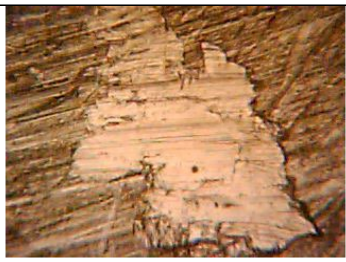
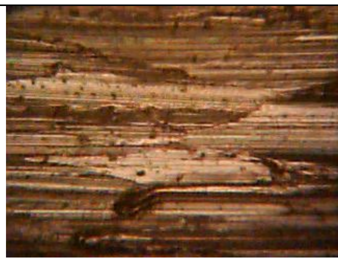
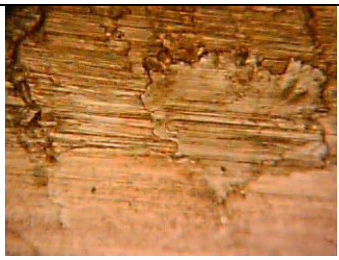
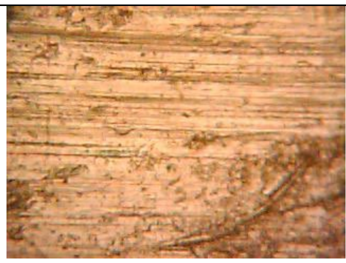
| | | | |
|---|---|---|---|
| Steel 45 |  1 |  2 |  3 |
| powder | Zn | Sn | Ni |
| Brass |  4 |  5 |  6 |
| powder | Diamagnetic | Diamagnetic | Ferromagnet |

**Figure 11** – Topographies of friction surfaces of steel 45 according to LS59-1 in a PEG400-50% medium

The finest particle of the powder conglomerate protects the surface of the sample, on which the technological topography of the surface is visible.

The study of triboelectric parameters of the process was determined by the finger-plane friction scheme, from which it is clear that the rate of stabilization of the triboelectric current in the PEG-400 medium (Fig. 12) correlates with the powder hardness parameters. Soft tin is already leveled at 14 minutes and holds stably until the end of the experiment (Table 3). Tin adhesion almost completely compensates for surface wear, and its topography shows that the adhered tin perceives all loads precisely at the contact spots (Fig. 11 – 2-5).

The nickel powder modified takes quite a long time, since the abrasive process constantly forms fresh friction surfaces, which is characterized by a large initial current

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of 0.06A and stabilization after 150 minutes (Fig. 12).

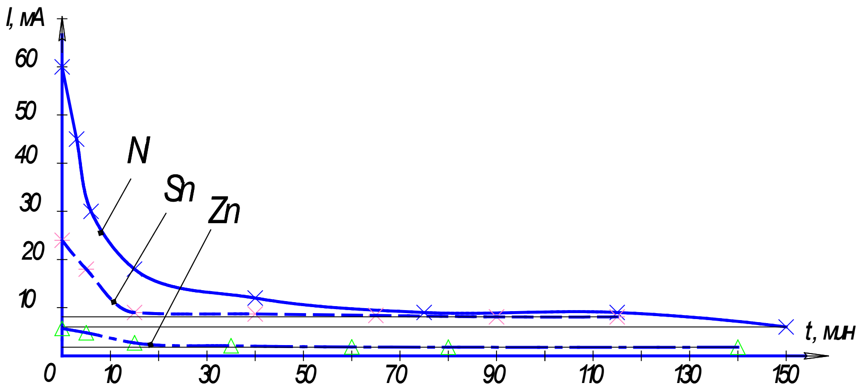


**Figure 12 –** Dependences of the change in current on time with the addition of finely dispersed powders in PEG-400 (50% concentration in water) without the influence of a magnetic field

**Table 3 – Parameters of current flow in the medium of PEG 400_50% powders in MP**

| Parameters | S/N | N/S | S/N | N/S | S/N | N/S |
|---|---|---|---|---|---|---|
| Modifying powders | Zn | | Ni | | Sn | |
| Starting current (A · 10 $^{-3}$) | 7 | 9 | 30 | 45 | 48 | 53 |
| Stabilization time ( min ) | 140 | 85 | 150 | 150 | 110 | 125 |
| Stabilization current (A · 10 $^{-3}$) | 3 | 2.5 | 6 | 6 | 23 | 12 |

Triboelectric friction characteristics of 45 according to LS-59-1 with modified zinc powder are determined by wear of 48 μm/km and a zinc tribofilm up to 10 μm thick, in addition, oxidation at the edges significantly increases wear. The low value of the tribocurrent is explained by the electrical resistance of oxides on the surface of the adhered zinc powder conglomerates.

Thus, during the reciprocating friction movement in the PEG400 50% medium, there is a correlation between the friction mechanism and the hardness of the powder, which modifies the friction node. The soft material is spread on the surface and the greater the difference in hardness, the faster the adhesion process of the soft component.

## 1.5. Tribological parameters of steel 45 hardened to martensite and a counterbody made of brass LS59-1 in a PEG-400 medium under the influence of a magnetic field

The studies were conducted at a speed of 0.2 m/s and a magnetic induction value of 0.15 T. Fig. 14. presents the tribological parameters of the friction pair, a sample of steel 45 on a brass counterbody LS59-1 depending on the direction of the magnetic field.

Analysis of the friction surface in PEG-400 with the addition of ferromagnetic nickel powder shows that in the direction of the magnetic lines S/N, wear of the countersample is noticeable up to 50 µm along 1000 мthe path, while the sample has increased in size up to 0.8 µm/km. What is is confirmed by the topography of the friction surfaces Fig. 14 – 5, 6. Changing the direction to N/S significantly reduces the wear of the counterbody, and increases the process of sample repair. The surface of the counterbody is smoother compared to S/N.

Studies of the diamagnetic material tin as a modifier for polyethylene glycol for sliding friction conditions are shown in Fig. 13.

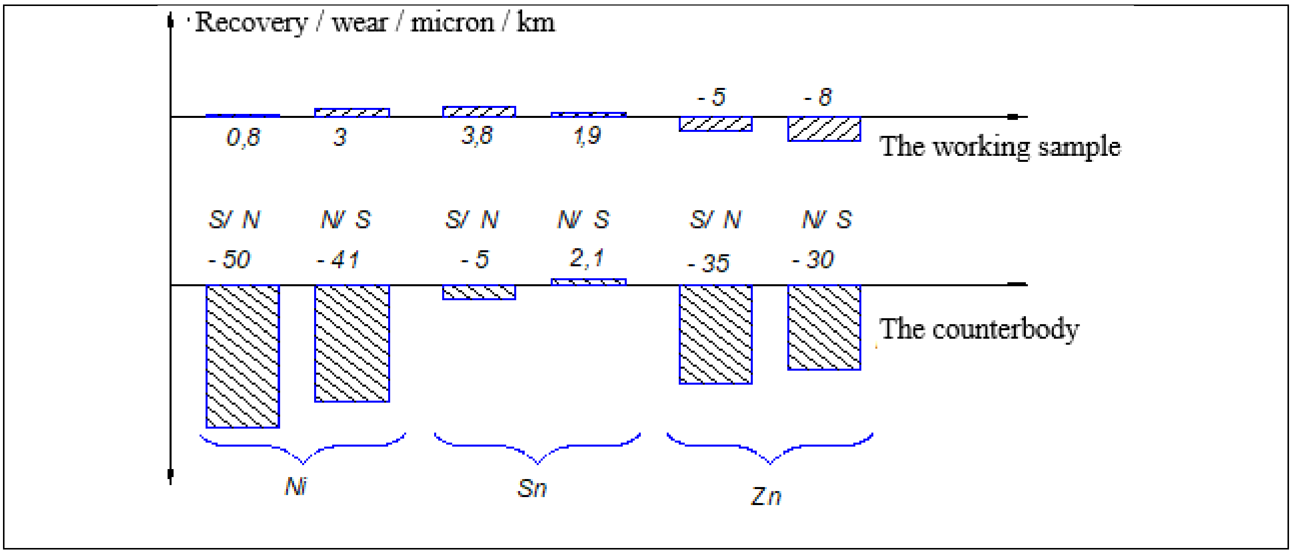


**Figure 13** – Diagram of the dependence of tribological parameters in the PEG 400-50% environment under the influence of a magnetic field

Based on the obtained histogram, it is seen that the repair conditions are fulfilled at the

N/S pole. This can be explained by the directional action of the magnetic field on the tin modifier. The repair mechanism in the N/S magnetic field is determined by two parameters acting on the diamagnet - tin: first, the diamagnet is pushed out of the MP with a minimum gradient along the lines of force; second, the directional action of the magnetic lines of force away from the N pole from the sample to the counterbody at the S pole. Fig. 14 - 10. The tribological characteristics of the sample made of steel 45 are explained by the enhanced magnetic field and the particularly directed action of the field towards the ferromagnet, in the S/N position a significant addition of the tin modifier to the sample is characterized by the displacement of tin into the zone of positive magnetic field gradient Fig. 14 – 5, 11.

At the same time, the topography of the friction surface of the sample Fig. 14 – 1,7 is characterized by an increase in roughness relative to the diamagnetic in the contact zones and the number of newly formed points on the friction surface.

Tin was concentrated along the perimeter of the sample in sharp areas and on the side surfaces. On the counterbody, a lot of tin was deposited along the edges of the friction track, in the middle of the track the surface had a "flaky" appearance Fig. 14 – 9.

The most inconvenient materials for a magnetic field are considered diamagnetic; they reduce the magnetic field strength and shift towards the negative gradient and are displaced beyond the friction zone.

Zinc powder was chosen for the study as a harder and relatively accessible material. The results of the studies are presented in Fig. 13, the analysis of the friction surface indicates wear of both the ferromagnetic sample and diamagnetic brass. The wear mechanism can be explained by the extraction of the diamagnetic component from the counterbody and its transfer under the action of a magnetic field beyond the friction zone, as well as the removal of diamagnetic carbon, thereby weakening the conditions for the passage of current through the friction zone (Fig. 15), supplied from an independent source, determines the activity of the formation of protective films.

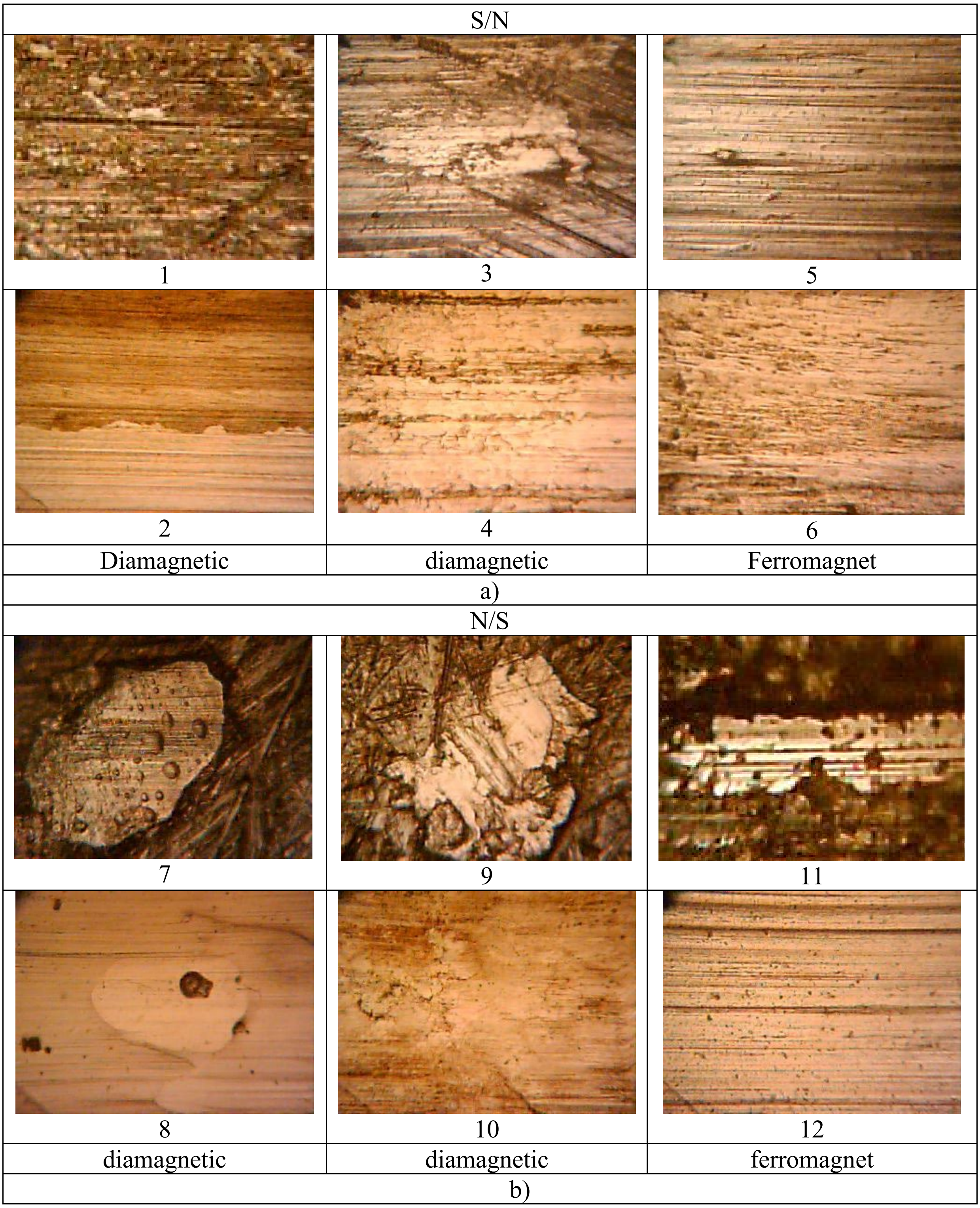


**Figure 14** – Topographies of friction surfaces 45 in the PEG400-50% medium according to LS59-1

Thus, the change in current strength in the contact passing through the friction surface is a characteristic of the formation and change in the conditions of coverage of each of the friction planes.

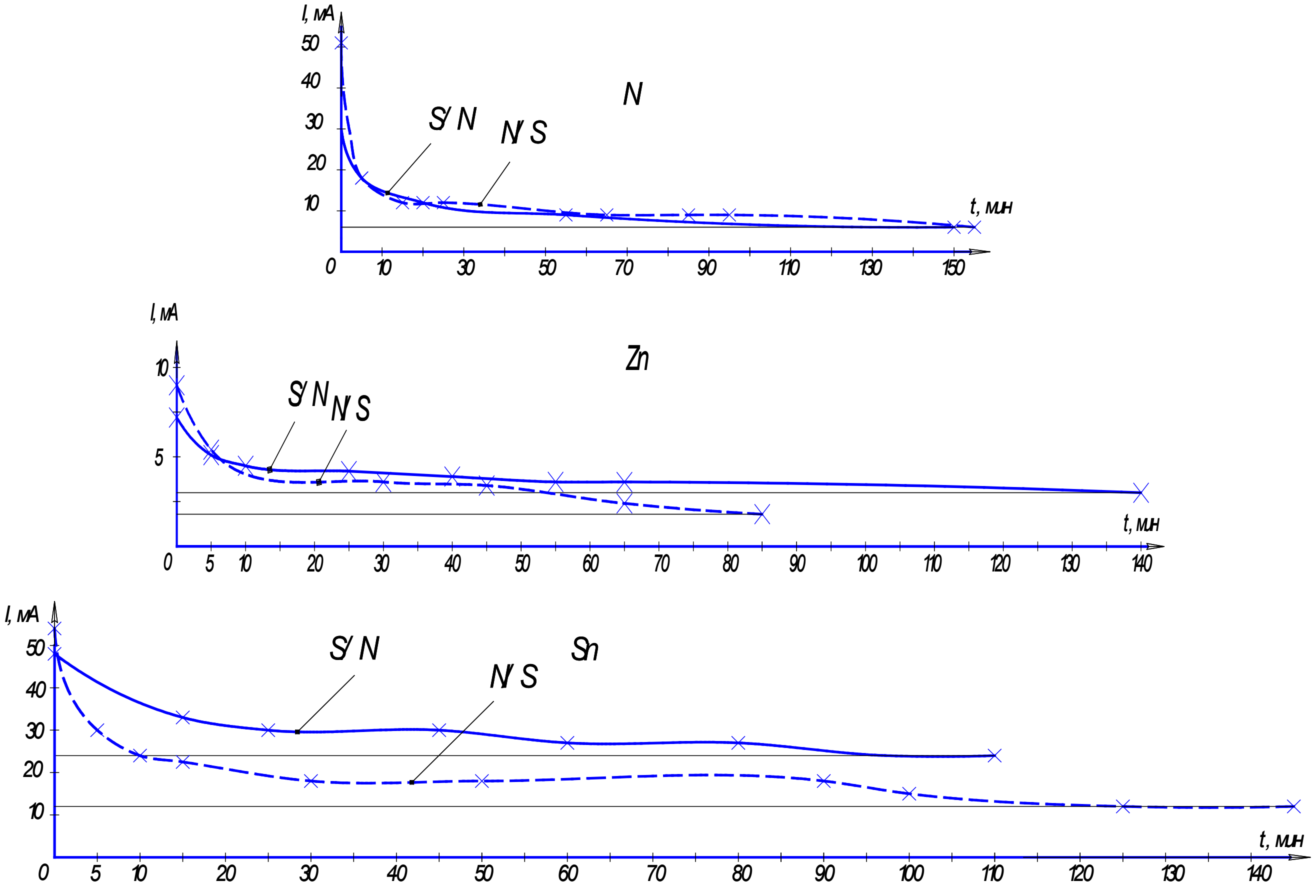


**Figure 15** – Current dependences on time with the addition of finely dispersed powders in PEG-400 50% under the influence of MP.

## Conclusions

Electromagnetic field processing of materials refers to technologies using highly concentrated energy sources. These technologies are diverse, progressive, widely used and have a number of advantages:

- universality – for the electromagnetic field used in the process of energy stabilization of tribosystems, there are practically no restrictions on the action on certain structural materials, geometric shapes of parts and working environment, including lubricating oil;

- continuity of the energy stabilization process of tribosystems and the possibility of its finest regulation and automation;

- the field energy and the interacting active particles (ions) affect the surface of the wear part and the lubricating oil. There is no need to convert electrical energy into thermal or mechanical energy and the complex devices used for this, as is the case with traditional methods of material processing.

The advantages provided prove that energy stabilization of tribosystems using materials and energy from external sources is economically justified.

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